EE 511 Protection of Power Systems II

Final Report

Protection of Renewable Penetrated Power System

December 2023

Submitted by

Athul Jose P
11867566

School of Electrical Engineering and Computer Science
Washington State University

Abstract

The integration of renewable energy sources such as wind and solar into existing power systems marks a crucial step towards sustainable electricity and environmental conservation. However, this integration introduces unique challenges, particularly in power system protection, as traditional protection schemes are not fully equipped to handle the distinct fault characteristics of renewables, especially inverter-based ones. This report investigates these complexities and suggests both adaptive and non-adaptive relaying strategies to maintain the dynamic and reliable operation of power systems with renewable integrations. It emphasizes the need for adaptable and innovative protection mechanisms that can respond effectively to the variable and intermittent nature of renewable energy sources.

Addressing the specific challenges of integrating Distributed Energy Resources (DERs) into distribution systems, the report delves into issues like bidirectional power flow and fault currents. It also explores the impact of inverter-based fault currents on network protection, stressing the importance of fault current management solutions that are tailored to the generation technologies in use. Furthermore, the report introduces an adaptive overcurrent protection system, designed for modern distribution networks, which dynamically adjusts relay settings in response to changes brought by distributed generation, active network management, and islanding operations. Ultimately, the report underscores the need for ongoing research and development in power system protection to ensure a seamless blend of traditional and renewable energy sources in power systems.

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1 Introduction

1.1 Overview

As the global energy landscape evolves, integrating renewable energy sources like wind and solar into existing power systems has become increasingly important[7]. These green energy alternatives are vital for meeting future electricity demands and reducing environmental impact. However, their integration presents unique challenges, particularly concerning the power system's protection mechanisms. In recent years, there has been a paradigm shift in the global energy sector, primarily driven by the integration of renewable energy sources such as wind and solar into existing power systems. This transformation is not just a trend but a necessity, as these green energy alternatives are pivotal in meeting the burgeoning electricity demands of the future while simultaneously reducing the environmental footprint. [8]

The adoption of wind and solar energy, among other renewables, is crucial for a sustainable energy future. These sources of energy offer a cleaner and more sustainable alternative to traditional fossil fuels, addressing both environmental concerns and the growing global demand for electricity. However, the integration of these renewable sources into existing power systems is not without its challenges. One of the primary concerns revolves around the protection mechanisms of power systems. Renewable energy sources, especially those that are inverter-based, exhibit distinct fault characteristics that traditional protection schemes are not designed to handle [9]. Traditional protection schemes are based on certain assumptions about network topology and fault characteristics. The integration of renewable energy sources often violates these assumptions, leading to new challenges in maintaining the reliability and safety of the power systems.

1.2 Integration Challenges

The incorporation of renewable sources into power systems changes the traditional dynamics of these systems. Understanding the diverse range of renewable sources and their varying impacts on the power grid is essential for effective integration. Some of the integration challenges are listed as:

1. **Variability in Fault Levels**
   The incorporation of renewable sources significantly alters the fault dynamics in power systems. Unlike traditional sources, renewables like wind and solar energy exhibit variable output, leading to fluctuating fault levels that challenge existing protection schemes.

2. **Intermittency of Renewable Resources**
   The intermittent nature of wind and solar energy results in inconsistent energy production. This intermittency impacts the reliability and stability of power systems, necessitating adjustments in protection mechanisms to handle these fluctuations.

3. **Renewable Energy Source Classification**
   The diverse range of renewable energy sources, classified based on their power output capacity, affects the design and adaptation of protection schemes. The classification helps in understanding the varying impacts each source has on the power grid.

1.3 Solutions and Adaptations

1. **Adaptive Relaying Schemes**
   To address the dynamic nature of renewable integrations, adaptive relaying schemes are essential. These schemes dynamically adjust the protection settings in response to changing network topologies and varying fault currents, ensuring continued reliability and safety.

2. **Non-Adaptive Relaying Strategies**
   These involve measures to limit or block the fault current contributions from renewable sources, thereby maintaining the integrity of the existing protection framework. Such strategies are crucial in scenarios where adaptive schemes are not feasible.

3. **Comprehensive Analysis of Protection Schemes**
   A thorough examination of various protection schemes tailored for distribution systems, transmission networks, and microgrids is crucial. This analysis covers both the advantages and limitations of each scheme, providing a holistic understanding of the best practices in renewable energy integration.

1.4 Implications for the Future

This chapter underscores the importance of innovation and adaptability in power system protection. As renewable energy sources become more prevalent, the need for advanced, flexible protection mechanisms will continue to grow. The insights presented here are instrumental for both practitioners in the field and researchers, guiding the development of smarter, more resilient power systems for the future. As the world moves towards a more sustainable energy future, understanding and addressing these protection challenges becomes essential. This section of the report sets the stage for a deeper exploration of these challenges and the innovative solutions being developed to overcome them.

1.5 Chapter Summary

The integration of renewable energy sources into power systems is at the forefront of the global energy transition. This integration, while essential, brings forth challenges that demand a shift in the traditional protection paradigms. The key lies in developing flexible and adaptable protection schemes that can accommodate the dynamic and distributed nature of renewable energy sources. Embracing these changes paves the way for a more sustainable, efficient, and resilient energy future. To address these challenges effectively, it is imperative to analyze the impact of renewable energy integration on both distribution and transmission systems separately. Each of these systems faces unique challenges due to the integration of renewables, necessitating a tailored approach in their respective protection schemes. This report will delve into these challenges in detail, exploring the various ways in which the integration of renewable energy sources is redefining the landscape of power system protection. We will separately discuss the implications and solutions for distribution and transmission systems, providing a comprehensive overview of this critical aspect of the energy transition.

2 Distribution Systems

2.1 Introduction

The integration of Distributed Energy Resources (DERs) into distribution systems brings challenges for traditional protection schemes. These challenges are due to the bidirectional flow of power and fault currents, which traditional systems are not designed to handle. Revisions to DER interconnection standards, particularly regarding voltage regulation and ride-through, have been made to address these complexities. This chapter reviews the state of the art in distribution system protection in this new environment, identifies gaps, and proposes near-term solutions.

The studies aims to concentrate on three primary objectives[1].

1. Identifying state-of-the-art solutions for protective relaying in environments with bidirectional power flow at distribution and microgrid levels.
2. Determining the best solutions for distribution and microgrid systems, ranking them based on various criteria such as protection metrics, effectiveness, cost, complexity, information requirements, supporting infrastructure, and the experience level of protection engineers.
3. Identifying gaps in addressing bidirectional flow that are not covered by current state-of-the-art solutions.

