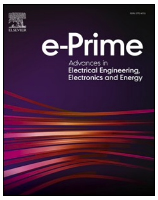
e-Prime - Advances in Electrical Engineering, Electronics and Energy 2 (2022) 100080

Contents lists available at ScienceDirect

e-Prime - Advances in Electrical Engineering, Electronics and Energy

journal homepage: www.elsevier.com/locate/prime



Modern trends in power system protection for distribution grid with high DER penetration

Rishabh Jain[a,1,*], Yaswanth Nag Velaga[a,2], Kumaraguru Prabakar[a,3], Murali Baggu[a], Kevin Schneider[b]

[a] National Renewable Energy Laboratory, Golden, CO - 80401, USA
[b] Pacific Northwest National Laboratory, Seattle, WA, USA

ARTICLE INFO

Keywords:
Power system protection
Distributed energy resources
IEEE 1547
Fault location isolation and service restoration
Microgrids
Modeling
Quasi steady state

ABSTRACT

Increasing renewable penetration and grid modernization initiatives are having a significant impact on the operating and fault characteristics of distribution systems. As a result, protection systems need to account for the changing nuances in systems transient response to disturbances and the resulting voltage and/or current to ensure safe and reliable operation. The approaches for modeling and analyzing power systems also need to evolve accordingly, based on the choice of protection system. Therefore, this paper reviews the state-of-the-art and evolving approaches for the protection of future energy systems. The approaches are categorized based on operating principles and variations in the underlying mathematical formulation – to present a comprehensive overview on fault detection and recommendations for future research. The evolving nature of distribution systems, interconnection requirements and standards, and system automation is also discussed in view of the need for higher fidelity models and/or limitations from current approaches. Finally, the protection algorhithms are compared based on their associated challenges with reliability, protection, and communication/design needs.

1. Introduction

Distributed energy resources (DERs) offer technical and economic advantages to both power system utilities and utility customers [1]. Originally, these systems operated radially to carry power from the substation to the end users. However, increasing penetration of inverter-based DERs (IBDERs) is significantly changing the control strategies and operation of modern power systems [2–4]. IBDERs such as solar photovoltaics (PV), battery energy storage, and fuel cells are a major fraction of DERs being integrated. There is ongoing research in different domains to address challenges introduced by the changes in distribution systems – including islanding detection, microgrid formation, transactive energy markets, power converters, fault detection, improving power system quality, declining system inertia, and network reconfiguration [5,6]. Systems with high DER penetration are developing their advanced metering infrastructure (AMI); and an increasing reliance on advanced distribution management systems (ADMS) to ensure the reliability of complex networks during normal operations and resiliency during extreme events [7]. The influence of these investments in phasor measurement unit (PMU) based wide-area monitoring [8], protection, and control systems can be seen in the research trends and resources available to grid operators [9,10]. The evolution is also introducing the need for a networking layer to allow interaction between cyber-physical assets for efficient secondary and tertiary controls for system management.

Fault location, isolation, and service restoration (FLISR), an important application of ADMS, performs three actions: locate, isolate the fault, and restore the power via a self-healing approach. It is important to maintain reliable protection during the faults [11]. Similar to other aspects of system operation, protection also needs to account for the intermittent DERs, changing network topology, smart volt-ampere reactive (VAR) compensation, generation loss, changing frequency, and other such challenges. Standards such as the IEEE 1547 aim at standardizing the interconnection of DERs to the distribution system.

---

* Corresponding author.
E-mail address: rishabh.jain@nrel.gov (R. Jain).
[1] ORCID(s): 0000-0001-5457-3929.
[2] ORCID(s): 000-0003-0555-5825.
[3] ORCID(s): 000-0001-5457-3929.

https://doi.org/10.1016/j.prime.2022.100080
Received 8 July 2022; Received in revised form 30 September 2022; Accepted 17 October 2022

While periodic revisions to the standards (e.g. IEEE 1548–2018) prepares the system for future challenges, they also add challenges to the legacy practices and operating principles. Further, FLISR uses the combination of protective relay status, and other smart devices to locate a fault. Fault location is a prerequisite and can have a significant impact on all subsequent actions performed by the FLISR application. After locating the fault, isolation action is performed by opening appropriate tie/sectionalizing switches. This in turn impacts the direction and magnitude of the current post-reconfiguration. Therefore, suitable protection and control strategies for different systems can vary significantly because of the changes in power system dynamics [12,13]. This evolving operating conditions also include reduced fault current contributions from the IBDERs ($\leq$ 2 p.u.) [14].

Service restoration is the final, integral part of the FLISR application that re-configures sections of the distribution system to stay grid-connected or as intentional islanded microgrids using DERs [15–17]. This ability can be a major asset for improving system resilience during outages [18]. But, IBDERs offer limited fault current given their design, control, and interconnection requirements [13] – which makes fault location more challenging. In the case of high impedance faults, the detection challenge is further exacerbated given the much smaller fault current. From FLISR's perspective, post-restoration island or grid resiliency is undermined if they can not be adequately protected. This will be discussed from the perspective of many promising approaches like adaptive overcurrent, differential current, and hybrid protection schemes. Similar to grid-connected operation, these challenges have also spurred strong research interest in analyzing the protection behavior from an islanded microgrid's perspective [18–20]. The impact of ride-through requirements, and the time-varying behavior of DERs in general remains a significant unknown.

The protection community is also seeing increased research in developing hybrid protection strategies using a combination of current and/or voltage measurements – almost exclusively for high-speed (subcycle) fault detection. Similar trends are being observed using data-driven methods - especially phasor measurement unit (PMU) based- and machine learning (ML-) approaches because of the available data and better computation abilities. We notice that the protection schemes will continue to evolve and may result in a mix of multiple approaches – to monitor specific system behavior and augment legacy protection.

This review is focused on comparing the operating principles, challenges, modeling needs, and, communication/data requirements. The intended outcome is to help readers understand the challenges specific to their protection algorithm of interest and/or evaluate the most suited algorithm given their system, modeling approaches and data/analysis. Essentially, reliable FLISR implementations will need to address these significant challenges - fault detection, location, restoration - all of which need reliable protection scheme [21]. Selective modeling and characterization of the changing power system - including IBDERs, fault response, bidirectional power flow, control objectives of DERs, and others - will be critical, and need to be factored into protection studies [20,22]. Fig. 1 presents a high-level overview of the protection schemes in view of the increasing DER penetration, the challenges considered, and the general direction of research. This figure presents the challenges as they become more prevalent given the level of DER penetration in a given system. Interestingly, very few papers focus on selective modeling strategies - tailored to the FLISR and interoperability challenges. Consecutively, this lack of discussion is also felt in reviews discussing the trends in protection research [23,24]. As summarized in Fig. 1, the available literature and reviews for low/medium DER penetration, and isolated operation as grid-connected or intentionally islanded are significant [23–25].

In this review paper, we present a much-needed review of the trends and needs in protection research by focusing on the outstanding approaches over the past 5–7 years. These discussions uniquely examine the assumptions in the literature reviewed, and possible blind spots – noting the trends of research in modeling system operation, and focusing on higher DER penetration and interoperability - like the ride-through requirements and CT saturation. We also contribute to the discussion on using hybrid approaches involving both voltage and current measurements, and the involved trade-offs. Finally, this review intends to serve as a broad-spectrum summary of the key phenomena of interest for system protection, modeling approaches, and underlying assumptions. Discussions on the trade-offs between improving the accuracy of the system modeling approaches and reliable protection analysis are among the contributions of this paper. While bad data and network intrusion can exacerbate the reliable operation of protection systems, their ideal operation will not resolve the above challenges. Therefore, the challenges due to the introduction of cyber-physical systems are not in the scope of this paper.

Section 2 highlights the key factors impacting the system operation and in turn the reliability of FLISR applications. The discussion presented in Section 2 facilitates the review presented in Section 3 – which presents the state of the art in different approaches for protection in distribution systems with high DER penetrations, associated problems, and potential future research opportunities. Section 4 elaborates on the review by discussing the associated modeling approaches, impact on protection studies, and offers insights including events of interest and modeling challenges. Finally, Section 5 concludes the review and

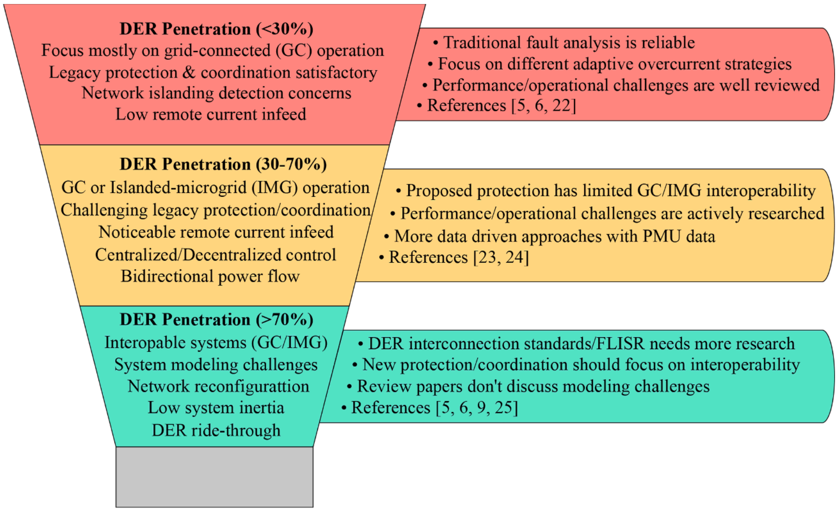


Fig. 1. Summary: Modern trends in Power System Protection with increasing penetration of DERs.

presents key findings. A crucial contribution of this review article is the exhaustive survey presented on distribution system protection topic.

2. Drivers for change in distribution system response due to high penetrations of DERs

Actively managing complex grid operations while achieving increased reliability and efficiency requires a wide variety of tools and grid visibility. The modern-day electric distribution systems are undergoing a paradigm shift toward bidirectional power flow with DERs located behind and in front of the meter. Utilities are facing different challenges on various fronts, from system studies to operations. This section discusses the main operating challenges affecting distribution system protection.

DMS is used by utilities for manual or autonomous control operations. This section discusses the effect of DERs on the important applications in DMS that contribute to the resilience and reliability of the system. Also, the proliferation of DERs in the distribution system can improve resilience through the formation of microgrids. The operation of a microgrid requires a better protection scheme to sustain generation and remove the faulted sections. This section also discusses the key challenges of microgrid protection and current research. Finally, increasing penetrations of DERs requires utilities to adopt their interconnection procedures for DERs and modify their grid operations. The IEEE 1547 interconnection standard defines DER criteria and the requirements related to the performance, operation, safety, and testing on the grid. The fault response requirements of IBDERs influenced by the new interconnection standard (IEEE 1547–2018) are altering the fundamental assumptions of traditional protection schemes, thereby presenting concerns for reliable operation. This section briefly discusses the requirements of IBDERs during a fault to highlight the need for accurate modeling of the system.

2.1. *Trends in FLISR application*

Many utilities are deploying a DMS as part of their distribution system modernization strategies. One of the most important applications of DMS that improves the resilience and reliability of the distribution system is FLISR. The FLISR application function operates by detecting, locating, and isolating the faulted section of the network to resume service to customers downstream of a fault through switching actions. Early FLISR applications were developed under the assumption of a single-source contribution to a fault. Multiple generation sources combined with low fault-current characteristics affect the traditional FLISR system to locate a fault. Fault location is paramount to the service restoration of the affected customers. For distribution system operators, any fault can trigger multiple alarms and failures. As a result, even when the fault has been isolated, identifying and repairing the faulted line sections for large distribution systems becomes an arduous task, especially during calamities inducing multiple failures [26].

Multiple researchers have proposed PMU-based measurements for easy fault location to aid service restoration. In [27], the authors present a single-ended fault location method based on pre- and post-fault impedance measurements. On the other hand, [26] locates the faults using a relationship matrix between multiple fault indicators deployed across the system and their status at any given time. In [28], the authors present a two-end fault location method using PMU measurements of voltage and current for a given line; however, a neural-network-based methodology for single-phase short-circuit location is presented in [29]. It models the feeder behavior during single-phase faults in terms of the fault distance, the network parameters, and the current and voltage measurements. Alternatively, [30] uses deep neural networks for fault location in transmission lines with parallel flexible AC transmission system (FACTS) devices. Finally, the authors in [31] use the time derivative of the quadrature and the zero-axis components of the fault current for fault detection and location in microgrids. Results show that different approaches proposed by the authors require more study on systems with a wide range of DER penetration levels.

2.2. *Interoperable distribution systems*

Microgrids are a group of interconnected loads and DERs within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid [32]. These microgrids can seamlessly transition between grid-connected and islanded modes. Reliable islanding detection will be imperative for adapting the protection settings to the system operation and detecting any inadvertent loss of the grid to protect personnel and equipment.

1. **Protection challenges in islanded microgrids:** As discussed in Section 1, microgrids often use IBDERs—known for characteristically lower fault current contribution (often several orders of magnitudes less than the utility grid). As a result, the distinction between the lowest possible fault current vs. the highest possible line load (including overload conditions) can be much lower for microgrids [33,34]. Further, given the DER composition within a microgrid, the available short-circuit current could be intermittent following the respective DERs (e.g., available solar insolation for PV plants). This scenario makes it difficult for protection schemes to distinguish between load and fault currents.
2. **Islanding detection:** Outages caused by faults or maintenance can lead to the formation of islands. To ensure personnel safety and protection of the connected equipment, unintentional islands must be detected and de-energized. On the other hand, detecting unscheduled intentional islands will allow a smooth transition to a stable island. As a result, there is significant work on passive and active islanding detection methods (IDMs). In [35], the authors present a scalable architecture to demonstrate a scheme for IDM, whereas [36] focuses on the operating guidelines for rate-of-change-of-frequency (ROCOF) relays. Passive IDMs might not be as reliable in non-detection zones (NDZ); e.g., during near-zero power exchange at the point of common coupling (PCC). Active protection methods are more reliable, but they are also more complicated, slower, and add additional interference to the grid [37]. The authors of [38] propose a decision tree learning method to address NDZs, whereas [39] present a hybrid approach depending on both active and passive methods to improve the reliability and speed of IDMs. Different IDMs have their advantages and disadvantages. It is imperative to select the proper IDM based on the grid requirements.

