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Article

THE EFFECT OF SOLAR PHOTOVOLTAIC (PV) INTEGRATION ON OVERCURRENT PROTECTION IN DISTRIBUTION NETWORKS

P. S. Patil[1], R. M. Moharil[2]

[1] Research Scholar, Department of Electrical Engineering, Yeshwantrao Chavan College of Engineering (YCCE), Nagpur, Maharashtra, India. psp4india16@gmail.com
ORCID: 0000-0002-0435-6261
[2] Professor, Department of Electrical Engineering, Yeshwantrao Chavan College of Engineering (YCCE), Nagpur, Maharashtra, India.rmm_ycce_ep@yahoo.com
ORCID: 0000-0002-1440-6744

Abstract: Solar photovoltaic (PV) systems are becoming more and more connected to power grids, which is changing the way security is usually done, especially when it comes to overcurrent protection. Solar photovoltaic (PV) technology helps the environment, saves energy, and gets people off the power grid, but it also makes operations more difficult, mostly because the power flows back and forth. This research paper explores the effects of solar PV penetration on overcurrent protection mechanisms, including fault detection, relay coordination, and protection device operation. The study uses in-depth case studies and models to show that adding more PV can change the size of fault currents and make them smaller. This can cause problems with how the system works, such as relays not responding quickly enough or safety devices not working together properly. Also, regular security methods often have trouble with flipped power flows, which makes it harder to find faults and could lower the system's reliability. The study looks at a number of advanced ways to deal with these problems, such as adaptive relaying schemes, directional overcurrent relays, inverter-based fault current limiters, and real-time synchronised inverter controls. The results of the simulations show that combining these methods keeps relay coordination and makes distribution network safety systems more reliable in situations with a lot of PV panels. In the end, this study stresses how important it is to use new planning methods and more advanced security techniques to make sure the grid is resilient. The results give utilities, system planners, and lawmakers' important information and useful tips that will help them deal with problems that come up when integrating PV and build modern distribution networks that are sustainable, reliable, and adaptable.

Keywords: Solar PV, Overcurrent Protection, Distribution Network, Relay Coordination, Fault Detection, Distributed Generation

1. Introduction

The introduction of green energy sources to power grids primarily solar photovoltaic (PV) systems has gained worldwide awareness as a good solution to address climate change, decrease reliance on fossil fuels and sustainability. The technological progress, the decrease in costs, and favorable regulations have boosted the uptake of solar PV (Olayiwola et al., 2025). Although these systems are environmentally and economically beneficial, their growing substitution of the traditional distribution networks dramatically changes the existing behaviour of their operations and creates new technical issues that planners and operators face. Considerable higher PV penetration is a significant issue to the traditional overcurrent protection schemes that were developed to maintain unidirectional power flow and foreseeable fault current magnitude (Venkatanagaraju et al., 2025). The distribution systems in the past were based on centralized and passive generation sources with established and predictable patterns of power flow. Based on stable upstream fault current characteristics, overcurrent relays, circuit breakers and reclosers were coordinated. Nevertheless, the introduction of distributed PV generation changes the nature of power flows that become both one-way and two-way, and it alters the magnitude and direction of fault currents considerably (Liang et al., 2023). Conventional protection coordination can therefore fail resulting in relay miscoordination, nuisance tripping or slow fault clearing. These operating problems jeopardize the safety and stability of current power distribution networks (Kamel et al., 2021).

The relationship between the growing penetration of PV and the variation of overcurrent protection dynamics is depicted in figure 1. With the increase of the PV integration there is a change in the fault current contribution patterns, possibly the increase in the relay response time and decrease in the coordination margins. These dynamic features require changing protection strategies that need to be adaptive and aided by communication to effectively respond to the changing conditions in the grid (Shariff et al., 2022). Recent research shows that PV penetration is high and this makes fault detection and coordination mechanisms difficult. The traditional protection systems use the magnitude and the direction of the fault current to discriminate the fault. Nevertheless, poor-quality PV systems with inverters usually restrict fault current production, which changes the predicted current shapes and may cause protection malfunction (Mahmud et al., 2021). Moreover, reverse power owing to PV can cause degradation in directional relays, which is more likely to cause protection blinding or unintentional tripping (Khederzadeh, 2021). Such technical issues put into focus the need to reconsider the design of overcurrent protection at different levels of PV penetration. In order to bridge these issues, this paper critically investigates solar PV integration effects on overcurrent protection in distribution networks. It performs the comparison of fault current variation, the behavior of relay coordination, and protection reliability in various conditions of PV penetration. Moreover, the research examines adaptive, directional, and intelligent protection systems to improve the resiliency of the grid and its stability of operation. Through literature review, trend analysis, and suggestions on mitigation measures, this paper seeks to make a contribution towards the creation of resilient and future protection systems of PV-integrated power networks.

The key contributions of this research paper are summarized as follows:

- This study systematically analyzes how varying penetration levels of solar PV influence fault current magnitudes and directions, providing critical insights into the limitations of traditional overcurrent protection schemes under contemporary operating conditions.
- The paper rigorously evaluates relay coordination challenges that emerge due to reverse and variable power flows induced by PV installations, identifying specific conditions under which relay maloperation or blinding occurs.
- The research proposes and assesses advanced protective strategies, including adaptive overcurrent relays, directional protection schemes, inverter-based fault current limiting methods, and coordinated inverter control strategies, to ensure reliable and resilient distribution network operation in PV-rich environments.

