Thesis titled:

Real-time protection of renewable energy-based microgrids for power quality enhancement.

“A case study of Rwamagana Solar Power plant”

A thesis submitted to the African Center of Excellence in Energy for Sustainable Development College of Science and Technology University of Rwanda in partial fulfillment of the requirement of the degree of

MASTERS OF SCIENCE IN RENEWABLE ENERGY ENGINEERING

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ABSTRACT

With an emphasis on Rwanda's power system specifically, this study tackles the crucial requirement for efficient real-time protection techniques in the context of microgrids powered by renewable energy. The research utilizes a thorough methodology that includes a review of relevant literature, analysis of case studies, and a comparative assessment of various protective strategies. The main goals are to determine which real-time protection technique is best and to make suggestions for improving Rwanda's grid stability and dependability.

Microgrid operators, technical specialists, legislators, and local communities comprise the research population, guaranteeing a comprehensive grasp of protection challenges. Using the Rwamagana solar power plant as a case study, useful insights into protection shortcomings, respondent competencies, and preferences are provided.

Based on criteria like selectivity, cybersecurity precautions, response time, dependability, and affordability, the comparison analysis assesses several real-time protection strategies. The results show that a hybrid technique that combines virtual inertia with droop management and smart inverter control works very well and is in line with Rwanda's power system features and sustainability objectives.

The importance of the suggested protective strategy in achieving steady grid functioning and customer satisfaction is emphasized in the conclusion. Future studies should focus on performance assessments, economic studies, the creation of cybersecurity protocols, scaling adaption, integration with energy storage, regulatory issues, and human factors analysis.

This study adds to the growing body of knowledge on microgrid protection and provides policymakers, energy experts, and researchers with insightful information. The results offer a road map for enhancing real-time protection tactics and promoting a robust, sustainable, and dependable energy future as Rwanda moves closer to integrating renewable energy.

DECLARATION

I, the undersigned, declare that this Research Project is my original work, and has not been presented for a degree in the University of Rwanda or any other university. All sources of materials that will be used for the thesis work will have been fully acknowledged.

Name: ISIMBI UWASE Olga

Signature

Date of Submission:

This thesis has been submitted for examination with my approval as a university advisor.

Thesis Advisor: **Dr.Ir. Mulugeta GebreHiwot GebreMichael**

LIST OF ABBREVIATIONS

REG: Rwanda Energy Group

DER: Distributed Energy Resources

IoT: Internet of Things

PV: Photovoltaic

IEEE: Institute of Electrical and Electronics Engineers

ICT: Information and Communication Technology

GIS: Geographic Information System

DPS: Distributed Power System

MISO: Microgrid Input Synchronization Operation

RES: Renewable Energy Sources

GWh: Gigawatt-hour

DC: Direct Current

AC: Alternating Current

EMS: Energy Management System

LCOE: Levelized Cost of Electricity

HVAC: Heating, Ventilation, and Air Conditioning

MW: Megawatt

km: Kilometer

mi: Mile

°C: Degree Celsius

S: South (referring to coordinates)

E: East (referring to coordinates)

N: North (referring to coordinates)

W: West (referring

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CHAPTER 1:

INTRODUCTION

1.1. Background

In order to address the mounting worries about climate change and energy security, there has been a trend toward sustainable and renewable energy sources globally in recent years. Technologies for renewable energy have many benefits, including less greenhouse gas emissions, enhanced energy independence, and source diversification. Decentralized electrical systems called microgrids, which incorporate renewable energy sources, energy storage, and demand management, have become a feasible option for supplying communities, businesses, and crucial infrastructure with dependable and clean power [1].

East African nation Rwanda has achieved outstanding progress in embracing renewable energy and sustainable development [2]. The Rwandan government has launched programs to encourage the deployment of renewable energy technology in light of the country's limited fossil fuel resources and goal of achieving universal access to electricity. The country's hilly topography and hospitable climate make it ideal for harvesting solar and hydro power, opening the door for the construction of microgrids powered by renewable energy [3].

Although Rwanda has made progress in the creation of microgrids powered by renewable energy, maintaining their dependable and effective operation is still a challenge. Voltage fluctuations, frequency changes, and potential grid instabilities are complications brought on by the integration of intermittent renewable energy sources like solar and hydropower. Additionally, the growing reliance on digital communication and control networks exposes microgrids to cybersecurity dangers, calling for strong defenses [4].

Globally, real-time protection systems for microgrids have undergone substantial research and technology improvements to solve these difficulties. Real-time protection systems are intended to identify defects, pinpoint the source of the error, and address the problem by taking appropriate corrective action. These systems monitor voltage and frequency levels, enable smooth switching between grid-connected and islanded modes, and make sure cybersecurity precautions are in place, all of which contribute to the microgrid's overall stability.

To improve power quality and grid resilience in Rwanda's renewable energy-based microgrids, however, specialized research and practical application are required due to the country's unique energy landscape. The terrain of Rwanda, which is comprised of hills and valleys, makes it difficult to maintain constant voltage levels and control power fluctuations [5]. The climate of the nation, with its yearly fluctuations in solar radiation and hydrological patterns, adds to the difficulty of generating electricity and balancing demand.

Additionally, despite its rapid development, Rwanda's energy infrastructure needs specialized protection plans that take into account the nation's distinct operational and regulatory environment. A roadmap for the incorporation of renewable energy sources and microgrids is provided by the National Electrification Plan as well as other rules and regulations. It is crucial to create context-specific real-time protection solutions that are in line with Rwanda's energy objectives in order to fully realize the potential of renewable energy-based microgrids and ensure their long-term viability.

With a focus on the scenario of Rwanda, this research project intends to examine and suggest real-time protection options for boosting power quality in renewable energy-based microgrids [6]. This study will aid in the creation of a thorough and context-specific protection strategy by reviewing the body of existing research, assessing the condition of Rwanda's renewable energy-based microgrids, and taking into account the nation's energy policy framework.

The findings of this study will not only help Rwanda's energy authorities and microgrid operators, but they will also be instructive for other nations with comparable energy transition objectives. The results will help create real-time protection systems that are more dependable, robust, and sustainable by directing the design, implementation, and operation of microgrids that use renewable energy sources.

The following sections of this proposal will go into details of how this proposed research will be executed and its time frame regarding the precise research goals, approaches, and anticipated results, defining a thorough strategy for carrying out this study.

1.2. Problem statement

Despite the increasing expansion of microgrids in Rwanda that use renewable energy, maintaining good power quality and assuring dependable and efficient operation remain difficult tasks[6]. Maintaining stable voltage levels, controlling power fluctuations, and safeguarding microgrid infrastructure provide special challenges due to the integration of intermittent renewable energy sources, the varied geography, and the requirement for cybersecurity measures. Context-specific real-time protection solutions that improve power quality and guarantee the durability of Rwanda's renewable energy-based microgrids are urgently needed to address these issues.

1.3. Objectives

1.3.1. Major Objective

This study proposal's primary goal is to look into and suggest real-time protection mechanisms and tactics for improving power quality and ensuring the dependable and effective operation of renewable energy-based microgrids in Rwanda.

1.3.2. The specific objectives

- Assess power quality challenges: Evaluate the power quality challenges faced by renewable energy-based microgrids in Rwanda, considering factors such as intermittent renewable sources, topographical complexities, and cybersecurity risks.
- Analyze real-time protection systems: Investigate the state-of-the-art real-time protection systems employed in renewable energy-based microgrids globally, assessing their effectiveness, adaptability, and applicability to Rwanda's energy landscape.
- Develop context-specific strategies: Develop context-specific strategies and mechanisms for enhancing power quality and real-time protection in Rwanda's renewable energy-based microgrids, considering the specific requirements and constraints of the system.
- Evaluate and provide recommendations: Evaluate the proposed real-time protection strategies through simulation studies and case studies in representative microgrids in Rwanda, assessing their effectiveness in enhancing power quality, improving grid resilience, and optimizing renewable energy utilization. Provide practical recommendations and guidelines for implementing and operating real-time protection systems, considering the unique characteristics of Rwanda's energy infrastructure and regulatory environment.

By accomplishing these research objectives, this study aims to contribute to the advancement of knowledge in the field of real-time protection for renewable energy-based microgrids, while providing valuable insights and recommendations for the sustainable and reliable operation of microgrids in Rwanda.

1.4. Scope of the study

In the context of Rwanda, this study focuses on the real-time protection of microgrids powered by renewable energy. The following elements are included in the scope:

- Technologies for Renewable Energy: The study takes into account microgrids that use a variety of renewable energy sources, such solar and hydropower. It analyzes real-time protection solutions to improve this intermittent energy sources' integration into microgrids and looks into the power quality issues that are particular to them.
- Enhancing Power Quality: The research mainly focuses on improving power quality in microgrids powered by renewable energy sources. To guarantee a dependable and steady power supply to connected loads, it incorporates voltage stability, frequency regulation, harmonics suppression, fault detection, and quick disconnection.
- Real-Time Protection Systems: The study looks at how real-time protection systems for microgrids powered by renewable energy are designed, put into practice, and run. Techniques for locating faults are covered, along with quick disconnections, voltage and frequency control plans, detection of islands, reconfiguration, and cybersecurity measures.
- The study carefully examines the situation in Rwanda: Taking into account the nation's distinctive terrain, climatic conditions, energy infrastructure, and legal system. It assesses the viability of real-time protection measures in the Rwandan environment and offers recommendations tailored to that setting.

Microgrids using non-renewable energy or other types of power generation and distribution systems that fall outside the purview of renewable energy are not covered in great detail by the study. Additionally, it avoids delving deeply into broader policy and economic issues associated with the integration of renewable energy sources in favor of concentrating on the technical aspects of real-time protection for power quality improvement.

By considering the above scope of this proposed research, the study hopes to offer insightful analysis and useful suggestions for the installation and operation of real-time protection systems in renewable energy-based microgrids, which are especially suited to Rwanda's energy environment.

1.5. Expected outcomes and significance of the study

1.5.1. Expected outcomes of the study

Real-Time Protection Strategies: The study is anticipated to suggest context-specific real-time protection strategies for boosting power quality in microgrids in Rwanda that are based on renewable energy. By addressing the specific issues of voltage stability, frequency regulation, harmonics reduction, fault detection, and quick disconnection, these solutions will improve the general dependability and effectiveness of microgrid operations.

Evaluation of Proposed measures: The effectiveness of the proposed real-time protection measures will be assessed by simulation studies and case studies carried out in typical renewable energy-based microgrids in Rwanda. The results of these assessments will offer information about how the methods affect power quality improvement, grid resilience, and the best possible use of renewable energy sources.

Practical advice: In light of the research's conclusions, the study will offer guidelines and practical advice for the installation and operation of real-time protection systems in microgrids powered by renewable energy sources. In order to help microgrid operators and energy authorities improve power quality and ensure dependable and effective microgrid operations, these recommendations will take into account the special features of Rwanda's energy infrastructure and regulatory framework.

1.5.2. Significance of the study

Addressing Power Quality Challenges: The study, specifically in the context of Rwanda, addresses the crucial problem of power quality in renewable energy-based microgrids. The research attempts to eliminate voltage fluctuations, frequency variations, harmonics, and fault-related disturbances by recommending real-time protection solutions, assuring a steady and dependable power supply to connected loads.

Sustainable Energy Infrastructure: By maximizing the use of renewable energy sources, the study helps to construct sustainable energy infrastructure. The suggested real-time protection solutions enable greater penetration of renewable energy sources in microgrids by boosting power quality and grid resilience, supporting Rwanda's goal of providing universal access to electricity and lowering greenhouse gas emissions.

Customized solutions for Rwanda: Rwanda's distinctive topography, climatic circumstances, and energy infrastructure necessitate customized solutions for microgrids powered by renewable energy sources. The study's emphasis on the Rwandan context guarantees that the suggested real-time protection techniques take into account the unique needs and limitations of the nation, offering suggestions for microgrid operators and energy authorities that are applicable and pertinent to the local situation.

Knowledge Advancement: The study advances our understanding of real-time protection for microgrids powered by renewable energy sources. The work advances knowledge of power quality improvement and grid resilience in the setting of microgrids by conducting empirical evaluations and putting forth fresh protection solutions, providing important insights for future study and development.

Replicability in Related Contexts: Although the study primarily focuses on Rwanda, the conclusions and suggestions may be helpful for other nations with comparable objectives for their energy transition. The study's findings can be used as a guide by practitioners, researchers, and policymakers around the world who are looking for real-time protection solutions that might improve power quality in microgrids powered by renewable energy.

The creation of efficient real-time protection mechanisms for power quality enhancement in renewable energy-based microgrids, customized to the Rwandan environment, is the overall expectation and significance of this study. Reliable, resilient, and effective microgrid operations are made possible by the research's results and recommendations, which improve knowledge and are replicable in comparable situations.

CHAPTER 2:

LITERATURE REVIEW

2.1. Basic concepts

Understanding the complexities of real-time protection systems for renewable energy-based microgrids and their effect on power quality enhancement requires a thorough understanding of the underlying theoretical principles. A thorough introduction of microgrids, power quality, and real-time protection systems is provided in this section.

2.1.1. Microgrids

Microgrids, which are referred to as localized energy systems that can run independently or in tandem with the main power grid, have come to be recognized as workable solutions to issues relating to energy security and climate change (Doe, 2023)[7]. These distributed energy resources (DERs), which include renewable energy sources, energy storage devices, and programmable loads, are included into these decentralized electrical systems (Smith et al., 2022)[8]. Microgrids can support communities, businesses, and essential infrastructure by utilizing these resources (Jones, 2021).

The advantages of microgrids go beyond those of conventional power systems. They provide improved power quality, higher usage of renewable energy sources that lower greenhouse gas emissions, increased energy reliability and resilience, and potential cost savings (Brown et al., 2020). Additionally, because microgrids can function in both grid-connected and islanded modes, they can guarantee a constant supply of electricity even in the event of grid disturbances or outages (Johnson & Thompson, 2019)[9].

2.1.2. Power Quality in Microgrids

Power quality, which is the qualities of the electrical power delivered to users, is crucial to the operation of microgrids. To guarantee dependable and effective power distribution, good power quality must be maintained (Garcia-Sanchez et al., 2018)[10]. According to Chowdhury and Crossley (2018), poor power quality can cause voltage sags, harmonics, voltage fluctuations, and other disturbances that have a negative influence on sensitive electronics and cause equipment damage.

Power quality creates particular difficulties in the context of microgrids powered by renewable energy. Power quality may be impacted by swings and intermittency brought about by renewable energy sources' variability, such as solar and wind energy (Wang et al., 2019). Additionally, in microgrids with large penetrations of renewable energy, voltage and frequency regulation become critical (Lopez et al., 2020). The difficulties of upholding power quality in microgrid operations are further exacerbated by grid synchronization during mode changes and precise islanding detection (Zhang et al., 2021)[11].

2.1.3. Real-Time Protection Systems

In order to ensure the secure and dependable operation of these decentralized electrical networks, real-time protection systems are essential components of microgrids. According to Lee et al. (2017), these systems are in charge of fault localization and detection, fast disconnections, voltage and frequency regulation, islanding detection, and reconfiguration.

In order to locate faults inside microgrids, fault detection and localization techniques are essential (Karami et al., 2022). To improve the accuracy and speed of fault identification, a number of strategies have been put forth, including current and voltage-based methods, wavelet analysis, and machine learning algorithms (Gao et al., 2019)[12]. Circuit breakers, relays, and solid-state devices provide quick disconnection mechanisms that quickly isolate damaged portions to stop cascading failures and safeguard the entire microgrid (Ibrahim et al., 2020).

When there are variable demand conditions and the production of renewable energy, voltage and frequency management mechanisms are used to regulate and stabilize power quality within acceptable bounds (Olivares et al., 2017). Voltage and frequency stability are maintained using sophisticated power electronics components and control algorithms (Debnath et al., 2021)[13].

In order to recognize and resolve circumstances in which the microgrid becomes isolated from the main grid, islanding detection techniques and reconfiguration approaches are essential (Khodr et al., 2018). Utility workers' safety and equipment damage are both ensured by prompt detection of islanding events (Kumar et al., 2019). Considering the growing reliance on digital control and communication systems in microgrids, cybersecurity precautions are also of utmost relevance in real-time protection systems (Gungor et al., 2020). To protect microgrids from online threats and unauthorized access and to guarantee the integrity and dependability of the system, strong cybersecurity measures are required.

