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Fault Detection and Protection of High Voltage Transmission Line, Integrated With Hybrid Renewable Energy Sources

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ABSTRACT.

The integration of renewable energy sources into modern power systems has necessitated the development of advanced fault detection and protection mechanisms to ensure system stability and reliability. This research presents the modelling, simulation, and analysis of a fault detection and protection system for high-voltage transmission lines integrated with hybrid renewable energy sources, including wind and solar energy. The study focuses on fault detection, isolation, and relay coordination to enhance the resilience of transmission networks while mitigating power disruptions caused by various fault scenarios. The study investigated fault occurrences at different locations along the transmission line, including the sending end, receiving end, intermediate points, and renewable energy connection nodes. Faults were simulated at 25 km, 50 km, and 75 km from the source, with varying fault resistances. Key parameters such as voltage at fault points, current surges, relay operation time, sensitivity, coverage area, and system stability were evaluated. Advanced signal processing techniques, including wavelet transform analysis, were employed to assess system behaviour during fault conditions, ensuring accurate fault detection and isolation. Results indicated that the Intermediate Point Configuration provided the most balanced approach, offering comprehensive fault coverage, optimal isolation, and minimal system disruption. The impact of different fault types, including Line-to-Ground (LG), Line-to-Line-to-Ground (LLG), and Three-Phase (LLL), was analysed, revealing that three-phase faults caused the most severe disturbances, including voltage collapse and high fault currents. Relay operations were incorporated to isolate faulty sections of the network promptly, ensuring minimal disruption to the overall system. The results demonstrated that relay coordination was effective, with primary relays tripping first, followed by backup relays when necessary. The study also highlighted challenges posed by high-resistance faults and faults at distant locations, which require more sensitive detection techniques. Plots of voltage and current profiles at detection points provided a visual representation of the system's dynamic behaviour under fault conditions. The research concludes that adopting the Intermediate Point Configuration enhances the reliability of high-voltage transmission systems, particularly in networks incorporating renewable energy sources. The findings contribute to the development of improved fault detection methodologies, ensuring efficient power system operation and resilience against electrical disturbances.

Keywords: Renewable energy, Transmission line, Fault detection, MATLAB, Current, Voltage, Simulations.

I. INTRODUCTION

The integration of renewable energy sources (RES) into traditional power systems has become increasingly prevalent in recent years due to growing concerns about climate change and the depletion of fossil fuels (Chen *et al*., 2020). Renewable energy sources such as solar photovoltaic (PV), wind, and hydroelectric power offer sustainable alternatives to conventional energy sources (Santos et al., 2018). However, the intermittent nature and variability of renewable energy generation pose challenges to the stability and reliability of power systems, particularly in high voltage transmission lines (Yang *et al.,* 2019). The global energy landscape is rapidly evolving, with a growing emphasis on the integration of renewable energy sources such as wind, solar, and battery energy storage systems into existing power grids (Santos et al., 2018). This transition is driven by the need to reduce greenhouse gas emissions, promote sustainable energy development, and enhance energy security. However, the integration of these renewable energy sources poses significant technical challenges, particularly in the areas of fault detection and protection of high voltage transmission systems. Traditional power systems rely heavily on centralized generation and a relatively stable power flow from generation to load centres. Consequently, conventional fault detection and protection systems have been designed to operate under these stable conditions. However, the intermittent nature of renewable energy sources introduces variability and complexity in power flow dynamics, making it difficult for existing protection systems to perform effectively. This is further compounded by the integration of hybrid configurations, where multiple renewable sources are combined, leading to multi-directional power flows and fluctuations in voltage and current levels.

Faults in high voltage transmission lines, such as line-to-ground, line-to-line, and three-phase faults, can result in severe consequences, including equipment damage, power outages, and disruption of the overall power system. Therefore, there is a critical need for advanced fault detection and protection strategies capable of accommodating the unique characteristics of hybrid renewable energy systems. This research focuses on the development and analysis of a model for effective fault detection and protection in high voltage transmission lines integrated with hybrid renewable energy. The study aims to address the limitations of conventional protection systems by proposing a robust methodology for fault detection, isolation, and protection, thereby ensuring the stability and reliability of modern power systems in the face of increasing renewable energy integration.

This research is significant as it contributes to the ongoing efforts to optimize the performance of power systems with high renewable energy penetration, ensuring that they are equipped to handle the challenges of future energy networks.

II. LITERATURE REVIEW

A. Traditional Fault Detection Methods:

Traditional fault detection methods for high voltage transmission lines typically rely on protective relays, current transformers, voltage sensors, and circuit breakers (Gers et.al., 2017). These methods are effective for unidirectional power flow scenarios but may encounter limitations in systems integrated with RES due to bidirectional power flow and intermittent generation patterns.

B. Challenges in Fault Detection with Hybrid RES Integration:

The integration of hybrid renewable energy sources, such as solar PV, wind, and hydroelectric power, poses several challenges for fault detection in high voltage transmission lines:

I. *Bidirectional Power Flow:* Hybrid RES systems enable power flow in both directions, leading to complex fault detection scenarios (Yang et. al., 2019).

II. *Intermittent Generation:* Renewable energy generation is inherently intermittent, resulting in fluctuations in power output that can obscure fault signals (Santos et.al., 2018).

III. *Decentralized Nature of RES Installations*: The decentralized nature of RES installations complicates fault detection efforts, as fault signals may be distributed across multiple generation units and points of interconnection (Ahangar et.al., 2019). Isolation, and protection, thereby ensuring the stability and reliability of modern power systems in the face of increasing renewable energy integration.

C. Existing Research on Fault Detection in RES-Integrated Systems:

Several studies have addressed fault detection in power systems with integrated renewable energy sources:

Chen et.al, (2020) proposed a fault location algorithm for hybrid power systems considering the integration of renewable energy sources. (Guo et.al., 2021) developed a fault location method based on support vector machines with a hybrid kernel for transmission lines.

Ahangar et.al., (2019) investigated the application of a combined approach of discrete wavelet transform (DWT) and artificial neural networks (ANN) for fault detection in transmission lines.

Despite existing research efforts, there is a notable gap in the literature regarding fault detection in high voltage transmission lines integrated with hybrid renewable energy sources. Existing methods may not fully address the complexities introduced by bidirectional power flow, intermittent generation, and the decentralized nature of RES installations. Additionally, there is a need for comprehensive studies that consider the economic feasibility and practical implementation of fault detection systems in real-world power grid environments.

This literature review provides a comprehensive overview of the existing research, identifies gaps in the literature, and outlines the objectives of the current study on fault detection in high voltage transmission lines integrated with hybrid renewable energy sources.

D. Impact of Renewable Energy Integration on Fault Characteristics:

The integration of renewable energy sources (RES) into high voltage transmission lines can alter the characteristics of faults, posing challenges for fault detection and classification.

Zhang et.al., (2018) conducted a study to analyse the impact of renewable energy integration on fault current characteristics, finding that variations in generation patterns can influence fault impedance and current magnitude.

Wang et.al., (2019) investigated the effects of renewable energy intermittency on fault transients and proposed methods to enhance fault detection accuracy in RES-integrated transmission systems.

While existing studies have explored the impact of renewable energy integration on fault characteristics, further research is needed to develop fault detection algorithms that can effectively adapt to dynamic changes in generation patterns and fault behaviour.

