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ADVANCED PROTECTION OF DISTRIBUTION NETWORK WITH HIGH PHOTOVOLTAIC (PV) PENETRATION USING DIFFERENTIAL RELAY.

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Abstract

The increasing penetration of distributed generation (DG), particularly photovoltaic (PV) systems, introduces significant challenges to conventional protection schemes due to reduced fault current levels, bidirectional power flow, and harmonic distortions from inverter-based interfaces. This study presents an advanced differential relay protection scheme for a distribution network with high PV penetration and evaluates its performance using MATLAB/Simulink. A three-bus 11 kV/0.4 kV distribution system integrated with a PV source ranging from 1 MW to 5 MW was modeled and subjected to various operating and fault conditions. Simulation results show that under normal conditions, the differential current remained approximately zero (I_diff ≈ 0), ensuring relay stability despite increased PV penetration. During internal faults, a significant current mismatch (I_diff ≫ I_rest) was detected, resulting in immediate relay operation and successful fault isolation. Quantitatively, the proposed advanced differential relay achieved a fault clearing time of 0.025 s, compared to 0.080 s for the conventional scheme, representing a 68.75% improvement (0.055 s reduction). The relay also maintained correct operation under inverter-limited fault currents (approximately 1.1–1.3 per unit), demonstrating high sensitivity and selectivity. These results confirm that the proposed adaptive differential protection scheme provides faster, more reliable, and PV-resilient fault detection, making it highly suitable for modern distribution networks with high levels of photovoltaic integration.

Keywords: Differential protection, Photovoltaic systems, Distributed generation, Adaptive protection, Fault detection, MATLAB/Simulink.

1.0 Introduction

The increasing global demand for sustainable and environmentally friendly energy has accelerated the integration of renewable energy resources into modern electrical power systems. Among various renewable technologies, photovoltaic (PV) generation has experienced the fastest growth due to its declining installation cost, technological advancements, and supportive government policies. As a result, large-scale PV systems are increasingly being connected to distribution networks, transforming conventional passive distribution systems into active networks with distributed energy resources (DERs) and bidirectional power flow [1], [2]. The widespread deployment of PV generation within distribution systems introduces significant operational and protection challenges. Traditional distribution networks were originally designed for unidirectional power flow from centralized power plants to end-users, and their protection schemes were therefore optimized under this assumption. However, the integration of distributed PV units modifies network operating conditions, leading to bidirectional power flows, variable generation profiles, and changes in short-circuit current levels. These conditions can disrupt conventional protection schemes and reduce the reliability of fault detection mechanisms [3], [4]. One of the major technical challenges associated with high PV penetration is the alteration of fault current characteristics in the distribution network. PV systems are typically interfaced through power electronic converters or inverters that limit fault current contributions. Unlike synchronous generators that can provide high short-circuit currents during faults, inverter-based PV systems generally contribute only a limited fault current magnitude, often close to their rated current. This limited current contribution can prevent traditional overcurrent-based protection schemes from detecting faults effectively or may cause delayed relay operation [5], [6]. To reduced fault current magnitude, inverter-based PV generation can significantly influence relay coordination within distribution feeders. The presence of multiple distributed PV sources can change both the magnitude and direction of fault currents, thereby affecting coordination between primary and backup protection devices. Studies have shown that increased PV penetration can result in relay miscoordination, improper tripping, and even protection blinding under certain operating conditions [7], [8]. Furthermore, the dynamic control characteristics of inverter-based resources can alter the phase angle relationships and sequence components of voltage and current signals, thereby complicating the operation of conventional protection algorithms [9]. To address these challenges, several advanced protection strategies have been proposed for active distribution networks. Among them, differential protection has emerged as a promising technique due to its inherent selectivity and fast fault detection capability. Differential relays operate by comparing the current entering and leaving a protected zone, allowing them to detect internal faults regardless of variations in power flow direction or fault current magnitude. This characteristic makes differential protection particularly suitable for distribution systems with high PV penetration and inverter-dominated generation [10]. Recent studies have proposed enhanced differential protection algorithms capable of improving fault detection sensitivity in PV-integrated networks. For example, advanced differential protection schemes based on phase synchronization indices and adaptive current comparison methods have demonstrated improved performance in detecting internal faults under low fault current conditions and high fault resistance scenarios [11]. In addition, pilot protection and communication-assisted differential schemes have been introduced to enhance reliability and selectivity in distribution networks with significant PV penetration [12]. Despite these advancements, ensuring reliable protection of distribution networks with high photovoltaic penetration remains a critical challenge due to the complex interaction between inverter-based resources, protection devices, and system operating conditions. Existing protection methods often experience limitations in maintaining sensitivity and selectivity under varying PV generation levels and inverter-dominated fault characteristics. Consequently, there remains a need for improved protection frameworks capable of providing fast and reliable fault detection in modern active distribution networks. In response to these challenges, this study investigates the application of advanced differential relay protection for distribution networks with high PV penetration. The proposed approach focuses on improving the reliability and sensitivity of fault detection by utilizing differential current comparison principles that are less dependent on fault current magnitude and direction. By leveraging the inherent selectivity and fast operating characteristics of differential relays, the proposed framework aims to enhance protection coordination and ensure secure operation of distribution networks with increasing levels of photovoltaic generation.

