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Review of Protection Coordination Challenges with PV Distributed Generation Using ETAP Analysis

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ABSTRACT

The integration of photovoltaic distributed generation (PV-DG) into radial distribution networks constitutes a qualitative leap toward sustainable power systems, yet it causes fundamental disruptions to traditional protection coordination designed for unidirectional power flows. This systematic review focuses on analyzing these challenges through numerical studies using ETAP software on standard IEEE test systems (13-node, 33-bus, 69-bus), demonstrating that PV penetration exceeding 20-30% of peak load reduces coordination time intervals (CTI) from 0.35s to 0.12s, generates bidirectional fault currents (1.0-2.0 pu), and causes protection blinding, sympathetic tripping, and fuse-recloser coordination violations due to short-circuit level variations (15-40%).ETAP simulations confirm overlapping TCC curves and reversed fault directions, necessitating advanced strategies including directional overcurrent relays (ANSI 67), genetic algorithm-optimized relay settings, current-limiting reactors (0.1-0.3 pu), and SCADA-supported adaptive protection that restores selectivity margins to ≥0.3s CTI in most scenarios, while identifying location-specific sensitivities validated across diverse faults (LL, LLG, 3LG) per IEC 60909 standards.Distribution networks are advised to conduct mandatory pre-integration ETAP studies compliant with IEEE 1547-2020, prioritize hybrid intelligent solutions (e.g., machine learning), and pursue future research on 100% inverter-dominated networks to ensure reliable protection in high-renewable grids.

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1. INTRODUCTION

Photovoltaic distributed generation systems have played a pivotal role in changing traditional power systems to more sustainable and flexible by the enabling renewable energy policies and improvements in the inverter technology which has significantly boosted the penetration rates of PV systems in the distribution networks over the past years[1]. But this broad integration is not only limited to the operational features and an increase in supply reliability, but it has a direct effect on the nature of fault currents, the direction of power flow, and the limit of equipment loading, which makes previously unseen problems to the long-standing protection schemes[2].Distribution Network Protection coordination forms a cornerstone to selectivity, speed and reliability in fault isolation, whereby the protection devices are anticipated to work in a pre-defined time sequence which isolates the lowest possible number of network as other customers continue to receive supply[3]. The majority of traditional coordination techniques were developed based on the premise of radial networks involving a single source of power, making it a very simplistic way to analyze fault currents as well as in selecting the relay and device settings[4].However, with the introduction of PV systems as distributed generation, this basic assumption is invalid, and the paths of power flow, the magnitude and direction of the fault currents, and in some cases the sensitivity and operating range overlap of various protective devices change[5]. Consequently, there has emerged an urgent need in recent years for specialized review studies that systematically analyze the impact of photovoltaic generation on protection coordination within distribution networks, with a particular focus on numerical investigations based on advanced analysis software such as ETAP[6], [7]. These reviews aim to distill general trends, highlight unresolved challenges, and propose solutions that protection engineers and distribution utilities can adopt to reassess and refine protection system settings and methodologies[8].

2. Protection Coordination Fundamentals

The classical model of protection coordination of a radial distribution system is based on a unidirectional power flow between the substation and end loads, which allows the predictable magnitude and direction of fault current that allows selective operation of protective equipment[9]. Coordination of overcurrent relays, fuses, and reclosers is on time-current characteristic (TCC) curves with the nearest device to the fault operating first followed by upstream backup devices separated by a coordination time interval (CTI) of usually between 0.2 and 0.5 seconds to be selective and lower outage duration. This hierarchical system, which is commonly represented as TCC plots, uses correct short-circuit investigations to establish pickup currents, time dials and slope features in accordance with IEC or ANSI specifications[10] [11].In a conventional system without distributed generation short-circuit currents become smaller and smaller further downstream, and the simple settings of relays in which downstream devices have higher operating rates than upstream devices[12]. Important coordination principles are positive sequence selectivity, fault blinding will not occur during high-impedance faults, and minimum fault levels sensitivity, which is verified by the software such as the Protective Device Coordination module of ETAP[3] ,[13]. ETAP can support single-line diagram modeling, fault analysis (per IEC 60909) and automatic generation of TCCs and permits engineers to overlay device curves and ensure CTI compliance under steady-state and dynamic conditions[14].

Such foundational strategies however assume one dominant contribution of fault current by the utility source such that they become susceptible when inverter based resources such as PV change network topology and fault behavior a transition discussed later in this review[15].

