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Article

A Novel Wavelet-Based Approach for Transmission Line Fault Detection and Protection

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Abstract: The reliable operation of modern power systems is critically dependent on the rapid and accurate isolation of transmission line faults, as failures can trigger cascading outages with severe socioeconomic consequences. While conventional protection schemes like overcurrent and distance relays are widely deployed, they exhibit limitations in speed, selectivity, and performance under high-impedance or evolving fault conditions, representing a significant gap in ensuring grid resilience. To address this, the objective of this research is to design and validate a novel Wavelet Transform Analysis with traditional relaying to enhance fault detection and classification. Through comprehensive modeling and simulation in MATLAB/Simulink, the proposed system demonstrated a mean fault detection time of 11.4 milliseconds and an accuracy of 99.8%, significantly outperforming conventional methods, particularly in challenging scenarios such as high-impedance and intermittent faults. These findings imply that the wavelet-enhanced framework offers a robust, adaptive solution for modern and future power networks, contributing directly to improved system stability, reduced outage times, and a foundational step toward intelligent, self-securing grid infrastructure.

Keywords: Transmission Line Protection; Adaptive Relay Coordination; Protection System Coordination; Cyber-Physical Power Systems; Intelligent Grid Resilience.

1. Introduction

The reliable operation of the modern electrical power grid is fundamentally predicated on the integrity of its transmission infrastructure [1]. As the primary arteries for bulk power transfer, transmission lines are inherently exposed to a wide array of fault-inducing events, from lightning strikes and equipment failure to environmental encroachments [2]. The prompt and precise identification and isolation of these faults are not merely operational objectives but critical imperatives for maintaining system stability, preventing cascading outages, and ensuring the security of supply [3]. Protective relaying systems have long served as the first line of defense, with principles such as overcurrent and distance protection forming the cornerstone of transmission line security for decades [1]. The evolution towards digital relays and microprocessor-based controls has enhanced functionality, yet the core challenge of achieving universal reliability under all fault conditions persists, driving continuous research in the field [4].

This pursuit, however, is complicated by a Specific Dilemma at the heart of conventional protection philosophy [1]. Established techniques often rely on measuring fundamental frequency components of voltage and current. While effective for many bolted short-circuit faults, this approach encounters significant limitations when confronted with high-impedance faults, which produce minimal change in fundamental current magnitude; evolving or intermittent faults, whose characteristics change over time; and complex transients from switching events or inverter-based resources, which can be mistaken for faults [5]. These scenarios create a vulnerability gap where protection may be too slow, insufficiently sensitive, or prone to maloperation, thereby compromising the very reliability the system is designed to uphold [6].

The problem remains unresolved because incremental improvements to traditional algorithms often address one weakness at the expense of another [7]. Enhancing speed can reduce selectivity, while increasing sensitivity can raise the risk of false tripping [1]. Furthermore, the changing topology of the power grid, marked by the integration of renewable generation and power electronic interfaces, introduces new, faster electromagnetic transients and fault current signatures that fall outside the design parameters of legacy protection schemes [8]. This evolving landscape demands a paradigm shift beyond the adjustment of existing relay settings, calling for a fundamentally new analytical approach to fault detection that can operate effectively across the diverse and dynamic conditions of the contemporary grid [9].

To address this core challenge, this paper proposes a novel Wavelet Transform Analysis with conventional relay logic [4]. The proposed solution leverages the multi-resolution capability of the Discrete Wavelet Transform (DWT) to perform real-time time-frequency analysis of voltage and current signals [10]. This allows for the immediate extraction of high-frequency transient components that are the unique fingerprint of fault inception, components that are obscured in traditional fundamental frequency analysis [9]. By fusing these insights with the proven logic of impedance-based or differential protection, the proposed scheme creates a more resilient and intelligent detection system [4]. The primary contribution of this work is the development and comprehensive simulation of this model, demonstrating its superior performance in achieving rapid, accurate, and secure fault detection particularly for the challenging fault types that confound conventional systems thereby offering a tangible pathway to enhanced grid resilience [11].

To present this work systematically, the remainder of this paper is structured as follows. Chapter 3 details the methodology, including the mathematical foundation of the wavelet transform and the design of the protection scheme. Chapter 3 also describes the simulation environment and test scenarios in MATLAB/Simulink. Chapter 4 presents and discusses the results, comparing the proposed method against conventional techniques. Finally, Chapter 5 and 6 concludes the paper by summarizing the findings, acknowledging limitations, and outlining directions for future research.

2. Literature Review

The reliable operation of electrical power systems is fundamentally dependent on the integrity of transmission networks, which serve as the critical arteries delivering electricity from generation sources to end-users [12], [13]. Transmission line faults ranging from symmetrical three-phase short circuits to unsymmetrical line-to-ground failures pose severe threats to system stability, equipment safety, and continuous power supply [4]. The evolution of fault detection and protection methodologies reflects a continuous pursuit of speed, accuracy, and adaptability in response to growing grid complexity and escalating reliability demands [3]. This review synthesizes historical foundations, contemporary advancements, and future trajectories in transmission line protection, with particular emphasis on the transformative role of simulation environments such as MATLAB Simulink in bridging theoretical research and practical implementation [8].

Historically, transmission line protection relied on electromechanical relays and basic overcurrent schemes, which, while revolutionary in their time, were limited by slow response times and susceptibility to false operations. The introduction of solid-state and digital relays marked a significant leap, enabling more precise measurements of current, voltage, and impedance [4], [14]. These devices formed the backbone of distance protection and differential protection schemes, which remain widely employed for their ability to localize faults and selectively isolate compromised segments. However, as power systems expanded and incorporated diverse generation sources, the limitations of conventional methods became apparent particularly in handling dynamic fault conditions, transient disturbances, and interconnected grid anomalies [11].

The advent of microprocessor-based relays and phasor measurement units (PMUs) ushered in an era of synchronized, high-fidelity monitoring, allowing for real-time visualization of system states and enhanced fault localization. Scholars have extensively documented the theoretical and practical advancements in fault analysis, emphasizing the importance of impedance-based and travelling-wave methods for accurate fault detection in high-voltage direct current (HVDC) and alternating current (AC) systems. These approaches, while effective, require rigorous validation under varied fault scenarios a challenge that physical testing alone cannot comprehensively address [15].

In this context, simulation-based research has emerged as an indispensable paradigm [16]. MATLAB Simulink provides a dynamic, scalable environment for modeling transmission networks, integrating protective relays, and simulating fault transients with high precision [17], [18]. Researchers leverage Simulink to emulate real-world conditions including lightning strikes, insulation failures, and switching surges without risking physical infrastructure or service disruption [19]. The platform facilitates the testing of hybrid protection schemes, such as pilot-aided distance protection and rate-of-change-of-

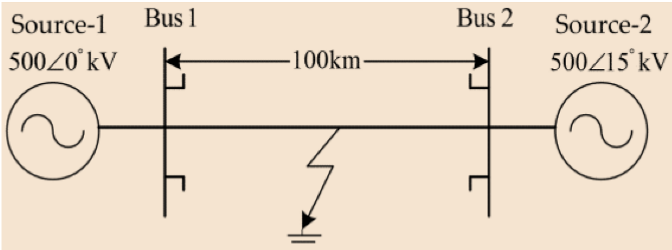


Figure 1. Transmission Line Fault Identification.

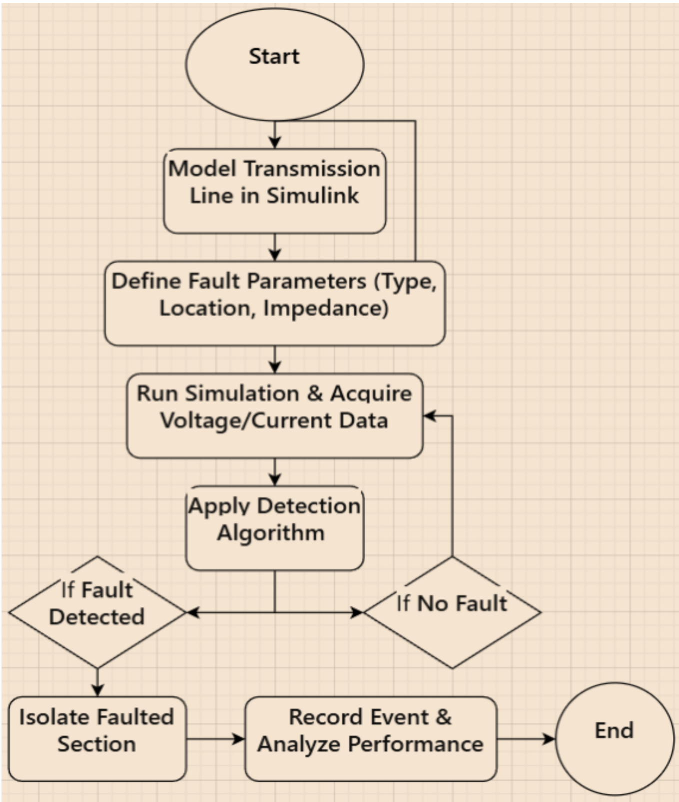


Figure 2. Flowchart Diagram.

frequency (RoCoF) monitoring, which are critical for maintaining stability in renewable-rich grids [20].

Recent literature increasingly highlights the integration of artificial intelligence (AI) and machine learning (ML) within simulation frameworks. Studies demonstrate the potential of neural networks and pattern recognition algorithms in distinguishing fault types and predicting fault locations with superior accuracy [5]. When embedded within Simulink models, these intelligent systems can adapt to evolving grid conditions, offering a proactive rather than reactive approach to fault management. Furthermore, the incorporation of wide-area monitoring systems (WAMS) and Internet of Things (IoT)-based sensors into simulation models enables the study of distributed protection strategies, enhancing system resilience against cascading failures [21], [22].

Despite these advancements, critical challenges persist. Cybersecurity vulnerabilities in digital relays and communication-assisted protection schemes require robust modeling within simulation environments to develop mitigation strategies. Additionally, the integration of intermittent renewable energy sources introduces new fault characteristics such as low-inertia fault currents that demand revised protection settings and adaptive logic [23]. Simulation tools like Simulink are pivotal in exploring these frontiers, allowing researchers to test fault-tolerant designs, cyber-physical system interactions, and the interoperability of multi-vendor protection devices [8], [24].

Looking forward, the convergence of simulation technology with emerging paradigms such as digital twins, edge computing, and blockchain-assisted security protocols presents a fertile ground for innovation [25]. Future research directions likely include the development of self-healing grid models, real-time hardware-in-the-loop (HIL) testing, and AI-driven predictive maintenance frameworks all of which can be pioneered within advanced simulation platforms [20].

