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Name: HABUMUGISHA Daniel
Student ID: 217072062

Supervisor: Assoc.Prof. JMV BIKORIMANA

IMPROVING POWER QUALITY IN MINI-GRID BY INTEGRATION WITH SOLAR POWER SYSTEM USING PREDICTIVE CONTROL: A CASE STUDY OF NYANKOROGOMA HYDRO MINI-GRID

Academic Year: 2023-2024

Declaration

I, **HABUMUGISHA Daniel**, declare that this project is my original work and has not been submitted for a degree at the University of Rwanda or any other university. All sources of material used in this thesis work have been fully acknowledged.

Signature: ……………….
Name: HABUMUGISHA Daniel
Student ID: 217072062

This thesis has been submitted for examination with my approval as the university supervisor.
Supervisor:
Signature: ....
Assoc. Prof. JMV BIKORIMANA

Date of Submission: .../…/2025

Abstract

The growing need for sustainable and reliable electricity in rural areas has led to the integration of renewable energy sources into mini-grids. However, power quality challenges arise due to fluctuations in solar irradiance and hydro resource availability. This study addresses these challenges by implementing Model Predictive Control (MPC) to optimize energy flow in the Nyankorogoma hydro mini-grid, enhancing voltage stability and reducing power losses.

A mathematical model of the hybrid solar-hydro system was developed and simulated in MATLAB/Simulink, incorporating real operational data from Nyankorogoma. The MPC algorithm was applied to control a boost converter, ensuring smooth solar power integration. Simulation results demonstrate that MPC effectively mitigates voltage fluctuations and reduces Total Harmonic Distortion (THD), improving overall power quality. FFT analysis revealed a reduction in THD from 12.07% to 4.02% after implementing MPC, indicating a significant improvement in waveform quality. Additionally, energy previously lost in dump loads was redirected for productive use, increasing system efficiency.

The findings confirm that MPC-based solar integration enhances mini-grid stability, making it a viable solution for renewable energy-based rural electrification. Further research should explore real-world implementation, battery storage integration, and artificial Neural network-driven predictive control for improved energy management.

Keywords: Model Predictive Control (MPC), Solar-Hydro Hybrid Mini-Grid, Power Quality, Voltage Stability, Total Harmonic Distortion (THD), Renewable Energy Integration, MATLAB/Simulink.

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Abbreviations

PV: Photovoltaic
MPC: Model Predictive Control
MPPT: Maximum Power Point Tracking
THD: Total Harmonic Distortion
AC: Alternating Current
DC: Direct Current
PI: Proportional-Integral
PWM: Pulse Width Modulation
HIL: hardware-in-the-loop
FFT: First Fourier Transform
HMI: Human Machine Interface

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Finally, my heartfelt appreciation goes to my family for their unwavering support, patience, and encouragement. Their belief in my abilities has been my greatest motivation throughout this academic endeavor. This achievement would not have been possible without their constant love and support.

To all those who have contributed to this journey in one way or another, I extend my sincere gratitude.

Dedication

I dedicate this work to my beloved family, whose unwavering support, patience, and encouragement have been my greatest source of strength throughout this journey. To my parents, whose sacrifices and guidance have shaped my academic and personal growth, I am forever grateful. Your belief in my potential has been the driving force behind my achievements. This thesis is also dedicated to my mentors and educators who have inspired me to pursue knowledge and excellence. Their wisdom and dedication have played a significant role in my academic journey.

Lastly, I dedicate this work to all aspiring engineers and researchers committed to advancing sustainable energy solutions. May this research contribute to a future where reliable and clean energy is accessible to all.

Chapter1: Introduction

1.1 Background

Due to the increasing need for clean and steady power, more specifically in distant and unapproachable regions, the application of ultra-modern renewable sources such as solar and hydroelectric power to mini-grids has been justified. Indeed, the outputs of mini-grids simply prove to be rather promising practical answers toward the energy requirements of peripheral and underprivileged communities in an economical, sustainable, and scalable manner of supplying electric power. Solar energy has particularly become very attractive when integrated into mini-grids because it meets the criteria of being clean, renewable, and abundant.

Nevertheless, there are some important problems in this respect that have to do with the quality and reliability of power in mini-grids. Fluctuations in solar radiation and, in the case of hydropower, fluctuations in the availability of water flow can cause levels of voltage and frequency to become unstable; this, in turn, leads to disruptions in service delivery and damage to connected appliances[1]. Subsequent further issues result from the fact that such intermittent generation cannot be efficiently handled by traditional control systems; this then increases operating costs and lowers the efficiency of the system.

In response to these challenges, there is a developing demand to enhance the power quality and reliability of mini-grids with advanced control strategies. Model Predictive Control (MPC) is one of the applied predictive control model approaches in offering an optimal integration of solar power systems into mini-grids[2]. It allows for regulation of system parameters to stabilize voltage and frequency, which assures reliable and consistent power supply by anticipating future load requirements along with renewable energy generation.

The thesis focuses on enhancing power quality and reliability of the NYANKOROGOMA hydro mini-grid by introducing solar power through predictive control techniques. A mathematical model that can mimic the behavior of the mini-grid system under any working condition has been developed with the objective of ensuring the most efficient flow of energy from both sources-solar and hydro. Data to validate the model will consist of actual data that will be collected on-site regarding energy production, energy sold to consumers, and energy dissipated from dump loads [4][3].

The goal of this research is to create and implement a Model Predictive Control (MPC) strategy that will improve the mini-grid's stability and performance, ensuring efficient integration of solar energy and improving overall grid reliability. This research has the potential to provide valuable insights into the design of resilient and efficient mini-grids, particularly in areas where renewable energy integration is critical for sustainable development.

1.2 Problem Statement

Despite the increasing adoption of mini-grids powered by renewable energy sources, the integration of solar power into these systems continues to face significant challenges related to power quality and reliability. In particular, fluctuations in solar radiation and variable hydropower generation lead to instability in voltage and frequency levels, affecting both the efficiency of the system and the performance of connected appliances. These instabilities result in power outages, poor power quality, and higher operational costs, all of which undermine the effectiveness of mini-grid solutions in rural and off-grid areas[3].

The NYANKOROGOMA hydro mini-grid, like many other renewable energy-based mini-grids, struggles with these issues, leading to frequent disruptions in service. Despite the presence of renewable energy sources such as hydro and solar, their intermittent nature makes it difficult to ensure a consistent and reliable power supply[4], [5]. The existing control mechanisms are not sufficient to mitigate the impact of these fluctuations, leading to inefficient energy use and increased dependency on backup systems, which are often costly and environmentally unfriendly. In addition, the lack of effective predictive control systems further exacerbates the situation. Without the ability to predict load demand and renewable energy generation, the mini-grid faces difficulties in managing the energy flow, resulting in energy losses and inefficient energy storage use. As a result, there is an urgent need to develop advanced control strategies that can predict and optimize system behavior, ensuring the stability of voltage and frequency, improving power quality, and enhancing overall system reliability.

This thesis aims to address these challenges by designing and implementing a predictive control strategy specifically Model Predictive Control (MPC) for the integration of solar power into the NYANKOROGOMA hydro mini-grid. By leveraging real-time data and predictive algorithms, the research intends to optimize the mini-grid’s performance, reduce energy losses, improve power quality, and ultimately provide a more reliable and sustainable energy solution for the local community.

1.3 Objectives

The primary objective of this research is to enhance the power quality and reliability of the NYANKOROGOMA hydro mini-grid through the effective integration of solar power systems with aid of model predictive control applied to boost converter. By addressing the current challenges of voltage and frequency instability caused by the intermittent nature of renewable energy sources, this study aims to ensure a consistent and high-quality power supply for the mini-grid. The research leverages Model Predictive Control (MPC) as an advanced control strategy to optimize energy flow and improve system stability, thereby meeting the growing demand for reliable and sustainable electricity in rural areas.

Furthermore, the research seeks to bridge the gap between theoretical models and practical implementation by developing a robust mathematical model that accurately represents the integration of solar power into the mini-grid. Through MATLAB-based simulations and the use of real data from the NYANKOROGOMA site, the study evaluates the performance of the proposed control strategy in enhancing grid reliability. Ultimately, the research aims to contribute to the development of resilient and efficient mini-grids, offering practical solutions for addressing energy challenges in similar rural and off-grid contexts.

1.3.1. Specific Objectives of the Study

To achieve the main goal of improving power quality and reliability in the NYANKOROGOMA hydro mini-grid, this research focuses on specific objectives that guide the development and implementation of effective solutions. These objectives encompass analyzing existing challenges, developing mathematical models, designing control strategies, and evaluating their performance.

- To conduct load assessment of NYANKOROGOMA hydro mini-grid.
- To design and develop a mathematical for boost converter with Model Predictive Control (MPC) strategy to optimize power flow and stabilize voltage and frequency.
- To simulate the proposed control strategy in MATLAB using real data from the NYANKOROGOMA site.

1.4 Uniqueness of the Thesis

This study stands out as a pioneering research effort in Rwanda, focusing on the integration of solar power into a mini-hydro grid using Model Predictive Control (MPC). While renewable energy integration has been explored in various contexts, the application of MPC for enhancing power quality and reliability in a mini-grid setting remains largely unstudied in Rwanda. Specifically, the Nyankorogoma hydro mini-grid has not yet been analyzed for hybrid solar-hydro integration using advanced control strategies. By introducing MPC, this research brings an innovative approach to managing energy flow, voltage stability, and frequency regulation, making it a novel contribution both to academic research and practical energy management in Rwanda’s mini-grid sector.

1.5 Contribution of the Thesis

The outcomes of this research will significantly contribute to improving the overall performance and reliability of the Nyankorogoma mini-grid. By integrating a photovoltaic (PV) system as a backup energy source, the mini-grid will gain resilience against fluctuations in hydro generation, ensuring a more stable power supply to end-users. Additionally, this study addresses the challenges posed by the intermittent nature of renewable energy sources, proposing a predictive control strategy that mitigates fluctuations and enhances the efficiency of energy dispatch. The implementation of MPC will lead to improved voltage stability and power quality, reducing the risks of power outages and system disturbances. Furthermore, the hybrid system will increase the overall generation capacity of the mini-grid, optimizing energy utilization and reducing waste associated with dumped loads. This research, therefore, has both immediate practical benefits and long-term implications for sustainable energy management in Rwanda.

1.6 Hypothesis

The integration of solar power into existing mini-grids offers significant potential to enhance power quality and reliability, particularly in rural and off-grid regions where energy demand is often inconsistent. Despite advancements in renewable energy integration, issues such as voltage instability, frequency fluctuations, and energy losses persist, undermining the efficiency and reliability of these systems. This research hypothesizes that implementing a Model Predictive Control (MPC) strategy can address these challenges by optimizing energy flow and stabilizing system parameters.

The hypothesis is based on the premise that MPC, with its ability to predict future system behavior, can dynamically adjust control actions to maintain stable voltage and frequency levels. By leveraging real-time data, the MPC strategy can effectively balance the intermittent nature of solar and hydropower generation with the varying load demands in mini-grids. Furthermore, it is hypothesized that replacing traditional control methods with MPC will reduce energy losses, particularly those caused by the dissipation of excess energy in dump loads, and improve overall system efficiency.

Additionally, this research posits that the integration of solar power, controlled by MPC, can expand the capacity of mini-grids to serve more consumers while ensuring power quality. By addressing harmonics, reducing total harmonic distortion (THD), and maintaining grid stability under dynamic load conditions, the proposed strategy is expected to improve the economic viability and sustainability of renewable energy mini-grids.