2.2 Summary of DER Interconnection Requirements in IEEE 1547

IEEE 1547-2018 establishes two categories of DER for voltage regulation and reactive power control:

- Category A for minimum performance.
- Category B for high-penetration scenarios

It also outlines three categories for response to disturbances:

- Category I for the essential needs of the bulk power system.

- Category II for ride-through compatibility.
- Category III for high-penetration scenarios.

The standard sets requirements for DER to cease energizing the utility power system and trip during faults. It allows limited reactive power exchange and adjustable time frames for detecting and ceasing to energize during unintended islands.

2.3 Topology based problems due to integration of DG

The integration of distributed generation (DG) into conventional distribution systems, which were originally designed for straightforward, unidirectional power flow, has led to significant changes in network topology and operational dynamics. This evolution is best understood through an examination of the voltage profiles of these systems.

Initially, distribution systems with a single power source exhibited a predictable voltage profile, represented in Figure 1. However, the addition of DG creates a more complex scenario, altering this voltage profile considerably, as illustrated in Figure 2. These changes have profound implications for the existing protection systems within the distribution network.

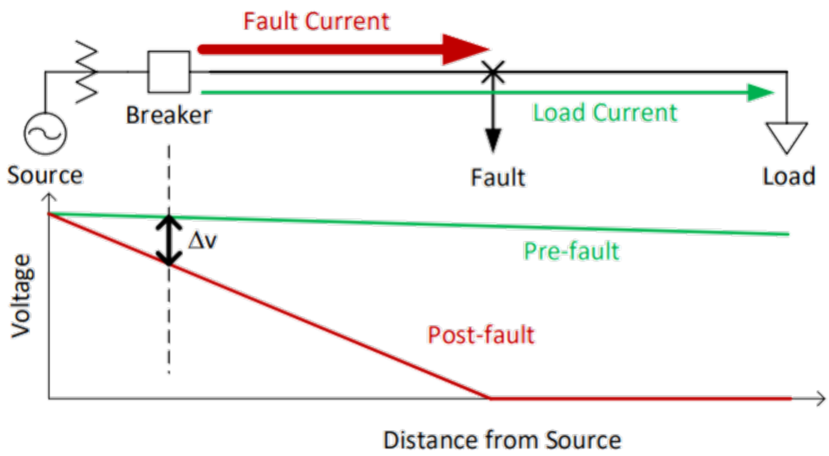

Figure 1: Voltage profile without DG [1]

The incorporation of DG not only alters the voltage profile but also introduces a range of operational challenges. One such challenge is highlighted in Figure 3, which shows how the sequence of protective device operations is affected by DG. In a traditional setup, a fault would typically trigger the recloser to activate before the fuse, ensuring system

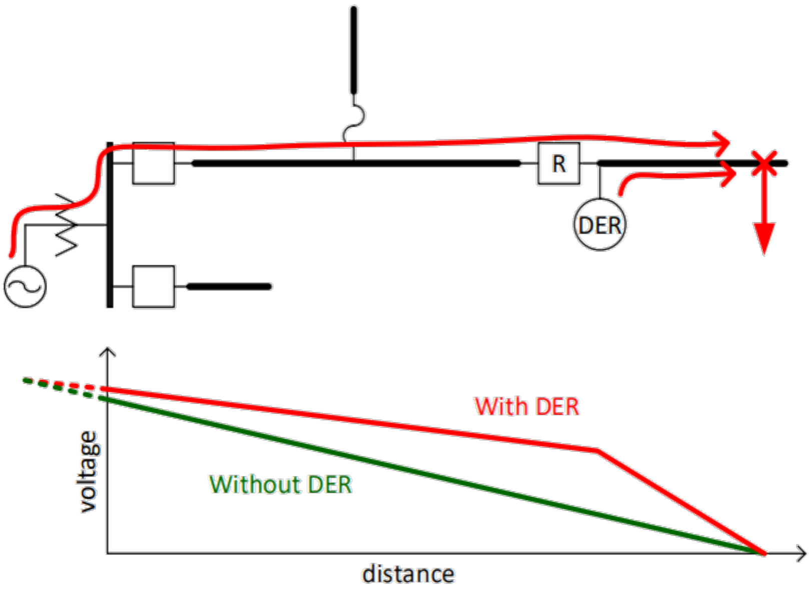

Figure 2: Voltage profile with DG [1]

protection and stability. However, with DG's contribution to fault current, there's an increased likelihood that fuses may blow prematurely, potentially before the recloser acts. This alteration in the protective sequence can lead to reliability and safety concerns in the distribution system.

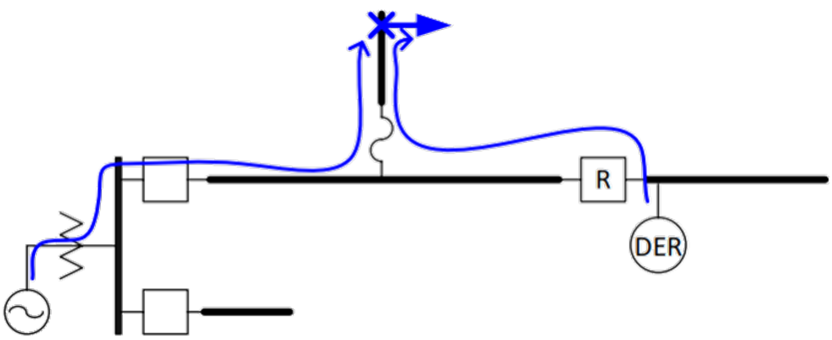

Figure 3: Impact on network topology [1]

Moreover, the presence of DG has been observed to cause sympathetic tripping, a phenomenon where protective devices incorrectly respond to disturbances in the system. Figure 4 delves into this issue, illustrating how DG can inadvertently trigger unwanted tripping in parts of the system that are not directly affected by a fault. Such incidents underscore the complexities introduced by DG, which require careful consideration and adaptation of protection strategies to maintain system integrity and reliability.

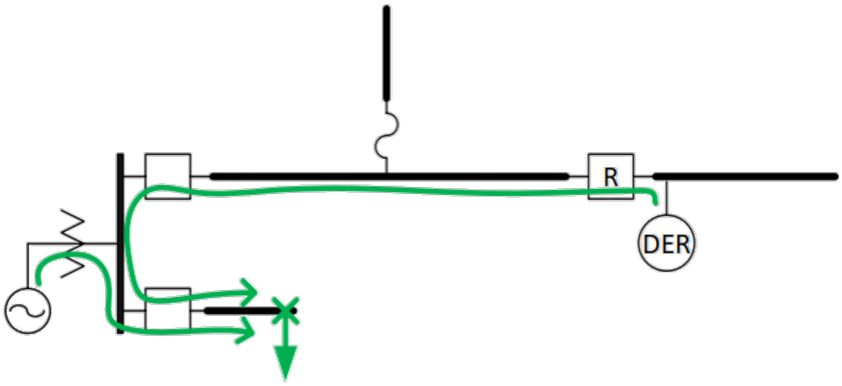

Figure 4: Sympathetic Tripping [1]

In summary, while the integration of DG offers numerous benefits, it also necessitates a reevaluation and potential redesign of conventional distribution systems to effectively manage the new dynamics and ensure continued reliability and safety.