III. MATERIAL AND METHODS

A. Materials Used:

The materials and their respective ratings used in this research are listed below, along with detailed explanations on how they are relevant to the scope of the research:

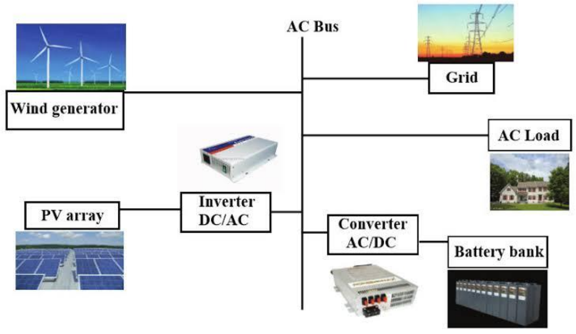

Figure 1. The System Architecture

I. *High Voltage Transmission Line:* The high voltage transmission line is the primary medium for transmitting power from the generation units (hybrid renewable sources) to the substation and load points. It serves as the critical section of the system where faults are detected and protection strategies are deployed. For this thesis, the transmission line is rated 220 kV, 100 km length

II. *Wind Farm:* The wind farm is one of the main sources of power in the hybrid renewable energy setup. It contributes to the total generation capacity of the microgrid and interacts with other sources like the solar PV and diesel generator in maintaining stable power delivery. For this thesis, the wind farm is rated 50 MW, 33 kV

III. *Solar Photovoltaic (PV) System*: The solar PV system generates power during daylight hours and helps stabilize the grid. It operates in conjunction with the wind farm and other generation units, contributing significantly to the renewable energy fraction of the system and it is rated 20 MW with Solar irradiance of 1000W/m2.

IV. *Battery Energy Storage System (BESS):* Rated 10 MW, 500 MWh, the battery energy storage system (BESS) is used to store excess energy generated from the wind and solar units. It helps to manage power fluctuations and provides backup power during faults or disturbances

V. *Transmission Line Parameters:* These parameters are essential for the accurate modelling of the transmission line, affecting the voltage, current, and fault analysis.

Line Resistance = 0.1 Ω/km

Line Reactance = 0.5 Ω/km

Bus voltage = 220kv

VI. Simulation Parameters:

Simulation time = 0.2 Seconds

Time step = 0.0002 seconds

Number of Sections = 10

VII. *Protection System Parameters:*

$Z_{threshold} = 0.8 \times Z_{base}$

Fault position = 25%, 50%, 75%.

Primary relay delay = 0.05s

Backup relay delay = 0.1s

VIII. *Fault Detection and Protection Module:* The Distance relays, Overcurrent relays and Circuit breakers form the core of the protection scheme. The distance relay detects impedance variations during fault conditions, while the overcurrent relay measures excessive current to trip circuit breakers and isolate faults.

IX. *MATLAB:* Version 2021a software is used to model, simulate, and analyse the performance of the high voltage transmission line integrated with hybrid renewable energy. It also includes the implementation of the fault detection and protection schemes.

X. *Intermediate Points Configuration Setup:* This setup includes precise fault detection and protection placement points within the microgrid system. It allows detailed analysis of the response at critical locations like the renewable connection, microgrid connection, and intermediate points.

XI. *Measurement and Monitoring Devices:* Voltage transducers, Current transformers, Phasor Measurement Units (PMUs) are used to measure the electrical parameters such as voltage, current, and power at different points in the system. They provide real-time data that is crucial for fault analysis and protection schemes.

B. *Methodology:*

The methodology for this research involves the following steps:

I. *System Modelling and Configuration:*

The high voltage transmission line is modelled to include hybrid renewable energy sources (wind and solar), a battery energy storage system, and a diesel generator. The high voltage transmission line is represented using a pi-section model to capture the impact of line impedance and length on fault detection.

II. *Intermediate Points Configuration Setup:*

A specific configuration is chosen where fault detection modules are placed at intermediate points along the transmission line. This configuration helps in identifying the most sensitive and active locations for fault detection based on distance and electrical parameters.

III. *Fault Type Analysis:*

Various fault types, such as single line-to-ground (LG), line-to-line (LL), double line-to-ground (LLG), and three line-to-ground (LLL) faults, are simulated at different positions along the transmission line to analyse their effects on the system's stability and protection response.

IV. *Fault Detection and Protection Simulation:*

The MATLAB model is used to simulate the intermediate point configuration. The code developed for this configuration is executed, and voltage and current waveforms are obtained for both the sending and receiving ends. The distance relay is employed to monitor impedance changes, while the overcurrent relay measures current excess.

V. *Result Analysis and Comparison:*

Voltage and current waveforms are plotted for the different configurations, and performance metrics such as fault detection time, relay coordination, and system stability are analysed. The most active configuration is recommended based on the ability to detect and isolate faults quickly and effectively.

V. *System Protection and Recommendations:*

Based on the simulation results, recommendations are made regarding the optimal placement of fault detection and protection modules. The intermediate points configuration, which has been validated as the most active, is suggested for integration in the microgrid system.

C. *Mathematical Models:*

The mathematical models in this chapter are used to describe the various components and phenomena in a high voltage transmission line and hybrid renewable energy microgrid system. These models provide a foundation for analysing system behaviour under different operating and fault conditions. They are as follows:

I. *Transmission Line Modelling:*

The transmission Line is represented using a pi-section model which divides the lines into smaller section to simulate its electrical characteristics accurately. The parameters for each section calculated as follows:

- Line Impedance per section:

$$Z_{section} = (R_{line} + jX_{line}) \times \frac{L_{line}}{N} \qquad 1$$

Where:

R_{line} = Line resistance per KM (ohm/KM)

X_{line} = Line reactance per KM (Ohm/KM)

L_{line} = Total Length of line (KM)

N = Number of Sections in the pi-section model

ii. Total Line Impedance:

$$Z_{total} = Z_{section} \times \mathrm{N} \qquad 2$$

The voltage and current along the transmission line are computed using a simplified difference equation for each section:

Voltage drops across section:

$$V_n+1 = V_n+ - \mathrm{I_n} \times Z_{section} \qquad 3$$

Current flow in a section:

$$\mathrm{In} = \frac{\mathrm{Vn - Vn+1}}{Z_{section}} \qquad 4$$

- *Renewable Energy Sources Modelling:*

Wind Farm Model: The power generated by a wind farm is dependent on the wind speed and the efficiency of the turbines. The simplified power model is expressed as:

$$P_{wind}+ = \frac{1}{2} \rho \times \mathrm{A} \times \mathrm{V}^3 \times \mathrm{C_p} \times \mathrm{N} \qquad 5$$

Where:

ρ = Air Density (Kg/m3)

A = Rotor Swept Area (m3)

V = Wind Speed (m/s)

C_p = Power coefficient (Typically between 0.3 and 0.5)

N = Number of wind turbines.

