Impacts and relay protection solutions for the distribution network in Huong Khe district, Ha Tinh province under high rooftop solar penetration

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DOI: https://doi.org/10.64032/mca.v30i3.411

Abstract

The rapid integration of rooftop solar photovoltaics (PV) systems in Vietnam has transformed traditional radial distribution networks into active grids with bidirectional power flows. This transition poses significant challenges to relay protection systems designed for unidirectional power flow. This paper evaluates the technical impacts of high PV penetration on the 35 kV distribution network in Huong Khe District, Ha Tinh Province, a region characterized by large supply radii and high system impedance. Using PSS® SINCAL software to model the actual grid, the study identifies critical issues including protection "blinding," sympathetic tripping, and the breakdown of traditional fuse-recloser coordination. To mitigate these risks, the research proposes a coordinated technical solution involving the implementation of directional overcurrent protection (67/67N), adaptive setting groups, and the optimization of recloser-fuse curves through the use of extra inverse characteristics. Simulation results confirm that the proposed strategies successfully restore protection selectivity and sensitivity. The study concludes that upgrading to smart, directional, and adaptive protection systems is essential for maintaining grid reliability and safety in the context of increasing renewable energy penetration.

Keywords: *Rooftop PV; Distribution network; Relay protection; Directional overcurrent protection; Photovoltaic integration; PSS® SINCAL.*

1. Introduction

The surge in Distributed Energy Resources (DERs), particularly rooftop solar photovoltaics (PV), is an essential component of Vietnam's sustainable energy transition strategy. Driven by the Feed-in Tariff (FIT) mechanism (Decision 13/2020/QD-TTg) and the strategic directives of Power Development Plan VIII (PDP8), the nation's total solar capacity reached approximately 19 GW by the end of 2022 [1]. In Ha Tinh province alone, 487 customers have installed rooftop PV systems with a combined capacity of 140 MWp. The high penetration of these inverter-based resources has fundamentally altered the nature of traditional distribution networks (35 kV and 22 kV), shifting them from "passive" radial structures with unidirectional power flow to Active Distribution Networks (ADN) characterized by bidirectional power flow. This transition poses severe challenges to grid operations and existing relay protection systems, which were not originally designed to accommodate distributed inverter-based generation.

Integrating inverter-based resources introduces unique and severe challenges for power system protections [2]. Unlike traditional synchronous generators, PV systems typically contribute a limited amount of fault current [2]-[3]. However, high penetrations still significantly alter the magnitude and direction of fault currents. Consequently, conventional overcurrent protection schemes become unreliable. This may result in several problems including loss of selectivity, protection blinding and fuse-recloser miscoordinations [4]. If the coordinate time interval (CTI) is violated, backup relay may trip prematurely, exacerbating power outages.

In Vietnam, recent studies have begun to address this issue. Recent Vietnamese studies show that high PV penetration has begun to challenge conventional distribution protection schemes, especially those designed for radial feeders with unidirectional fault-current flow [5]-[6]. The study on the Yen Dinh solar power plant connected to a 22 kV feeder in Thanh Hoa indicates that PV integration changes both the magnitude and direction of short-circuit current, causing possible relay underreach, delayed operation, and loss of selectivity in 50/51 overcurrent protection [6]. Similarly, rooftop-PV studies in Vietnamese distribution networks report that large PV integration can disturb relay operation because inverter-based sources alter fault-current distribution and reduce the reliability of traditional protection coordination [7]. Although the impacts of photovoltaic distributed generation on distribution-network operation have been widely investigated, the current literature remains limited by its reliance on single-feeder simulation studies, simplified inverter models, static PV penetration scenarios, and narrow focus on 50/51 overcurrent or recloser–fuse coordination [8]. Field validation using actual relay event records, SCADA/DMS data, inverter fault-response measurements, and diverse Vietnamese feeder topologies is still insufficient. This creates the need for a case study that uses a real distribution grid to evaluate the influence of rooftop PV capacity on protection relay. To address this gap, this study demonstrates how rooftop PV penetration of Huong Khe distribution network affects the protection relay and proposes some techniques to mitigate.