2. Solar Pv Penetration In Distribution Networks

2.1 Overview of Solar PV Systems

According to the photovoltaic effect, solar photovoltaic (PV) gadgets are made out of semiconductor materials like silicon, which is able to directly transform sunlight into electricity. These are scalable systems that could be installed in many different forms including small rooftop installations in residential areas and large utility-scale solar farms. The majority of rooftop PVs are developed to serve the energy requirement of one household and the excess electricity is stored in battery system or exported into the grid under net meters schemes. Conversely, centralized PV farms are normally connected to the distribution or transmission system where generated electricity is directly fed into distribution system to serve the local energy requirements. A typical PV system comprises of the following parts; solar modules, an inverter which converts direct current (DC) to alternating current (AC) and a control unit which monitors and optimizes the performance of the system. PV systems can be in a grid-connected or standalone (off-grid) mode depending on configuration. The grid-connected PV systems are more common because they are flexible in their operation and help in curbing the fossil fuel dependence. Additionally, PV systems based on inverters are becoming more grid-supportive, including features like a voltage control and fault ride-through, which determine the protection and operational principles (Zhang et al., 2022).

Solar PV is decentralized and the property improves energy security and minimizes losses in transmission. Nonetheless, uncertainty in the operation is brought about by variability in the solar irradiance as a result of the weather conditions and day/night cycles. Such variations have impacts on the fault current properties and coordination of protection in the distribution systems, especially the grid-connected systems (Mahmud et al., 2021). Moreover, to guarantee accurate system operation under intermittent generation scenarios, the extensive reliability analysis and adjustable planning processes are necessary (Kaur and Khanna, 2022). With the ever-growing penetration of PV, there will be a need to gain an in-depth knowledge on the operating principles and grid integration needs in order to ensure stability in the system, and coordination of protection and the entire network efficiency.

$$P_{pv} = \left(\frac{S_{pv}}{S_{load}}\right) * 100 \qquad (1)$$

The above equation is used to determine the percentage of solar PV capacity to the total load. It assists in evaluating the extent to which the distributed PV systems are satisfying the network demand.

$$\Delta I_f = \left(\frac{I_{base} - I_{pv}}{I_{base}}\right) * 100 \qquad (2)$$

Measured to determine the reduction in the fault current in PV integration. It points out the capability of inverter-limited output to decrease the sensitivity of fault detection of conventional overcurrent protection systems.

$$I_f, total = I_{grid} + \Sigma\, I_{pv}, i \qquad (3)$$

Significant to the evaluation of the protection devices performance in the case of distributed faults.

$$I_{pu} = \frac{I_{fault}}{I_{rated}} \qquad (4)$$

This normalized measure shows the inverter's fault current relative to its rated output. Typically limited to 1.1–1.3 pu, it impacts the overall system's short-circuit capacity.

$$M = T_{backup} - T_{primary} \qquad (5)$$

It is normally restricted to 1.11.3 pu, and it affects the short circuit capacity of an entire system.

$$\theta = cos^{-1}\left(\frac{V \cdot I}{|V||I|}\right) \qquad (6)$$

This is so as to make sure that backup relays can only be used when the main one fails. Lower margins because of the variability caused by PV result in greater likelihoods of protection miscoordination or lagging response.

$$P = V \cdot I \cdot \cos(\varphi) \qquad (7)$$

Directional protection may be challenging because PV production may affect this angle.

$$MVA_{sc} = \frac{V^2}{Z_{total}} \qquad (8)$$

Finishes the fault level by use of system voltage and impedance. PV systems vary local impedance resulting in variation of short-circuit power and fault current magnitude.

$$t_{ride} < t_{fault_{clear}} \qquad (9)$$

Early disconnection of inverters will further minimise fault current, which may not allow proper functioning of relays.

$$I_{pv} = I_f * \left(\frac{Z_{grid}}{Z_{pv} + Z_{grid}}\right) \qquad (10)$$

This determines the proportionality of PV source fault current. The low impedance will lead to high contribution.

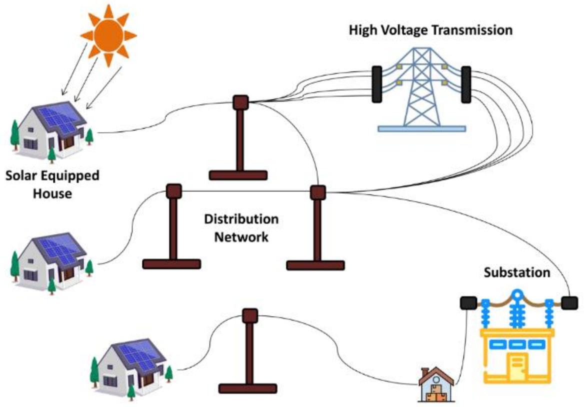

Figure 1. Solar PV Systems into a Distribution Network with Substation and High Voltage Transmission

Figure 1 illustrates the energy flow in a distribution system that has a high number of solar photovoltaic (PV) panels. To the left we have the solar equipped houses. They both have solar panels on the roof which convert sunlight into energy. The houses can utilize the solar power directly or any additional energy can be exported to local grid. The distribution network consists of power towers and wires, which transmit this energy to other users or to other substations. One of the major components of the distribution of the flow of energy between the high voltage transfer system and the distribution network is a substation, which is depicted on the right side of the image. Power levels are elevated or reduced in substations so that they can be transmitted more effectively in long distances. High-voltage transmission lines can bring or send power where required to larger area grids. Therefore, in the illustration, distributed solar generation is depicted in case of conventional power infrastructure. It also demonstrates the role of the collaboration of decentralised and centralised energy systems to maintain the grid stable, reliable, and energy distributed effectively.

2.2 Impact of Distributed Generation on Network Protection

A lot of literature has been done on the effect of distributed solar PV generation to reliability and coordination of protection systems in power distribution networks. As mentioned by Singh et al. (2024), the growing share of PV penetration in microgrids present substantial coordination issues especially because of the changing contribution of faults by inverter-based resources. Likewise, Venkatanagaraju et al. (2025) revisited the new protection issues in photovoltaic systems and highlighted the shortcomings of the traditional overcurrent relays when integrated with high PV. Directional protection problems have been also largely reported. Rana et al. (2019) have shown that backwards power flow of a rooftop PV system may interfere with the operation of relays and result in unintended tripping. In line with this finding, Khederzadeh (2021) demonstrated that directional overcurrent relays are not always able to read the direction of faults in the context of a PV-based distributed generation, which lowers selectivity and system security.

