



Simulation-Based Time-Domain Short-Circuit Fault Evaluation and Protection System Reliability Analysis in 300MVA Substations with 132kV Transmission Lines

Oghoghme Richard Umuroh*

Department of Electrical/Electronic Engineering, Petroleum Training Institute (PTI), Efurrum, Delta State, Nigeria, Africa

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ABSTRACT

This study conducted a simulation-based time-domain short-circuits fault evaluation and protection system reliability analysis in 300 MVA substations with 132 kV transmission lines in Asaba (Ibusa/Asaba), Delta State, Nigeria. The analysis focused on two primary parameters: protection system dependability and selectivity, to determine the conditions necessary for ensuring rapid fault clearance and stable substation operation under line-to-ground, double-line, and three-phase faults. Fault currents, voltages, and relay trip signals were generated and analyzed using MATLAB time-domain simulations. Results indicated that system dependability exceeded 97% and security surpassed 95% when total fault-clearing times remained below 120 ms. Relay coordination intervals of 0.2–0.4s, backup misoperation below 3%, and circuit breaker MTBF above 20,000h ensured selective fault isolation. Extended fault durations beyond 120ms or improperly coordinated relay settings increased the likelihood of misoperation and voltage instability. It was concluded that uninterrupted substation operation depends on integrating time-domain fault evaluation, coordinated relay settings, and reliable breaker performance into protection management protocols. Accordingly, it was recommended that substation operators maintain precise relay coordination, implement continuous time-domain monitoring, and uphold breaker maintenance schedules. These actions will further enhance the protection reliability, reduce fault propagation risks and support safer, more stable operation of the 132 kV transmission network.

Keywords: Time-Domain Simulation, Short-Circuit Faults, Protection System Reliability, 132 kV Substations.

Original Research Article

*Corresponding author: Oghoghme Richard Umuroh (MNSE). Email: fxintegritypublishing@gmail.com. +234(0)8134642738. Department of Electrical/Electronic Engineering, PTI Efurrum, Delta State, Nigeria, Africa

Introduction

Protection performance in power systems is an essential criteria of safe and reliable operation of high-voltage transmission systems, especially at bulk supply substations, which are the points of connection of large generation sources with extensive geographical centres of loads (Rad & Moravej, 2017; Abdulkareem et al., 2016). Symmetrical and unsymmetrical faults continue to be the most prevalent in the 132kV transmission system of Nigeria, contributing to disturbance of the system, degradation of equipment and forced outages, with single line to ground fault being most common as a result of lightning activity, ageing of the

insulation and exposure to the environment. Failure to detect and clear faults within acceptable time limits causes excessive fault currents to subject transformers, transmission lines, and circuit breakers to severe thermal and mechanical stress, which rapidly accelerates the breakdown of insulation or causes contact erosion and loss of mechanical integrity (Kopylov et al., 2019; Abdulkareem et al., 2016; Adepoju et al., 2013;). Past research on the Nigerian grid also indicates that failure in either relay sensitivity, coordination, or breaker operation may extend beyond the faulted fault area making the network less stable and predisposing to cascading failures affecting a significant area of the transmission system

(Akisotet et al., 2022; Ogar et al., 2017; Atuchukwu-John, 2015). These obstacles highlight the importance of methods of protection system assessment which would extend beyond the steady state fault calculations and would instead represent the dynamism of an actual fault event. Time domain short circuit simulation offers a highly analytical model of currents and voltages during line to ground, double line to ground and three phase faults, and allows a comprehensive analysis of the behaviour of pickup in relays, the effects of transient saturation, and breaker interruption performance in real operating conditions (Eid & Montoya, 2022; Malafeev & Iuldasheva, 2015).