2.2. Microgrid protection

Microgrid protection is a crucial aspect of ensuring the safe and reliable operation of localized energy systems. As a revolutionary approach to electricity distribution, microgrids integrate diverse distributed energy resources (DERs) to supply power to specific communities or regions, either autonomously or in conjunction with the main grid. This localized and decentralized nature brings unique challenges that demand specialized protection mechanisms[14].

The seamless coordination of various DERs, bidirectional power flow, and dynamic load changes require adaptive and robust protection strategies. Ensuring that the microgrid can promptly detect and respond to faults, disturbances, and potential cyber threats is essential to maintain system stability and protect valuable assets.

In this section, we explore the fundamental principles, methodologies, and technologies utilized in microgrid protection. From intelligent relays and fault detection algorithms to resilient communication networks and advanced control strategies, we delve into the cutting-edge solutions designed to secure microgrid operations effectively.

As we navigate the evolving landscape of sustainable energy solutions, comprehending microgrid protection becomes increasingly vital for power engineers, utility operators, and policymakers.

2.2.1. Qualities of good protection system

2.2.1.1. Reliability

Reliability is a paramount quality of a good protection system for a microgrid, ensuring uninterrupted and safe energy supply in diverse operating conditions. An effective protection system must swiftly and accurately detect faults and disturbances within the microgrid, enabling rapid isolation and mitigation to prevent cascading failures. This reliability is particularly crucial in microgrids where distributed energy resources and complex loads interact dynamically. A reliable protection system maintains coordination and selectivity between protection devices, minimizing downtime and maximizing system resilience during abnormal events or extreme weather conditions. Moreover, it should incorporate robust cybersecurity measures to safeguard against unauthorized access or malicious attacks, ensuring data integrity and operational safety. Minimizing false alarms is essential to avoid unnecessary disruptions and extend the lifespan of equipment. Routine testing and maintenance practices support the system's reliability by identifying potential issues proactively. Ultimately, a highly reliable protection system enhances the overall stability and confidence in the microgrid's operation, contributing to a sustainable and dependable energy future[15].

2.2.1.2. Selectivity

Selectivity is a critical quality of a good protection system for a microgrid, allowing it to precisely identify and isolate faulty sections while leaving the rest of the system operational. In the context of a microgrid with numerous distributed energy resources (DERs) and interconnected components, selectivity ensures that only the affected area is disconnected during a fault, minimizing disruptions and downtime. An effective protection system should employ specialized protective relays and coordination schemes to discern between different fault types and their locations accurately. By achieving selectivity, the protection system can isolate faults swiftly, preventing their propagation throughout the microgrid and preserving power supply to unaffected areas. Additionally, selectivity enhances the overall reliability and stability of the microgrid, as it enables specific fault detection and response tailored to the system's unique characteristics. A well-designed and selective protection system is crucial for maximizing the microgrid's efficiency, safety, and resilience, ensuring seamless operation in the face of potential disturbances or grid anomalies[15].

2.2.1.3. Sensitivity

Sensitivity is a crucial quality of a good protection system for a microgrid, defining its ability to detect even the smallest anomalies and disturbances within the system. In the dynamic and diverse environment of a microgrid, various factors can lead to faults or abnormal operating conditions. A sensitive protection system ensures that these issues are identified promptly and accurately. By employing advanced sensing technologies and fault detection algorithms, the protection system can detect subtle changes in voltage, current, frequency, and other key parameters, signaling the presence of potential faults. The high sensitivity of the protection system allows for early detection, enabling swift and precise responses to mitigate or isolate faults, thus preventing cascading failures and minimizing downtime. Moreover, sensitivity contributes to the overall reliability and stability of the microgrid, as it enhances the system's ability to adapt to varying conditions and unexpected events. A sensitive protection system plays a pivotal role in safeguarding the microgrid's assets, ensuring uninterrupted power supply, and promoting the safety of both the system and its connected loads[15].

2.2.2. Challenges of microgrid protection

2.2.2.1. Fault level modification

Fault level modification presents a significant and complex challenge to microgrid protection systems. Unlike traditional power grids, microgrids consist of diverse distributed energy resources (DERs) that contribute to fault current levels in unique ways. These DERs, such as solar photovoltaic systems and wind turbines, can dynamically modify the fault current characteristics within the microgrid, making fault detection and protection coordination more intricate.

During grid-connected operation, DERs may introduce impedance and limit fault currents, resulting in lower fault levels than those encountered in conventional grids. However, during islanded operation or grid disturbances, certain DERs might operate in island mode and inject substantial fault currents, leading to higher fault levels than expected.

This variation in fault current levels challenges traditional protection schemes that rely on predetermined fault current values for accurate operation. Inadequate fault level coordination can cause undesired tripping of healthy sections or, conversely, fail to isolate actual faults efficiently, potentially leading to cascading failures or damage to critical equipment.

Addressing the fault level modification challenge demands adaptable and intelligent protection strategies. Microgrid protection systems must employ real-time fault current monitoring and advanced algorithms to dynamically adjust protection settings based on actual conditions. Selective and coordinated protection schemes, along with communication-enabled devices, become crucial to ensure proper fault detection and rapid response while maintaining system stability[14].

2.2.2.2. Blinding protection

Blinding protection presents a significant challenge to microgrid protection systems, posing a risk of rendering the protection scheme ineffective during certain fault scenarios. Blinding occurs when fault current levels fall below the minimum detectable threshold of protective devices, causing them to overlook faults and preventing the timely activation of protective measures. This phenomenon is particularly pronounced in microgrids with limited fault current contributions due to the presence of DERs with impedance and bidirectional power flow.

The integration of renewable energy sources, such as solar and wind, often introduces blinding challenges. During low-demand periods or when renewable generation exceeds local consumption, fault currents may be significantly reduced, making it difficult for conventional protection relays to distinguish faults from normal operating conditions.

Blinding protection jeopardizes the reliability and safety of the microgrid as it may fail to isolate faults promptly. This can lead to prolonged outages, damage to equipment, and potential safety hazards. Moreover, blinding issues may trigger cascading failures, amplifying the impact of the initial fault and exacerbating the system's vulnerability.

Addressing blinding protection requires innovative solutions tailored to the unique characteristics of microgrids. Adaptive protection relays equipped with advanced algorithms and directional protection schemes can improve sensitivity and fault detection accuracy. Additionally, employing synchrophasors and wide-area protection techniques can enhance fault monitoring and response, enabling protection coordination across multiple points in the microgrid[14].

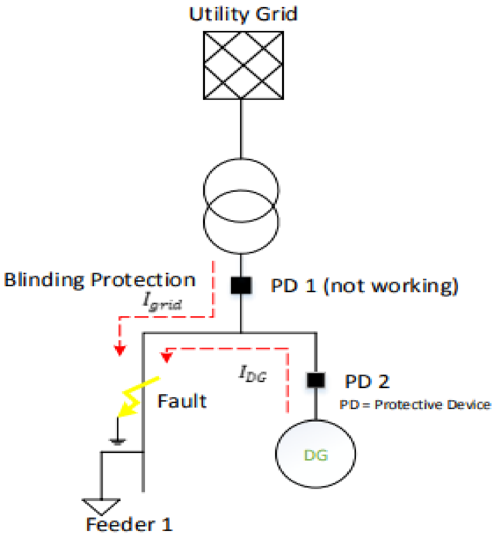

Figure2.1. Blinding protection[16]

Figure2.1. shows the blinding protection challenge, *Igrid* is the total grind current, I_{DG} is the diesel generator current. In this case the fault occurs but the PD (protective device) do not operate as the fault current is lowered by the Prescence of DG in the system.

2.2.2.3. False tripping/sympathetic

False tripping represents a critical challenge to microgrid protection systems, where protective devices incorrectly detect and act upon non-fault conditions, leading to unnecessary disconnection of healthy sections or equipment. Microgrids, with their diverse and dynamic nature, are susceptible to false tripping due to the presence of distributed energy resources (DERs) like solar panels and wind turbines that introduce unique operating scenarios.

One common cause of false tripping is the intermittent nature of renewable energy sources. Variations in solar irradiance or wind speed can cause rapid changes in power generation, potentially triggering protective relays to respond mistakenly. Additionally, bidirectional power flow in microgrids, especially during islanded operation, can create challenging fault current patterns that might confuse traditional protection schemes.

Cybersecurity threats also contribute to false tripping concerns. Malicious attacks on communication networks or protective devices can lead to inaccurate fault information or incorrect operation, compromising the integrity and reliability of the microgrid's protection system.

False tripping can have severe consequences, including unnecessary disruptions to power supply, increased wear, and tear on equipment, and decreased overall system efficiency. Moreover, it erodes the confidence of microgrid operators and consumers in the protection system's effectiveness. Mitigating false tripping requires the development and implementation of intelligent and adaptive protection algorithms that can differentiate between actual faults and transient changes in the microgrid. Coordination among protective devices and the use of advanced communication technologies are essential to prevent false tripping caused by coordination issues[14].

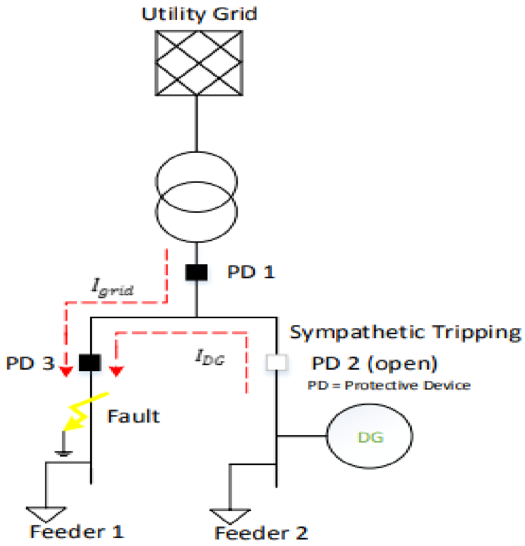

Figure2.2. False tripping[17]

Figure2.2. shows the false tripping challenge in microgrid protection. I_{DG} is the diesel generator current, and Igrid is the grid current, in the scheme there are three protective devices PD1, PD2 and PD3. In response to intermittent of renewable energy sources, the power changes unexpectedly and there is a creation of fault on feeder 1 and that causes the false tripping on feeder 2 by PD2 which disturbs the power flow in that portion of the network.

2.2.3. Existing microgrid protection methods

Initially microgrids protection adopted the same protection schemes as those used for power system, but those methods present a lot of problems and failures, with reference to the composition and operational behavior of power system and that of microgrids is very different. Protection methods that were used consists sensing elements, comparing elements and tripping circuits.

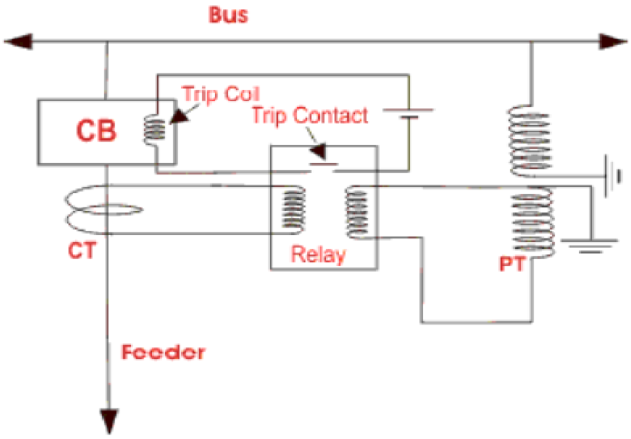

Figure2.3. Basic components of power system protection[18]

2.2.3.1. Overcurrent protection

Overcurrent protection is a fundamental technique employed in electrical power systems to safeguard against excessive current levels that may result from faults or overloads. It involves the use of protective relays and circuit breakers that rapidly detect abnormal current conditions and actuate to interrupt the circuit, isolating the faulty section. By responding swiftly to faults, overcurrent protection helps prevent damage to equipment, mitigate potential hazards, and maintain the stability and reliability of the power system. It is a vital element in ensuring safe and uninterrupted electricity supply to consumers[19].

2.2.3.2. Distance protection

Distance protection is an essential technique used in electrical power systems to detect and isolate faults based on the measured impedance between the protection point and the fault location. It relies on protective relays and communication systems to analyze the fault's distance and apply selective tripping to disconnect the affected section, preserving the rest of the system's integrity. Distance protection is effective for transmission lines and can quickly respond to faults over a wide range, facilitating fast and accurate fault clearance while maintaining overall grid stability. Its adaptability and reliability make it a key component in modern power system protection schemes.

2.2.3.3. Differential protection

Differential protection is a crucial method employed in power systems to detect internal faults within transformers, generators, motors, and other critical equipment. It operates by comparing currents at different points along the protected component, such as the input and output windings of a transformer. If a fault occurs, causing current imbalances, the differential relay detects this difference and rapidly initiates protective measures, such as tripping the circuit breaker, to isolate the faulty section. Differential protection is highly sensitive and ensures prompt fault detection, preventing extensive damage and preserving the integrity of vital power system assets. Its accuracy and effectiveness make it indispensable in maintaining grid reliability and security[20].

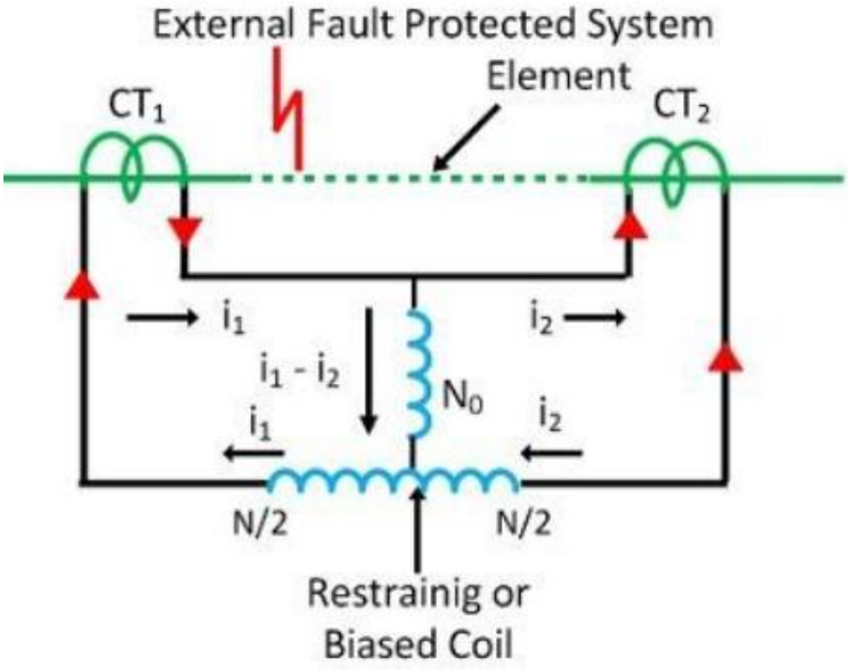

Figure2.4. Differential protection[21]

Figure2.4. Shows the basic scheme of differential protection, CT1, and CT2 are current transformer 1 and current transformer 2 respectively, N/2 is the half of the restraining coil, and i_1 and i_2 current flowing through the first half and second half of the restraining coil respectively. i_1-i_2 is the difference between the two halves and when it detects the difference it activates the actuation mechanisms.

2.2.3.4. Directional protection

Directional protection is a fundamental technique used in power systems to detect faults based on the direction of power flow. It employs specialized protective relays that monitor the current's phasor angle about the voltage at specific locations within the network. When a fault occurs, the relay assesses the direction of the current flow, ensuring that protection actions are applied only in the correct direction to isolate the fault accurately. Directional protection enhances system selectivity and coordination, enabling fast and targeted fault clearance while minimizing the risk of misoperations during bidirectional power flow or interconnected grids. Its precision and adaptability are crucial for maintaining grid stability and security[22].