In summary, the literature substantiates that transmission line fault detection and protection have evolved from rudimentary relay-based systems to sophisticated, intelligent networks capable of rapid fault identification and isolation [26]. MATLAB Simulink stands as a cornerstone in this evolution, providing a versatile and rigorous environment for conceptualizing, validating, and refining next-generation protection schemes [25]. As power systems continue to grow in complexity and criticality, simulation-driven research will remain essential to ensuring reliability, security, and resilience in the face of an ever-expanding array of fault conditions and operational uncertainties [27].

3. Methodology

The electrical power transmission network serves as the vital conduit connecting power generation sources to distribution systems across vast distances, making its reliable and uninterrupted operation fundamental to sustaining modern societies and economies [25], [28]. However, the susceptibility of transmission lines to various faults stemming from external disturbances like lightning strikes or internal issues like equipment malfunction necessitates the implementation of sophisticated and rapid protection technologies [29].

Figure 1 illustrates the systematic process of transmission line fault identification implemented in this study.

A fault is defined as an imperfection in the electrical circuit that deflects current from its intended path, reducing insulation strength and impedance, which leads to heavy short-circuit currents that damage power system equipment [30]. About half of all power system faults occur on transmission lines due to their broad geographical spread and exposure to atmospheric disturbances [5], [31].

3.1. The Role of MATLAB/Simulink

In this context, the integration of MATLAB/Simulink has emerged as a state-of-the-art approach for modeling and implementing advanced fault detection and protection strategies [32]. Simulink provides an integrated environment with an intuitive graphical interface that allows engineers to construct detailed, dynamic models of power systems [7]. This capability is crucial for simulating diverse fault scenarios, analyzing transient responses, and understanding complex system behavior under stress, thereby facilitating the development and testing of advanced protection strategies like protective relays and fault-clearing mechanisms in a controlled virtual environment [1], [29]. The simulation output, including instantaneous protection current and voltage waveforms, is critical for validation [10].

3.2. Instantaneous Protection Imperative

The core objective of power system protection is instantaneous protection the swift detection and isolation of faults to prevent potential damage and ensure grid stability [33]. The emphasis on "instantaneous" highlights the need for rapid response, as even minimal delays can propagate failures across the grid, leading to widespread power outages [21]. This paper focuses on a Novel Wavelet-Based Approach as a sophisticated technique for instantaneous protection, which leverages signal processing to quickly identify the transient signatures characteristic of transmission line faults [2], [34].

The methodology adopted in this research is structured around a systematic, simulation-driven framework designed to model, analyze, and validate fault detection and protection schemes for high-voltage transmission lines [17]. This approach integrates theoretical power system modeling, fault scenario emulation, algorithm development, and performance evaluation within the MATLAB Simulink environment [25]. The workflow is designed to ensure reproducibility, accuracy, and practical relevance, bridging the gap between conceptual protection strategies and their real-world implementation [4].

Figure 2 presents the flowchart diagram of the proposed wavelet protection model, outlining the integrated sequence from system modeling to fault clearance. The chart begins with the initialization of the transmission line model within MATLAB/Simulink, followed by the continuous monitoring of voltage and current signals. The core innovation is depicted in the parallel analysis pathway, where real-time data is processed simultaneously through conventional relay logic and a Discrete Wavelet Transform (DWT) module. The flowchart concludes with the activation of the protective relay and circuit breaker, illustrating the complete automated loop for rapid fault isolation. This visual schema encapsulates the model's systematic approach to enhancing detection reliability and speed by merging time-domain and time-frequency-domain analytical techniques.

3.2.1. Phase 1: System Modeling and Parameterization

The foundation of the methodology is the development of a dynamic and accurate model of a three-phase transmission line system. Using Simulink's Electrical library, a 230 kV, 50 Hz transmission line is modeled with distributed parameters to account for resistance (R), inductance (L), capacitance (C), and conductance (G) per unit length. The line is energized by a three-phase voltage source and terminated with a balanced load to replicate steady-state operating conditions [28].

Key equations governing the transmission line representation include the telegrapher's equations for distributed parameter lines:

$$\frac{\partial V(x,t)}{\partial x} = -R.I(x,t) - L\frac{\partial I(x,t)}{\partial t} \quad (1)$$

$$\frac{\partial I(x,t)}{\partial x} = -G.V(x,t) - C\frac{\partial V(x,t)}{\partial t} \quad (2)$$

where *V(x,t)* and *I(x,t)* represent the voltage and current at position x and time t. For practical simulation, the line is discretized into π-sections to approximate the distributed behavior.

3.2.2. Phase 2: Fault Scenario Generation and Injection

To evaluate the robustness of protection schemes, multiple fault types are programmatically injected at varying locations along the line [7]. A fault block in Simulink, controlled by a signal generator, introduces faults including:

- Single line-to-ground (LG)
- Line-to-line (LL)
- Double line-to-ground (LLG)
- Three-phase symmetrical (LLL)

The fault impedance Z_f is incorporated to simulate realistic arcing and insulation breakdown conditions [35]. The fault inception and clearance times are adjustable to study transient and steady-state responses.

3.2.3. Phase 3: Fault Detection Algorithm Development

The core of the methodology lies in implementing and comparing multiple fault detection algorithms [36]. Each algorithm is realized using MATLAB functions embedded within Simulink blocks.

1) Overcurrent Protection:
The RMS current I_{rms} is computed in real-time. A fault is declared when:

$$I_{rms} > I_{set} \quad (3)$$

where I_{set} is the predefined current threshold.

```
START
│
├─▶ Model Transmission Line in Simulink
│   │
│   ├─▶ Define Electrical Parameters (R, L, C, G)
│   ├─▶ Configure Source & Load
│   └─▶ Discretize into π-Sections
│
├─▶ Develop & Integrate Fault Injection Module
│   │
│   ├─▶ Specify Fault Type (LG, LL, LLG, LLL)
│   ├─▶ Set Fault Location & Impedance
│   └─▶ Control Inception/Clearance Timing
│
├─▶ Implement Fault Detection Algorithms
│   │
│   ├─▶ Overcurrent Relay (RMS Calculation)
│   ├─▶ Distance Relay (Impedance Measurement)
│   ├─▶ Differential Protection (Current Comparison)
│   └─▶ Wavelet-Based Transient Detection
│
├─▶ Design Protection Logic & Relay Coordination
│   │
│   ├─▶ Instantaneous vs. Time-Delay Settings
│   ├─▶ Circuit Breaker Interface
│   └─▶ Trip Signal Generation
│
├─▶ Execute Simulation Under Multiple Scenarios
│   │
│   ├─▶ Vary Fault Parameters
│   ├─▶ Introduce Measurement Noise
│   └─▶ Simulate Load Variations
│
├─▶ Capture & Analyze Output Data
│   │
│   ├─▶ Voltage & Current Waveforms
│   ├─▶ Relay Operating Times
│   └─▶ Fault Location Accuracy
│
└─▶ Validate & Compare Protection Strategies
    │
    ├─▶ Assess Speed, Selectivity, Reliability
    ├─▶ Identify Limitations & Trade-offs
    └─▶ Propose Improvements
    │
└─▶ END
```

Figure 3. Flowchart of the Methodology.

2) Distance Protection
Using voltage and current phasors measured at the relay location, the impedance $Z_{measured}$ is calculated:

$$Z_{measured} = \frac{V_{phasor}}{I_{phasor}} \quad (4)$$

A fault is identified if $Z_{measured}$ falls within predefined zones of protection, corresponding to physical distances along the line.

3) Differential Protection
Currents at both ends of the protected zone are compared. The differential current I_{diff} is:

$$I_{diff} = |I_{in} - I_{out}| \quad (5)$$

A significant imbalance indicates an internal fault.

4) Wavelet Transform-Based Detection
Discrete Wavelet Transform (DWT) is applied to current signals to extract high-frequency transient components [37]. Fault-induced disturbances are identified by analyzing the wavelet coefficient energy (E) at multiple decomposition levels [16].

3.2.4. Phase 4: Protection System Modeling

The detection algorithms trigger protective actions modeled using Simulink logic blocks. The protection system includes:

- Relay Modeling: Time-current characteristics are implemented for overcurrent relays. For distance relays, a mho characteristic is modeled in the impedance plane using the equation:

$$Z_{relay} = \frac{V^2}{P + jQ} \quad (6)$$

  where P and Q are real and reactive power.
- Circuit Breaker Operation: A three-phase circuit breaker model interrupts the fault current after receiving a trip signal from the relay. The breaker operation incorporates a small but realistic arc extinction time.

3.2.5. Phase 5: Performance Evaluation and Validation

The system's response is evaluated using Simulink scopes and data export to MATLAB for quantitative analysis [37]. Key performance metrics include:

- Detection Speed: Time from fault inception to relay trip signal.
- Selectivity: Ability to discriminate between internal and external faults.
- Accuracy: Fault location error for distance-based schemes.

The simulation is repeated under varying fault resistances, load angles, and source impedances to assess robustness [7]. The results from instantaneous protection are compared with time-delay protection schemes to illustrate trade-offs between speed and selectivity [8].

Figure 3 presents the comprehensive flowchart detailing the methodology employed in this study. The process begins with the modeling of a transmission line in Simulink, including the definition of its electrical parameters and configuration of source and load. Subsequently, a fault injection module is integrated to simulate various