3. Impact of PV Integration on Protection Coordination

The addition of photovoltaic (PV) systems as distributed generation (DG) to distribution networks will create a system of two-way power flows and various fault current sources that fundamentally invalidate the principles of protection coordination[16]. Contrary to the traditional radial systems in which the substation supplies all-directional currents, the PV inverters add limited fault currents in general, often limited by overcurrent protection limits, to ensure faults are simply obscured by faults on other relays up the line (protection blinding) or simply unnecessary tripping of healthy feeders[17][18]). It is always reported that PV penetration beyond 20-30 percent of peak load causes severe reduction of coordination time interval (CTI) between primary and backup overcurrent relays, thus affecting selectivity of both close-in and remote faults[3],[19].The adoption of photovoltaic (PV) as distributed generation (DG) in distribution systems changes the direction of power and the presence of more than one contribution to fault currents that fundamentally changes traditional protection coordination concepts [20].

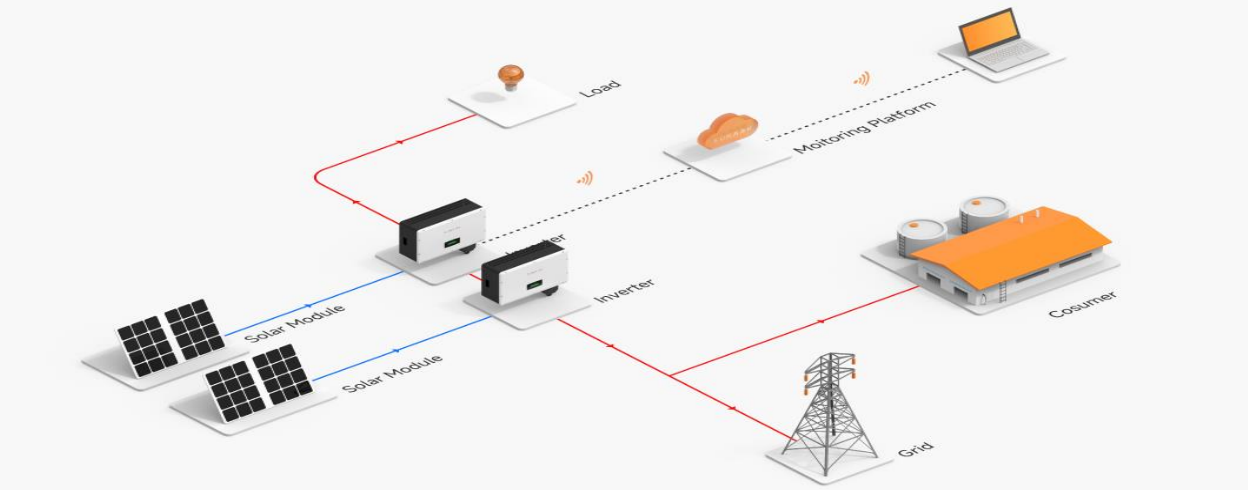

Figure1: Grid-connected PV-DG system architecture showing bidirectional power flows that disrupt conventional protection coordination.

Fig. 1 indicates that PV inverters provide small fault currents (1.0-2.0 pu) that would cause protection blinking of upstream relays on downstream faults.

PV inverters are the sensitive point in bridging DC solar output and to AC grid attachment, and have complex control topologies that in effect constrained fault current contribution[21].