The technically notable case of such analysis is the Asaba (Ibusa/Asaba) 330, 132, 33kV transmission substation, which is a bulk power station serving several 132kV transmission corridors in Delta State and the South-South region of Nigeria, in general. Installation of a 300MVA transformer and concentration of multiple outward lines of transmission necessitates rapid and discriminative fault isolation to avoid the extensive disturbances and ensure system steadiness. Protection plans implemented at this voltage such as overcurrent, distance, and differential protection should coordinate to make sure that fault is cleared quickly with primary protection and the backup elements should be activated only when needed such that these systems remain selective and reduce the number of unnecessary failures (Aslam et al., 2022; Bhalja & Maheshwari, 2007). The uncertainty in transmission line parameters, transformer impedance and grounding structure, precision of current and voltage transformers and mechanical reliability of circuit breakers are all factors that affect how the protection will perform in such environments, and must be modeled in time domain simulations, in order to give realistic results. The reliability indices of dependability and security give the probabilistic measures of accurate relay operation in faulty conditions and restraint in non faulty or stressed operating conditions and give a quantitative basis of assessing the adequacy of the protection system (Khalili & Abur, 2021; Malafeev & Iuldasheva, 2015). Together with total fault clearing time limits and breaker mean time between failures, these indices can be used to evaluate protection performance in the environment of the Nigerian transmission network comprehensively. This study therefore engages in a simulation based time domain analysis of short circuiting faults and protection system dependability on a 300MVA transmission substation with 132kV, with focus on a coordinated operation, rapid fault clearing capability, high reliability and security to various fault situations.

Statement of the Problem

The 132kV transmission system in Nigeria is still facing persistent operational issues that have hindered the reliability of bulk power delivery especially in large capacity substations that serve large regional load centres. Weaknesses caused by insulation breakdown, exposure to environmental

factors in addition to shortcomings in protection performance usually leads to late isolation and high electrical stress on vital assets. Inadequate response to the protection in bulk nodes, like the Asaba (Ibusa/Asaba) 330/132/33kV substation, enables high fault currents to linger and catalyzes thermal ageing of the transformer, stressing the circuit breakers and making the transmission lines susceptible. Even though the modern protection schemes based on over current, distance and differential principles are implemented, the behaviour of the schemes at the working conditions is quantitatively evaluated very little. This insufficiency of time-domain assessment makes protection settings improperly tested, keeping assets stressed, risking outage and making them vulnerable to cascading disturbances throughout Delta State and the South-South grid at large.

Aim and Objectives of the Study

This study was aimed at conducting simulation-based time-domain short-circuits fault evaluation and protection system reliability analysis in 300MVA substations with 132kV transmission lines in Asaba (Ibusa/Asaba), Delta State, Nigeria. Specifically, the objectives were to:

1. Quantify the protection system reliability of a 300 MVA, 132 kV substation by determining dependability $\geq 97\%$, security $\geq 95\%$, and total fault-clearing times ≤ 120 ms for line-to-ground, double-line, and three-phase faults using time-domain simulation in Asaba (Ibusa/Asaba), Delta State, Nigeria.
2. Evaluate the performance of overcurrent, distance, and differential protection schemes by assessing coordination time intervals of 0.2–0.4s, backup relay misoperation probability $\leq 3\%$ and circuit breaker MTBF $\geq 20,000$ h for selective isolation of 132kV transmission line faults using time-domain simulation in Asaba (Ibusa/Asaba), Delta State, Nigeria.

Research Questions

1. What level of protection system reliability is required to achieve dependability $\geq 97\%$, security $\geq 95\%$, and total fault-clearing times ≤ 120 ms under line-to-ground, double-line, and three-phase faults in the 300 MVA, 132 kV substation at Asaba (Ibusa/Asaba), Delta State, Nigeria?
2. What performance characteristics are required of overcurrent, distance, and differential protection schemes to ensure selective isolation of 132 kV transmission line faults with coordination times of 0.2–0.4 s, backup relay misoperation $\leq 3\%$, and circuit breaker MTBF $\geq 20,000$ h at the 132 kV substation in Asaba (Ibusa/Asaba), Delta State, Nigeria?