2.3. *IEEE 1547–2018 interconnection standard*

IEEE 1547–2018 might significantly affect the nature in which the IBDERs interact with the grid, especially during faults. With the increasing ride-through requirements, protection relays need to detect faults given the current contribution from IBDERs. The standard classifies DERs under categories I–III (Fig. 2) based on their ride-through requirements/capabilities and rating. The highest disturbance ride-through capabilities are reserved for Category III, shown in Fig. 2. Specific requirements from IEEE 1547–2018 that are of specific interest to the protection schemes are:

- Clause 6.2.2: IBDERs should trip within 2 s for single-phase trips. Traditional means of detection using zero-/negative-sequence current might be difficult because IBDERs tend to balance the system—needing more transfer-trip-based schemes.
- Clause 6.4.2.4: High-voltage ride-through requirement. The islanded sections can be subjected to load rejection overvoltage. The impact on ground fault overvoltage also needs to be determined similarly by the connected phase-to-ground load and the transformer for the IBDER.

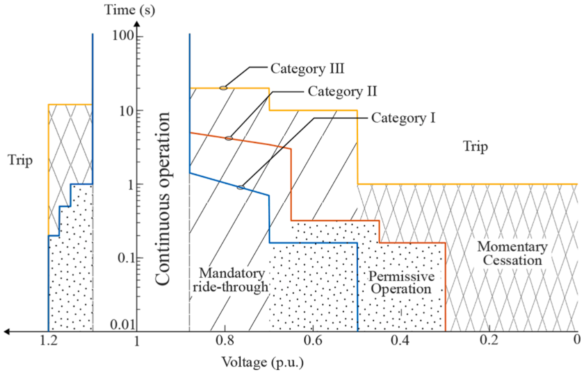


Fig. 2. DER voltage ride-through categories during a fault.

- Clause 6.4.2.7.1: During the post-disturbance period, DERs with voltage ride-through without dynamic voltage support is required to restore output to the pre-disturbance active current level within 0.4 s. As the DERs ramp up their output, maximum load current and fault current levels might change momentarily, negatively affecting the system protection. This is more prevalent in networks with high penetrations of DERs. Besides field testing, the impact can be assessed only by modeling the section of a network with an accurate model of IBDERs and their controls.

In other words, all fault ride-through (FRT) of an IBDER need to be coordinated with protection trip times which otherwise can cause stability issues. The fault contribution and interaction of the IBDERs will change with the new interconnection and ride-through requirements; therefore, a combination of system models is needed to accurately understand and anticipate the interaction between the IBDERs and the system under the new IEEE 1547–2018 guidelines. We see that the fundamental assumptions to design a protection scheme are no longer valid because of the fault contributions of IBDERs, including islanded operation. The next section discusses the different approaches to distribution protection with IBDERs are discussed.

3. Approaches for distribution system protection

As discussed previously, protection strategies need to accommodate the evolving nature of the power systems they need to protect. For example, legacy overcurrent schemes will not always work with multiple sources. For distribution systems, allowing bidirectional current flow, islanded operation, and low fault currents resulting from increasing penetrations of DERs are a few of these changes. Several protection schemes borrowed from transmission systems—such as directional, distance, impedance, differential, and transient protection schemes—are being implemented as potential solutions for distribution system protection. Adaptive setting-based schemes are being developed to accommodate the changes in system operation and behavior—e.g., microgrids. ML- and PMU-based novel protection schemes are also being developed for distribution systems. Although the state of the art in research on protection systems does not resolve these challenges, it provides valuable insights and approaches to build on. This section presents a comprehensive review of these trends and discusses additional opportunities where relevant. Fig. 3 provides the classification of all protection strategies based on the operating quantity from the literature. The current research on protection schemes is discussed in detail here and is shown in Fig. 3.

3.1. Overcurrent protection

Overcurrent-based approaches (Fig. 4) rely on a foundational principle: *The current from the sources distribute themselves inversely proportional to equivalent impedance to the source*. Under a fault, the given line will see an increase (given the fault impedance) in the current because of

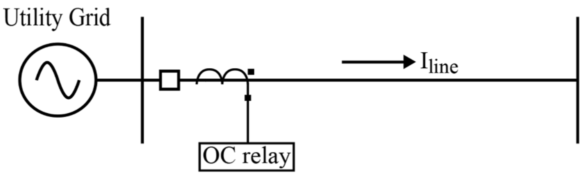


Fig. 4. Typical radial distribution system line with overcurrent protection.

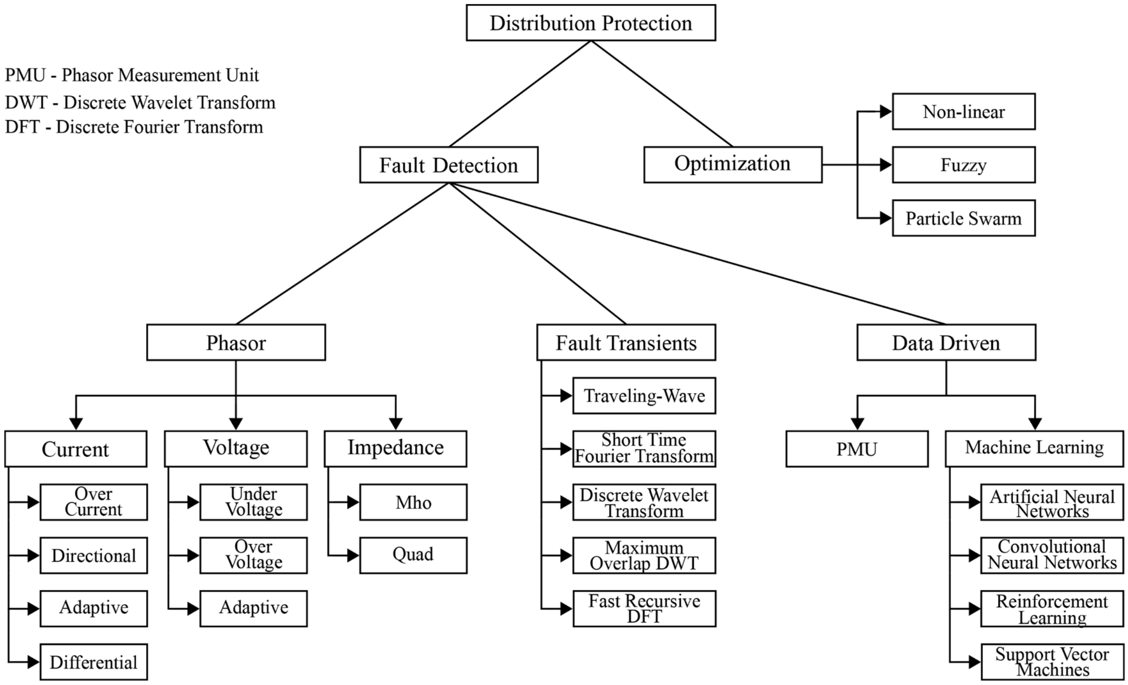


Fig. 3. Classification of the distribution system protection approaches based on the operating quantity.

the reduced impedance. Note that the current can also increase because of an increase in load. However, HIF can also cause a low fault current magnitude. HIF is referred to as a group of faults that have characteristically high fault impedance and therefore low fault current. This current magnitude is often close to the load current level, which is difficult to detect by traditional algorithms. The authors in [40] review the multiple approaches for HIF detection, including measurements (voltage, current, field intensity, and others), feature extraction (time, frequency, hybrid domains), and fault identification. Overcurrent relays are traditionally set to not operate during heavily loaded conditions but to reliably detect all the faults; therefore, it is important for protection engineers to accurately estimate the least fault current and the highest load current seen as the line current, I_{line}, by a given relay to set the relay pickup at an intermediate value. Fig. 5 demonstrates the principle of setting the overcurrent element. The pickup setting needs to be secure against the highest possible load current but sensitive enough to detect the lowest possible fault current.

As expected, multiple sources can reduce the I_{line} seen by a relay and lead to major protection issues, such as nuisance tripping and loss of coordination. Further, traditional overcurrent schemes involve backup from secondary devices using the time coordination principle; therefore, the primary and secondary devices need to coordinate their operation by using either a time delay or a communications-assisted mechanism. Relay coordination is an active area of research, and the use of optimization-based problem formulation is common in these problems [41]. With this perspective, the next few subsections present the different forms of overcurrent research in improving a relay's sensitivity to faults and selectivity to ensure coordination.

3.1.1. Directional supervision

Directional supervision adds security to any relay by ensuring that relays respond only to the fault in the given direction. Traditional directional supervision estimates the fault direction by current phase angle polarity relative to the reference voltage phasor (polarization element). These directional elements generally require both voltage and current measurements—and will need increased investment in voltage sensors for the relay. There are some current-only directional supervision [42] approaches as well. In [42], the pre-fault current, I_{pre}, is used as the polarization element. The post-fault current, I_{fault}, phasors are compared to the I_{pre} to determine whether the fault is upstream or downstream. Regardless of the choice of the directional element, *fault selectivity will be increasingly critical for reliable relay operation with modern distribution systems*.

Challenges: Although most upcoming research considers the directionality of the relay, there are shortcomings with the application in systems with high penetrations of DERs. Directional supervised relays can trip as the VAR output from the DERs increases. There is a need to secure the overcurrent element for all possible generation load angles [43]. DERs with broad VAR output could be subject to similar challenges. As a result, more research and better power system models are needed to review and improve the effectiveness of the state-of-the-art directional elements in the presence of DERs.

3.1.2. Adaptive protection with relay coordination

Fault current changes are based on increasing DER penetrations, active network management, and islanded mode of operation. Depending on the system operating conditions, topology, DER variability, mode of operation, and multiple other factors, the fault current contributions change. Therefore, adaptive protection schemes are being developed (Section 3.1.2) with a focus on the algorithms that can adapt the relay settings based on the changes in the system state. In the traditional adaptive overcurrent protection problem formulation, the adaptive settings are either recalculated and programmed into the relay upon significant change of state or as several group settings based on precomputed scenarios [44–46].

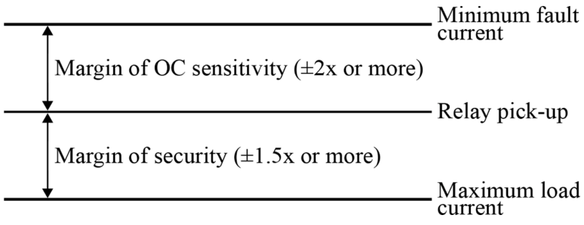


Fig. 5. Principle: Setting the overcurrent element.

To adapt the system actively with the same principles, the formulation assumes the form of an optimization problem with multiple constraints. These problems include coordination time between protection relays, and they can be very computationally intensive, depending on the problem formulation and the choice of optimization algorithm [44]. Single- and multiobjective optimization approaches are used by researchers to solve the time-coordination problem. Some researchers expand the problem formulation to three phases by considering additional factors, such as phase unbalance, grounding, or N-1 contingencies [47–49]. In [50], the researchers propose a stability-constrained protection coordination problem formulation to account for the transient stability parameters when determining the protection settings. Most coordination approaches in [51,52] use a single objective function to optimize the operating time. Additional objectives might include optimizing the operating cost and/or relay locations [53–55]. Difficult optimization techniques used to solve the coordination time are mixed-integer linear programming [52,55,56], genetic algorithms [57, 58], particle swarm optimization [54,59,60], symbiotic organisms [61], metaheuristics [59,62,63], and differential evolution [64–66].

Challenges with coordination: Using only the fault current for coordination to minimize the operating time can be very challenging, however, especially with low levels of faults currents (e.g., microgrids operating as intentional islands or for weak grids with high penetrations of DERs) or when coordinating with fuses. As a result, many approaches focus on accurate short-circuit fault current estimation to help adapt the relays in real-time [67,68]. This can be a challenge to time-based coordination (depending on how low the fault current can get), which compromises the operating time for a backup relay in its primary fault zone. So the authors in [69–71] propose a communications-based coordination to reduce the time delay between trips of the primary and backup protection. These strategies have an inherent risk of communications failure, and they still need a good non-communications-based backup coordination strategy or other backup relays to ensure coordination at all times; however, reducing the operating time for relays is a critical challenge without the use of communications channels.

Approaches addressing relay-coordination: Many resea-rchers have studied the operating characteristics of distribution system configurations [72] and proposed new characteristics to determine trip times. This can help the protection relays to trip faster while ensuring coordination [73]. In [74–76], the authors propose the use of dual-setting characteristics for directional overcurrent. The choice of the curve could be determined by the fault direction or the load/source configuration (types of machines, DERs), as discussed in [74,75]. The authors in [77] propose an operating characteristic for distance relays to address the nonlinear problem of coordinating distance and overcurrent relays. Other researchers have proposed the use of the critical fault point—the fault point with the least current distinction between the primary and backup relay—instead of close-in faults (given the primary protection relays) to be used for relay coordination. The authors in [78] determine the critical fault point using the impedance matrix of the network. Every time the system topology changes, [79] updates the settings for the overcurrent relays and the Zone 2 settings of the distance relays from the pre-optimized relay group settings. Relay coordination research can be further expanded to identify other characteristics that can account for increasing penetrations of DERs and load/use-specific challenges.

