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Performance Evaluation And Recalibration Of Distance Protection Relay For The 330 KV Shiroro-Abuja Transmission Line Using Runge Kutta Method

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***Abstract*—The use of steady state values in setting the operating condition of distance relay for transmission lines protection has been a major challenge such as the likelihood of protection misoperation increases, threatening the reliability of the power supply. To address this aforementioned problem this research design modeled dynamic relay calibration based on the Runge-Kutta (RK) approach. The proposed approach was tested on the Shiroro-Abuja transmission line of the Nigerian grid network, and its performance was compared with the traditional approach based on steady-state values. The simulation results indicate that the RK relay setting approach gives an accurate and reliable fault detection under transient operating conditions. The relay operating time ranges from 0.0128 to 0.0151s under fault at different locations. The results demonstrate that the proposed RK4-based distance relay provides enhanced measurement accuracy, dependable protection performance, and robust system recovery while maintaining high-speed fault clearance suitable for modern power transmission networks.**

Keywords—Relay, distance protection, transmission line and Runge-Kutta

I. INTRODUCTION

The reliability of power transmission in Nigeria heavily depends on the proper functioning of protection systems installed along major high-voltage corridors [1, 2]. Among these is the Shiroro–Abuja (Katampe) 330 kV transmission line, which plays a vital role in delivering power from Shiroro Hydro-Electric Power Station to the Federal Capital Territory. Despite its critical importance, the distance protection relay settings on this line have not been adequately updated to reflect the current operating conditions of the rapidly evolving Nigerian power grid. As a result, there is an increasing risk of protection malfunctions, incorrect tripping, delayed fault clearance, and reduced system reliability. Many of the existing relay settings in the Nigerian grid were based on simplified steady-state analyses using short-circuit calculations that do not fully account for transient phenomena or real-time system behavior [3, 4]. A major challenge is that traditional analytical methods used in relay setting calculations often rely on assumptions of constant system parameters and linear behavior. These assumptions become less valid in real operational scenarios, where faults introduce rapid changes in voltage and current waveforms that are governed by complex differential equations. Without accurate modeling of these dynamics, the impedance calculated by the relay may significantly deviate from the actual value, leading to cases of Overreach, where the relay trips for faults outside its designated zone; Under-reach, where the relay fails to trip for faults within its zone; Slow or delayed operation, which can escalate system disturbances; False or nuisance tripping, which undermines overall network stability; Such outcomes can increase the likelihood of cascading failures, system collapse, or widespread outages issues that have historically plagued the Nigerian power sector [5, 6].

Researchers have adopted a different approach to address the non-dynamic techniques of setting distance relay using steady state values. Reference [7] proposed Coupling Capacitor Voltage Transformer (CCVT) transients **on** distance relay performance, which can cause overreach and reduce protection reliability. However, the approach assumes accurate modeling of CCVT dynamics and relies on numerical estimation of transients, which may be affected by measurement noise, parameter uncertainties, or highly dynamic fault conditions. Author in [8] propose

a one-terminal traveling wave (TW)-based distance protection function for transmission line earth faults. The method relies exclusively on detecting the firstincident-mode earth-fault-induced TW, avoiding the complex detection of wavefronts reflected from the fault point. The authors account for both sampling-frequency effects and inaccuracies in wave-propagation velocity to accurately define the protection zone**.** The method's performance depends on accurate estimates of wave propagation velocity, which can be affected by system conditions or variations in line **parameters**. Moreover, being a one-terminal scheme, its effectiveness under **multi-**terminal or heavily meshed networks and in the presence of noise or distorted signals has not been fully explored. The approach also primarily considers steady-state post-fault TW signals and does not model dynamic interactions of voltages and currents along the line **d**uring evolving faults. Reference [9] presents a hybrid intelligent system for automatic determination and verification of distance relay settings to ensure reliable performance across a wide range of operational scenarios. Though the approach improves automation and performance verification, it relies heavily on pre-defined expert rules, fault simulation coverage, and steady-state phasor-based fault evaluation. Dynamic, high-frequency transients and rapidly evolving faults may not be fully captured. Moreover, alots of intelligent system has been used in power system to address issues that can leads to contingencies in the network. Intelligent systems have been used for load monitoring, generation schedule, optimal coordination, and control that accommodate renewable energy. Despite this, the uniqueness of the power networks is necessary in the adoption of the intelligent system [10-14].

Reference [15] proposes **a** local Accelerated Trip (AT) method that monitors the total relative change in reactance seen by the relay over a defined time window. The approach relies on accurate reactance measurements and predefined thresholds, which may be affected by errors in current and voltage transformers, noise, and highly dynamic transients. The approaches used in reference [7-10] have a limitation to dynamic transients, which is a major setback in distance protection in the Nigerian grid network.