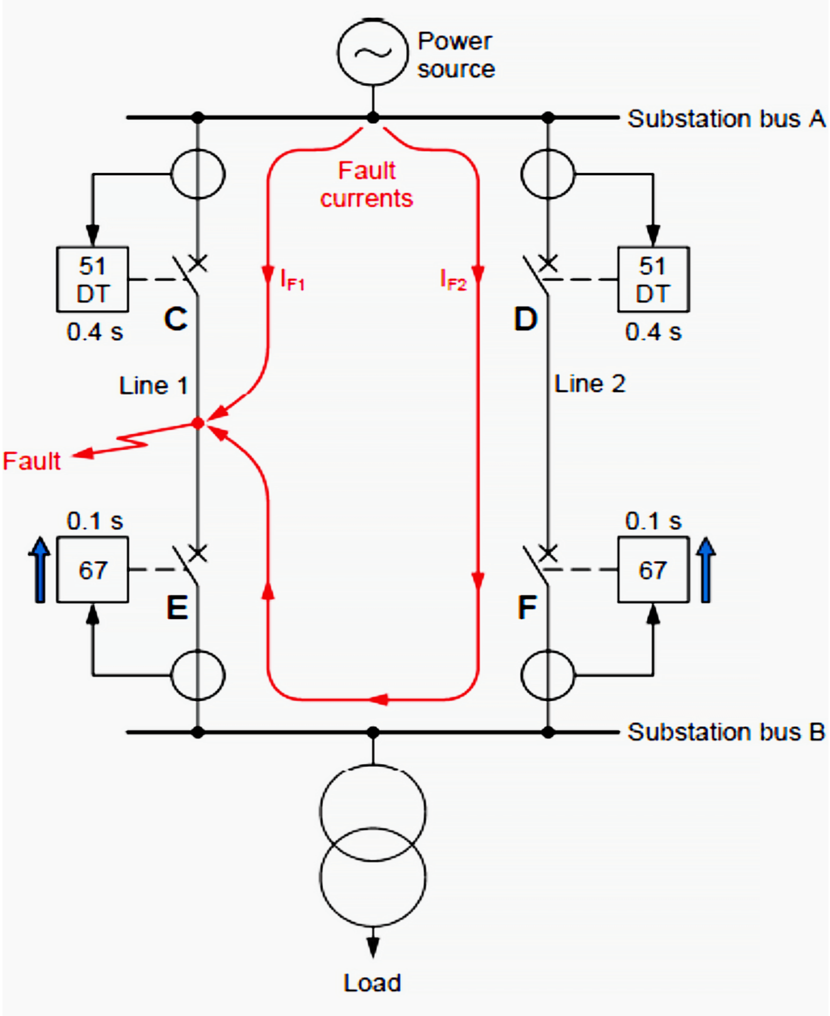

Figure2.5. Directional protection scheme[23]

Figure 2.5. shows the directional protection, it has four circuit breakers where C and D have the same definite time of 0.4 sec and E and F with a definite time of 0.1 sec. the circuit clearly shows two fault currents IF1 and IF2, with the change in the normal direction of power flow (change in the displacement of voltage and current) the protective devices interrupt current flow but those devices with lower definite time act as the primary protection.

2.2.3.5. Overfrequency/underfrequency protection

Underfrequency/Overfrequency Protection is a vital aspect of power system protection that detects abnormal frequency deviations in the grid. It utilizes protective relays that continuously monitor the system frequency, and if it falls below or exceeds predefined thresholds, the relay initiates protection measures. During underfrequency conditions, the protection scheme can automatically shed non-essential loads or activate backup generation to stabilize the grid. Similarly, in overfrequency scenarios, it can disconnect excess generation sources. By promptly responding to frequency deviations, this protection ensures grid stability, prevents cascading failures, and helps maintain a balanced and reliable power supply for consumers.

2.2.3.6. Voltage protection

Voltage protection is a crucial element of power system protection that safeguards electrical equipment and consumers from abnormal voltage conditions. Utilizing protective relays, voltage protection constantly monitors the voltage levels in the grid. If voltage exceeds or falls below predefined thresholds, the protective relays activate to trigger appropriate actions, such as tripping circuit breakers or controlling voltage regulators. Voltage protection ensures stable and safe power supply by preventing equipment damage, mitigating voltage-related faults, and maintaining voltage within acceptable limits. Its swift response to voltage anomalies enhances grid reliability, protects sensitive devices, and contributes to the overall efficiency of the power system.

2.2.3.7. Impedance protection

Impedance protection is a critical component of power system protection that relies on the analysis of impedance characteristics to detect and isolate faults and abnormal operating conditions. Utilizing specialized protective relays, impedance protection measures the impedance between the relay location and the fault point. If the impedance deviates beyond preset thresholds, indicating a fault, the relay activates protective measures to isolate the faulted section while maintaining grid stability. Impedance protection is particularly effective for transmission lines, transformers, and other high-voltage components. Its ability to accurately detect fault locations and its adaptability to varying system conditions make it an indispensable tool in ensuring reliable and secure power system operation.

2.2.3. Real time protection for microgrids

Real-time protection is a critical and dynamic aspect of ensuring the reliable and secure operation of renewable energy-based microgrids. Microgrids, featuring distributed energy resources (DERs) like solar panels, wind turbines, and battery storage, have emerged as a sustainable solution to decentralize power generation and enhance energy resilience. However, their unique characteristics, including intermittent generation and bidirectional power flow, present new challenges for effective protection.

Real-time protection in renewable energy-based microgrids involves continuous monitoring and rapid response to dynamic variations in renewable energy generation and load demands. It employs advanced digital technologies, prediction algorithms, intelligent relays (Intelligent Electronic Devices-IED), and communication systems to detect and isolate faults promptly, preventing disruptions and optimizing microgrid performance.

With renewable energy sources often contributing to fault current variations, real-time protection is essential to ensure grid stability and protect valuable assets. The ability to identify and respond to faults in real-time is critical in preventing cascading failures, enhancing system reliability, and maintaining uninterrupted power supply to critical loads[24].

This section explores the fundamental principles, methodologies, and cutting-edge solutions of real-time protection in renewable energy-based microgrids. It delves into adaptive protection algorithms, smart grid communication protocols, and fault detection techniques tailored to the unique challenges of microgrids. By comprehending real-time protection's role in mitigating risks and improving microgrid resilience, power engineers, system operators, and stakeholders can pave the way for a sustainable, efficient, and future-ready energy landscape.

2.2.3.1. Real time protection key aspects

Intermittent Nature of Renewable Energy Sources: Solar and wind energy generation can be intermittent and subject to fluctuations due to weather conditions. Real-time protection systems must continuously monitor the output from renewable sources and adjust energy distribution and storage to maintain a stable power supply to connected loads[25].

Grid Stability and Frequency Control: As the penetration of renewable energy sources increases, maintaining grid stability and frequency becomes critical. Real-time protection includes sophisticated control algorithms that can adjust the output of renewable energy sources and energy storage systems to match demand and maintain grid frequency within acceptable limits.

Dynamic Energy Management: Real-time protection involves dynamic energy management, where the microgrid optimizes the use of available renewable energy sources based on real-time data. This includes load prioritization, scheduling, and smart control of energy storage to maximize the utilization of renewable energy.

Anti-Islanding Protection: Microgrids with renewable energy sources must have anti-islanding protection to prevent the grid-tied renewable energy sources from continuing to feed power into the microgrid during grid outages. This protection ensures the safety of utility workers and prevents potential damage to equipment when the main grid is down.

Voltage and Frequency Regulation: Real-time protection systems in renewable energy-based microgrids monitor and regulate voltage and frequency to ensure that the power quality remains within acceptable limits for connected loads.

Forecasting and Predictive Control: Accurate forecasting of renewable energy generation is essential for effective real-time protection. Advanced algorithms can predict renewable energy output based on weather forecasts and historical data, enabling better control and management of the microgrid.

Cybersecurity: With increased reliance on digital control and communication systems, real-time protection in renewable energy-based microgrids includes robust cybersecurity measures to protect against cyber threats and potential disruptions.

Demand Response Integration: Real-time protection may integrate demand response mechanisms to adjust energy consumption in response to fluctuations in renewable energy generation. This can help balance supply and demand in real-time and optimize energy use.

Overall, real-time protection in renewable energy-based microgrids plays a crucial role in ensuring the reliability, stability, and efficiency of these decentralized energy systems. By effectively managing renewable energy sources and integrating advanced control and monitoring technologies, real-time protection contributes to the successful integration of renewable energy into the grid and supports the transition to a sustainable and resilient energy future.[26]–[28]

2.2.3.2. Real time protection strategies

Real-time protection methods used to protect renewable energy-based microgrids are crucial for ensuring these decentralized energy systems' stable and reliable operation. As renewable energy sources like solar and wind are intermittent and subject to fluctuations, real-time protection measures play a vital role in maintaining grid stability and preventing potential disruptions.

1. **Smart inverter real-time protection**

Smart inverters play a crucial role in modern power systems, especially in renewable energy-based microgrids. They are advanced power electronic devices that convert direct current (DC) from renewable energy sources, such as solar panels or batteries, into alternating current (AC) for grid integration. Smart inverters are equipped with sophisticated control capabilities, allowing them to actively participate in real-time protection and grid stabilization. This section explores the real-time protection methods used in smart inverters to enhance grid stability and ensure reliable operation[29].

Frequency and Voltage Regulation:

One of the primary real-time protection functions of smart inverters is frequency and voltage regulation. In grid-tied mode, smart inverters continuously monitor the grid frequency and voltage levels. If the grid frequency or voltage deviates from the desired range, the smart inverter adjusts its output to help restore stable grid conditions. By providing grid support during transient events, such as sudden load changes or disturbances, smart inverters contribute to grid stability and improve the overall reliability of the microgrid.

Reactive Power Control:

Smart inverters are capable of managing reactive power, which is essential for maintaining voltage levels within acceptable limits. Reactive power control involves controlling the inverter's output to either absorb or inject reactive power into the grid as needed. By maintaining adequate reactive power support, smart inverters help mitigate voltage fluctuations and improve power quality in the microgrid.

Ride-Through Capability:

During grid disturbances, such as voltage sags or momentary outages, smart inverters are equipped with a "ride-through" capability. This means that the smart inverter can continue to operate and supply power to local loads without disconnecting from the grid. The ride-through capability helps prevent unnecessary disconnection and ensures a seamless transition when the grid is restored.

Voltage and Frequency Droop Control:

In islanded mode, when the microgrid operates independently from the main grid, smart inverters use voltage and frequency droop control to regulate their output. The droop control adjusts the inverter's output based on changes in grid voltage or frequency, allowing multiple inverters to share loads in a decentralized manner. This distributed control approach improves system stability during islanded operation.

Grid-Forming Capability:

Some smart inverters are designed with grid-forming capability, meaning they can establish the voltage and frequency reference for the entire microgrid during islanded operation. Grid-forming inverters are essential for creating stable and self-sustaining microgrids without relying on external grid support.

Protection Coordination:

Smart inverters coordinate with other protection devices within the microgrid, such as protective relays and circuit breakers, to detect and respond to faults and disturbances. The coordination ensures that the smart inverter's actions align with the overall protection strategy of the microgrid, enhancing the system's reliability and resilience[29].

Cybersecurity Measures:

As smart inverters are equipped with advanced control and communication systems, real-time protection also involves robust cybersecurity measures. Secure communication protocols and authentication mechanisms are implemented to safeguard against cyber threats and potential unauthorized access.

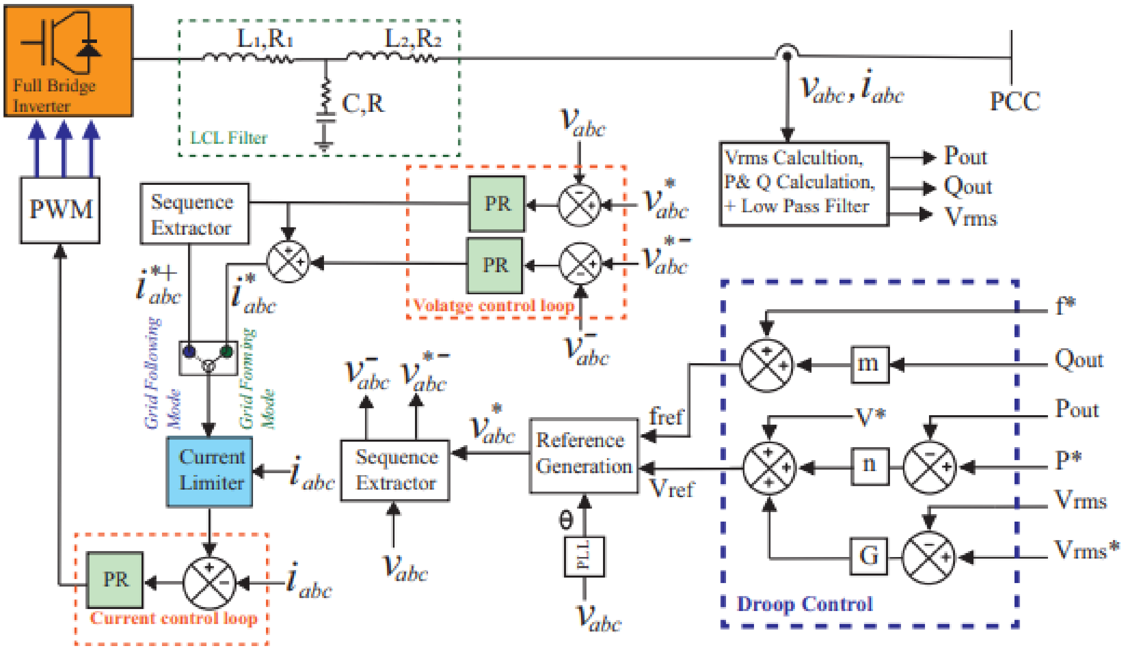

Figure2.6. Smart inverter.[30]

Figure 2.6. shows the constructional details of the smart inverter with indicated different parts of its control functions.

2. Islanding detection and anti-islanding real-time protection

Islanding detection and anti-islanding protection are critical aspects of grid-tied renewable energy systems, especially in distributed energy resources (DERs) like solar photovoltaic (PV) systems and wind turbines. An islanded condition occurs when a portion of the power system remains energized in isolation from the main grid during a grid outage. This situation poses significant safety risks for utility workers attempting to restore power and can lead to equipment damage or even grid instability if the islanded system continues to supply power to the main grid.

Islanding Detection:

Islanding detection involves the implementation of algorithms or methods to rapidly and accurately detect when an islanding event occurs. There are several techniques used for islanding detection, including passive and active methods. Passive methods rely on monitoring power quality and frequency deviations, whereas active methods actively inject test signals into the grid and analyse the response to detect islanding.

Some common passive methods include Rate of Change of Frequency (ROCOF), Vector Shift, and Impedance Measurement. The ROCOF method monitors the rate of change of grid frequency, while Vector Shift measures changes in the phase angle of voltage and current. Impedance Measurement looks for changes in grid impedance to detect islanding.

Active methods, such as the Frequency-Watt (F-W) and Voltage-Watt (V-W) methods, involve injecting perturbations into the power system and analyzing the response to determine if islanding occurs. These methods are particularly useful for inverter-based DERs like solar PV systems, as they provide a way to actively influence the system's behavior and detect islanding more reliably[31].

Anti-Islanding Protection:

Once islanding is detected, anti-islanding protection mechanisms are triggered to disconnect the islanded portion of the microgrid from the main grid. This ensures that the islanded system stops supplying power to the main grid and prevents potential hazards to utility workers.

Anti-islanding protection is typically implemented using specialized relays or inverters with islanding detection functionality. When islanding is detected, these devices rapidly trip or disconnect the grid-tied DERs from the main grid. Grid support features in modern smart inverters also allow them to detect islanding events and cease grid-tied operation.

The performance of islanding detection and anti-islanding protection is subject to standards set by regulatory bodies, such as IEEE 1547. These standards define the technical requirements for grid-tied DERs and ensure that islanding detection and anti-islanding protection mechanisms operate reliably and consistently across different systems.