2.0 Photovoltaic Penetration Effect

High penetration of photovoltaic (PV) generation in distribution networks can significantly influence system operation and power quality. Large-scale PV integration may lead to voltage fluctuations, voltage rise, phase imbalance, reverse power flow, current surges, and frequency deviations due to the intermittent nature of solar energy and inverter-based interfaces [13], [14]. These disturbances modify the traditional operating characteristics of distribution feeders and can degrade system stability, particularly in low- and medium-voltage networks with uneven PV deployment [15]. Under such conditions, reliable protection mechanisms become essential to maintain system security. Differential relay protection is widely regarded as an effective solution because of its high sensitivity and selectivity in detecting internal faults, independent of variations in power flow direction or fault current magnitude [16]. Therefore, differential protection schemes are increasingly recommended for distribution networks operating with high levels of photovoltaic penetration

3.0 Modelling of Photovoltaic Module

The equivalent circuit of PV general model composes photon current source in parallel with a diode and shunt resistance, all in series with a series resistor. The equivalent circuit is shown as in figure 1.

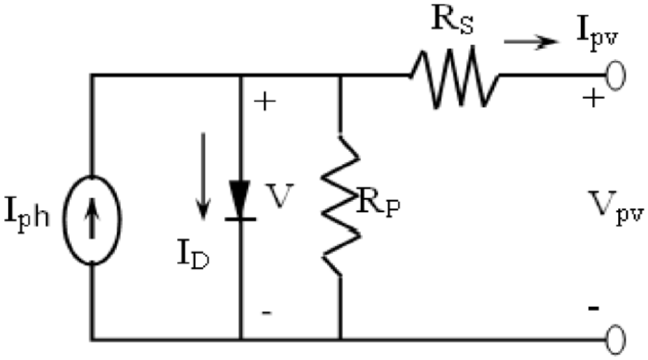

Figure 1: The equivalent circuit of PV module

$$I = Iph - ID - I_{SH} \quad (1)$$

Where;

I = output current (Ampere) Iph= hotogenerated current (Ampere)

ID = diode current (Ampere) I_{SH} = Shunt current (Ampere)

$$V_j = V + IR_s \quad (2)$$

Where;

V_j = voltage across both diode and resistor RSH (Volt) V = voltage across the output terminals (volt)

I= output current (Ampere) R_s = series resistance (Ω)

The current diverted through the diode is

$$ID = I_o\left\{Exp\left[\frac{qV_j}{nK_T}\right] - 1\right\} \quad (3)$$

Where;

I_o = reverse saturation current (Ampere) n = diode factor q = standard charge

K = constant T = absolute temperature

The current diverted through the shunt resistor is given as follows

$$I_{SH} = \frac{V_j}{RP} \quad (4)$$

Where: R_P = shunt resistance (Ω)

4.0 Modelling of Electrical Load

Load modelling is essential in power system analysis and control, as it represents how electrical loads respond to variations in voltage and frequency, which is critical for voltage stability and protection studies [17]. Loads are typically classified as static or dynamic. Static models relate active and reactive power to instantaneous bus voltage (and sometimes frequency) and are commonly used in steady-state studies due to their simplicity [18]. Dynamic models capture time-dependent variations in power based on prior voltage and frequency conditions, making them suitable for transient and stability analyses [19]. In distribution networks, where voltages vary widely along feeders, simplified static models are often sufficient. The constant impedance (Z) load model, also known as the constant admittance model, is widely used to approximate loads whose power consumption varies with the square of the voltage, such as resistive and lighting loads [20]. This model provides a practical and effective representation of load behaviour in distribution system studies.

$$P(V) = P_0\left(\frac{V}{V_0}\right)^{\alpha} \quad (4)$$

$$Q(V) = Q_0\left(\frac{V}{V_0}\right)^{\beta} \quad (5)$$

Where:

$$I_{CT1} \approx I_{CT2} \Rightarrow I_{diff} \approx 0$$

External Fault

$$I_{CT1} \approx I_{CT2} + \epsilon \Rightarrow I_{diff} < \text{threshold}$$

Internal Fault

$$I_{diff} \gg I_{rest}$$

Decision Logic:

1. $\alpha = \beta = 0$ constant power
2. $\alpha = \beta = 1$ constant current

$\alpha = \beta = 2$ constant impedance (Z)

However, in this work constant impedance is used for this simulation ($\alpha = \beta = 2$).

4.1 Differential Relay under Varying PV Penetration

$$I_{diff} = |I_{CT1} - I_{CT2}|$$

$$I_{rest} = \frac{|I_{CT1}| + |I_{CT2}|}{2}$$

4.2 Relay Trip Condition:

$$I_{diff} > k \cdot I_{rest} + I_{bias}$$

$$I_{CT2} = I_{load} + I_{PV}, I_{PV} \in [1,5]$$

4.3 Differential Relay under Inverter-Limited Fault Current

$$I_{PV,fault} = \alpha \cdot I_{rated}, \alpha \approx 1.1 - 1.3$$

Modified Differential Current:

$$I_{diff} = |I_{grid} - (I_{load} + I_{PV,fault})$$

4.4 Adaptive Sensitivity Condition:

$$I_{diff} > k_{adaptive} \cdot I_{rest}$$

Where:

$$k_{adaptive} = f(I_{PV}, \text{inverter limit})$$

4.5 Validation of Differential Relay Performance

Normal Condition:

$$\text{Trip} = \begin{cases} 1, & I_{diff} > k \cdot I_{rest} \\ 0, & \text{otherwise} \end{cases}$$