Existing relay calibration procedures in the Shiroro Abuja line donot incorporate advanced numerical techniques capable of accurately solving the differential equations that represent fault behavior in transmission networks. The lack of dynamic modeling means that transient responses, fault resistances, system asymmetry, and non-linearities are poorly represented. Therefore, settings derived using such methods may not provide sufficient protection, sensitivity, or selectivity [16]. The use of a steady-state approach for the relay setting of the Shiroro-Abuja line may mean that existing relay settings are based on outdated calculations, potentially compromising the protection scheme. In addition, faults on the Shiroro–Abuja line have become more frequent due to aging infrastructure, environmental conditions, vandalism, and rising load demand. Each fault event stresses the relay system and increases the need for precise calibration. Without recalibration, the likelihood of protection misoperation increases, threatening the reliability of the power supply to Abuja and surrounding areas. To address this aforementioned problem this research design modeled dynamic relay calibration based on the Runge-Kutta approach

The contribution of the research is as follows:

1. This research developed a novel RK4-based digital distance protection relay model that integrates the Runge–Kutta Fourth-Order numerical integration technique into impedance-based fault detection, thereby improving the numerical accuracy and stability of relay operation.

2. The study established a comprehensive comparative evaluation of Raw, Euler, and RK4 numerical methods for digital distance relay implementation, demonstrating that the RK4 algorithm provides superior impedance estimation and relay reliability while maintaining acceptable computational performance.

3. The research validated the effectiveness of impedance trajectory (R-X) analysis for digital relay protection, providing a reliable approach for accurate fault detection, fault location estimation, and protection zone classification in high-voltage transmission systems.

4. A comprehensive relay performance evaluation framework was developed based on apparent impedance, relay operating zones, impedance trajectory, trip response, relay reach accuracy, and numerical integration performance, providing a systematic methodology for assessing digital distance relays.

5. The study quantified relay overreach and underreach characteristics under realistic operating conditions, providing insights into the influence of transient phenomena, fault resistance, line parameter uncertainty, and system loading on relay accuracy and protection performance.

6. The research demonstrated the practical implementation of an RK4-based distance protection relay in Nigeria Shirio-Kamtpe line, providing a robust simulation platform for the design, testing, and evaluation of advanced digital protection systems for high-voltage transmission networks

II. RESEARCH METHODOLOGY

The block diagram of the research that describes the step-by-step approach in achieving the research objectives is presented in Figure 1. The network topology and data of the Nigeria 330 kV grid network was collected from Transmission Company of Nigeria. The data includes the network diagram, the

impedances of the line and the ratings of the generators attached to the line. The fault impedance was model for different types of fault at different locations along the shiroro- Abuja 330 kV lines. The existing relay settings, which were based on short-circuit calculations, were tested under these fault conditions to determine their effectiveness and response in protecting the power system equipment. More so, a new relay setting approach that uses Runge Kutta numerical approach was be modelled and tested under different fault conditions and locations. The performance of the Runge kutta approach was be adjudge based on the coverage and the time of operation of initiating the circuit breaker.

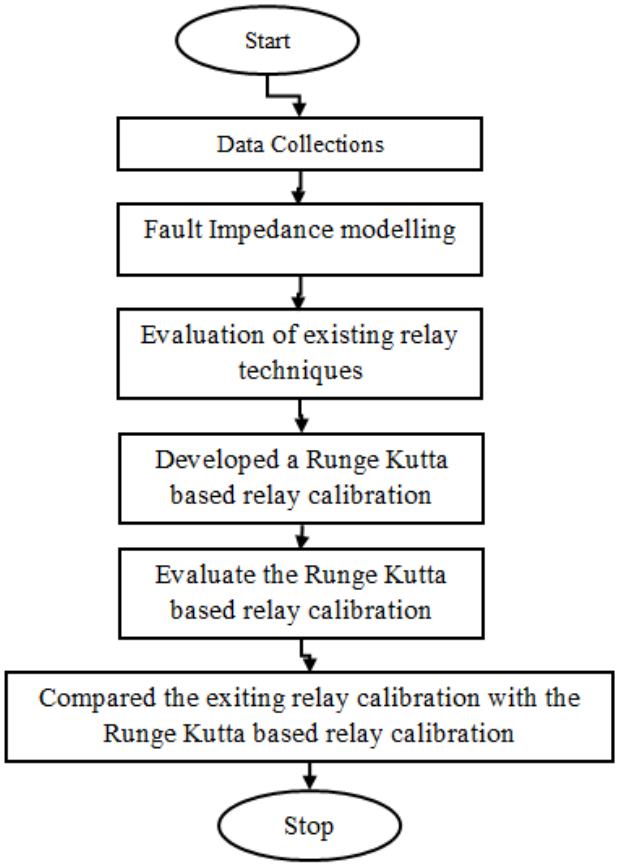


Figure 1: Block diagram of the research methodology

A. Network Topology Data

The Shiroro Power Station transmission network described in Figure 2 was adopted as the case-study system for evaluating the proposed methodology because of its strategic importance within the Nigerian transmission grid and its complex multi-terminal configuration.