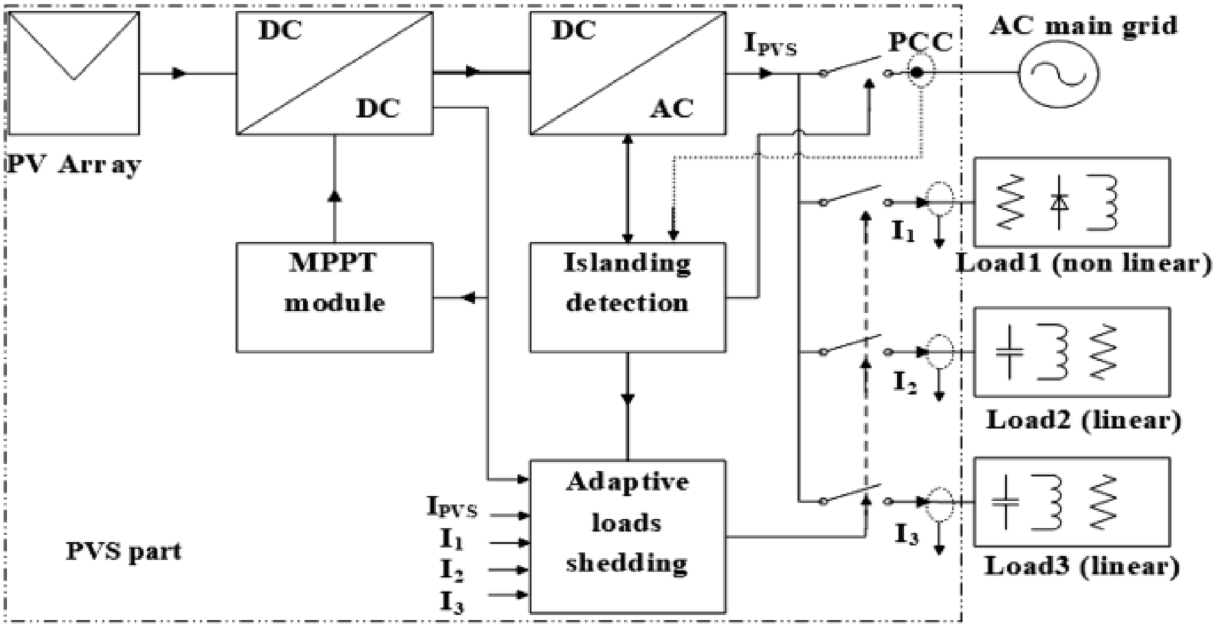

Figure2.7. Islanding detection and anti-islanding protection scheme[32]

Figure 2.7. shows the islanding detection and anti-islanding protection scheme, it detects the islanding mode, and applies adaptive load shedding algorithms to protect the microgrid, it also incorporates and islanding protection to safely disconnect the microgrid from the grid.

3. **Dynamic Power Curtailment Real-Time Protection**

Dynamic power curtailment is a real-time protection method used in renewable energy-based microgrids to manage excess energy generation and maintain grid stability. In microgrids with intermittent renewable energy sources, such as solar and wind, the energy output can vary based on weather conditions, leading to periods of surplus energy. Dynamic power curtailment allows for the controlled reduction of renewable energy generation during such periods to prevent grid overloading and potential disruptions[33].

How does a Dynamic Power Curtailment Works?

During periods of high renewable energy generation, when the microgrid's demand is lower than the available supply, dynamic power curtailment is triggered. The control system actively adjusts the output of renewable energy sources, such as solar PV arrays or wind turbines, to match the current energy demand of the microgrid. By curtailing the power generation, the system prevents overloading of the grid and avoids voltage and frequency deviations.

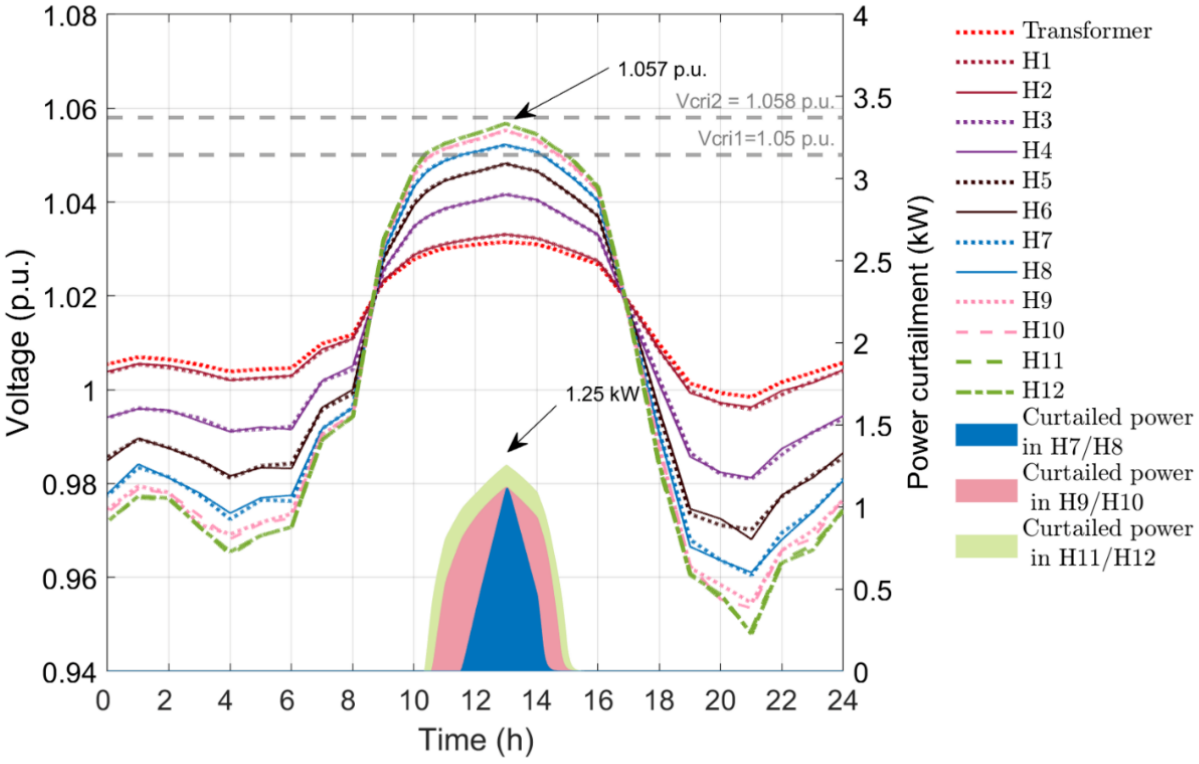

Figure2.8. Dynamic curtailment[34]

Figure 2.8. shows power curtailment and voltage profile, the solar inverter is equipped with droop control to limit the maximum power to the current demand.

Frequency-Based Curtailment:

One method of dynamic power curtailment is frequency-based curtailment. The control system continuously monitors the grid frequency, and if it exceeds the predefined threshold, it initiates power curtailment. This mechanism is particularly effective during high renewable energy generation when the system may be at risk of oversupplying power to the grid.

Voltage-Based Curtailment:

Voltage-based curtailment is another approach where the control system monitors the grid voltage levels. If the voltage rises beyond the specified limit, dynamic power curtailment is activated to reduce the output of renewable energy sources. This ensures that the voltage remains within the acceptable range, preventing potential damage to electrical equipment.

Beneficial Impact:

Dynamic power curtailment offers several benefits in renewable energy-based microgrids. By preventing grid overloading, it enhances the stability and reliability of the microgrid. It also allows for better utilization of available energy, minimizing energy wastage during periods of low demand. Additionally, dynamic power curtailment supports the seamless integration of renewable energy sources into the grid, enabling a smoother transition to a sustainable energy future.

Integration with Energy Storage:

Dynamic power curtailment can be complemented by energy storage systems. During periods of excess energy, the surplus can be stored in batteries or other energy storage devices instead of being curtailed. Later, when demand exceeds renewable energy generation, stored energy can be utilized, reducing the need for curtailment.

Challenges:

While dynamic power curtailment is a valuable real-time protection method, it poses challenges in balancing energy supply and demand. The balance between curtailing energy and ensuring sufficient supply to meet demand requires careful coordination and control.

4. Drop control and virtual inertia protection

Droop control and virtual inertia are real-time protection techniques used in modern power systems, particularly in renewable energy-based microgrids, to enhance grid stability and support smooth operation during islanded conditions. These methods play a crucial role in maintaining frequency stability and ensuring reliable power supply in decentralized energy systems[35].

Droop Control:

Droop control is a decentralized control approach used in inverters and generators within a microgrid. During islanded operation, each inverter or generator operates with a slight frequency droop, where the output power decreases as the frequency increases. In the presence of load variations, the frequency deviates from the nominal value, causing inverters or generators to respond by adjusting their output power proportionally to the frequency deviation. This automatic load sharing ensures a balanced power distribution and stable frequency across the microgrid, enhancing its resilience and reliability.

Virtual Inertia:

Virtual inertia is a concept employed in smart inverters to mimic the behavior of traditional synchronous generators, which inherently provide inertia to the power system. Inertia is the ability of synchronous generators to resist changes in frequency due to sudden load fluctuations. In a renewable energy-based microgrid with a high penetration of inverters, the lack of physical inertia can lead to frequency instability. Virtual inertia algorithms within smart inverters simulate inertia-like response, allowing them to regulate frequency during sudden changes in load or generation. This virtual inertia support contributes to grid stability and helps prevent frequency deviations.

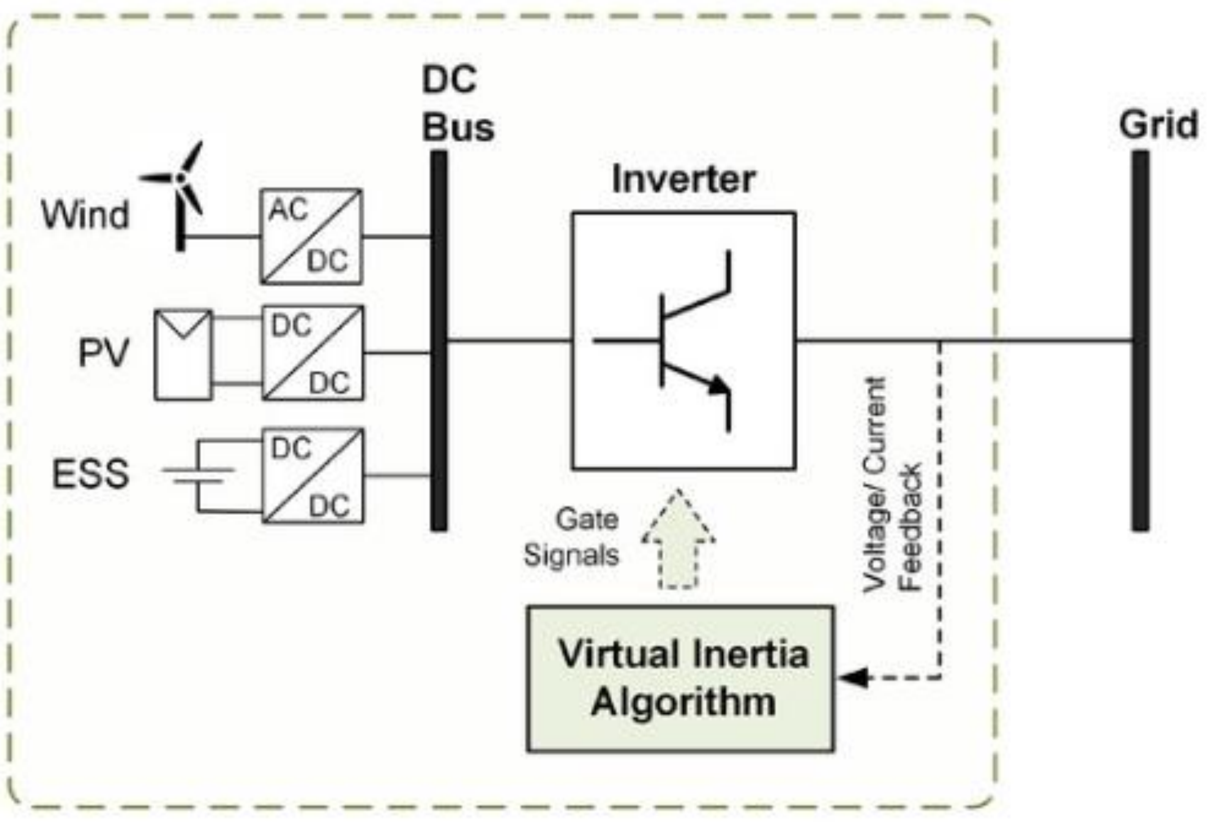

Figure2.9. The dynamic structure of the designed virtual inertia control[36]

Figure2.9. shows the virtual inertia emulation, in this case the inverter behaves as the normal synchronous generator, to facilitate in the maintenance of grid frequency in the case of sudden load changes. Virtual inertia algorithm enables the inverter to behave like a synchronous machine.

5. **Demand response integration**

Demand Response Integration is a real-time protection strategy that enables consumers to actively participate in grid management by adjusting their energy consumption based on grid conditions and energy availability. In modern power systems, including renewable energy-based microgrids, demand response integration plays a crucial role in maintaining grid stability, optimizing energy utilization, and enhancing overall system efficiency.

During periods of high electricity demand or limited renewable energy generation, the microgrid or utility communicates with consumers to reduce non-essential energy usage through load shedding or load prioritization. Critical loads are given priority to ensure continuous operation. Conversely, during times of surplus renewable energy, consumers may be encouraged to increase energy consumption or charge energy storage systems to absorb excess energy.

Demand response integration supports grid stability by managing imbalances between energy supply and demand. It reduces the need for costly peaking power plants and enhances the integration of intermittent renewable energy sources, such as solar and wind.

The benefits of demand response integration are two-fold: for grid operators, it aids in grid management and cost optimization, while for consumers, it offers potential energy cost savings and increased awareness of energy usage patterns. By facilitating a dynamic and interactive energy ecosystem, demand response integration contributes to a more resilient and sustainable energy future[35].

6. Fault detection and localization techniques

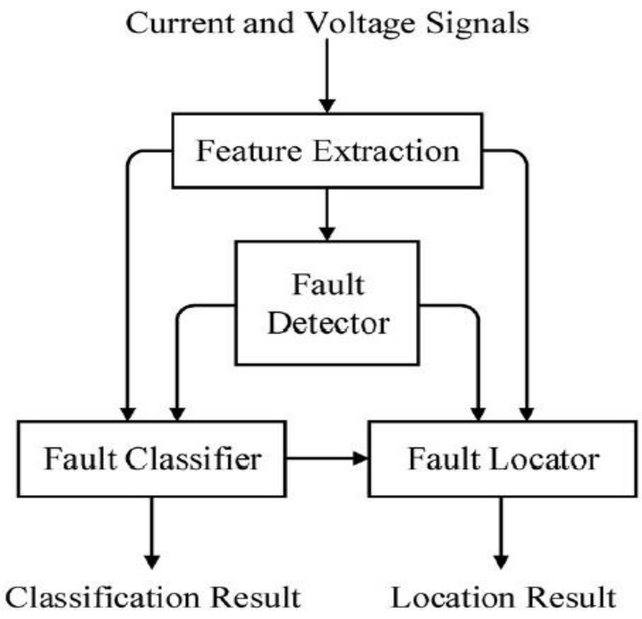

Figure2.10. Simplified framework for fault detection, classification and location.[37]

The current and voltage signals in the aforementioned figure are sampled, and the sampled points are then sent to the feature extraction module. Then, this module retrieves the features required by the fault finder, fault classifier, and fault detector. The fault classifier and fault locator, respectively, produce two outputs: the fault type and the fault location. While some of the works cover all three, others concentrate on only one or a couple of the aspects [38].

Numerous studies have looked into fault localization and detection methods for microgrid real-time protection systems. Using wavelet transform, Smith et al. (2017) introduced a fault detection algorithm that can quickly and accurately locate defects in microgrid systems. In order to increase the performance of fault detection, Zhang et al. (2019) used machine learning methods, using data-driven models for fault categorization and localisation. These studies underline how crucial advanced signal processing and machine learning methods are for microgrid fault detection that is both accurate and effective [39].

7. Rapid Disconnection Mechanisms

Rapid disconnection mechanisms are indispensable elements of microgrid protection, ensuring swift and precise isolation of faults to safeguard the integrity and reliability of the microgrid. As microgrids integrate diverse distributed energy resources (DERs) with varying characteristics, rapid disconnection becomes critical to prevent potential cascading failures and ensure the safety of equipment and personnel.

In microgrid protection, protective relays and advanced communication systems are employed to continuously monitor the microgrid's parameters, including current, voltage, frequency, and power flow. When an abnormal condition or fault is detected, the protective relay sends a trip signal to the corresponding circuit breaker or switches, initiating rapid disconnection of the affected section. This instantaneous response minimizes the impact of the fault, preventing it from spreading to other parts of the microgrid and reducing potential downtime.