This hypothesis underpins the belief that hybrid systems combining hydro and solar power, managed by advanced control strategies, can serve as a replicable model for rural electrification in similar settings, particularly in Sub-Saharan Africa. Through simulations using real data from the NYANKOROGOMA mini-grid, the research aims to validate this hypothesis and demonstrate its feasibility and impact.

1.7 Scope

This thesis focuses on the development of a control strategy for the boost converter in a solar PV-integrated mini-grid. The work includes modeling, simulation using different data for solar irradiance and load profiles. The study is limited to theoretical simulations without real-world implementation.

1.8 Thesis Organization

This thesis is structured into six chapters, each designed to address specific aspects of the study, culminating in the successful integration of solar power into the NYANKOROGOMA hydro mini-grid using Model Predictive Control (MPC). Below is an overview of each chapter

Chapter 1: Introduction

This chapter provides the background, problem statement, and objectives of the study. It highlights the challenges of power quality and reliability in mini-grids, emphasizing the need for advanced control strategies. The objectives include assessing the load profile, developing a mathematical model, designing an MPC strategy, and simulating the proposed solution.

Chapter 2: Literature Review

The literature review explores the state-of-the-art technologies and strategies for integrating renewable energy sources into mini-grids. Key topics include solar power, power quality issues, traditional control strategies, and the application of MPC in hybrid systems. This chapter identifies gaps in existing research and establishes the foundation for the study.

Chapter 3: Methodology

This chapter outlines the different methods used in this study including documentation, data collection process, mathematical modeling, and theoretical framework used in the study. It describes the design of the solar power integration system, including the development of the MPC strategy. The chapter also elaborates on the simulation setup and the parameters for MATLAB/Simulink simulations.

Chapter 4: System Modeling & Simulation

This chapter focuses on mathematical and detailed design and modeling of the solar PV system, boost converter, integrated with MPC. It provides technical insights into system components, their interactions, and the implementation of the MPC algorithm to optimize power flow and ensure grid stability.

Chapter 5: Results and Discussion

In this chapter, the results of the simulations are presented and analyzed. Key performance metrics, such as voltage, total harmonic distortion (THD), and power quality improvements, are evaluated. The effectiveness of the MPC strategy is compared with traditional methods, and its impact on the NYANKOROGOMA mini-grid’s performance is discussed.

Chapter 6: Conclusion and Recommendations

The final chapter summarizes the findings of the study and their implications for improving power quality and reliability in mini-grids. It also provides recommendations for future research, including the practical implementation of the proposed system and its replication in other rural settings.

Chapter 2: Literature Review

The literature extensively documents the challenges and opportunities in deploying solar and hybrid renewable energy systems. This section synthesizes theoretical perspectives and findings from key studies to establish a foundation for improving power quality and reliability in solar-hydro mini-grids using Model Predictive Control (MPC).

2.1 Solar Power and Mini-Grids

Solar energy, as one of the most abundant renewable resources, has become a cornerstone of sustainable electrification projects. Hernández-Mayoral et al. (2023) highlight the advantages of integrating solar photovoltaics (PV) into mini-grids, emphasizing its environmental benefits, scalability, and decreasing costs[1]. However, the intermittent nature of solar energy poses challenges for maintaining voltage and frequency stability in mini-grids. This instability is further exacerbated in rural settings where grid infrastructure is less robust. The study underscores the need for advanced control strategies, such as MPC, to address these challenges.

In the context of Sub-Saharan Africa, Ekpotu. (2023) assess the viability of off-grid systems, noting that mini-grids are critical for rural electrification. Their findings reveal that while solar and hybrid systems hold promise, their potential is limited by inefficiencies in energy management and control[2]. This gap points to the importance of integrating predictive control methods to optimize energy flow and enhance reliability.

Solar power has become one of the most promising renewable energy sources due to its abundant availability and decreasing costs. Solar PV systems convert sunlight into electricity and are often integrated into mini-grids in rural areas where access to the main grid is limited or non-existent. Mini-grids provide localized power distribution, typically using a combination of renewable energy sources and battery storage to ensure a reliable supply. Below there is table which shown the Mini-Grid capacity in Rwanda.

Table 1:Rwanda mini_grid

	Mini-grid	Capacity	Customers	Developer	operational
1	Mukungu	14kW		EUCL	YES
2	Mudasomwa	35kW	260	HOBUKA	
3	CHE Nyakiramba	11kW		ECOS LTD	
4	Nyakiramba	750kW	15	Tubahabona-Nyakiramba	YES
5	Gatare	12kW	50	Cooperative Iterambere Rubyiniro	
6	Rusumo	3kW	102	Karegeya Charles	
7	Rwaminyoro	800kW	20	Uwiragiye Juvenal	
8	Nyankorongoma	13kW	207	Hydropower NYANKOROGOMA Ltd	
9	Banda	30kW		RENERG ® LTD	No
10	Rutenderi	55kWp	583	Absolute power	YES
11	Rushonga	30 kWp	250	NESELTEC Ltd	
12	Rutobotobo	34 kWp	422	ARCPOWER	
13	Gatare	38.7 kWp	1084		
14	Kigabiro	47.4 kWp	583		
15	Gakagati 1	50.7 kWp	393	Equatorial Power	
16	Agakenyeri	38.025 kWp	276		
17	Rubira	11.73 kWp	143		
18	Agatovu 1	6.825 kWp	40		
19	Agatovu 2	6.825 kWp	37		
20	Gakagati 2	7.8 kWp	79		

2.1.1. Nyankorogoma Hydro Mini-Grid

The Nyankorogoma hydro mini-grid represents a pivotal initiative in Rwanda’s journey toward rural electrification. Located in the Kirehe district of Rwanda's Eastern Province, this 13 kW mini-hydro power plant operates independently of the national grid and leverages the principle of energy conversion by transforming potential energy stored in water into electrical energy. The facility was established at an estimated cost of $86,000, funded collaboratively through a mix of grants, community contributions, and developer-led initiatives. Specifically, 10% of the cost was covered by the developer, 7% by the local community in cash or labor, and 13% raised through debt financing by the developer[6].

Figure 1:Nyankorogoma Mini-Grid

The plant’s technical specifications include a net head of 16.6 meters, a nominal water flow of 170 liters per second, and a mechanical power capacity of 15kW. The turbine operates at a nominal speed of 550 revolutions per minute (rpm) and a runaway speed of 990 rpm. As a run-of-river system without water storage reservoirs, the design ensures minimal environmental impact while catering to the energy needs of the surrounding population. The mini-grid supplies electricity to 141 households, 17 commercial centers, three churches, and one grain milling machine, thereby addressing critical energy demands and enhancing local socio-economic activities.

Voltage and frequency regulation are critical to the stable operation of the NYANKOROGOMA mini-grid. The system relies on an Electronic Load Controller (ELC) to maintain a steady frequency of 52 Hz, despite variations in load demand. This regulation method ensures the mini-grid can operate within the allowable frequency range, safeguarding the generator and other system components from fluctuations.

2.1.2. Power Quality Issues in Mini-Grids

Power quality remains a central concern in mini-grid systems, particularly those integrating intermittent renewable sources like solar PV. Sandi (2024) provides a comprehensive review of power quality challenges, focusing on harmonic distortions, voltage fluctuations, and frequency instability. The study attributes these issues to the dynamic and nonlinear behavior of solar PV systems, especially during periods of fluctuating solar irradiance[3]. Traditional control methods, such as Proportional-Integral (PI) controllers, often fall short in addressing these rapid changes, necessitating the adoption of more advanced control strategies like MPC.

Power quality in solar-integrated mini-grids is affected by several factors, including

Voltage Fluctuations; Caused by variability in solar generation, especially during cloudy conditions or during the night.

Harmonic Distortions; Nonlinear loads and the switching actions of power converters introduce harmonics, degrading the quality of the waveform.

Frequency Instability; Inconsistent power generation can lead to deviations in grid frequency, affecting sensitive equipment connected to the grid.

2.2. Control Strategies for Power Quality Improvement

Kumar et al. (2024) explore various control strategies to improve microgrid performance, emphasizing the role of predictive control schemes. Their study demonstrates that MPC can significantly enhance system stability by forecasting future states and optimizing control actions in real-time[7]. However, the research acknowledges the limited application of MPC in hybrid systems combining solar and hydro power. This limitation presents an opportunity for further exploration in integrating these renewable sources effectively.

Traditional control approaches, such as PI and PID controllers, are reactive and struggle to maintain stability under rapidly changing conditions, as noted by Sandi (2024). By contrast, MPC offers a proactive solution, leveraging dynamic models to anticipate system behavior. This capability makes MPC particularly well-suited for hybrid systems, where the interaction between solar and hydro power introduces additional complexity.

2.2.1. Model Predictive Control (MPC)

MPC has emerged as a transformative approach in the field of renewable energy systems, offering precise control over dynamic and nonlinear processes. Alamir and Allgöwer (2008) describe MPC as a control algorithm that uses a mathematical model to predict future system behavior over a finite horizon. At each control step, MPC solves an optimization problem to minimize deviations from desired reference values while adhering to system constraints[8]. This ability to optimize control actions in real-time makes MPC an ideal candidate for managing the complexities of hybrid solar-hydro mini-grids.

Cartland et al. (2023) apply MPC to hybrid systems, highlighting its potential to stabilize voltage and frequency while minimizing energy losses. Their study on the Kisiizi Hydro Power Mini-Grid in Uganda demonstrates that MPC can effectively balance energy flow between solar, hydro, and generator set components. However, the research identifies a gap in adapting MPC for systems with higher variability in solar irradiance and load demand, as is common in rural Sub-Saharan Africa.

Traditional control methods, such as PI and PID controllers, have been widely used in power systems to regulate voltage and frequency. However, these methods are reactive and often struggle to maintain stability under rapidly changing conditions. The introduction of Model Predictive Control (MPC) offers a proactive solution, as it uses a dynamic model of the system to forecast future states and optimize control actions[9].

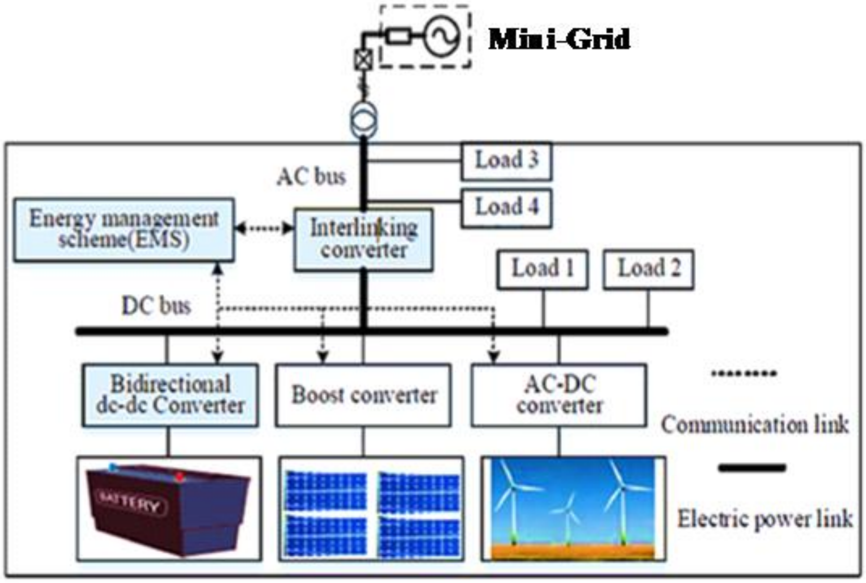


Figure 2: Block diagram of renewable integration to control power quality[10]

MPC is a control algorithm that uses a mathematical model of Euler's forward method system to predict its future behavior over a finite horizon. At each control step, the MPC optimizes a cost function to minimize deviations from the desired reference and constraints. This makes MPC particularly well-suited for managing the dynamic and nonlinear behavior of solar PV systems integrated into mini-grids[11].