3.1.3. *Need for changes in problem formulation and execution of adaptive strategies*

Fig. 6 demonstrates the general approach for estimating the adaptive settings for overcurrent protection. Most adaptive relaying approaches are based on updating the overcurrent relays in the system with the new settings calculated every time the system state changes significantly; however, upon being reprogrammed, modern microprocessors can be down for 1 s to 2 s or more, making the relay oblivious to any system operation before the updated settings can be activated [44,46,80]. Even when switching between the setting groups with preprogrammed values for different operating conditions, there is a brief period (a few seconds) when the relay is blinded.

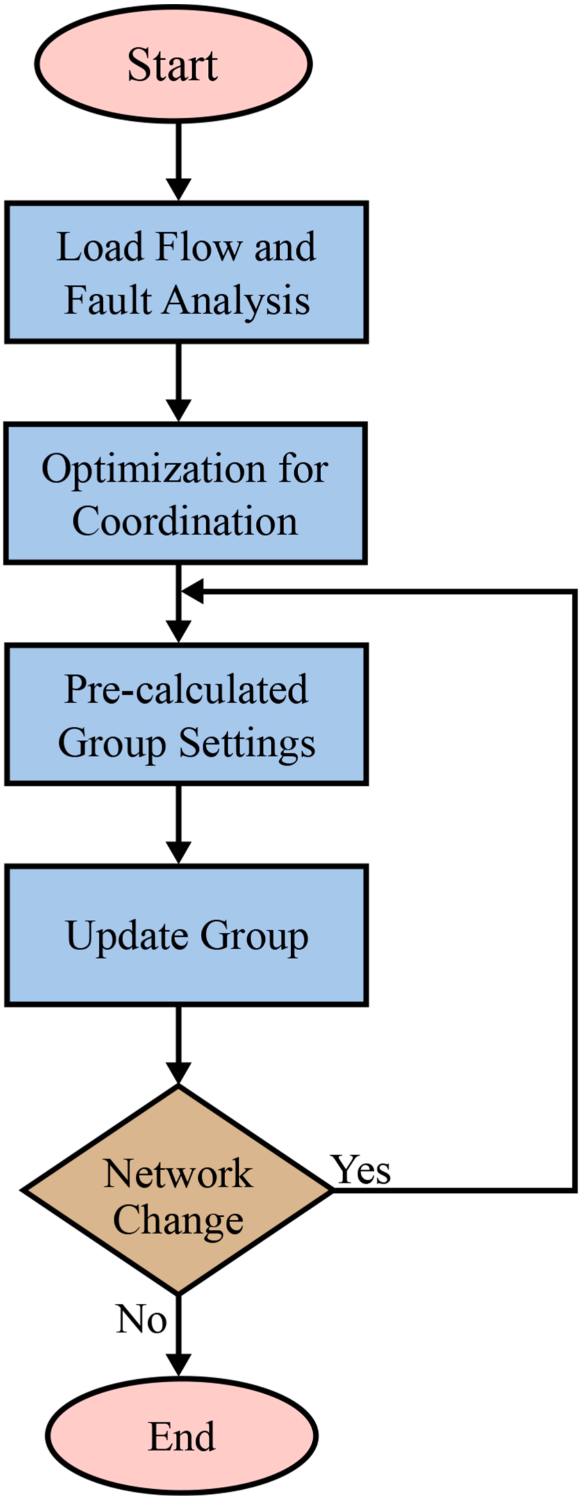


Fig. 6. Flowchart: Generalized approach for adaptive overcurrent setting estimation.

Potential with decentralized approaches: One solution is to simplify the formulation of the optimization problems that do not need a powerful centralized solver to estimate the new relay settings. This approach makes the protection schemes inherently centralized, thus creating a single point of failure. To promote the distributed schemes, the mathematical formulation of the problem for estimating the settings will need to be less computationally intensive. With the increasing number of constraints, researchers proposed alternate algorithms to simplify the problem formulation. The proposed methods reduce the constraints using other measurements for coordination [56] (negative-sequence current [81,82]) and selective consideration of DERs for fault current estimation [46].

Adaptivity within the relay: Simplifying the setting estimation will also allow for the use of programming capabilities within the relay to develop more versatile settings that adapt automatically without reprogramming the relay. In [46], based on the number of DERs online, the relay can automatically pick appropriate fault current estimates from its lookup tables and adjust the relay pickup accordingly. Such algorithms will allow the relay to estimate its adaptive settings locally and make it easier for the relays to work effectively in both islanded and grid-connected modes of operation. The parameters can be communicated by external agents [33], but, more importantly, the relay need not be reprogrammed, thereby alleviating the challenge with relay blinding and reclosers, as discussed in Section 4.1.

3.2. *Differential protection*

Differential relays operate on the principle that the net current in a protection zone is (close to) zero during regular operation. During an internal fault inside the protection zone, the net sum is significantly higher, thereby tripping the respective relays to isolate the section. This means that the differential relays need to exchange time-stamped data at a relatively high rate with each other in the system for the protection scheme to perform reliably. Further, given the setup (or a differential zone), the differential relays can be used only to detect faults within the zone (Fig. 7). For faults inside the protective zone, the currents shown in Fig. 7 will flow into the fault and sum to zero (approx.). High-speed communications play a vital role in the implementation of differential protection schemes. Any loss of communication will impact its ability to respond to a fault.

Modern differential relays are digital and use two key quantities—the operating current, I_{op} (vector sum of all the currents entering or leaving the given zone), and the restraining current, I_{rst} (individual sum of the magnitude of the current vectors used in the operating current)—to differentiate between faulted and unfaulted operation. The ratio of two quantities $(\frac{I_{op}}{I_{rst}})$ is located inside the restraining zone under normal operation, as shown in Fig. 8. The operating characteristic shown in

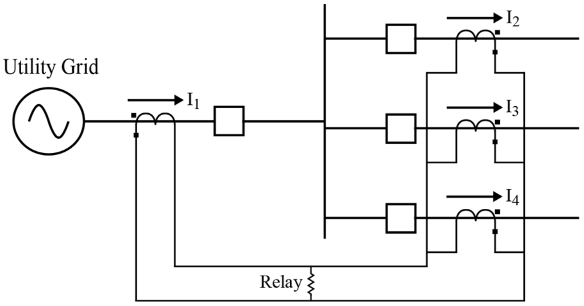


Fig. 7. General setup: Internal fault detection using differential protection.

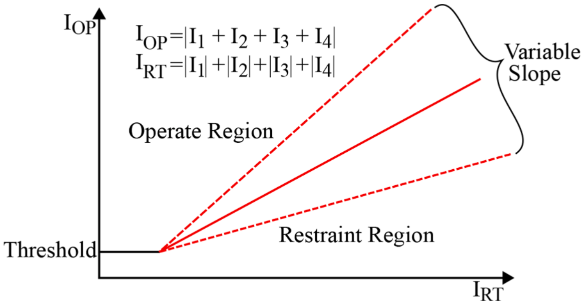


Fig. 8. Operating characteristics based on operating and restraint current: Differential relay.

Fig. 8 varies for different applications. In addition to classic approaches, there are some modified versions by using a positive-sequence fault component instead of the phase currents [83] or by injecting a current with off-nominal frequency using the DERs during fault conditions for faster fault detection [84]. There are also hybrid implementations in microgrids where differential protection is used along with adaptive microgrid protection [85]. Hence, the application of differential relays is limited because of the dependence on communications and the associated cost.

3.3. Voltage-based protection

Challenges with current-only-based protection: There are multiple challenges posed by current-based protection schemes. For example, overcurrent schemes need a high magnitude of current to differentiate between a fault and normal conditions. DERs can contribute to remote infeed and decrease the fault current seen by the primary relays, which in turn impacts fault detection. Moreover, the use of fault current limiters to protect equipment from large current surges further complicates fault identification. Similarly, fault currents change based on the status of DERs (infeed and generation), fault impedance, distance from the relay, type of fault (number of phases, grounded or ungrounded), and many other parameters.

Using voltage for fault detection: Voltage is more stable and less sensitive to any change in system operating conditions and faults; therefore, voltage-based backup (over/under-voltage) protection and use in directional supervision are common in modern-day systems at the substation. As a result, downstream protection is often non-directional. With declining fault current (e.g., islanded microgrids), however, voltages can be a more sensitive element for fault detection. For grid-connected systems, they can offer additional information to improve the relay’s sensitivity and selectivity.

As a result, there is research on using voltage for primary, backup, and supervisory protection to augment/replace the overcurrent-based protection [86]. An adaptive voltage-based primary and backup protection scheme is presented in [87]. The algorithm is based on the relationship between the before-fault and after-fault phase voltage difference and the phase current. In [88], the authors present localized voltage-based protection with current as a backup for distribution systems with DERs. Even though the application of voltage-based protection can reduce dependence on the variable-fault current level, close-in faults and the loss of voltage measurement can blind the relay. Research can be further expanded to make the elements secure for very close-in faults and loss-of-measurement scenarios.

3.4. Impedance relays

Impedance (or distance) relays use both voltage and current information to estimate the apparent impedance (or electrical distance) from the relay. During faults, the apparent impedance seen by the relay is very low, and the loads appear much closer to the relay (indicating a fault) than during normal operation. Three zones of protection and load encroachment characteristics are shown in Fig. 9. Typically, Zone 1 is set to provide instantaneous tripping, and Zone 2 and Zone 3 are set to a delayed trip and act as a backup for downstream relays. When the apparent impedance falls within the impedance characteristic (e.g., the Mho-impedance characteristic shown in Fig. 9), the relay asserts a fault. Misoperations happen because of measurement errors caused by various factors, such as loss of excitation [89], remote infeed [90,91], decaying DC component, harmonics, or coupling capacitor voltage transformer transients [92,93].

Similarly, power swings can cause the impedance to appear like a fault and lead to the misoperation of Zone 3 protection [94,95]. Using the local relay measurements, [94] calculates the relative speed of swing for a fictitious equivalent machine. This method supervises Zone 3 protection based on whether the estimated speed goes through a zero crossing (stable swing) or not (unstable swing). The authors in [95] use PMU measurements to distinguish power swings from faults. For an adaptive Zone 1 setting scheme, [96] proposes using the pre-fault data from the impedance relays from both line ends. In [93], the authors focus on mitigating the influence of harmonics on the impedance relay and propose a matrix pencil method-based preprocessing filter for PMU-assisted distance relays. The measurements are used to estimate the impedance trajectories for Zone 3 impedance relays. To determine the influence of the remote infeed, [90] proposes a compensation method to estimate the impedance more precisely.

3.5. PMU-based applications

As stated previously, PMU-based applications have seen tremendous growth with the increased deployment of AMI. PMUs are being used extensively to log system states and use them for wide-area monitoring, state estimation, and cyber-secure operations. As an extension to protection applications, these data can also be used for backup/wide-area protection and to enable active network management and the allowable reconfiguration topologies (Fig. 10). All PMUs shown in Fig. 10 communicate on a specific protocol with a centralized controller to relay the status in the field and receive any possible instructions from the controller. IEC 61850 and IEEE C37.118 are common protocols used in distribution protection and synchrophasor measurements. Network management, in turn, can help maximize DER penetration without extreme consequences on protection by accounting for factors affecting FLISR, power balance, and islanding options [21]. Dynamic state estimation (DSE) using PMU data [97] helps track the system behavior by comparing measurements to obey physical laws like Kirchhoffś current/voltage laws and others; and can be used for multiple applications including protection.

PMU-based protection applications: Fig. 10 shows that PMU-based applications depend on wide-area networks to exchange and analyze data, sometimes combined with optimization/state estimation. As a result, the response is slow (>200 ms) and primarily suited for backup

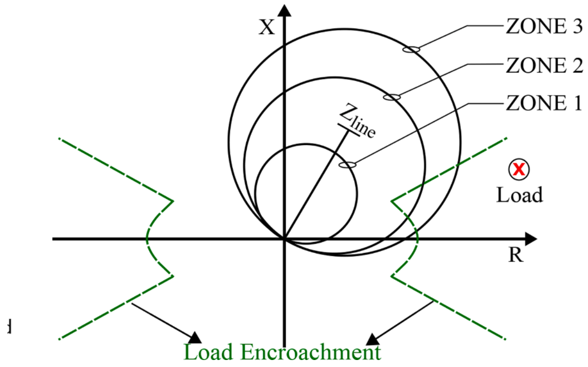


Fig. 9. Operating characteristics for a Mho-impedance relay.

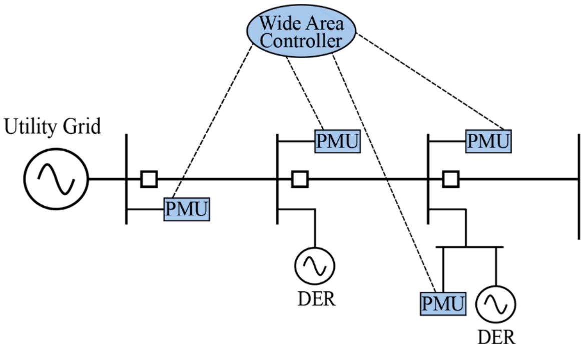


Fig. 10. Generalized representation of a PMU-based wide-area monitoring/ coordination setup.

protection or coordination and secondary/tertiary control applications. In [98], the researchers present a PMU- and frequency-based mechanism to coordinate system protection and control the DERs under permanent line faults using a centralized fault detector. Voltage phasors and frequency data are used for fault location and identification. Archived synchrophasor-based controllers can help with voltage/frequency recovery by adapting reference points of local controllers to the post-fault conditions. In [99], the authors present a wide-area criterion based on the absolute value of the rate of change of the voltage phase angle difference at the PCC for protection monitoring. Further, following an island, the low inertia and a load-generation mismatch might result in high-frequency oscillations in system voltage and frequency. As a result, PMU-based system operations and protection could also misoperate; therefore, [100] presents PMU data indices to monitor the power flow (magnitude and angle) between buses. The resulting supervisory element helps improve the selectivity of primary and backup protection. DSE based protection applications [97] can reinforce traditional distribution system protection, and help introduce additional visibility including fault location, or hidden failure detection.