Strategies of adaptive protection have been suggested to deal with such concerns. Shariff et al. (2022) also stated that conventional fixed level relay environments do not perform in a high-PV environment and suggested real-time adjusting protection plans. Mahmud et al. (2021) also elaborated that inverter-limited fault currents also change the dynamic fault behavior dramatically, necessitating new protection methods. Besides that, Zhang et al. (2022) have studied fault ride-through capability of inverter-based PV systems and highlighted the necessity of a coordinated inverter-grid interaction to ensure the stability of the protection in a disturbance situation. Detection and monitoring of the system and islanding have also been considered. Elshaer and Mokhlis (2020) described the threats of unintentional islanding that occurs in PV-concentrated distribution network and emphasized the significance of effective detection systems. The authors suggested using synchrophasor-based monitoring as a way of enhancing situational awareness and increasing the effectiveness of protection coordination in conditions of rapidly varying voltage and current (Sathyan et al., 2023). Additionally, Kaur and Khanna (2022) examined the implications of intermittent PV generation to the reliability and the impact of the technology on the protection zone of a feeder. Hybrid relay designs and artificial intelligence are also on the verge of becoming a trend in the field.

Natsheh et al. (2023) have shown that AI-oriented fault detection and classification methods offer a great improvement in the performance of protection in PV-integrated networks. Also, Patel et al. (2023) proposed hybrid overcurrent relays that have a current magnitude sensing component and a voltage dip detecting component to provide higher sensitivity and coordination in the smart grids where there is a large number of PV penetration. Recent developments also highlight the importance of smart and combined systems to facilitate PV-controlled distribution systems. Adaptive digital twins have become a promising solution to the modeling and optimization of complex energy infrastructures under dynamic working conditions, and they can monitor and predictively control under an energy-intensive environment (Timothy et al., 2024). Besides, the more sophisticated load forecasting models like hybrid ARIMALSTM help in making better predictions of regional and residential energy demand, thus contributing to better grid planning and operational management in a grid with high renewable content (Bopche et al., 2026). In general engineering terms, interdisciplinary innovations, which face the challenge of thermal and system efficiency, also underscore the significance of incorporating more sophisticated physical model methods in the renewable energy systems to promote performance and sustainability (Matey et al., 2025). These studies combined highlight the increasing importance of smart modeling, predictive control, and optimization methods in ensuring the availability of dependable and efficient incorporation of solar PV into the contemporary power systems.

Much is yet to be achieved in regards to the development of actual time, scalable solutions that integrate inverter control logic with safety coordination in a manner that would be effective. The majority of the existing strategies are reactive in nature, are not scalable or require significant modifications to the grid system. To seal this breach, our work proposes a hybrid model of prevention that incorporates flexible directional relays, fault current shape inverting coordination and protection coordination algorithm supported by data analytics in real-time. Table 1 is a review of earlier research indicating that PV-integrated grids contain reduced fault currents, coordination issues and non-functioning relays. The majority of the studies consider the case of just a single situation, and there are not any current, scala-able approaches to flexible security.

Table 1. Summary of related work

Focus Area	Key Findings	Protection Issue Addressed	Limitation
PV Impact on Fault Current	Fault current magnitude decreases with PV integration	Underdetection of faults	Inflexible to dynamic PV penetration levels
Relay Coordination with PV	Inverter limits cause miscoordination	Time-current miscoordination	Assumes fixed relay settings
Reverse Power Flow	Reverse current causes false tripping of relays	Relay false operation	No directional relay adaptation
Relay Directionality under PV Influence	PV causes relay blinding due to directional uncertainty	Relay blinding	Did not consider inverter ride-through support
Adaptive Protection Need	Existing protection schemes fail under high PV	Real-time adaptability	Requires frequent calibration
Dynamic Fault Characteristics	Inverter response varies across events	Dynamic fault response	Lacks hardware-level implementation detail
Fault Ride-Through	Grid support by inverters essential for fault tolerance	Fault ride-through coordination	High dependency on smart inverters
Unintentional Islanding	Islanding compromises safety unless properly detected	Islanding detection	Delayed response in passive techniques
Synchrophasor-Based Monitoring	PMUs can track voltage/current changes	Fast-changing fault monitoring	Needs high infrastructure

	to improve response		investment
PV Variability & Reliability	Intermittency affects feeder-level coordination	Zone-based relay stability	Not suitable for meshed networks
AI in Protection Schemes	AI models improve fault classification with PV	Multi-fault classification	Requires training and real-time data integration
Hybrid Relays & Voltage Sag Detection	Combined sensing improves protection reliability	Enhanced relay selectivity	Complex relay configuration

3. Fundamentals Of Overcurrent Protection

3.1 Role of Overcurrent Protection in Distribution Systems

Another significant aspect of maintenance of electrical distribution systems is overcurrent control. It achieves this by detecting and halting any over current flows that are occasioned by short circuiting, equipment failures or prolonged overloads. In case of fault, the current is running at a pace that is beyond the capability of the wires and equipment. Unless the fault is isolated promptly, it may destroy equipment, lead to fire and interrupt service. The overcurrent safety systems are designed to detect such cases and shut down the portions of the network affected by them in order to prevent the escalation of the issue. The primary objective is to continue providing service to locations that are not contacted and safeguard the electricity systems and end customers. An effective overcurrent system must be sensitive enough to locate actual issues in a short time, yet intelligent enough not to call for connection disconnection whenever temporary conditions exist. Figure 2 indicates how the lightning safety is configured in the case of a DC and AC powered solar power system. It shows the manner in which lightning arresters are installed in every channel to protect the electrical components against shocks. The grounding bar and grid are combined to form a point of reference. This ensures that the lightning currents are properly discharged to the earth which enhances the safety and reliability of the system.