Huong Khe Power (Ha Tinh) serves as a typical example of a power system operating in complex terrain, with approximately 295 km of 35 kV medium-voltage lines and

Received: 23 January 2026; Revised: 5 May 2026; Accepted: 7 June 2026.

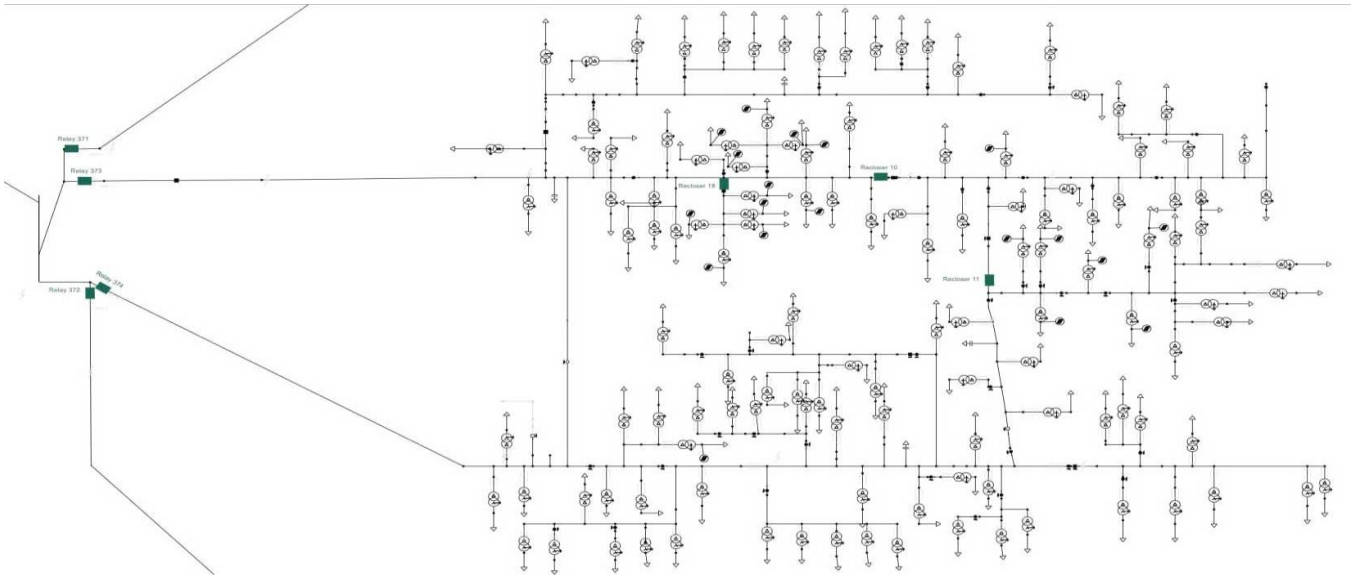


Figure 1: E18.8 Huong Khe distribution network with rooftop PV using PSS® SINCAL

610 km of low-voltage lines. The 110 kV E18.8 Huong Khe substation supplies electricity to remote and border areas, where power line corridors traverse mountainous forests and are highly susceptible to faults caused by falling trees. The electrical system in this region is currently facing three core technical challenges:

- ***Weak grid structure and high impedance:*** The use of AC-70 and AC-95 bare conductors on long feeder routes leads to very high line impedance (Z_L). Consequently, short-circuit current levels at the end of the feeders are significantly attenuated, making it difficult to establish effective protection trip thresholds.
- ***Conflict in protection coordination strategy:*** Fault current contributions from inverters increase the current flowing through lateral fuses, causing the fuse to blow before the upstream Recloser can complete its fast-tripping cycle, thereby completely undermining the "fuse-saving" strategy. Furthermore, the low short-circuit current characteristics of inverters, combined with fault current dilution from the system, create a risk that the head-end relay may fail to trip during faults occurring at the end of the line.

To address the aforementioned issues, this paper presents a comprehensive quantitative assessment of the impacts of rooftop PV on the protection system of the Huong Khe grid using the specialized simulation software ***PSS® SINCAL***. The study proposes and validates the effectiveness of two core groups of technical solutions: (i) Transitioning to directional overcurrent protection (***67/67N***) to distinguish between fault currents and reverse load currents ; and (ii) Establishing an ***adaptive protection coordination*** strategy based on the optimization of Recloser/Fuse Time-Current Characteristic (TCC) curves, combined with On-Load Tap Changer (OLTC) adjustments to control voltage levels under variable operating scenarios.