DER placement using PMU data: As mentioned previously, utilities are accumulating a lot of PMU data to gain a historical sense of change in system behavior, disturbance-sensitive areas, and other operational insights. The DER placement problem can use these archives to strategize the location of DERs to reduce line losses or maximizing the fault current to aid the response of primary protection relays. In [101], the researchers formulate a nonlinear problem with multiple constraints—such as power balance, bus voltage limits, and harmonic distortion limits—to optimize the selection of the types, locations, and sizes of utility-owned DERs. The authors in [102] formulate the reconfiguration as a fuzzy optimization problem, including reduced losses while maintaining short-circuit levels, and they use a fuzzy imperialism competitive algorithm to reach the global optimum. In [103], the authors use particle swarm optimization to optimize the fault current in the system, size the DERs, and optimally place the protection devices for more robust protection coordination. As an alternative to optimally locating DERs, [104] optimizes the use of energy storage (location and size) to help reduce DER curtailment and improve the load factor using system reconfiguration.

In other words, PMU data can be used both in (near) real-time or as an archive to accomplish very different objectives of system operation/ planning. The use cases presented in this section were strictly analytic. The next subsection discusses more generalized ML-based approaches that are also being researched to accomplish similar tasks.

3.6. *ML approaches*

Traditional analysis in power system protection is based on analytic methods and models. Alternatively, ML based approaches offer an inference-based model given the historical or mathematical trend of the relationship between the input and output parameters of interest. In general, ML applications are commonly used in computer vision, language analysis, and forecasting. Also, parameter selection and training of the models can be challenging for power systems–primarily because of the geographic variation in power system behavior. Models can suffer because of a lack of good training data, which, in, turn can be because of insufficient AMI and/or data availability. Nevertheless, when they are designed with adequate parameters and are well trained, these methods can analyze large volumes of PMU/other measurement data to derive inference models for complicated systems. This is not always possible with analytic approaches. Artificial neural networks, convolutional neural networks, reinforcement learning, and support vector machines are some common approaches.

Review of ML-based approaches: In recent years, research in using ML-based approaches for power system operations and protection applications is also gaining traction. In [105], the researchers present an artificial neural network-based algorithm for the anti-islanding protection of the distributed generators, whereas [106] proposes a convolutional neural network-based islanding detection method. In fault detection, [107] presents a fault zone identification scheme based on a logistic regression binary classifier by using one-cycle post-fault current signals. In [108], the researchers use heuristics to determine the fault location for power distribution networks with DERs using voltage and current phasor measurements. In [109], directional overcurrent coordination is provided using metaheuristics, a differential evolution strategy, and linear programming formulations. In [110], the authors use a support vector machine-based regression model for disturbance detection in low-voltage islanded microgrids.

Discussion: A general critique for ML-based approaches is that *the ML model is derived by inferring a relationship between the inputs and outputs—which might or might not exist*. Further, the data available from power system measurements are often infrequently sampled and depend on a multitude of factors influencing the system at any time, including connected assets, operating conditions, system topology, and others; therefore, the same contingencies can affect a given system in different ways on different days and produce different sets of data during different times of the year. None of the proposed approaches consider these aspects. Also, the ML-based models need to be trained over large data sets to improve their accuracy. Existing approaches train their inference engine using simulations of approximate power system models, which also generally have noise- and error-free measurements. Given the sensitivity of the ML-based approaches to measurements, a subset of wrong measurements (caused by meter failure) can lead to an incorrect interpretation of the system state by a larger number of protection devices. This concern is also not addressed in most ML-based power system protection schemes. In other words, the risk of false positives and false negatives for power systems can be significant; therefore, the research in protection using ML should account for the real-world operational challenges for power systems to develop models with higher fidelity to ensure reliable performance.

3.7. *Protection based on signal processing techniques*

Different signal processing techniques—such as Fourier transform, wavelet transforms, discrete wavelet transforms (DWT), and Stockwell transform—are widely researched for protection. The use of transients and harmonic signals to identify faults (particularly high impedances) and other disturbances is becoming more feasible with better measurements and faster computation in digital relays. Often, Fourier transform-based techniques are used when the disturbance of interest has a known harmonic signature. Because time information is completely lost using Fourier transform, localized and nonperiodic events such as transients are often difficult to detect. Algorithms such as short-time Fourier transform can partially overcome this limitation by dividing the signal into windows for localized analysis. Wavelet transforms can decompose input signals into coefficients at different levels (relative frequencies) and have also been used for fault detection. Sometimes they are deemed more effective for isolating singular events and changes [111] because they can preserve the time information. DWT and maximum overlap discrete wavelet transform are the most common techniques for wavelet transform analysis.

The authors in [112] use a fast-recursive discrete Fourier transform algorithm embedded with fuzzy logic decision-making to adapt the settings to the changing system conditions. In [113], the authors propose a multiscale wavelet packet decomposition as the fault detection algorithm to detect the faults more efficiently and quickly. Authors in [114] use DWT to detect the fault using high-frequency wavelet coefficients. They use an event count to add security and to ensure that the fault condition persists before the relay classifies any event as a fault. A hybrid ML approach is proposed in [115] to detect high-impedance faults by comparing the phase angles on the wavelet coefficients. This phase displacement between wavelet coefficients is calculated for I0 and V0 at a chosen high-level frequency. Results show that the transients of the zero-sequence currents in a faulty feeder are in opposition to the healthy feeder transients. Because voltage is a common reference to all the feeders, it can be used as a reference to detect the fault. The scheme is similar to the approach in some implementations of directional elements. Based on this, an event counting method is demonstrated to detect faults (similar to [114]). Alternatively, an artificial neural network was also trained to present an alternative implementation as well. Similarly, in [116], DWT is used to locate and isolate faulted sections in distribution systems with distributed generation.

The polarities of the wavelet coefficients of the high-frequency components of the current measurements from different zones are compared to determine the fault categories and to differentiate between in-zone and out-of-zone faults. It is claimed that time synchronization and centralized schemes are not needed to implement this scheme. Other approaches estimate the ”wavelet energy” (the sum of the absolute or squared values of individual coefficients of the wind turbine output) instead of directly using the coefficients. The authors in [117] use the DWT decomposition on zero-sequence currents and voltage for fault detection. They also propose a basic directional element using the sum of the instantaneous transient power summed over two power cycles. The polarity of the sum tells whether the fault is behind the node (+) or in front of it (-). In [118,119], the authors add an additional sensitivity using boundary wavelets to detect transient phenomenon, such as a HIF. Fault detection using a Stockwell transform-based median was proposed in [120]. This approach calculates the fault index from the median of the Stockwell matrix and declares a fault for the respective phase if the index is greater than a set threshold. The authors in [121] computed the fault index of the current signals from the Wigner distribution function and the alienation coefficient. The threshold point is selected from the historical data sets; however, the threshold set point sensitivity to different types of faults and energy resources is not investigated. The authors in [122] propose a traveling wave transient-based protection system for medium-voltage system lines using only local high-frequency current measurements and power frequency voltage measurements. In [123], the researchers propose a sub-cycle distance relay using the least error squares method. It uses a data interface module implemented on a field-programmable gate array, which benefits from its inherent parallelism and pipe-lined architecture for real-time communications.

There is a risk of misoperation, however, with higher frequency coefficients. The use of zero-sequence components is not recommended by itself because it could also limit the application in distribution systems with a high operating imbalance on some circuits. Further, transients are visible to a large number of relays across the system, given the location of the disturbance and the apparent impedance to a given relay. This makes selectivity a primary challenge for transient-based protection schemes; therefore, there is a significant need to develop reliable directional elements to complement fault detection. Another challenge is the need for sampling the measurements at a high rate, which might discourage or limit the applications of these schemes. There is also an opportunity to research schemes that could use existing sampling rates (a few kilohertz) for fault detection.

3.8. *Discussion: Contrast in protection approaches*

This section discusses the prominent approaches under active research for improving the protection response for the evolving distribution systems. *Different approaches have varying timescale requirements, response speeds, assumptions, and resource requirements*. To help visualize these differences, Fig. 11 provides the operating timescales of various protection strategies. As shown, traditional protection schemes sample the operating quantities every few milliseconds; whereas high-speed protection schemes, such as the wavelet-based or traveling waves, require sampling every few micro/nanoseconds. This drastically changes the requirements for the measurement devices (current transformers and potential transformers) in the distribution system, which may or may not capture the fault transients at the needed rate. It can be concluded that the challenge of ensuring reliable protection for distribution feeders is a multifaceted problem. Every protection approach has its own set of merits and demerits. The current-based approach requires adaptive settings with relay coordination because of changing fault currents from IBDERs. The application of voltage-based protection needs further research to secure the protection elements for close-in faults and loss-of-measurement scenarios. Impedance-based schemes are less affected by changes in the fault current and configuration because they achieve selectivity based on impedance rather than fault current. Their application is restricted to three-phase distribution mainly at the medium-voltage level because of its dependence on the sequence components for direction. Protection strategies similar to differential protection are expensive to widely implement in a distribution system. Current research into fault transient-based strategies require a high sampling rate, which makes it difficult to use existing infrastructure. Utility visibility into the distribution system is minimal—implying that ML-based approaches might require multiple years of data to design reliable schemes. Although it is imperative to accurately estimate the operating quantity (current or voltage) during faults, optimally placing DERs, optimizing system topology, and using wide-area monitoring can help determine a more effective FLISR strategy. Next, we discuss the overarching challenges among these approaches and highlight the need for other research areas.

4. Challenges with protection approach and system modeling

As noted in Sections 2 and 3, multiple factors affect distribution system operation. Section 3 discussed multiple challenges and the evolution of protection schemes to ensure reliable fault detection. Regardless of whether the models are analytic (network models and traditional power system analysis) or inference (ML) based, there is a need to

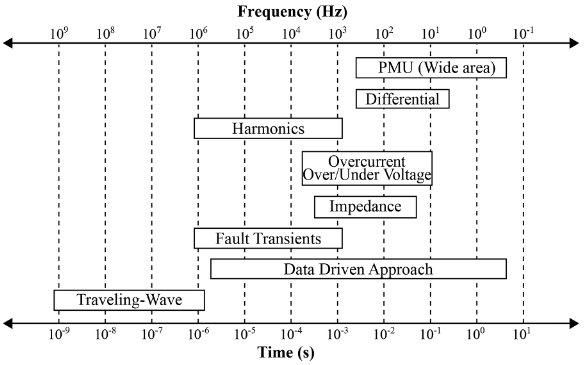


Fig. 11. Summary: Approaches for distribution system protection vs. operating timescale.

consider a wide spectrum of system attributes that accurately capture the system behavior. In other words, it is quintessential that power systems are modeled more accurately to identify these changes in behavior and to refine the underlying assumptions on system operation (e.g., level of DER penetration, topology, or ride-through requirements) or fault current (e.g., grid-connected vs. islanded); therefore, this section discusses the key factors and challenges among different approaches/applications to highlight specific attributes that should be accurately estimated or modeled for more robust system protection.

4.1. Protection challenges

Challenges for protection schemes that are attributed to changes in system behavior or fault characteristics could lead to relay misoperation. These include:

- **Modeling assumptions**: The approaches based on the overcurrent detection solve the equivalent phasor domain or quasi-steady-state (QSS) system model in the steady state. As a result, the success of most of these approaches relies on their assumptions of the network topology and the accuracy of the fault current estimation method being used.
- **Fault impedance**: Fault impedance plays a critical role in determining the fault current. HIFs are more common in the distribution system and are generally difficult to detect under a 15-kV distribution voltage level [124]. Traditional fault studies are based on short-circuit current estimates with additional relaxations to accommodate the uncertainty in the fault impedance. Although there are specific protection elements for the HIFs, even traditional fault impedances (e.g., 1, 10, 25 ohms) can be particularly challenging, especially for weak systems or when operating as intentional islands.
- **Remote infeed**: When two or more sources of power are feeding current to a fault, the net current contribution of all the sources not seen by the given protection relay is referred to as a remote infeed. With revised DER interconnection standards (IEEE 1547–2018), the DERs are expected to be connected longer [46] and ride through external faults. The adaptive strategies try to compensate for the remote infeed by adjusting the sensitivity of the protection relay settings; however, there are cases where the existing problem formulation of overcurrent protection might be fundamentally unable to address the challenge. There is some research focused on estimating and/or offsetting the influence of DER infeed on the fault current seen by the primary protection relays [125].
- **Current as the primary operating parameter**: As shown, all the previously mentioned demerits deal with the inability to accurately estimate the lowest fault current. Further, with islanded systems and systems with limited short-circuit capacity, it is becoming increasingly difficult to distinguish between the nominal load current and the lowest fault current.

- **Fault direction**: With radial systems and the grid as a source, traditional overcurrent protection responds to the fault in one direction. The need for a directional feature arises in a system with multiple sources to maintain selectivity [91]. Fault directionality is typically provided by adding a potential transformer measurement to the relay. Voltage polarization becomes unreliable when faults are close to the relay. Fault currents might become too low if there is a high penetration of DERs. The dependability of a directional feature approach in the protection schemes becomes important to ensure reliable and safe operation.