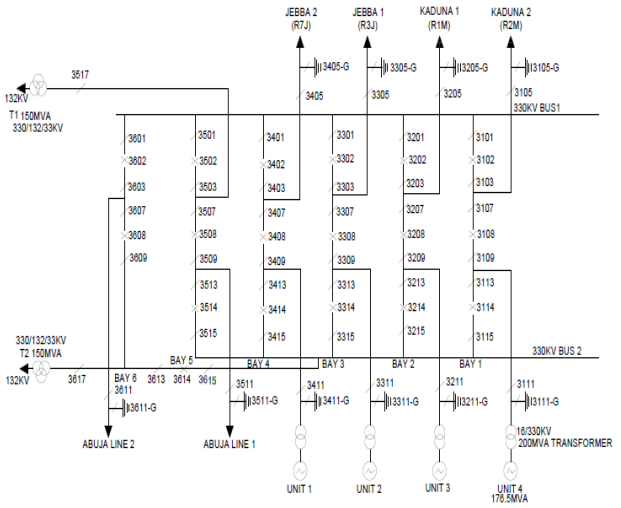


Figure 2: Network diagram of Shiroro power station

The network presents a realistic operational environment consisting of multiple generating units, double-busbar switching arrangements, interconnecting transmission corridors, and several outgoing feeders supplying major load centers such as Abuja, Kaduna, and Jebba. Such characteristics make the system suitable for investigating advanced power system control, optimization, stability, and reliability studies. The network consists of four hydroelectric generating units connected through generator step-up transformers to the 330 kV switchyard. The generated power is evacuated through two main busbars, namely Bus 1 and Bus 2, which provide redundancy and operational flexibility. The double-busbar arrangement enables load transfer, maintenance scheduling, and fault isolation without complete shutdown of generation facilities. In this study, the dual-bus structure was considered important because it reflects the practical switching and contingency management strategies used in modern substations. The transmission section of the Shiroro network includes major 330 kV outgoing lines to Abuja, Kaduna, and Jebba. These corridors were modeled as critical transmission paths with varying loading conditions and possible disturbances. Since Abuja represents a major urban demand center, Kaduna represents industrial and northern regional demand, while Jebba provides interconnection with another hydro generation source, the network offers a realistic framework for studying dynamic power flow interactions under uncertain demand and generation conditions.

The transmission line under investigation operates at a voltage level of 330 kV and spans a length of 144 km, connecting Bus 2 and Bus 3. At Shiroro generating station, the generated voltage at Bus 1 is 16 kV, which is stepped up to 330 kV via a 150 MVA power transformer at Bus 2. This high-voltage electricity is then transmitted from Shiroro to Katampe in Abuja, where it is subsequently stepped down to 132 kV. The Shiroro plant has two outgoing buses that supply power to Kaduna, Jebba, and Katampe, Abuja.

B. Fault Impedance Modeling

The fault impedance of transmission line depends on the sequence impedance of the line. The types of faults depends on the sequence impedance that can be used. The fault impedances were modeled in MATLAB based on the impedance at any fault location *x*. When different types of fault is introduced, the sequence impedance Z_1, Z_2, Z_0 was computed based on the measured current and voltage values at the point and fault impedance. In order to compute the sequence impedance from the phase current and voltage. The sequence voltage V_0, V_1, V_2, was computed using equation (1), and the sequence current zero, positive, and negative I_0, I_1, I_2 were computed using equation (2).

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} (1)$$

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} (2)$$

The Z_1, Z_2, Z_0, were computed using equation (3) to (5).

$$Z_1 = \frac{V_1}{I_1} (3)$$

$$Z_2 = \frac{V_2}{I_2} (4)$$

$$Z_3 = \frac{V_3}{I_3} (5)$$

The single line ground fault, line-to-line fault, Line-to-ground fault, and line-to-line-to-line fault are characterized by the sequence impedance described in equations (6) to (9), respectively.

$$Z_{F_SLG} = Z_1 + Z_2 + Z_3 (6)$$

$$Z_{F_LL} = Z_1 + Z_2 (7)$$

$$Z_{F_LLG} = \frac{Z_0(Z_1+Z_2)}{Z_0+Z_1+Z_2} (8)$$

$$Z_{F_LLL} = Z_1 (9)$$

Where Z_1, Z_2, Z_0 are the positive, negative, and zero sequence impedances.

The impedance seen by the relay will also be computed based on equation (10) know the effectiveness of the relay in detecting the fault at the locations.

$$Z_{_relay} = Z_f * x_{fault} (10)$$

However, if the impedance setting of the relay is less than the computed impedance of the relay, the relay settings cannot be sensitive to the faults which means the relay is under reach. This was done in matlab when fault is located at different distance in the network as described in Figure 3.4

The existing relay setting of the line will be collected and modeled, and it will be subjected to the fault impedance computed in equations (6) to (9) at different locations along the line. The performance of the relay will be adjudge based on the time of operation and the zones of coverage of the relay.