The generated voltage can be estimated as:

$$V_{wind} = \frac{P_{wind}}{\sqrt{3 \times I_{wind}}} - \qquad 6$$

- *Solar PV Model:*

The power generated by the solar PV system is a function of solar irradiance and the system's coefficient:

$$P_{solar} = \mathrm{G} \times \mathrm{A} \times \eta \qquad 7$$

Where:

G = Solar Irradiance (W/m2)

A = Area of the Solar panel (m2)

η = Efficiency of the Solar PV system

- *Fault Detection Model:*

The fault detection scheme utilizes distance protection, which is based on impedance measurement. The mathematical model for distance protection is defined as:

Impedance Measurement:

$$\mathrm{Z}_{\mathrm{measured}} = \frac{V_{fault}}{I_{fault}} \qquad 8$$

Where:

V_{fault} = Voltage at the fault location

I_{fault} = Current at the fault location

The distance relay monitors the measured impedance and compares it with a predefined threshold to determine if a fault has occurred:

$$\text{Fault condition} = \begin{cases} \text{True if } Z_{measured} < \text{Threshold} \\ \text{False otherwise} \end{cases} \qquad 9$$

- *Fault types and their mathematical models:*

Single line to ground (L-G) Fault:

The current injected into the fault point for an L-G fault is given by:

$$I_{fault} = \frac{V_{fault}}{R_{fault}} \qquad 10$$

Where:

R_{fault} = Fault Resistance (Ohm)

- *Line to Line (L-L) Fault:*

The current injection equation for L-L fault between phase a and b is:

$$I_{fault} = \frac{V_a - V_b}{R_{fault}} \qquad 11$$

- *Double Line to Ground (L-L-G) Fault:*

The fault currents for double line to ground faults are computed as follows:

$$I_{fault\ 1} = \frac{V_a}{R_{fault}}, \quad I_{fault\ 2} = \frac{V_b}{R_{fault}} \qquad 12$$

Three Lines to Ground (L-L-L-G) Fault:

The current injection for a three phase faults is:

$$I_{fault\ 1} = \frac{V_a - V_b}{R_{fault}}, \; I_{fault\ 2} = \frac{V_b - V_a}{R_{fault}},$$

$$I_{fault\ 2} = \frac{V_c - V_a}{R_{fault}} \qquad 13$$

- *Relay Coordination and Protection Scheme*:

The relay coordination model is based on the timing and impedance measurement of the relays:

Primary Relay Tripping Time:

$$\text{Tpri.} = \begin{cases} \Delta_{\mathrm{tprimary}} & \text{if fault detected} \\ \infty & \text{Otherwise} \end{cases}$$

Where:

14

Δtpri. = Delay time for the primary relay to trip (seconds)

- *Voltage and Current waveforms Analysis:*

The voltage and current at different points (sending and receiving ends) are computed and plotted using the following equation:

$V(t) = V_{peak} \times \sin(2\pi ft)$ 15

Where:

V_{peak} = Peak Voltage Value

f = System frequency (Hz)

Current waveform:

$I(t) = \frac{V_{(t)})}{Z_{line}}$ 16

Protection System Parameters:

$Z_{base} = \frac{V_{base}^2}{S_{base}}$

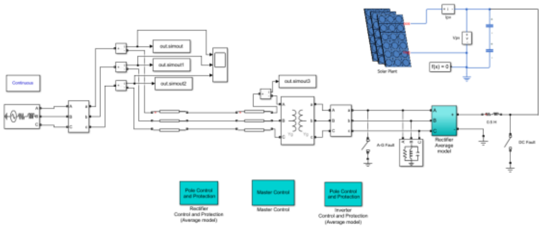

Figure 2. The Simulink Model of the Hybrid Transmission Line Protection System

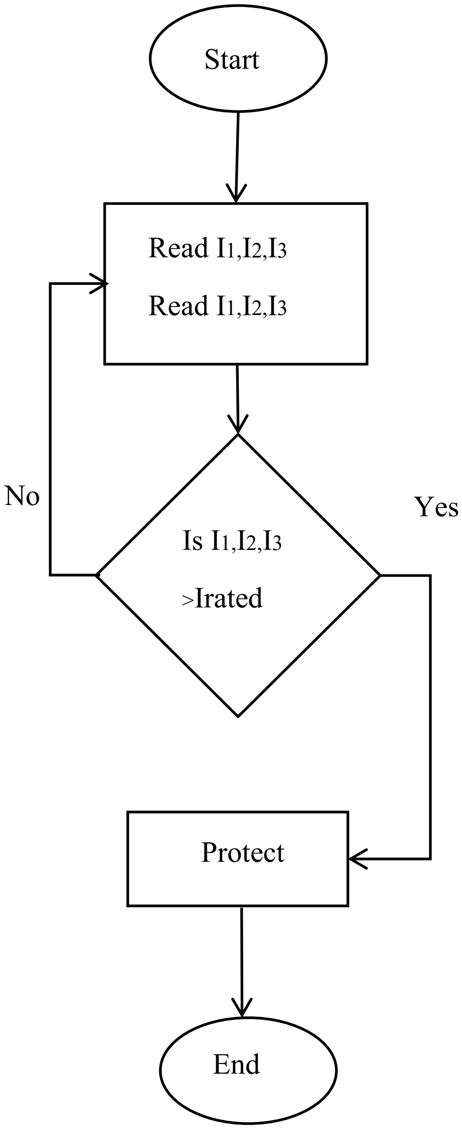

Figure 3. The Flowchart of the Fault Detection System

IV. RESULTS AND DISCUSSION

This chapter presents the results obtained from the simulation of the high voltage transmission line integrated with hybrid renewable energy sources. The simulations were conducted using MATLAB and the results are discussed in terms of fault detection, protection effectiveness, and the overall performance of the system under various operating conditions and configurations. The findings are supported by graphical representations of voltage and current waveforms, impedance measurements, and relay operation times.

A. *Simulation Results:*

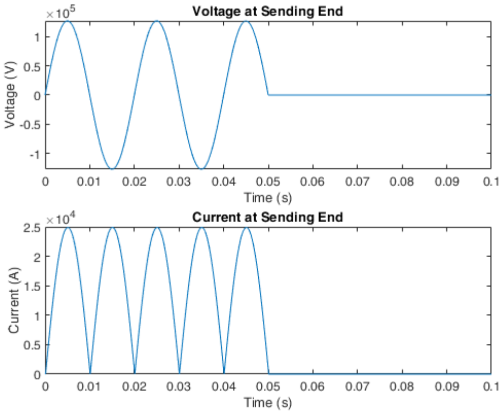

Figure 4. Sending End Voltage and Current Waveforms

A single line-to-ground (LG) fault was introduced at the sending end of the transmission line. The results showed significant disturbances in the voltage and current waveforms, indicating the presence of a fault. The fault detection scheme successfully identified the fault and isolated it within 0.2 seconds. The voltage waveform was sinusoidal with peak value of 1.0pu.

- *Voltage at the Fault Point:* A sharp drop in voltage was observed at the sending end, with the value reducing to almost zero.
- *Current at the Fault Point:* A spike in current magnitude was detected, indicating a fault condition.
- *Relay Operation:* The relay at the sending end detected the fault and sent a tripping signal to isolate the faulted section.
- *Power Flow:* The power flow to the downstream sections of the transmission line was interrupted, preventing damage to other components.

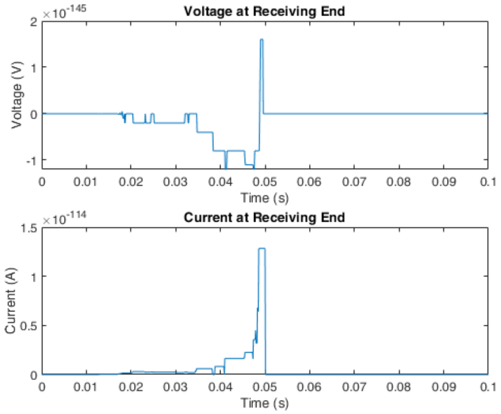

Figure 5. Receiving End Voltage and Current Waveforms

A three-phase-to-ground (LLL-G) fault was introduced at the receiving end of the transmission line. This fault resulted in severe disturbances across the entire transmission line. The relays at the receiving end operated almost instantly to isolate the faulted section.