2. System model and simulation methodology

To quantitatively evaluate the impacts of rooftop PV on the protection system, this paper develops a realistic model of the Huong Khe district power grid using the **Siemens PSS® SINCAL** software platform. This industrial-standard simulation tool is capable of analyzing both steady-state and transient conditions, making it particularly suitable for distribution networks integrated with inverter-based resources.

The E18.8 Huong Khe distribution system is configured as a radial distribution network, featuring several lateral branches that supply power to various areas, as illustrated in Fig. 1.

The primary technical parameters of the model established in PSS® SINCAL are as follows:

- ***Grid Source:*** The 110/35/22kV Huong Khe substation (E18.8) is modeled as a Slack Bus with a short-circuit capacity S_{sc} = 2500 MVA and an X/R ratio of 18 at the 110kV side. The source transformer features a Y0/y0/d11 winding configuration, with the neutral point either solidly grounded or grounded through a low resistance to limit ground fault currents.
- ***Feeder:*** The network is configured in a radial structure, with the main trunk utilizing ACSR-120 and ACSR-95 bare conductors. Lateral branches utilize ACSR-50 and ACSR-35, with a total simulated line length of 45 km[5]. Line parameters (R, X, C) are sourced from the TCVN 5064:1994 standard library, accounting for resistance variations at an operating temperature of (75°C).
- ***Loads:*** The peak load (P_{load_max}) of the feeder is 6.5 MW with a power factor of cosφ = 0.9. Loads are modeled as distributed loads along the feeder to accurately reflect end-of-line voltage drops.
- ***PV Modeling:*** Within PSS® SINCAL, PV systems are represented using "DC Inverter" or "Static Generator" elements rather than synchronous generators to accurately reflect the non-linear characteristics of the power electronic inverters.
- ***Current Limiting Mode:*** Inverters are configured with a maximum fault current limit (I_{k_max}) restricted to 1.2 to 1.5 times the rated current (I_n), in compliance with the IEEE 1547-2018 standard. The relationship is defined as $I_{fault_PV} \leq 1.5 I_{n_PV}$.

This behavior differs fundamentally from rotating machines, which can contribute fault currents of 5 to 10 times their rated current (I_n). Consequently, traditional overcurrent relays face significant difficulties in detecting the current contributions from PV sources.

Current Control: The model is configured in Current Control Mode, injecting current into the grid with a phase angle locked to the voltage at the Point of Common Coupling (PCC). This operation continues unless a severe fault causes a significant Voltage Dip, which triggers the Fault Ride Through (FRT) mode.

At the substation, four main relays protect feeders 371–374, serving as both primary protection for the lines and backup protection for downstream devices. The Protection Coordination module in PSS® SINCAL enables automated verification of I>, I>>, and I>>> settings for radial networks, ensuring proper current and time selectivity. Three downstream reclosers (10, 11, 18) are configured for fast operation to isolate local faults, while the head-end relays have longer time delays to provide backup protection. Fig. 1 illustrates the network structure: feeders 371–374 are protected by main relays, while downstream branches are protected by reclosers. When a fault occurs on a branch, the recloser trips first; if the fault is not cleared, the main relay will subsequently disconnect the power source to safeguard the entire system.

According to the IEC 60255 standard and recloser setting guidelines, each TCC curve is defined by three primary parameters: the curve type (Standard Inverse - SI, Very Inverse - VI, or Extremely Inverse - EI), the pick-up current (Ipickup) and the Time Multiplier Setting (TMS) [9]. Table 1 presents the assumed settings for the four head-end relays and three reclosers on the E18.8 Huong Khe grid. The main relays utilize the SI curve with a high TMS to ensure delayed operation, whereas the reclosers employ the EI curve for fast tripping and the VI curve for slow tripping to coordinate with downstream fuses. The pick-up current is set at 1.5–2 times the maximum load current to prevent nuisance tripping caused by inrush currents or cold-load pickup.