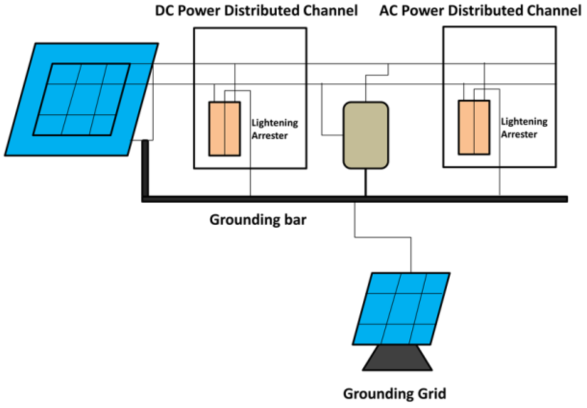

Figure 2. Lightning Protection Arrangement for DC and AC Power Distributed Channels in Solar Power Systems

The rate of relays tripping is defined in the following equation as a direct result of the magnitude of fault current. Increased fault currents lead to quicker tripping to guarantee that protection equipment is selective and fast.

$$T_{relay} = \frac{K}{\left(\frac{I_{fault}}{I_{pickup}}\right)^{n} - 1} + TMS \qquad (11)$$

Calculations Fault current at a node of the network is obtained by summing the contributions of the line, grid and spread sources. It assists in determining the number of faults which actually exist in PV-integrated distribution networks.

$$I_{fault} = \frac{V_{pre}}{Z_{grid}|Z_{line}|Z_{DG}||} \qquad (12)$$

Where:

- I_fault = Total fault current at the bus
- V_pre = Prefault voltage at the faulted bus (volts)
- Z_grid = Impedance of the utility grid
- Z_line = Line impedance to the fault
- Z_DG = Equivalent impedance of distributed generation
- || = Parallel impedance operation

Ensures that there is a satisfactory delay in the transfer between the primary and the backup transfer processes in order to retain the choice.

$$CTI = T_{backup} - T_{primary} \geq T_{clear} + M + S \qquad (13)$$

Where:

- CTI = Coordination Time Interval (seconds)
- T_backup = Operating time of backup relay
- T_primary = Operating time of primary relay
- T_clear = Breaker clearing time
- M = Safety margin
- S = System tolerance (e.g., time delay due to device error)

Decomposes asymmetrical fault currents to positive, negative and zero sequences. It is used in relays to determine the type and direction of faults to enhance accuracy of the protection of SLG and L-L faults.

$$I_{phase} = I1 + I2 + I0 \qquad (14)$$

Where:

- I_phase = Phase current under fault conditions
- I1 = Positive sequence current component
- I2 = Negative sequence current component
- I0 = Zero sequence current component

It relies on the kind of failure, the distance and the gap on the wire to determine the level of danger an arc may be.

3.2 Protective Device

The group of devices that offer overcurrent safety in the distribution networks includes fuses, circuit breakers, and switches. Every of such devices performs a certain yet closely related task. Protective switches are intelligent sensors and they monitor the current of electricity in circuits continuously. These switches, when they detect unusual levels of current, which may be on each side of a fault or an overload, transmit control messages to de-energize the circuit. This is mostly performed by circuit breakers. Circuit breakers refer to motorised switches, which are capable of shutting and reopening circuits during normal and troublesome circumstances. Circuit breakers are suitable to the modern contemporary automatic security system because they are adaptable and operate rapidly. Fuses on the other hand are passive safety gadgets, which contain a metal wire or strip within, which melts and cuts off the circuit when the current exceeds a specified level. Fuse boxes are simple to operate and not very expensive, however, they have to be replaced after the use and are not as intelligent and versatile as switches and breakers.

1. Energy Let-Through by Fuse (I^2t)

$$E = \int_0^t i(t)^2 dt \quad (15)$$

- This integral is the energy (in Joules) conducted by a fuse in a fault.
- It defines the amount of thermal stress which the fuse is able to sustain before melting.

2. Arc Energy Absorbed by Circuit Breaker Contacts

$$W_{arc} = \int_0^{t_{clear}} V_{arc(t)} \cdot i(t) dt \quad (16)$$

Breaks contacts and extinguishing apparatuses of high fault in a helping size.

3. Electromechanical Relay Torque Balance (Differential Equation)

$$J \cdot \frac{d^2\theta}{dt^2} + D \cdot \frac{d\theta}{dt} + K \cdot \theta = T_{electromagnetic} \quad (17)$$

- Models the movement of electromechanical relay arms under magnetic torque.
- Includes inertia (J), damping (D), and spring constant (K).

4. Overcurrent Relay Operating Time (IEEE Moderately Inverse)

$$T = \frac{0.0515 \times TMS}{\left(\frac{I}{I_{pickup}}\right)^{0.02} - 1} \quad (18)$$

- Gives the time delay before a relay trips based on the fault current magnitude.
- TMS = Time Multiplier Setting.

5. Fuse Melting Time Equation

$$t = \frac{K}{\left(\frac{I}{I_{rated}}\right)^{n}} \quad (19)$$

- Predicts how long a fuse takes to melt at a certain overcurrent.
- K and n are fuse-type-specific constants.

6. RMS Current through Protective Device

$$I_{rms} = sqrt\left(\left(\frac{1}{T}\right) \cdot \int_0^t i(t)^2 dt\right) \quad (20)$$

- Calculates the Root Mean Square (RMS) current over a cycle.
- Important for fuse sizing and breaker thermal limits.