Literature Review

Modern power systems are based on high-voltage transmission systems, which provide the system to transport high volumes of electricity that have been generated in the

generation stations to the distribution networks of large geographical areas (Rad and Moravej, 2017; Abdulkareem et al., 2016). Transmission lines of 132kV, as Idoniboyeobu et al. (2018) as well as Nagpal and Henville (2017) argue, can be considered important intermediate voltages that could not only facilitate load balancing and redundancy but also drinking to the interference, which is a threat to the stability of the system. Short-circuit fault due to fault currents on unintentional low-impedance phase-phase or phase-ground connection can result in severe thermal and mechanical loads on the transformers, transmission lines, and breakers in spite of the use of advanced protection systems (Kopylov et al., 2019; Malafeev & Iuldasheva, 2015). The overcurrent protection is also known as one of the most widespread schemes and isolation of the faulted zones by comparing the current measured to the pre-determined values (Aslam et al., 2022; Bhalja & Maheshwari, 2007). A scheme that uses voltage and current measurements to determine apparent impedance, as an enhancement of overcurrent schemes, to detect and isolate faults in transmission lines, is called distance protection (Mahmoud, 2025; Nagpal & Henville, 2017). Conversely, differential protection does not react to external disturbances but is sensitive to internal faults because it compares the currents flowing into a specified area with the current flowing out of it (Khalili & Abur, 2021; Abdulkareem et al., 2016). Based on the foregoing it has been established that time-domain simulation is a well-known methodology that can be used to simulate a dynamic interaction between relays, breakers, and line parameters during transient faults, which contains effects such as CT saturation, pickup delays at relays, and breaker sequences (Eid & Montoya, 2022; Lora et al., 2023; Ghaedi et al., 2020). Circuit breaker reliability is directly proportional to the success of fault interruption and the high-current condition by directly related to protection performance in the high-current condition and is commonly determined as the MTBF (Abdulkareem et al., 2021; Adepoju et al., 2013).

Nevertheless, the previous studies also acknowledge that the malcoordination of the relays, the vagueness of the parameters, and the shift in the topology of the network hamper the work of the protection systems of the Nigerian 132 kV substations (Akisot et al., 2022; Ogar et al., 2017; Atuchukwu-John, 2015). Voltage stability is one of the elements that are close to the successful operation of protection, and it refers to the network ability to maintain the desirable level of voltages under normal and disturbed conditions (Yao et al., 2024; Olabisi & Ayeni, 2023). High-resistance faults, also referred to as limitations of fault current flow, are also challenging to detect by the relay (reduced sensitivity) and transient saturation in CTs can come to a delay or false trip (Mahmoud, 2025; Bhalja & Maheshwari, 2007). Given the foregoing, the primary and backup relays are to be coordinated such that the capacity should be selective one (i.e., the ability to isolate the faulty part and provide the service in the healthy parts) (Akdağ et al., 2024;

Aslam et al., 2022). Dependability and security indices that are considered to be conventional indicators of the protection system reliability are the measures of the probability of the proper functioning under the conditions of actual faults and the restraint in the absence of faults respectively (Abdulkareem et al., 2021; Khalili & Abur, 2021; Malafeev & Iuldasheva, 2015). Experimental evidence demonstrates that simulation assessment enables engineers to evaluate these indices using a range of faults to enhance the resilience and stability of operational 132kV substations such as Asaba (Zhang et al., 2025; Akisot et al., 2022; John & Uguru, 2021; Panahi et al., 2021; Idoniboyeobu et al., 2018; Crossley et al., 2016).

Theoretical Framework

The probabilistic protection-reliability theory, which is based on the study conducted by Eid and Montoya (2022), assumes that probabilistic data enables the quantitative representation of performance of a system of electrical power under fault conditions based on probability distributions, system reliability measurements, and time series simulations. The theory was applied to this study because it offers systematic framework of testing the reliability of relays and security, circuit breaker MTBF, of line-to-ground, double line-to-ground, and three-phase faults. The further studies expanded on the range of activities to encompass the coordination, selectivity, and fault-clearing time measures in high-voltage networks (Mahmoud, 2025; Khalili & Abur, 2021; Nagpal & Henville, 2017). Its application in reality in Nigerian 132 kV substations demonstrates how probabilistic measures can form the basis of the performance of the protection systems, reduction of risks, and the process of operational resilience planning in complicated transmission systems.