2.4 Characteristics of DER for Protection

DERs vary in their fault current magnitude and angle:

- Rotating-machine DERs behave similarly to substation sources but are weaker.
- Inverter-based DERs provide less fault current and have fast-acting controls that can quickly adjust the phase angle between current and voltage.

2.5 Analysis of Inverter-Based Fault Current

This section presents an analysis of the effects of distributed generation (DG) technologies on network fault levels, focusing on the comparison between inverter-based (IBDG) and synchronous-based DG systems. The research reveals that synchronous generators contribute more significantly to fault levels compared to induction generators. In contrast, inverter based systems have the lowest contribution to fault levels owing to their non-overload characteristics, though this is contingent on the control methods employed [10].

A detailed exposition of a three-phase IBDG system is provided[2], elucidating its connection to various energy sources, the utilization of voltage source inverters, and the integration into distribution networks. Notably, the paper delves into the control methods used to manage fault currents, such as proportional-integral control and space vector modulation, highlighting their efficacy in fault current regulation. The section also addresses several critical challenges in network protection within highly distributed power systems. These challenges include issues like automatic reclosing, protection blinding, and sympathetic tripping, which are pertinent concerns in the context of modern power systems [11].

Furthermore, comprehensive recommendations for fault management in scenarios where IBDG systems dominate are offered. These recommendations include strategies for limiting inverter output current during faults and protocols for inverter tripping to mitigate fault impacts. To substantiate the theoretical aspects, four case studies conducted using simulations are included. These case studies demonstrate various scenarios, including high fault current situations, faults through high impedance paths, and sympathetic tripping, thereby providing practical insights into the behavior of IBDG under different fault conditions and its implications for network protection. Typical fault current from a synchronous generator and IBDG is shown in Figure 5.

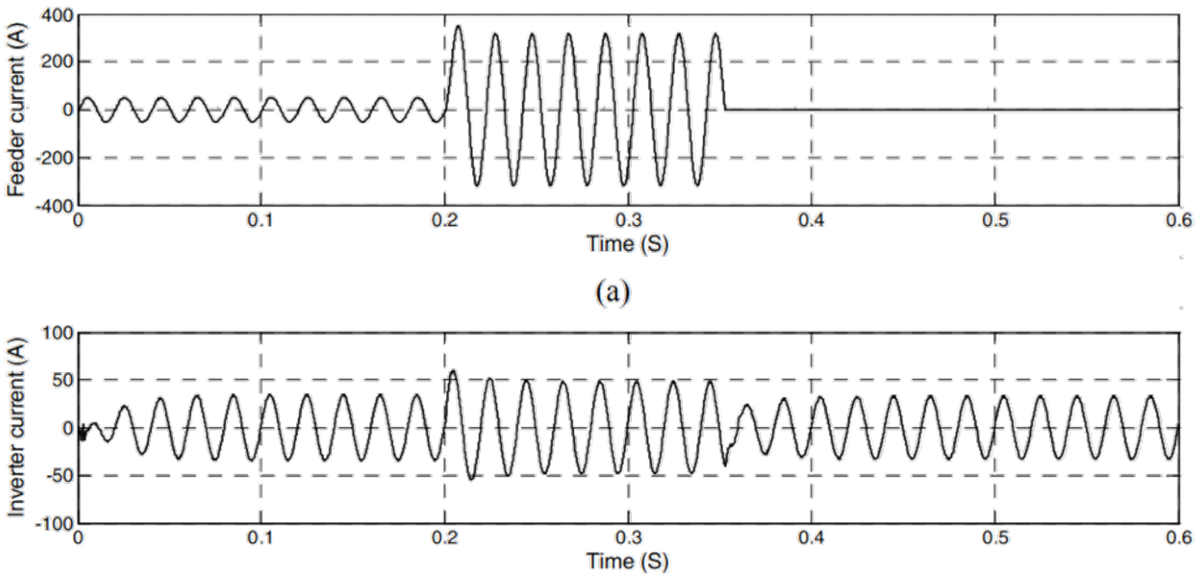

Figure 5: Fault Current from SG vs IBDG [2]

In conclusion, the necessity for fault current management solutions to be specifically tailored to the generation technologies in use is underscored. It highlights the distinct requirements for systems dominated by conventional rotating plants compared to those employing newer generation technologies connected via inverter interfaces, emphasizing the unique challenges and solutions pertinent to each technology type.

2.6 Adaptive Over Current Relaying Schemes

Modern distribution networks are moving towards the smart grid concept, characterized by increased distributed generation (DG), active network management (ANM), and potential islanded operations. These developments significantly alter fault levels and paths, posing challenges to traditional overcurrent protection systems. This section examines an adaptive overcurrent protection system [3] designed to dynamically adjust the settings of all overcurrent relays in response to changes brought by DG, ANM, and islanding operations. The scheme, developed using commercially available protection devices, leverages IEC61850-based communications. It has been extensively tested in a hardware-in-the-loop laboratory setting, demonstrating its effectiveness over conventional systems by reducing false operations and enhancing mean operating time.

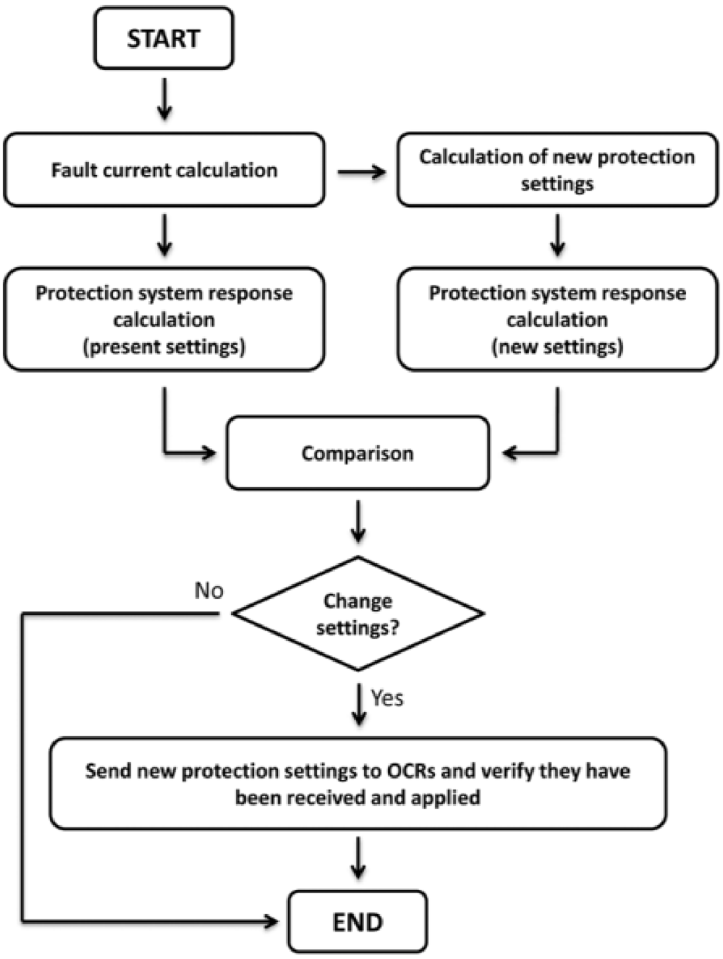

Figure 6: Adaptive Over Current Algorithm [3]