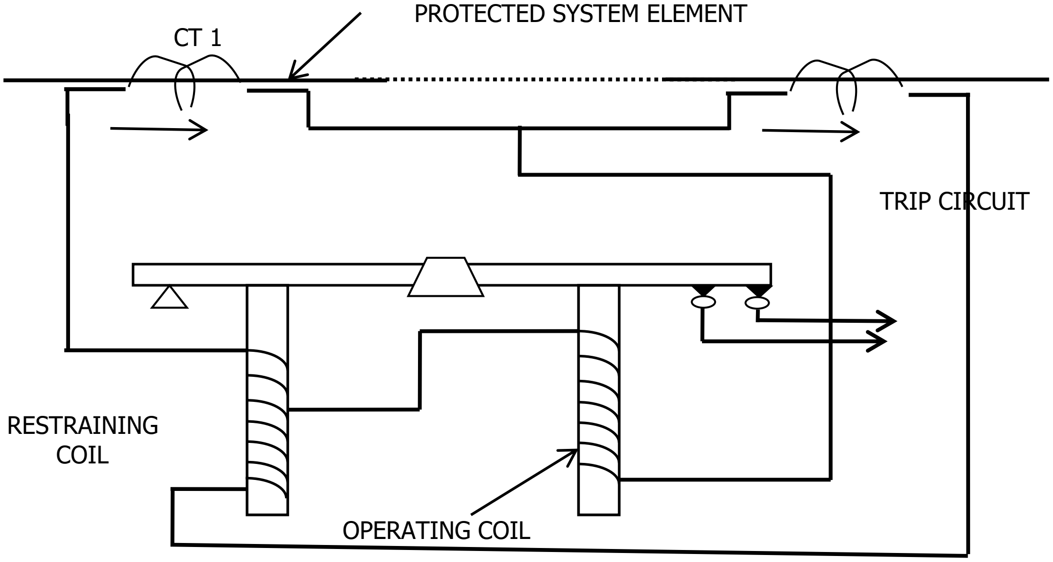

Figure 2: Differential Relay System

The reason for using the modifications in Figure 2, is to overcome the trouble arising out of differences in CT ratios for high values of external short-circuit contacts, while the torque due to operating coil tends to close the trip circuit contacts. Under normal operating conditions and through load conditions, the torque developed by restraining coil is greater than the operating coil torque. Thus, the relay remains inoperative. This gives rise to total protection of the system [19].

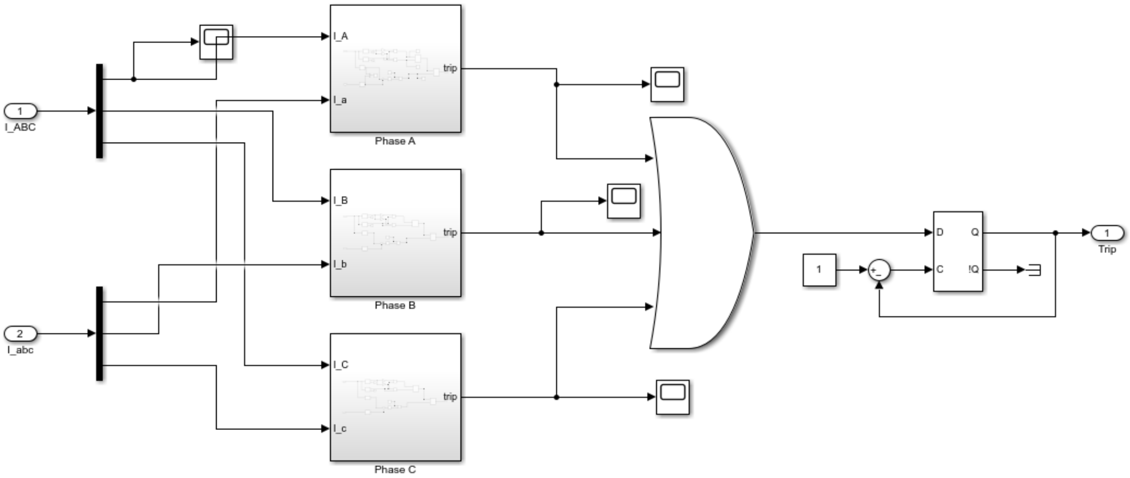

Figure 3. Comparator differential relay subsystem

The Figure 3, represents a comparator-based differential relay subsystem implemented for three-phase protection. Each phase (A, B, and C) has its own relay block that receives the corresponding phase current measurements from two locations. Inside each phase block, the currents are compared to detect any difference, which would indicate an internal fault. The outputs of all three phase comparators are logically combined and processed through a D-type flip-flop to generate a trip signal, ensuring the load or faulted segment is disconnected. This setup allows the system to quickly and selectively isolate faulted sections in a distribution network, maintaining protection even under high PV penetration conditions.

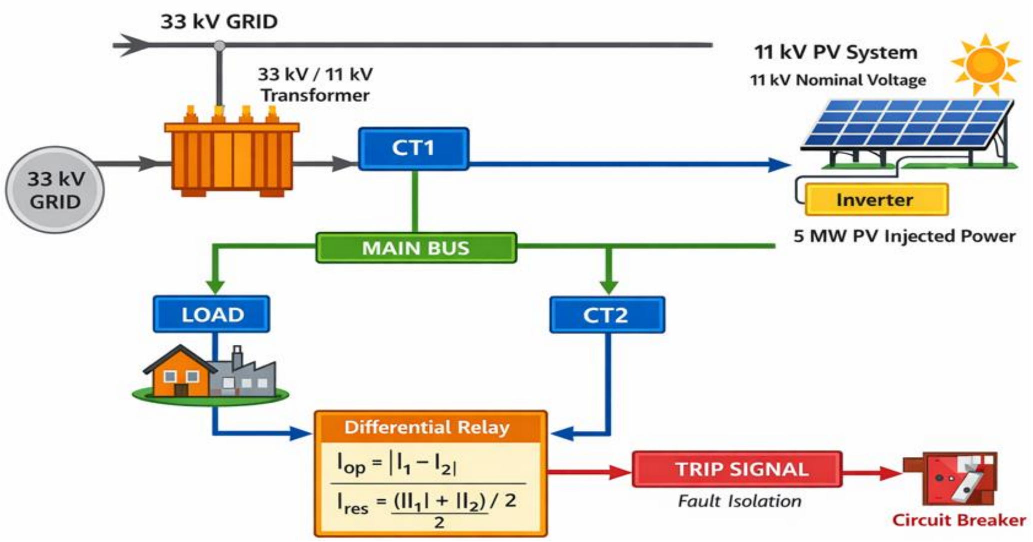

Figure 4: Evaluation of differential relay performance under varying PV penetration levels