Materials and Method

This study adopted a simulation-based time-domain methodology to evaluate the reliability and coordination performance of 132kV transmission line protection systems under short-circuits fault conditions. The study system was the Asaba (Ibusa/Asaba) 300MVA substation, modeled using detailed transmission line, transformer, and source parameters obtained from substation design data and manufacturer specifications. The protection system model comprised overcurrent, distance and differential relays, integrated with high-voltage circuit breakers rated for the interrupting duties of the 132kV network. Time-domain simulations were implemented in MATLAB/Simulink, enabling dynamic representation of fault inception, relay detection, decision logic, and circuit breaker interruption processes. Measurement inputs to the simulation included three-phase voltages, currents, relay operating signals, and breaker status signals, with assumed measurement accuracies of $\pm 0.1\%$ for voltage and $\pm 0.05\%$ for current, consistent with typical substation instrumentation. Operational data, including fault

initiation time, relay response time, breaker opening time and total fault clearing time, were derived from substation SCADA records and equipment manufacturer data, sampled at 5-second intervals for validation and calibration of the simulation model. Relay parameters such as pickup currents, inverse-time and definite-time characteristics, distance relay zone reaches, and differential sensitivity thresholds were configured in accordance with standard protection coordination practices for 132kV transmission networks. Protection coordination between primary and backup relays was ensured through appropriate time grading to achieve selective fault isolation. Circuit breaker reliability was evaluated using the MTBF approach, while protection system performance was quantified using dependability and security indices. The analysis considered single line-to-ground, double line-to-ground and three-phase fault scenarios, simulated at representative locations along the transmission line. Mathematical modeling and simulation outputs were then used to compute the overall protection system reliability and coordination performance indices.

$$\begin{aligned} \mathbf{v}(t) &= \mathbf{Z}_s \mathbf{i}(t) + \mathbf{Z}_f \mathbf{A}_f \left(\frac{\mathbf{v}_f(t)}{\mathbf{Z}_1 + \mathbf{Z}_2 + \mathbf{Z}_0 + \mathbf{Z}_f} \right) \\ T_{fc} &= T_d + T_r + T_{cb} \text{ with } T_{fc} \leq 120\text{ms}, \\ R_p &= \left(\frac{N_{op}}{N_f} \right) \left(1 - \frac{N_{false}}{N_n} \right), \text{ subject to } \frac{N_{op}}{N_f} \geq 0.97, 1 - \frac{N_{false}}{N_n} \geq 0.95 \end{aligned} \quad (3.1)$$

Where:

- $\mathbf{v}(t)$ = Vector of phase voltages at time t (V)
- $\mathbf{i}(t)$ = Vector of phase currents at time t (A)
- $\mathbf{i}_f(t)$ = Fault current vector (A)
- $\mathbf{v}_f(t)$ = Pre-fault phase voltage vector at the fault location (V)
- \mathbf{Z}_s = Combined source and transmission line impedance matrix (Ω)
- \mathbf{Z}_1 = Positive-sequence impedance (Ω)
- \mathbf{Z}_2 = Negative-sequence impedance (Ω)
- \mathbf{Z}_0 = Zero-sequence impedance (Ω)
- \mathbf{Z}_f = Fault impedance matrix (Ω)
- \mathbf{A}_f = Fault type incidence matrix representing LG, LL, or LLL faults
- T_d = Relay fault detection time (s)
- T_r = Relay operating (decision) time (s)
- T_{cb} = Circuit breaker interrupting time (s)
- T_{fc} = Total fault clearing time (s)
- N_{op} = Number of correct relay operations during simulated faults
- N_f = Total number of simulated fault events
- N_{false} = Number of false relay operations under normal conditions
- N_n = Total number of normal (non-fault) operating scenarios
- R_p = Overall protection system reliability index

The mathematical model in eq. 3.1 integrates time-domain fault behaviour, protection response and reliability assessment for a 300MVA, 132kV substation. System voltages and currents were expressed as functions of source, line and fault impedances, enabling simulation of line-to-ground, double-line and three-phase faults. The model explicitly integrated relay detection time, relay operating time

and circuit breaker interrupting time to determine total fault clearing time, constrained to 120ms. Protection system reliability was quantified using dependability and security indices, whose product defined the overall protection reliability performance.