The adaptive system's architecture spans three layers - the primary system (comprising physical components like lines, transformers, DG units), the execution layer (with intelligent electronic devices like overcurrent relays), and the coordination layer (monitoring and coordinating IEDs). A key feature is its fault current calculation and real-time setting adjustment based on network conditions, including DG connectivity and islanded/grid-connected status. Systematic simulations showed that the adaptive scheme offers significant improvements in dependability, security, and mean operation time compared to traditional systems. It effectively addresses challenges like the altered magnitude and direction of fault currents due to DG, reconfigurations triggered by ANM, and varying fault levels in islanded mode[12].

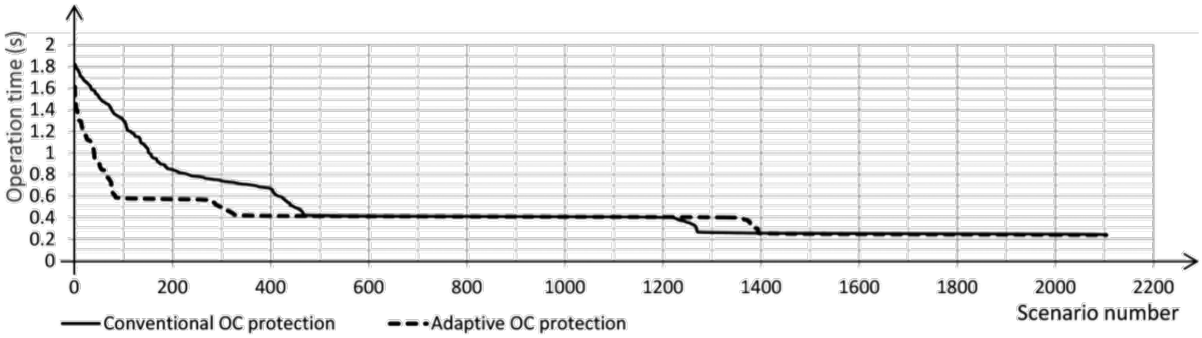

Figure 7: Conventional OCR vs Adaptive OCR [3]

Specific scenarios, such as network reconfiguration, DG integration, and transition to islanded operation, were simulated to test the system's responsiveness. The adaptive scheme successfully mitigated issues like miscoordination of relays, false tripping due to DG-induced fault current increases, and delayed or non-operation during islanded conditions. The adaptive overcurrent protection system represents a significant advancement in network protection, offering flexibility and comprehensive coverage for evolving smart grid scenarios. Its centralized algorithm-based approach, tailored to real-time network conditions, provides a robust solution to the complexities introduced by modern distributed generation and active network management technologies.

2.7 Adaptive Voltage Restrained OCR

The integration of solar photovoltaic (PV) plants in distribution systems alters fault current behavior, limiting the effectiveness of traditional overcurrent relays (OCRs). Voltage restrained overcurrent relay (VR-OCR) offers a potential solution, but its performance is affected by the system's loading condition. This study [4] proposes an adaptive scheme for VR-OCR settings to accommodate varying power system conditions in PV connected distribution systems.

The integration of inverter-based PV plants in distribution systems presents challenges for conventional OCR due to limited fault current, making it difficult to distinguish between fault and normal conditions. The paper proposes an adaptive VR-OCR scheme to address this issue. In systems with integrated PV plants, fault currents are often comparable to load currents, making it challenging for VR-OCR to differentiate between faults and normal operating conditions. The study highlights the need for an adaptive protection scheme that can respond to varying fault current magnitudes in PV connected distribution systems.

The proposed method adjusts VR-OCR pickup settings based on prefault current data and input voltage as shown in Figure 8, updating settings each cycle to make accurate protection decisions. This adaptive approach aims to address the limitations of conventional VR-OCR in the presence of PV plants. The equation corresponding to the pickup is given by 1:

$$I_{pickup_new} = I_{pre}e^{V-1} \tag{1}$$

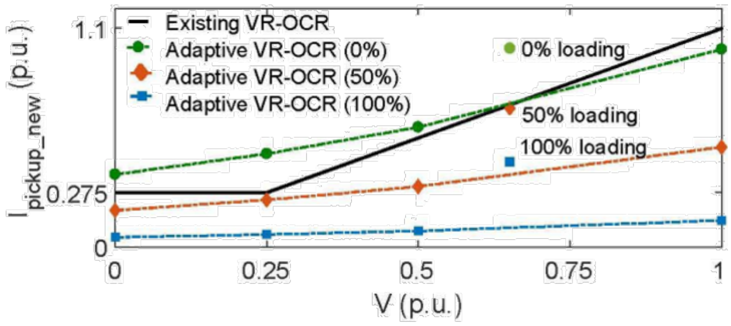

Figure 8: Adaptive Voltage Restrained Over Current Relaying Scheme [4]

The adaptive VR-OCR method successfully addresses the challenges posed by the integration of PV plants in distribution systems. By adaptively updating its settings in response to prefault conditions and input voltage variations, the proposed method improves the reliability and efficiency of line protection in PV connected systems. The study suggests that this approach is suitable for PV integrated distribution systems with varying loading conditions, demonstrating its potential for future applications in smart grids. Overall, the paper presents a significant advancement in protection schemes for distribution systems with integrated PV plants, offering a promising solution to the challenges posed by renewable energy integration in modern power networks.

2.8 Chapter Summary

The chapter underscores the necessity of fundamentally rethinking traditional protection strategies in distribution systems, driven by the increasing integration of Distributed Energy Resources (DERs). It draws attention to the critical role of flexible and dynamic protection systems, along with the need to update current methodologies, to maintain reliability and safety amidst the changing network dynamics and growing presence of DERs. In essence, the incorporation of Distributed Generation (DG) into distribution systems demands sophisticated, adaptable protection approaches to manage these new dynamics effectively. The chapter offers valuable perspectives on the emerging solutions and necessary modifications for contemporary power networks that incorporate renewable energy sources.