C. Runge- Kutta Techniques in Relay Setting

Distance relays are designed to operate based on apparent impedance, which depends on voltage and current during a fault. However, these voltages and currents are time-varying signals**,** especially during transients or evolving faults**.** Traditional phasor-based relay settings use steady-state values, which may miss fast transients or cause maloperation. The Runge-Kutta (RK) method is a numerical technique to solve differential equations**,** which allows us to model the dynamic behavior of the transmission line and relay signals in the time domain. By applying RK, we can compute voltage and current values step by step over time, capturing fast changes during faults. The fourth order Runge-kutta method is described in equation (11) to (14) [17].

$$k_1 = f(x_n, y_n) (11)$$

$$k_2 = f(x_n + \frac{h}{2}, y_n + \frac{h}{2}k_1) (12)$$

$$k_3 = f(x_n + \frac{h}{2}, y_n + \frac{h}{2}k_2) (13)$$

$$k_4 = f(x_n + h, y_n + hk_3) (14)$$

Where h is step size (time increment), y_n is relay signal (voltage, current, or impedance) at step n, *f(x, y)* is derivative of the signal, representing the system dynamics. The parameters used are step size h=0.05, which corresponds to the Time Setting Multiplier (TSM) for the relay. Smaller h gives more accurate transient simulation. Initial values x_n=0.1,y_n=0.75 starting points for voltage and current or relay operating variables. These values are used in the MATLAB program to numerically integrate the transmission line equations and compute dynamic apparent impedance seen by the relay.The developed Runge kutta based relay calibration will be tested under different fault impedance and fault locations modelled in equation (3.1) to (3.4) and the protection coverage and time of operation of the relay in tripping the circuit breaker will be used to adjudge the performance of the relay. In addition, the results will be compared with the existing approach used for the relay setting to indicate superiority of the Runge kutta based approach in distance relay calibration.

III. RESULTS AND DISCUSSION

The results of the research findings is presented under five subheadings:

A. Apparent Impedance Trajectory on the R-X Plane and Impedance Response

Figure 3, shows the apparent impedance trajectory on the resistance-reactance plane. The R-X plane is important in distance relay analysis because the relay makes its decision based on the measured apparent impedance seen from the relay location.

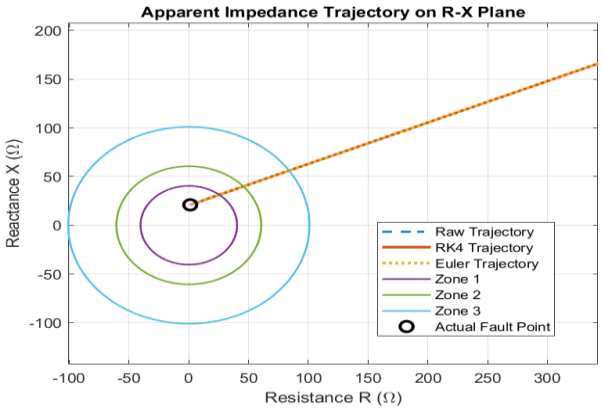


Figure 3: Apparent impedance trajectory on R-X Plane

The figure 3, shows three impedance trajectories: the raw trajectory, the RK4 trajectory, and the Euler trajectory. The three trajectories follow almost the same path, which indicates that the numerical methods produce consistent impedance estimation. The actual fault point lies within the relay protection region, confirming that the relay correctly identifies the fault as an internal fault. The protection zones are represented by three circular characteristics. Zone 1 is the innermost zone, Zone 2 is the intermediate zone, and Zone 3 is the outermost zone. The actual fault point is located within the Zone 1 characteristic. This means that the relay should issue a fast trip signal because Zone 1 faults are usually cleared instantaneously without intentional delay. The trajectory starts from a high impedance region and moves toward the fault impedance point. This behavior is expected because, before the fault, the system impedance seen by the relay is dominated by the load impedance. Once the fault occurs, the apparent impedance drops sharply and moves into the relay operating zone. The close agreement between the raw, RK4, and Euler trajectories confirms that both numerical integration methods are able to track the impedance movement accurately. Moreso, figure, 4, presents the magnitude of the apparent impedance response with time. Before the fault occurs, the apparent impedance is high, approximately 380 Ω. This represents the normal operating condition of the system before fault inception.