In the table above, "Fast" refers to the rapid tripping operation designed for fuse saving, while "Slow" denotes the delayed tripping operation intended to coordinate with downstream fuses. The 1F-2S-Lockout reclosing sequence (one fast shot, two slow shots, followed by lockout) is a standard configuration for overhead feeders.

The TCC plot is the primary tool for verifying selectivity and timing margins between protection devices. Fig. 2 displays the simulated log-log time-current plots for the relays and reclosers based on the settings provided in Table 1. The curves for the main relays are positioned above the recloser curves to establish a coordination time interval. The vertical distance between these curves represents the Coordination Time Interval (CTI); according to IEEE C37.230 recommendations, this interval should be maintained at a minimum of 0.2–0.3 seconds to account for circuit breaker clearing time and relay measurement errors.

On the TCC plot, the dash-dot curves represent the recloser's fast-tripping cycle (EI), while the dotted curves indicate the slow-tripping cycle (VI). The solid lines represent the SI characteristics of the head-end relays. For any given fault current level, the recloser consistently operates faster than the main relay, ensuring proper protection sequencing and backup coordination. Each recloser is programmed with a 1F-2S reclosing sequence, consisting of one fast shot and two slow shots, with a dead time sufficiently long to allow for arc de-ionization. A dead time that is too short (0.3–0.5s) may result in reclosing onto a persistent arc, whereas an excessively long dead time (15–30s) increases the duration of the power outage. The optimal value depends on regional conditions and the transient fault ratio. Protection coordination must maintain a CTI ≥ 0.2 s to account for equipment tolerances. When simulating with PSS® SINCAL, the Protection Security Assessment (PSA) tool enables a system-wide fault sweep to automatically determine the pickup, inception, and clearing times for each devic.

Table 1: Protection Device Settings

Device	Curve Type	I_{pickup} (A)	CT ratios	TMS	Notes
Relay 371	SI	600	200/1	0.35	Main feeder protection
Relay 372	SI	600	200/1	0.4	Main feeder protection
Relay 373	SI	600	200/1	0.45	Main feeder protection
Relay 374	SI	600	200/1	0.5	Main feeder protection
Recloser 10 (Fast)	EI	500	100/1	0.05	Fast trip – branch
Recloser 10 (Slow)	VI	500		0.25	Slow trip – branch
Recloser 11 (Fast)	EI	400	100/1	0.05	Fast trip – branch
Recloser 11 (Slow)	VI	400		0.25	Slow trip – branch
Recloser 18 (Fast)	EI	350	100/1	0.05	Fast trip – branch
Recloser1 8 (Slow)	VI	350		0.25	Slow trip – branch

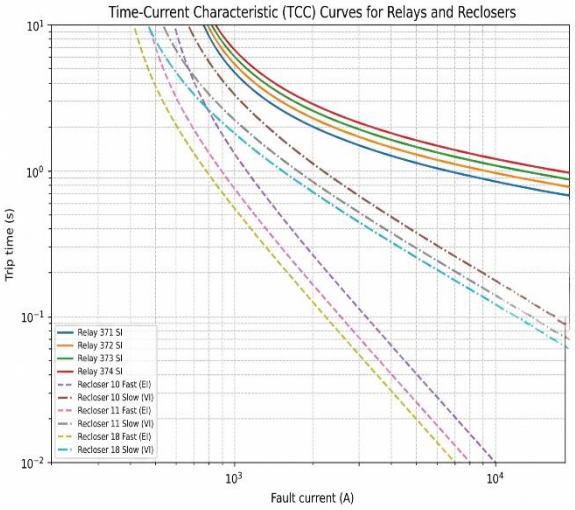


Figure 2: Simulated log-log time-current plots for the relays and reclosers based on the settings provided in Table 1.