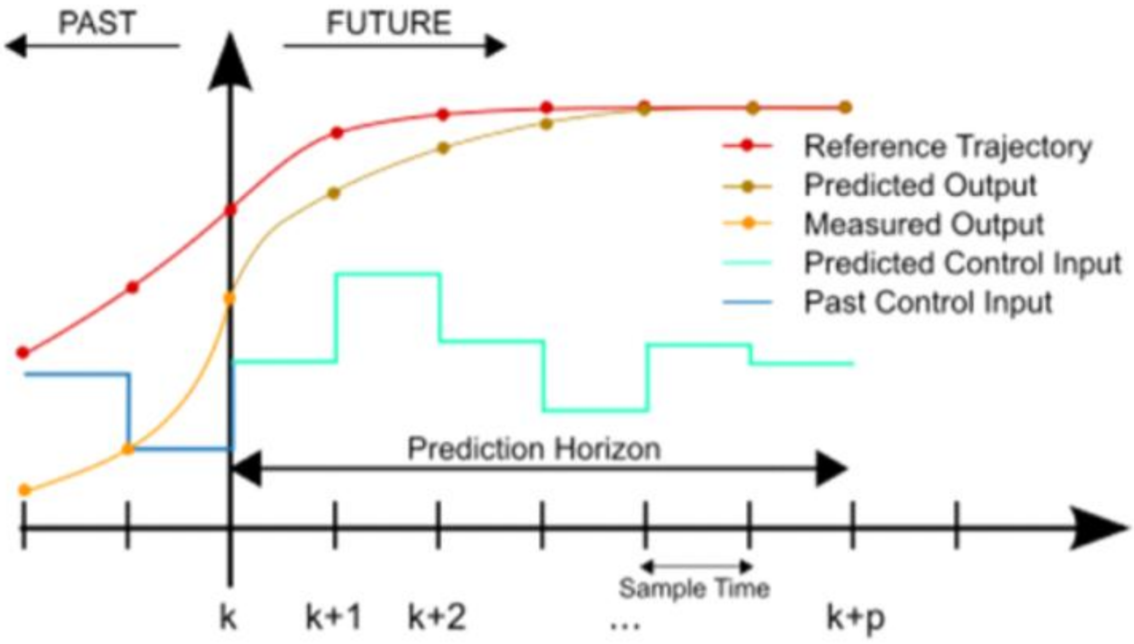


Figure 3:Discrete Model Predictive control [9]

The benefits of integrating solar power with MPC are manifold. Energy previously dissipated in dump loads can now be used to serve additional consumers or stored for future use, increasing the system’s overall efficiency. This approach also expands the mini-grid’s capacity, allowing it to meet the growing energy demands of the local population, thereby promoting rural electrification. Furthermore, reduced energy wastage and enhanced supply reliability contribute to economic development in the area. On a broader scale, the adoption of solar power aligns with sustainable development goals by fostering the use of renewable energy[12].

Despite its advantages, the proposed system poses challenges, including the initial investment required for solar infrastructure and control system development. Additionally, implementing and maintaining an MPC-based control system demands technical expertise, and the success of the system hinges on the availability of accurate, real-time data for monitoring and decision-making.

Integrating solar power with MPC at the NYANKOROGOMA mini-grid represents a transformative approach to energy management. By addressing current inefficiencies and optimizing system performance, this solution offers a path toward improved power quality, reliability, and sustainability for the local community.

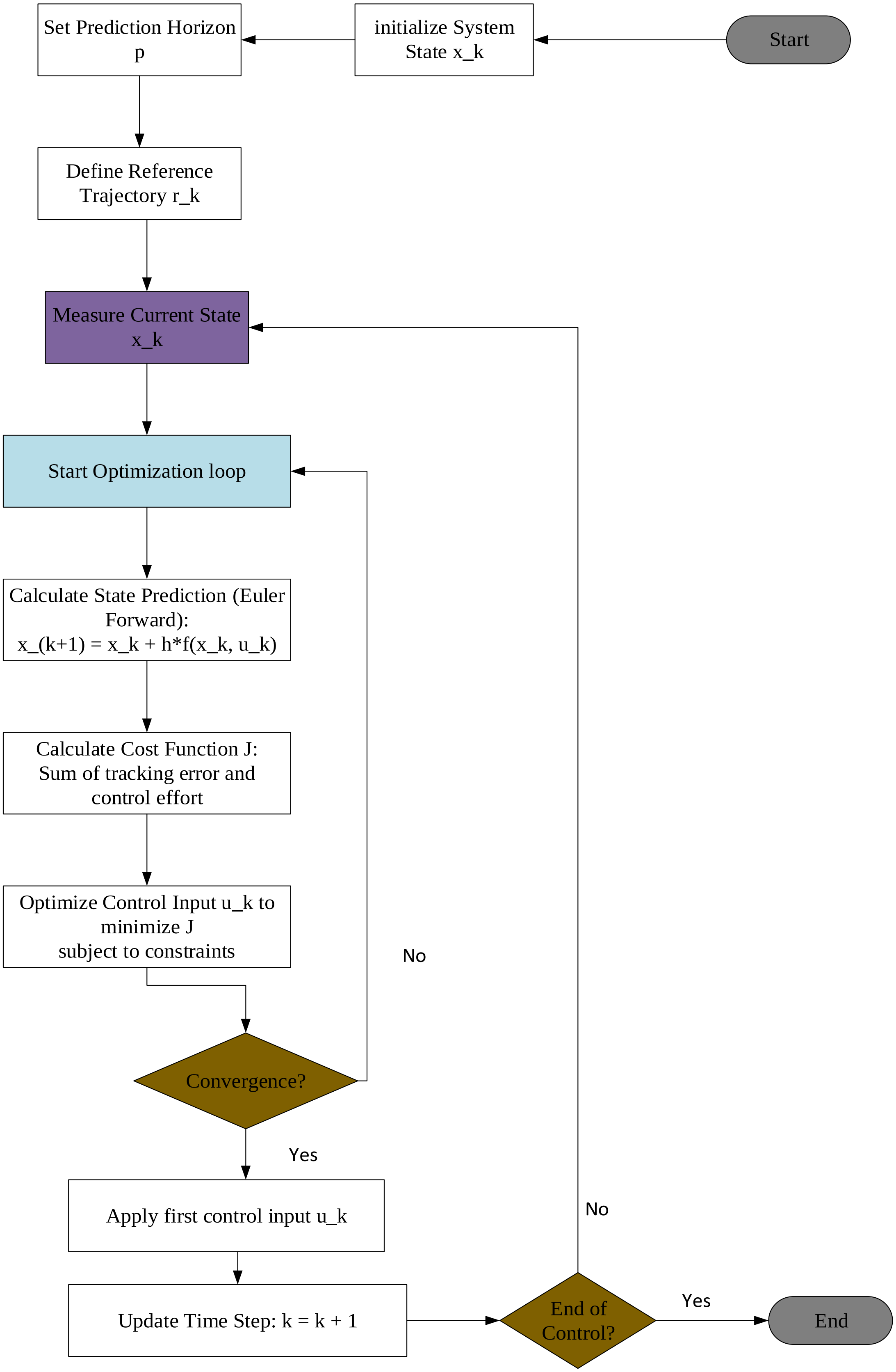


Figure 4: Flow Chart of Model Predictive control by Euler's Forward method[13]

The Model Predictive Control (MPC) algorithm begins with a crucial initialization phase. The system state x_k is initialized, establishing the starting point for the control process. The prediction horizon p is then defined, which determines how far into the future the controller will predict system behavior. Additionally, a reference trajectory r_k is established, representing the desired path or behavior that the system should follow. Once initialization is complete, the main control loop commences with the measurement of the current system state x_k. This measurement provides the foundation for the prediction phase, where Euler's forward method is employed. The prediction equation x_(k+1) = x_k + h*f (x_k, u_k) is used, where h represents the time step and f (x_k, u_k) describes the system dynamics[14]. This method allows the controller to estimate future system states based on potential control inputs.

The optimization phase forms the core of the MPC algorithm. During this phase, a cost function g is calculated, which typically incorporates two main components: the tracking error (the deviation between predicted and reference trajectories) and the control effort penalty. The controller then works to optimize the control inputs u_k while adhering to system constraints. This optimization process iterates until convergence is achieved, ensuring the best possible control strategy is found. After optimization, the controller implements only the first computed control input u_k to the system[15]. This implementation follows the receding horizon principle, which is a key characteristic of MPC. The time step is then updated k = k + 1, and the controller evaluates whether the control objectives have been met or if further control actions are needed.

If the control objectives haven't been met, the process loops back to the state measurement step, beginning a new iteration of the control loop. This recursive process continues until the final control objectives are achieved. The continuous update and optimization of control inputs, combined with the forward prediction using Euler's method, allows the system to effectively track the reference trajectory while handling constraints and disturbances. This entire process creates a robust control strategy that can handle complex systems while maintaining optimal performance. The use of Euler's forward method provides a straightforward yet effective means of predicting future system states, while the optimization loop ensures that the control actions are both feasible and optimal within the given constraints. The receding horizon approach allows the controller to adapt to changing conditions and disturbances, making it particularly effective for real-world applications.

2.2.2. Gaps in Existing Research

While the integration of RES into mini-grids has been extensively studied, significant gaps remain in optimizing hybrid systems for rural and off-grid applications. Hernández-Mayoral et al. (2023) and Kumar et al. (2024) both point out the lack of real-world case studies demonstrating the practical implementation of MPC in hybrid solar-hydro systems[1][7]. Similarly, Sandi (2024) and Cartland et al. (2023) emphasize the need for advanced modeling techniques to capture the dynamic behavior of such systems under varying conditions.

Another critical gap lies in the integration of predictive algorithms with real-time data. Ekpotu. (2023) and Kathiresh et al. (2021) note that most studies rely on theoretical models or simulations without incorporating real-world data. This limitation reduces the applicability of their findings to practical scenarios, where inaccuracies in data collection and processing can significantly impact system performance.

Table 2: papers with Gaps

TITLE	AUTHOR	PAPER OVERVIEW	GAPS REMAIN
A Comprehensive Review on Power-Quality Issues, Optimization Techniques, and Control Strategies of Microgrid Based on Renewable Energy Sources	Hernández-Mayoral et al., 2023	Reviews power quality challenges in microgrids, optimization techniques, and control strategies, emphasizing renewable integration.	Limited focus on hybrid hydro-solar mini-grids. Need for practical implementation insights for rural settings.
Assessing the Viability and Impact of Off-Grid Systems for Sustainable Electrification of Rural Communities in Sub-Saharan Africa	Ekpotu and O., 2023	Evaluates the potential of off-grid systems in electrifying rural Sub-Saharan Africa.	Insufficient exploration of advanced control strategies like MPC in hybrid renewable systems.
Performance Improvement of Integrated Microgrid Based Predictive Control	Kumar et al., 2024	Discusses predictive control strategies for microgrid performance	Lack of case studies from Sub-Saharan Africa; limited data for

Scheme		improvement, focusing on integrated setups.	rural deployment.
Examining Power Quality Challenges in Photovoltaic-Grid Integration: A Critical Review	Sandi, 2024	Reviews power quality challenges specific to PV-grid integration, highlighting harmonic distortion and frequency instability.	Minimal discussion on hybrid systems involving hydro and solar power.
Performance Analysis of a Hybrid of Solar Photovoltaic, Genset, and Hydro of a Rural-Based Power Mini-Grid: Case Study of Kisiizi Hydro Power Mini-Grid, Uganda	Cartland et al., 2023	Analyzes hybrid systems' performance in rural Uganda, focusing on solar, genset, and hydro integration.	Limited exploration of predictive control strategies for optimization.
Integration of Renewable Energy Sources with Smart Grid	Kathiresh et al., 2021	Explores the integration of renewable sources into smart grids, discussing challenges and solutions.	Insufficient focus on small-scale rural mini-grids and their unique reliability challenges.