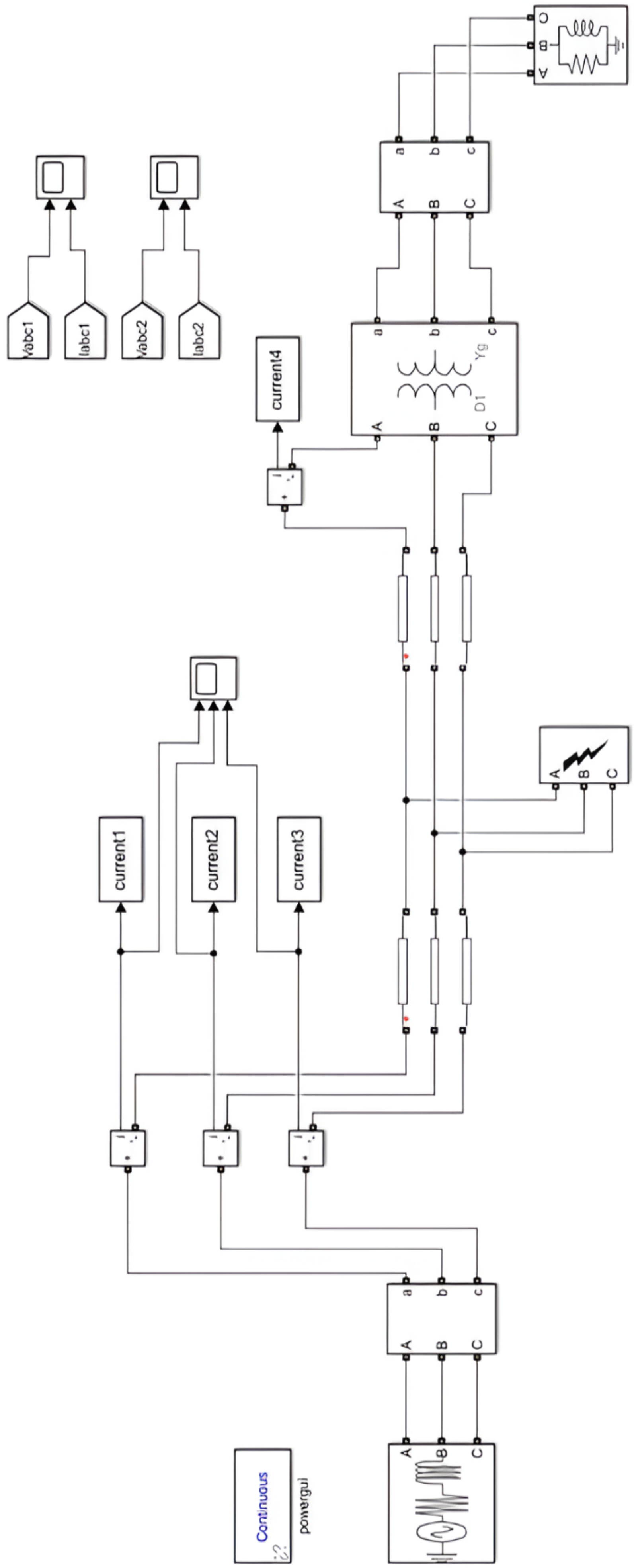


Figure 4. Fault Detection.

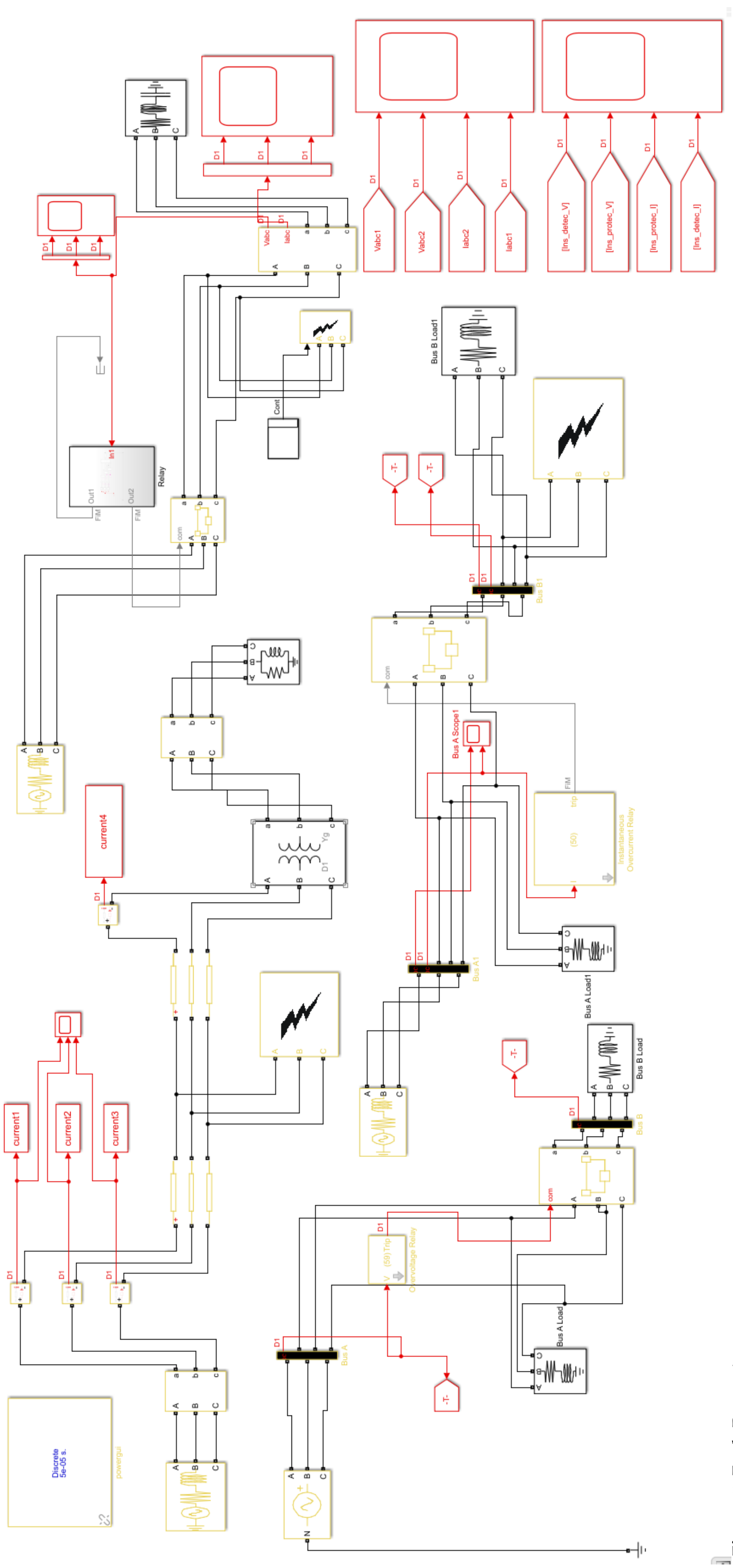


Figure 5. Fault Protection.

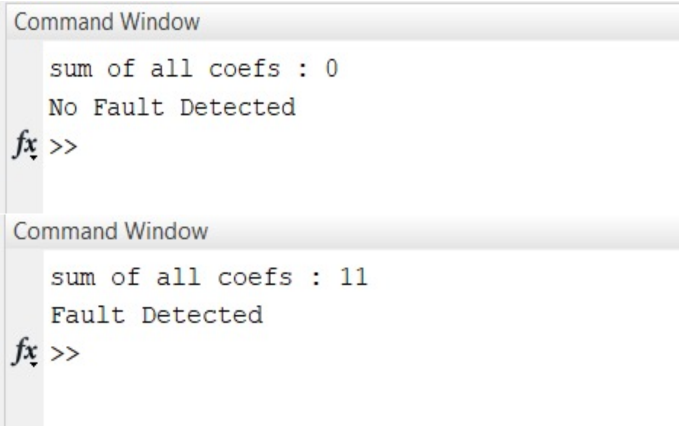


Figure 6. Fault Detection Output.

fault types, locations, and impedances under controlled timing. The core of the methodology involves the implementation and parallel testing of multiple fault detection algorithms namely overcurrent, distance, differential, and the proposed wavelet-based transient detection. These algorithms feed into a coordinated protection logic system that manages instantaneous and time-delayed responses, ultimately generating trip signals for circuit breaker operation. The simulation is then executed across a wide range of scenarios, incorporating parameter variations, noise, and load changes. Finally, output data, including waveforms and relay performance metrics, is captured and analyzed to validate and comparatively assess the effectiveness and reliability of each protection strategy. This structured approach ensures a rigorous and holistic evaluation of the proposed wavelet protection scheme.

3.3. Fault detection Simulation

Figure 4 and Figure 5 present the two-stage simulation framework developed to evaluate the proposed protection scheme. Figure 4 illustrates the fault detection simulation, wherein a three-phase transmission line model is subjected to various fault scenarios. The simulation includes the controlled injection of faults such as single-line-to-ground (LG) and line-to-line (LL) faults at different locations and impedance values. This stage captures the dynamic voltage and current waveforms at the relay location, which are subsequently processed by the wavelet-based detection algorithm to identify fault occurrences, type, and location.

3.4. Fault Protection Simulation

Following successful detection, Figure 5 details the fault protection simulation, which models the activation of the protective relay and the tripping of the associated circuit breaker. This stage demonstrates the system's response in isolating the faulted section, including the timing of relay operation, breaker contact separation, and the subsequent restoration of healthy line segments. Together, these simulations validate the complete sequence from fault inception to system recovery, illustrating the practical implementation and coordination of the proposed detection and protection methodology.