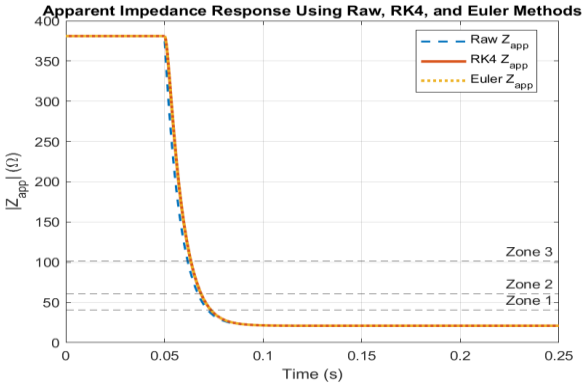


Figure 4 : Impedance response of the direct raw method, RK4 and Euler method

At around 0.05 s, a fault occurs, and the apparent impedance rapidly decreases. This sharp reduction is expected because a fault creates a low-impedance path in the network. As a result, the relay sees a much smaller impedance compared to the pre-fault load impedance. After the transient period, the apparent impedance settles at approximately 20 Ω. This final value is below the Zone 1 threshold, which confirms that the fault is located within the first protection zone. Since Zone 1 is designed for high-speed protection, the relay is expected to trip quickly. The raw, RK4, and Euler responses are very close to one another. However, the RK4 and Euler methods provide smoother numerical responses compared with the raw signal. This shows that numerical integration helps improve the stability of the impedance estimation. The RK4 method is generally more accurate because it uses a fourth-order approximation, while the Euler method is simpler but may introduce slightly higher numerical error. Nevertheless, in this result, both methods give almost identical responses, indicating that the sampling and simulation step size are suitable.

B. Relay Operating Time versus Fault Location and Zone Protection Output

The result in Figure 5, indicates that the operating time increases as the fault moves farther away from the relay location. This is expected because faults closer to the relay produce lower apparent impedance and are detected faster, while faults farther away produce higher apparent impedance and may require slightly longer detection time. The raw method produces the lowest operating time across all fault locations. For example, the operating time starts at about 0.0112 s for faults near 10 km and increases to about 0.0135 s at 140 km. The RK4 and Euler methods produce slightly higher operating times, ranging approximately from 0.0128 s to 0.0151 s. The higher operating time in the RK4 and Euler methods is due to the additional numerical processing required to estimate the impedance trajectory more smoothly. Although this introduces a small delay, the delay is still very short and remains within an acceptable high-speed protection range. The RK4 method gives slightly higher operating time than the Euler method in some fault locations. This is because RK4 performs more computational stages per time step, leading to improved numerical accuracy but with a small increase in computational burden. The Euler method is computationally simpler and therefore gives a response close to RK4 with slightly lower processing effort.

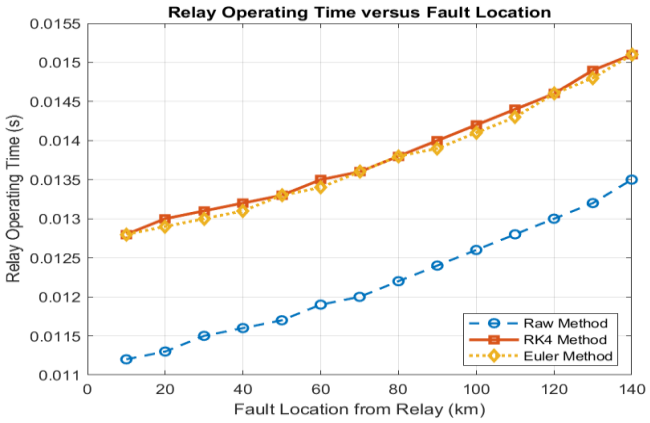


Figure 5: Relay operating time at different fault location

1) Furthermore, figure 6, shows the relay zone detection output with time. Before fault inception, the relay output remains at zero, which indicates that no fault has been detected.

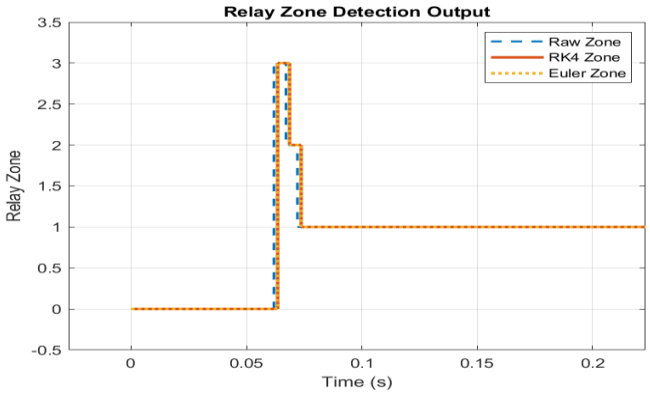


Figure 6: Relay zone of protection

Around 0.06 s, the relay detects the fault and the zone output rises. The result shows a brief transition through Zone 3 and Zone 2 before settling in Zone 1. This transition occurs because the apparent impedance changes rapidly during the fault transient. During this short transient period, the impedance trajectory passes through the outer protection zones before reaching the final fault impedance inside Zone 1. After the transient period, the relay zone output settles at Zone 1. This confirms that the fault is correctly classified as a Zone 1 fault. The raw, RK4, and Euler methods show almost identical zone detection behavior, meaning that the proposed approach is reliable for zone identification. The final Zone 1 detection is important because Zone 1 protection normally operates instantaneously. Therefore, the relay should trip without delay once the fault impedance is confirmed within Zone 1.