2.3. Opportunities for Future Research

The theoretical insights from the reviewed literature underscore the potential of MPC to transform energy management in hybrid mini-grids. By leveraging real-time data and predictive algorithms, MPC can address critical challenges such as voltage and frequency instability, energy losses, and inefficient load balancing. Future research should focus on developing robust mathematical models that accurately represent the dynamics of hybrid solar-hydro systems. Additionally, integrating real-world data into simulation frameworks can enhance the reliability and applicability of MPC-based solutions.

This study aims to bridge these gaps by designing and implementing an MPC strategy tailored to the unique challenges of the NYANKOROGOMA hydro mini-grid. By simulating the proposed control strategy using real data from the Nyankorogoma site, this research seeks to provide actionable insights into the design and optimization of resilient and efficient hybrid mini-grids.

The ELC is a vital component that stabilizes the generator's output frequency by dynamically managing power flow to dump loads. When a load is disconnected, the generator's output power remains unchanged, potentially causing frequency fluctuations. To counter this, the ELC senses the reduced load demand and redirects the surplus energy to dump loads in figure 5, preventing generator instability. Conversely, when additional loads are connected, the ELC reduces the energy sent to the dump loads, redirecting it to the active consumer loads.

Figure 5: Nyankorogoma Dump loads

This approach provides fast and reliable frequency stabilization, aided by the swift reaction time of the ELC. The dump loads typically resistive loads absorb excess energy, maintaining a near-constant load on the generator. Additionally, protective mechanisms like circuit breakers, relays, and current transformers (CTs) are incorporated into the system to ensure the generator and connected components are safeguarded from electrical faults and overloads.

While effective for frequency control, this method is not economically optimal. A significant proportion of generated energy is dissipated in dump loads, representing a loss of potential electricity that could otherwise be utilized for productive activities. This inefficiency underscores a pressing need for improvement in the energy management system of the mini-grid. Voltage and frequency regulation are critical to the stable operation of the Nyankorogoma mini-grid. The ELC plays a vital role by redirecting surplus energy to dump loads during periods of low demand and reallocating it to active loads as demand increases. While effective, this approach is not economically optimal, as a significant portion of generated energy is wasted. Protective devices such as circuit breakers, relays, and current transformers ensure system safety but do not address the inefficiencies inherent in the energy management process.

Replacing dump loads with solar power integration offers a promising solution. Solar PV systems, controlled via MPC, can dynamically balance energy supply and demand, stabilizing voltage and frequency while reducing energy losses. By integrating solar power, the mini-grid can serve more consumers, expand productive activities, and enhance overall reliability.

Chapter 3. Methodology

The methodology for this research follows a systematic approach to integrating solar power into the Nyankorogoma hydro mini-grid using Model Predictive Control (MPC). The process includes literature review, data collection, analysis, mathematical modeling, and simulation to evaluate the effectiveness of the proposed control strategy. This methodology ensures a comprehensive understanding of power quality and reliability issues while providing a structured approach for developing and validating the hybrid control system.

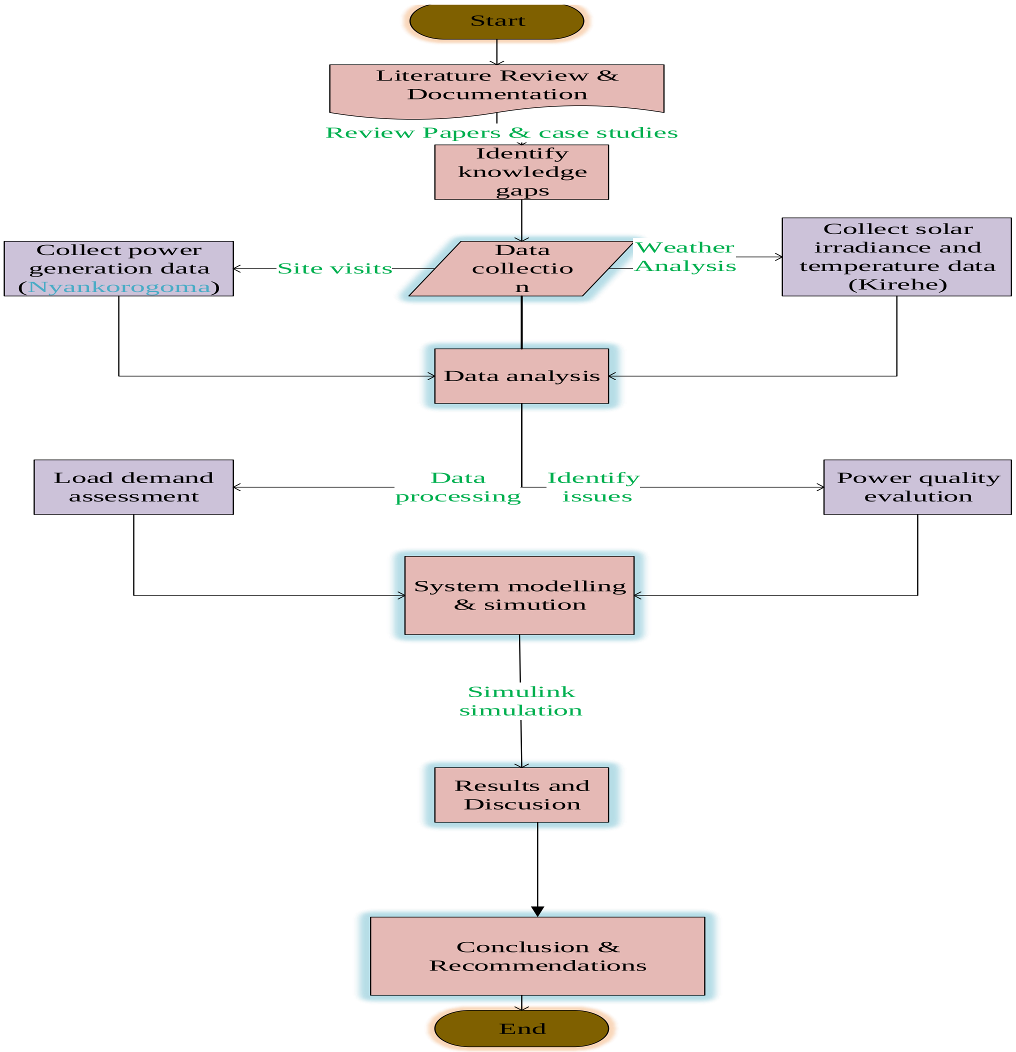


Figure 6:methodology Flow chat

3.1 Data Collection

The data collected is critical for developing a reliable model of the Nyankorogoma hydro mini-grid and integrating solar PV. The primary data sources include site visits, historical records, and weather analysis.

3.1.1 Data collection from Nyankorogoma Hydro Mini-Grid

Site visits to the Nyankorogoma hydro mini-grid have been done to collect real-time power generation data; the key parameters recorded include Hydro power output (kW), Energy demand variations, Voltage and frequency variations over time and Load demand variations. These data help in understanding the existing system behavior before integrating solar power. The plant's technical specifications include a net head of 16.6 meters, a nominal water flow of 170 liters per second, and a mechanical power capacity of 15kW. The turbine operates at a nominal speed of 550 revolutions per minute (rpm) and a runaway speed of 990 rpm. As a run-of-river system without water storage reservoirs, the design ensures minimal environmental impact while catering to the energy needs of the surrounding population. The mini-grid supplies electricity to 141 households, 17 commercial centers, three churches, and one grain milling machine, thereby addressing critical energy demands and enhancing local socio-economic activities.

(a) **(b)**

Figure 7: Nyankorogoma Small HMI (a) and Energy Consumed (b)

Table 3:Average Load and Voltage Profile of Hydropower NYANKOROGOMA LTD

Hour	**Hourly Average Load (kW)**	**Voltage (V)**	**Frequency (Hz)**
00:00	4.2	231.5	50.0
1:00	4.1	231.34	49.8
2:00	3.9	232.00	50.0
3:00	4.0	231.42	50.0
4:00	4.2	231.12	49.9
5:00	4.8	231.10	49.9
6:00	8.5	229.10	49.5
7:00	9.8	228.9	49.8
8:00	9.2	239.23	50.0
9:00	7.5	230.12	50.0
10:00	6.8	230.98	49.4
11:00	7.2	230.45	49.8
12:00	7.8	230.68	50.0
13:00	7.4	230.00	49.8
14:00	6.9	229.70	49.9
15:00	7.1	228.46	51.0
16:00	7.6	227.08	49.5
17:00	8.4	228.56	50.0
18:00	10.2	238.081	50.0
19:00	11.5	230.57	50.0
20:00	11.2	231.58	49.8
21:00	9.8	230.23	49.9
22:00	7.2	230.09	51.0
23:00	5.4	231.01	49.5

Table 4: Average Energy consumption at NYANKOROGOMA MINI-GRID in Six Months

Time(Day)	**Average Total Energy produced (kWh)**	**Average Energy dissipated in dump loads (kWh)**	**Average Total Energy sold to the customers (kWh)**
1	73.5	25.48	48.02
2	113.74	27.72	86.03
3	89	26.81	62.18
4	151.75	27.70	124.04
5	145.75	27.665	118.08
6	57.25	19.66	37.59
7	138	24.90	113.09
8	182	26.4	155.6
9	124	26.54	97.45
10	119	25.85	93.14
11	116.25	24.74	91.50
12	128.5	27.92	100.58
13	118	26.54	91.45
14	124.25	24.54	99.58
15	130	28.50	101.49
16	126.25	24.80	101.44
17	111.25	21.72	89.53
18	127.25	28.58	98.67
19	100	20.45	79.55
20	113.25	27.88	85.37
21	105	23.79	81.20
22	89.5	21.46	68.03
23	87.25	25.34	61.90
24	126	26.86	99.14
25	108.25	30.22	78.02
26	92	28.93	63.07
27	83	20.90	62.09

28	71.75	24.03	47.71
29	67.75	12.55	55.2
30	60	12.24	47.75
31	66	11.06	54.94

3.1.2 Solar Irradiance and Temperature Data Collection

For proper modeling of the solar PV system, solar irradiance and temperature data are collected from meteorological sources. These parameters influence the power output of the PV modules and are essential for developing an accurate solar power model.

Table 5:Solar Irradiance and Temperature

	Daily irradiation (Watt/m2)	**Clearness index**
January	700.98	0.484
February	700.32	0.505
March	800.09	0.484
April	750.88	0.484
May	650.67	0.494
June	800.01	0.553
July	800.44	0.591
August	700.49	0.562
September	600.37	0.521
October	700.91	0.469
November	630.63	0.449
December	700.74	0.466

3.2 Data Analysis

Data analysis is a critical step in evaluating the performance of the Nyankorogoma mini-grid and assessing the impact of integrating solar power using Model Predictive Control (MPC). This process involves examining load demand patterns, power quality indicators, and system stability under varying conditions. The collected data, including voltage profiles, frequency variations, and energy consumption trends, is systematically processed to identify key performance characteristics and existing inefficiencies. Statistical tools and software, have been employed to analyze fluctuations in voltage and frequency, quantify Total Harmonic Distortion (THD), and assess the efficiency of energy utilization. This analysis provides valuable insights into the operational dynamics of the mini-grid, guiding the development of an optimized control strategy for improving power quality and reliability.