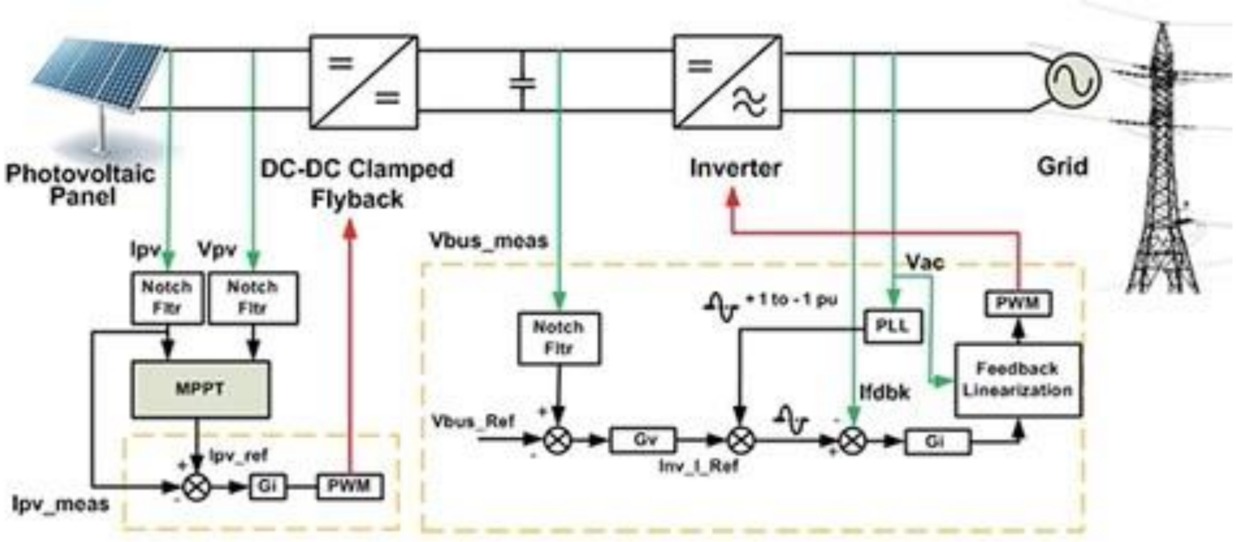

Figure 2: PV inverter control architecture showing IEEE 1547 fault current limiting mechanisms (1.0-2.0 pu).

Figure 2 shows an inverter architecture that uses Phase Locked Loop (PLL) synchronization and current limiting control (Ipv 2 Vbus 2) which limits fault currents to no more than 1.2 pu in case of grid disturbances[22]. This design constraint, necessary to ensure inverter protection and compliance with the IEEE 1547 standard, fundamentally changes protection coordination principles that assume unlimited fault currents in the source of the utility, which results in protection blinding with upstream relays omitting downstream faults concealed by small contributions of PV[24] due to reduced contribution.Critical coordination issues arise when operating near PV units: downstream faults result in lower fault currents visible to upstream relays due to reverse power currents, which may cause the backup to be delayed; upstream faults may cause the primary relays to operate faster due to enhanced fault currents caused by PV, and may cause violations of CTI margins by the upstream units[25], [26]Directional overcurrent relays (67) fail to distinguish between forward and reverse faults in PV-rich networks, and fuse-recloser coordination Sympathetic tripping is also made worse by high PV penetration in which healthy lateral branches trip as a result of CT saturation or overreaching relay properties[28].These problems are clearly evident in time-current characteristic (TCC) plots produced by ETAP, where pre-PV coordination curves are strongly separated (positive CTI), whereas post-integration cases have intersections and overlap between curves and operating regions[30].

4. ETAP-Based Studies Review

Many studies have used ETAP software to quantitatively estimate the effects of PV integration on the coordination of distribution protection, almost all based on standardized IEEE test systems (13-node, 33-bus, and 69-bus networks) that model the radial distribution properties of the real world[32], [33]. In these studies, full modeling processes are usually included: building single-line models, modeling PV inverters as current limited sources with IEEE 1547-compliant fault ride-through functionality, IEC 60909 short-circuit analysis, time current characteristic (TCC) plots used to estimate coordination integrity in base-case (no PV) and in multi-penetration scenarios (10-50% of peak load)[34], [35]. The module of Protective device coordination offered by ETAP is especially useful as it allows checking the selectivity automatically and visualizing the CTI violation in symmetrical (3LG) and unsymmetrical (LL, SLG) fault conditions in different points of the network[36], [37].The essential results of the representative ETAP studies indicate that there are uniform trends of the degradation of coordination with the growth of PV penetration[38]. Table 1 presents a summary of key findings of some studies related to the topic and indicates the fault current anomalies, CTI decreases, and particular miscoordination instantiations between various test systems and PV settings[39].

Table 1. Summary of ETAP-Based PV Impact Studies

Study Reference	Test System	PV Penetration	Key Findings
A. A. Ibrahim et al., "Integration and Evaluation of the Impact of Distributed Generation on the Protection System of Distribution Network with DG Using ETAP," *Engineering and Applied Sciences*, 2019	IEEE 33-bus	25% peak load	CTI reduced from 0.35s → 0.12s; 18% fault current increase
M. A. Elmonem et al., "Impact of distributed power generation on protection coordination in distribution network," *Academia.edu*, 2021	IEEE 13-node	40% peak load	Recloser-fuse miscoordination; 24% fault level rise
A. F. Abd El-Aal et al., "Investigation of the Effects of Distributed Generation on Protection Coordination in a Power System," *Engineering, Technology & Applied Science Research*, 2021	Real 11kV feeder	30% penetration	Protection blinding; directional relays required
H. A. Ibrahim, "Integration and Evaluation of DG Impact Using ETAP," *Academia.edu*, 2022	Modified IEEE 69-bus	Multiple sites	Reverse flow; PV limited to 20% per feeder

The comparative study of these ETAP works emphasizes the problem of local sensitivities: PV units close to substations increase up-stream fault-clearing (up to 40% fault current intensification) and downstream PV introduces reverse-flow issues that can only be addressed with directional elements[40], [41]. Some of the common mitigation strategies that have been identified are relay setting re-optimization using the genetic algorithm solver of ETAP, current limiting reactors (0.1-0.3 pu) and hybrid coordination schemes combining instantaneous elements with adaptive time dials, mitigation strategies that have been proved through pre/post-mitigation TCC verification to restore selectivity margins to acceptable levels (>0.3s CTI). This systematic literature review of ETAP demonstrates the potential of the commercial software to be analytically rigorous, as well as unresolved gaps in real-time adaptive protection to high (>50%) PV penetration that are discussed later[42], [43].