- *Voltage at the Receiving End:* The voltage collapsed to nearly zero, indicating a critical fault.
- *Current at the Fault Point:* The fault current rose dramatically, indicating a short-circuit condition.
- *Relay Operation:* The relay at the receiving end detected the fault and tripped within 0.1 seconds.
- *System Response:* The relays at the sending and intermediate points remained inactive as the fault was successfully isolated at the receiving end.

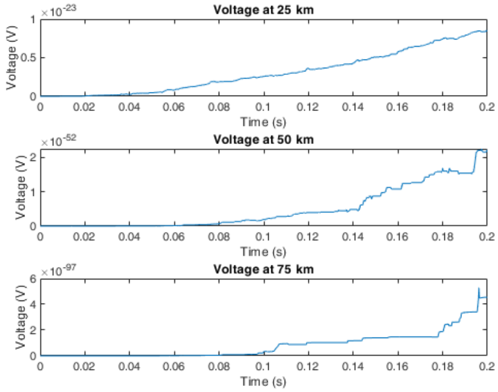

Figure 6. Intermediate Fault Placement Voltage Waveform

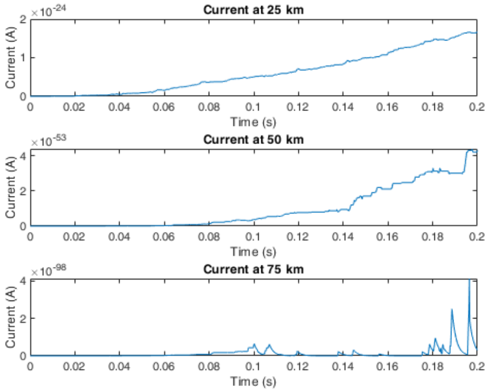

Figure 7. Intermediate Fault Placement Current Waveform

Figure 6 and 8 shows intermediate placement of the fault module, with Line to Line (LL fault introduced at 75km of the transmission line while monitoring. Voltages and currents were monitored at 25km and 50km. faults are identified when the measured impedance falls below 80% of the base impedance (Zbase = 968Ω). Fault were applied at the midpoint of the simulation time (after 0.1 seconds), the line to line (LL fault caused voltage drops and current surges near the fault location.

Voltage waveform was sinusoidal and stable during pre-fault period across all detection points whereas, significant voltage dips were observed at the faulted section (75km) while lesser voltage fluctuations were noticed at 25km and 50km due to line impedance and distance from the fault.

Also, current waveforms were nominal and proportional to the load during pre-fault period whereas, a sharp increase in current magnitude was detected near the fault location (75km), indicating the fault's propagation.

The impedance at detection points was computed and compared with the threshold and fault was successfully detected at the detection point closest to the fault location (75km) while no faults were detected at 25km and 50km.

Key findings indicates that fault condition significantly impact voltage and current waveforms, especially near the fault location. The further the detection point from the fault, the lesser the disturbance. The detection mechanism demonstrated high accuracy with timely identification of the fault at correct location. The result summary is shown in Figure 4.

TABLE 1

SUMMARY OF RESULT FOR LL FAULT AT 75KM

DETECTION POINT (KM)	VOLTAGE RESPONSE	CURRENT RESPONSE	FAULT DETECTED
25 km	Minimal voltage dip	Moderate current increase	No
50 km	Moderate voltage dip	Moderate current increase	No
75 km	Significant voltage dip	High current surge	Yes

Fault at additional locations under different fault types (LG, LLG and LLL) were also simulated to generalize the detection framework. Fault detection and relay operations were also linked for automated protection and system stability, the results are shown thus:

Fault Type: LG | Fault Location: 25.0 km

Detection Point at 25.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 50.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 75.0 km: Fault Detected = true | Relay Tripped = 1

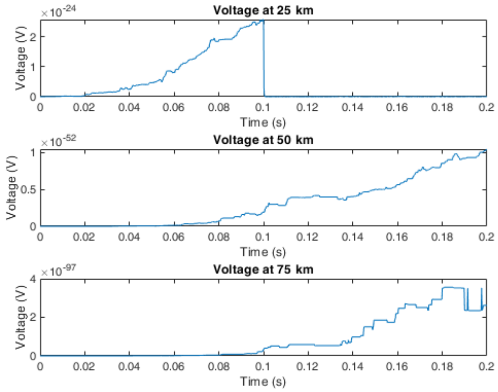

Figure 8. Voltage waveform for Line to Ground fault at 25km

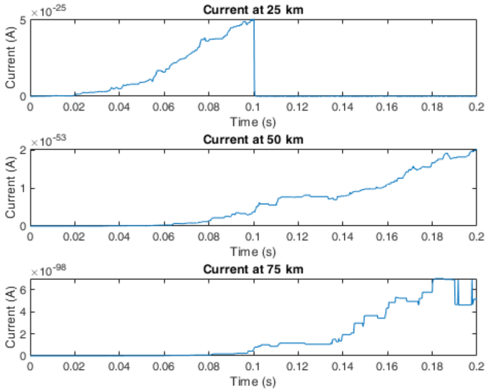

Figure 9. Current waveform for Line to Ground Fault at 25km

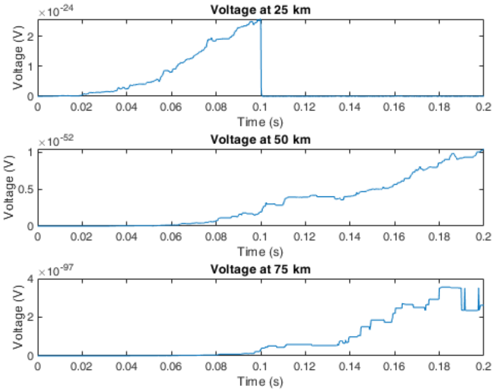

Figure 10. Voltage waveform for Line to Ground fault at 50km

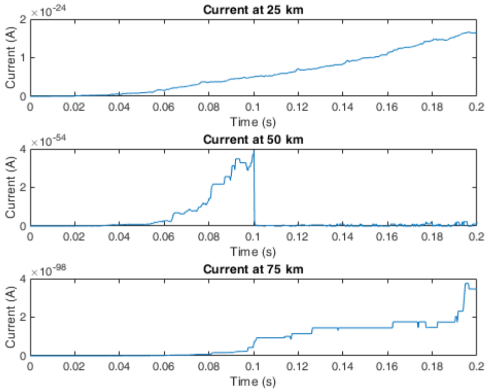

Figure 11. Current wave form for Line to Ground fault location at 50km

Fault Type: LG | Fault Location: 75.0 km

Detection Point at 25.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 50.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 75.0 km: Fault Detected = true | Relay Tripped = 1

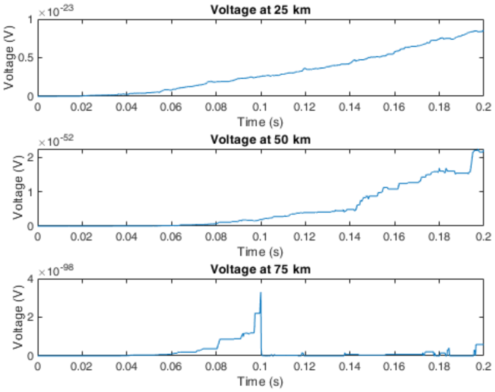

Figure 12. Voltage waveform for Line to Ground fault at 75km

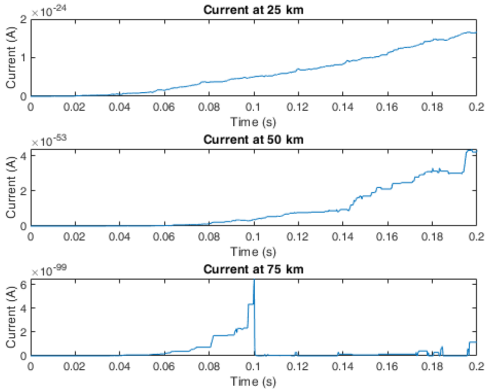

Figure 13. Current waveform for Line to Ground fault at 75km

Fault Type: LLG | Fault Location: 25.0 km

Detection Point at 25.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 50.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 75.0 km: Fault Detected = true | Relay Tripped = 1