- **Impact of inrush currents**: Inrush currents are high currents drawn by equipment with reactance (e.g., transformers, motors, capacitors, and others) when subjected to a sudden change in operating state––commonly caused by a fault or during a black start. Recovering the voltage after the fault causes the current to significantly increase beyond pre-fault levels. The resulting high current causes magnetic devices such as transformers to saturate and adds a DC offset to the phasor measurements. For better phasor estimation, some researchers introduce inbuilt DC offset [126] and filters into the current measurements. IEEE 1547 interconnection standard requires DERs to restore output to 80% of pre-disturbance levels within 0.4 s. There is a momentary period after the fault when the inrush current is supplied by the grid and the DERs are ramping up their output to pre-fault levels. It is imperative for protection relays to detect these transitions and to be secure against the inrush phenomenon.
- **Mode of operation**: Future distribution systems are being designed to be fault resilient, and they might be expected to operate in both grid-connected and intentional islanded modes. As a result, the distribution protection relays need to operate reliably independent of the respective modes of operation. Some proposed algorithms are designed to work with multiple modes of operation [46,127]; however, most proposed adaptive algorithms do not consider the differences in the fault current between islanded and grid-connected operation. Further research on this application is essential to developing more versatile protection algorithms.

4.2. Modeling challenges with DERs

Accurate power system models are vital for analyzing, validating, and improving the protection response during the disturbances. Given the assumptions, these models can be broadly classified into three domains: the phasor domain, the QSS domain, and the electromagnetic transient (EMT) domain.

- Phasor domain models assume balanced three-phase operation and are more common for transmission systems. Given the phasor output, these models are unable to consider transient (sub-cycle) events. Also, in the phasor domain, IBDERs are modeled as voltage sources behind an impedance (as generators). This can misrepresent the current behavior during faults and other disturbances. Finally, phasor domain models have a limited ability to consider an unbalanced system [91] and the response of IBDERs.
- The QSS domain modeling is more common for distribution systems and can model balanced and unbalanced modes of operation including IBDERs. The dynamic simulations available in this domain are very limited and might not accurately represent the dynamic behavior of the system. Similar to the phasor domain, transient conditions cannot be simulated. QSS modeling can accommodate simplified inverter controls and reactive power behavior to enable some analysis of the IBDER behavior; however, the current contribution for edge cases such as ride-through depends on the terminal voltage, system impedance, and topology, and thus the behavior in actual systems could vary from modeled behavior.
- Finally, EMT solvers can model IBDER behavior in microseconds or less as needed. This is ideally suited for transient analysis and the response of the inverters during disturbances. Given the significant computational burden and the need for a detailed model, however, the analysis could often be restricted to phenomena local to the given model and not be used for large-scale systems.

As shown, the modeling domain determines the level of detail that can be analyzed, thereby affecting the protection studies. Conversely, to understand the impact of DER interconnection on a distribution system, accurate modeling is required; therefore, protection engineers need to balance the choice of modeling domain against the complexity of the models for the power system under study (Section 2.3). The domain-specific model challenges are discussed next.

4.2.1. Phasor and QSS domain modeling challenges

Phasor and QSS domain simulations share similar model representations of power system components. As a result, challenges associated with respective domains are similar. Traditional short-circuit analysis is reliable when estimating the settings of conventional distribution system protection; however, more detailed models will be needed to capture the nuances of the evolving behavior of modern distribution systems. In a conventional distribution system, IBDERs are modeled as a voltage source behind impedances using positive-, negative-, and zero-sequence impedance. Present-day DERs employ different technologies in controlling the fault response. IBDERs, in particular, limit the fault current injection to 1–2 times the rated current and suppress the negative sequence current injection [128,129]. Because of the non-standardized controls in IBDERs from different manufacturers, there is no generic model that can capture the behavior during faults. Fault response of IBDERs is evaluated experimentally in [130–132]. Appropriate models are required that would capture the IBDER behavior [128,133] in short-circuit studies.

The highly variable nature of the inverter-based DERs causes the fault current contribution to vary with time. Changing conditions make it difficult to model and find the optimal relay settings. IEEE 1547–2018 introduced fault ride-through requirements for DERs to ensure the stability of a grid by staying connected. One particular challenge is that most software packages do not contain the capability to model the ride-through requirements. Utilities lack reliable details of the distribution network, and their visibility into the network is also limited. For these reasons, researchers studying protection issues in the phasor and QSS domains need to represent the network as accurately as possible to obtain reliable results.

4.2.2. EMT modeling challenges

Traditional protection studies do not consider transient system behavior and find classic phasor and QSS domain models sufficient for their needs; however, factors such as penetration level and distribution of DERs in the system, grounding, controls/ride-through periods of DERs, and current transducer saturation affect the fault current seen by the protection relays. These representations need to be considered and sometimes might necessitate the use of EMT domain models to analyze the system before simplifying to a phasor/QSS domain.

Ungrounded DERs do not have a noticeable impact on the original grounding of the respective distribution system [134]. However, the low-resistance grounding or solidly gro-unded DERs have an impact on the original grounding method of a distribution network. DER grounding can also affect the nature of the zero-sequence fault current and the neutral voltage, thereby affecting system protection. This makes the choice of DER grounding an important factor, especially for high penetration levels. Also, undervoltage can cause disconnection of the DERs (as per IEEE 1547–2018). Consequently, large-scale disconnection of DERs resulting from undervoltage—such as that caused by cloud cover—could, in turn, affect a system's stability and security. In [135], the authors evaluate the resilience of Portugal's distribution system using power quality monitoring data for the countrywide geographic occurrence of voltage dips at the distribution system originating from the fault at the transmission system.

Current transducer saturation can affect the fault current seen by the protection relays. As a result, [136] models current transducer saturation from actual installations to estimate the performance of protective relays and discusses ways to improve coordination. In, [137] the authors present an analytic approach to identify the impact of FACTS devices and DERs on distance relay tripping characteristics. EMT studies indicate that DERs could adversely affect the voltage characteristic and compromise the accuracy of voltage sag-based fault location methods [138]. Further, inverter voltage and current control modes have a direct impact on the fault current and duration [139]. As a result, it should be possible to use the controller response for coordinated (or localized) detection of faults in the system.

Such modeling efforts are important to understand the impact of DER penetration on the operation and design choices of the system. This, in turn, will provide a ground-up approach to improve the reliability of the system.

4.2.3. High-fidelity models for EMT-based fault analysis

Transient- (EMT-) based fault analysis requires an accurate representation of the network components—such as lines, transformers, DER response, transients, and others—for a wide frequency range (>10 kHz). The transient signatures are processed to distill the main operating parameters for classifying disturbances and/or isolating faults. Wideband modeling of transformers helps to detect the internal transients, which are otherwise undetected in traditional protection. In the case of lines, frequency-dependent wideband models are used to study the high-frequency transients (including traveling waves) during disturbances such as a fault or component switching. The shorter line lengths in the distribution system can make it challenging to study very high-frequency components (usually >20 kHz); in some cases, smaller time steps (<50 μs) will be needed to accurately analyze them. This further compounds the computational complexity of EMT models, and it requires theoretical and experimental validation of higher frequency domain models.

Although EMT and high-fidelity models are complex, careful evaluation can help cosimulate parts of the network models in different domains together. This will allow selecting the best protection schemes for a given section while simplifying the complexity when possible. As discussed in Section 2.3, sections of the network with high penetrations of IBDERs require high-fidelity models to understand the interconnection standard effects on protection. It reiterates the need for cosimulation between models in different domains without increasing the computational complexity. Given the state of the art, significant research is needed to develop reproducible models that can help users make these distinctions and develop scalable models. Additional challenges include proper modeling of the IBDER control modes (often proprietary), their fault response characterization, and the lack of a reliable network model.

Table 1 summarizes the different challenges relevant to protection and modeling for the respective broad algorithms used for distribution protection.

4.3. Future research recommendations

Section 3 presented the operating principles for the most prevalent distribution system protection approaches including modern trends and research gaps. In Section 3.8, we summarized the dependencies of the different protection algorithms on system characteristics. Building upon this, and the discussions in Section 4, here we present some recommendations for future research in power system protection.

Essentially, current-based schemes need careful consideration of power system models, DER controls, and timescale of operation. While voltage is also impacted by the above factors, the changes in current are more severe - and may be further impacted by the measurement accuracy, especially at low values ($\leq$ 10% rated current). A lot of research is needed in developing the DER models grid-interconnection standard compliant (e.g. IEEE 1547–2018) ride-through behavior. While EMT models can be more accurate, they need more development and computational resources. Therefore, research in developing high-fidelity QSTS models of DERs, and, integrating them with existing distribution system models for comparative analysis of change in protection is essential. Researchers should also consider the benefits and drawbacks of the timescale of operation for their algorithm of choice and determine the modeling framework/timescale. It will be worthwhile to consider the limitations if the users can not use the recommended modeling approach. Finally, for communication-dependent approaches like adaptive overcurrent, differential, PMU-based, and others, the impact of setting updates on the protection relays and primary relay failure conditions needs to be carefully considered. Finally, with DERs providing unbalance compensation, the impact on existing supervisory and protection elements needs to be carefully analyzed, and, addressed.

Table 1
Review summary: Associated challenges for different protection algorithms .

Challenges → Approaches/ Applications ↓	Protection	Modeling	Communication and others
Traditional overcurrent	Remote infeed	Low fault currents	Communication needed for permissive trip
Adaptive overcurrent	Remote infeed,	Operation mode	Optimization complexity
	current sensitivity,	(Grid-connected/ islanded)	Communication needed
	fault directionality		Cyber-security challenges
Differential	Internal faults	-	Communication Reliability and Speed
Voltage based	Close-in faults	Voltage ride-through	-
Impedance	Remote infeed	-	Permissive trip will need communication
Machine learning	Training/ validation data sets	-	Multiple years
			of training data
Fault transients	Switching and	Short line-lengths,	High-frequency current
	lightning transients	high-fidelity models	transformers and
			potential Transformers
PMU-based and	Remote infeed	Low fault currents and	Communication needed
optimization		ride-through	co-ordinated operation for

5. Conclusions

This paper reviews the evolving challenges in improving the reliability of distribution system operations and the requirements for a reliable protection scheme to ensure the robust and resilient operation of power systems. The literature survey presented in this paper shows that the challenges and opportunities for protection stem from many different areas, including new DER interconnection standards, changing system operation, and the ability to operate systems as reconfigurable networks with intentional islanding capabilities. This paper also quantified the differences in protection approaches (presented in Fig. 11 and Table 1). The quantification presented in this work can be used to understand the modeling requirements and trade-offs for different protection approaches. Overcurrent protection, which is the most popular method for the protection of distribution systems, needs further research to transform the static overcurrent setting into adaptive settings. The challenges with relay coordination in adaptive settings and approaches to address those challenges were also discussed. Similarly, other well-established schemes–such as impedance-based and differential protection–also require further improvements. The trend in the increasing focus on using voltage-based schemes as the primary mode of protection was observed in the survey; however, voltage-based protection schemes need more development and should show reliable operations targeting faster protection. PMU data and ML-based approaches in general are also being recommended in the literature for both primary and complementary modes of protection. Research on the use of transient signatures for fault detection is promising, but more reliable, secure, and selective supervisory elements need to be developed to be used as primary protection. These challenges also highlight the need for accurate modeling of power systems, with a direct focus on protection applications such as fault current and apparent impedance estimation. Finally, researchers are also working on identifying the best interconnection practices and locations that would minimize the challenges for coherent operation between protection relays and distribution systems. Further research is needed to help the utilities quantify the response of different protection approaches - and ensure reliable protection response for their systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Contributions to this project were achieved through the Grid Modernization Laboratory Consortium (GMLC), a strategic partnership between the U. S. Department of Energy and the National Laboratories. The GMLC was established as part of the U.S. Department of Energy Grid Modernization Initiative (GMI) to accelerate the modernization of the U. S. electricity infrastructure. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

References

[1] J.C. Gomez, J. Vaschetti, C. Coyos, C. Ibarlucea, Distributed generation: impact on protections and power quality, IEEE Lat. Am. Trans. 11 (1) (2013) 460–465, https://doi.org/10.1109/tla.2013.6502846.

[2] A. Sinclair, D. Finney, D. Martin, P. Sharma, Distance protection in distribution systems: how it assists with integrating distributed resources, IEEE Trans. Ind. Appl. 50 (3) (2014) 2186–2196, https://doi.org/10.1109/tia.2013.2288426.

[3] E. Hossain, J. Hossain, F. Un-Noor, Utility grid: present challenges and their potential solutions, IEEE Access 6 (2018) 60294–60317, https://doi.org/10.1109/access.2018.2873615.

[4] S.-E. Razavi, E. Rahimi, M.S. Javadi, A.E. Nezhad, M. Lotfi, M. Shafie-khah, J. P. Catalão, Impact of distributed generation on protection and voltage regulation of distribution systems: a review, Renew. Sustain. Energy Rev. 105 (2019) 157–167, https://doi.org/10.1016/j.rser.2019.01.050.

[5] M. Monadi, M. Amin Zamani, J. Ignacio Candela, A. Luna, P. Rodriguez, Protection of ac and dc distribution systems embedding distributed energy resources: a comparative review and analysis, Renew. Sustain. Energy Rev. 51 (2015) 1578–1593, https://doi.org/10.1016/j.rser.2015.07.013.

[6] P.T. Manditereza, R. Bansal, Renewable distributed generation: the hidden challenges – a review from the protection perspective, Renew. Sustain. Energy Rev. 58 (2016) 1457–1465, https://doi.org/10.1016/j.rser.2015.12.276.

[7] K.P. Schneider, S. Laval, J. Hansen, R.B. Melton, L. Ponder, L. Fox, J. Hart, J. Hambrick, M. Buckner, M. Baggu, K. Prabakar, M. Manjrekar, S. Essakiappan, L.M. Tolbert, Y. Liu, J. Dong, L. Zhu, A. Smallwood, A. Jayantilal, C. Irwin, G. Yuan, A distributed power system control architecture for improved distribution system resiliency, IEEE Access 7 (2019) 9957–9970, https://doi.org/10.1109/ACCESS.2019.2891368.