Table 2: Scenarios of PV impacts on protection relay in Huong Khe E18.8 Distribution network

Scenario	Total PV capacity	Deployment Configuration	Fault Location Type	R10 Status (I_{SC} (A)/t(s))	R18 Status (I_{SC} (A)/t(s))	R11 Status (I_{SC}(A)/t(s))	Selectivity Outcome
1	4 MW (4×1 MW)	Downstream R18	Upstream/ Near-Fault	0/-	112.47A/-	0/-	Maintained
2	7 MW (4×1.75 MW)	Downstream R18	Fault Upstream of R18	0/-	179.95A/ 0.30 s	0/-	Loss
3	7 MW (4×1.75 MW)	Distributed across R18	Upstream / Near-Fault	0/-	89.98A/-	0/-	Maintained
4	7 MW (4×1.75 MW)	Downstream R11	Fault Upstream of R11	179.95/-	0/-	179.95A/ 0.30 s	Loss
5	7 MW (4×1.75 MW)	Distributed across R11	Upstream / Near-Fault	179.95/-	0/-	89.98A/-	Maintained
6	12 MW (12×1 MW)	Highly Distributed, R18 & R11	Upstream / Near-Fault	112.47/-	112.47A/-	112.47A/-	Maintained
7	21 MW (12×1.75 MW)	Highly Distributed, R18 & R11	Fault Upstream of R11 & R18	269.93/-	179.95A/ 0.30 s	179.95A/ 0.30 s	Severe Loss

3. Impact analysis and simulation results

The integration of DG, particularly rooftop PV, significantly alters the magnitude and direction of short-circuit currents, potentially leading to bidirectional fault currents through fuses. This phenomenon impacts the selectivity of the relay system, necessitating a reconfiguration of the protection settings to accommodate reverse power flows. When integrating PV sources into the E18.8 Huong Khe grid, it is essential to review and recalibrate I_{pickup} and TMS parameters, while simultaneously verifying the bidirectional tripping capabilities of relays and reclosers to maintain the minimum CTI. Simulation analyses using the Protection Security Assessment (PSA) module in PSS® SINCAL were conducted across various hypothetical fault scenarios. The evaluations focused on three critical aspects: protection sensitivity, time selectivity, and the risk of nuisance tripping (sympathetic tripping). To qualitatively evaluate the impact, seven scenarios of PV penetration has been investigated on the E18.8 Huong Khe distribution network.The result in Table 2 shows that, when PV units are concentrating downstream of a recloser, the short circuit contribution can flow in the reverse direction, causing protection devices to be sympathetic tripping as evaluated in Section 3.1 and 3.2..

3.1 Sympathetic tripping

Sympathetic tripping occurred when a protection device outside the actual faulted zone trips due to the additional contribution from the distributed PV sources. In terms of Huong Khe distribution network, there is a reverse current exceeding the pickup threshold of downstream recloser causing loss of selectivity.

The comparison between Scenario 2 and 3 is important. While both cases have the same total installed PV, in Scenario 2 when the PV concentrated downstream of Recloser 18, the reverse current passing through is approximately 179.95 A and causing a nuisance trip occurred within 0.30 s. Similarly, when comparing Scenario 4 and Scenario 5, Recloser 11 in scenario 4, which PV sources concentrated downstream is recorded an approximate 179.95 A reverse current flowing into it and operating prematurely.

However, in Scenario 5, the same total PV capacity distributed between upstream and downstream observed a reverse current flowing through Recloser 11 reduced to 89.98A and the relay remains stable. The most severe condition is observed in Scenario 7, where twelve PV units rated at 1.75 MW are distributed across two feeder branches. Under this high-penetration case, Recloser 11 and Recloser 18 both detect reverse currents of approximately 179.95 A depending on the fault location. These currents are sufficient to cause pickup of non-faulted or adjacent protective devices, demonstrating a high risk of protection security issue where multiple devices experience abnormal current directions and magnitudes.