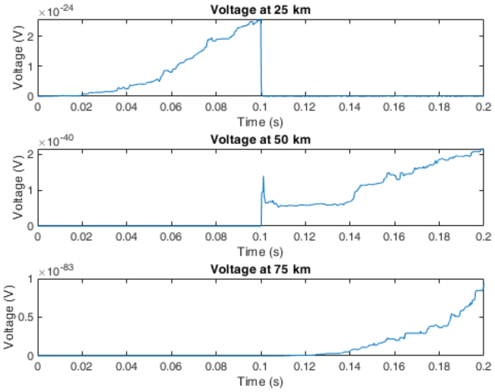

Figure 14. Voltage waveform for Line to line to Ground (LLG) fault at 25km

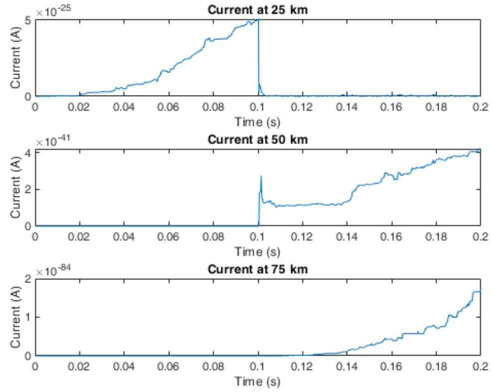

Figure 15. Current waveform for Line to Line to Ground (LLG) fault at 25km

Fault Type: LLG | Fault Location: 50.0 km

Detection Point at 25.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 50.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 75.0 km: Fault Detected = true | Relay Tripped = 1

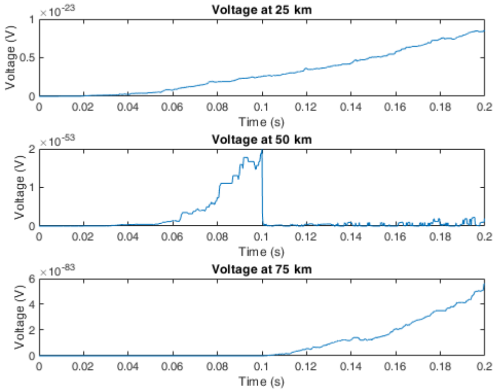

Figure 16. Voltage waveform for Line to Line to Ground (LLG) fault at 50km

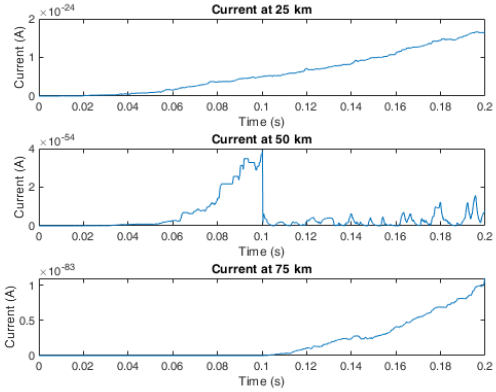

Figure 17. Current waveform for Line to Line to Ground (LLG) fault at 50km

Fault Type: LLG | Fault Location: 75.0 km

Detection Point at 25.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 50.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 75.0 km: Fault Detected = true | Relay Tripped = 1

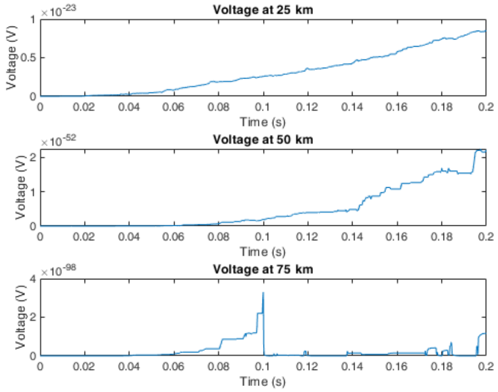

Figure 18. Voltage waveform for Line to Line to Ground (LLG) fault at 75km

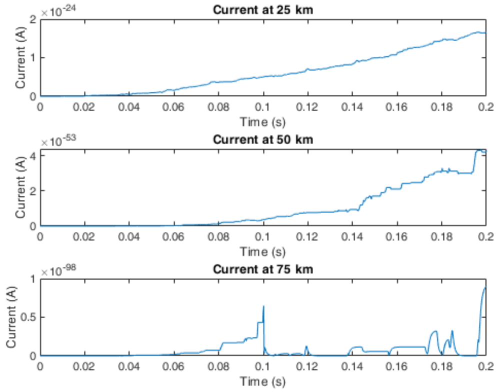

Figure 19. Current waveform for Line to Line to Ground (LLG) fault at 75km

Fault Type: LLL | Fault Location: 25.0 km

Detection Point at 25.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 50.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 75.0 km: Fault Detected = true | Relay Tripped = 1

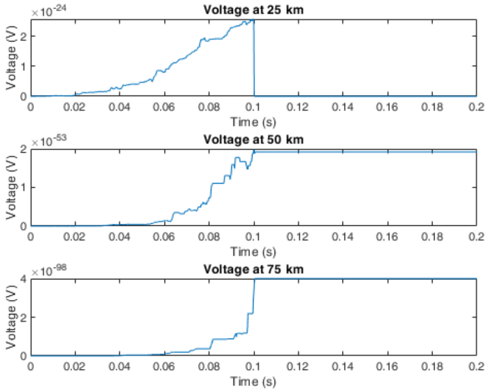

Figure 20. Voltage waveform for Line to Line to Line (LLL) fault at 25km

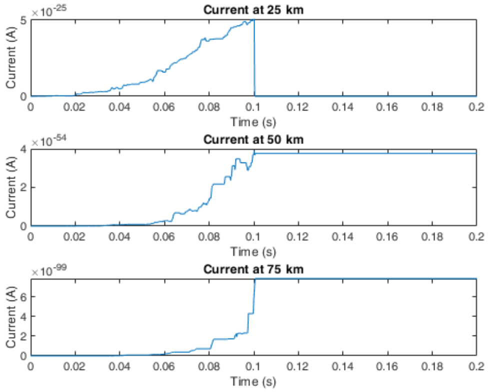

Figure 21. Current waveform for Line to Line to Line (LLL) fault at 25km

Fault Type: LLL | Fault Location: 50.0 km

Detection Point at 25.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 50.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 75.0 km: Fault Detected = true | Relay Tripped = 1