3 Transmission Systems

3.1 Overview

In contemporary power systems, the need for advanced protection strategies is paramount, especially with the complexities introduced by modern network topologies and the bidirectional flow of power. Numerical relays emerge as sophisticated protection elements, leveraging digital processing techniques to enhance the accuracy and reliability of power system protection. Numerical relays are the cornerstone of modern protection schemes. These microprocessor-based devices perform various functions, including measurement, signal processing, and decision-making, based on the algorithms programmed into them. Unlike their electromechanical and static relay predecessors, numerical relays offer enhanced precision, adaptability, and functionality within compact and integrated units.

The core principle behind protection schemes in numerical relays is the analysis of fault current and voltage. These relays continuously monitor the electrical parameters of the network and, upon detecting anomalies that suggest fault conditions—such as overcurrent, voltage sags, or phase imbalances—they initiate protective actions. The schemes are intricately designed to discern between transient disturbances and persistent fault states, ensuring prompt and appropriate responses. The topology of the power network plays a critical role in the configuration and operation of protection schemes. As power systems evolve into more complex and interconnected networks, the topological arrangement of lines, buses, and nodes becomes increasingly vital. Numerical relays must account for these arrangements to ensure protection schemes are both effective and coordinated across the network.

With the rise of distributed generation sources, such as solar and wind, power flow in networks is no longer unidirectional—from generation to consumption—but bidirectional. This transition poses significant challenges for traditional protection schemes. Numerical relays are equipped with algorithms capable of handling these bidirectional flows, ensuring protection mechanisms remain robust and responsive in diverse operating conditions. A single numerical relay can incorporate multiple protection elements, each designed for specific functions like overcurrent, distance, differential, or voltage protection. This multifunction capability allows for a more integrated and space-efficient approach to network protection. Additionally, the use of multiple elements within a single relay facilitates comprehensive protection strategies that can adapt to a range of fault scenarios.

At the heart of numerical relay operation is phasor domain analysis. Numerical relays use phasor measurements to analyze the magnitude and phase angle of current and voltage waveforms, enabling accurate real-time monitoring of power system dynamics. This phasor-based approach is essential for the effective operation of protection schemes, particularly in systems where power flow patterns are variable and complex. Numerical relays represent a significant advancement in power system protection technology. By leveraging detailed phasor domain analysis and accommodating the intricacies of modern network topologies and bidirectional power flows, these devices form the backbone of adaptive, reliable, and efficient protection schemes. As power systems continue to evolve, the role of numerical relays in maintaining system integrity and stability will only become more crucial.

3.2 Need of EMT Analysis

The integration of Inverter-Based Resources (IBRs) into power systems has prompted a reevaluation of traditional protection schemes. The distinct characteristics of IBRs, such as their weak fault contributions and non-traditional fault current profiles, necessitate advanced simulation methods for accurate protection studies. This section explores the significance of Electromagnetic Transients (EMT)-type simulations for power systems incorporating IBRs [13]. EMT-type simulations are critical for capturing the nuanced behaviors of power systems with IBRs, particularly during transient events. These simulations, which solve differential equations using numerical methods, are capable of representing a broad frequency spectrum, essential for analyzing high-frequency transient phenomena. The detailed grid and control modeling facilitated by EMT programs like EMTP (Electromagnetic Transients Program) are unparalleled in phasor-domain simulations.

Conventional phasor-domain simulations, while useful for representing the fundamental frequency components, fall short in capturing transient events that IBRs introduce. These events can significantly impact the performance of phasor-based protection elements [14]. EMT-type simulations offer the granularity needed to evaluate the impact of IBRs during fault conditions, making them an indispensable tool for modern protection studies. The transient events associated with IBRs, such as inverter power switching and PLL operation, can introduce distortions and frequency deviations. These can affect the accuracy of phasor estimations, consequently impacting the performance of protection schemes. EMT-type simulations can replicate these transient events, providing a realistic portrayal of their effects on protection elements.

3.3 Modeling Recommendations for EMT-Type Simulations

For EMT-type simulations to be effective in protection studies, certain modeling recommendations must be followed:

1. **Frequency Dependence of Line Parameters**

To accurately represent traveling waves (TWs), models that consider the frequency-dependent behavior of line parameters are essential.

2. **Earth Resistivity Uncertainties**
   Accurate modeling of earth resistivity is crucial as it influences ground mode TWs and the mixing mode phenomenon during fault conditions.

3. **Line Termination Features**
   Detailed representation of line terminations, including busbar and transformer stray capacitances, is necessary to ensure the correct reflection and attenuation characteristics of TWs.

4. **IBR Transient Events**
   Models must account for transient events such as crowbar operation in DFIG units and variations in PLL behavior under fault conditions.

As TW-based protection solutions gain popularity, particularly in systems with IBRs, EMT-type simulations become essential. They enable the evaluation of transient phenomena that cannot be accurately represented by phasor-domain simulations. The fidelity of EMT simulations in replicating these transients is crucial for the development and testing of TW-based protection elements. The integration of IBRs into power systems introduces a range of transient events that traditional phasor-domain simulations cannot adequately represent. EMT-type simulations, while computationally intensive, provide the necessary resolution to study these events and their impacts on protection systems. As power grids evolve and the penetration of IBRs increases, EMT-type simulations will play an increasingly vital role in ensuring the reliability and accuracy of protection studies.

3.4 Impact of Inverter-Based Resources (IBRs) on System Protection: An In-Depth Analysis

The rapid rise of Inverter-based resources (IBRs) has ushered in a transformative period in power system operations. This shift has precipitated a critical examination of the interactions between IBRs and existing system protection schemes. Traditional schemes, designed in the era of synchronous generators (SGs), may not perform adequately when faced with the different operational characteristics of IBRs. This paper presents a comprehensive analysis of the effects that IBRs exert on conventional protection mechanisms and outlines potential strategies for maintaining system integrity.

Globally, the energy sector is witnessing a transition towards renewable sources such as wind turbine generators (WTGs) and photovoltaic (PV) systems. This change, driven by technological advancements and cost reductions, has led to the increased connection of these sources through power electronics. Unlike traditional SGs, IBRs exhibit distinct fault current characteristics that pose new challenges for protection schemes. The research aims to scrutinize the repercussions of this paradigm shift and propose modifications to legacy protection systems to ensure their continued efficacy.

3.4.1 Line Distance Protection

The paper [15] elucidates two primary concerns regarding line distance protection in the context of IBRs:

1. **Reduced Reach Accuracy**
   The dynamic nature of IBR impedance can lead to unpredictable variations in the mho circle expansion of distance relays, which may result in either overreach or underreach.
2. **Misoperation Due to Low Supervising Current**
   The inherently lower fault current from IBRs may not meet the minimum operating thresholds set for distance relays, leading to potential non-operation in fault conditions.