3.2.1 Load Demand Assessment

The energy consumption patterns of the Nyankorogoma mini-grid are analyzed to determine peak and off-peak load variations as in figure 9. The demand curve is plotted to assess the adequacy of current hydro generation and potential solar integration. The load assessment of the Nyankorogoma mini-grid provides critical insights into its operational dynamics and energy utilization patterns. Load data reveals distinct consumption trends, characterized by low demand during early hours (3.9–5.0 kW from 1:00 AM to 5:00 AM), moderate demand during daytime (6.0–7.50 kW), and peak demand during evening hours (8.0–11kW from 6:00 PM to 9:00 PM). Voltage profiles range from 220V to 240.5 V, with frequency consistently regulated at approximately 50 Hz by an Electronic Load Controller (ELC).

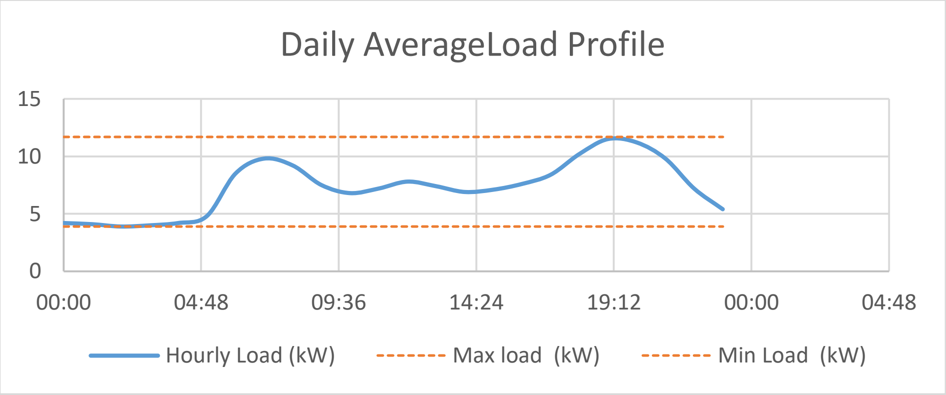


Figure 8:Daily Average Load Profile

Energy metrics collected over a month underscore inefficiencies in the current system. Daily energy production ranges from 73.5 kWh to 182 kWh, of which 37.59 kWh to 155.6 kWh is sold to consumers, while 25.48 kWh to 30.22 kWh is dissipated in dump loads, for frequency regulation. For instance, on Day 8, 182 kWh was generated, 155.6kWh was sold, and 26.4 kWh was dissipated. This highlights a mismatch between energy production and utilization, indicating opportunities for optimizing energy management.

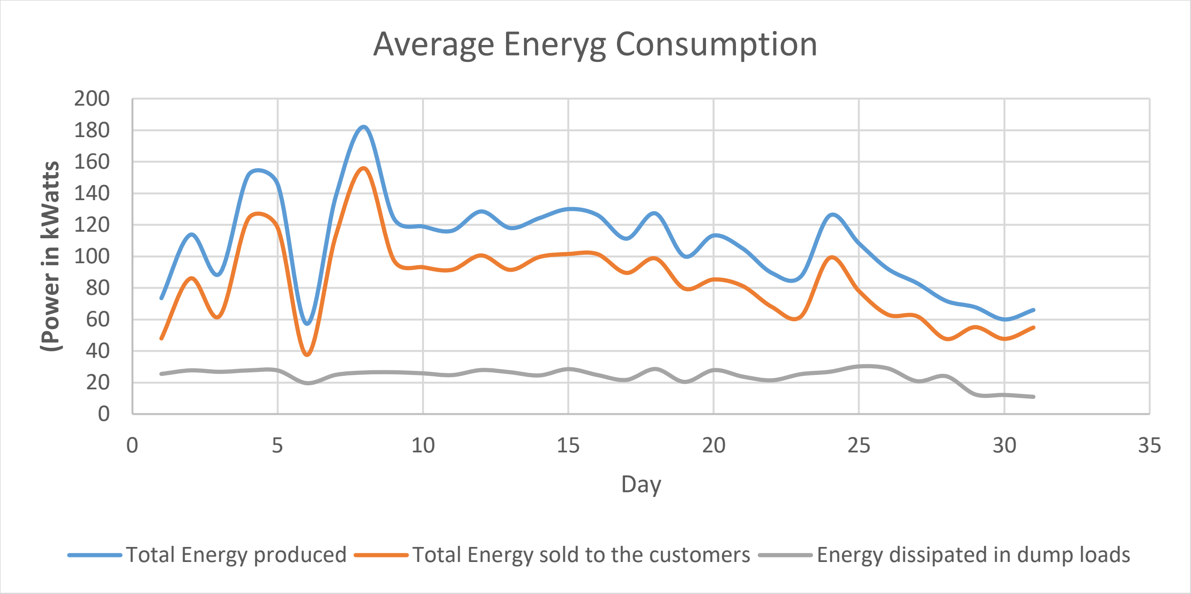
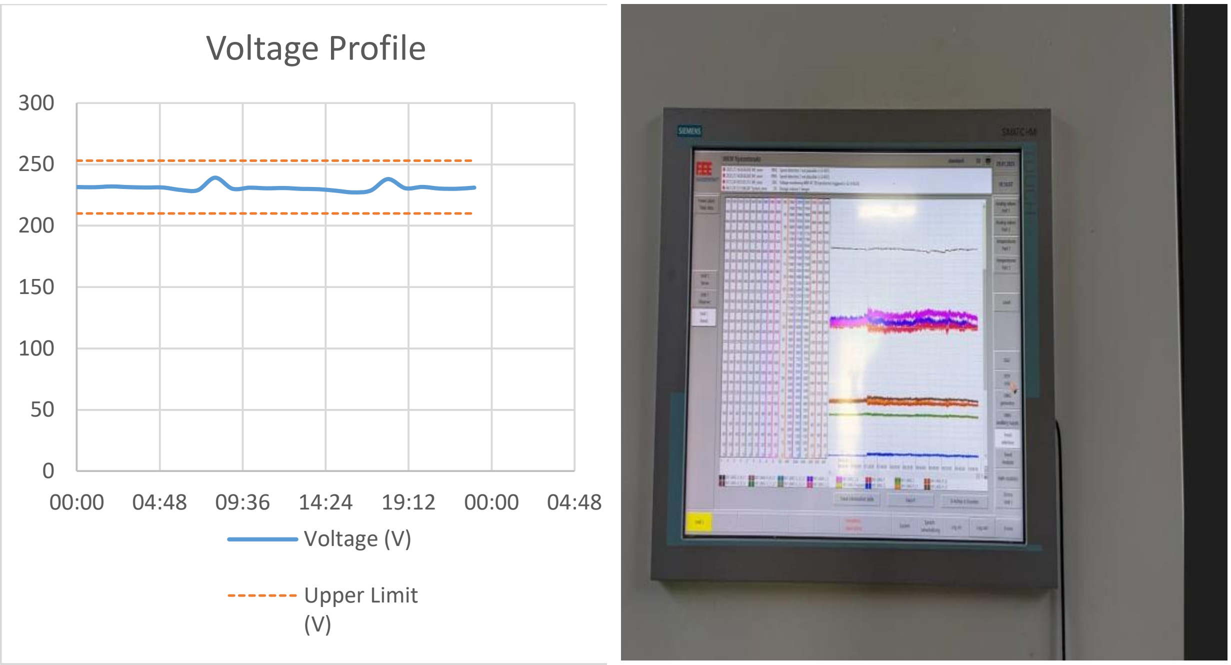


Figure 9: Energy Consumption

The reliance on dump loads for stabilizing frequency reveals systemic inefficiencies. Despite maintaining grid stability, the energy dissipated in dump loads represents lost potential that could otherwise power additional productive activities. Voltage regulation, while generally within permissible limits, requires careful adjustment when integrating solar power to ensure stable operation under dynamic load conditions. Monthly load assessments in figure 10 indicate base, transitional, and peak periods, emphasizing the importance of dynamic energy management strategies. These findings will inform the integration of solar power into the mini-grid, leveraging advanced control strategies like Model Predictive Control (MPC) to optimize energy flow and minimize waste.

3.2.2 Power Quality Evaluation

Key power quality parameters such as voltage stability, frequency variations, and Total Harmonic Distortion (THD) have analyzed as shown in figure11. These assessments help in identifying issues that may arise during solar PV integration.



(a) **(b)**

Figure 10:Voltage Profile (a) and Voltage Profile on HMI (b)

3.2.3. Solar irradiance in Kirehe (Western Province of Rwanda)

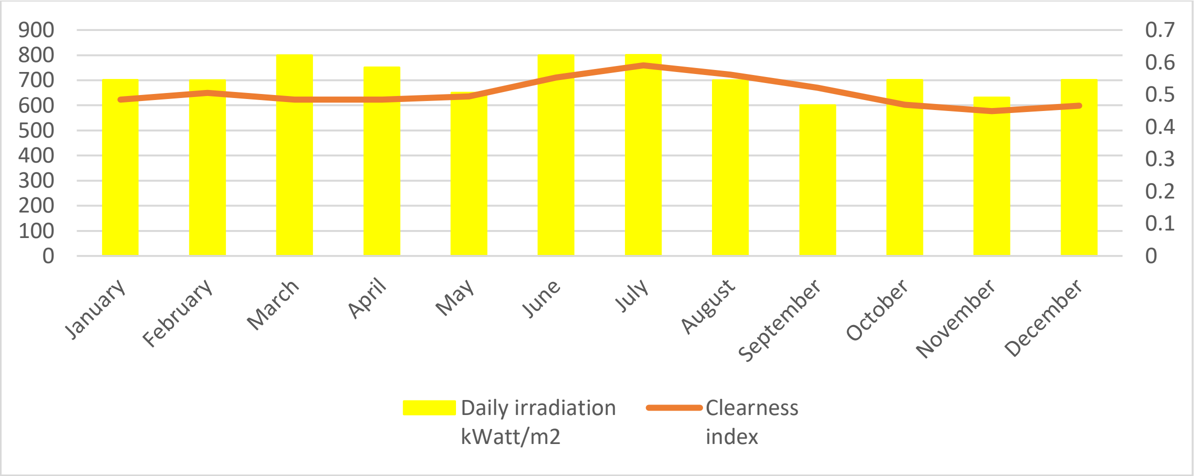


Figure 11: Kirehe irradiance

The data for Kirehe was collected by Homer software and reveals notable seasonal variations in both daily solar irradiation and the clearness index. From January to December, daily irradiation ranges between 600 and 800 Watt/m², while the clearness index fluctuates from 0.449 to 0.591. The highest daily irradiation is observed in July at 80 Watt/m², coinciding with a relatively high clearness index of 0.552. This suggests optimal solar energy conditions during this month, as high irradiation combined with a higher clearness index indicates minimal atmospheric interference.

Conversely, the lowest daily irradiation occurs in September at 600 Watt/m², paired with the lowest clearness index of 0.449. This reflects diminished solar energy potential in November, likely due to increased cloud cover or atmospheric turbidity during that period. Similarly, October and May exhibit lower irradiation values of 600 Watt/m²/day, with corresponding clearness indices of 0.469 and 0.494, respectively.