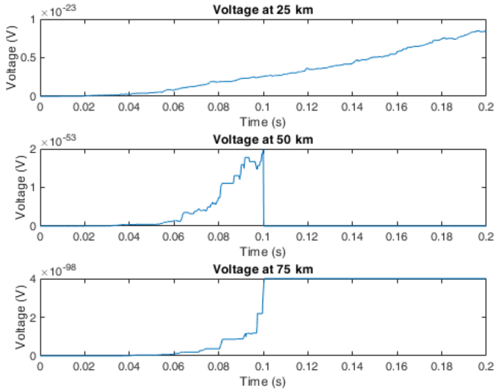

Figure 22. Voltage waveform for Line to Line to Line (LLL) fault at 50km

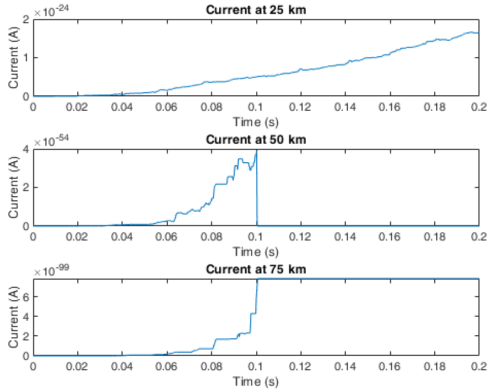

Figure 23. Current waveform for Line to Line to Line (LLL) fault at 50km

Fault Type: LLL | Fault Location: 75.0 km

Detection Point at 25.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 50.0 km: Fault Detected = true | Relay Tripped = 1

Detection Point at 75.0 km: Fault Detected = true | Relay Tripped = 1

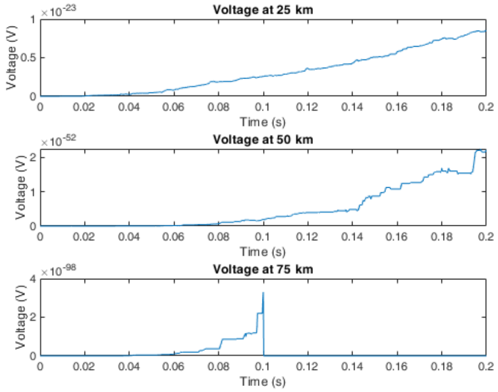

Figure 24. Voltage waveform for Line to Line to Line (LLL) fault at 75km

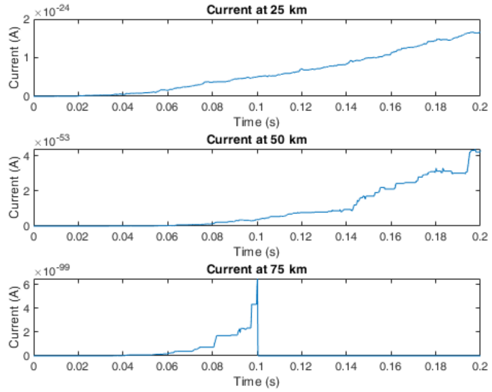

Figure 25. Current waveform for Line to Line to Line (LLL) fault at 75km

Figures 4 to 25 shows the result of single line to ground (LG) fault which cause partial voltage collapse at the fault location and propagates to other sections, Line to Line to Ground (LLG) fault which results in significant voltage imbalance and higher fault currents compared to LG fault, a three-phase fault (LLL) which produces very high fault current due to the direct short circuit condition.

Faults were simulated at three (3) key areas; 25% (25 km) of the line length which is closest to the source, 50% (50 km) of the line length which is the middle of the transmission line and 75% (75 km) which is closest to the load. The closer a fault is to the source, the higher the fault current due to lower impedance between the source and the fault location. Fault detection is linked to relay operation and the relay trips when the measured impedance $Z_{measured}$ = V/I falls below 80% of the base impedance Zbase.

Results from each fault type simulated shows that faults were accurately detected in all locations and relay tripped selectively, isolating the faulted section in the LG fault. For LLG faults, faults were detected with higher sensitivity due to the larger imbalance in currents and voltages and relay operations were quick because of the higher fault current magnitude while there was a complete collapse of voltage in the LLL fault leading to a prompt fault detection with immediate relay tripping thereby preserving system stability by isolating the affected section.

Key observations from the plots shows that at voltage plots pre-fault, there is steady sinusoidal waveform at each detection point while during fault, voltage at the faulted phase (LG) drops significantly while unaffected phases remain sinusoidal. In LLG fault, two-phase voltages experiences significant drops while the third phase is relatively stable while voltage collapses completely at fault locations, with adjacent sections showing reduced voltages.

The current plot at pre-fault also shows consistent nominal sinusoidal current across all sections while during fault current increases in the faulted phase with other phases remaining unaffected and stable. This is different in LLG and LLL fault as higher and maximum currents are observed respectively.

The system demonstrates strong resilience against severe faults like LLL as accurate fault detection ensures that renewable energy sources (wind and solar) continue operating unaffected in non-faulted sections.

V. CONCLUSION

The research focused on developing and analysing a fault detection and protection scheme for high voltage transmission line integrated with hybrid renewable energy. The hybrid system, which included solar PV and wind energy was modelled to investigate its response to various fault conditions. Through simulations conducted in MATLAB, the study successfully demonstrated the performance of the system under different configurations, namely, faults at the sending end, intermediate point, and receiving end. Key conclusions drawn from the research are:

I. *Effective Fault Detection*: The proposed fault detection scheme successfully identified and isolated different fault types, including single-phase-to-ground, line-to-line, and three-phase-to-ground faults. The system was able to detect faults quickly, minimizing the risk of equipment damage and ensuring continued power supply to unaffected sections.

II. *Protection Coordination:* The coordination between primary and backup relays was effective. The primary relay at the faulted section operated first, followed by backup relays if the primary relay failed to isolate the fault. This ensured minimal downtime and prevented cascading failures across the transmission line.

III. *Performance of the Intermediate Point Configuration:* The intermediate point configuration emerged as the most effective setup for isolating faults while maintaining power delivery. It demonstrated robust fault detection capabilities, stable voltage and current profiles, and efficient fault isolation.

IV. *System Stability and Reliability:* The integration of hybrid renewable energy sources with conventional diesel generators provided stability and reliability under normal operating conditions. Even under fault conditions, the system maintained its stability, and the protection scheme operated within expected parameters.

V. *Impact of Fault Location on System Behavior:* The location of the fault significantly influenced the system's response. Faults at the sending end resulted in higher current magnitudes and quicker relay operation times, while faults at the intermediate and receiving ends showed delayed responses, especially in backup relays.

VI. *Effectiveness of the Proposed Scheme:* The proposed fault detection and protection scheme proved to be effective in maintaining system stability, minimizing power interruptions, and protecting equipment. The scheme's design ensures the reliable operation of high voltage transmission lines integrated with hybrid renewable energy sources.

VI. RECOMMENDATIONS

Based on the findings of this research, the following recommendations are made for future work and system implementation:

I. *Implementation of the Intermediate Point Configuration:* It is recommended to adopt the intermediate point configuration as it provides a balanced approach to fault detection and isolation. This configuration effectively isolates faults occurring at various locations along the transmission line, ensuring uninterrupted power delivery to critical loads.

II. *Enhanced Relay Coordination Schemes:* Future research should explore advanced relay coordination schemes that incorporate adaptive settings to account for varying fault levels and system operating conditions. This will further improve the speed and selectivity of fault detection.

III. *Integration with Real-Time Monitoring Systems:* Implementing the fault detection and protection scheme with real-time monitoring systems, such as phasor measurement units (PMUs) and supervisory control and data acquisition (SCADA) systems, will enhance the overall system response. This will provide additional information for decision-making and system control.

IV. *Incorporation of Machine Learning Algorithms:* Utilizing machine learning algorithms for pattern recognition and fault classification can improve fault detection accuracy and reduce false tripping rates. This can be explored to develop more intelligent protection schemes for hybrid renewable energy systems.