[8] V. TERZIJA, Y. LIU, Guest editorial: special issue on wide area monitoring, protection and control in smart grid, J. Mod Power Syst. Clean Energy 4 (3) (2016) 317–318, https://doi.org/10.1007/s40565-016-0221-8.

[9] J.R. Aguero, Guest editorial special section on protection and real-time monitoring of transmission and distribution systems with high penetration of distributed generation and microgrids, IEEE Trans. Power Delivery 32 (1) (2017) 333–334, https://doi.org/10.1109/tpwrd.2017.2650358.

[10] M.M. Eissa, Challenges and novel solution for wide-area protection due to renewable sources integration into smart grid: an extensive review, IET Renew. Power Gener. 12 (16) (2018) 1843–1853, https://doi.org/10.1049/iet-rpg.2018.5175.

[11] P. Denholm, B. Kroposki, Understanding Power Systems Protection in the Clean Energy Future. Technical Report, 2022, https://doi.org/10.2172/1870415.

[12] M.A. Zamani, T.S. Sidhu, A. Yazdani, Investigations into the control and protection of an existing distribution network to operate as a microgrid: a case study, IEEE Trans. Ind. Electron. 61 (4) (2014) 1904–1915, https://doi.org/10.1109/tie.2013.2267695.

[13] M.A. Haj-ahmed, E.A. Feilat, H.J. Khasawneh, A.F. Abdelhadi, A. Awwad, Comprehensive protection schemes for different types of wind generators, IEEE Trans. Ind. Appl. 54 (3) (2018) 2051–2058, https://doi.org/10.1109/tia.2018.2789865.

[14] J. Keller, B. Kroposki, R. Bravo, S. Robles, Fault current contribution from single-phase PV inverters. 2011 37th IEEE Photovoltaic Specialists Conference, IEEE, Seattle, WA, USA, 2011, pp. 001822–001826, https://doi.org/10.1109/PVSC.2011.6186307.

[15] S. Poudel, P. Sharma, A. Dubey, K.P. Schneider, Advanced FLISR with intentional islanding operations in an ADMS environment using GridAPPS-D, IEEE Access 8 (2020) 113766–113778, https://doi.org/10.1109/ACCESS.2020.3003325.

[16] Y. Wang, Y. Xu, J. He, C. Liu, K.P. Schneider, M. Hong, D.T. Ton, Coordinating multiple sources for service restoration to enhance resilience of distribution systems, IEEE Trans. Smart Grid 10 (5) (2019) 5781–5793, https://doi.org/10.1109/TSG.2019.2891515.

[17] Y. Xu, C. Liu, Z. Wang, K. Mo, K.P. Schneider, F.K. Tuffner, D.T. Ton, Dgs for service restoration to critical loads in a secondary network, IEEE Trans. Smart Grid 10 (1) (2019) 435–447, https://doi.org/10.1109/TSG.2017.2743158.

[18] A. Hooshyar, R. Iravani, Microgrid protection, Proc. IEEE 105 (7) (2017) 1332–1353, https://doi.org/10.1109/jproc.2017.2669342.

[19] V. Telukunta, J. Pradhan, A. Agrawal, M. Singh, S.G. Srivani, Protection challenges under bulk penetration of renewable energy resources in power systems: a review, CSEE J. Power Energy Syst. 3 (4) (2017) 365–379, https://doi.org/10.17775/cseejpes.2017.00030.

[20] S. Beheshtaein, R. Cuzner, M. Savaghebi, J.M. Guerrero, Review on microgrids protection, IET Gener. Transm. Distrib. 13 (6) (2019) 743–759, https://doi.org/10.1049/iet-gtd.2018.5212.

[21] H. Laaksonen, P. Hovila, Future-proof islanding detection schemes in sundom smart grid, CIRED Open Access Proc. J. 2017 (1) (2017) 1777–1781, https://doi.org/10.1049/oap-cired.2017.0310.

[22] K.A. Wheeler, M. Elsamahy, S.O. Faried, A novel reclosing scheme for mitigation of distributed generation effects on overcurrent protection, IEEE Trans. Power Delivery 33 (2) (2018) 981–991, https://doi.org/10.1109/tpwrd.2017.2743693.

[23] S.A. Gopalan, V. Sreeram, H.H. Iu, A review of coordination strategies and protection schemes for microgrids, Renew. Sustain. Energy Rev. 32 (2014) 222–228, https://doi.org/10.1016/j.rser.2014.01.037.

[24] E.C. Piesciorovsky, T. Smith, T.B. Ollis, Protection schemes used in north american microgrids, Int. Trans. Electr. Energy Syst. n/a (n/a) (2020) e12461, https://doi.org/10.1002/2050-7038.12461.

[25] B. Hartmann, I. Vokony, I. Táczi, Effects of decreasing synchronous inertia on power system dynamics—overview of recent experiences and marketisation of services, Int. Trans. Electr. Energy Syst. 29 (12) (2019) e12128, https://doi.org/10.1002/2050-7038.12128.E12128 ITEES-18-1219.R1

[26] J.-H. Teng, W.-H. Huang, S.-W. Luan, Automatic and fast faulted line-section location method for distribution systems based on fault indicators, IEEE Trans. Power Syst. 29 (4) (2014) 1653–1662, https://doi.org/10.1109/tpwrs.2013.2294338.

[27] K. Jia, D. Thomas, M. Sumner, A new single-ended fault-location scheme for utilization in an integrated power system, IEEE Trans. Power Delivery 28 (1) (2013) 38–46, https://doi.org/10.1109/tpwrd.2012.2215346.

[28] M.M.M. Aly, M.A. El-Sayed, Enhanced fault location algorithm for smart grid containing wind farm using wireless communication facilities, IET Gener. Transm. Distrib. 10 (9) (2016) 2231–2239, https://doi.org/10.1049/iet-gtd.2015.1488.

[29] P. Escalante Farias, A. Peres de Morais, G. Cardoso Junior, J. Pereira Rossini, Fault location in distribution systems: a method considering the parameter estimation using a rna online, IEEE Lat. Am. Trans. 14 (12) (2016) 4741–4749, https://doi.org/10.1109/tla.2016.7817005.

[30] M. Mirzaei, B. Vahidi, S.H. Hosseinian, Accurate fault location and faulted section determination based on deep learning for a parallel-compensated three-terminal transmission line, IET Gener. Transm. Distrib. 13 (13) (2019) 2770–2778, https://doi.org/10.1049/iet-gtd.2018.6982.

[31] M. Singh, P. Basak, Adaptive protection methodology in microgrid for fault location and nature detection using q0 components of fault current, IET Gener. Transm. Distrib. 13 (6) (2019) 760–769, https://doi.org/10.1049/iet-gtd.2018.6347.

[32] D.T. Ton, M.A. Smith, The us department of energy's microgrid initiative, Electr. J. 25 (8) (2012) 84–94.

[33] S.A. Hosseini, S.H.H. Sadeghi, A. Nasiri, Decentralized adaptive protection coordination based on agents social activities for microgrids with topological and operational uncertainties, IEEE Trans. Ind. Appl. 57 (1) (2021) 702–713, https://doi.org/10.1109/TIA.2020.3028351.

[34] M. Moshoeshoe, S. Chowdhury, Adaptive overcurrent protection scheme with zonal approach for a stand-alone renewable-based microgrid. 2021 IEEE PES/IAS PowerAfrica, 2021, pp. 1–5, https://doi.org/10.1109/PowerAfrica52236.2021.9543357.

[35] G. Artale, A. Cataliotti, V. Cosentino, D. Di Cara, S. Guaiana, S. Nuccio, N. Panzavecchia, G. Tine, Smart interface devices for distributed generation in smart grids: the case of islanding, IEEE Sens J 17 (23) (2017) 7803–7811, https://doi.org/10.1109/jsen.2017.2726185.

[36] M.R. Alam, M.T.A. Begum, K.M. Muttaqi, Assessing the performance of rocof relay for anti-islanding protection of distributed generation under subcritical region of power imbalance, IEEE Trans. Ind. Appl. 55 (5) (2019) 5395–5405, https://doi.org/10.1109/tia.2019.2927667.

[37] M. Lukač, Z. Matišić, Anti-islanding protection of distributed generators with regard to sensitivity in a balance and power system stability, CIRED Open Access Proc. J. 2017 (1) (2017) 943–946, https://doi.org/10.1049/oap-cired.2017.0368.

[38] Q. Cui, K. El-Arroudi, G. Joós, Real-time hardware-in-the-loop simulation for islanding detection schemes in hybrid distributed generation systems, IET Gener. Transm. Distrib. 11 (12) (2017) 3050–3056, https://doi.org/10.1049/iet-gtd.2016.1562.

[39] A. Pouryekta, V.K. Ramachandaramurthy, N. Mithulananthan, A. Arulampalam, Islanding detection and enhancement of microgrid performance, IEEE Syst. J. 12 (4) (2018) 3131–3141, https://doi.org/10.1109/jsyst.2017.2705738.

[40] A. Ghaderi, H.L. Ginn, H.A. Mohammadpour, High impedance fault detection: a review, Electr. Power Syst. Res. 143 (2017) 376–388, https://doi.org/10.1016/j.epsr.2016.10.021.

[41] P. Naveen, P. Jena, Adaptive protection scheme for microgrid with multiple point of common couplings, IEEE Syst. J. 15 (4) (2021) 5618–5629, https://doi.org/10.1109/JSYST.2020.3039881.

[42] L. Pintos, M. Moreto, J. Rolim, Applicability analysis of directional overcurrent relay without voltage reference in microgrids, IEEE Lat. Am. Trans. 14 (2) (2016) 687–693, https://doi.org/10.1109/tla.2016.7437211.

[43] D. Jones, J.J. Kumm, Future distribution feeder protection using directional overcurrent elements, IEEE Trans. Ind. Appl. 50 (2) (2014) 1385–1390, https://doi.org/10.1109/tia.2013.2283237.

[44] Z. Liu, C. Su, H.K. Hoidalen, Z. Chen, A multiagent system-based protection and control scheme for distribution system with distributed-generation integration, IEEE Trans. Power Delivery 32 (1) (2017) 536–545, https://doi.org/10.1109/tpwrd.2016.2585579.

[45] B. Fani, M. Dadkhah, A. Karami-Horestani, Adaptive protection coordination scheme against the staircase fault current waveforms in PV-dominated distribution systems, IET Gener. Transm. Distrib. 12 (9) (2018) 2065–2071, https://doi.org/10.1049/iet-gtd.2017.0586.

[46] R. Jain, D.L. Lubkeman, S.M. Lukic, Dynamic adaptive protection for distribution systems in grid-connected and islanded modes, IEEE Trans. Power Delivery 34 (1) (2019) 281–289, https://doi.org/10.1109/tpwrd.2018.2884705.

[47] J.J.G. Ledesma, L.R.d. Araujo, D.R.R. Penido, J.L.R. Pereira, Algorithm for the analysis of coordination of protection for distribution systems, IEEE Lat. Am. Trans. 13 (7) (2015) 2168–2175, https://doi.org/10.1109/tla.2015.7273773.

[48] K.A. Saleh, H.H. Zeineldin, E.F. El-Saadany, Optimal protection coordination for microgrids considering N - 1 contingency, IEEE Trans. Ind. Inf. 13 (5) (2017) 2270–2278, https://doi.org/10.1109/tii.2017.2682101.

[49] Y. Tang, R. Ayyanar, Methodology of automated protection analysis for large distribution feeders with high penetration of photovoltaic systems, IEEE Power Energy Technol. Syst. J. 4 (1) (2017) 1–9, https://doi.org/10.1109/jpets.2016.2578942.

[50] T.S. Aghdam, H. Kazemi Karegar, H.H. Zeineldin, Transient stability constrained protection coordination for distribution systems with DG, IEEE Trans. Smart Grid 9 (6) (2018) 5733–5741, https://doi.org/10.1109/tsg.2017.2695378.

[51] H.H. Zeineldin, Y.A.-R.I. Mohamed, V. Khadkikar, V.R. Pandi, A protection coordination index for evaluating distributed generation impacts on protection for meshed distribution systems, IEEE Trans. Smart Grid 4 (3) (2013) 1523–1532, https://doi.org/10.1109/tsg.2013.2263745.

[52] D. Gutierrez-Rojas, P.H.J. Nardelli, G. Mendes, P. Popovski, Review of the state of the art on adaptive protection for microgrids based on communications, IEEE Trans. Ind. Inf. 17 (3) (2021) 1539–1552, https://doi.org/10.1109/TII.2020.3006845.

[53] Z. Liu, H.K. Hoidalen, M.M. Saha, An intelligent coordinated protection and control strategy for distribution network with wind generation integration, CSEE J. Power Energy Syst 2 (4) (2016) 23–30, https://doi.org/10.17775/cseejpes.2016.00045.

[54] F.G. Kaehler Guarda, G. Cardoso Junior, C.D. Lana da Silva, A. Peres de Morais, Fault current limiter placement to reduce recloser - fuse miscoordination in electric distribution systems with distributed generation using multiobjective particle swarm optimization, IEEE Lat. Am. Trans. 16 (7) (2018) 1914–1920, https://doi.org/10.1109/tla.2018.8447357.

[55] M. Lwin, J. Guo, N.B. Dimitrov, S. Santoso, Stochastic optimization for discrete overcurrent relay tripping characteristics and coordination, IEEE Trans. Smart Grid 10 (1) (2019) 732–740, https://doi.org/10.1109/tsg.2017.2751596.

[56] E. Purwar, D.N. Vishwakarma, S.P. Singh, A novel constraints reduction-based optimal relay coordination method considering variable operational status of distribution system with dgs, IEEE Trans. Smart Grid 10 (1) (2019) 889–898, https://doi.org/10.1109/tsg.2017.2754399.