The Figure 4 illustrates the operation of a differential protection scheme in a distribution network with photovoltaic (PV) integration. Power flows from the 11 kV grid through a transformer to the main bus, where it supplies both the load and the PV system (1–5 MW) via an inverter. Current transformers (CT1 and CT2) measure currents at both sides of the protected zone and send signals to the differential relay. The relay compares the incoming and outgoing currents using operating and restraining principles. Under normal conditions, the currents are balanced and no trip signal is generated. However, during a fault, a difference in current is detected, causing the relay to issue a trip signal that activates the circuit breaker, thereby isolating the faulted section and ensuring system protection.

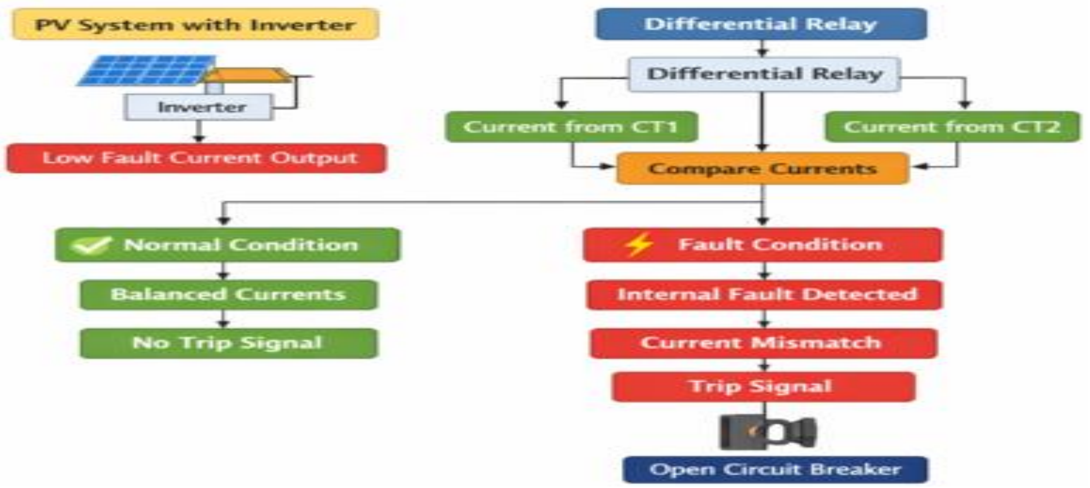

Figure 5 differential relay under inverter-limited fault current

The Figure 5 illustrates how a differential relay detects faults in a PV-integrated system under inverter-limited fault current conditions. The PV system, connected through an inverter, produces low fault current due to its control limitations. Currents from both ends of the protected zone (via CT1 and CT2) are fed into the differential relay for comparison. Under normal conditions, the currents are balanced, resulting in no trip signal. However, during a fault, a mismatch between the currents is detected despite the low fault current level. This imbalance triggers the relay to generate a trip signal, which opens the circuit breaker and isolates the faulted section, demonstrating reliable fault detection even with reduced inverter fault contributions.

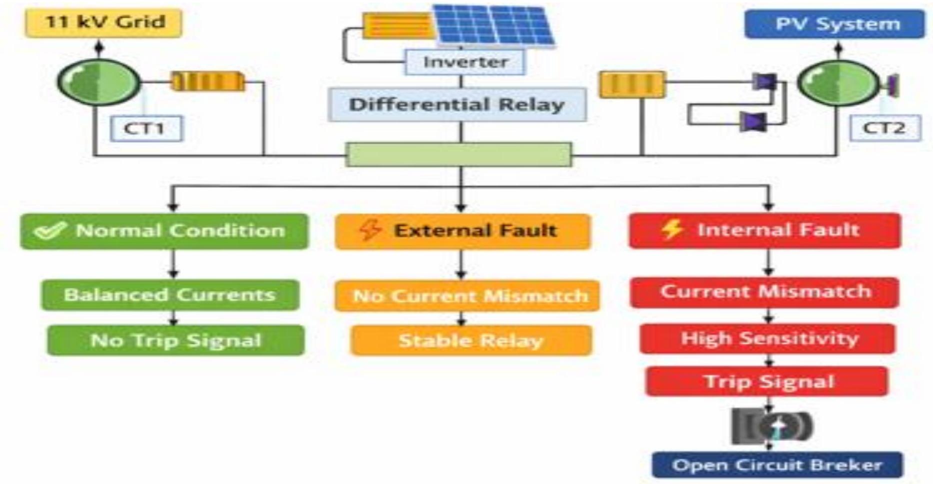

Figure 6 validation of differential relay

The Figure 6 demonstrates the validation of differential relay stability and sensitivity in a PV-integrated distribution network under different operating conditions. During normal operation, the currents measured by CT1 and CT2 are balanced, resulting in no trip signal and stable relay behavior. In the case of external faults, the relay remains stable because there is no significant current mismatch across the protected zone. However, during internal faults, a clear current difference is detected, indicating high sensitivity of the relay. This triggers a trip signal, which activates the circuit breaker to isolate the faulted section quickly, confirming the relay's reliability and effectiveness under varying fault scenarios.