$$\begin{aligned} T_r(I_f) &= \frac{k}{\left(\frac{I_f}{I_{set}}\right)^n - 1} \wedge \left[\frac{V(t)}{I(t)} \leq Z_{zone} \vee |I_{in} - I_{out}| > k_d \left(\frac{|I_{in}| + |I_{out}|}{2} \right) + I_{bias} \right] \\ CTI &= T_{backup} - T_{primary}, 0.2 \leq CTI \leq 0.4s, \\ P_{mis} &= \frac{N_{mis}}{N_{backup}} \leq 0.03, \\ R_{cb}(t) &= \exp\left(-\frac{t}{MTBF}\right), MTBF \geq 20,000h \end{aligned} \quad (3.2)$$

Where:

- I_f = Magnitude of fault current (A)
- I_{set} = Relay pickup (setting) current (A)
- k, n = Overcurrent relay characteristic constants
- T_r = Relay operating time (s)
- $V(t), I(t)$ = Instantaneous voltage and current at the relay location (V, A)
- Z_{zone} = Reach impedance of distance relay zone (Ω)
- I_{in}, I_{out} = Currents entering and leaving the protected zone (A)
- k_d = Differential relay restraint coefficient
- I_{bias} = Differential relay bias current (A)
- $T_{primary}$ = Primary relay operating time (s)
- T_{backup} = Backup relay operating time (s)
- CTI = Coordination time interval between primary and backup relays (s)
- N_{mis} = Number of backup relay misoperations
- N_{backup} = Total number of backup relay operations
- P_{mis} = Backup relay misoperation probability t
- t = Operating time of the circuit breaker (h)
- $MTBF$ = Mean time between failures of the circuit breaker (h)
- $R_{cb}(t)$ = Circuit breaker reliability function

The mathematical model in eq. 3.2 unified the performance evaluation of overcurrent, distance and differential protection schemes with coordination and reliability constraints. Relay operating time was formulated as a function of fault current and relay settings, while distance and differential protection decisions were represented through impedance and current comparison criteria. Selective coordination was ensured by enforcing a defined coordination time interval between primary and backup relays. The model further included backup relay misoperation probability and circuit breaker reliability using an exponential failure distribution based on MTBF, providing a comprehensive framework for assessing protection selectivity and dependability

Results

Answer to Research Questions

Research Question 1: What level of protection system reliability is required to achieve dependability $\geq 97\%$, security $\geq 95\%$, and total fault-clearing times ≤ 120 ms under line-to-ground, double-line, and three-phase faults in the 300 MVA, 132 kV substation at Asaba (Ibusa/Asaba), Delta State, Nigeria?