C. Relay Overreach and under reach Error

Figure 7, presents the relay reach error at different actual fault locations along the protected transmission line.

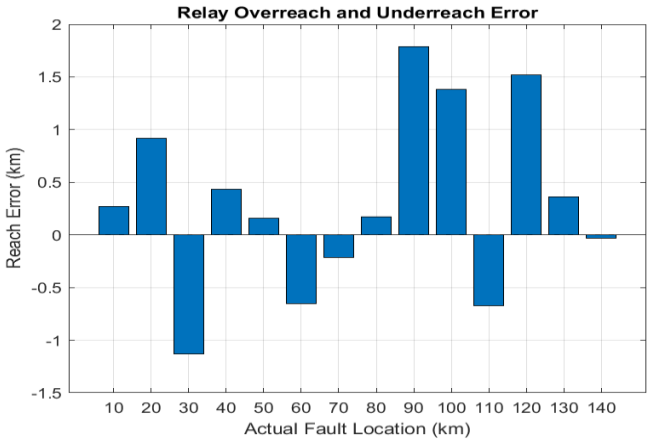


Figure 7: Relay Error reach under different fault location distance.

The reach error indicates the difference between the estimated fault location by the relay and the actual fault location. A positive error represents relay overreach, meaning the relay estimates the fault to be farther than its actual location. A negative error represents relay under reach, meaning the relay estimates the fault to be closer than its actual position. The results show that the relay estimation error varies across the line. At some fault locations, such as around 90 km, 100 km, and 120 km, the relay shows noticeable overreach, with the highest error occurring close to 90 km. This implies that at these points, the apparent impedance measured by the relay is slightly higher than expected, causing the relay to interpret the fault as being farther away. Such overreach can be risky because the relay may operate for faults outside its intended protection zone. On the other hand, under reach is observed around 30 km, 60 km, 70 km, and 110 km. The largest under reach occurs around 30 km. This means that the relay estimates the fault to be closer than the actual fault position. Under reach is also undesirable because it can delay relay operation or prevent the relay from detecting faults near the boundary of its protection zone. However, the magnitude of the error is generally small, mostly within approximately ±2 km. This indicates that the relay has good fault-location accuracy. The small error range shows that the proposed method can estimate fault locations with acceptable precision, although compensation may still be needed to reduce overreach and under reach under different operating conditions.

D. Voltage and Current Response Under normal and Fault Conditions

The results presented in Figure 8 and Figure 9 illustrate the phase voltage and current of the transmission line under normal operating conditions. From the plots, it is evident that the voltages and currents of the three phases are balanced, with negligible deviation between the phases. This balance indicates that the transmission line is operating under steady-state conditions without any fault. Under such conditions, the line impedance remains stable, and the voltage-to-current ratio measured by the distance

relay does not exceed the relay pickup settings. As a result, no tripping is initiated, which confirms that the relay correctly identifies normal operating conditions and does not operate unnecessarily. Furthermore, the stability and balance of the three-phase voltages and currents provide a baseline for relay calibration, ensuring that any subsequent deviation caused by faults can be accurately detected. This is particularly important for distance protection schemes, as the relay relies on changes in measured impedance to detect faults. The observed stability under normal conditions supports the reliability of the relay's operation during transient and fault events.