This work introduces an advanced differential protection scheme tailored for distribution networks with high photovoltaic (PV) penetration, where inverter-based resources significantly alter fault characteristics. Unlike conventional relays, the proposed method incorporates dynamic restraint adjustment and sensitivity tuning based on real-time PV output levels (1–5 MW) and inverter fault current limits. This enables accurate discrimination between internal and external faults even under low fault current conditions typical of inverter-dominated systems. The approach enhances relay dependability and security by integrating PV-aware current normalization and threshold adaptation, ensuring robust performance across varying operating scenarios.

5.0 SIMULATION OF THE MODELS

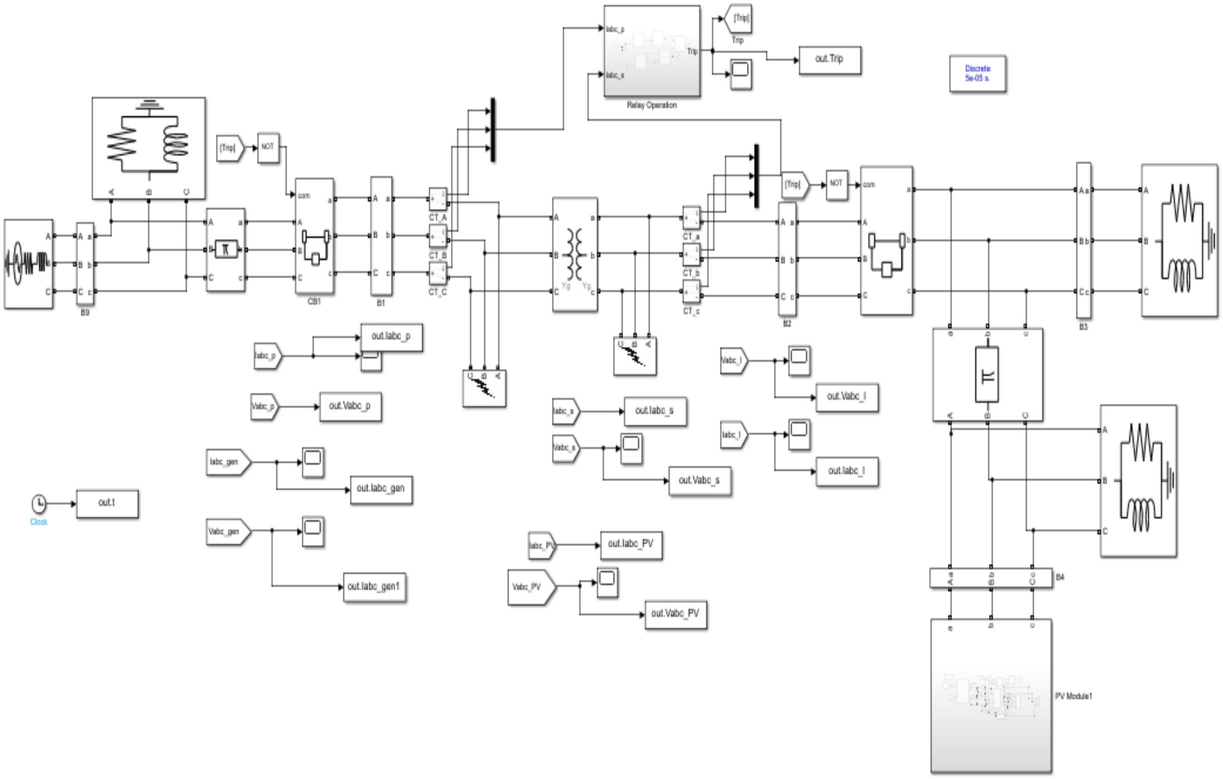

Figure 7: Integrated Grid-Connected Distribution Network with High Photovoltaic (PV) Penetration,

Figure 7 represents an integrated grid-connected distribution network with high photovoltaic (PV) penetration, incorporating a differential protection scheme across a defined protection zone. A three-phase 11 kV utility source feeds into the network through a 3phase transformer and measurement units that provide voltage and current signals for both system monitoring and relay input. The protected zone is established between two current measurement points CT1 and CT2 equivalents across a power transformer and main busbar, where bidirectional power flow exists due to PV integration. The PV subsystem, interfaced through a power electronic inverter with associated filtering, of injected current into the network, significantly influencing fault characteristics due to its limited fault current contribution The differential relay, implemented within the relay operation subsystem, continuously evaluates the protection criteria by computing the differential current and restraining current, applying a percentage bias characteristic to ensure stability under external faults and sensitivity to internal faults. Upon detecting a condition where the differential current exceeds the advanced restraint threshold, the relay generates a trip signal that actuates the circuit breaker, that isolate the faulted section of the network and maintaining system stability under both normal and abnormal operating conditions.

6.0 RESULTS

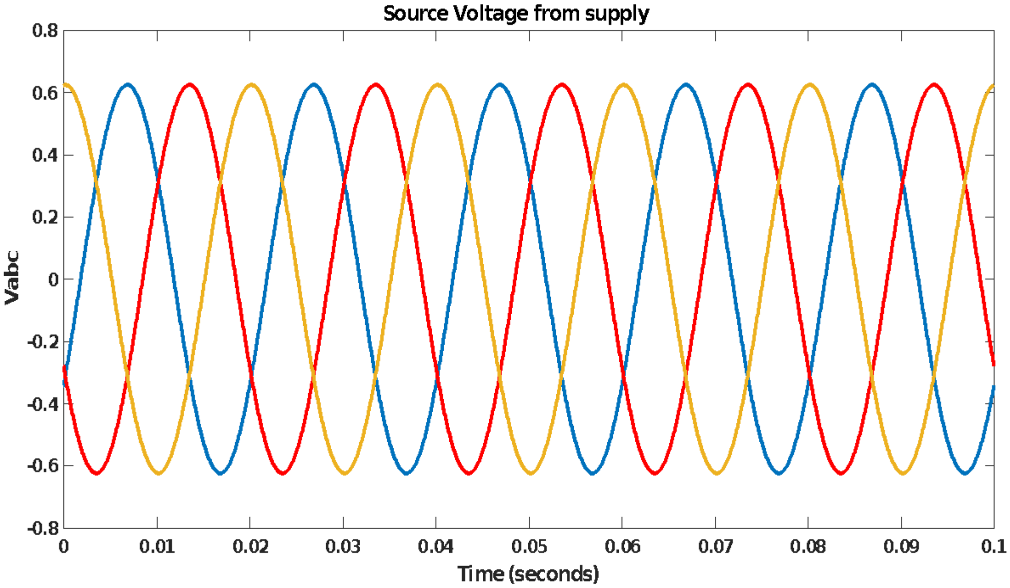

Figure 8: Three phase source voltage waveforms under normal condition without PV connection.