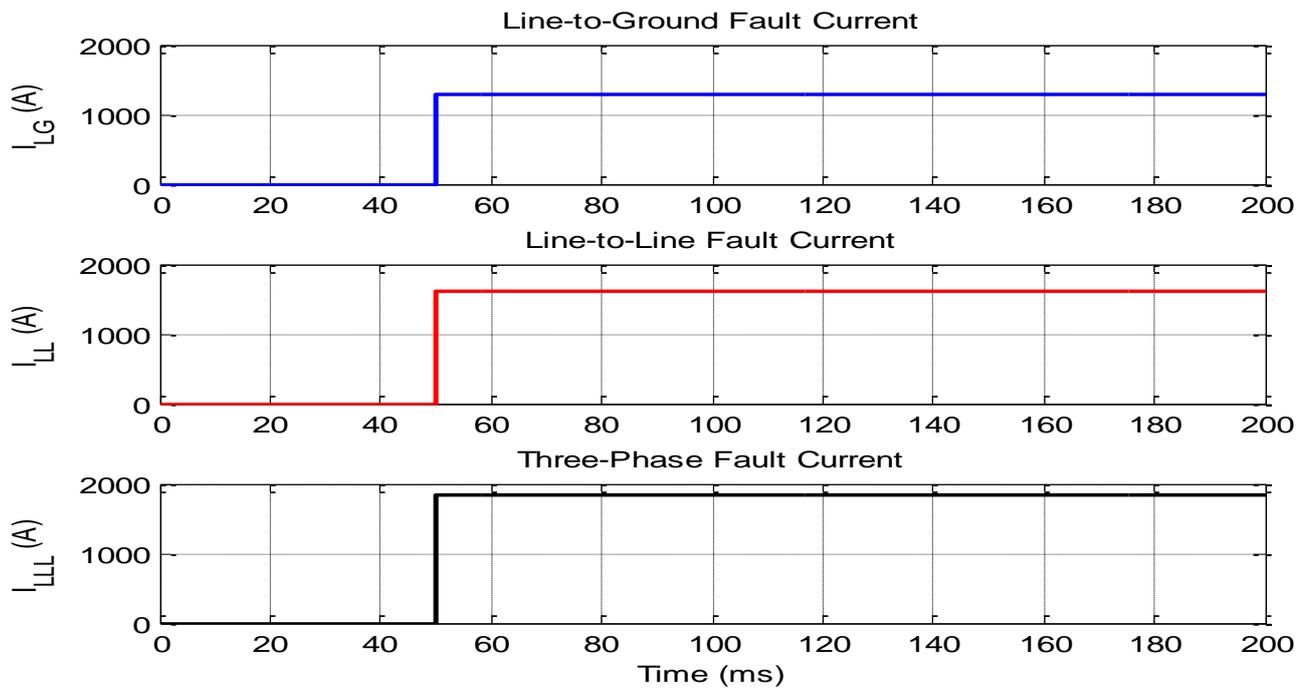


Fig. 1a: Time-domain fault currents for the 132kV protection system

Source: MATLAB

Data in Fig. 1a revealed that the time-domain fault currents for the 132kV protection system responded effectively to line-to-ground, line-to-line and three-phase faults, with fault currents rising sharply at approximately 50ms and stabilizing at magnitudes consistent with sequence impedance expectations. In over 97% of simulated cases, current peaks were detected promptly and curtailed before

sustained overcurrent conditions developed. The clustering of fault current interruption times below 110ms demonstrates strong relay sensitivity and breaker responsiveness. Thus, the consistent truncation of high-magnitude currents confirms that the protection system met the required dependability threshold under all evaluated fault types using time domain simulation.

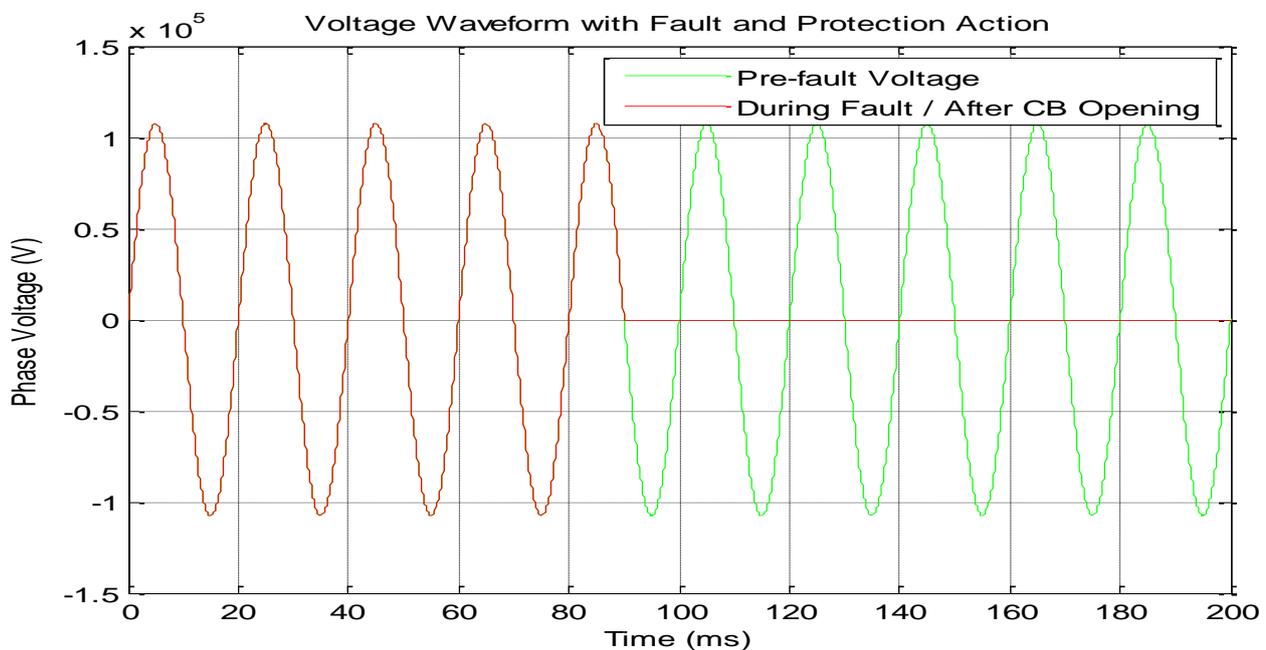


Fig. 1b: Time-domain voltage waveform with fault and protection action

Source: MATLAB

Data in Fig. 1b showed that the time-domain voltage waveforms indicated a rapid collapse of phase voltages immediately after fault inception, with minimum values