3.3 Relay Coordination of Overcurrent Relays

Relay coordination is a significant aspect of overcurrent safety since it ensures that a damaged section of a power distribution network is isolated and leave the unaffected parts to continue operating normally. This choice is highly significant in ensuring the system is reliable and the service interruptions are also minimised in case of a problem. This ensures that the nearest safety device to the issue responds first which restricts the damage and preserves the valuable equipment. Such aspects as load current, problem current levels, relay working times, and breaker cleaning times have to be considered when coordinating. It is a relatively simple task to do in linear systems but it is more difficult to coordinate in modern grids with spread generation such as solar PV since power flows in both directions and fault currents vary with time. Table 2 presents the key issues that the introduction of solar PV leads to with regard to overcurrent safety systems. Low fault currents and reverse power flow are some of the large problems and are primarily due to inverter limited output and two-way flow of energy. All these complicate the process of searching mistakes, arranging relays, and selecting the appropriate gadget. You should counter these effects with flexible security configuration, directed switches, real-time tracking aids that are communication assisted to make it more dependable.

Table 2. Analysing the effects of solar PV on overcurrent protection

Aspect	Key Challenge	Cause	Impact on Protection	Required Modification	Suggested Solution
Fault Current Level	Reduced fault current	Inverter current limitation	Protection devices may not detect faults	Sensitivity recalibration	Use of adaptive relays and PMU-assisted monitoring
Relay Coordination	Miscoordination due to variable current direction and magnitude	Bidirectional power flow from PV	False trips or failure to trip	Dynamic time-current settings	Communication-based relay coordination
Directional Overcurrent Protection	Fault direction misinterpretation	Inverter-induced phasor shift	Relay blinding or misoperation	Directional sensing enhancement	Voltage polarizing DOCRs with negative-sequence logic
Fuse Operation	Failure to melt under fault	Low fault current from downstream PV	Recloser-fuse miscoordination	Fuse threshold adjustment	Replace fuses with electronic fault interrupters
Recloser Coordination	Reclosing onto sustained fault	Incomplete fuse clearing	Equipment damage, safety hazard	Recloser logic revision	Smart reclosers with directional and current profiling
Voltage Fluctuation	Nuisance relay operations	PV output intermittency	Instability in protection margin	Voltage-based tripping logic	Integrated voltage and current monitoring relays
Reverse Power Flow	Relay coordination breakdown	Export of power from PV to grid	Malfunction in conventional OCR coordination	Relay polarity reassessment	Directional protection schemes
Selectivity	Larger fault zones impacted	Lack of adaptive selectivity	Reduced grid reliability	Coordination margin optimization	Adaptive and zone-based protection schemes
Relay Sensitivity	Underreaching during PV off-peak or cloudy conditions	Reduced PV contribution	Delayed or missed fault detection	Real-time relay calibration	Load-dependent adaptive protection algorithms
Grid Resilience	Inconsistent performance under high PV penetration	Legacy protection not designed for DERs	Vulnerability to cascading failures	System-wide protection redesign	AI-enabled protection and DERMS-assisted grid coordination

4. Effects Of Solar Pv On Overcurrent Protection

4.1 Changes in Fault Current Levels

The conventional overcurrent protection relies on fault currents that are highly disparate in case of the addition of solar photovoltaic (PV) systems to the distribution systems. Under normal conditions, most of the fault currents are provided by synchronous generators that possess a high short-circuit capacity. However, in the event of a fault, solar PV systems do not behave in an identical way. This is more so in those systems that are connected to the grid through power electrical transformers. When this behaviour occurs, the general problem current levels observable by safety devices reduce by an extensive percentage. Table 3 presents the comparison of the fault current level with the integration of solar PV under the various type of faults and network sites. The results demonstrate that the fault current is significantly lower since PV inverters regulate the passage of current.

Table 3. Analysis of Fault Current Levels with and Without Solar PV Integration

Fault Type	**Location**	**Without PV (kA)**	**With PV (kA)**	**% Reduction in Fault Current**	**Inverter Contribution (kA)**
3-Phase Fault	Feeder Head	6.5	5.1	21.5%	0.8
Single Line-to-Ground	Mid Feeder	4.2	3.4	19.0%	0.6
Line-to-Line	End of Feeder	3.6	2.3	36.1%	0.4
3-Phase Fault	Lateral Branch	2.8	1.9	32.1%	0.3
Single Line-to-Ground	Near Substation	7.0	5.6	20.0%	1.0
Line-to-Line	Industrial Load Zone	5.1	3.7	27.5%	0.7

The lower fault levels or may be unable to reach them in time or may be too slow to operate traditional overcurrent relays (OCRs) which require a definite separation between fault current and load current. This may reduce reliability of the defence system and the time it takes to clear faults which may damage equipment and may have safety concerns. The fault current available is also not necessarily the same since the amount of solar generated varies with the weather. It becomes difficult to establish rigid safety settings. The quantity of PV entering the network and, by implication, the fault current may vary significantly at various times of the day or with varying amount of sunlight. The issue is aggravated in cases where the PV is high, as then is the time when the large share of the load is satisfied through the local production. The network resistance and fault current paths vary when the number of inverters in a network is large. This may result in the failure to achieve or false-negative of safety zones. Due to this fact, the entire concept of fault identification should be transformed to address these emerging facts.

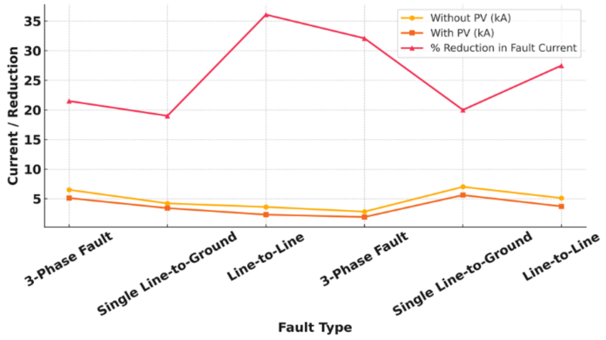

Figure 3. Impact of PV Integration on Fault Current Levels

This can be done by using dynamic models of fault current behaviour and inverter behaviour when there is a breakdown. Phase measurement unit (PMU) real-time data can also be included, figure 3 is the impact analysis. Other power companies are even considering flexible security systems which can be modified in regard to the sensitivity of the system depending on the grid and the generation conditions. In this manner one can detect faults even when the output of PVs varies.