Simulation studies substantiate these concerns, and the paper advocates for recalibrated settings that account for the unique characteristics of IBRs, including minimal phase overcurrent supervision and the integration of undervoltage protection as a safeguard.

3.4.2 Zero Sequence Directional Protection

The study spotlights a critical vulnerability in zero-sequence directional protection due to the IBRs' swift control response times. This rapid response can induce a phase angle shift in voltage that may not be anticipated by traditional protection logic, causing erroneous directional decisions during fault conditions. The paper suggests solutions such as self-polarization and memory voltage angle compensation to realign protection performance with the altered system dynamics [16].

3.4.3 Negative Sequence Components Based Protection Schemes

The effectiveness of protection functions that depend on negative sequence components, like 50Q and 51Q, is compromised by the lower amplitude and altered phase angle of I2 in IBR scenarios. The analysis recommends the adoption of IBR I2 control strategies, such as those specified in the German grid code, to mitigate these effects. The paper underscores the necessity for careful calibration of I2 injection to balance fault detection capabilities with the current limitations of IBRs [17].

3.4.4 Line Current Differential Protection and IBR Challenges

Line Current Differential (LCD) protection (87L) is a critical scheme for the security of power systems, particularly for protecting essential lines and very short lines where traditional distance relays might not be effective. LCD protection operates by assessing the sum of currents entering a protected zone, which should ideally be near zero except during internal faults[18].

The 87L elements are segregated into phase (87LP), negative-sequence (87LQ), and zero-sequence (87LG) differential elements. LCD schemes include the conventional amplitude-based method and the Alpha Plane method that employs a complex current ratio. However, the integration of Inverter-Based Resources (IBRs) introduces different fault current patterns, potentially affecting the reliability of LCD relays. The fault current might fall within an incorrect region of the LCD characteristic, leading to the misclassification of an internal fault as external. This risk varies between the traditional and Alpha Plane schemes due to their distinct detection algorithms.

Traditional LCD Performance: Simulation tests demonstrate that the traditional LCD scheme effectively identifies internal faults within its protection zone across various fault scenarios and generation types, including IBRs. Faults are indicated by "x" markers and, regardless of whether the source on bus L is a Synchronous Generator (SG) or an IBR, all faults fall within the LCD's operate region. This suggests that the traditional LCD is not prone to misoperation due to IBRs, although it may fail to detect faults at very high resistance values, a limitation shared with SG sources.

Alpha Plane LCD Analysis: For the Alpha Plane LCD, the post-fault trajectories for the 87L elements indicate that under SG conditions, the relay functions correctly, with the current ratios moving into the operate region. In contrast, under Type IV IBRs without I2 control, the trajectories stay within the restrain zone, leading to a failure in detecting internal faults. This failure is attributed to the low amplitude and altered phase angle of I2 from the Type IV IBR, which produces a post-fault operating point that remains within the restraining region.

With Type IV-based IBR featuring I2 control, the misoperation is rectified for both 87LA and 87LQ elements. The 87LQ element exits the restraining zone due to an enhanced amplitude of I2, and the 87LA element's trajectory also leaves the restrain zone

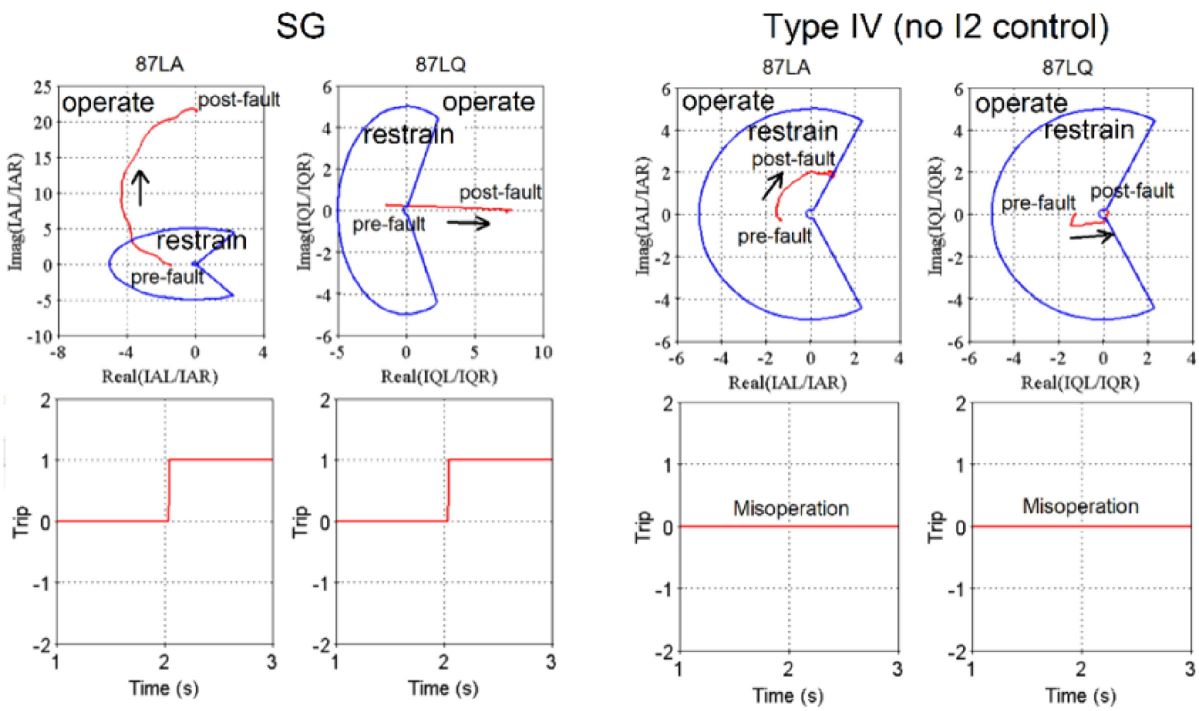

Figure 9: Line Current Differential [5]

owing to the adjusted phase angle of ILA influenced by the injected reactive I2.

Recommendations: The case study indicates a potential risk of misoperation for Alpha Plane LCD schemes when interfacing with IBRs. Simulations suggest that implementing I2 control on IBRs can correct this misoperation. Unlike the Alpha Plane LCD, the traditional LCD appears to remain unaffected by the peculiarities introduced by IBRs, maintaining its operational integrity.

3.4.5 Rate-of-Change-of-Frequency Protection

ROCOF protection plays a vital role in detecting unintentional islanding in power systems. This protection mechanism measures the rate of frequency change, where a rapid shift within a short period signals potential island formation, prompting the tripping of generation sources or interconnection transformers to de-energize the island. Traditional ROCOF relay settings, ranging from 0.1 Hz/s to 1 Hz/s, are based on expectations of high inertia systems[19].