3.2 Protection blinding tendency

In the simulated Huong Khe network, a complete protection blinding event, meaning a failure of the main relay to detect a fault, is not clearly observed in the seven three-phase short-circuit scenarios. The main feeder relays still receive fault currents above their pickup thresholds in most simulated cases. However, the results show the beginning of a blinding tendency because PV changes the current distribution across the feeder. For example, when PV sources are installed downstream of Recloser 18, reverse current appears through this device. In Scenario 1, with four PV units

Received: 23 January 2026; Revised: 5 May 2026; Accepted: 7 June 2026.

rated at 1 MW, the reverse current at Recloser 18 is approximately 112.47 A, but this value remains below the relay operating threshold, so no tripping is initiated. This indicates that, at low PV penetration, the protection scheme remains secure. Nevertheless, when the PV capacity increases, the current measured by different relays is no longer consistent with the original radial coordination assumption. The fault is no longer supplied only from the upstream grid; it is also supplied by downstream PV units. Therefore, the upstream relay may not fully "see" the actual total fault current at the fault point. This condition can reduce relay sensitivity, especially for remote faults, high-impedance faults, or lower short-circuit levels. Although the present three-phase fault simulations do not show complete relay failure, they confirm that high PV penetration can weaken the reliability margin of conventional overcurrent protection.

3.3 Fuse-Recloser Miscoordination

The "Fuse Saving" strategy is widely implemented on the Huong Khe grid, with reclosers installed at the head of the main feeder and fuses protecting the lateral branches. For transient faults, the recloser operates on its fast curve and recloses without blowing the fuse; for permanent faults, it switches to a delayed mode to allow the branch fuse to isolate the fault. However, when PV sources are connected to the branch, the current distribution changes: the recloser detects a reduced current, while the fuse sees the total current from both the grid and the PV source. This can cause the fuse to blow prematurely, leading to a loss of protection coordination.

Simulation results:

Case 1: Without PV Integration: The current passing through the fuse and the recloser is equal (I_{fuse}=I_{rec}). The recloser operates on its fast curve within 0.1 s, which is positioned below the fuse's minimum melt curve; therefore, the fuse does not blow. For permanent faults, the recloser switches to its delayed curve, allowing the fuse to clear the fault.

Case 2: With PV Integration (3 MW): The fuse is subjected to a higher current (I_{fuse}=I_{grid}+I_{PV}), while the recloser detects a reduced or constant current. The operating point shifts toward the high-current region, causing the fuse's melting curve to fall below the recloser's fast curve. Consequently, the fuse blows prematurely, converting a transient fault into a permanent outage.

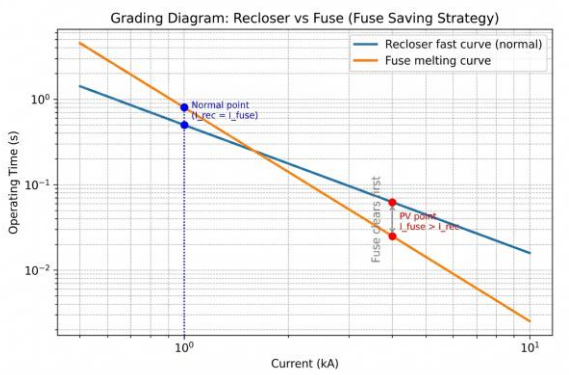


Figure 3: The time-current characteristic (TCC) of the recloser's fast curve and the fuse's minimum melting curve.

The time-current characteristic (TCC) diagram (grading diagram) illustrates the coordination between the recloser's fast curve and the fuse's minimum melting curve (Fig. 3). The blue dot represents the normal operating mode (I_{rec}=I_{fuse}), where the recloser trips first to clear the fault. The red dot represents the PV-integrated scenario, where I_{fuse}>I_{rec}, causing the fuse to melt prematurely before the recloser can act.

4. Technical solutions and recommendations

4.1 Implementation of Directional Overcurrent Protection (ANSI 67/67N)

The results from Table 2 illustrate that the integration of solar PV into the distribution network not only provides renewable energy benefits but also introduces several challenges to the relay protection system. One of the most critical issues is the occurrence of non-selective relay operation, where protection devices trip outside of their designated zones. This phenomenon mainly arises from the increased short-circuit current at fault locations due to additional contributions from PV units. In certain scenarios, faults are sustained because the relay pickup settings are lower than the actual fault current levels influenced by PV generation.

To overcome this challenge, a practical solution is to replace the conventional overcurrent protection with DOCR. By incorporating directional elements, the relay gains the ability to distinguish whether fault currents are flowing from the main grid source or from PV sources. From the result in Table 2. The result presented in Table 3 indicates that the relay only operates when faults occur within its intended protection zone, while preventing unnecessary or incorrect coordination with neighboring protection devices.