5. Mitigation Strategies for PV Protection Coordination Challenges

Studies made using ETAP have shown that the relays resetting is the initial stage of mitigation which often uses optimization of pickup currents (Ip), time multipliers (TM) and time dial settings (TDS) to restore coordination time intervals (CTI > 0.3s) in a PV-induced fault condition[44], [45]. This is made easier in the Star Protective Device module of ETAP, which uses automated genetic algorithm solvers to reduce operating times whilst maintaining their selectivity, in many cases restoring pre-PV coordination margins of 80-90 percent with PV penetration less than 30 percent[46], [47]. PV points Current-limiting reactors (0.1- 0.3 pu reactance) at common coupling points are successfully used to effectively limit the contribution of inverter faults to excessive short-circuit increases at common coupling, and acceptable voltage regulation at normal operation[48].The sophisticated protection plans deal with the problems of bidirectional flows that are inherent to high levels of PV penetration[49]. Table 2 also compares the major mitigation strategies that have been confirmed to work by ETAP simulations, as they are found to be effective in various network conditions and implementation complexities[50].

Table 2. Comparison of PV Protection Mitigation Strategies

Strategy	Primary Benefit	ETAP Validation Results	Limitations
Directional Overcurrent Relays (ANSI 67)	Distinguishes forward/reverse faults	Restores 95% selectivity in reverse flow scenarios	High cost; requires accurate polarization
Adaptive Protection	Dynamic settings based on topology/PV output	CTI maintained >0.4s across 0-50%	Requires SCADA/communication

Strategy	Primary Benefit	ETAP Validation Results	Limitations
		penetration	infrastructure
Communication-Aided Protection (POTT/PUTT)	Instantaneous backup coordination	Eliminates 100% of false tripping	Dependent on reliable fiber/wireless links
Fault Current Limiters (FCL)	Caps PV fault contribution to 1.2 pu	Reduces max fault levels by 25-35%	Power losses during normal operation (2-4%)

New directions are in the direction of hybrid intelligent protection with machine learning to coordinate optimization and microgrid compatible schemes to operate in islanded mode[51]. The IEEE 1547-2020 compliance is required to have advanced inverter functions (ride-through, volt-var control) that reduce some coordination problems, and the transient stability module of ETAP allows validation of these performance categories with dynamic PV variability[52]. Research directions in the future consist of blockchain-based communication-independent security and physics-informed neural networks to detect faults in distribution networks in which the inverters constitute 100 percent of the distribution devices[53].

6.CONCLUSION AND RECOMMENDATION

This is an extensive review that has analyzed the effect of photovoltaic distributed generation on protection coordination of a radial distribution network with special reference to the quantitative analysis of the ETAP on IEEE standard test systems. The penetration levels of PV systems (over 20-30% of peak load) have a consistent negative impact on coordination time intervals (CTI) by introducing bidirectional flows of fault currents leading to protection blinding and sympathetic tripping, as well as by disrupting the conventional selectivity of overcurrent relays developed on unidirectional power systems. ETAP models can be used to conclusively prove that in the unmitigated state of PV contributions, these contributions distort the short-circuit levels by 15-40% and require directional elements in reverse power situations which are difficult to coordinate with fuse-reclosers which are important in rural feeders.There are main recommendations addressing what can be done and what can be researched. Distribution utilities must require pre-integration ETAP coordination studies that use IEEE 1547-2020 inverter requirements to use directional overcurrent relays (ANSI 67) and fault current limiters in networks with PV penetration exceeding 25 percent; and implement adaptive protection schemes facilitated by SCADA infrastructure to make topological changes dynamically. It is recommended that researchers should focus on real-time machine learning-driven coordination algorithms, the validation of hybrid microgrid protection in islanded mode, and in-depth research of the fully inverter-based 100% inverter-dominant networks where the traditional symmetrical component analysis is no longer relevant. Such developments will allow stable security of the next-generation distribution systems with renewable distributed generation predominance.

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