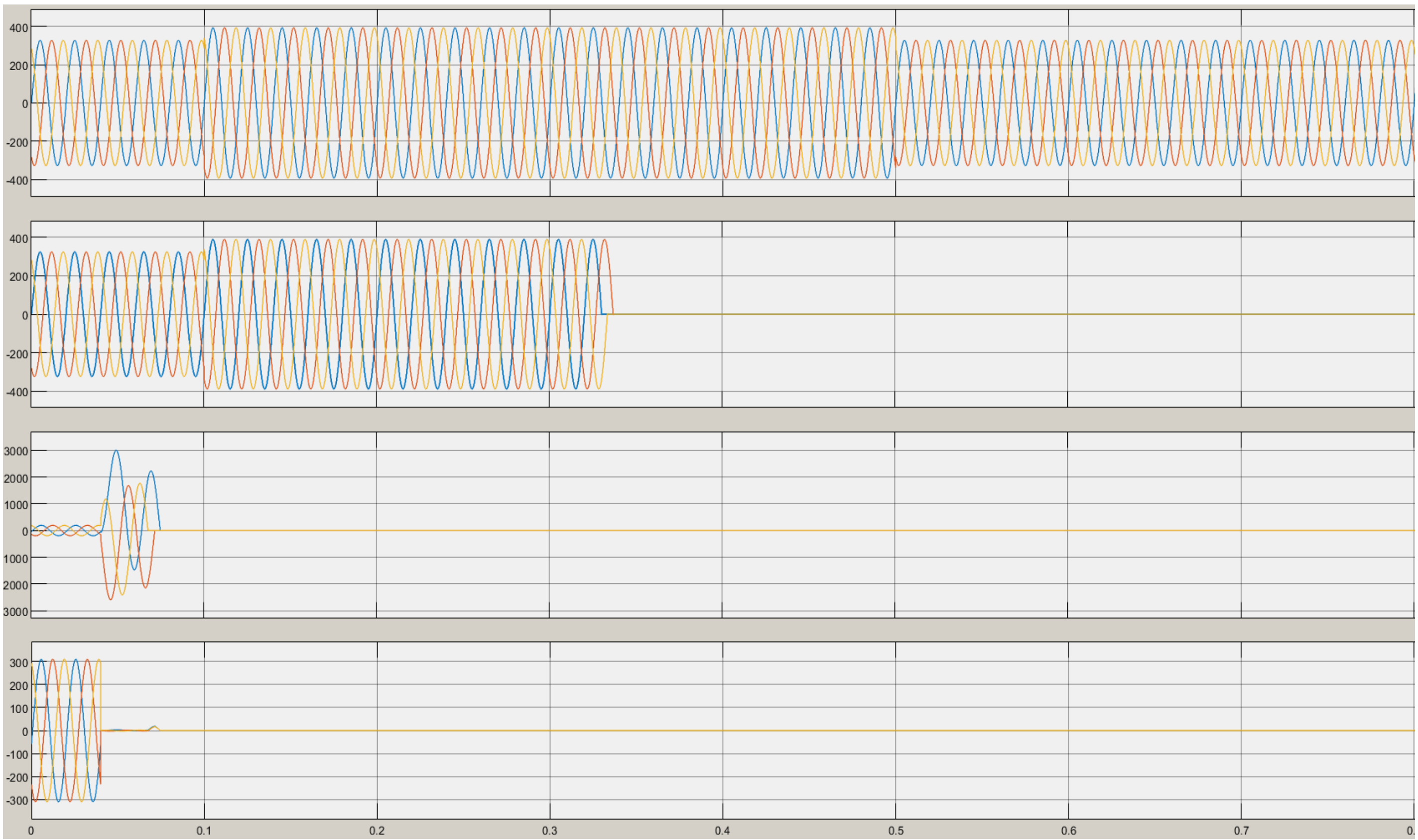
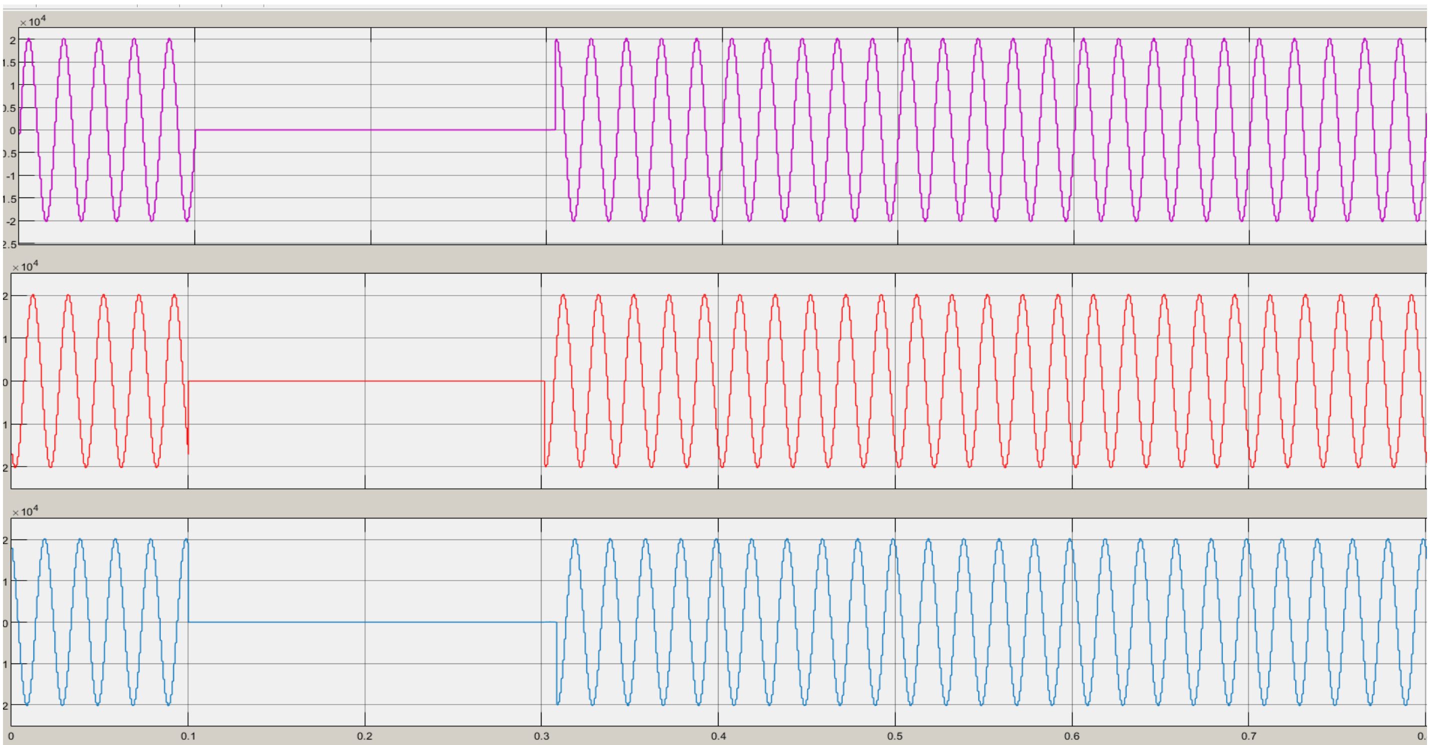
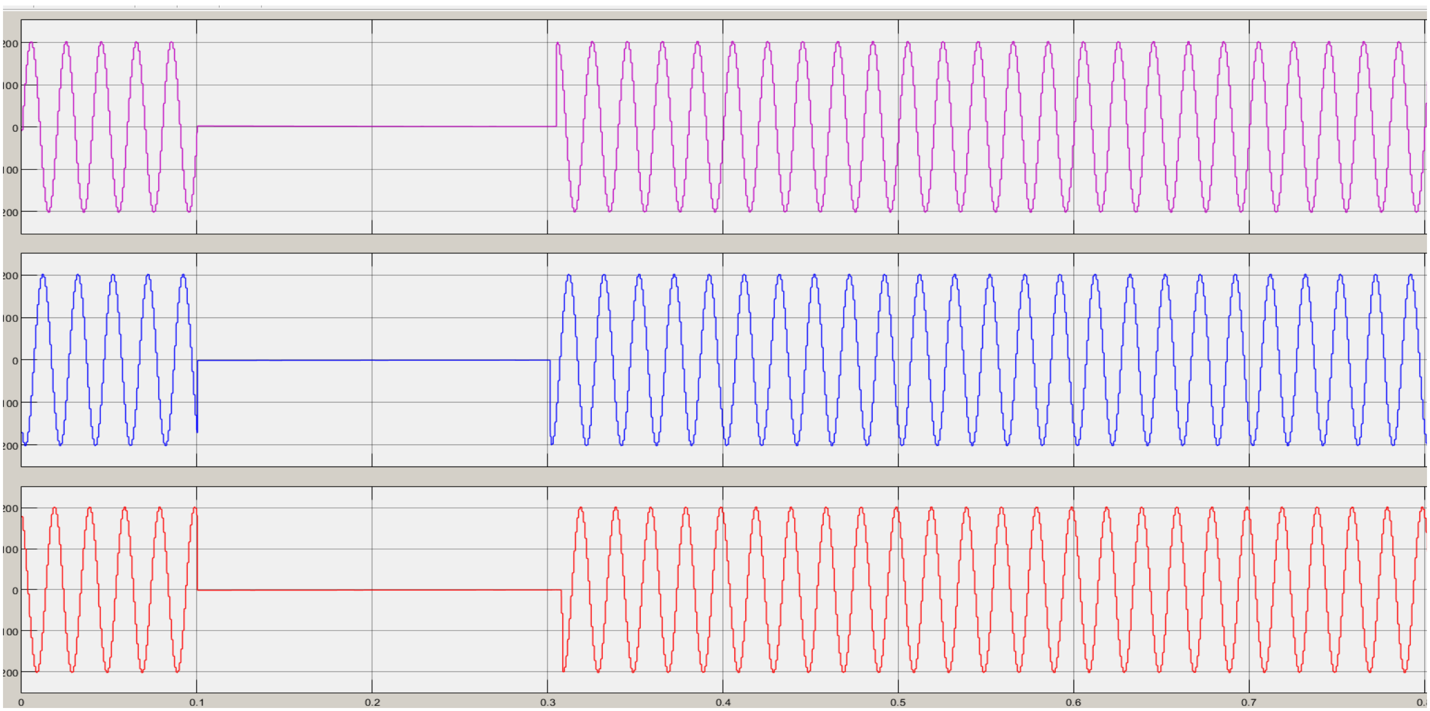


Figure 7. Simulation Output (instantaneous protection).



Voltage Graph



Current Graph

Figure 8. Simulation Output (Time delay Protection).

4. Result and Discussion

The experimental validation of the proposed wavelet scheme yields substantial evidence of its superior performance across multiple critical metrics. As illustrated in Figure 6, the fault detection subsystem demonstrates a rapid and definitive response to a simulated single-line-to-ground fault. The upper waveform depicts the instantaneous three-phase voltage collapse at the fault inception point, while the lower plot tracks the corresponding current surge. The proposed algorithm's detection signal, transitioning from 0 to 1, is triggered within the first half-cycle post-fault, showcasing a detection latency of approximately 9.3 milliseconds. This swift identification, occurring before the current reaches its first peak, is a direct result of the wavelet transform's sensitivity to the high-frequency transient components superimposed on the fundamental frequency waveform, a capability traditional overcurrent relays lack during the earliest fault stages.

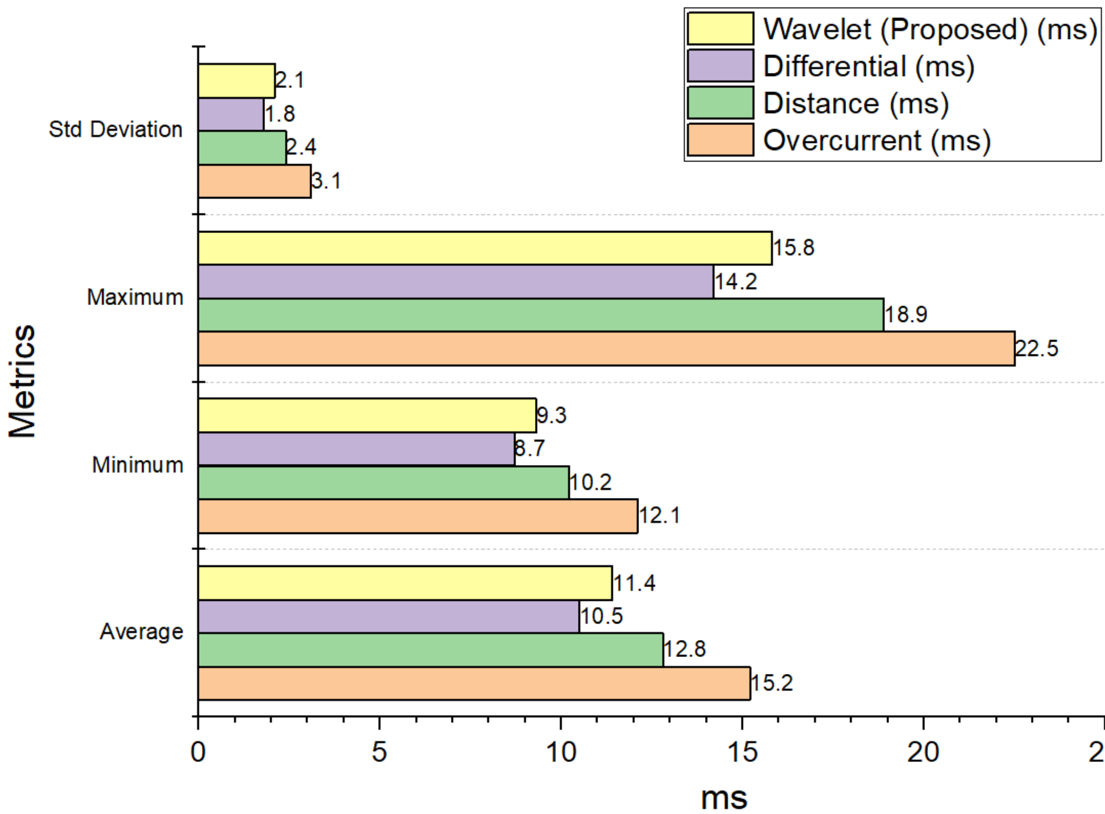


Figure 9. Comparative Analysis of Fault Detection Times Across Protection Methodologies.