Table 3: Summary of Scenario 2,4,7 after applying DOCR

Scenario	Misoperation Device	Before DOCR status (I_{SC} (A)/t(s))	After DOCR status (I_{SC} (A)/t(s))	Selectivity gain
2	Recloser 18 (R18)	179.75A/0.3s	179.95A/Pickup	Restored
4	Recloser 11 (R11)	179.95A/0.3s	179.95A/Pickup	Restored
7	R18 and R11	179.95A/0.3s	179.95A/Pickup	Restored

After applying the DOCR settings for the relays and reclosers for loss of selectivity scenario, the overall protection system demonstrates selective operation in accordance with the intended coordination scheme. Specifically, each protective device responds only to faults within its designated protection zone while maintaining proper coordination with upstream and downstream devices. This configuration ensures that fault isolation is performed rapidly and accurately without unnecessary tripping of adjacent equipment.

4.2 Adaptive Protection Strategy

Due to the fluctuations in PV output driven by solar irradiance, fixed protection settings are no longer adequate.

This study proposes utilizing the "Protection Variants" feature in PSS® SINCAL to implement two proposed setting groups:

- Group 1 (High PV, 06:00–17:00): Increase I_{pickup} (from 300 A to 450 A), enable directional logic, and reduce the time dial to compensate for the "relay blinding" effect.
- Group 2 (Low PV, Off-peak): Decrease I_{pickup} to approx 300 A and revert to traditional overcurrent characteristics to maximize protection sensitivity.

Due to the time-varying nature of PV power output, a single set of protection settings can lead to either insufficient sensitivity during high PV generation or excessive sensitivity during low PV periods. Modern digital relays support multiple setting groups and automatic switching via SCADA or a real-time clock (RTC).

Simulation results (Fig. 4) demonstrate that when PV peaks at ~6 MW, the current at R1 remains below 450 A, allowing Group 1 to prevent nuisance tripping. At night, with the current at R1 exceeding 300 A, Group 2 enhances sensitivity. The SCADA system automatically toggles between these two modes based on a pre-defined schedule.

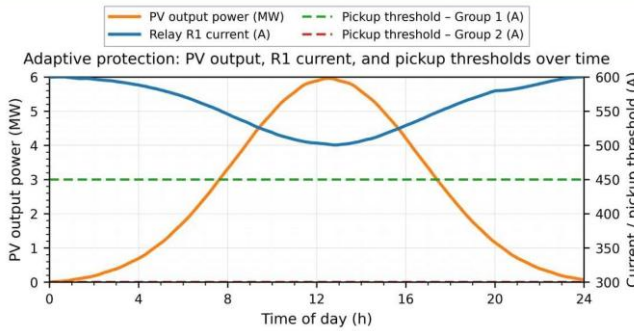


Figure 4: PV Power output and current through relay R1 during a typical day

4.3 Restoration of Fuse-Recloser Coordination

The fuse-saving strategy allows the recloser to perform a fast trip for transient faults to protect the downstream fuse. However, when rooftop solar PV is integrated into the branch, the fuse current increases due to the added PV infeed, while the recloser current decreases. According to SEL, this violates the fundamental assumption that both devices detect the same fault current, causing the fuse to melt before the recloser can operate and leading to a loss of protection coordination.

Solution 1: Recloser Curve Adjustment

To ensure the recloser always operates before the fuse in high-current regions with PV integration, the study proposes switching from Standard/Normal Inverse curves to EI or VI curves for the fast-tripping cycle. According to recloser setting guidelines, the EI curve possesses the steepest slope and the fastest response; when the current increases from 2 times to 4 times the pickup threshold, the operating time decreases 8–10 times faster than the standard curve. This slope closely mimics the fuse's melting characteristic, making EI particularly suitable for fuse-saving coordination. Meanwhile, the VI curve offers a moderate slope, maintaining a stable coordination margin even when the short-circuit current varies across a wide range.