[57] R.M. Chabanloo, M. Safari, R.G. Roshanagh, Reducing the scenarios of network topology changes for adaptive coordination of overcurrent relays using hybrid ga–lp, IET Gener. Transm. Distrib. 12 (21) (2018) 5879–5890, https://doi.org/10.1049/iet-gtd.2018.5810.

[58] F. Freitas, C. Donadel, M. Co, E. Silva, Optimal coordination of overcurrent relays inradial electrical distribution networks, IEEE Lat. Am. Trans. 17 (03) (2019) 520–527, https://doi.org/10.1109/tla.2019.8863323.

[59] A.Y. Hatata, A. Lafi, Ant lion optimizer for optimal coordination of doc relays in distribution systems containing DGs, IEEE Access 6 (2018) 72241–72252, https://doi.org/10.1109/access.2018.2882365.

[60] H.R. Baghaee, M. Mirsalim, G.B. Gharehpetian, H.A. Talebi, Mopso/fdmt-based pareto-optimal solution for coordination of overcurrent relays in interconnected networks and multi-der microgrids, IET Gener. Transm. Distrib. 12 (12) (2018) 2871–2886, https://doi.org/10.1049/iet-gtd.2018.0079.

[61] B. Hoseinzadeh, F.F. da Silva, C.L. Bak, Decentralized coordination of load shedding and plant protection considering high share of ress, IEEE Trans. Power Syst. 31 (5) (2016) 3607–3615, https://doi.org/10.1109/tpwrs.2015.2493101.

[62] A. Sharma, B.K. Panigrahi, Phase fault protection scheme for reliable operation of microgrids, IEEE Trans. Ind. Appl. 54 (3) (2018) 2646–2655, https://doi.org/10.1109/tia.2017.2787691.

[63] D. Sampath Kumar, D. Srinivasan, A. Sharma, T. Reindl, Adaptive directional overcurrent relaying scheme for meshed distribution networks, IET Gener. Transm. Distrib. 12 (13) (2018) 3212–3220, https://doi.org/10.1049/iet-gtd.2017.1279.

[64] J. Moirangthem, S.S. Dash, R. Ramaswami, K.R. Krishnanand, Adaptive differential evolution algorithm for solving non-linear coordination problem of directional overcurrent relays, IET Gener. Transm. Distrib. 7 (4) (2013) 329–336, https://doi.org/10.1049/iet-gtd.2012.0110.

[65] M.Y. Shih, A. Conde, Z. Leonowicz, L. Martirano, An adaptive overcurrent coordination scheme to improve relay sensitivity and overcome drawbacks due to distributed generation in smart grids, IEEE Trans. Ind. Appl. 53 (6) (2017) 5217–5228, https://doi.org/10.1109/tia.2017.2717880.

[66] B. Polajzer, M. Pintaric, M. Roser, G. Stumberger, Protection of mv closed-loop distribution networks with bi-directional overcurrent relays and goose communications, IEEE Access 7 (2019) 165884–165896, https://doi.org/10.1109/access.2019.2952934.

[67] A. Mahari, H. Seyedi, An analytic approach for optimal coordination of overcurrent relays, IET Gener. Transm. Distrib. 7 (7) (2013) 674–680, https://doi.org/10.1049/iet-gtd.2012.0721.

[68] P. Nuutinen, P. Peltoniemi, P. Silventoinen, Short-circuit protection in a converter-fed low-voltage distribution network, IEEE Trans. Power Electron. 28 (4) (2013) 1587–1597, https://doi.org/10.1109/tpel.2012.2213845.

[69] I. Xyngi, M. Popov, An intelligent algorithm for the protection of smart power systems, IEEE Trans. Smart Grid 4 (3) (2013) 1541–1548, https://doi.org/10.1109/tsg.2013.2244621.

[70] F. Coffele, C. Booth, A. Dysko, An adaptive overcurrent protection scheme for distribution networks, IEEE Trans. Power Delivery 30 (2) (2015) 561–568, https://doi.org/10.1109/tpwrd.2013.2294879.

[71] M.H. Marcolino, J.B. Leite, J.R. Sanches Mantovani, Optimal coordination of overcurrent directional and distance relays in meshed networks using genetic algorithm, IEEE Lat. Am. Trans. 13 (9) (2015) 2975–2982, https://doi.org/10.1109/tla.2015.7350048.

[72] L. Chávarro-Barrera, S. Pérez-Londoño, J. Mora-Flórez, An adaptive approach for dynamic load modeling in microgrids, IEEE Trans. Smart Grid 12 (4) (2021) 2834–2843, https://doi.org/10.1109/TSG.2021.3064046.

[73] K.A. Saleh, H.H. Zeineldin, A. Al-Hinai, E.F. El-Saadany, Optimal coordination of directional overcurrent relays using a new time–current–voltage characteristic, IEEE Trans. Power Delivery 30 (2) (2015) 537–544, https://doi.org/10.1109/tpwrd.2014.2341666.

[74] H.H. Zeineldin, H.M. Sharaf, D.K. Ibrahim, E.E.-D.A. El-Zahab, Optimal protection coordination for meshed distribution systems with dg using dual setting directional over-current relays, IEEE Trans. Smart Grid 6 (1) (2015) 115–123, https://doi.org/10.1109/tsg.2014.2357813.

[75] H.M. Sharaf, H.H. Zeineldin, E. El-Saadany, Protection coordination for microgrids with grid-connected and islanded capabilities using communication assisted dual setting directional overcurrent relays, IEEE Trans. Smart Grid 9 (1) (2018) 143–151, https://doi.org/10.1109/tsg.2016.2546961.

[76] T. Soleymani Aghdam, H. Kazemi Karegar, H.H. Zeineldin, Optimal coordination of double-inverse overcurrent relays for stable operation of DGs, IEEE Trans. Ind. Inf. 15 (1) (2019) 183–192, https://doi.org/10.1109/tii.2018.2808264.

[77] Y. Damchi, J. Sadeh, H. Rajabi Mashhadi, Optimal coordination of distance and overcurrent relays considering a non-standard tripping characteristic for distance relays, IET Gener. Transm. Distrib. 10 (6) (2016) 1448–1457, https://doi.org/10.1049/iet-gtd.2015.1087.

[78] D.S. Alkaran, M.R. Vatani, M.J. Sanjari, G.B. Gharehpetian, A.H. Yatim, Overcurrent relays coordination in interconnected networks using accurate analytical method and based on determination of fault critical point, IEEE Trans. Power Delivery 30 (2) (2015) 870–877, https://doi.org/10.1109/tpwrd.2014.2330767.

[79] M. Singh, T. Vishnuvardhan, S. Srivani, Adaptive protection coordination scheme for power networks under penetration of distributed energy resources, IET Gener. Transm. Distrib. 10 (15) (2016) 3919–3929, https://doi.org/10.1049/iet-gtd.2016.0614.

[80] E.O. Schweitzer, B. Kasztenny, A. Guzman, V. Skendzic, M.V. Mynam, Speed of line protection - can we break free of phasor limitations?. 2015 68th Annual Conference for Protective Relay Engineers, 2015, p. nil, https://doi.org/10.1109/cpre.2015.7102184.

[81] H. Muda, P. Jena, Superimposed adaptive sequence current based microgrid protection: a new technique, IEEE Trans. Power Delivery 32 (2) (2017) 757–767, https://doi.org/10.1109/tpwrd.2016.2601921.

[82] H. Muda, P. Jena, Sequence currents based adaptive protection approach for DNs with distributed energy resources, IET Gener. Transm. Distrib. 11 (1) (2017) 154–165, https://doi.org/10.1049/iet-gtd.2016.0727.

[83] H. Gao, J. Li, B. Xu, Principle and implementation of current differential protection in distribution networks with high penetration of DGs, IEEE Trans. Power Delivery 32 (1) (2017) 565–574, https://doi.org/10.1109/tpwrd.2016.2628777.

[84] A. Soleimanisardoo, H. Kazemi Karegar, H.H. Zeineldin, Differential frequency protection scheme based on off-nominal frequency injections for inverter-based islanded microgrids, IEEE Trans. Smart Grid 10 (2) (2019) 2107–2114, https://doi.org/10.1109/tsg.2017.2788851.

[85] T.S. Ustun, R.H. Khan, Multiterminal hybrid protection of microgrids over wireless communications network, IEEE Trans. Smart Grid 6 (5) (2015) 2493–2500, https://doi.org/10.1109/tsg.2015.2406886.

[86] S.-H. Lim, S.-T. Lim, Analysis on coordination of over-current relay using voltage component in a power distribution system with a SFCL, IEEE Trans. Appl. Supercond. 29 (5) (2019) 1–5, https://doi.org/10.1109/tasc.2019.2904668.

[87] J. Ma, W. Ma, X. Wang, Z. Wang, A new adaptive voltage protection scheme for distribution network with distributed generations, Can. J. Electr. Comput. Eng. 36 (4) (2013) 142–151, https://doi.org/10.1109/cjece.2014.2302858.

[88] S. Jamali, H. Borhani-Bahabadi, Protection method for radial distribution systems with DG using local voltage measurements, IEEE Trans. Power Delivery 34 (2) (2019) 651–660, https://doi.org/10.1109/tpwrd.2018.2889895.

[89] A.P. Morais, A.S. Bretas, S. Meyn, G. Cardoso, Adaptive mho relay for synchronous generator loss-of-excitation protection: a capability curve limit-based approach, IET Gener. Transm. Distrib. 10 (14) (2016) 3449–3457, https://doi.org/10.1049/iet-gtd.2015.1552.

[90] K. Pandakov, C.M. Adrah, Z. Liu, H.K. Høidalen, o. Kure, Hardware-in-the-loop testing of impedance protection with compensation of fault impedance and dg infeed current, J. Eng. 2018 (15) (2018) 1018–1022, https://doi.org/10.1049/joe.2018.0189.

[91] C. Chao, X. Zheng, Y. Weng, Y. Liu, P. Gao, T. Nengling, Adaptive distance protection based on the analytical model of additional impedance for inverter-interfaced renewable power plants during asymmetrical faults, IEEE Trans. Power Delivery (2021), https://doi.org/10.1109/TPWRD.2021.3138128.1–1

[92] A. Mahari, M. Sanaye-Pasand, S.M. Hashemi, Adaptive phasor estimation algorithm to enhance numerical distance protection, IET Gener. Transm. Distrib. 11 (5) (2017) 1170–1178, https://doi.org/10.1049/iet-gtd.2016.0911.

[93] T. Prakash, S.R. Mohanty, V. Pratap Singh, Distance relaying algorithm for phasor measurement unit assisted zone-3 relays of series compensated wind integrated system, IET Gener. Transm. Distrib. 13 (21) (2019) 4788–4797, https://doi.org/10.1049/iet-gtd.2019.0488.

[94] D. Kang, R. Gokaraju, A new method for blocking third-zone distance relays during stable power swings, IEEE Trans. Power Delivery 31 (4) (2016) 1836–1843, https://doi.org/10.1109/tpwrd.2016.2520394.

[95] J.G. Rao, A.K. Pradhan, Supervising distance relay during power swing using synchrophasor measurements, IET Gener. Transm. Distrib. 11 (17) (2017) 4136–4145, https://doi.org/10.1049/iet-gtd.2016.1110.

[96] S. Paladhi, A.K. Pradhan, Resilient protection scheme preserving system integrity during stressed condition, IET Gener. Transm. Distrib. 13 (14) (2019) 3188–3194, https://doi.org/10.1049/iet-gtd.2018.5513.

[97] Y. Liu, A.K. Singh, J. Zhao, A.P.S. Meliopoulos, B. Pal, M.A.b.M. Ariff, T. Van Cutsem, M. Glavic, Z. Huang, I. Kamwa, L. Mili, A.S. Mir, A. Taha, V. Terzija, S. Yu, Dynamic state estimation for power system control and protection, IEEE Trans. Power Syst. 36 (6) (2021) 5909–5921, https://doi.org/10.1109/TPWRS.2021.3079395.

[98] Y. Seyedi, H. Karimi, Coordinated protection and control based on synchrophasor data processing in smart distribution networks, IEEE Trans. Power Syst. 33 (1) (2018) 634–645, https://doi.org/10.1109/tpwrs.2017.2708662.

[99] N.K. Sharma, S.R. Samantaray, Assessment of pmu-based wide-area angle criterion for fault detection in microgrid, IET Gener. Transm. Distrib. 13 (19) (2019) 4301–4310, https://doi.org/10.1049/iet-gtd.2019.0027.

[100] P. Kundu, A.K. Pradhan, Supervisory protection of islanded network using synchrophasor data, IEEE Trans. Smart Grid 10 (2) (2019) 1772–1780, https://doi.org/10.1109/tsg.2017.2777873.

[101] V.R. Pandi, H.H. Zeineldin, W. Xiao, Determining optimal location and size of distributed generation resources considering harmonic and protection coordination limits, IEEE Trans. Power Syst. 28 (2) (2013) 1245–1254, https://doi.org/10.1109/tpwrs.2012.2209687.

[102] A. Esmaeili, S. Esmaeili, H. Hojabri, Short-circuit level control through a multi-objective feeder reconfiguration using fault current limiters in the presence of distributed generations, IET Gener. Transm. Distrib. 10 (14) (2016) 3458–3469, https://doi.org/10.1049/iet-gtd.2016.0013.

[103] F. Guilherme Kaehler Guarda, G. Cardoso, U. Holanda Bezerra, J. Paulo Abreu Vieira, Minimising direct-coupled distributed synchronous generators impact on electric power systems protection, IET Gener. Transm. Distrib. 13 (18) (2019) 4190–4196, https://doi.org/10.1049/iet-gtd.2018.6757.

[104] M. Plećaš, H. Xu, I. Kockar, Integration of energy storage to improve utilisation of distribution networks with active network management schemes, CIRED Open Access Proc. J. 2017 (1) (2017) 1845–1848, https://doi.org/10.1049/oap-cired.2017.1090.