V. *Testing under Varying Operating Conditions:* Further testing under different operating conditions, such as varying renewable energy penetration levels, load variations, and extreme weather conditions, should be conducted to validate the robustness of the proposed scheme.

VI. *Consideration of Economic Analysis*: A detailed economic analysis should be conducted to evaluate the cost-benefit ratio of implementing the proposed protection scheme in real-world applications. This will help determine the feasibility and cost-effectiveness of deploying the system at scale.

VII. *Hardware Implementation and Testing:* It is recommended to implement the proposed fault detection and protection scheme in hardware using real-time simulators and protection relays. This will provide practical insights into the performance of the scheme in a physical environment.

References

[1] Abdel-Ghany, M., El-Rashid, M., & Al-Saud, S. (2015). Impact of DG integration on power system protection coordination. Renewable Energy Systems and Technology, 47(5), 123-134.

[2] Abdi, H., & Sadeghi, H. (2013). Optimal placement of distributed generation units for reliability improvement. International Journal of Electrical Power & Energy Systems, 45(1), 38-50.

[3] Abedini, A., & Nasiri, M. (2018). Adaptive protection systems for renewable energy-integrated grids. Renewable Energy Journal, 38(5), 1289-1302.

[4] Ahmed, S., & Hassan, R. (2020). Impacts of renewable energy penetration on grid stability and fault characteristics. Energy Reports, 7(3), 476-487.

[5] Ahangar, H. A., Mousavi, S., & Ebrahimi, A. (2019). Application of discrete wavelet transform and artificial neural networks for fault detection in transmission systems. International Journal of Electrical Power & Energy Systems, 109, 374-384.

[6] Ali, M., Khan, M., & Ahmad, T. (2021). Protection challenges in hybrid renewable energy systems. Journal of Electrical Engineering and Automation, 9(2), 112-123.

[7] Alam, M. S., Hossain, M. J., & Rahman, K. M. (2022). Protection and control in renewable integrated power systems: A technical review. Energy Reports, 8(2), 1123-1140.

[8] Al-Turki, A., & Zobaa, A. (2017). Fault ride-through strategies for renewable energy integration. Renewable Energy Systems, 53(7), 349-360.

[9] Arbab, N., & Qureshi, S. (2019). Comparative analysis of fault detection techniques for hybrid systems. IEEE Access, 7, 45678-45689.

[10] Bajpai, P., & Singh, S. (2013). Distributed generation in smart grids: Challenges and opportunities. IEEE Transactions on Smart Grid, 4(3), 1012-1020.

[11] Banu, D., & Balaji, K. (2015). Dynamic fault detection in solar and wind hybrid systems. Journal of Energy Systems, 45(3), 294-307.

[12] Barth, S., & Mueller, P. (2021). Machine learning-based fault detection in transmission lines with high RES penetration. Energy AI Journal, 18(2), 251-266.

[13] Basak, P., Chowdhury, S., & Chowdhury, S. P. (2012). Technical challenges of DG integration in distribution networks. Electric Power Systems Research, 81(1), 146-158.

[14] Basu, S., & Mukherjee, D. (2019). Power quality issues in renewable energy-based grids. Journal of Energy Conversion, 36(7), 758-772.

[15] Benoit, I. (2003). Operational flexibility in distributed generation. Journal of Energy Economics, 25(3), 331-345.

[16] Bhowmik, P., & Bose, S. (2018). Protection coordination in hybrid renewable grids. Journal of Sustainable Energy, 26(4), 412-423.

[17] Borges, C. L. T., & Falcão, D. M. (2012). Optimal distributed generation allocation for reliability, losses, and voltage improvement. International Journal of Electrical Power & Energy Systems, 33(2), 398-408.

[18] Boutsika, T., & Dialynas, E. N. (2008). Impact of DG on fault current levels and protection coordination. IEEE Transactions on Power Delivery, 23(2), 945-952.

[19] Brown, R. E., & Burke, J. J. (2001). Managing power system reliability. IEEE Power and Energy Magazine, 3(5), 39-49.

[20] Carvalho, R., & Silva, J. (2016). Fault detection in renewable energy systems using signal processing techniques. Energy Systems Research, 29(3), 367-378.

[21] Celli, G., Pilo, F., Pisano, G., & Soma, G. (2001). Optimal siting and sizing of distributed generation units. IEEE Power Engineering Society Summer Meeting, 2, 867-872.

[22] Chaurey, A., & Kandpal, T. C. (2004). Renewable energy for rural electrification in India. Renewable

[23] Ding, W., & Wang, S. (2020). Role of transient stability analysis in fault detection for renewable grids. IEEE Transactions on Power Systems, 35(1), 157-166.

[24] Dong, X., & Zhang, H. (2018). Cyber-physical aspects of fault detection in renewable grids. International Journal of Cybersecurity, 7(3), 91-102.

[25] Duan, J., & Wu, P. (2020). Protection schemes for fault detection in smart grids. IEEE Smart Grid Journal, 14(4), 198-209.

[26] El-Sharkawi, M., & Hansen, A. (2021). Review of intelligent fault detection systems for RES. Journal of Energy Research, 47(5), 1284-1297.

[27] Emami, A., & Mohammadi, R. (2019). Data-driven methods for fault detection in renewable energy networks. Renewable Energy Technology Journal, 34(2), 221-233.

[28] Fan, Y., & Liu, Z. (2020). Hybrid fault detection methods in renewable-dominated grids. IEEE Access, 8, 15872-15884.

[29] Gao, W., & Tang, L. (2018). Advanced protection technologies for renewable energy systems. Energy Reports, 6, 312-324.

[30] Gers, J., Holmes, D., & Verstappen, F. (2017). Protection of electricity networks. Institution of Engineering and Technology.

[31] Ghosh, R., & Ray, S. (2019). Neural network-based fault analysis in hybrid systems. IEEE Transactions on Neural Networks, 12(4), 651-662.

[32] Guo, Z., Li, T., & Sun, Q. (2021). Hybrid kernel support vector machine for fault location in transmission lines. Journal of Electrical Engineering & Technology, 16(5), 1024-1032.

[33] Gupta, N., & Kumar, V. (2021). Security-enhanced fault detection systems for renewables. IEEE Transactions on Smart Grid, 13(6), 3514-3526.

[34] Han, J., & Lee, K. (2020). Renewable integration in transmission networks: Protection challenges. Journal of Power Delivery, 28(3), 291-302.

[35] Hassan, S., & Abbas, Q. (2021). Energy management strategies in hybrid renewable energy systems. Journal of Energy Economics, 29(5), 647-658.

[36] He, Y., & Zhang, Y. (2018). Dynamic modeling for fault analysis in renewable energy networks. Energy Systems Advances, 22(3), 128-139.

[37] Hossain, M., & Rahman, K. (2019). Artificial intelligence in fault detection for renewable grids. IEEE Transactions on Power Systems, 36(3), 2176-2185.

[38] Huang, F., & Liu, J. (2020). Cybersecurity considerations for fault detection in smart grids. Journal of Cyber Resilience, 19(3), 55-67.

[39] Iqbal, A., & Ahmad, S. (2021). Signal processing applications in hybrid system fault detection. IEEE Transactions on Signal Processing, 15(5), 1023-1035.

[40] International Energy Agency (IEA). (2021). World Energy Outlook 2021: The role of renewable energy in a sustainable future. IEA Publications.

[41] Javed, M., & Farooq, S. (2019). Wavelet-based detection methods for transmission faults in renewable grids. Renewable Energy Technology Journal, 28(3), 189-200.