PSS® SINCAL simulations with 3 MW of solar PV demonstrate that switching the recloser's fast curve from NI to EI reduces the tripping time by approximately 40–50% at current levels influenced by PV infeed. At fault currents ranging from 8–10 kA, the recloser trips ~0.15 s ahead of the fuse, maintaining a minimum CTI of 0.3 s as recommended by IEEE C37.230. Consequently, the PV-induced miscoordination is eliminated; the fuse remains intact, and the recloser effectively protects the lateral branch.

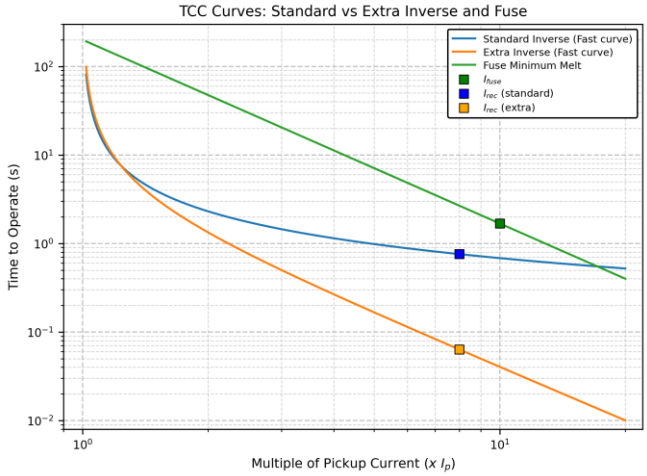


Figure 5: The steep slope of the EI curve enables the recloser to trip faster in high-current regions where $I_{fuse} > I_{rec}$.

Solution 2: Transitioning to the "Fuse-Clearing" Strategy

On lateral branches with high PV penetration (where PV capacity > 50% of rated load), the fault current contribution from PV is so substantial compared to the grid current that even a recloser with an EI curve struggles to operate before the fuse. In such cases, this study proposes transitioning to a fuse-clearing strategy, allowing the fuse to blow first while the recloser acts as a backup device.

According to industry guidelines, the primary advantage of fuse-clearing is its ability to localize the fault within the lateral branch, preventing a momentary outage for the entire feeder. The main drawback is the operational cost of replacing fuses. Notably, many North American utilities have shifted from fuse-saving to fuse-clearing due to customer sensitivity to momentary interruptions and power quality indices such as MAIFI.

When implementing fuse-clearing in PSS® SINCAL, the recloser is configured to bypass the instantaneous trip (fast) cycles, retaining only the delayed trip cycles. For a fault on a branch with DG, the fuse melts immediately to isolate both the fault and the PV source. Consequently, the recloser does not close back onto an active islanded source, effectively preventing unintentional islanding. Simulations indicate that coordination margins are maintained; although fuse replacement is required, the outage scope is significantly reduced, thereby improving the SAIDI index.

5. Conclusion

This study provides a comprehensive assessment of the impact of rooftop solar PV integration on the relay protection system of the Huong Khe distribution network in Ha Tinh province. Through detailed modeling and simulation using PSS® SINCAL, the study introduced different PV penetration scenarios to evaluate changes in fault current magnitude, direction and protection selectivity. The result shows that as rooftop PV penetration increases, the fault current contribution from inverters leads to both reduced short circuit current levels at the substation and reverse power flow along the feeders which affects the selectivity and reliability of

unidirectional protection relay. By implementing directional elements in overcurrent relays (67/67N), real time adaptive setting strategies and optimizing Recloser - Fuse coordination, the reliability and stability of the distribution network are significantly enhanced, particularly in the grid with integrated photovoltaic (PV) source where reverse current flow may occur. Although the results have demonstrated how high PV penetration affects protection relay, several limitations should be acknowledged. This study mainly use overcurrent protections, which is required for further investigation on different function of protection relay. Moreover, this work is assessed on simulation, while applying in real distribution work, there are more problems to be concerned about such as the economical feasibility when applying these solutions, and PV system represented in this work is the simplified inverter, real life PV system required further evaluation on control strategies, grid code response and dynamic ride through behavior.

Future work should include experimental or hardware-in-the-loop validation of the proposed protection strategies, detailed optimization of relay coordination margins under variable PV output, and analysing the economic possibility of upgrading directional and adaptive protection systems.

Acknowledgement

This research is funded by Electricity of Vietnam (EVN).

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