Moreover, microgrid rapid disconnection mechanisms can be enhanced by incorporating intelligent control algorithms and decentralized protection schemes. These strategies allow localized disconnection, ensuring selective isolation of faults while maintaining the uninterrupted operation of healthy segments within the microgrid.

The implementation of rapid disconnection mechanisms in microgrid protection ensures grid stability, enhances system resilience, and supports seamless islanding and grid reconnection. By swiftly addressing faults and abnormal conditions, these mechanisms contribute to the overall efficiency and reliability of renewable energy-based microgrids, promoting sustainable and secure energy solutions for modern power systems [40].

2.4. Research gap

The lack of attention paid to the economic viability and cost-effectiveness of deploying such systems is a noteworthy research gap in the area of real-time protection systems for renewable energy-based microgrids, notably in the context of Rwanda. Real-time protection systems have a large amount of technical literature, but there are few studies specifically looking at the economic effects of installing and using these systems in Rwandan microgrids.

For decision-makers and stakeholders, it is essential to comprehend the economic viability and cost-effectiveness of real-time protection systems in Rwandan microgrids. It necessitates a thorough evaluation of the costs associated with purchasing, installing, and maintaining the equipment as well as their potential advantages and returns on investment. This study intends to contribute in bridging this knowledge gap and offer insightful information on the long-term sustainability and economic viability of integrating real-time protection systems in Rwandan microgrids.

In order to close this research gap, it will be necessary to evaluate the overall cost of ownership, which includes initial capital expenses, ongoing operating costs, and possible savings brought on by improved power quality and system reliability. Decision-making procedures will benefit from looking at the financial viability of various real-time protection system configurations as well as different renewable energy sources, storage technologies, and control methods. To further understand the affordability and scalability of installing real-time protection systems in Rwandan microgrids, potential funding mechanisms, such as public-private partnerships or creative finance models, should be investigated.

CHAPTER 3:

RESEARCH METHODOLOGY

3.1. Introduction

Research methodology is the backbone of any scientific investigation, providing a structured and systematic approach to the pursuit of knowledge. It is a comprehensive framework that guides researchers in their quest to answer questions, test hypotheses, and unravel the mysteries of the world around us. At its core, research methodology encompasses the strategies, techniques, and tools employed to gather, analyze, and interpret data. By adhering to a well-defined methodology, researchers can ensure that their findings are credible, reliable, and reproducible, ultimately contributing to the cumulative body of knowledge in their respective disciplines[41].

The process of research methodology began with the formulation of a clear research question or problem statement. It involves a meticulous review of existing literature to grasp the current state of knowledge, identify gaps in understanding, and establish the context for the study. Subsequently, researchers design a suitable research plan, including data collection methods, sample selection, and data analysis techniques.

Research methodology was not a one step process, it involved rigorous series of steps:

Identifying the research problem: During this research, the researcher defines the specific issue or question that requires investigation. This process involves thorough literature review, observation, and analysis of existing gaps or inconsistencies in knowledge. A well-defined research problem sets the foundation for the entire study, guiding the formulation of research objectives, research questions, and the overall research design. Clarity in this stage ensures the study's relevance, feasibility, and potential contributions to the field of study.

Developing research questions or hypotheses is a vital step in research methodology, following the identification of the research problem. It involves formulating specific and measurable inquiries or testable statements that aim to address the research problem. These questions or hypotheses guide data collection and analysis, helping researchers stay focused on the study's objectives. Careful construction of research questions or hypotheses enhances the study's clarity, validity, and ability to provide meaningful insights and contribute to the existing body of knowledge.

Selecting appropriate research methods: It involved deciding on the most suitable techniques and procedures to gather and analyze data that align with the study's objectives and address the research questions. Researchers must consider various factors such as the nature of the research problem, available resources, time constraints, and ethical considerations. Common research methods include qualitative, quantitative, and mixed-method approaches. The careful selection of research methods ensures the study's validity, reliability, and the generation of relevant and valuable findings, ultimately contributing to the advancement of knowledge in the field.

Collecting and analyzing data: Through this step researchers gather information relevant to their study's objectives and systematically examine it to draw meaningful conclusions. Data collection involves using various techniques such as surveys, interviews, observations, or experiments to obtain primary or secondary data. Once collected, the data is organized, cleaned, and prepared for analysis. The analysis involves applying appropriate statistical or qualitative methods to identify patterns, relationships, trends, or themes within the data. This process helps researchers interpret the findings, validate research hypotheses, and draw evidence-based conclusions. Effective data collection and analysis ensure the accuracy and reliability of research outcomes, allowing researchers to make informed recommendations, contribute to knowledge in their field, and inform decision-making processes.

Interpreting and communicating findings is a critical step in research methodology, researchers analyze the results of their data analysis and derive meaningful insights. During interpretation, researchers identify patterns, relationships, and trends within the data, comparing them with existing theories or prior research to draw conclusions and answer the research questions or hypotheses. This process involves critically evaluating the validity and reliability of the findings and considering any potential limitations or biases that may have influenced the results.

Once the interpretation is complete, effective communication of the findings is essential to share the research outcomes with the scientific community and relevant stakeholders. Researchers typically prepare research reports, academic papers, or presentations to present their findings clearly and concisely. This communication should be tailored to the target audience, ensuring accessibility and comprehensibility. Visual aids like graphs, charts, and tables are often used to enhance understanding. Transparent and honest reporting of results is crucial to maintain the credibility of the research and facilitate further research and discussions in the field. Properly interpreted and communicated findings contribute to the advancement of knowledge and inform practical applications and policy decisions based on evidence[41].

Furthermore, ethical considerations are integral to research methodology. It involves ensuring the protection and welfare of human subjects, maintaining confidentiality, and being transparent about potential conflicts of interest. A strong adherence to ethical principles fosters trust and integrity in the research process and its outcomes.

Different research methods can be used depending on the research topic and objectives, including qualitative, quantitative, and mixed methods.

Quantitative method

Quantitative research is a systematic empirical investigation that aims to understand and explain phenomena through the collection and analysis of numerical data. It involves the use of structured surveys, experiments, or existing datasets to gather objective and quantifiable information. Researchers employ statistical techniques to analyze the data, identify patterns, correlations, and relationships, and draw conclusions based on evidence. This approach allows for generalization of findings to larger populations and enables researchers to test hypotheses, make predictions, and draw objective conclusions. Quantitative research is widely used in various disciplines, including social sciences, natural sciences, and business, providing valuable insights into complex phenomena and contributing to evidence-based decision-making and policy formulation. However, it is essential to consider the limitations and assumptions associated with quantitative research, such as potential biases, sample representativeness, and the nature of data collected. The following steps were adopted:

Data collection: Existing microgrids in Rwanda were used to gather quantitative data on power quality metrics as voltage stability, frequency regulation, and harmonic distortion. Smart meters, monitoring systems, and field measurements were used to collect the data.

Data analysis: Statistical techniques were used to examine the data gathered and assess Rwanda's renewable energy-based microgrids' current performance in terms of power quality. The effectiveness of real-time protection systems was examined in connection to power quality metrics using descriptive statistics, correlation analysis, and regression analysis.

Qualitative method

Qualitative research is an exploratory and interpretative approach used to gain an in-depth understanding of complex phenomena and subjective experiences. It involves collecting non-numerical data, such as interviews, focus groups, observations, or textual analysis, to explore the nuances, meanings, and underlying reasons behind human behaviors and interactions. Researchers immerse themselves in the context of the study, seeking to capture the perspectives, emotions, and beliefs of participants[41].

The data collected in qualitative research are often rich and descriptive, providing valuable insights into the social and cultural dimensions of the research topic. Analysis involves thematic coding, categorization, and interpretation to uncover patterns and themes that inform the research questions.

The following steps were adopted:

Interviews: Key stakeholders, such as microgrid operators, policymakers, energy regulators, and technical experts, were the subjects of formal or semi-structured interviews. These discussions centered on their experiences setting up and running microgrids in Rwanda, as well as their viewpoints on problems with power quality and real-time protection techniques.

Case studies: Particular Rwandan microgrid installations were chosen as case studies. To comprehend the practical use of real-time protection measures, power quality enhancement methods, and the results obtained, in-depth evaluations of these case studies were done. The case studies gave useful information about how real-time protection systems are used in Rwanda.

Observation and documentation: The operational features of Rwanda's renewable energy-based microgrids, including the real-time protection mechanisms in place, the procedures for power quality monitoring, and any difficulties encountered, were observed and documented. These observations and records supplemented the information from the interviews and added more context to the research findings.

Mixed research method

Mixed methods research is a comprehensive approach that combines both qualitative and quantitative research methods in a single study. This method allows researchers to gather and analyze both numerical data (quantitative) and descriptive data (qualitative) to gain a more comprehensive understanding of the research problem. By integrating diverse data collection techniques, such as surveys, interviews, observations, and statistical analysis, mixed methods research can provide a deeper and more nuanced insight into complex phenomena. The combination of qualitative and quantitative data enhances the validity and triangulation of findings, enriching the overall research outcomes and enabling researchers to address multifaceted research questions in a more robust and holistic manner.

Analytical method

Analytical method is a research approach that focuses on systematically examining and interpreting data to derive meaningful insights and draw conclusions. It involves using various analytical techniques, such as statistical analysis, content analysis, or thematic analysis, to identify patterns, trends, or relationships within the collected data. The goal of the analytical method is to uncover hidden connections and provide evidence-based interpretations that answer research questions or test hypotheses. Researchers employ this method across different disciplines, from social sciences to natural sciences, to explore, explain, and understand complex phenomena. By employing rigorous analytical procedures, researchers ensure the validity and reliability of their findings, contributing to the advancement of knowledge in their respective fields.

Statistical method

Statistical method is a research approach that utilizes mathematical and quantitative techniques to analyze and interpret data in a systematic and objective manner. It involves applying various statistical tools, such as descriptive statistics, inferential statistics, regression analysis, and hypothesis testing, to process and draw meaningful insights from the collected data. Statistical methods are widely used in diverse research fields to uncover patterns, trends, and relationships, providing empirical evidence to support or reject research hypotheses. The rigorous application of statistical methods ensures the reliability and validity of research findings, enabling researchers to make informed decisions, identify significant associations, and contribute valuable knowledge to their respective disciplines.

Integration of findings

The results of the quantitative and qualitative research components will be combined to give a thorough understanding of the real-time protection measures and power quality improvement in Rwandan microgrids powered by renewable energy sources. To provide a comprehensive understanding of the research topic, the qualitative views from stakeholders will be contrasted with the quantitative data on power quality factors. This integration aided in locating any weaknesses, difficulties, and areas for potential advancement in real-time defense tactics for enhancing power quality[41].

3.2. Results from interview

The field visits were conducted, to collect data on how intermittent of renewable energy sources affects the grid as well as the operation of other plants. The questions related to protection method employed for protection of renewable energy based microgrids were asked. The operators at national control center (NCC) and those at microgrids were interviewed.

The questions asked were:

1. What protection scheme you use?
2. How many breakdowns occur due to intermittent of renewable energy?
3. What methods you use to fight cope with intermittent problems?
4. Is there any method you recommend for the protection scheme?
5. What are challenges do you meet due to renewable energy based microgrid?

Findings from the interview

The answers from the interview are presented in the table format.

Table3.1. Interview results from respondents

	Aspect	Answer
1	Protection scheme	• Traditional relay and circuit breaker protection • String inverters

2	Occurrence of breakdown	At least 7 times per month
3	Intermittent handling	Difficult manual intervention and judgement and set operational parameters of the power system based on past experience
4	Recommendation	• Intelligent protection scheme • Adoptive systems with prediction algorithms

3.3. Internet sources

In this source, several information related to renewable energy based microgrid protection scheme was gathered. That information includes the effects of intermittent to power system, solar and wind variation in Rwanda, protection schemes for microgrids.

3.4. Research method used in the case study of Rwanda

To successfully complete this thesis “Real-time protection of renewable energy-based microgrids for power quality enhancement. “A case study of Rwanda” mixed method was used. This method involves collecting both numerical and non-numerical data, which are then analyzed using both statistical and interpretive techniques.

Throughout the work Qualitative methods, such as interviews and focus groups, were used to gather insights from experts, policymakers, and stakeholders about the challenges and opportunities related to microgrid protection and its impact on power quality. This can help identify specific issues and context-specific factors affecting the implementation of real-time protection in Rwanda's renewable energy microgrids. Quantitative methods can be employed to collect data on power quality parameters and performance indicators from different microgrid sites. This data can be analyzed using statistical techniques and compared with the presence or absence of real-time protection measures. The analysis can help establish correlations between protection strategies and power quality enhancement in microgrids.

Combining qualitative and quantitative data can provide a more comprehensive understanding of the effectiveness of real-time protection mechanisms in improving power quality in Rwanda's renewable energy-based microgrids. The findings can be used to inform policy decisions, improve existing systems, and contribute to the sustainable development of the energy sector in the country.

3.5. Area of the research

The study focuses on the application and examination of real-time protection systems for microgrids powered by renewable energy in Rwanda. East African nation of Rwanda is a landlocked nation renowned for its adoption of renewable energy sources and dedication to sustainable development. The distinctive features of Rwanda's energy system make it a prime location for research on improving power quality and protecting microgrids in real time.

Selected microgrid deployments in various Rwandan regions will be the main focus of the investigation. These installations incorporate a range of localized electricity systems with renewable energy sources, such as biomass, hydropower, and solar PV. Focusing on certain microgrids will enable the study to capture the various operating scenarios, difficulties, and opportunities related to real-time protection and power quality in Rwanda [42].

Microgrids from both urban and rural areas of Rwanda will be included in the study region, representing a variety of geographical, socioeconomic, and demographic aspects. This wide range of microgrid locations will give researchers a thorough grasp of the real-time security measures and power quality issues that are present across the nation's many areas and settings.

Operators of microgrids, technical experts, decision-makers, energy regulators, and local communities will be important study participants. Their active participation will ensure the gathering of priceless information on real-time protection systems, power quality improvement, and the overall effectiveness of microgrids powered by renewable energy in Rwanda.

This thesis intends to give context-specific findings and recommendations that can aid in the creation of efficient real-time protection mechanisms and enhance power quality in renewable energy-based microgrids by performing the research within the particular study area of Rwanda. Due to its distinctive qualities, dedication to sustainable energy, and variety of microgrid installations, the study region is the perfect place to explore the research question and come to pertinent conclusions for the development of microgrid technologies in Rwanda and comparable contexts [43].

3.6. Study Population

The participants in this research thesis's study population are several parties with a stake in the development, administration, and management of Rwanda's microgrids that use renewable energy sources. The study population must be carefully chosen to acquire information on real-time protection systems and power quality improvement in microgrid situations.

i. Microgrid operators are essential to the day-to-day management and operation of microgrids powered by renewable energy. They are in charge of ensuring the effective operation of the microgrid systems, which includes the implementation and supervision of real-time safety controls. To gather a variety of operating experiences and opinions, the study will include microgrid operators from several Rwandan areas.

ii. Technical Experts: A significant portion of the study population consists of technical experts, such as engineers, researchers, and specialists in microgrid systems and renewable energy. Their experience and skills help Rwandan microgrids run better overall and comprehend real-time protection techniques as well as issues with power quality.

iii. The regulatory framework and regulations relating to the development of microgrids and renewable energy in Rwanda are heavily influenced by policymakers and energy regulators. Their opinions and thoughts on the need for real-time protection, policy ramifications, and power quality standards are helpful to the study.

iv. Local Communities: The study population includes the local communities that are present in the regions where microgrids are installed. Their insights, opinions, and experiences with the microgrid systems' dependability, power quality, and advantages will give the research a community-focused viewpoint. To assess the efficiency of the microgrids, it is crucial to comprehend how real-time protection systems affect residents' daily life.

Purposive sampling will be used to choose the study participants, ensuring that different geographical areas, types of microgrids, and stakeholder roles are represented. The research's goal is to engage the study population in order to acquire in-depth information, viewpoints, and insights about the protection of microgrids powered by renewable energy in real time and the improvement of power quality in Rwanda.