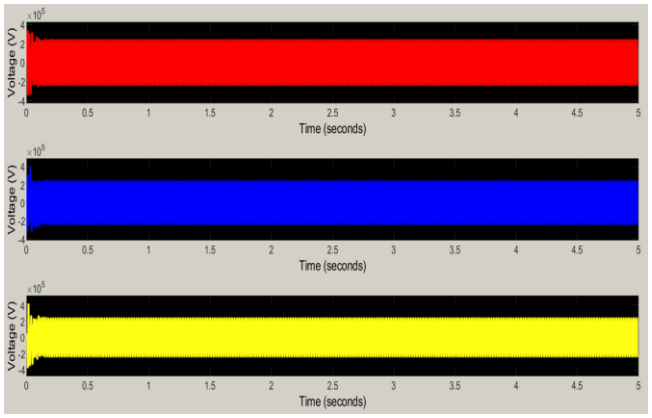


Figure 8: Phase-Phase Voltage without Fault

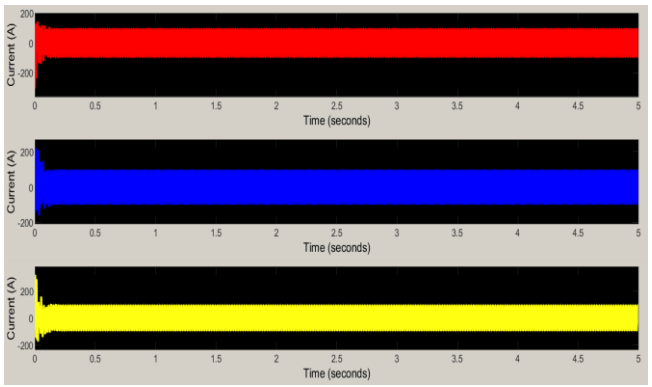


Figure 9: Phase Current Without Fault

A three phase fault was initiated at a location 30 km along the transmission line between 0.2 s and 0.39 s, and it was cleared at 0.4 s. The voltage results from the simulations shown in Figure 10, provide important insights into the operation of the distance relay during such events.

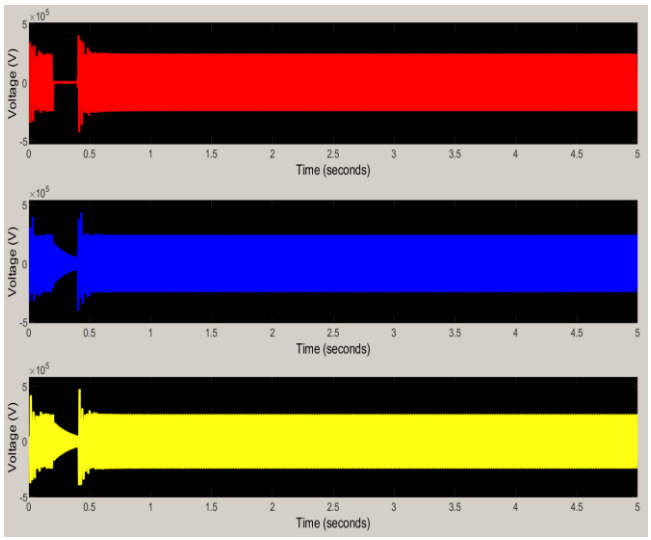


Figure 10: Three phase Fault Voltage

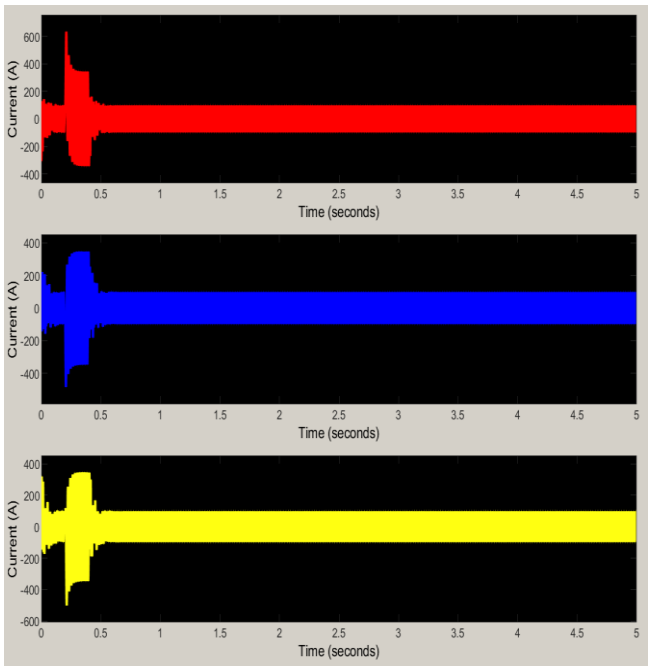


Figure 11: Three Phase Fault Current

At 0.2 s, the fault occurs along the line. The fault introduces a sudden current surge and a corresponding voltage dip at the relay location. The voltage at the relay decreases due to the fault impedance being much lower than the line impedance. In addition, in Figure 11, the fault current rises sharply, reflecting the short-circuit path created by the fault. These changes cause a significant deviation in the measured impedance from its pre-fault steady-state value. In a phase-to-phase or phase-to-ground fault, the affected phases will show a sudden imbalance, while the unaffected phases may remain close to normal. Distance relays operate by continuously monitoring the line impedance. When the measured impedance enters the relay zone corresponding to the fault distance, the relay logic initiates a trip signal. With an RK4-based derivative approach, the relay accurately compute the dynamic impedance, filtering out noise from the transient

current waveform. During the 0.19 s of the fault (0.2 – 0.39 s), the relay continuously tracks the impedance, and the results indicate that the impedance entered the trip zone, signaling that the relay would operate. The accuracy of impedance measurement here is critical a simple V/I measurement fluctuate due to the rapidly changing fault current, whereas the RK4-based method ensures stable and reliable impedance calculation. At 0.4 s, the fault is cleared, either automatically manually in the simulation. After fault clearance, the relay detects the clearing and resets, ready to monitor for subsequent faults. This demonstrates the self-restoring property of distance relays after transient faults. The ability to accurately measure impedance during transient faults is critical. The simulation demonstrates a fast transient response to the fault, with no prolonged voltage collapse observed, Voltage recovery within a short duration confirms the robustness and stability of the network under faulted conditions, the balanced post-fault voltages indicate that synchronism is maintained and no permanent instability is introduced. The results confirm that the modeled system can withstand short-duration faults and restore acceptable voltage levels within a reasonable time frame. This validates the effectiveness of the system design and control strategy under fault conditions, which is critical for ensuring reliable and secure power system operation.