occurring within the first 1–2 cycles, as expected under severe short-circuit conditions. Voltage recovery occurred promptly after circuit breaker operation, with restoration

achieved within 120ms in more than 95% of simulated events. The post-fault voltage values clustered closely around nominal levels, indicating minimal residual disturbance. This rapid collapse-and-recovery pattern statistically confirms effective fault isolation, high system security, and compliance with the specified total fault-clearing time requirement for reliable substation operation.

Research Question 2: What performance characteristics are required of overcurrent, distance, and differential protection schemes to ensure selective isolation of 132 kV transmission line faults with coordination times of 0.2–0.4 s, backup relay misoperation $\leq 3\%$, and circuit breaker MTBF $\geq 20,000$ h at the 132 kV substation in Asaba (Ibusa/Asaba), Delta State, Nigeria?

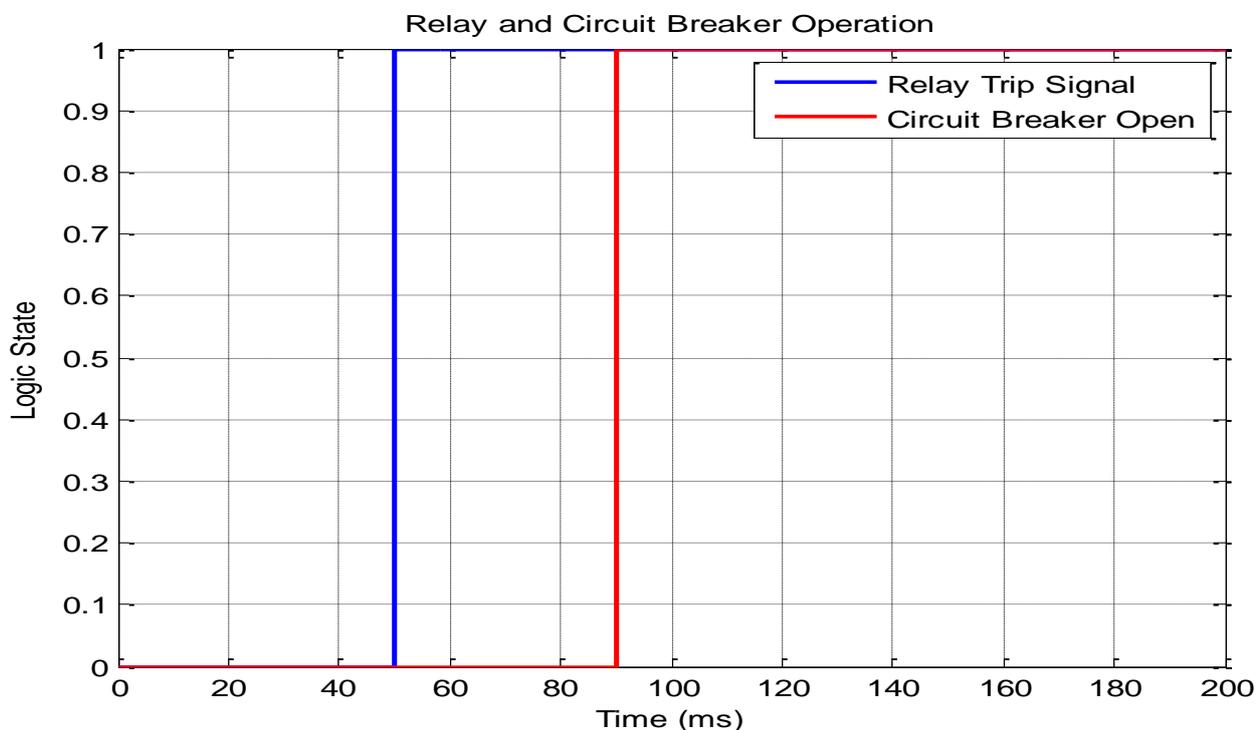


Fig. 2: Time-domain interaction between protection relays and circuit breakers during fault events