4.2 Impact on Relay Coordination

In case of an issue, relay coordination will ensure that the nearest defensive device to the fault clears it, and all the devices upstream remain in place. This keeps the service running in the affected non-part parts of the grid. This concept is referred to as selection and forms the core of classic overcurrent safety devices particularly in radial distribution systems. However, increasingly solar PV systems are being brought to the grid, complicating matters immensely and rendering conventional relays forms of communication very difficult to operate.

To ensure that everything works well together, utilities are considering flexible security systems where the settings of the relays are modified in real time using real-time data. These include coordinated protection systems that employ IEC 61850 means of communication to allow relay to exchange information and adjust their settings according to the current state of affairs on the grid. GPS time stamps and observing the entire system are also useful in ensuring that the defence activities are aligned in various sources. There is also the use of modelling tools which reveal the behaviour of dynamic PV in the event of a fault, which allows engineers to make safety plans that collaborate even in the event of a fault. Finally, the necessity to replace simple settings with smart, situation-aware security structures is required to ensure a better relay coordination in PV-integrated systems.

4.3 Directional Overcurrent Protection Challenges

Directional overcurrent relays (DOCRs) are significant components of systems of passing power, when more than one source of power is used, such as in solar PV systems. They are not merely a way of determining the presence of overcurrents; they are also a way of determining the direction in which the fault current is flowing relative to some point in the network. This is particularly so in systems where power flows in both directions since one must be able to distinguish forward and backward faults so as to isolate only the faulty portion. Installing PV systems in various areas of the distribution grid, such as on lateral lines and at customer ends, provides options of flowing the fault current in other directions, depending on the location of the fault, and the amount of power flowing to it being sent by PV converters in real time.

4.4 Effect on Fuse and Recloser Operation

Fuses and reclosers are quite essential in radial distribution networks since they resist over currents and short-lived issues fast and with high reliability. An organised plan tends to ensure that fuses lower downstream prevent permanent failures whilst reclosers higher upstream attempt to clear temporary failures and start service back on line. The effectiveness of this teamwork relies on the possibility to anticipate the fault currents sizes and directions. Though introducing solar PV, particularly by spread generation using inverter, disrupts the size and direction of fault currents, so that the conventional fuse-recloser mechanism of operation is no longer useful.

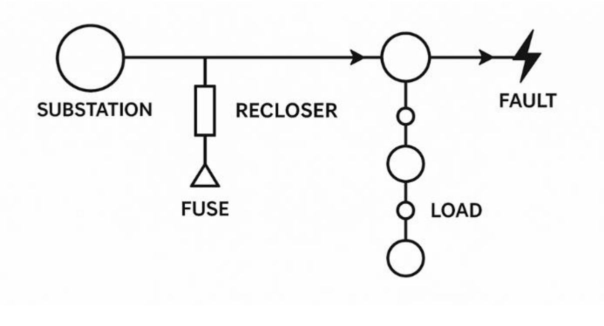

Figure 4. Overview of fuse and recloser operation

A large issue is that the inverter restricts itself to allow the fault current values to decrease significantly. Normal currents in faults are high and are likely to blow a fuse or release a reclose, operation architecture will be in figure 5r. PV converters, however, are frequently of such a nature that they do not contribute much fault current necessary to power such devices. This implies that at times a fuse does not melt despite the presence of a fault and therefore the recloser opens and closes again to attempt to clear the fault. Repeat of a similar change adds a lot of strain to the recloser systems and can bring bigger parts of the network to a standstill which is not in line with the concept of selective security.

5. Case Studies And Simulation Results

5.1 Methodology for Assessing PV Impact on Overcurrent Protection

There should be a methodology that is grounded on frequent simulations to determine how the addition of solar photovoltaic (PV) will impact on overcurrent safety systems. To begin with, a sample radial distribution network model is selected. This model is typically feed fed, branched, and multi-loaded. Stereotypical safety elements such as overcurrent switches, fuses and reclosers should be present in the model with a distinct time-current character. Network modelling software such as ETAP, PSCAD or MATLAB/Simulink is employed to determine significant electrical considerations such as resistance, lines layout and problem points.

In order to replicate various scenarios, the model is equipped with solar photovoltaic (PV) systems at various levels of entry and at strategic locations like the feeder head, mid-feeder and end node. These systems are modeled by inverter-based production blocks to simulate them in a manner that makes them realistic both in terms of current limits and grid-following control modes. Then the faults of three phase, single line to ground (SLG) faults and line to line faults are introduced on the key nodes to observe how the system responds to them with and without PV integration. Within the modelling system, each situation is measured in terms of fault current, relay operating time, breaker response to tripping and the gaps in coordination. The direction and magnitude of the fault currents that are transformed by PV systems is very important to pay attention to. The results of increasing the number of PV are displayed in Table 4 and their impact on the success of relays is observed. With increasing PV, the coordination gaps reduce with the increasing levels and the relay operation time increases. This implies that fault detection and selective protection become more difficult to maintain.

Table 4. Results of PV Impact Assessment on Overcurrent Protection

PV Penetration Level (%)	**Fault Type**	**Fault Location**	**Relay Operation Time (ms)**	**Coordination Margin (ms)**
0 (Baseline)	3-Phase Fault	Feeder Head	45	250
20	Single Line-Ground	Mid Feeder	52	230
40	Line-to-Line	End of Feeder	70	160
50	3-Phase Fault	Lateral Branch	85	130
60	SLG Fault	Near Substation	98	90
60	3-Phase Fault	Industrial Load Zone	110	75

The approach involves comparing the traditional performance (without PV) and the situation that involves PV in several scenarios. Sensitivity analysis to establish the levels at which standard security becomes compromised, the penetration rates of PVs and fault resistance are varied.