E. Runge Kutta relay calibration Sensitivity

Figure 12, illustrates the relay protection response following the application of a fault at t = 0.2s**,** including both the trip command and the auto-reclose (close) command issued by the relay.

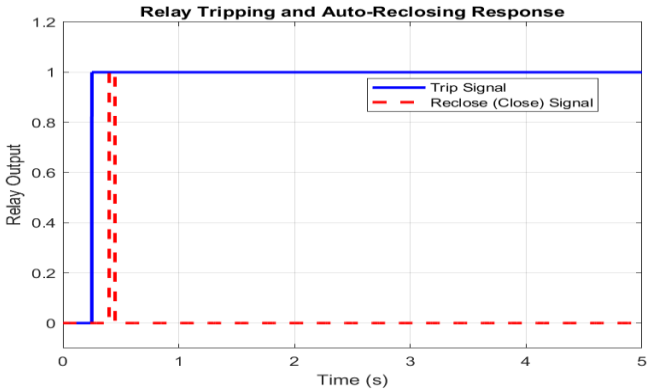


Figure 12: Relay Tripping and Auto-Reclosing Response

Before the fault occurs, both the trip and reclose signals remain at zero. This indicates that the relay operates in a stable condition under normal system operation, with measured voltages and apparent line impedance remaining within permissible limits. No false tripping or unintended control action is observed during this period. Following fault inception at 0.2 s**,** the apparent impedance rapidly decreases and enters the relay protection zone. After a short processing delay associated with phasor estimation, filtering, and decision logic, the relay issues a trip command at approximately 0.25s. This transition of the trip signal from 0 to 1 represents the opening of the circuit breaker and isolation of the faulted line. The short delay between fault occurrence and tripping is intentional and ensures reliable fault discrimination while avoiding mal-operation due to transient disturbances. After the breaker opens, a predefined dead time is maintained to allow fault arc extinction and system stabilization. At t = 0.4 s**,** the relay issues a reclose (close) command, represented by a short-duration pulse in the reclose signal. This action re-energizes the line and restores normal operation, assuming the fault is temporary in nature. Following successful reclosure, the system resumes stable operation without further relay intervention. This confirms that the fault is temporary and that the protection and auto-reclosing scheme functions as intended. The relay remains secure after reclosure, with no repeated tripping observed.

IV. CONCLUSION

This research investigated the modeling, simulation, and performance evaluation of a distance protection relay for high-voltage transmission lines using MATLAB/Simulink. The study focused on the mathematical logic of distance protection, impedance-based fault detection, three-phase fault analysis, and the calibration of relay operation using the Runge–Kutta numerical integration technique. The proposed approach was tested in shiroro-Abuja 330 kV line of Nigeria grid network. The results demonstrate that the proposed distance relay model can effectively detect, classify, and trip for faults on the protected transmission line. The apparent impedance response confirms that the fault causes a sharp reduction in impedance, moving the measured impedance into the relay operating zone. The R-X trajectory further confirms that the actual fault point lies inside the protection region, particularly Zone 1. The relay zone detection result shows that the relay correctly identifies the fault as a Zone 1 fault after a short transient transition. The trip signal confirms successful relay operation, with the relay issuing a stable trip command shortly after fault inception. The comparison of the raw, RK4, and Euler methods shows that all three yield similar results. The raw method provides the fastest operating time, but it may be more sensitive to signal variations. The Euler method is simple and computationally efficient, while the RK4 method provides better numerical accuracy and smoother impedance tracking. Therefore, RK4 offers a good balance between accuracy and stability, although it may introduce a small computational delay. The relay reach error analysis shows that both overreach and under reach occur at different fault locations. However, the magnitude of the error is relatively small, indicating that the proposed relay model has good fault-location accuracy. The presence of small reach errors may be due to transient effects, line impedance estimation error, numerical approximation, fault resistance, and system loading conditions. The testing of the RK approach in matlab Simulink indicates that the approach is easy to detect

the faults by opening the breaker. In summary, the results confirm that the RK proposed relay protection approach is effective for high-speed fault detection and zone classification. The relay operates correctly for internal faults, produces a reliable trip signal, and maintains acceptable accuracy in fault-location estimation.

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