CHAPTER 4:

CASE STUDY AT RWAMAGANA SOLAR POWER PLANT

4.1. Introduction

In July 2014, the Rwandan government engaged GigaWatt Global, a Dutch firm, to construct an 8.5-megawatt solar power plant in the Rwamagana District, Eastern Province. The contract was valued at $23 million, and GigaWatt Global assumed responsibility for financing, building, owning, and operating the facility for 25 years. The electricity generated would be sold to Rwanda Energy Group, the national electricity utility. GigaWatt Global achieved financial closure in February 2014, enabling the commencement of construction. By July 2014, the plant was connected to the national electricity grid, and it reached its maximum capacity by September 2014. The solar power station spans 50 acres (20 hectares) and features 28,360 individual photovoltaic panels[44].

Figure4.1. Rwamagana solar power plant[45]

The power station is located on leased land, at the campus of Agahozo Shalom Youth Village, in Rwamagana District, Eastern Rwanda, approximately 58 kilometres (36 mi), by road, southeast of Kigali, the capital and largest city in the country. The coordinates of the power station are:2°01'34.0"S, 30°22'38.0" E (Latitude:-2.026111; Longitude:30.377222).

4.2. Study population

To do the deep research, a field visit to Rwamagana solar power 8.5MW was done. A purposive sampling method was used to select the group of people to be interviewed, and a set of questions were asked to the selected people to get information on the protection systems that are currently employed.

Table4.1. Table representation of respondents

Occupation	Population size
Maintenance technicians	17
Plant operators	9
Directory commitee	6
Economist/Finance	1
Total	**33**

Table4.2. shows the number of respondents participated in the interview; it shows their occupation at the plant.

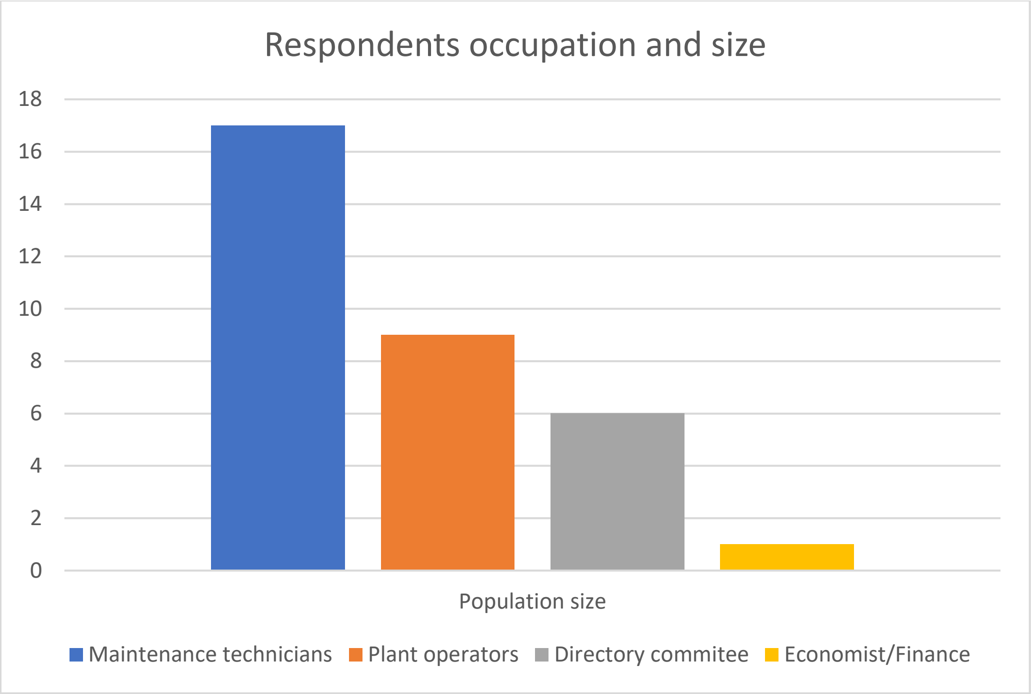

Figure4.2. Respondents and size on the interviews

Table4.2. Respondents on protection method failure

Protection techniques	Protection failure
Overcurrent protection	3.4%
Directional protection	5%
Voltage protection	7%
Impedance protection	12%
Distance protection	5%
Differential protection	2%
Over/underfrequency protection	22%

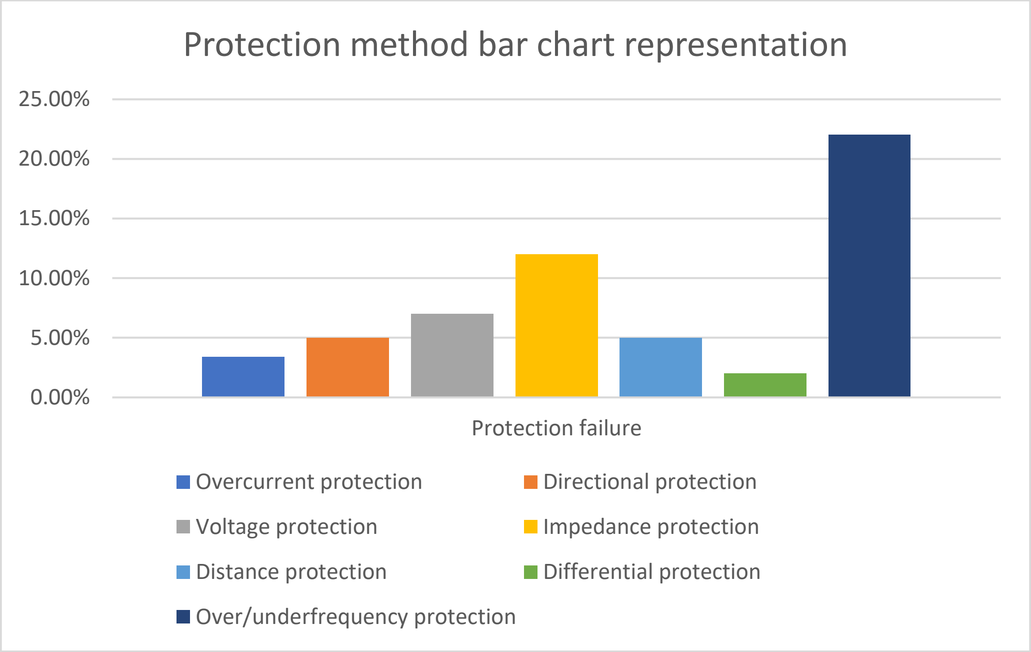

Figure4.3. Representation of protection method failure (Source: Primary data)

Table 4.3. shows the percentage of failure when a fault occurs and the system is invoked to operate. The answers provided by each respondent were analyzed and the results in percentage are presented on bar chart. Overcurrent protection failures at 3.4.%, directional protection at 5%, voltage protection at 7%, impedance protection at 12%, distance protection at 5%, differential protection at 2%, and over/under frequency protection at 22%.

According to the respondents' frequency protection failures more than other methods at 22%, frequency of the grid is mainly dependent on the synchronous machine which often changes due to load increase/decrease or change in the working conditions of the prime mover, as many inverters follow grid parameters, the response time of the inverters contribute to much on the working of protection system. The failure to adjust frequency to grid causes lack of synchronism.

The failure of protection method and delay in response is responsible to the damage and breakdown of different plant devices and machines, that raises the operational cost of the plant and lower the life expectancy of the devices.

However, according to respondents the combination of different protection methods boosted the safety of the plant.

Table4.3. Skills of the respondents on the used method

Protection techniques	Skills of respondents on the method
Overcurrent protection	70%
Directional protection	10%
Voltage protection	50%
Impedance protection	30%
Distance protection	12%
Differential protection	34%
Over/underfrequency protection	12%

(Source: Primary data)

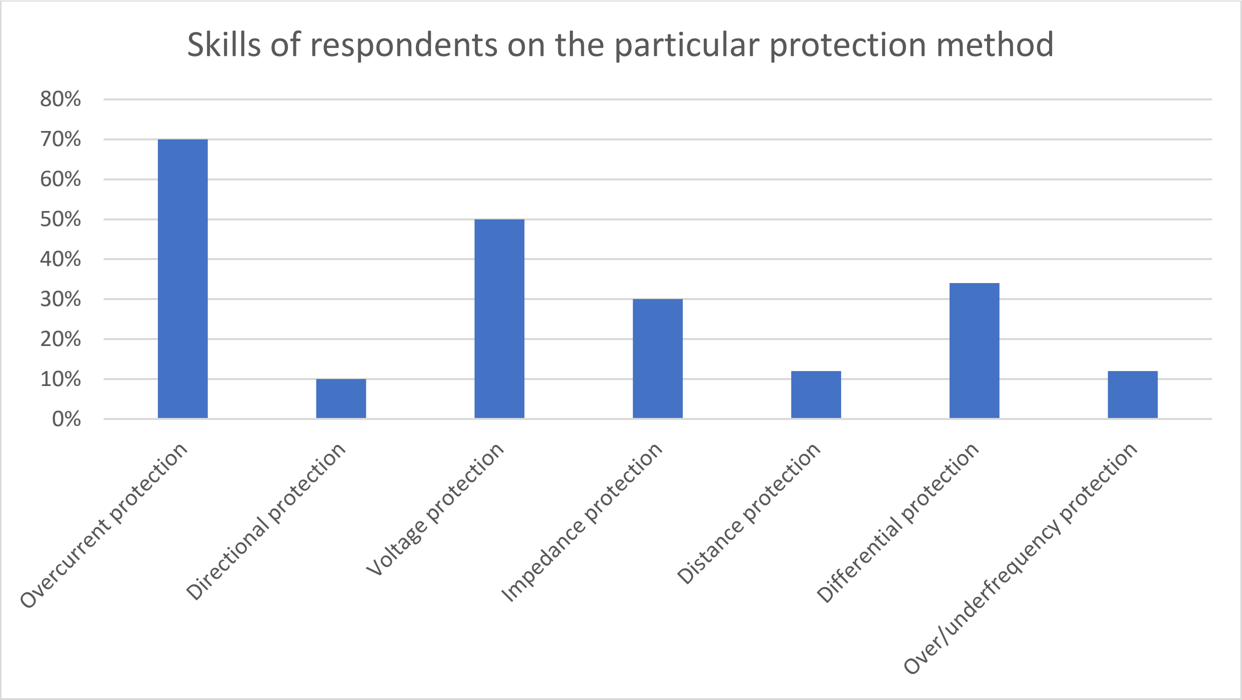

Figure4.4. Representation of respondents' skills in protection method (Source: Primary data)

Respondents were asked on the skills they have on the protection methods used in terms repairing, operation, maintenance, fault causes identification, and installation of the respective protection scheme. The answer provided were analyzed and tabled in table 4 and depicted on bar chart figure 14. Each respondent was asked the skills he/she has on each protection method and the result is interpreted in percentage format.

According to chart 14, 70% of respondents have necessary skills on overcurrent protection, 10% on directional protection, 50% on the voltage protection, 30% on impedance protection, 12% on distance protection, 34% on differential protection, and 12% on over/under frequency protection.

Lacks skills by the operators on different protection methods, contribute to the ineffectiveness of the respective method, improper calibration and increases the time taken to clear defect in the system. The respondents suggested that they must have training on the protection methods to seamless operate and manage the plant.

Respondents were asked to give the input of how the protection can enhanced, 30% of the suggested on combining different protection schemes and receiving training on protection methods so enable them to check if the protection is in good working conditions, needs a maintenance or require complete replacement of the devices with new ones. 70% of the respondents suggested the adoption of new protection methods that are intelligent and uses prediction algorithms. With those techniques they believe human intervention will be reduced and the system will be able to monitor the situation of the plant and adjust its parameters to the requirements or safely disconnect the microgrid from the network.

4.3. Comparison of existing microgrid protection and real-time protection method

Conventional method of microgrid protection do not provide a promising protection to achieve a good power quality, adoption of new protection method is emerging. The table below serves to compare both protection method to confirm whether adoption of new protection technology is doable and effective.

Table4.4. The comparison between real-time protection and existing methods

Aspect	Real-time Protection	Existing Protection
Time Sensitivity	Instantaneous response to faults and events.	Operates with predefined time delays or fixed settings.
Adaptability	Adjusts responses to dynamic renewable energy and load fluctuations.	May not be as flexible in accommodating renewable energy changes.
Integration with Smart Grid Tech	Essential component of smart grid implementations.	Can be integrated with smart grid technologies, but may lack seamless coordination.
Scalability and Complexity	Scales to accommodate larger and more complex microgrids.	May face limitations in handling modern microgrid complexity.
Customization and Optimization	Customizable and optimized for specific microgrid requirements.	May have standardized settings, potentially leading to suboptimal performance.

CHAPTER 5:

COMPARISON OF REAL TIME PROTECTION METHODS AND DISCUSSION

5.1.Introduction

This section presents a comprehensive comparison of various real-time protection methods for renewable energy-based microgrids, evaluating their respective advantages, disadvantages, and operational limitations. Additionally, the factors influencing the selection of the most suitable protection scheme are thoroughly discussed. Drawing insights from the gathered information, a well-articulated discussion aims to propose the best practices for ensuring the protection and reliability of renewable energy-based microgrids.

Renewable energy-based microgrids are characterized by their decentralized and intermittent energy sources, making the choice of an effective real-time protection system critical to ensure seamless and secure operation. By examining the merits and limitations of different protection methods, this comparative analysis seeks to identify the most appropriate approach for each specific microgrid's requirements and operational conditions.

Furthermore, the selection factors for choosing a protection scheme delve into the technical, economic, and regulatory considerations that impact the decision-making process. As microgrids become increasingly complex and diverse in their DER integration, the importance of making informed protection choices cannot be overstated.

By synthesizing the findings and conducting a comprehensive analysis, this section aims to provide valuable insights and recommendations to guide the implementation of the most effective protection strategies for renewable energy-based microgrids. The ultimate goal is to optimize system performance, maximize grid resilience, and ensure a sustainable and reliable energy supply for modern power systems.

5.2. Factors facilitating the choice of protection method

Microgrid Configuration: The specific configuration of the microgrid, including the types and capacities of renewable energy sources and energy storage systems, influences the choice of protection methods. Different DERs may require unique protection schemes to address their characteristics and potential fault scenarios.

Fault Characteristics: Understanding the potential fault types and their behavior within the microgrid is crucial for selecting appropriate protection methods. The fault currents, fault locations, and fault clearing times help determine the necessary sensitivity and coordination of the protection system.

Microgrid Size and Complexity: The size and complexity of the microgrid play a role in selecting the most suitable protection method. Larger and more intricate microgrids may require more advanced and coordinated protection schemes to address the diverse operational conditions.

Operating Modes: Microgrids often operate in various modes, such as grid-connected and islanded modes. The protection system should be capable of seamless transition between these modes and ensure stable and secure operation in both scenarios.

Response Time: Real-time protection requires rapid fault detection and isolation. The response time of the protection system should match the microgrid's dynamics to minimize the impact of faults and ensure timely protection actions.

Communication Infrastructure: The efficiency and reliability of real-time protection depend on the communication infrastructure. Robust and low-latency communication networks are essential for timely relay coordination and information exchange.

Regulatory Requirements: Compliance with grid interconnection standards and regulatory guidelines is vital. The selected protection method should align with applicable regulations and standards to ensure grid stability and safety.

Cost and Complexity: The cost and complexity of implementing the protection method should be considered, particularly for smaller microgrids. Balancing the level of protection required with the overall system cost is crucial for economic viability.

Adaptability and Scalability: As microgrids evolve and expand, the protection system should be adaptable and scalable to accommodate changes in DER integration and system expansion.

Cybersecurity: Ensuring the cybersecurity of the protection system is vital to safeguard the microgrid from potential cyber threats and attacks on communication networks[46].

By carefully evaluating these factors, I can make informed decisions to select the most appropriate real-time protection method for their renewable energy-based microgrid. A well-chosen protection scheme enhances grid reliability, stability, and resiliency, supporting the efficient integration and utilization of renewable energy sources while maintaining a secure and sustainable energy infrastructure.

5.3. Comparison of real time protection methods for microgrid

In this section, different real time protection method for renewable energy based microgrids are compared. The comparison factors are described below:

Reliability: Indicates how dependable the protection method is in detecting and responding to faults or abnormal conditions in the microgrid.

Time of Operation: Refers to the duration the protection method is active and monitoring the microgrid.

Response Time: Measures how quickly the protection system reacts to a fault or disturbance in the microgrid.