Seasonal trends indicate that the months of June through September are characterized by relatively high daily irradiation values exceeding 700 Watt/m², with clearness indices ranging from 0.521 to 0.591. These months likely represent the dry season, providing favorable conditions for solar energy generation. In contrast, the period from March to May and October to December shows reduced irradiation and clearness index values, suggesting cloudier or wetter conditions during these months.

The relationship between daily irradiation and the clearness index highlights that higher clearness indices correspond to higher irradiation values. This trend underscores the importance of atmospheric clarity in maximizing solar energy potential. Overall, Kirehe experiences favorable solar conditions for much of the year, particularly during the mid-year dry months, making it a viable region for solar energy applications.

Chapter 4: System Modeling & Simulation

4.1 System Modeling

In modern renewable energy integration, various control strategies are employed to regulate system performance. Model Predictive Control (MPC) has recently gained prominence in managing power electronics devices such as inverters and converters due to its ability to anticipate system dynamics and optimize control actions in real-time. In this study, MPC is applied to a boost converter to regulate the power transfer between the solar photovoltaic (PV) system and the mini-grid as in block diagram figure 13. A mathematical model is developed to represent the interaction between the solar PV system and its output through the MPC-controlled boost converter. The proposed system is simulated in MATLAB/Simulink to evaluate its performance under different operating conditions.

The solar PV system comprises a photovoltaic array, a boost converter, and an inverter, with the boost converter being the central element controlled by MPC. The PV array converts sunlight into DC power, which is then stepped up by the boost converter to match the voltage required for mini-grid integration. The MPC algorithm dynamically adjusts the boost converter's switching duty cycle to ensure stable and efficient power delivery. Subsequently, the inverter converts the regulated DC voltage into AC, ensuring synchronization with the mini-grid for reliable energy distribution. The implementation of MPC enhances system stability by mitigating voltage fluctuations, improving power quality, and optimizing energy flow within the mini-grid.

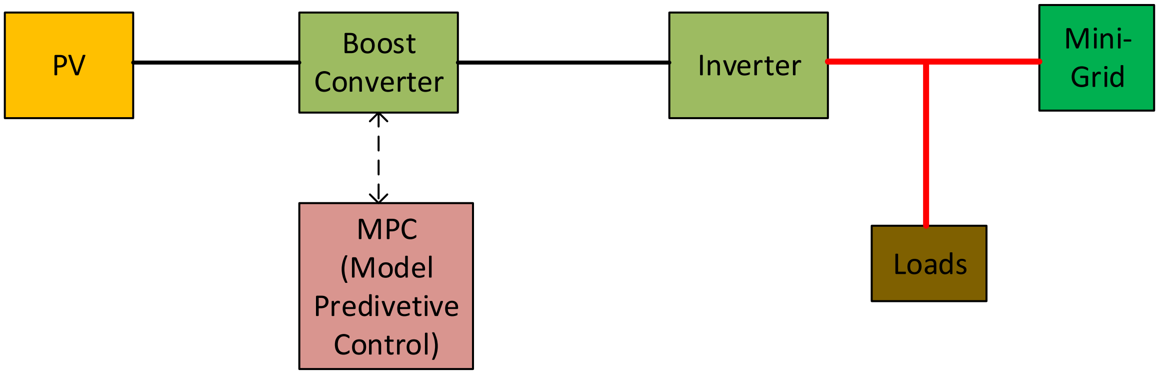


Figure 12:Block diagram of the solar PV system integrated into the mini-grid by Model predictive

control.

The design and modeling of the boost converter with Model Predictive Control (MPC) developed based on previously defined parameters to optimize power flow and enhance power quality. The boost converter plays a crucial role in stepping up the PV array's voltage to the required level for seamless integration into the mini-grid. In this configuration, the duty cycle D is the primary control variable, dynamically adjusted by the MPC algorithm to regulate the output voltage. By leveraging predictive control, the system anticipates variations in solar irradiance and adjusts the duty cycle accordingly, ensuring stable voltage output. The mathematical relationship between the input and output voltage of the boost converter is defined by Equation 1.

$$V_o = \frac{V_{pv}}{1-D} \qquad \text{Eq.1}$$

The central component of the overall system is the boost converter is in figure 14, which plays a critical role in regulating the DC bus voltage under varying solar irradiance conditions. Model Predictive Control (MPC) is implemented to dynamically adjust the boost converter's operation, ensuring optimal energy transfer from the photovoltaic (PV) system to the mini-grid. By continuously predicting and optimizing the duty cycle of the converter, MPC maintains a stable and efficient power flow, enhancing system reliability. The fundamental structure of the boost converter, including its key operational principles, is illustrated in Figure 14.

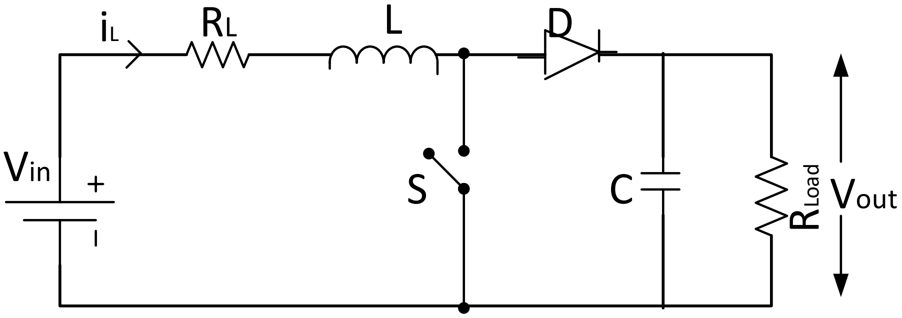


Figure 13: Circuit of boost converter

By analyzing both the high and low states illustrated in the figure 14 above and applying Kirchhoff's Voltage Law (KVL) to the circuit, the behavior of the boost converter can be mathematically modeled. When the switch is ON the circuit equitant is figure15 (a), the inductor stores energy as current flows through it, causing an increase in inductor current while the output capacitor supplies the load as in equation 2. Conversely, when the switch is OFF the circuit equitant is figure15 (b), the stored energy in the inductor is released, transferring power to the output capacitor and load, thereby increasing the output voltage; the resultant equation 3. This cyclic operation ensures that the output voltage remains higher than the input voltage, and the precise control of the switching mechanism is achieved using Model Predictive Control (MPC), optimizing the boost converter's performance under varying solar irradiance conditions.

$V_L = L\frac{di_L}{dt} - V - iR$ ………………………………………………………………… Eq.2

$V_L = L\frac{di_L}{dt} = (V_{in} - i_L R_L - V_{out}$ ……………………………………………………………Eq.3

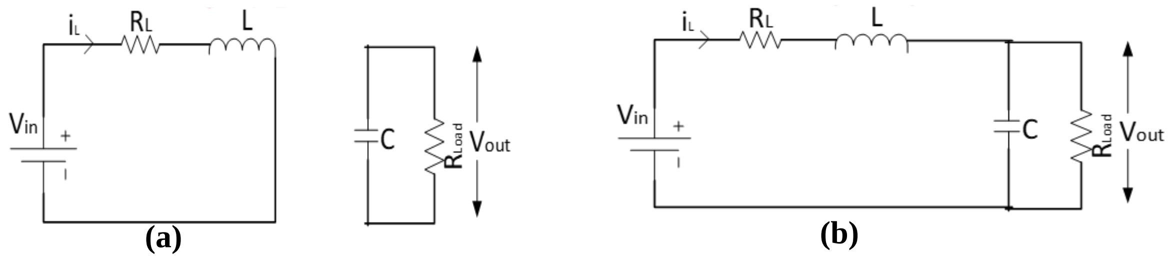


Figure 14:Equivalent circuit of boost converter when   switch is ON   (a) and Equivalent circuit of boost converter when   switch is ON is OFF (b)

The boost converter's primary role is to step up the PV array's voltage to match the grid’s requirements. The MPC controls the duty cycle D of the boost converter’s switching device to maintain a stable output voltage Vo, despite fluctuations in the input from the PV array due to changing irradiance.

The boost converter plays a crucial role in stepping up the voltage from the PV array to meet the grid’s requirements. The Model Predictive Control (MPC) regulates the switching duty cycle D to ensure a stable output voltage Vo, despite variations in solar irradiance. By continuously predicting system behavior, MPC optimizes the duty cycle by minimizing a predefined cost function, ensuring smooth voltage regulation while maintaining efficient energy conversion.

MPC enhances the boost converter’s performance by dynamically adjusting the inductor current i_L, which serves as the control variable to achieve the desired output voltage. The predictive control approach allows the converter to respond proactively to fluctuations in solar power, reducing voltage ripples and improving transient response. The interplay between inductor currents, capacitor voltages, and switching actions is crucial in maintaining voltage stability. Furthermore, fine-tuning the weighting factors in the cost function optimizes the trade-off between performance and computational efficiency.

Compared to conventional control strategies, MPC offers a flexible and adaptive approach to boost converter regulation, making it particularly effective for renewable energy applications. By leveraging real-time data and predictive algorithms, MPC ensures that the boost converter consistently delivers a stable voltage, enhancing the reliability of solar integration into the mini-grid.

4.1.1 Design of Model Predictive Control (MPC)

Model Predictive Control (MPC) is employed to optimize energy dispatch and enhance power stability in the solar-integrated mini-grid. MPC operates as an advanced control strategy that utilizes a dynamic mathematical model based on Euler’s forward method to predict future system behavior within a finite horizon. At each control step, MPC minimizes deviations from the reference values by optimizing a cost function g in equation 4 while considering system constraints. This predictive capability makes MPC highly effective in handling the nonlinear and time-varying characteristics of solar PV systems integrated into mini-grids. In this study, MPC is applied to regulate the boost converter, ensuring stable voltage output despite fluctuations in solar irradiance. The control strategy revolves around manipulating the inductor current (iL) to achieve the desired output voltage, thereby facilitating seamless integration of solar power into the Nyankorogoma mini-grid[16]. The predictive model incorporates real-time data and constraints to adjust switching actions dynamically, reducing voltage ripples and improving power quality. To evaluate the performance of the MPC-controlled boost converter, an appropriate cost function is formulated, aiming to minimize voltage deviations and enhance overall system efficiency.

$$g = i_L^{*}(k) - (k-1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq. 4$$

As solar output vary the prediction of control variable vary too as indicate in below equation 5

As solar output varies, the prediction of the control variable also fluctuates. This is due to the intermittent nature of solar irradiance, which directly affects the power generation of the photovoltaic system. Model Predictive Control (MPC) dynamically adjusts the control inputs by continuously predicting the system's future states based on real-time solar variations. The predictive model integrates the Euler’s forward method to estimate future control actions, ensuring that the boost converter maintains a stable output voltage despite fluctuations in solar power input. This allows for a more efficient energy dispatch and reduces voltage ripple, ultimately improving the overall stability and reliability of the mini-grid[16].

$$i_L = i_L(k+1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .... Eq. 5$$

To incorporate the predictive capability in the boost converter model, Euler’s forward method has been applied to estimate future system states as in equation 6. This numerical integration approach enables the Model Predictive Control (MPC) algorithm to anticipate voltage fluctuations and dynamically adjust the control inputs for optimal performance. By discretizing the system dynamics, the predictive model ensures accurate voltage regulation and smooth power flow within the mini-grid. This approach allows the boost converter to adapt to varying solar irradiance conditions, maintaining stable output voltage and improving overall power quality.

$$\frac{di_L}{dt} \approx \frac{i_L(k+1) - i_L}{T_S} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq.6$$

In this study on equation 6, the variation in dt has been accounted for within the sampling time Ts , ensuring a precise numerical representation of system dynamics. By incorporating this adjustment, the mathematical formulation of Equation (6) evolves into Equation (7), capturing the predictive behavior of the system more accurately. This transformation enhances the robustness of the Model Predictive Control (MPC) approach, enabling more effective voltage regulation and power optimization in the boost converter.

$$i_L(k+1) = \frac{di_L}{dt} T_s + i_L(k) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq.7$$

The objective function in Model Predictive Control (MPC) is designed to optimize the performance of the boost converter by minimizing voltage ripples, regulating output voltage, and maximizing overall system efficiency. To achieve this, the controller incorporates constraints on control inputs and system states to ensure the physical feasibility of operation. The MPC algorithm dynamically solves an optimization problem at each time step, determining the optimal switching sequence for the Insulated Gate Bipolar Transistor (IGBT) that minimizes the cost function while satisfying system constraints.