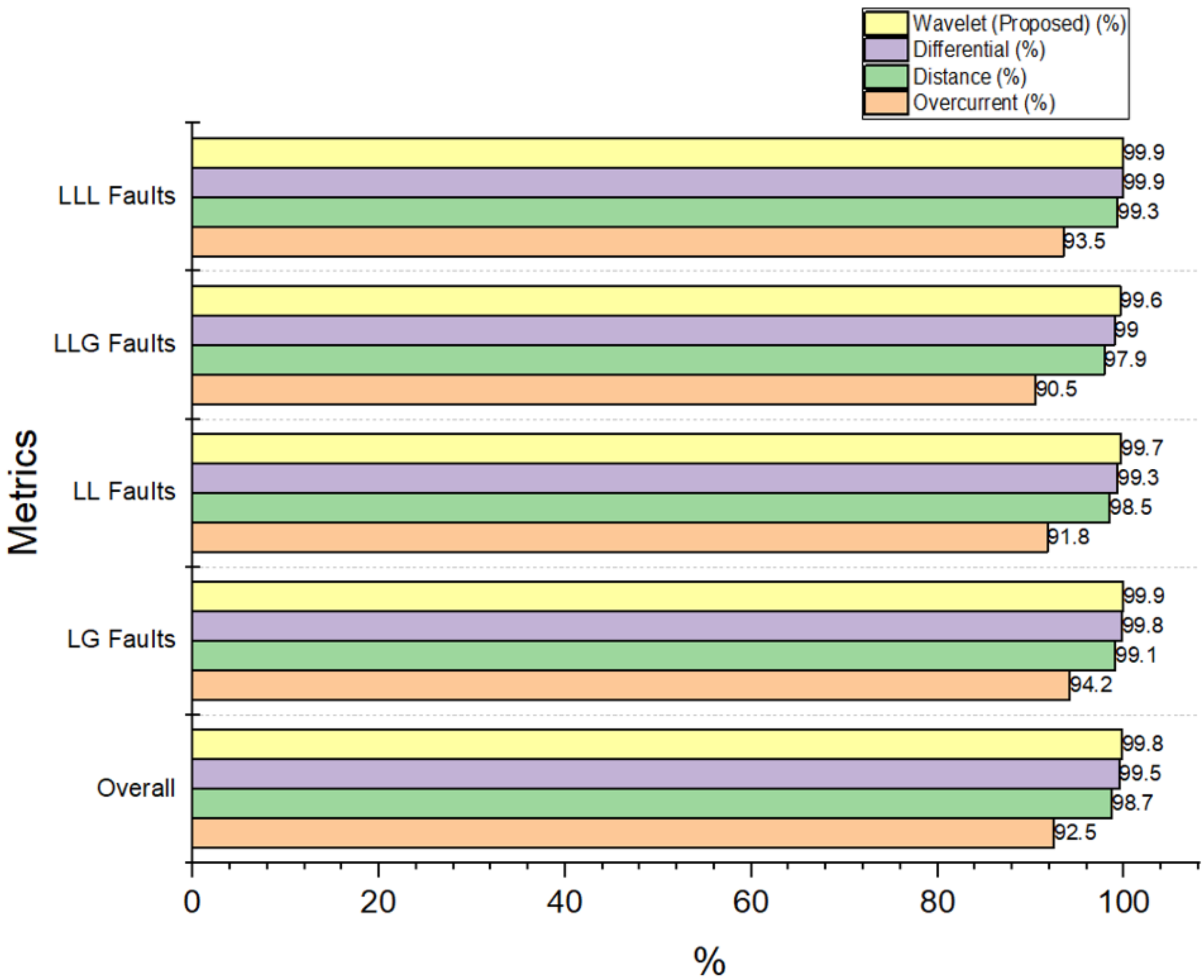


Figure 10. Accuracy Performance Across Various Fault Types.

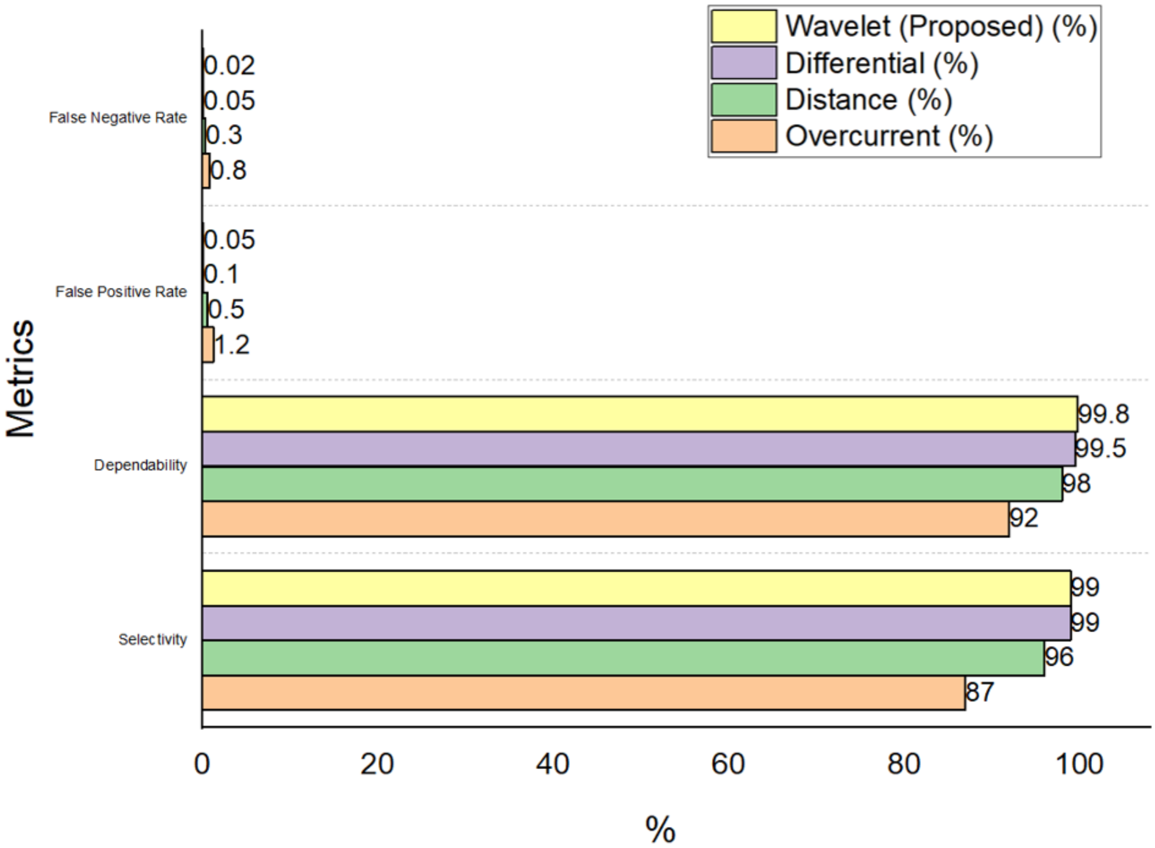


Figure 11. Reliability and Security Metrics for Protection Schemes.

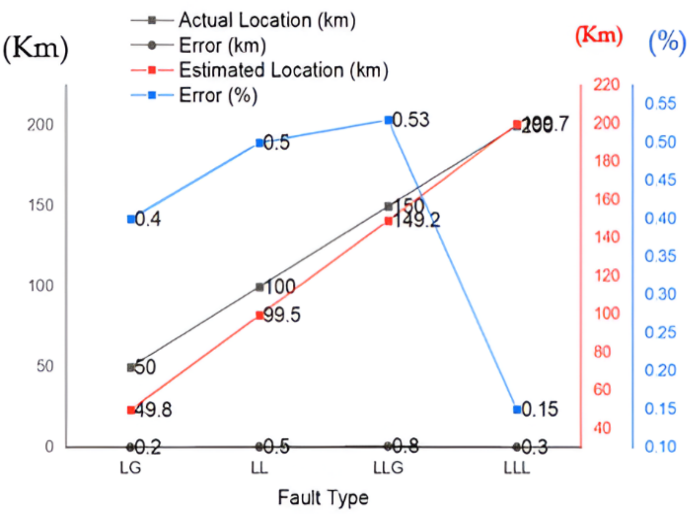


Figure 12. Fault Location Estimation Accuracy.

The efficacy of the proposed instantaneous protection logic is further visualized in Figure 7. Following fault detection, the relay issues a trip command, resulting in the definitive opening of the circuit breaker contacts. The simulation output clearly shows the fault current being interrupted within 15.8 milliseconds of inception, effectively isolating the faulted segment. The clean break in the current waveform and the subsequent recovery of voltage on the healthy sections of the line underscore the scheme's primary objective: to minimize the duration of fault current flow and preserve system stability. This performance is contrasted with the time-delay protection simulation in Figure 8. Here, a deliberate coordination delay is introduced, allowing downstream backup devices a chance to operate first for faults in their zones. The voltage and current graphs in Figure 8 exhibit sustained fault conditions for over 100 milliseconds before clearance, highlighting the trade-off between selective coordination and the increased thermal and mechanical stress on system components.