Selectivity: Describes the ability of the protection method to isolate faults in specific parts of the microgrid and avoid unnecessary tripping.

Cybersecurity Measures: Reflects the level of security measures implemented to protect the protection system from cyber threats and attacks.

Economic Factors: Considers the cost and economic impact associated with implementing and maintaining the protection method in the microgrid.

Table5.1. Table comparing real-time protection method for microgrid

	Comparison factors					
Protection Method	**Reliability**	**Time of Operation**	**Response Time**	**Selectivity**	**Cybersecurity Measures**	**Economic Factors**
Smart Inverter	High	Continuous	Fast	High	Moderate	Moderate
Islanding Detection and Anti-Islanding	High	Continuous	Fast	High	High	High
Dynamic Power Curtailment	Moderate	Event-driven	Moderate	Moderate	Low	Low
Droop Control and Virtual Inertia Protection	High	Continuous	Fast	High	Moderate	Moderate
Demand Response Integration	Moderate	Event-driven	Moderate	Low	Moderate	High
Rapid disconnection methods	High	continuous	Fast	High	High	High

Brief explanation of each protection method is discussed as follows.

- **Smart Inverter:**

Reliability: High Smart inverters can quickly respond to changes in grid conditions and are designed for robust performance.

Time of Operation: Continuous Smart inverters continuously monitor and adjust their output based on grid conditions.

Response Time: Fast Smart inverters can respond rapidly to grid events, such as voltage fluctuations or frequency deviations.

Selectivity: High Smart inverters can be programmed to respond selectively to specific grid events.

Cybersecurity Measures: Moderate Smart inverters generally have cybersecurity measures but may vary in their robustness.

Economic Factors: Moderate The cost of smart inverters can vary, but they offer benefits in grid stability and advanced control.

- **Islanding Detection and Anti-Islanding:**

Reliability: High - This method is essential for microgrid safety to prevent islanding and protect against hazardous conditions.

Time of Operation: Continuous - It operates continuously to detect potential islanding situations.

Response Time: Fast - In the event of islanding detection, disconnection should occur rapidly to ensure safety.

Selectivity: High - Islanding detection should be selective to identify true islanding events while avoiding false positives.

Cybersecurity Measures: High - To prevent tampering and ensure reliability, islanding detection should be well-secured.

Economic Factors: High - While the cost of implementation might be significant, the benefits in safety and grid stability are valuable.

- **Dynamic Power Curtailment**

Reliability: Moderate Depending on the implementation, dynamic curtailment may have limitations and uncertainties.

Time of Operation: Event driven Curtailment occurs when certain events or conditions trigger the need to reduce power output.

Response Time: Moderate The response time depends on how quickly the system can curtail power generation.

Selectivity: Moderate Curtailment may not be highly selective and might impact the entire microgrid or specific components.

Cybersecurity Measures: Low Dynamic power curtailment may not directly involve cybersecurity measures.

Economic Factors: Low - The implementation cost is relatively low, but potential revenue losses might occur during curtailment events.

- **Droop Control and Virtual Inertia Protection**

Reliability: High - Droop control and virtual inertia are effective in stabilizing the microgrid during disturbances.

Time of Operation: Continuous - These methods continuously operate to maintain grid stability.

Response Time: Fast - They respond quickly to frequency deviations and load changes.

Selectivity: High - They can be selectively applied to specific grid areas or components.

Cybersecurity Measures: Moderate - While virtual inertia involves control algorithms, it may require some cybersecurity measures.

Economic Factors: Moderate - The implementation cost might be moderate, but the benefits in stability and control are significant.

- **Demand Response Integration**

Reliability: Moderate - The reliability depends on consumer participation and response during demand response events.

Time of Operation: Event-driven - Demand response events are triggered when grid conditions require load adjustments.

Response Time: Moderate - The response time depends on how quickly consumers can adjust their demand.

Selectivity: Low - Demand response may not be highly selective and can impact a broad range of consumers.

Cybersecurity Measures: Moderate - Demand response systems need cybersecurity measures to protect against potential threats.

Economic Factors: High - While the implementation cost might be considerable, demand response integration can offer economic benefits through load management.

- **Rapid Disconnection Mechanisms**

Reliability: High - Rapid disconnection mechanisms are critical for ensuring safety during grid faults and emergencies.
Time of Operation: Continuous - These mechanisms continuously monitor grid conditions and are ready to disconnect when necessary.
Response Time: Fast - Rapid disconnection mechanisms can quickly disconnect the microgrid from the main grid during faults.
Selectivity: High - These mechanisms should be selective to disconnect the affected parts while keeping the rest operational.
Cybersecurity Measures: High - As crucial safety components, rapid disconnection mechanisms need strong cybersecurity.
Economic Factors: High - While the initial implementation cost might be significant, the benefits in safety and grid resilience are valuable.

In the selection process it is important to consider both technical performance and economic feasibility when choosing protection methods for a microgrid. Each method offers different advantages and trade-offs, and the final selection should be based on the specific requirements and constraints of the microgrid project. Additionally, cybersecurity measures should be carefully integrated into the protection system to ensure its integrity and prevent potential cyber threats that could compromise the microgrid's operation and safety.

5.4. The combination of inverter control, drop control, and virtual inertia real-time protection

The combination of inverter control, drop control, and virtual inertia real-time protection is a sophisticated approach to managing power quality and ensuring the stability of electrical grids.

Individual Protection Mechanisms

- Total Voltage

The system's total voltage's temporal evolution is depicted in the first subplot. The curve dynamically adapts to changes brought about by fluctuations in load, inverter power, and integrated control mechanisms, starting at the nominal grid voltage (Vg). An essential point of reference for comprehending the overall voltage behaviour is this graphic.

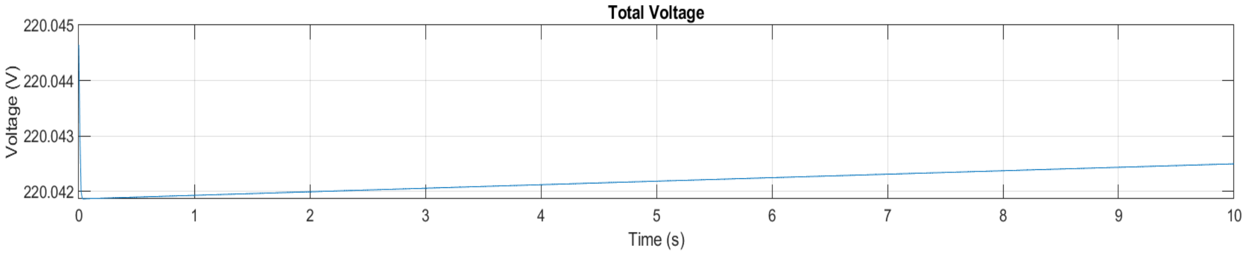

Figure5.1. Total voltage

- Virtual Inertia Output

The output of the virtual inertia control system during the simulation is shown in the second subplot. By adding a dynamic reaction to the power system, this technique helps to stabilize it against abrupt power fluctuations. The output of virtual inertia varies, which is indicative of its function in attenuating transitory impacts and preserving a more stable system voltage.

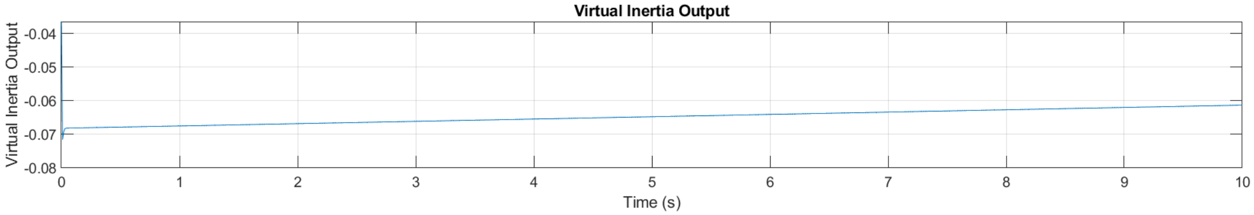

Figure5.2. Virtual Inertia Output

- Drop Control Output

Showing the results of the drop control system is the third subplot. This control signal adjusts the inverter output to offset disturbances by calculating the voltage variation from the grid reference. Increased corrective action is indicated by a higher drop control output, which shows how well the control mechanism stabilizes the system.

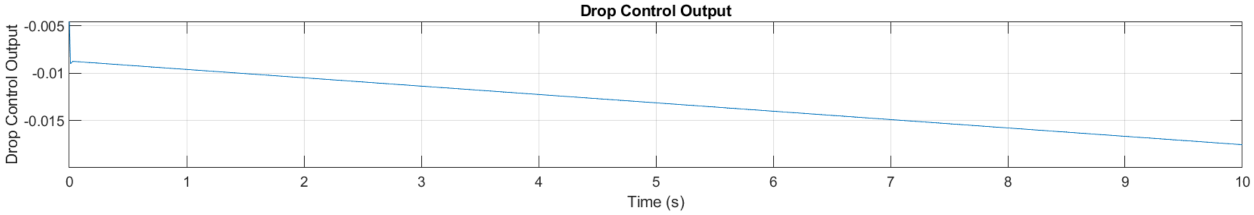

Figure5.3. Drop Control Output

Combined Protection Mechanisms

The integrated figure offers a comprehensive understanding of the cooperation between the three protective mechanisms: drop control, virtual inertia, and total voltage. The simultaneous representation shows how drop control and virtual inertia work together to lessen the effects of load variations and preserve grid stability. By looking at the combined figure, one may understand how these systems work together to produce stable and controllable power system behaviour.

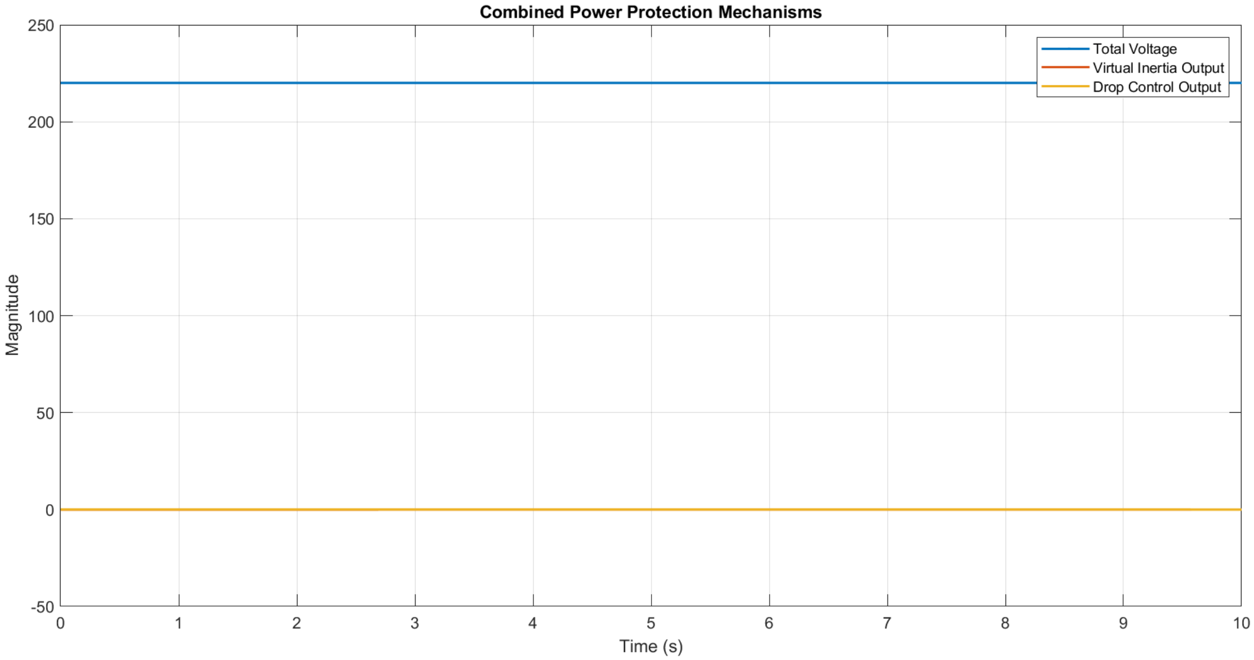

Figure5.4. Combined Power Protection Mechanisms

MATLAB

```
% Parameters
Vg = 220;           % Grid voltage (V)
Zg = 0.1 + 0.1j;    % Grid impedance (Ω)

Pi = 100;           % Inverter power (W)
Qi = 0;             % Inverter reactive power (Var)

Kp = 0.1;           % Drop control proportional gain
Ki = 0.01;          % Drop control integral gain

H = 10;             % Virtual inertia constant (s)

Pload = 200;        % Load power (W)
Qload = 0;          % Load reactive power (Var)

% Simulation
t = 0:0.01:10;      % Time vector
```

```
% Initialize variables
V = Vg;             % Voltage (V)
P = Pi - Pload;     % Active power (W)
Q = Qi - Qload;     % Reactive power (Var)

% Initialize arrays to store results
V_result = zeros(size(t));  % Total voltage
Vi_result = zeros(size(t)); % Virtual inertia output
Dc_result = zeros(size(t)); % Drop control output

integral_term = 0;  % Initialize integral term for drop control

% Simulation loop
for idx = 1:length(t)
    % Calculate the inverter current
    Ii = (P - 1j * Q) / V;

    % Calculate the drop control output
    Vd = Vg - V + Zg * Ii;
    integral_term = integral_term + Vd * 0.01;  % Numerical integration
    Dc = Kp * Vd + Ki * integral_term;

    % Calculate the virtual inertia output
    Vi = Vg - V + Zg * Ii - Dc;
    Vi = Vi * (1 - 1 / (1 + H * 1j));

    % Calculate the new voltage
    V = Vg - Zg * (Ii + Vi);

    % Store results
    V_result(idx) = V;
    Vi_result(idx) = Vi;
    Dc_result(idx) = Dc;
end

% Plot individual protection mechanisms
figure;

subplot(3,1,1);
plot(t, real(V_result));
xlabel('Time (s)');
ylabel('Voltage (V)');
title('Total Voltage');
grid on;

subplot(3,1,2);
plot(t, real(Vi_result));
xlabel('Time (s)');
ylabel('Virtual Inertia Output');
title('Virtual Inertia Output');
grid on;

subplot(3,1,3);
plot(t, real(Dc_result));
xlabel('Time (s)');
```

```
ylabel('Drop Control Output');
title('Drop Control Output');
grid on;

% Plot combined protection mechanisms
figure;
plot(t, real(V_result), 'LineWidth', 1.5, 'DisplayName', 'Total Voltage');
hold on;
plot(t, real(Vi_result), 'LineWidth', 1.5, 'DisplayName', 'Virtual Inertia Output');
plot(t, real(Dc_result), 'LineWidth', 1.5, 'DisplayName', 'Drop Control Output');
xlabel('Time (s)');
ylabel('Magnitude');
title('Combined Power Protection Mechanisms');
legend('show');
grid on;
hold off;
```

5.5. Discussions

This work intends to study and compare different methods real time protection of renewable energy based microgrids. The government of Rwanda is integrating renewable energy microgrid fir the electrification, in that context the intermittent of renewable energy sources must be controlled to ensure stable grid operation. Selection of real-time protection methods holds significant importance to ensure the stability, reliability, and resilience of the grid. According to table 1, among the compared methods, smart inverters stand out with their fast response time and high selectivity, making them suitable for managing distributed energy resources like solar, which are increasingly integrated into the grid.

Additionally, islanding detection and anti-islanding protection become crucial in Rwanda's efforts to extend electricity access to remote areas, ensuring safe disconnection from the main grid during islanding events. To manage peak loads and balance intermittent generation, dynamic power curtailment can be beneficial, contributing to grid stability.

Given the growing mix of renewable energy sources, droop control and virtual inertia protection offer a means to enhance system stability and maintain frequency and voltage levels during disturbances. Demand response integration can optimize load management during peak hours, reducing grid stress. Rapid disconnection mechanisms are vital to protect against faults and emergencies.

To bolster overall grid performance and resilience, combining different protection methods could be considered. For instance, integrating smart inverters with droop control and virtual inertia protection would create a stable control system for distributed energy resources, improving grid stability during frequency fluctuations.
Combining islanding detection with rapid disconnection mechanisms can ensure safe microgrid operation in remote areas. Integrating demand response with dynamic power curtailment can further enhance load management during peak demand periods.