[105] N.B. Hartmann, R.C. dos Santos, A.P. Grilo, J.C.M. Vieira, Hardware implementation and real-time evaluation of an ann-based algorithm for anti-islanding protection of distributed generators, IEEE Trans. Ind. Electron. 65 (6) (2018) 5051–5059, https://doi.org/10.1109/tie.2017.2767524.

[106] S.K. Manikonda, D.N. Gaonkar, Idm based on image classification with cnn, J. Eng. 2019 (10) (2019) 7256–7262, https://doi.org/10.1049/joe.2019.0025.

[107] S. Jena, B.R. Bhalja, Development of a new fault zone identification scheme for busbar using logistic regression classifier, IET Gener. Transm. Distrib. 11 (1) (2017) 174–184, https://doi.org/10.1049/iet-gtd.2016.0785.

[108] G. Manassero, S.G. Di Santo, L. Souto, Heuristic method for fault location in distribution feeders with the presence of distributed generation, IEEE Trans. Smart Grid 8 (6) (2017) 2849–2858, https://doi.org/10.1109/tsg.2016.2598487.

[109] F.B. Costa, A. Monti, S.C. Paiva, Overcurrent protection in distribution systems with distributed generation based on the real-time boundary wavelet transform, IEEE Trans. Power Delivery 32 (1) (2017) 462–473, https://doi.org/10.1109/tpwrd.2015.2509460.

[110] A. Arunan, J. Ravishankar, E. Ambikairajah, Improved disturbance detection and load shedding technique for low voltage islanded microgrids, IET Gener. Transm. Distrib. 13 (11) (2019) 2162–2172, https://doi.org/10.1049/iet-gtd.2018.5707.

[111] M.H.J. Bollen, I.Y.-H. Gu, Processing of Nonstationary Signals, John Wiley & Sons, Inc., 2005, pp. 296–297.

[112] D.S. Kumar, D. Srinivasan, T. Reindl, A fast and scalable protection scheme for distribution networks with distributed generation, IEEE Trans. Power Delivery 31 (1) (2016) 67–75, https://doi.org/10.1109/tpwrd.2015.2464107.

[113] G. Bao, F. Zeng, H. Sun, Design of a short-circuit detection intelligent release using discrete wavelet algorithm, IEEE Access 7 (2019) 104228–104240, https://doi.org/10.1109/access.2019.2931704.

[114] C.-H. Kim, H. Kim, Y.-H. Ko, S.-H. Byun, R.K. Aggarwal, A.T. Johns, A novel fault-detection technique of high-impedance arcing faults in transmission lines using the wavelet transform, IEEE Trans. Power Delivery 17 (4) (2002) 921–929, https://doi.org/10.1109/TPWRD.2002.803780.

[115] M. Michalik, W. Rebizant, M. Lukowicz, S.-J. Lee, S.-H. Kang, High-impedance fault detection in distribution networks with use of wavelet-based algorithm, IEEE Trans. Power Delivery 21 (4) (2006) 1793–1802, https://doi.org/10.1109/TPWRD.2006.874581.

[116] N. Perera, A.D. Rajapakse, T.E. Buchholzer, Isolation of faults in distribution networks with distributed generators, IEEE Trans. Power Delivery 23 (4) (2008) 2347–2355, https://doi.org/10.1109/TPWRD.2008.2002867.

[117] N.I. Elkalashy, M. Lehtonen, H.A. Darwish, A.M.I. Taalab, M.A. Izzularab, Dwt-based detection and transient power direction-based location of high-impedance faults due to leaning trees in unearthed mv networks, IEEE Trans. Power Delivery 23 (1) (2008) 94–101, https://doi.org/10.1109/TPWRD.2007.911168.

[118] F.B. Costa, Boundary wavelet coefficients for real-time detection of transients induced by faults and power-quality disturbances, IEEE Trans. Power Delivery 29 (6) (2014) 2674–2687, https://doi.org/10.1109/TPWRD.2014.2321178.

[119] F.B. Costa, B.A. Souza, N.S.D. Brito, J.A.C.B. Silva, W.C. Santos, Real-time detection of transients induced by high-impedance faults based on the boundary wavelet transform, IEEE Trans. Ind. Appl. 51 (6) (2015) 5312–5323, https://doi.org/10.1109/TIA.2015.2434993.

[120] Intelligent computing techniques for smart energy systems: proceedings of ICTSES 2018, in: A. Kalam, K.R. Niazi, A. Soni, S.A. Siddiqui, A. Mundra (Eds.), Lecture Notes in Electrical Engineering, volume 607, Springer Singapore, Singapore, 2020, https://doi.org/10.1007/978-981-15-0214-9.

[121] S. Ram Ola, A. Saraswat, S.K. Goyal, S.K. Jhajharia, B. Khan, O.P. Mahela, H. Haes Alhelou, P. Siano, A protection scheme for a power system with solar energy penetration, Applied Sciences 10 (4) (2020) 1516, https://doi.org/10.3390/app10041516.

[122] N. Davydova, G. Hug, Travelling wave protection with disturbance classification for distribution grids with distributed generation, J. Eng. 2018 (15) (2018) 830–835, https://doi.org/10.1049/joe.2018.0176.

[123] S. Liu, X.S. Jin, R.R. Gokaraju, High-speed distance relaying using least error squares method and testing with FPGA, IET Gener. Transm. Distrib. 13 (16) (2019) 3591–3600, https://doi.org/10.1049/iet-gtd.2019.0088.

[124] PSRC Working Group D15, High Impedance Fault Detection Technology. Technical Report, IEEE - Power System Relay Committee, 1996.

[125] X. Song, Y. Zhang, S. Zhang, S. Song, J. Ma, W. Zhang, Adaptive protection scheme for distributed systems with DG, J. Eng. 2017 (13) (2017) 1432–1436, https://doi.org/10.1049/joe.2017.0568.

[126] M. Kavi, Y. Mishra, M. Vilathgamuwa, Morphological fault detector for adaptive overcurrent protection in distribution networks with increasing photovoltaic penetration, IEEE Trans. Sustain. Energy 9 (3) (2018) 1021–1029, https://doi.org/10.1109/tste.2017.2759158.

[127] S.F. Zarei, M. Parniani, A comprehensive digital protection scheme for low-voltage microgrids with inverter-based and conventional distributed generations, IEEE Trans. Power Delivery 32 (1) (2017) 441–452, https://doi.org/10.1109/tpwrd.2016.2566264.

[128] Y.N. Velaga, R. Jain, J. Sawant, Modeling Distributed Energy Resources for Analyzing Distribution Systems with High Renewable Penetration. 2022 IEEE Rural Electric Power Conference (REPC), IEEE, Savannah, GA, USA, 2022, pp. 11–17, https://doi.org/10.1109/REPEC55671.2022.00011.

[129] A. Haddadi, M. Zhao, I. Kocar, U. Karaagac, K.W. Chan, E. Farantatos, Impact of inverter-based resources on negative sequence quantities-based protection elements, IEEE Trans. Power Delivery 36 (1) (2021) 289–298, https://doi.org/10.1109/TPWRD.2020.2978075.

[130] N.S. Gurule, J. Hernandez-Alvidrez, M.J. Reno, A. Summers, S. Gonzalez, J. Flicker, Grid-forming inverter experimental testing of fault current contributions. 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), 2019, pp. 3150–3155, https://doi.org/10.1109/PVSC40753.2019.8980892.

[131] N.S. Gurule, J.A. Azzolini, R. Darbali-Zamora, M.J. Reno, Impact of grid support functionality on PV inverter response to faults. 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), IEEE, Fort Lauderdale, FL, USA, 2021, pp. 1440–1447, https://doi.org/10.1109/PVSC43889.2021.9518953.

[132] A. Nelson, G. Martin, J. Hurtt, Experimental evaluation of grid support enabled PV inverter response to abnormal grid conditions. 2017 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), IEEE, Washington, DC, USA, 2017, pp. 1–5, https://doi.org/10.1109/ISGT.2017.8086016.

[133] Luka V Strezoski, Nikola R Vojnovic, Vladmir C Strezoski, Predrag M Vidovic, Marija D Prica, Kenneth A Loparo, Modeling challenges and potential solutions for integration of emerging DERs in DMS applications: power flow and short-circuit analysis, J. Mod. Power Syst. Clean Energy 7 (2019) 1365–1384, https://doi.org/10.1007/s40565-018-0494-1.

[134] W. Qian, L. Jun, D. Jiandong, T. Wangjing, Analysis of the impact of distributed generation on grounding method of distribution network, J. Eng. 2017 (13) (2017) 907–910, https://doi.org/10.1049/joe.2017.0461.

[135] L. Rosa, M. Louro, B. Almeida, F. Gonçalves, A.M. Rodrigues, J. Ferreira Pinto, Distributed generation at distribution system level resilience to voltage dips – a real case, CIRED Open Access Proc. J. 2017 (1) (2017) 1703–1706, https://doi.org/10.1049/oap-cired.2017.1055.

[136] T. Smith, R. Hunt, Current transformer saturation effects on coordinating time interval, IEEE Trans. Ind. Appl. 49 (2) (2013) 825–831, https://doi.org/10.1109/tia.2013.2243397.

[137] R. Dubey, B.K. Panigrahi, S.R. Samantaray, Simultaneous impact of unified power flow controller and off-shore wind penetration on distance relay characteristics, IET Gener. Transm. Distrib. 8 (11) (2014) 1869–1880, https://doi.org/10.1049/iet-gtd.2014.0066.

[138] P.-C. Chen, V. Malbasa, Y. Dong, M. Kezunovic, Sensitivity analysis of voltage SAG based fault location with distributed generation, IEEE Trans. Smart Grid 6 (4) (2015) 2098–2106, https://doi.org/10.1109/tsg.2014.2387153.

[139] M.A. Haj-ahmed, M.S. Illindala, The influence of inverter-based DGs and their controllers on distribution network protection, IEEE Trans. Ind. Appl. 50 (4) (2014) 2928–2937, https://doi.org/10.1109/tia.2013.2297452.

Rishabh Jain (S'12 - M'18) received his bachelors in electrical engineering (EE) from Indian Institute of Technology Dhanbad, India, and, M.S. and Ph.D. in EE from University of Idaho and North Carolina State University, USA in 2014, and 2018 respectively. Rishabh is currently a research engineer at the National Renewable Energy Laboratory. In this position, he is working on protection, control, and operational challenges of distribution system management, commercial fleet vehicle electrification, and, grid integration of hydrogen systems. He specializes in developing power- and control-hardware-in-the-loop modeling for power system analysis, and grid-integration challenges of distributed energy resources. Previously, he worked at Schweitzer Engineering Labs on analysis/development of protection schemes for transmission and distribution systems with high renewable penetration. His research interests are focused in scalable integration and protection challenges for autonomous energy systems, wide-area transportation fleet electrification, and grid support using alternate fuel technologies.

Yaswanth Nag Velaga (Member, IEEE) received the Ph.D. and M.S. degrees in electrical engineering (energy systems) from Colorado School of Mines, CO. He worked as a Protection Engineer with Schweizer Engineering Laboratories, Denver, CO. He is currently a Research Engineer with the National Renewable Energy Laboratory, Golden, CO. His research is focused on protection, renewable energy, and distributed generation.

Kumaraguru Prabakar (Senior Member, IEEE) received the M.S. degree from Arizona State University, in 2011, and the Ph.D. degree from The University of Tennessee, in 2016. He is currently a Senior Research Engineer with the National Renewable Energy Laboratory, Golden, CO. He leads research projects targeting improvements in distribution system protection, and interoperability of distribution system assets. He is a Technical Contributor in multiple microgrid controller evaluation projects and advanced distribution management systems evaluation projects. His research work focuses on the use of controller hardware-in-the-loop (HIL), power HIL experiments, and remote HIL experiments to evaluate controller hardware and power hardware.

Murali Baggu (Senior Member, IEEE) received the B.Tech. degree in electrical and electronics engineering from Kakatiya University, India, the M.S. degree in electrical engineering from the University of Idaho, Moscow, ID, USA, and the Ph.D. degree in electrical engineering from the Missouri University of Science and Technology, Rolla, MO, USA, in 2009. Currently, he is the Laboratory Program Manager for grid integration at the National Renewable Energy Laboratory (NREL), Golden, CO, USA. In this role, he leads the DOE Office of Electricity and Grid Modernization's Initiative Program, NREL. He currently directs and leads the NREL's Advanced Distribution Management Systems and Puerto Rico Grid Recovery and Resilience Efforts. He has extensive experience in advanced grid control and evaluation for future power systems with high penetrations of distributed energy resources. Before joining NREL, he worked as a Lead Power Systems Engineer at GE Global Research, Niskayuna, NY, USA, where he developed advanced volt/VAR control and DER management algorithms. At GE, he also led the technology development and deployment of large-scale energy storage integration with photovoltaic systems for the Department of Defense Marine Corps Installations. He has four issued patents and more than 50 publications in these areas. His research interests include grid integration of renewables systems (wind and PV), energy storage system integration, distribution automation, and grid operations and control. He is presently the Chair of the IEEE Distribution System Operation and Planning Sub-Committee.

Kevin P. Schneider (Fellow, IEEE) received the B.S. degree in physics and the M.S. and Ph.D. degrees in electrical engineering from the University of Washington. He is currently a Laboratory Fellow with the Pacific Northwest National Laboratory, the Manager of the Distribution and Demand Response Sub-Sector, and a Research Professor with Washington State University as part of the PNNL/WSU Advanced Grid Institute. He is an Affiliate Associate Professor with the University of Washington and a Licensed Professional

Engineer with Pullman, WA, USA. His main research interests include distribution system analysis and power system operations. He is the Past Chair of the Power and Energy Society Distribution System Analysis Sub-Committee and the Analytic Methods for Power Systems Committee.