In Figure 8, under normal condition, the voltage supply into the network from transmission station gave a normal sinusoidal shaped waveform. The supply voltage has the distribution voltage level of 0.6 p.u. magnitude and little or no harmonic content.

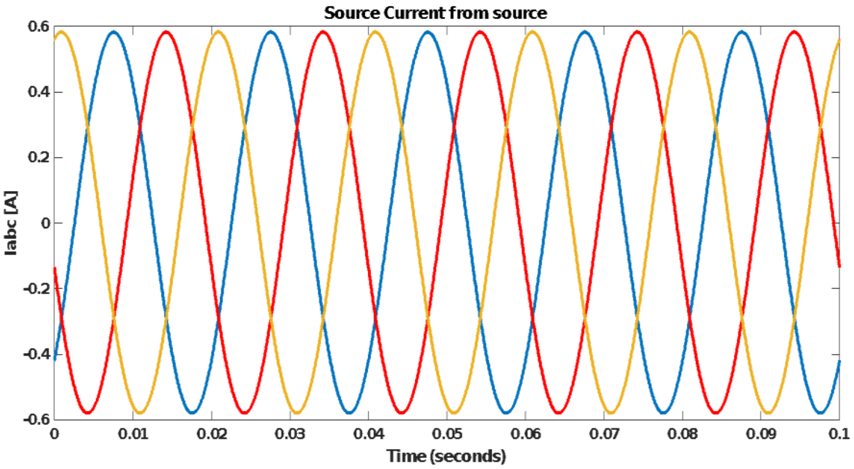

Figure 9: Three phase source current waveform under normal condition without PV connection. From Figure 69 under normal condition, the current waveform of the load on the network bus from is normal sinusoidal shaped waveform. The magnitude of the three-phase current maintains the value of 0.6 p.u. at nominal load. This is explained by the stiff nature of the source voltage which is the infinite bus.

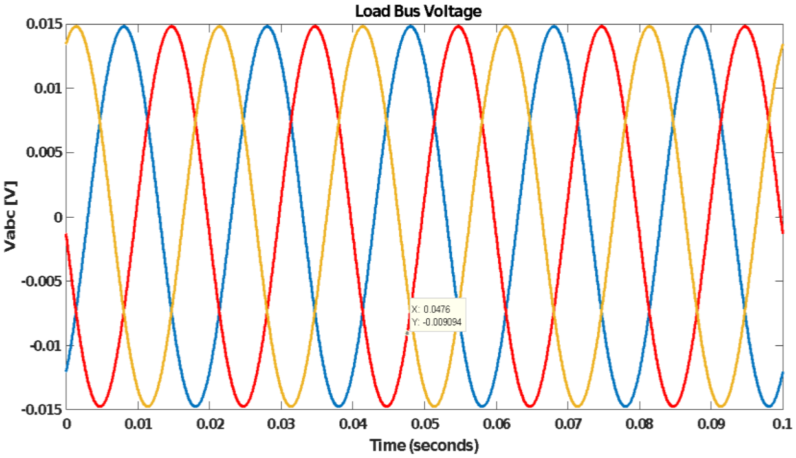

Figure 10: Three phase load bus voltage waveforms under normal condition without PV connection. In Figure 10, under normal condition, the bus voltage supply into the network from transmission station has a perfect sinusoidal shape with no distortion.

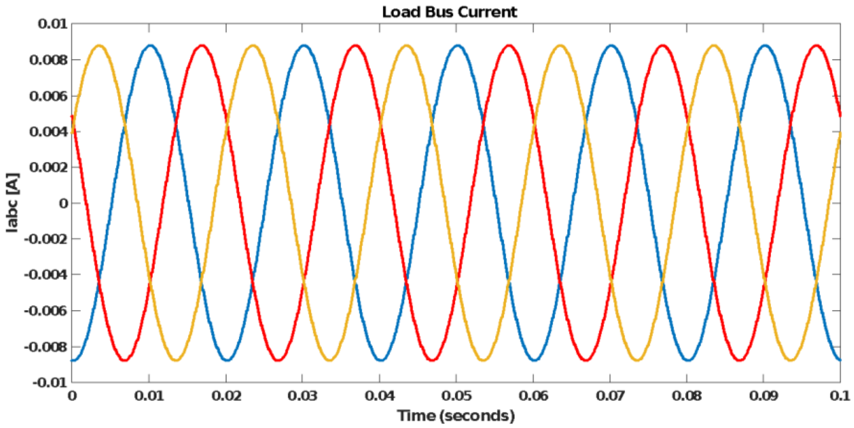

Figure 11: Three phase load bus current waveform under normal condition without PV connection.In Figure 11, under normal condition, the current waveform of the load on network bus from transmission station is normal, sinusoidal shaped waveform.