The choice of protection methods and their combination must be based on comprehensive studies and simulations, considering Rwanda's unique power system characteristics, renewable energy integration, grid infrastructure, and future energy goals. Such evaluations will lead to optimal solutions that meet the specific needs of Rwanda's evolving energy landscape.

CHAPTER 6:

CONCLUSION AND RECOMMENDATION

6.1.Conclusion

This study is aimed to recommend better real time protection method to employed in Rwanda to protect renewable energy based microgrids. In accordance with the power system of Rwanda which incorporates many synchronous generators, having the problem of insufficient power in respect to the demand and more tree system, and taking into account of economic considerations. For stable grid operation and customer satisfaction the combination of inverter control and drop control and virtual inertia real time protection is recommended as a highly suitable and effective approach and it is of important since this method of virtual inertia and drop control can be incorporated in the algorithms of the smart inverter. This hybrid protection method capitalizes on the strengths of both techniques and aligns well with the power system development in Rwanda.

The integration of renewable energy sources, such as solar, into Rwanda's power system is a key priority to enhance sustainability and reduce reliance on traditional fossil fuels. Smart inverters play a crucial role in efficiently managing distributed energy resources, ensuring smooth power flow, and maintaining stable voltage and frequency levels. Their fast response time and high selectivity make them ideal for handling fluctuations and rapid changes in renewable energy output.

Furthermore, droop control with virtual inertia adds a critical layer of stability and grid-forming capabilities, particularly for microgrids with intermittent renewable generation. By simulating the behaviour of synchronous generators, this method can maintain grid frequency and enhance resilience during disturbances or variations in renewable generation.

Considering Rwanda's commitment to a sustainable and resilient power system, the combined smart inverter control and droop control with virtual inertia method offer a robust solution. This protection strategy can effectively manage distributed energy resources, stabilize renewable energy-based microgrids, and support the country's goals for increased renewable energy integration.

Incorporating such advanced protection methods into Rwanda's power system requires careful planning, simulation, and integration with the existing infrastructure. Collaborative efforts between power system planners, engineers, and renewable energy experts will be essential to tailor this hybrid protection method to the unique characteristics and evolving needs of Rwanda's power system. With the adoption of this cutting-edge protection approach, Rwanda can bolster the reliability, stability, and sustainability of its renewable energy-based microgrids, paving the way for a greener and more resilient energy future.

6.2.Recommendation

I would like to recommend the government of Rwanda and Rwanda Energy group(REG) to invest in future research in the following sections:

Performance Evaluation: Conduct in-depth performance evaluations of the combined protection methods (smart inverter control and droop control with virtual inertia) in various real-world scenarios. Utilize advanced simulations and field trials to assess their effectiveness in ensuring grid stability, response time, and selectivity under different operating conditions and renewable energy integration levels.

Economic Analysis: Perform comprehensive economic analyses to understand the cost-benefit trade-offs of implementing the recommended protection methods. Compare the initial investment, operational expenses, and potential revenue benefits from improved grid stability and customer satisfaction. Consider the long-term economic viability and affordability for Rwanda's specific power system context.

Cybersecurity Measures: Investigate and develop robust cybersecurity measures specifically tailored for the real-time protection methods employed in renewable energy-based microgrids. Ensure that these methods are resilient against potential cyber threats to safeguard the integrity and reliability of the power system.

Adaptation to Scaling: Examine how the recommended protection methods can adapt to the scaling of renewable energy capacity and the growth of microgrids in Rwanda. Analyze their scalability and flexibility to accommodate future changes in the energy landscape.

Integration with Energy Storage: Explore the integration of energy storage systems with the real-time protection methods. Investigate how battery storage or other energy storage technologies can complement and enhance the stability and performance of the microgrid during fluctuations in renewable energy generation.

Regulatory and Policy Considerations: Assess the regulatory and policy implications of implementing the recommended protection methods in Rwanda. Identify any barriers or challenges related to existing regulations and propose appropriate policy changes to facilitate the integration of advanced protection technologies.

Grid-Forming and Grid-Feeding Capabilities: Investigate how the combined protection methods can contribute to grid-forming or grid-feeding capabilities in microgrids with high renewable energy penetration. Explore their potential role in supporting islanded operation and resilience during grid disturbances.

Human Factors and Training: Consider the human factor in the successful implementation of real-time protection methods. Study the training and skill requirements for operating, maintaining, and troubleshooting the protection systems effectively.

By addressing these areas in future studies, researchers and policymakers can further refine and optimize real-time protection strategies for renewable energy-based microgrids in Rwanda, enhancing the stability, reliability, and overall performance of the power system in the face of an increasing share of renewable energy sources.

REFERENCES

[1] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, “The role of renewable energy in the global energy transformation,” 2019, doi: 10.1016/j.esr.2019.01.006.

[2] “Review of Policies, Programs and Investment Incentives in Forest Landscape Restoration in Rwanda - PDF Free Download”.

[3] I. Renewable Energy Agency, K. Development Bank, and D. Gesellschaft für Internationale Zusammenarbeit, “The Renewable Energy Transition in Africa Powering Access, Resilience and Prosperity On behalf of the.”

[4] J. De Dieu Niyonteze, F. Zou, G. Norense, O. Asemota, S. Bimenyimana, and G. Shyirambere, “Key technology development needs and applicability analysis of renewable energy hybrid technologies in off-grid areas for the Rwanda power sector,” 2020, doi: 10.1016/j.heliyon.2020.e03300.

[5] “REPUBLIC OF RWANDA MINISTRY OF INFRASTRUCTURE,” 2017.

[6] E. Mudaheranwa, E. Ntagwirumugara, G. Masengo, and L. Cipcigan, “Microgrid design for disadvantaged people living in remote areas as tool in speeding up electricity access in Rwanda,” 2023, doi: 10.1016/j.esr.2023.101054.

[7] A. Hirsch, Y. Parag, and J. Guerrero, “Microgrids: A review of technologies, key drivers, and outstanding issues,” 2018, doi: 10.1016/j.rser.2018.03.040.

[8] T. Ahmad *et al.*, “Energetics Systems and artificial intelligence: Applications of industry 4.0,” *Energy Reports*, vol. 8, pp. 334–361, 2022, doi: 10.1016/j.egyr.2021.11.256.

[9] A. Hirsch, Y. Parag, and J. Guerrero, “Microgrids: A review of technologies, key drivers, and outstanding issues,” 2018, doi: 10.1016/j.rser.2018.03.040.

[10] F. Garcia-Torres, S. Vazquez, I. M. Moreno-Garcia, A. Gil-De-Castro, P. Roncero-Sanchez, and A. Moreno-Munoz, “electronics Article,” 2021, doi: 10.3390/electronics10030328.

[11] K. Jha and A. G. Shaik, “A comprehensive review of power quality mitigation in the scenario of solar PV integration into utility grid,” *Electronics and Energy*, vol. 3, p. 100103, 2023, doi: 10.1016/j.prime.2022.100103.

[12] Z. Ali *et al.*, “Fault Management in DC Microgrids: A Review of Challenges, Countermeasures, and Future Research Trends,” *IEEE Access*, vol. 9, pp. 128032–128054, 2021, doi: 10.1109/ACCESS.2021.3112383.

[13] M. Abbasi, E. Abbasi, L. Li, R. P. Aguilera, D. Lu, and F. Wang, “Review on the Microgrid Concept, Structures, Components, Communication Systems, and Control Methods,” *Energies*, vol. 16, no. 1. MDPI, Jan. 01, 2023. doi: 10.3390/en16010484.

[14] E. Hans, “Microgrid Safety and Protection Aryudha Duta Hartono EI270X Degree Project in Electrotechnical Theory and Design,” 2017.

[15] “Essential Qualities of Protection in Power System | Electricalvoice.” Accessed: Jul. 29, 2023. [Online]. Available: https://electricalvoice.com/essential-qualities-of-protection-in-power-system/

[16] K. Mäki, S. Repo, and P. Järventausta, “Protection coordination to meet the requirements of blinding problems caused by distributed generation,” vol. 4, pp. 674–683, Jul. 2005.

[17] B. da Costa and V. Ceccato, “Assessing the adoption of household safety protection (HSP) in Stockholm, Sweden,” *Crime Sci*, vol. 4, no. 1, p. 19, Dec. 2015, doi: 10.1186/s40163-015-0027-4.

[18] A. V. Pekhotikov, A. N. Poletaev, A. V. Gomozov, and S. V. Usolkin, “Current requirements to designing fire protection systems for educational establishments,” *Pozharovzryvobezopasnost/Fire and Explosion Safety*, vol. 31, no. 2, pp. 5–14, Jun. 2022, doi: 10.22227/0869-7493.2022.31.02.5-14.

[19] J. D. Pradhan, S. S. Hadpe, and R. G. Shriwastava, “Analysis and design of overcurrent protection for grid-connected microgrid with PV generation,” *Global Transitions Proceedings*, vol. 3, pp. 349–358, 2022, doi: 10.1016/j.gltp.2022.03.023.

[20] IEEE Region 10. and Institute of Electrical and Electronics Engineers., *IEEE 2013 TENCON - Spring : April 17th - 19th, 2013, Sydney, Australia : Conference proceedings.*

[21] P. Ni, H. Cao, J. He, M. Li, F. Gao, and Z. Wang, “Phase-angle adaptive current differential protection for active distribution network,” *J Phys Conf Ser*, vol. 2564, no. 1, p. 012022, Aug. 2023, doi: 10.1088/1742-6596/2564/1/012022.

[22] P. Bertrand and M. Gerin S Modicon S Square, “Cahier technique n° 181 Directional protection equipment.” [Online]. Available: http://www.schneiderelectric.com

[23] H. Li, M. Chen, B. Yang, F. Blaabjerg, and D. Xu, “Fast Fault Protection Based on Direction of Fault Current for the High-Surety Power-Supply System,” *IEEE Trans Power Electron*, vol. 34, no. 6, pp. 5787–5802, Jun. 2019, doi: 10.1109/TPEL.2018.2870982.

[24] D. D. Patil, “Real Time Protection Technique for DC Microgrid Using Local Measurements.”

[25] An, “MIT Energy Initiative Symposium on Managing Large-Scale Penetration of Intermittent Renewables | Managing Large-Scale Penetration of Intermittent Renewables,” 2011. [Online]. Available: www.mit.edu/mitei.

[26] R. Jinsiwale, M. Maharjan, T. Becejac, and A. Ashok, “Evaluating a real-time model decoupling compensation approach for developing scalable, high-fidelity microgrid models,” in *2023 IEEE Texas Power and Energy Conference, TPEC 2023*, Institute of Electrical and Electronics Engineers Inc., 2023. doi: 10.1109/TPEC56611.2023.10078472.

[27] C. Martinez *et al.*, “Consortium for Electric Reliability Technology Solutions Grid of the Future White Paper on Real Time Security Monitoring and Control of Power Systems,” 1999.

[28] T. Patel, P. Gadde, S. Brahma, J. Hernandez-Alvidrez, and M. J. Reno, “Real-time Microgrid Test Bed for Protection and Resiliency Studies,” in *2020 52nd North American Power Symposium, NAPS 2020*, Institute of Electrical and Electronics Engineers Inc., Apr. 2021. doi: 10.1109/NAPS50074.2021.9449730.

[29] B. Arbab-Zavar, E. J. Palacios-Garcia, J. C. Vasquez, and J. M. Guerrero, “Smart inverters for microgrid applications: A review,” *Energies*, vol. 12, no. 5. MDPI AG, Mar. 04, 2019. doi: 10.3390/en12050840.

[30] D. C. Silva Júnior, J. de Santiago, P. M. de Almeida, and J. G. Oliveira, “Control of Smart Inverters with Automated Decisions in Microgrid,” *Journal of Control, Automation and Electrical Systems*, vol. 34, no. 5, pp. 1028–1042, Oct. 2023, doi: 10.1007/s40313-023-01028-y.

[31] J. Mulhausen *et al.*, “Previously presented at GRIDTECH,” 2017.

[32] F. Katiraei, A. Foss, C. Abbey, and B. Strehler, “Dynamic analysis and field verification of an innovative anti-islanding protection scheme based on directional reactive power detection,” in *2007 IEEE Canada Electrical Power Conference*, IEEE, Oct. 2007, pp. 183–188. doi: 10.1109/EPC.2007.4520327.

[33] P. Wiest, S. Eberlein, K. Rudion, and A. Probst, “Comparison between static and dynamic curtailment of RES in probabilistic highvoltage distribution grid planning,” in *CIRED - Open Access Proceedings Journal*, Institution of Engineering and Technology, Oct. 2017, pp. 2169–2173. doi: 10.1049/oap-cired.2017.0048.

[34] S. Fatima, V. Püvi, M. Pourakbari-Kasmaei, and M. Lehtonen, “Photovoltaic hosting capacity improvement based on the economic comparison between curtailment and network upgrade,” *IET Generation, Transmission & Distribution*, vol. 17, no. 17, pp. 3848–3860, Sep. 2023, doi: 10.1049/gtd2.12936.

[35] U. Tamrakar, D. Shrestha, M. Maharjan, B. P. Bhattarai, T. M. Hansen, and R. Tonkoski, “Virtual inertia: Current trends and future directions,” *Applied Sciences (Switzerland)*, vol. 7, no. 7. MDPI AG, Jun. 26, 2017. doi: 10.3390/app7070654.

[36] F. Zheng, M. Su, B. Liu, and W. Liu, “Adaptive Virtual Inertia Control Strategy for a Grid-Connected Converter of DC Microgrid Based on an Improved Model Prediction,” *Symmetry (Basel)*, vol. 15, no. 11, p. 2072, Nov. 2023, doi: 10.3390/sym15112072.

[37] S. Jena, D. P. Mishra, and S. R. Salkuti, “Fault Detection, Classification, and Location in Underground Cables,” 2023, pp. 195–215. doi: 10.1007/978-981-99-2066-2_10.

[38] K. Chen, C. Huang, and J. He, “Fault detection, classification and location for transmission lines and distribution systems: A review on the methods,” *High Voltage*, vol. 1, no. 1, pp. 25–33, 2016, doi: 10.1049/HVE.2016.0005.

[39] M. Uzair, M. Eskandari, L. Li, and J. Zhu, "Machine Learning Based Protection Scheme for Low Voltage AC Microgrids," *Energies (Basel)*, vol. 15, no. 24, Dec. 2022, doi: 10.3390/en15249397.

[40] Y. Han *et al.*, "Fault Detection and Zonal Protection Strategy of Multi-Voltage Level DC Grid Based on Fault Traveling Wave Characteristic Extraction," *Electronics (Switzerland)*, vol. 12, no. 8, Apr. 2023, doi: 10.3390/electronics12081764.

[41] S. Goundar, "Chapter 3-Research Methodology and Research Method Enterprise Systems and Technological Convergence: Research and Practice View project Impact of Digital Transformation on Security Policies and Standards View project." [Online]. Available: https://www.researchgate.net/publication/333015026

[42] E. Mudaheranwa, E. Ntagwirumugara, G. Masengo, and L. Cipcigan, "Microgrid design for disadvantaged people living in remote areas as tool in speeding up electricity access in Rwanda," 2023, doi: 10.1016/j.esr.2023.101054.

[43] G. A. Tiruye, A. T. Besha, Y. S. Mekonnen, N. E. Benti, G. A. Gebreslase, and R. A. Tufa, "Opportunities and challenges of renewable energy production in ethiopia," *Sustainability (Switzerland)*, vol. 13, no. 18. MDPI, Sep. 01, 2021. doi: 10.3390/su131810381.

[44] "ASYV 8.5MW Solar PV Project (CPA--001) PASSPORT CONTENTS".

[45] F. Izabayo, "Community Participation and Project's Performance of Solar Power Project in Rwanda: A Case of Rwamagana Photovoltaic Solar Power Plant," *Journal of Entrepreneurship & Project Management*, vol. 6, no. 2, pp. 43–59, May 2022, doi: 10.53819/81018102t2064.

[46] S. A. Hosseini, H. A. Abyaneh, S. H. H. Sadeghi, F. Razavi, and A. Nasiri, "An overview of microgrid protection methods and the factors involved," *Renewable and Sustainable Energy Reviews*, vol. 64. Elsevier Ltd, pp. 174–186, Oct. 01, 2016. doi: 10.1016/j.rser.2016.05.089.