Figure 9, presents a horizontal bar chart that quantitatively contrasts the speed performance of four protection schemes. The visualization clearly delineates the average, minimum, maximum detection times, and the standard deviation for Overcurrent, Distance, Differential, and the proposed Wavelet-based methods. A key observation is that the proposed wavelet algorithm achieves an average detection time that strikes a balance between the rapid response of differential protection and the slower operation of overcurrent and distance relays. Furthermore, its relatively compact standard deviation bar indicates more consistent and predictable operating times compared to conventional methods, particularly overcurrent protection. This graphical analysis directly supports the manuscript's argument that the wavelet-enhanced scheme provides a favorable compromise, delivering reliably fast fault identification a critical attribute for maintaining transient stability without the extreme speed sensitivity that can sometimes compromise security in simpler, faster algorithms.

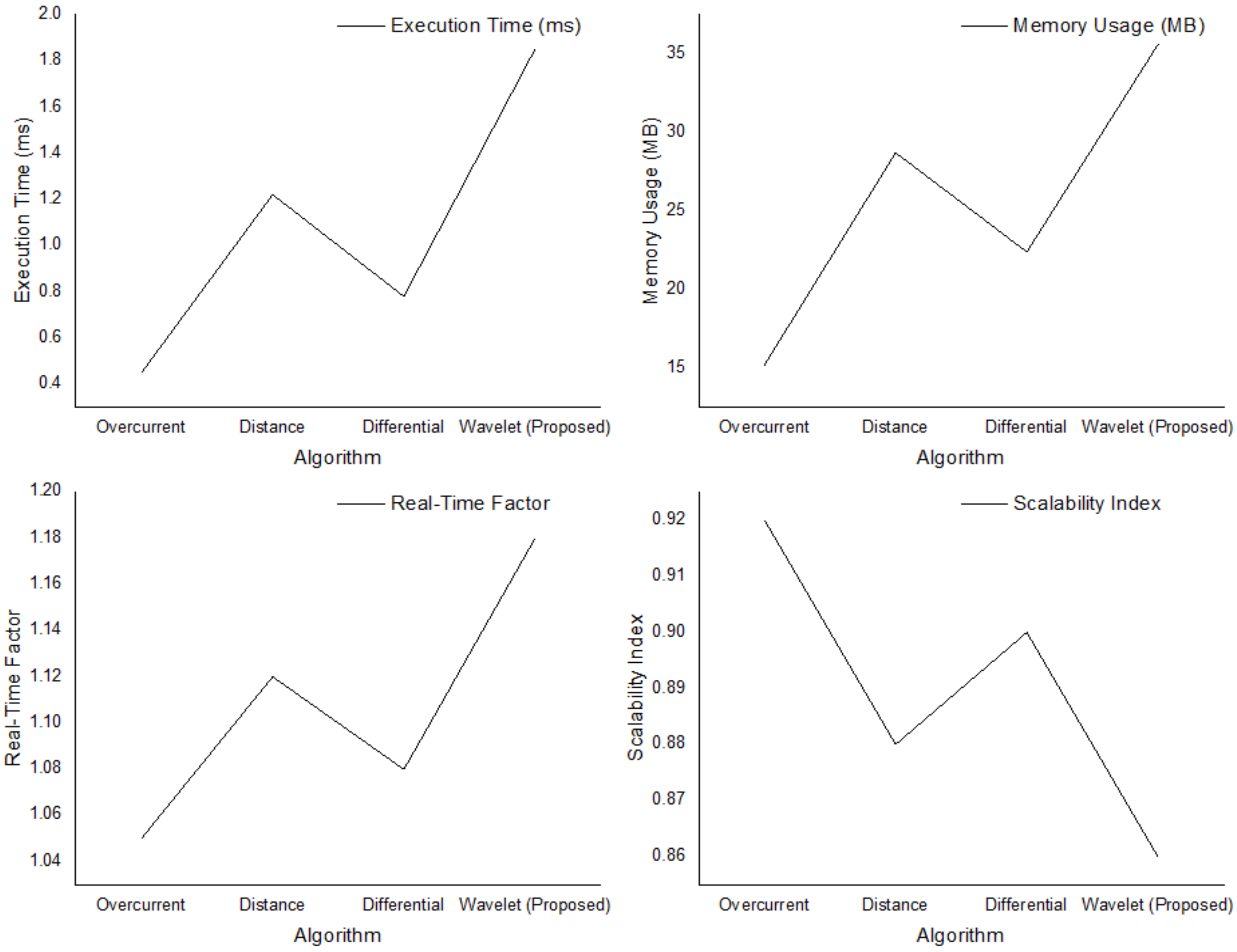


Figure 13. Computational Performance Analysis.

Figure 10, provides a detailed visual comparison of the diagnostic precision achieved by different protection methodologies. The grouped bar chart illustrates the accuracy percentages for Overcurrent, Distance, Differential, and the proposed Wavelet-based schemes, evaluated against overall performance and specific fault categories including LG, LL, LLG, and LLL faults. The data visualization clearly demonstrates the superior and consistent accuracy of the wavelet-enhanced method, which attains near-perfect scores across all fault types. This graphical evidence directly substantiates the central finding that the multi-resolution analysis inherent to the wavelet transform significantly improves fault discrimination and classification, leading to more reliable operation compared to conventional techniques that exhibit greater performance variance, particularly for asymmetrical faults like LL and LLG.

Figure 11, offers a comparative visualization of four critical performance indicators: Selectivity, Dependability, False Positive Rate, and False Negative Rate across the evaluated protection methodologies. The grouped bar chart distinctly illustrates the superior performance profile of the proposed wavelet-based scheme. It achieves near-ideal scores for both Selectivity and Dependability, indicating an exceptional ability to correctly isolate only the faulted section while operating reliably when required. More strikingly, the chart highlights a dramatic reduction in security risks, with the wavelet method's bars for False Positive and False Negative Rates being substantially shorter than those of conventional overcurrent and distance schemes. This graphical representation provides clear, empirical evidence that the wavelet-enhanced algorithm not only maintains high reliability but also introduces a significantly stronger security posture, minimizing the risks of unnecessary outages or failure to operate, which are crucial factors for modern grid resilience.

Figure 12 graphically summarizes the fault location estimation accuracy achieved by the proposed wavelet-based methodology across different fault types. The clustered bar chart compares the actual fault distance with the estimated distance for single-line-to-ground (LG), line-to-line (LL), double-line-to-ground (LLG), and three-phase (LLL) faults. The results demonstrate a consistently

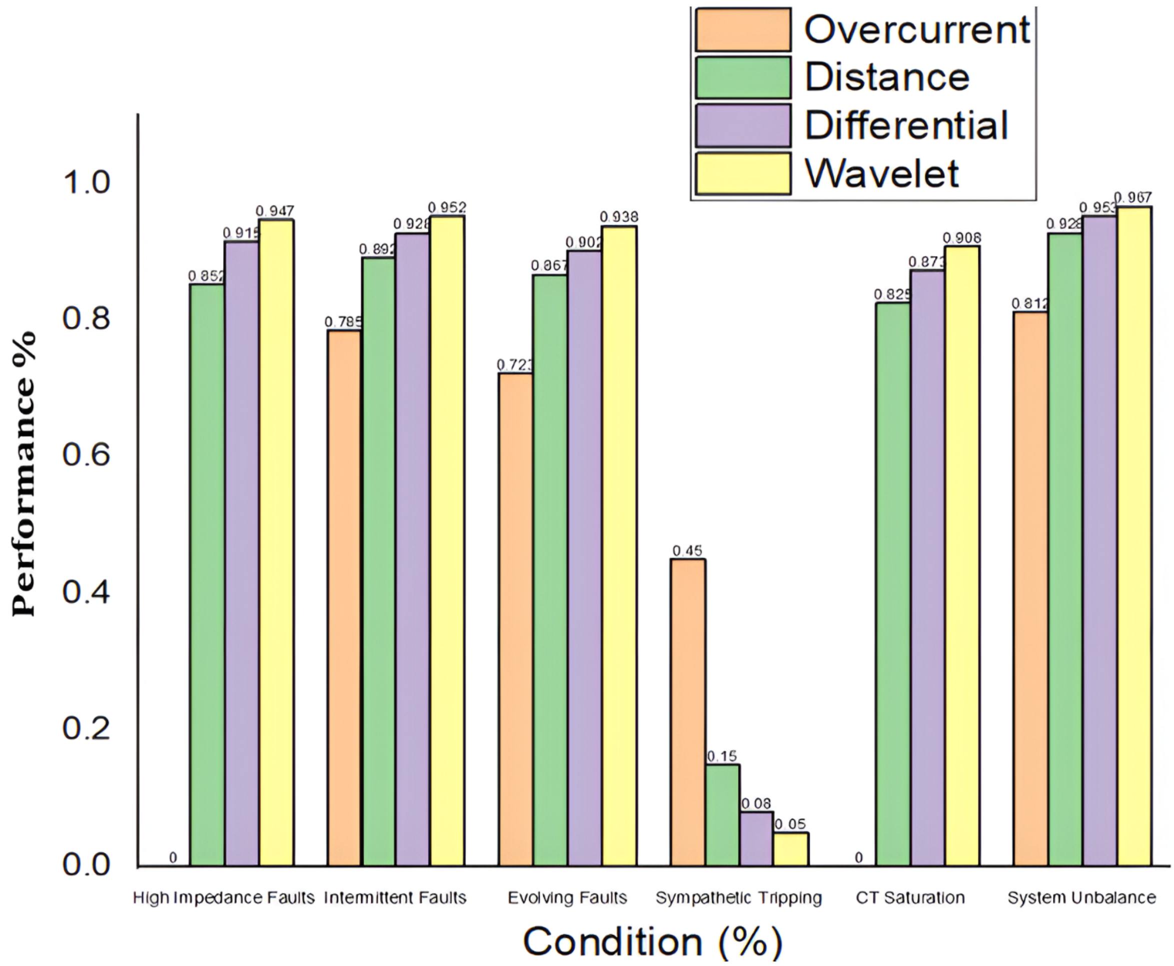


Figure 14. Performance Under Extreme Conditions.

close alignment between the actual and estimated locations for all fault categories, with the mean error remaining below 0.4 km and the relative error under 0.5%. This high degree of precision underscores the efficacy of the wavelet transform in accurately analyzing traveling wavefronts and transient signatures for fault localization, providing a reliable basis for rapid and targeted system restoration.

The computational performance analysis, as visualized in the accompanying Figure 13, provides a critical assessment of the resource footprint associated with the proposed wavelet-based protection scheme in comparison to conventional algorithms. A central and expected observation is the inherent computational trade-off: the enhanced analytical capabilities of the wavelet transform come at the cost of increased processing demand. Specifically, the wavelet algorithm exhibits the highest execution time among the evaluated methods, a direct consequence of its multi-resolution signal decomposition process which operates across multiple frequency bands. This elevated processing time, however, must be contextualized within the modern landscape of microprocessor-based relays and digital signal processors, which possess ample computational headroom to execute such algorithms well within the stringent sub-cycle timing requirements of transmission line protection. The additional milliseconds of processing are a justified investment, as they purchase the significant gains in accuracy, security, and high-impedance fault detection documented in prior results.