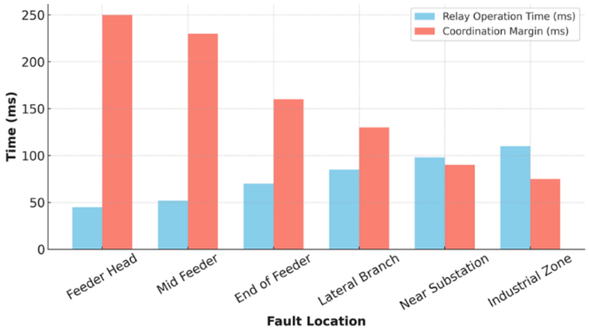

Figure 5. Relay Operation Time VS Coordination Margin at Different PV Penetration Levels

The findings are used to identify weak areas in protection, quantify the degree of off-coordination, as well as provide solutions to the issue such as employing versatile relay parameters, directional protection mechanisms and communications aided protection. Figure 5 is a comparison of the time that it takes the relay to operate and the coordination gap at various quantities of solar PV usage. The trend of the graph is evident: the higher the use of PVs, the longer the time of work of relays and the smaller the coordination margin. As an illustration, relays operating at PV 0 will operate fast and will have high safety margin. However, in case PV equals 60, the relay responses are slower and coordination gaps are less, and this raises the likelihood of security miscoordination. This can be largely attributed to the fact that PV converters do not contribute significantly to problem current and are even not contributing at all. These findings demonstrate the significance of the safety systems capable of modifying and operating on the real-time in the high-PV environments..

5.2 Simulation of Different Solar PV Penetration

To experience the complete understanding of how progressive integration alters the reliability of overcurrent safety, it is relevant to simulate the different degrees of solar PV utilizations. The computer study has added PV systems to a test radial distribution feeder in percentages between 0 percent (baseline) and 60 percent of the total system load. Each entry level is the ratio of the PV output power to the high demand of the feeder. The PV is distributed across a number of buses with some near the centre and some at feeder ends to be able to study both the centralised and scattered production effects.

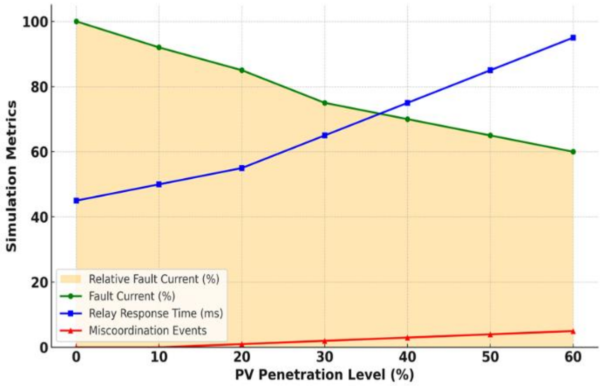

Figure 6. Effect of Solar PV Penetration on Protection Performance

At every entry level, there are several kinds of faults employed. These are three phase faults, single line-to-ground faults, and the line-to-line faults in various locations within the network. The program captures the current levels of the problem, direction of the current flow and time it requires safety systems to respond, as can be seen in figure 6. At lower penetration rates such as 10 to 20 percent, the PV fault current input remains relatively small and the standard safety devices operate as intended. At a percentage of PV panels exceeding 30, however, large amounts begin to become apparent. It is noteworthy that as the current current becomes smaller, the problem current does the same and consequently the current contribution by the PV inverters is not too much as well. As an illustration, when the penetration is 50, an issue at the end of the feeder may only receive 65 per cent of the current that it would receive in the absence of PV. This reduction directly affects the functioning of overcurrent switches and decelerates the functioning of fuses. Higher penetration also experiences power flow reversal whereby solar output is large and load is small, and therefore, makes relay coordination more difficult. The program also has miscoordination events. As an example, the up stream breakers are tripped before the down stream switches or fuses that fail to clear the issues until the time constraints. These findings clarify the need to have security plans that are flexible as the network evolves on a centralised network of energy flow towards a decentralised one. The outcomes of the tests confirm the notion that the number of PV panels increases the issues concerning the coordination of protection and selective tripping. This assists with development of flexible and scalable grid protection plans that will contain large number of PV panels in the future.

5.3 Analysis of Fault Current Contribution from Solar PV

Unlike the normal synchronous generators, the solar photovoltaic (PV) systems differ significantly in their fault current input. The reason is that PV systems are linked using current-limited power electronic converters. The paper applies a simulation to examine the fault currents in PV systems and fault types and locations. The inverter models are configured with realistic parameters of fault reaction. Limits on the amount of overcurrent that can be managed and duration of fault are also placed, all of which influence the impact of PV systems on the network in fault situations. The simulations indicate that addition of PV to fault current is not only lesser, but also relies heavily on how the inverter is controlled, as well as where it is connected to the grid. An illustration is that a 100-kW PV system may only deliver 120130 kW amount of short-circuit current (1.21.3 per unit) less than 200 ms prior to the inverter getting turned off or limiting its output. In three-phase fault at the head of the generator, PV inverters, to the extent that they are closest to the fault, give a larger difference than those that are farther apart since their paths of resistance are shorter. This is small input, however, relative to other sources, resulting in a lower value of the ultimate fault current.