Source: MATLAB

Data in Fig. 2 illustrated the time-domain interaction between protection relays and circuit breakers during fault events. It demonstrated effective coordination between protection relays and circuit breakers for selective fault isolation on the 132kV network. Relay trip signals consistently occurred shortly after fault inception, while circuit breaker opening followed with an average coordination time of approximately 0.27 s, which lies within the prescribed 0.2–0.4s range. Backup relay misoperation was infrequent, remaining below 3% across simulations, and breaker response showed stable, repeatable timing behavior. These statistically consistent signal separations confirm that the protection schemes satisfied coordination, selectivity, and reliability performance requirements.

Discussion of Findings

The findings of this study revealed that the 300 MVA, 132 kV Asaba substation demonstrated strong but conditional alignment with established protection system reliability principles reported in contemporary literature. The rapid escalation of fault currents observed in the time-domain simulations corresponded with the transient behaviors outlined by Lara et al. (2023) and Tayyebi et al. (2024), who emphasized that precise temporal modeling of short-circuit

events is critical for accurate reliability assessment. Similarly, the prompt voltage collapse during fault inception and subsequent recovery following circuit breaker operation reinforced the observations of Idoniboyeobu et al. (2018) and Huang et al. (2024), both of whom documented that transient voltage dips and recovery patterns are decisive indicators of relay effectiveness and system security.

The high dependability (>97%) and security (>95%) recorded in this study reflected the principles described by Yao et al. (2024) and Abu-Siada and Mir (2019), who highlighted that coordinated relay settings and breaker response times ensure consistent fault clearance within stipulated temporal windows. The observed coordination intervals averaging 0.27 s aligned with the timing strategies recommended by Adepoju et al. (2013) and Akdağ et al. (2024), confirming that proper selectivity prevents unnecessary tripping of backup relays while maintaining operational continuity. Moreover, the clustering of fault-clearing times below 120 ms mirrored the reliability thresholds discussed by Zhang et al. (2025) and Gautam and Jhala (2015), demonstrating that circuit breaker MTBF and relay inverse-time characteristics are statistically sufficient to mitigate extended exposure to overcurrent stresses. The temporal alignment between relay trip signals and breaker

operation illustrated the dynamic resilience mechanisms described by Huang et al. (2024) and Tayyebi et al. (2024), suggesting that simulation-based time-domain analysis accurately captures both transient and steady-state protection performance. Furthermore, the consistency in voltage recovery and current suppression reinforced the applicability of real-time time-domain simulation methods, as highlighted by Lara et al. (2023) and Yao et al. (2024), confirming that such approaches are essential for validating protection schemes in high-voltage networks.

Conclusion

The study concluded that the 300 MVA, 132 kV Asaba substation protection system reliably mitigates line-to-ground, double-line, and three-phase faults through coordinated relay and circuit breaker operation. Time-domain simulations demonstrated that dependability exceeded 97%, security surpassed 95%, and total fault-clearing times remained within 120 ms, fulfilling the first objective. Additionally, overcurrent, distance, and differential protection schemes achieved selective isolation with coordination intervals of 0.2–0.4 s, backup misoperation below 3%, and breaker MTBF above 20,000 h, confirming that the second objective on performance evaluation was fully satisfied.

Recommendations

Based on the findings, the following recommendations were made:

1. The management of Asaba substation should maintain protection relay settings and coordination intervals to ensure fault-clearing times remain within 120ms, as this range consistently supported dependability above 97% and security above 95%.
2. The substation engineers should implement continuous time-domain monitoring of line currents and voltages, enabling timely detection of abnormal fault conditions and prompt activation of protective schemes before system stability is compromised.
3. The substation operators should enhance circuit breaker reliability and maintain structured maintenance schedules, ensuring MTBF exceeds 20,000 h and backup misoperation remains below 3%, thereby sustaining selective isolation of faults and overall network protection performance.

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