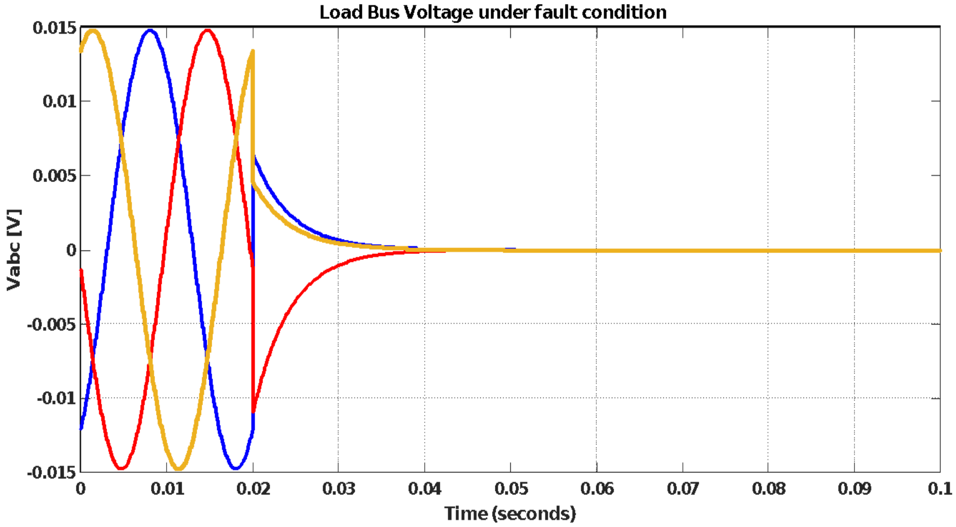

Figure 12: Three phase Load Bus voltage waveform under fault condition without PV connection.

From Figure 12, the three-phase fault was applied at the load bus at time 0.02s. Before the fault, the load voltage had its nominal magnitude of 0.015 p.u. After the fault was applied, the phase voltages dropped to zero exponentially due to the capacitive nature of the network.

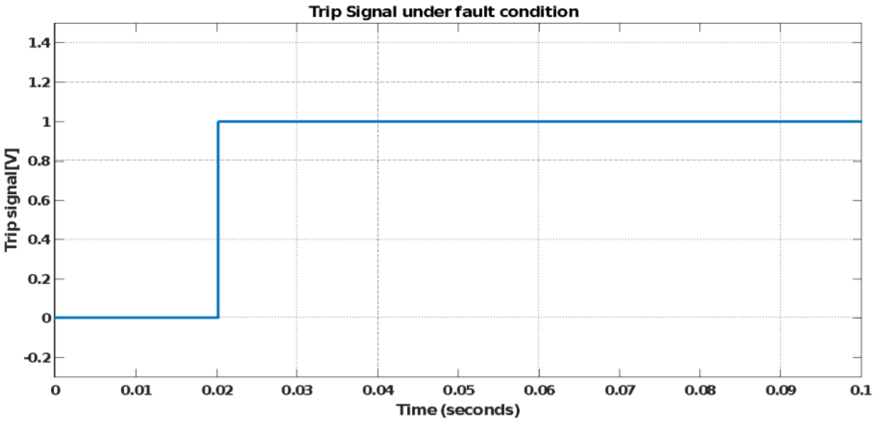

Figure 13: Trip signal of Differential Relay under fault condition without PV voltageIn Figure 13, under fault condition, the relay signal is zero at initially and suddenly rise to 1V when the fault occurred. Due to the difference in between the current on both sides of the transformer, the relay generates a trip signal which is sent to the circuit breaker. Hence the circuit breakers are tripped, and simultaneously the load is disconnected from the bus. This validates the performance of the differential relay on a conventional power system network.

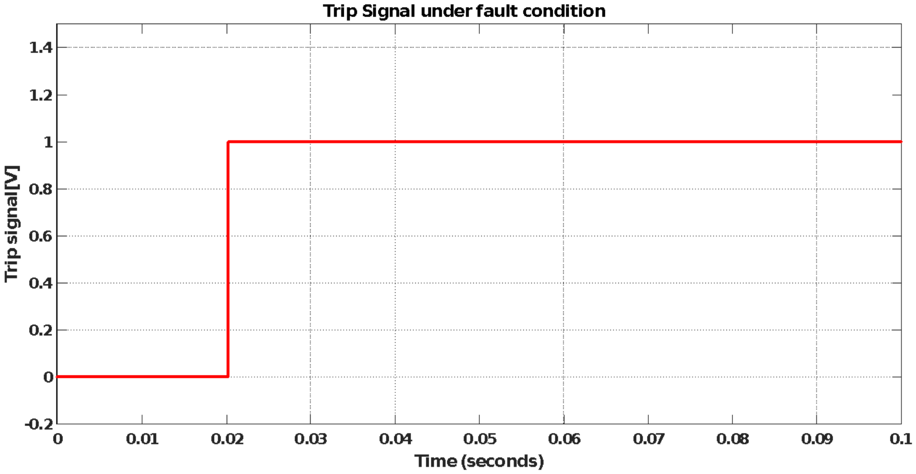

Figure 13: Trip signal of differential relay under fault condition with PV voltage

From Figure 13, until the time of the fault $t < 0.02s$, the differential mainatins a trip signal value of zero. Even with the high PV penetration, the relay maintains a normal operating condition. After the fault is applied, the relay sees a differential current flowing through its current transformer. This leads to a trip signal being sent to the circuit breaker initially isolation of the faulted part of the network. This shows the capability of the differential relay scheme to work in a hybrid power system network under all conditions.