It also examines the dependence of the contribution made by the fault current as a function of the PV penetration. The total fault current decreases marginally at low penetration (1020 percent). At greater currents (greater than 40 per cent) the fault current total can fall below the lowest current that can be sensed by safe relays. There are fewer faults to detect in PV systems which are not grounded or grounded to resistance when there is a single line-to-ground fault. The other significant outcome is that it reverses the course of the fault current. In case PV systems are subsequently installed, after the fault, they can feed fault current in the wrong direction, and can fool directed overcurrent switches, causing coordination issues. Additionally, the change of the angle brought about by inverter-based sources alters the phase relationship between the voltages and current which further complicates the determination of the direction of a signal. Table 5 indicates the contribution of fault current solar PV with varying amounts of penetration and fault type. The current of total fault decreases as the percentage of PV penetration increases to 10 percent to 3.5 kA at 60 percent penetration as the inverter has a limited capacity to handle. During the less than 200 microseconds, the fault current of the inverter is ranging between 1.1 and 1.3 pu. Direction reversal is observed in higher levels of entry (≥40%) that makes directional defence more difficult to utilize. Evidently based on these findings, PV-dominated power networks have coordination issues that must be resolved by means of flexible safety plans and proper inverter modelling. Table 5 indicates that the value of the PV increase leaves the fault current in the inverter constant (1.1 1.3 ps) and the fault short constant (120 190 ms) and this implies that the maximum fault current decreases. It is worth noting that direction reversal occurs at the higher levels of PV (≥40 percent) and this renders it difficult to utilize the standard directional relays, unless, using relaxed approaches to security.

Table 5. Fault Current Contribution from Solar PV under Various Conditions

PV Penetration Level (%)	Fault Type	Inverter Fault Current (pu)	Duration (ms)	Total Fault Current (kA)	Direction Reversal Detected
10	3-Phase Fault	1.2	180	6.3	No
20	Line-to-Line	1.3	190	5.8	No
30	SLG	1.2	150	4.9	Partial

	Fault				
40	3-Phase Fault	1.1	160	4.2	Yes
50	Line-to-Line	1.2	130	3.8	Yes
60	SLG Fault	1.3	120	3.5	Yes

These findings render it evident that the notion of having safety plans considering the nature of functioning of PV systems when they do not work properly is extremely significant. However, some of these recommendations include frequent magnitude and angle tracking, in directional switches place negative-sequence parts, and collaboration with inverter manufacturers to ensure that fault reaction patterns are equal to the security requirements. It is based on this that there is a high need to model fault current of the PV sources accurately when designing robust security systems of the current distributed energy networks.

6. Mitigation Strategies And Solutions

6.1 Adaptive Protection Schemes

Since the standard distribution network is shifting to involve more solar PV, there must be a transformation of fault currents due to the fact that they vary over time to a dynamic approach to safety. Adaptive schemes are in contrast to traditional systems in which the security settings remain constant, in real-time adaptive schemes monitor grid parameters such as load demand, production output and fault current behaviour and modify relay settings as necessary. Although the power flows in each direction and the PV output varies, this is done to ensure the security is valid.

6.2 Directional Relays and Adaptive Relay Settings

Directional overcurrent relays (DOCRs) are highly needed in a power grid with high spread production such as a solar PV power generation. These receivers do not only measure the quantity of the current, they also determine the direction that the current is taking. This assists in determining the origin and course of fault. Because solar PV is able to transmit fault current at multiple locations, it is possible to flow in either direction when faulty. This complicates collaboration of normal relays. Directional relays are able to distinguish between the forward and the backward faults; hence, they do not trip due to any cause or do not leave the actual damaged region unseparated. DOCRs can be enhanced to be more useful by providing them with more flexible settings that allow them to alter the way they operate as the network events vary.

6.3 Implementation of Communication-Based Protection

The rapid reaction to the problem, which is accurate and structured requires a communication-based security system as distribution networks that have numerous PVs are becoming increasingly complex. Communication-assisted protection methods use high-speed information exchange among switches, breakers and control centres to make real time decisions regarding protection based on the conditions throughout the entire system. This allows them to collaborate in order to stumble, isolate defects, and rectify errors. One example of a system that enables it to be possible to make security decisions concurrently across nodes at dissimilar locations is wide-area monitoring systems (WAMS) and phasor measurement units (PMUs). Communication-based systems also prove to be quite useful when inverter-based sources provide reverse or low-magnitude fault currents, which may not be detected by standard switches. These systems are more responsive and properly responsive to faults due to shared real time information. Safety enhanced by communication is a significant move towards the creation of safe and smart grids capable of withstanding the issues that are associated with the wide-scale use of solar PV power sources although they will necessitate investments in infrastructure and cybersecurity.

7. Conclusion

The purpose of this paper is to deal with the overall effect of incorporation of solar photovoltaic (P V) panel on overcurrent safety systems within distribution networks. It established the problem of work and provided viable solutions to the problem. As the PV use will rise, the fault current will drop as the inverters are limited, reaction time of relays is augmented and coordination gap among relays is minimized. This makes the traditional security systems ineffective. Simulations and case studies showed that traditional two-way power flow safety procedures, in support of high fault currents, are ineffective in a distributed PV system with two-way power flow and low fault currents. According to the experiment, the miscoordination of relays, delayed tripping, directed uncertainty is more with high degree of power penetration of PV stations (over 30 per cent), when the power is back-to-back and when power is operated intermittently by the inverter. The contribution of the PV systems to the faults is typically less than 1.1 or 1.3 faults per unit in short-term (less than 200 ms) and this contribution may result in fault or a false alarm on the safety devices. Because of these reasons, the traditional security systems are to be substituted with the versatile ones. The practice put forward and tested new prevention ways of these issues. They include adaptive relay schemes, directional overcurrent relays (DOCRs) with dynamically adjusted real-time sensitivity, communication-supported protection and IEC 61850 protocols and PMU data. The strategies allow the identification of chosen, delicate and intelligent security operations which are in line with the evolving solar PV. To stabilize and render the protection in PV-saturated networks sustainable, the protection design should be modified to take into account the working principles of inverters, the direction of the flow of power, and the changes in the system. The ideas and suggestions of this study gives utilities and grid planners an approximate framework of how to make sure in the future the decentralised energy systems are stable and secure to operate in.

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