By controlling the switching state of the IGBT in the boost converter, the system alternates between two states ON and OFF corresponding to different circuit configurations. When the switch is ON (s = 1), the inductor stores energy, and the governing equation transforms from Eq.2 to Eq.8. Conversely, when the switch is OFF (s = 0), the stored energy is transferred to the load, and by Kirchhoff's Voltage Law, Eq.2 transforms into Eq.9a and Eq.9b. These state transitions are fundamental to the MPC strategy, enabling precise control over voltage regulation and power flow optimization within the mini-grid.

$$V_L = L\frac{di_L}{dt} = \left(V_{pv} - i_L R_L\right)S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq.8$$

$$V_L = L\frac{di_L}{dt} = \left(V_{pv} - i_L R_L - V_{out}\right)(1-S) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. Eq.9a$$

$$\frac{di_L}{dt} = \frac{1}{L}\left(V_{pv} - i_L R_L - V_{out}\right)(1-S) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. Eq.9b$$

After carefully rearranging the predictive function given in Equation 3, the resulting expression is simplified to the form presented in Equation 10. This transformation retains the essential system dynamics and ensures that the predictive control approach aligns with the optimization criteria set for energy flow and stability in the integrated solar-hydro system. The adjustments made to the original equation are crucial for accurately modeling the energy interaction between the solar and hydro components, thus allowing the Model Predictive Control (MPC) strategy to effectively manage the dynamic behavior of the mini-grid system.

$$i_L(k+1) = \frac{T_s}{L}\left(V_{pv} - i_L R_L - V_{out}\right)(1 - S) + i_L(k) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. Eq. 10$$

In the integration of solar power into the Nyankorogoma hydro mini-grid, achieving synchronization between the boost converter shown in figure 16 and the grid is paramount for ensuring a stable and reliable energy supply. This synchronization is facilitated by employing a feedback control mechanism that dynamically adjusts the boost's output. Model Predictive Control (MPC) in figure 16 plays a key role in this process by optimizing the control inputs, specifically the switching signal "s'' on output of model predictive control in figure 16, to ensure that the boost's output aligns with the reference voltage. The synchronization is achieved in terms of magnitude and maintaining high precision. A boost converter is incorporated to provide high voltage gain, thus enabling the MPC algorithm to effectively maximize power output. This arrangement ensures that the solar energy is efficiently integrated into the mini-grid, contributing to improved power quality and reliability.

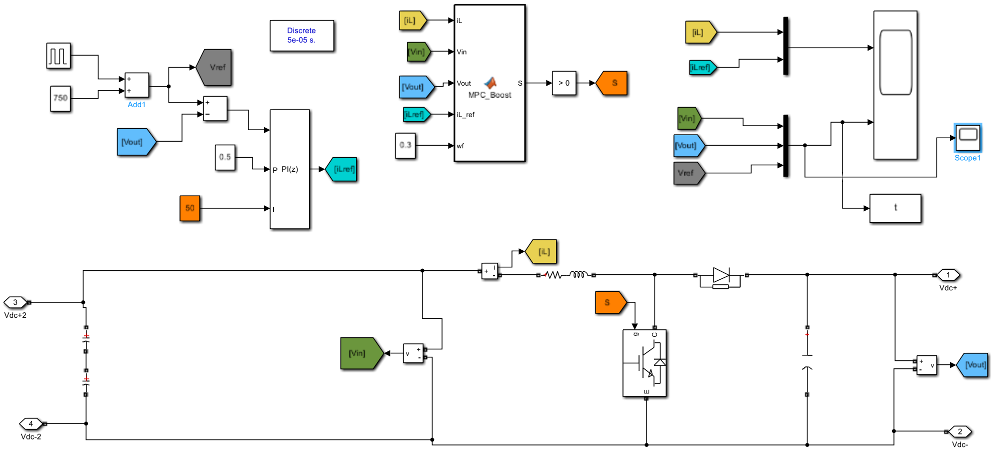


Figure 15: Boost converter with MPC

The flowchart in figure 17 illustrates the implementation of Model Predictive Control (MPC) for optimizing the switching states of the boost converter, which plays a crucial role in stabilizing the voltage and improving power quality in the mini-grid. The process begins with defining system parameters, initializing key variables, and setting the previous switching state (S_old). The MPC algorithm then iterates over all possible switching states to determine the optimal control action at each time step. Within each iteration, the algorithm predicts the inductor current based on the selected state and computes associated costs, including the switching cost and tracking cost. The total cost function is then evaluated to assess the performance of the given switching state. A decision criterion is applied to check whether the computed cost is lower than the predefined optimal threshold (E_op). If the condition is met, the optimal state is updated. Otherwise, the loop continues to evaluate other possible states.

Once all possible switching states are analyzed, the optimal state with the lowest cost function is selected. This selected switching state is stored for the next iteration, ensuring dynamic adaptation to system variations. By continuously optimizing the switching decisions, the MPC strategy effectively enhances voltage regulation, minimizes power losses, and ensures stable integration of solar power into the mini-grid.

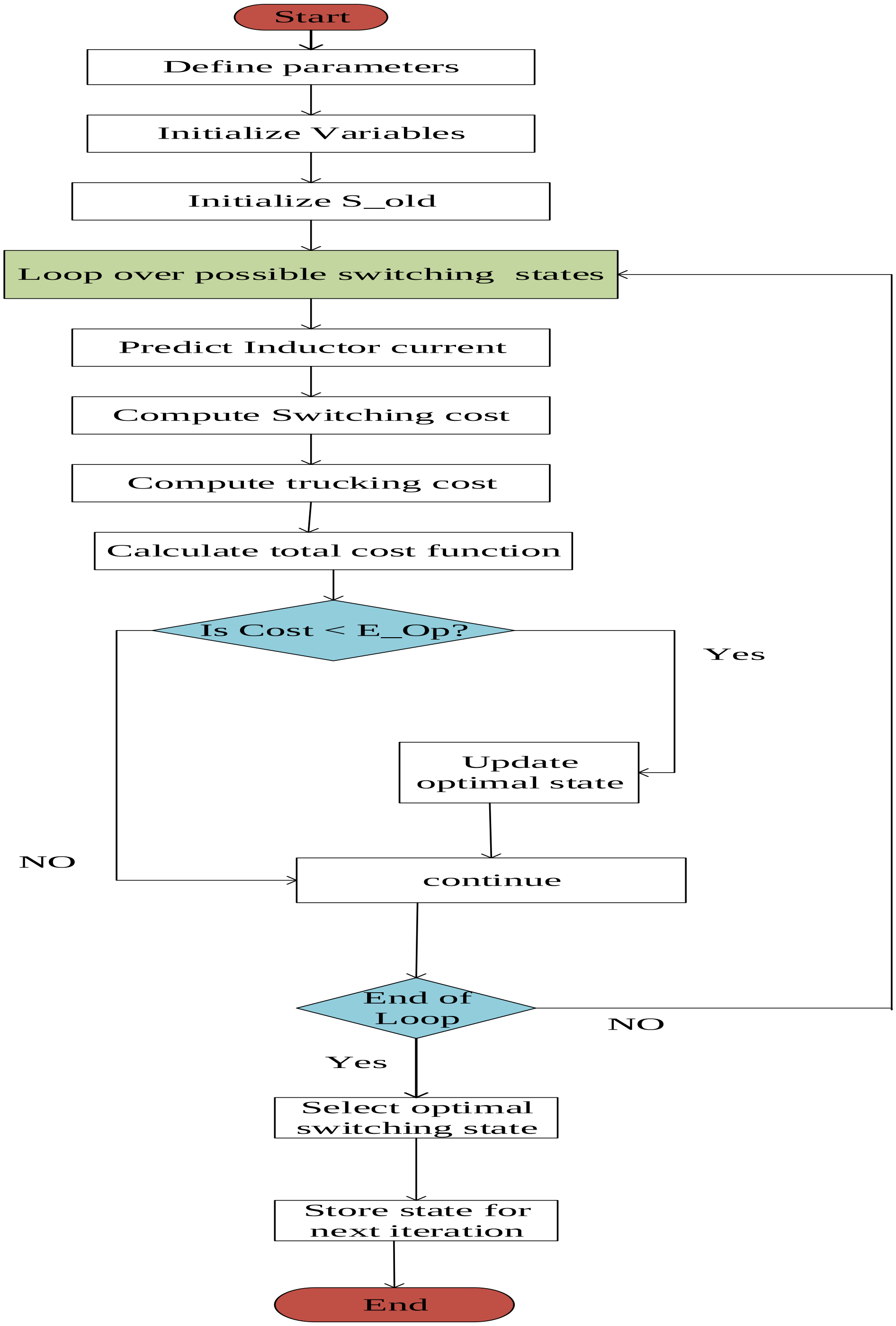


Figure 16: Flow chart of Model Predictive Control for Boost Converter

4.1.2 Simulation in MATLAB/Simulink

The hybrid system has simulated with real data from Nyankorogoma. The main components include Solar PV model, Boost converter wit Model predictive control, Mini-grid and load models has modeled and simulated in MATLAB/Simulink. The steps taken to perform the simulation include the solar PV system and the MPC strategy are modeled and simulated using MATLAB/Simulink. The simulation includes the components of Solar PV Array Model; the PV array has modeled based on the current-voltage characteristics described. collected data for solar irradiance and NYANKOROGOMA mini-grid have collected to simulate realistic system throughout the day.

Boost Converter Model; The boost converter has modeled using the algorithm for the inductor current I_L and output voltage Vo. The MPC controls the duty cycle to regulate the output voltage.
Inverter Model; The inverter is modeled as a full-bridge inverter, converting the DC output of the boost converter into AC for grid supply. The MPC also controls the inverter to ensure synchronized output with the mini-grid.
Load Profile Simulation; A load profile is used to simulate varying demand conditions in the mini-grid. The load demand fluctuates between 1 kW and 11 kW throughout the day.

Initialize System Parameters; The system has initialized with realistic parameters for the PV array, boost converter, and inverter, as shown in table.
Run Simulation; The system has simulated under varying solar irradiance and load conditions. The MPC algorithm is applied to regulate the output voltage of the boost converter and synchronize the inverter with the grid.
Performance Evaluation; The key performance metrics, including voltage regulation, power quality, and THD, are measured and compared between the MPC-controlled system and a traditional PI-controlled system.