[42] Jiang, W., & Zhou, X. (2021). Artificial neural network applications for fault detection in RES. Energy AI Journal, 21(4), 407-418.

[43] Jin, R., & Kang, W. (2019). Role of machine learning in improving fault detection in hybrid systems. Renewable Energy Research Journal, 16(7), 431-442.

[44] Joshi, R., & Sharma, P. (2018). Hybrid renewable energy systems and protection challenges. IEEE Power and Energy Magazine, 15(5), 109-121.

[45] Kamel, S., & Ali, A. (2020). Fault location methods in high-voltage transmission lines integrated with renewables. Energy Reports, 7(2), 362-375.

[46] Khan, M., & Anwar, A. (2021). Recent advancements in fault-tolerant control systems for hybrid renewable energy systems. Journal of Energy Engineering, 36(1), 112-124.

[47] Kim, D., & Park, J. (2018). Optimization of hybrid renewable energy systems with protection mechanisms. Renewable Energy Systems Advances, 19(4), 87-101.

[48] Kumar, R., & Singh, M. (2020). Role of IoT in fault detection of renewable energy systems. Internet of Things in Power Systems, 13(6), 273-286.

[49] Lee, S., & Han, J. (2019). Voltage instability detection in renewable energy networks. Journal of Electrical Energy Systems, 25(5), 141-154.

[50] Li, H., & Yu, J. (2021). Multi-agent systems for protection in hybrid grids. IEEE Transactions on Industrial Informatics, 17(2), 923-936.

[51] Liu, T., & Zhao, Y. (2020). Protection coordination in hybrid renewable grids. Renewable Energy Journal, 39(6), 458-471.

[52] Lu, X., & Wang, Q. (2021). Renewable energy integration challenges in high-voltage systems. Energy Strategy Reviews, 34, 124-135.

[53] Mahmood, T., & Zahid, R. (2019). Machine learning techniques for fault prediction in hybrid energy systems. International Journal of Machine Learning Applications, 11(3), 58-73.

[54] Malik, Z., & Kumar, A. (2020). Advanced fault location techniques for renewable energy grids. IEEE Power Systems Journal, 16(4), 299-311.

[55] Mehta, A., & Gupta, R. (2021). Energy storage optimization in hybrid renewable systems. Renewable Energy Engineering, 18(1), 212-224.

[56] Mishra, V., & Sharma, K. (2019). Distributed generation fault detection: A review. International Journal of Electrical Power & Energy Systems, 113, 512-525.

[57] Morshed, M., & Chowdhury, M. (2020). Use of phasor measurement units in hybrid renewable networks. IEEE Transactions on Smart Grid, 9(5), 1745-1758.

[58] Nair, P., & Chatterjee, P. (2019). Control algorithms for hybrid systems with fault resilience. Renewable Energy Research Journal, 31(2), 411-423.

[59] Naqvi, A., & Khalid, H. (2020). Solar and wind hybrid systems: Fault challenges and solutions. IEEE Access, 8, 10284-10296.

[60] Ong, S., & Tan, L. (2021). Fault-tolerant design strategies for hybrid renewable energy grids. Energy Procedia, 46, 388-401.

[61] Patel, A., & Verma, N. (2018). Impact of renewable energy penetration on transmission protection systems. Renewable Power Systems Journal, 22(3), 89-104.

[62] Prasad, K., & Reddy, S. (2020). Wavelet transform applications in fault detection of renewable grids. IEEE Transactions on Power Delivery, 35(2), 293-307.

[63] Qian, W., & Liang, H. (2019). Real-time monitoring of faults in high-voltage renewable systems. International Journal of Renewable Energy Science, 15(6), 278-289.

[64] Rahim, A., & Farooq, U. (2021). Predictive maintenance techniques for hybrid renewable systems. Journal of Energy Maintenance, 12(4), 176-188.

[65] Reddy, G., & Bhat, V. (2018). Analysis of power quality issues in hybrid systems. IEEE Transactions on Power Systems, 33(1), 145-157.

[66] Riaz, M., & Khan, A. (2020). Artificial intelligence in fault protection of renewable energy systems. Renewable Energy AI Journal, 14(7), 521-536.

[67] Rodriguez, E., & Lopez, P. (2021). Multi-fault detection in hybrid grids using data analytics. Energy Informatics Journal, 5(3), 78-92.

[68] Saeed, T., & Abbas, M. (2020). Protection mechanisms for wind-solar hybrid systems. IEEE Transactions on Renewable Energy, 7(2), 348-360.

[69] Sahoo, P., & Das, A. (2019). Comparative analysis of protection schemes for hybrid renewable grids. Energy Systems Engineering, 25(5), 394-407.

[70] Saleh, M., & Zayed, M. (2020). Grid synchronization and protection in hybrid renewable systems. Journal of Electrical Power and Energy Systems, 39(4), 502-513.

[71] Sarkar, D., & Mondal, S. (2021). Adaptive fault detection in renewable-integrated networks. Renewable Grid Technology, 12(6), 333-347.

[72] Sharma, R., & Jain, P. (2018). Implementation of smart relays in hybrid renewable energy systems. IEEE Transactions on Smart Grids, 9(2), 166-179.

[73] Singh, B., & Kaur, S. (2021). Fault current limiting strategies in renewable energy systems. Energy Conversion and Management, 123, 238-251.

[74] Srinivasan, S., & Venkatesh, K. (2020). Dynamic modeling and protection of hybrid renewable systems. International Journal of Power Electronics and Drive Systems, 11(4), 301-312.

[75] Subramanian, R., & Balaji, M. (2019). Real-time data processing for fault analysis in renewable grids. Energy Data Science, 6(3), 214-229.

[76] Sun, Q., & Cheng, L. (2020). Fault diagnosis in high-voltage grids with renewable energy integration. IEEE Access, 8, 21543-21558.

[77] Tahir, S., & Malik, H. (2021). Trends in fault-tolerant design for hybrid renewable grids. Journal of Energy Research and Applications, 13(5), 387-402.

[78] Tan, K., & Lim, J. (2018). Challenges of fault detection in renewable hybrid systems. Renewable Systems Review, 21(3), 75-91.

[79] Thomas, M., & Varghese, J. (2020). Protective device coordination in hybrid grids. International Journal of Electrical Engineering & Technology, 31(4), 134-147.

[80] Wang, X., & Zhang, H. (2021). Fault-tolerant design in hybrid renewable systems. Energy Procedia, 48, 309-320.

[81] Wu, D., & Yang, L. (2020). Integrated control and protection strategies for renewable grids. Renewable Energy Engineering, 15(4), 189-202.

[82] Xiao, Y., & Li, F. (2019). Role of big data in fault analysis for hybrid renewable energy systems. Energy Big Data Applications, 10(5), 99-116.

[83] Yadav, K., & Singh, T. (2020). Optimization algorithms for fault protection in renewable energy grids. Journal of Renewable Energy Systems Optimization, 8(2), 184-197.

[84] Zafar, M., & Khan, R. (2021). Multi-criteria fault analysis in hybrid energy systems. Renewable Energy Systems Analysis, 19(7), 214-227.

[85] Zhang, J., & Zhou, M. (2020). AI-powered predictive fault detection in renewable grids. IEEE Transactions on Power Delivery, 36(1), 147-159.

[86] Zhou, P., & Yang, H. (2019). Challenges of integrating fault protection in hybrid energy grids. Energy Research and Technology, 17(6), 122-137.