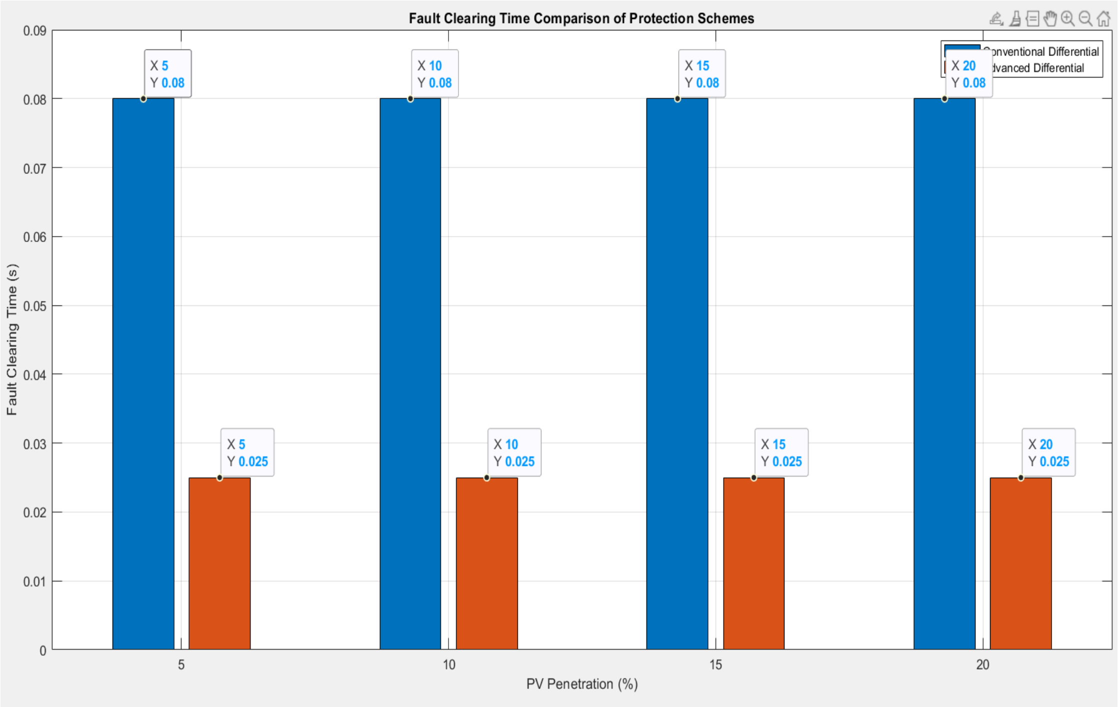

Figure 14 Comparison of fault clearing time between Conventional Advanced Differential Protection under varying PV penetration levels.

The figure 14 presents a comparison of fault clearing time between Conventional Differential Protection and Advanced Differential Protection under varying PV penetration levels of 5%, 10%, 15%, and 20%. The results indicate that the conventional differential protection relay exhibits a constant fault clearing time of approximately 0.08 seconds across all PV penetration levels. This behavior reflects the reliance of conventional protection schemes on fixed operating delays and predetermined relay settings, which limits their ability to respond faster under different network conditions. Although the conventional relay effectively detects and isolates faults, the relatively longer clearing time may increase the risk of system disturbances, equipment stress, and reduced protection efficiency in modern power systems.

the advanced differential protection relay demonstrates a significantly faster fault clearing time of about 0.025 seconds for all PV penetration levels considered. This improved performance suggests the use of enhanced fault detection algorithms, adaptive relay characteristics, and improved signal processing techniques, enabling the relay to respond more rapidly to fault conditions. The results show a consistent performance improvement of approximately 0.055 seconds compared to the conventional scheme. Faster fault clearing enhances power system stability, protection reliability, and operational security, which is particularly important in networks with increasing distributed generation and photovoltaic (PV) integration.

Table 1: Comparison of Conventional and Advanced Differential Relay

PV Penetration (%)	Conventional Differential Relay Clearing Time (s)	Advanced Differential Relay Clearing Time (s)	Time Difference (s)
5%	0.080	0.025	0.055
10%	0.080	0.025	0.055
15%	0.080	0.025	0.055
20%	0.080	0.025	0.055

The Table show that the Advanced Differential Protection Relay clears faults significantly faster than the Conventional Differential Protection Relay across all PV penetration levels. The conventional relay maintains a fault clearing time of approximately 0.08 s, whereas the advanced relay clears the fault in about 0.025 s. This produces an average improvement of roughly 0.055 s in fault clearing performance. The reduced clearing time demonstrates that the advanced differential protection scheme provides quicker fault isolation and enhanced overall protection performance, which is particularly beneficial in power systems with increasing levels of PV penetration, where fast and reliable fault detection is essential for maintaining system stability and reliability.

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7.0 CONCLUSION.

This study has presented an advanced differential protection scheme for distribution networks with high photovoltaic (PV) penetration and evaluated its performance using MATLAB/Simulink simulations. The results demonstrate that the proposed scheme maintains high stability under normal operating conditions, with the differential current remaining approximately zero ($I\_diff \approx 0$) even as PV penetration increases from 1 MW to 5 MW. Under internal fault conditions, a clear current mismatch ($I\_diff \gg I\_rest$) was consistently detected, enabling accurate and selective fault identification, while external faults did not trigger false tripping, confirming relay security.

Quantitatively, the advanced differential relay achieved a fault clearing time of 0.025 s, significantly outperforming the conventional scheme, which recorded 0.080 s. This represents a reduction of 0.055 s, corresponding to an improvement of approximately 68.75% in fault clearing speed. Additionally, the relay demonstrated reliable operation under inverter-limited fault currents in the range of 1.1–1.3 p.u., maintaining sensitivity despite reduced fault current contribution from PV systems.

Overall, the proposed protection scheme enhances fault detection speed, selectivity, and reliability in PV-integrated distribution networks. These improvements contribute to better system stability, reduced equipment stress, and increased resilience of modern power systems with high levels of renewable energy penetration.

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