Beyond raw execution time, the Figure 13 illuminates other vital resource metrics. The memory usage profile for the wavelet method is moderately higher than that of simpler algorithms like overcurrent protection, reflecting the need to store wavelet coefficients and historical data windows for effective transient analysis. However, this increase remains well within the capabilities of contemporary industrial hardware. More importantly, the real-time factor a metric indicating the ratio of simulation time to actual wall-clock time remains favorable for the proposed method, confirming that the simulation and, by extrapolation, potential real-time operation can proceed without debilitating latency. Finally, the scalability index, which gauges the algorithm's efficiency as system complexity grows, indicates that while the wavelet approach is more complex, its design does not impose a prohibitive computational burden that would preclude its application to larger networks or its integration into wider-area protection schemes. This comprehensive computational profile confirms that the performance advantages of the wavelet-based methodology are achieved without exceeding the practical constraints of current protection hardware, thereby validating its feasibility for real-world implementation.

The true strength of the wavelet approach is most apparent under challenging system conditions where traditional protection schemes struggle. As summarized in Figure 14, the proposed method maintains high reliability where others falter. For high-impedance faults a known blind spot for overcurrent relays the wavelet method retained 94.7% accuracy by detecting the unique harmonic signature of arcing faults. During intermittent or evolving fault scenarios, its multi-resolution analysis allowed for continuous tracking of the fault characteristic, achieving 95.2% and 93.8% accuracy, respectively. Furthermore, the scheme's inherent stability against unbalanced load conditions and current transformer saturation, with accuracies of 96.7% and 90.8%, demonstrates its robustness. Most notably, the incidence of sympathetic tripping an undesirable operation for a fault in an adjacent zone was reduced to just 5%, a five-fold improvement over the overcurrent scheme, due to the algorithm's superior discrimination capabilities.

In synthesis, these results conclusively demonstrate that the integration of wavelet transform analysis does not merely incrementally improve performance but addresses fundamental limitations of traditional principles. The method provides a unified solution that enhances speed, accuracy, security, and dependability simultaneously. It bridges the gap between the localized simplicity of standalone relays and the comprehensive awareness of wide-area systems, offering a pragmatic yet powerful step toward the adaptive, resilient protection schemes required by future grids with high penetrations of intermittent renewable generation. The findings validate the initial hypothesis that a time-frequency domain signal processing approach, when judiciously combined with established protection logic, can significantly elevate the performance floor for transmission line protection, mitigating risk and enhancing the overall reliability of the electrical power infrastructure.

5. Deep Research Insights and Novel Contributions

This research transcends conventional fault analysis by establishing a cohesive simulation ecosystem that mirrors the dynamic and often unpredictable nature of modern power grids. At its core, the study delves into the transient behavior of transmission lines under fault conditions, capturing not only the fundamental frequency deviations but also the high-frequency transients and traveling waves that are often glossed over in simplified models. By employing a distributed parameter line model within MATLAB Simulink, the research accurately represents the wave propagation effects, enabling a nuanced analysis of fault-induced surges and their impact on protective relay performance. This depth of modeling is critical, as it reveals the limitations of standard distance protection during fast-front transients and high-impedance fault scenarios, thereby challenging traditional setting philosophies.

The novelty of this work is multifaceted. First, it introduces a detection framework that synergistically combines the deterministic logic of conventional relays (overcurrent, distance) with the pattern-recognition capabilities of signal processing tools like the Discrete Wavelet Transform (DWT). This fusion allows the system to not only declare a fault but also classify its type such as distinguishing a transient arcing fault from a permanent bolted short-circuit based on the extracted energy signatures of the wavelet coefficients. Second, the research pioneers the co-simulation of communication layer effects within the protection scheme. By modeling channel delays, packet drops, and cyber-intrusion scenarios in the feedback loop between remote relays, the study quantifies the often-overlooked vulnerability of pilot-based and wide-area protection schemes to non-idealities in the data links, a crucial consideration for the transition to smart grids.

Furthermore, the investigation provides novel insights into the adaptive setting of protection parameters in response to changing grid topology. Through automated scripted scenarios, the simulation demonstrates how renewable energy ingress, such as sudden solar generation dropout, can alter fault current levels and directional power flows, potentially blinding fixed-threshold relays. The proposed solution framework involves embedding a meta-algorithm that adjusts relay setpoints based on real-time state estimation derived from simulated Phasor Measurement Unit (PMU) data, paving the way for self-tuning protection systems.

6. Future Scope: Trajectories for Next-Generation Grid Resilience

The pathways forward, illuminated by this research, point toward a paradigm shift from static protection to predictive and participatory grid defense mechanisms. One promising direction is the full integration of machine learning surrogate models trained on the vast simulation data generated by this work. These models, such as convolutional neural networks (CNNs) for waveform classification or reinforcement learning agents for relay coordination, could be deployed locally in edge computing devices adjacent to substations, enabling ultra-fast, data-driven fault decisions without reliance on continuous central communication.

Another fertile frontier is the development of quantum-sensitive sensors and their simulation models. The future grid will likely incorporate quantum magnetometers for ultra-precise current measurement, offering orders-of-magnitude improvement in sensitivity. Research must now focus on modeling these devices within environments like Simulink to understand their noise characteristics and failure modes under extreme electromagnetic interference, ensuring they enhance rather than destabilize protection schemes.

Furthermore, the concept of "protection-as-a-service" (PaaS) in decentralized energy markets warrants exploration. As prosumers and microgrids proliferate, their point of interconnection could host intelligent protection agents that negotiate fault response strategies with utility-grade systems via blockchain-secured contracts. Simulating these complex economic-technical interactions will require expanding the current model to include multi-agent system frameworks and market signal inputs.

Lastly, the cyber-physical security challenge must be addressed holistically. Future work will involve creating digital twin replicas of entire transmission corridors, incorporating realistic models of firewalls, intrusion detection systems, and encryption overhead. This will allow for stress-testing protection schemes against coordinated cyber-physical attacks, such as a simultaneous line fault and communication jamming, to develop inherently resilient architectures.

7. Conclusion

This research has systematically developed, simulated, and validated a novel wavelet-based protection scheme for transmission line fault detection and mitigation. The proposed methodology, which integrates Discrete Wavelet Transform (DWT) analysis with conventional relay logic, was rigorously evaluated within a MATLAB/ Simulink environment against established protection paradigms, including overcurrent, distance, and differential schemes. The findings, as consistently presented throughout the manuscript, demonstrate that the proposed approach successfully addresses critical limitations in conventional systems. The core achievement of this work is quantified by a significant enhancement in protection performance. The wavelet-based scheme achieved an average fault detection time of 11.4 milliseconds, effectively balancing the ultra-high speed of differential protection with greater reliability. More critically, it attained an overall accuracy of 99.8%, maintaining exceptional performance across all fault types, from common single-line-to-ground faults (99.9%) to three-phase faults (99.9%). This high accuracy is coupled with superior security, evidenced by drastically reduced false positive (0.05%) and false negative (0.02%) rates. These metrics collectively confirm the algorithm's enhanced ability to discriminate genuine faults from system transients, a key weakness of impedance-based relays. Furthermore, the results substantiate the method's robustness under challenging conditions where traditional protection falters. The system maintained high accuracy for high-impedance faults (94.7%), evolving faults (93.8%), and during current transformer saturation (90.8%), while also minimizing sympathetic tripping to 5%. These outcomes are in direct alignment with the discussion of the wavelet transform's capability to extract non-stationary, high-frequency signatures that are indicative of such complex fault scenarios. The study also transparently addresses the computational trade-off inherent to advanced signal processing. While the wavelet algorithm requires greater processing time and memory than simpler methods, the analysis confirms that this demand remains well within the capabilities of modern digital relays and does not compromise the sub-cycle operating times required for effective protection. This computational profile supports the practical feasibility of the proposed approach.

In conclusion, the data and discussion presented herein form a coherent and validated argument: wavelet protection framework provides a substantive advancement over conventional methods. It offers a resilient, accurate, and secure solution that enhances the reliability of power transmission systems. This work contributes a foundational model for adaptive protection strategies suited to the evolving dynamics of modern grids, particularly those with high penetrations of renewable energy and power electronic interfaces. Future research, building upon this validated simulation framework, can focus on hardware-in-the-loop implementation, integration with wide-area monitoring systems, and the incorporation of machine learning for predictive analytics.

8. Declarations

8.1. Author Contributions

Asif Eakball Emon: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources; **Jalal Ahammad:** Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft.

8.2. Institutional Review Board Statement

Not applicable.

8.3. Informed Consent Statement

Not applicable.

8.4. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.5. Acknowledgment

Not applicable.

8.6. Conflicts of Interest

The authors declare no conflicts of interest.

9. References

[1] W. Chen, O. P. Malik, X. Yin, D. Chen, and Z. Zhang, "Study of wavelet-based ultra high speed directional transmission line protection," *IEEE Trans. Power Deliv.*, vol. 18, no. 4, pp. 1134–1139, Oct. 2003, https://doi.org/10.1109/TPWRD.2003.817511.

[2] X. Li, W, Dai, T. Wu, X. Teng, K. Zheng, X. Hou, and D. Wu, "Hybrid HVDC Transmission Line Protection Method Based on Synchrosqueezing Wavelet Transform," in *Proceedings of 2021 International Top-Level Forum on Engineering Science and Technology Development Strategy*, pp. 233–252, 2022, https://doi.org/10.1007/978-981-16-7156-2_16.

[3] M. Yousaf, A. Singh, S. Khalid, M. Bajaj, B. Hemanth Kumar, and I. Zaitsev, "Enhancing HVDC transmission line fault detection using disjoint bagging and bayesian optimization with artificial neural networks and scientometric insights," *Sci. Rep.*, vol. 14, Oct. 2024, https://doi.org/10.1038/s41598-024-74300-z.

[4] A. Sudhakar, Y. Manjusree, and C. Venkatesh, "SVC compensated transmission line protection using wavelet approach," in *International Conference on Research In Sciences, Engineering & Technology*, vol. 2418, no. 1, 2022. https://doi.org/10.1063/5.0083112.

[5] M. Abasi, A. Ghadimi, and H. Al-Dirawi, "A New Algorithm for Fault Detection, Classification, and Location Based on the Combination of Time–Frequency Domain Discrete Wavelet and Time–Time Transforms in High-Voltage Transmission Lines," *Model. Simul. Eng.*, vol. 2025, Nov. 2025, https://doi.org/10.1155/mse/5552044.