However, the growing integration of Inverter-Based Resources (IBRs), which are asynchronously connected to the grid, leads to reduced system inertia. This decrease in inertia adversely impacts ROCOF protection's performance, as ROCOF is inversely proportional to system inertia. Consequently, after a generator loss, ROCOF may exceed its set thresholds, causing the relays to falsely detect islanding events. This can lead to unnecessary tripping of IBRs, creating power imbalances with destabilizing effects on the network.

To address these misoperations, it's recommended to adjust the ROCOF settings in the grid code. Examples include the National Grid UK, which revised its grid code to increase the ROCOF Loss-of-Mains setting from 0.125 Hz/s to 1 Hz/s, and EirGrid in Ireland, which raised the setting from 0.5 Hz/s to 1 Hz/s. While these adjustments can mitigate the issue of relay misoperation due to high ROCOF, they also have the potential drawback of desensitizing islanding protection. This desensitization might delay the response to actual islanding events, posing a challenge in maintaining the delicate balance between preventing false trips and ensuring reliable islanding detection.

3.4.6 Power Swing Protection Challenges and Solutions

Power swings in electrical systems are fluctuations in power flow triggered by various disturbances such as line switching, generator disconnection, and significant load variations. These swings cause voltage and current changes that protective relays, tasked with measuring these quantities, may mistakenly interpret as faults, leading to the inadvertent disconnection of critical system components. Power swing protection aims to prevent such erroneous tripping by distinguishing between actual faults and power swings, thereby maintaining relay operation during swings [5].

Power swing protection is essential for two main reasons:

1. **Power Swing Blocking (PSB)**
   This function differentiates between a fault and a power swing by monitoring the rate of change in swing impedance. During a power swing, this rate is slower due to the substantial rotational inertia of generators, unlike during a fault where the rate is rapid, influenced by the relay's signal filtering timeline[20].

2. **Out-of-Step Tripping (OST)**
   This function discerns between stable and unstable power swings, activating system partitioning in response to an unstable swing to circumvent a comprehensive outage. The OST settings derive from the most severe stable swing trajectory, while PSB settings are based on the quickest impedance change rate.

However, the integration of Inverter-Based Resources (IBRs) alters the dynamic characteristics and inertia of the power system, potentially impacting the protection functions:

3.4.7 PSB Function

The acceleration in impedance vector change may cause PSBs to misread swings as faults, failing to declare a swing condition. The remedy involves adjusting the PSB time delay settings according to the swiftest swing when IBRs are present. However, too small a time delay might lead to the PSB incorrectly blocking relay zones during actual faults[21].

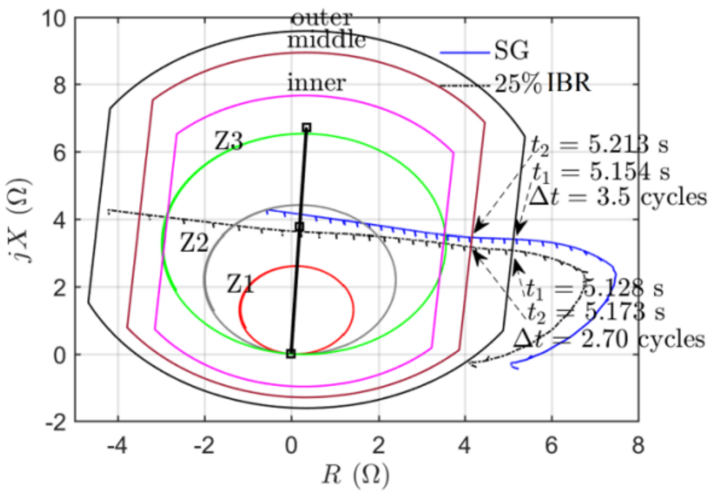

Figure 10: Power Swing Blocking [5]

3.4.8 OST Function

With IBRs, the trajectory of the swing impedance might change, leading the OST to falsely identify a stable swing as unstable, triggering unnecessary system separations. This issue can be rectified by recalibrating the OST settings based on the most severe stable swing in the presence of IBRs [22].

3.4.9 Effective Location of OST

As the level of IBR generation increases, the effective center (EC) of the power system shifts due to the altered source impedance from IBRs. This shift necessitates the reassessment of the EC's location to determine the optimal placement for the OST function.

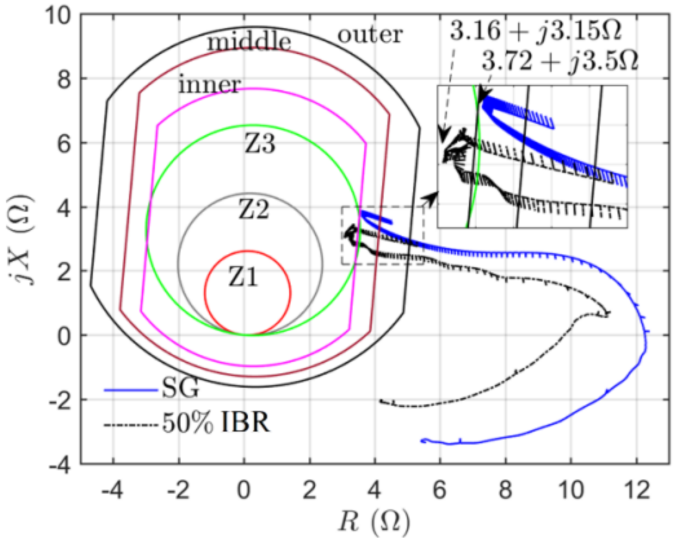

Figure 11: Out of Step Tripping [5]

3.4.10 Influence of IBR Characteristics

The capacity, type, and Grid-Support Converter (GSC) control strategies (decoupled or coupled) significantly affect the power swing characteristics. Thus, these factors must be taken into account during protection studies, as they influence the PSB and OST functions and the EC location. In summary, power swing protection is a critical component in safeguarding power systems against unnecessary tripping during power swings. The evolving energy landscape, with increased IBR integration, requires ongoing adjustments and refinements to protection settings and strategies.

3.4.11 Summary

The integration of IBRs into power systems introduces significant challenges for traditional protection schemes due to their unique fault current characteristics and the general reduction in system inertia. The literature concludes that while certain strategies, such as dynamic I2 control, have shown promise in resolving some misoperation issues, they are subject to inherent limitations and cannot be viewed as universal remedies. There is a clear imperative for continued research to evaluate the efficacy of proposed solutions and to explore the broader implications of high IBR penetration on system protection. Additionally, the potential impacts of grid-forming IBRs, with their distinct control mechanisms, warrant further investigation.