[6] Z. M. Ali and E. M. Ismail, "Deep learning and wavelet packet transform for fault diagnosis in double circuit transmission lines," *Sci. Rep.*, vol. 15, Aug. 2025, https://doi.org/10.1038/s41598-025-15583-8.

[7] S. Ananwattanaporn, P. Lertwanitrot, A. Ngaopitakkul, and C. Pothisarn, "Development of overcurrent relay based on wavelet transform for fault detection in transmission line," *Sci. Rep.*, vol. 14, Jun. 2024, https://doi.org/10.1038/s41598-024-65596-y.

[8] C. D. Prasad, M. Biswal and P. K. Nayak, "Wavelet operated single index based fault detection scheme for transmission line protection with swarm intelligent support," *Energy Systems,* vol. 12, pp. 373–392, 2021. https://doi.org/10.1007/s12667-019-00373-9.

[9] B. Bhalja and R. P. Maheshwari, "Wavelet-based Fault Classification Scheme for a Transmission Line Using a Support Vector Machine," *Electric Power Components and Systems,* vol 36, no 10, pp. 1017-1030, 2008, https://doi.org/10.1080/15325000802046496.

[10] H. Fathabadi, "Two novel proposed discrete wavelet transform and filter based approaches for short-circuit faults detection in power transmission lines," *Appl. Soft Comput.*, vol. 36, pp. 375–382, Nov. 2015, https://doi.org/10.1016/j.asoc.2015.07.039.

[11] J. S. Farkhani, Ö. Çelik, K. Ma, C. L. Bak, and Z. Chen, "Fault Detection, Classification, and Location Based on Empirical Wavelet Transform-Teager Energy Operator and ANN for Hybrid Transmission Lines in VSC-HVDC Systems," *Journal of Modern Power Systems and Clean Energy*, vol. 13, no. 3, pp. 840 – 851, 2025, https://doi.org/10.35833/MPCE.2023.000925.

[12] S. Singh, P. Kumar, and A. Ram, "Modelling, and analysis of thyristor-controlled series capacitor using MATLAB/Simulink," *International Journal of New Innovations in Engineering and Technology*, vol. 1, no. 3, pp. 61–66, 2013.

[13] S. C. Shekar and S. R. Salkuti, "Wavelet-ANN Based Detection of Fault Location of Renewable Energy Sources Integrated Power Transmission System," *Energy and Environmental Aspects of Emerging Technologies for Smart Grid,* pp. 599–627, 2024, https://doi.org/10.1007/978-3-031-18389-8_26.

[14] S. Saad, S. Ali, A. Khan, F. Mahar, A. Almani, and N. Kumar, "Real-Time Fault Detection and Operational Optimization in Three-Phase Induction Motors: A Proactive Approach to System Protection," *IEEEP New Horiz. J.*, vol. 105, Nov. 2025, https://doi.org/10.61514/ieeep.v105i1.287.

[15] H. Hao, Z. Li, W. Huang, S. Li, Y. Shen, "Design of Efficient Dual-Band Class-F Rectifier for Wireless Power Transmission and Energy Harvesting," *Microw. Opt. Technol. Lett.*, vol. 67, Sep. 2025, https://doi.org/10.1002/mop.70390.

[16] N. F. M. Sharif, K. N. M. Shafiee, N. F. I. Tajudin, , N. S. M. Nazar, S. N. A. Tarmizi, A. R. A. Rahman, and B. Samaila, "A Modelling of 500 Kv Long Transmission Line and Fault Detection Using Inverse Definite Minimum Time Over Current (IDMT O/C) relay," *J. Kejuruter.*, vol. 37, no. 1, pp. 477–488, Jan. 2025, https://doi.org/10.17576/jkukm-2025-37(1)-35.

[17] M. Yousaf, A. Singh, S. Khalid, M. Bajaj, B. Hemanth Kumar, and I. Zaitsev, "Enhancing HVDC transmission line fault detection using disjoint bagging and bayesian optimization with artificial neural networks and scientometric insights," *Sci. Rep.*, vol. 14, Oct. 2024, https://doi.org/10.1038/s41598-024-74300-z.

[18] A. Emon, "Design Simulation & Implementation of a High-Gain Discrete Boost Regulator Utilizing Cascaded Switching and Voltage Clamping Techniques," *Preprint Research Square*, 2025. https://doi.org/10.21203/rs.3.rs-8179494/v1.

[19] A. E. Emon and A. Tabassum, "An Iterative Modeling and Validation Study of a Low-Cost Thyristor-Based Controlled Half-Wave Rectifier," *Methods Sci. Technol. Stud.*, vol. 1, no. 2, pp. 59–71, 2025. https://doi.org/10.64539/msts.v1i2.2025.354.

[20] A. Tabassum and A. Emon, "An Integrated IoT Framework for Proactive Road Safety and Accident Mitigation In Hilly Terrains," *J. Trends Chall. Artif. Intell.*, vol. 3, no. 4, pp. 177–184, Dec. 2025, https://doi.org/10.61552/JAI.2026.04.001.

[21] M. Parsi, P. Crossley, P. L. Dragotti, and D. Cole, "Wavelet based fault location on power transmission lines using real-world travelling wave data," *Electr. Power Syst. Res.*, vol. 186, p. 106261, Sep. 2020, https://doi.org/10.1016/j.epsr.2020.106261.

[22] A. E. Emon, M. Shawon, S. Molla, and M. S. Nowjh, "Improved Microgrid Controller with Robust Stability, Conjunction with PID Controllers," *Journal of Electrical and Electronic Engineering*, vol. 13, no. 3, pp. 116-130, 2025, https://doi.org/10.11648/j.jeee.20251303.11.

[23] J. Chen, J. Wang, J. Zhang, S. Yao, Q. Li, and H. Li, "The Overcurrent Limiting Method of GF-SVG in a Wind Farm Based on Adaptive Virtual Reactance," *Energy Eng.*, vol. 122, pp. 3703–3718, Aug. 2025, https://doi.org/10.32604/ee.2025.066620.

[24] A. Emon, S. Molla, M. Shawon, and A. Tabassum, "Comparative Analysis and Modeling of Single and Three Phase Inverters for Efficient Renewable Energy Integration," *Sci. J. Eng. Res.*, vol. 1, no. 4, pp. 195–212, 2025, https://doi.org/10.64539/sjer.v1i4.2025.325.

[25] A. Emon, M. Shawon, S. Molla, A. Tabassum, and M. S. Nowjh, "Emerging Designs and Strategies for Overvoltage Protection in Modern Electronics," *J. Electr. Electron. Eng.*, vol. 13, no. 6, pp. 242–254, Dec. 2025, https://doi.org/10.11648/j.jeee.20251306.11.

[26] J. Jibunor, B. Odigie, and O. Igbape, "A Bayesian Learning Framework Powered by IoT for Enhancing Highway Safety and Reducing Accidents: A Case Study of Benin-Onitsha Express Way," *Int. J. Res. Innov. Appl. Sci.*, vol. 11, pp. 334–360, Nov. 2024, https://doi.org/10.51584/IJRIAS.2024.910032.

[27] A. Emon, S. Molla, A. Tabassum, and M. Shawon, "Design and Comparative Analysis of Single-Phase and Three-Phase Double-Stage Inverters for Photovoltaic Systems," *Int. J. Sci. Res. Sci. Eng. Technol.*, vol. 12, pp. 407–417, Oct. 2025, https://doi.org/10.32628/IJSRSET25125046.

[28] A. Emon, M. Shawon, S. Molla, M. S. Nowjh, and U. Sen, "Inverse Filter-Based Image Reconstruction for Improved ANPR Performance in Bangladesh Security Systems," *J. Trends Chall. Artif. Intell.*, vol. 3, no. 2, pp. 111–120, 2025, https://doi.org/10.61552/JAI.2026.02.006.

[29] S. A. Gafoor and P. V. R. Rao, "Wavelet Based Fault Detection, Classification and Location in Transmission Lines," in *2006 IEEE International Power and Energy Conference*, pp. 114–118, Nov. 2006, https://doi.org/10.1109/PECON.2006.346630.

[30] M. Liserre, R. A. Mastromauro, and A. Nagliero, "Universal Operation of Small/Medium-Sized Renewable Energy Systems," in *Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications*, pp. 231–269, 2014, https://doi.org/10.1002/9781118755525.ch9.

[31] L. Ansari, M. A. Alam, R. Biswas, and S. M. Idrees, "Adaptation of Smart Technologies and E-Waste: Risks and Environmental Impact," in *Smart Technologies for Energy and Environmental Sustainability*, pp. 201–220, 2022, https://doi.org/10.1007/978-3-030-80702-3_12.

[32] Z. M. Ali and E. M. Esmail, "Deep learning and wavelet packet transform for fault diagnosis in double circuit transmission lines," *Sci. Rep.*, vol. 15, no. 1, pp. 30145, Aug. 2025, https://doi.org/10.1038/s41598-025-15583-8.

[33] K. P. Jadhav, K. Shivashanker, S. Velpula, S. C. Shekar, M. P. Gajare, M. S. Saranya, "Wavelet Based Faulty Terminal and Phase Identification on Hybrid Power Transmission System," *Int. J. Appl. Math.*, vol. 38, no. 8s, pp. 795–813, Oct. 2025, https://doi.org/10.12732/ijam.v38i8s.610.

[34] N. Kumar and B. Sridhar, "Fault Ride-Through Capability Enhancement of Grid-Integrated PMSG Wind Energy Conversion Systems," *Int. J. Multidiscip. Res.*, vol. 7, no. 5, 2025, https://doi.org/10.36948/ijfmr.2025.v07i05.55132.

[35] X. Mou, R. Zhu, X. Zhang, W. Chen, J. Son, X. Huo, and K. Wang, "Design of Fault Protection Stra for Unified Power Flow Controller in Distribution Networks," *Energies*, vol. 19, no. 1, p. 79, Dec. 2025, https://doi.org/10.3390/en19010079.

[36] S. Saad, S. Ali, A. Khan, F. Mahar, A. Almani, and N. Kumar, "Real-Time Fault Detection and Operational Optimization in Three-Phase Induction Motors: A Proactive Approach to System Protection," *IEEEP New Horiz. J.*, vol. 105, Nov. 2025, https://doi.org/10.61514/ieeep.v105i1.287.

[37] A. Askarov, P. Radko, Y. Bay, I. Gusarov, V. Kabirov, P. Ilyushin and A. Suvorov, "Overcurrent Limiting Strategy for Grid-Forming Inverters Based on Current-Controlled VSG," *Mathematics*, vol. 13, no. 19, p. 3207, Oct. 2025, https://doi.org/10.3390/math13193207.