3.5 Adaptive Distance Protection

In the study by Liang, Li, and Zha (2020), [6] a novel approach to distance protection for transmission lines connected to photovoltaic (PV) power plants is proposed, addressing the challenges posed by unbalanced faults. The adaptive mho characteristic-based distance protection scheme is designed to enhance the reliability and accuracy of fault detection in the context of PV integration into the power grid[23].

The traditional distance protection schemes are often challenged by the integration of PV power plants, especially under unbalanced fault conditions [24]. The variable nature of PV generation and its impact on fault current levels can lead to protection maloperation. Liang et al.'s research aims to devise a protection mechanism that can dynamically adjust to the distinctive electrical behaviors introduced by PV systems, thereby improving fault detection and isolation efficiency. The authors developed an adaptive mho characteristic-based distance protection that adjusts the reach settings of the relay in response to the varying fault current contributions from PV plants[25]. The adaptability is achieved through the continuous monitoring of the PV plant's output, which influences the impedance measurement by the distance relay.

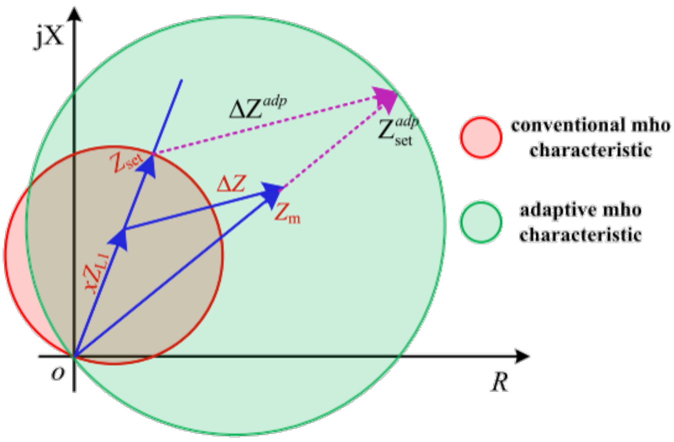

Figure 12: Adaptive MHO Relaying Scheme [6]

The proposed scheme was evaluated against various fault scenarios, including single-line-to-ground, line-to-line, and double-line-to-ground faults. The performance was benchmarked against conventional non-adaptive protection schemes. Results showed that the adaptive approach significantly reduced the instances of both underreach and overreach, leading to a higher degree of protection accuracy. The paper emphasizes the importance of adaptive protection schemes, especially in power systems with a high penetration of PV plants. The dynamic nature of PV output, influenced by factors such as irradiance and temperature, necessitates a more flexible approach to protection that can accommodate

Protection Function	Challenge and Potential Solution
Line distance protection	Lower fault current amplitude leads to failure to trip. Solutions include minimally set phase overcurrent supervision and zero sequence overcurrent protection.
Memory-polarized zero sequence directional protection	Faster IBR control may cause incorrect directionality. Solutions include self-polarization and memory voltage angle compensation.
Negative sequence based directional ground fault protection	Lack of I2 contribution by IBRs. Solutions involve using directional zero-sequence protection and dynamic I2 injection
Negative sequence overcurrent elements	Lack of I2 contribution by IBRs. Solution is providing dynamic I2 injection.
Pilot Protection	Malfunctioning elements cause incorrect tripping. Use POTT scheme with zero-sequence and echo logic
LCD	Changed fault current patterns may misclassify faults. Solution is to provide dynamic current injection and additional countermeasures.
ROCOF	High IBR integration triggers ROCOF protection. Solution is to increase the ROCOF setting.
Power Swing Protection	Reduced inertia under IBRs can cause misinterpretation of power swings. Solutions include reducing PSB delay setting and modifying OST settings

Table 1: Protection Challenges and Solutions due to IBRs [5]

these fluctuations and maintain system stability.

The distance protection schemes for lines connected to PV power plants can be significantly improved with adaptive mho characteristics that respond to the conditions of PV output. This adaptive method offers a promising solution to mitigate the protection challenges inherent in modern power systems with renewable energy sources. The study underscores the need for continued innovation in protection technology to ensure the reliability of power systems amid the growing prevalence of renewable generation.

3.6 Chapter Summary

The integration of Inverter-Based Resources (IBRs) into power systems, a transition from traditional synchronous generators, necessitates a reevaluation of existing protection schemes due to the unique dynamics and fault current characteristics of IBRs. This shift highlights the critical role of advanced simulation tools, especially Electromagnetic Transient (EMT)-type simulations, in accurately capturing the complex transients of IBRs. The emergence of dynamic and flexible protection strategies, like adaptive mho characteristic-based protection, demonstrates the need for tailored solutions to ensure reliable fault detection in renewable energy-dominated systems. Ongoing research and innovation are vital in refining these strategies, considering the potential impacts of grid-forming IBRs and their control mechanisms. As the energy sector moves towards a more renewable-centric model, collaborative efforts between researchers, engineers, and policymakers are essential to develop robust, adaptive, and efficient protection schemes, ensuring sustainable, stable, and resilient power systems amidst the growing prevalence of renewable energy sources.

4 Conclusion

The progressive integration of renewable energy sources into existing power systems marks a pivotal transition in the global energy landscape. While this shift heralds a more sustainable and environmentally friendly future, it also brings to the fore significant challenges in the realm of power system protection. The unique characteristics of renewable sources, particularly those that are inverter-based, diverge significantly from traditional generators, necessitating a reevaluation and adaptation of conventional protection mechanisms.

The integration of renewables like wind and solar energy introduces variability and intermittency in power generation, leading to fluctuations in fault levels and challenging the stability and reliability of power systems. These changes demand innovative solutions, such as adaptive relaying schemes, that can dynamically adjust to the evolving network topologies and varying fault currents. Conversely, non-adaptive relaying strategies also play a crucial role in scenarios where adaptive schemes are not feasible, by limiting or blocking the fault current contributions from renewable sources.

A comprehensive analysis of protection schemes tailored for distribution systems, transmission networks, and microgrids becomes crucial. This analysis must encompass the advantages and limitations of each scheme to provide a holistic understanding of best practices in renewable energy integration. As we move towards a more sustainable energy future, addressing these protection challenges becomes paramount. This report sets the stage for an in-depth exploration of these challenges and the innovative solutions developed to overcome them, paving the way for smarter, more resilient power systems.

In summary, the journey towards integrating renewable energy sources into power systems is fraught with challenges but also presents opportunities for innovation and advancement in protection technologies. Embracing these changes is essential for the development of a sustainable, efficient, and resilient energy infrastructure. The future calls for a concerted effort in research and development to further refine and adapt protection schemes, ensuring the harmonious coexistence of traditional and renewable energy sources in our power systems.

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