Table 6:System Parameters for Solar PV and Boost Converter

Parameter	**Value**	**Units**
Solar Irradiance	600- 800	W/m²
PV Array Open Circuit Voltage	48	V
PV Array Short Circuit Current	8.5	A
Inductance L	50.4e-6	H
Capacitance C	4.375e-3	F

Table 7:System Parameters for MATLAB/Simulink Simulation

Component	**Parameter**	**Value**	**Units**
Solar PV Array	Peak Irradiance	800	W/m²
	Open Circuit Voltage	48	V
	Short Circuit Current	8.5	A
Boost Converter	Inductance L	50.4e-6	H
	Capacitance C	4.375e-3	F
Inverter	Output Voltage	230	V
	Frequency f	50	Hz
Load	Power Demand (varying)	1 – 11.9	kW

The table 5 and 6 include the system parameters used in simulation of solar PV models; the PV array to produce varying power based on irradiance data. Model Predictive Control on boost ensures that the PV array operates at its highest efficiency by continuously adjusting the operating point to extract maximum available power. This optimization is crucial for maintaining a stable and efficient power supply within the mini-grid.

The boost converter steps up the PV array’s output voltage to match the grid voltage using Model Predictive Control (MPC). By dynamically controlling the duty cycle of the converter, MPC stabilizes the output voltage, ensuring seamless integration with the mini-grid. This regulation is essential for preventing voltage fluctuations that could affect system performance.

The inverter plays a critical role in converting DC voltage from the PV array into AC power suitable for grid use. Its output is synchronized with the grid in both frequency and phase, ensuring smooth operation and avoiding power quality issues. Proper synchronization is necessary to maintain a stable and reliable power supply within the mini-grid.

Load variability is a key factor in the simulation, as the load demand fluctuates throughout the day, reflecting real-world conditions in a mini-grid. The MPC strategy continuously adjusts to these variations, maintaining system stability and ensuring a balanced power supply. This adaptability is essential for integrating renewable energy sources into existing power networks.

The system’s overall performance is evaluated based on key parameters such as voltage regulation, total harmonic distortion (THD), and grid stability under varying conditions. By analyzing these factors, the effectiveness of the MPC strategy in optimizing power quality and reliability is assessed, confirming its suitability for enhancing mini-grid operations.

Chapter 5: Results & Discussion

The integration of a solar PV system into the Nyankorogoma Hydro Mini-Grid using Model Predictive Control (MPC) has been analyzed through MATLAB/Simulink simulations. The results provide insights into system performance, including voltage, current, power quality improvement, and harmonic reduction. This chapter presents the findings and discusses their implications and system response.

5.1 Boost Converter Performance and Voltage Stability

To ensure effective solar power integration, the boost converter was controlled using MPC to regulate voltage. Figure 18 illustrates the variation in solar irradiance and the corresponding output voltage of the boost converter.

Table 8: Result table of Voltage

Parameter	Before MPC	After MPC
Input Voltage (V)	35–45	35–45
Output Voltage (V)	200–230	230 (Stable)
Voltage Ripple (%)	7.5%	2.3%

The implementation of Model Predictive Control (MPC) ensures that the output voltage remains consistently regulated at 230V, despite variations in solar irradiance. By dynamically adjusting the control inputs of the boost converter, MPC effectively mitigates voltage fluctuations, enhancing system stability. The reduced voltage ripple from 7.5% to 2.3% further highlights the controller’s capability to maintain a smooth and reliable voltage profile. This stability is crucial for ensuring uninterrupted power supply to consumers and minimizing the risk of voltage-related equipment failures.

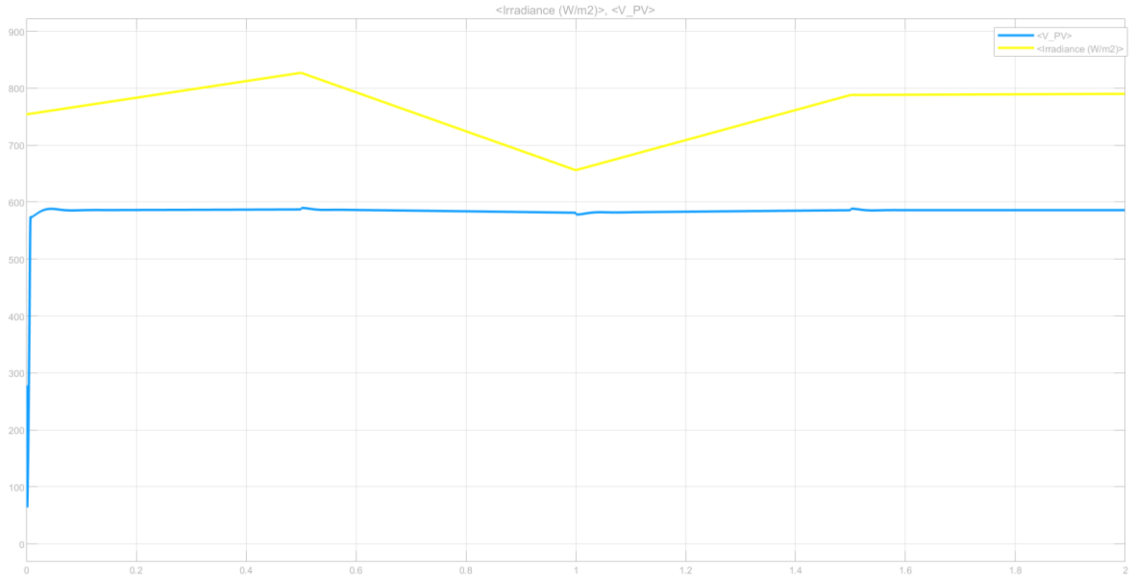
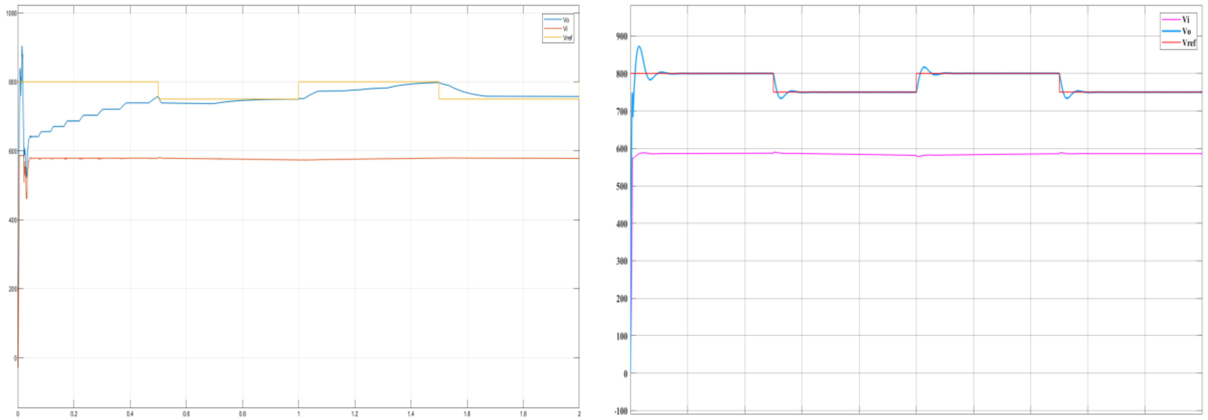


Figure 17: PV input , output and boost converter voltage

The application of Model Predictive Control (MPC) to the boost converter has led to significant improvements in both input and output performance parameters. As depicted in Figure 19, the system effectively maintains the output voltage within the desired reference range, ensuring stable operation. Prior to implementing MPC, the system exhibited a settling time of 0.5 seconds, as shown in Figure 19(a). However, after applying MPC, the settling time was significantly reduced to 0.1 seconds, as seen in Figure 19(b). This improvement demonstrates the enhanced dynamic response and voltage regulation achieved through predictive control, minimizing transient effects and ensuring faster convergence to steady-state conditions. The results confirm that MPC optimally adjusts the switching of the boost converter, leading to better system stability and efficiency in solar power integration.



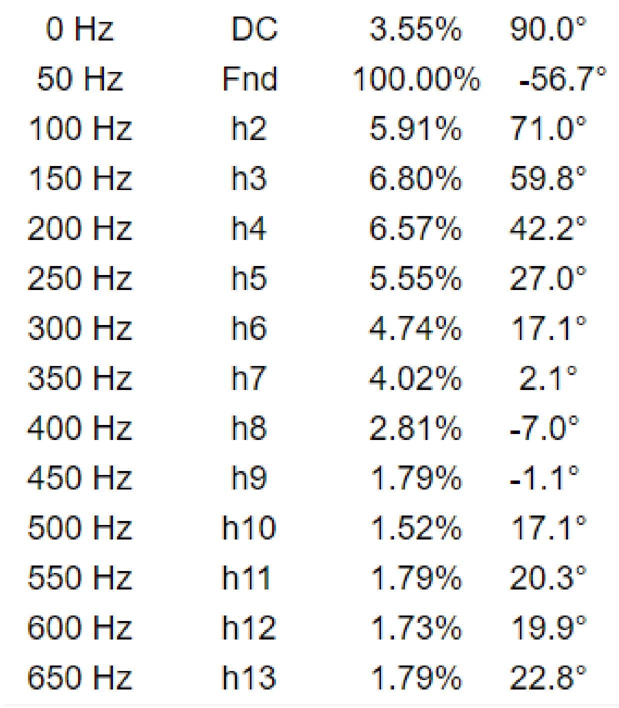
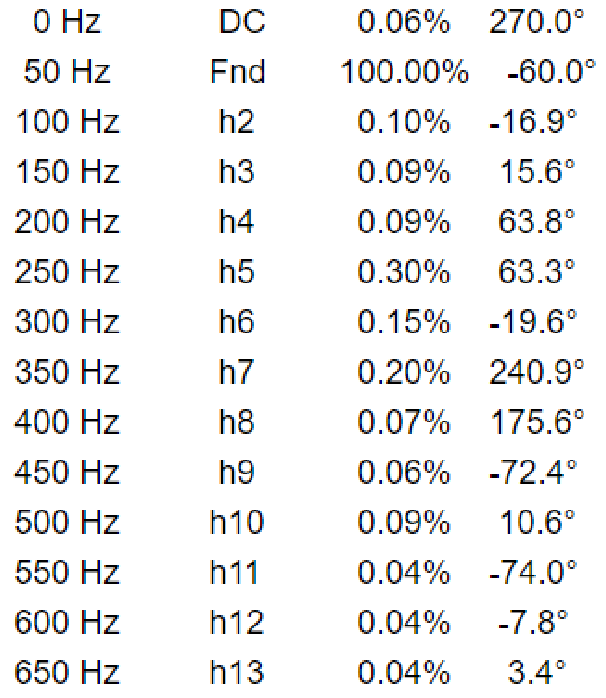
(a) **(b)**

Figure 18: Before applying MPC on Boost converter (a) and After applying MPC on Boost converter (b)

5.2 Total Harmonic Distortion (THD) Reduction

Power quality improvement was evaluated using Fast Fourier Transform (FFT) analysis, focusing on Total Harmonic Distortion (THD) before and after implementing Model Predictive Control (MPC). The FFT analysis results, summarized in Table 8, reveal a significant reduction in harmonic distortion following the application of MPC. Prior to implementation, the mini-grid exhibited a THD of 12.07%, which was reduced to 4.02% after applying MPC. This improvement highlights the effectiveness of the predictive control strategy in mitigating harmonic distortions, leading to enhanced waveform quality and overall power system stability. By reducing harmonic distortions, MPC contributes to improved voltage and current profiles, ensuring a more reliable and efficient operation of the mini-grid.

Table 8: Result FFT analysis on mini-grid current before and after of Model Predictive control

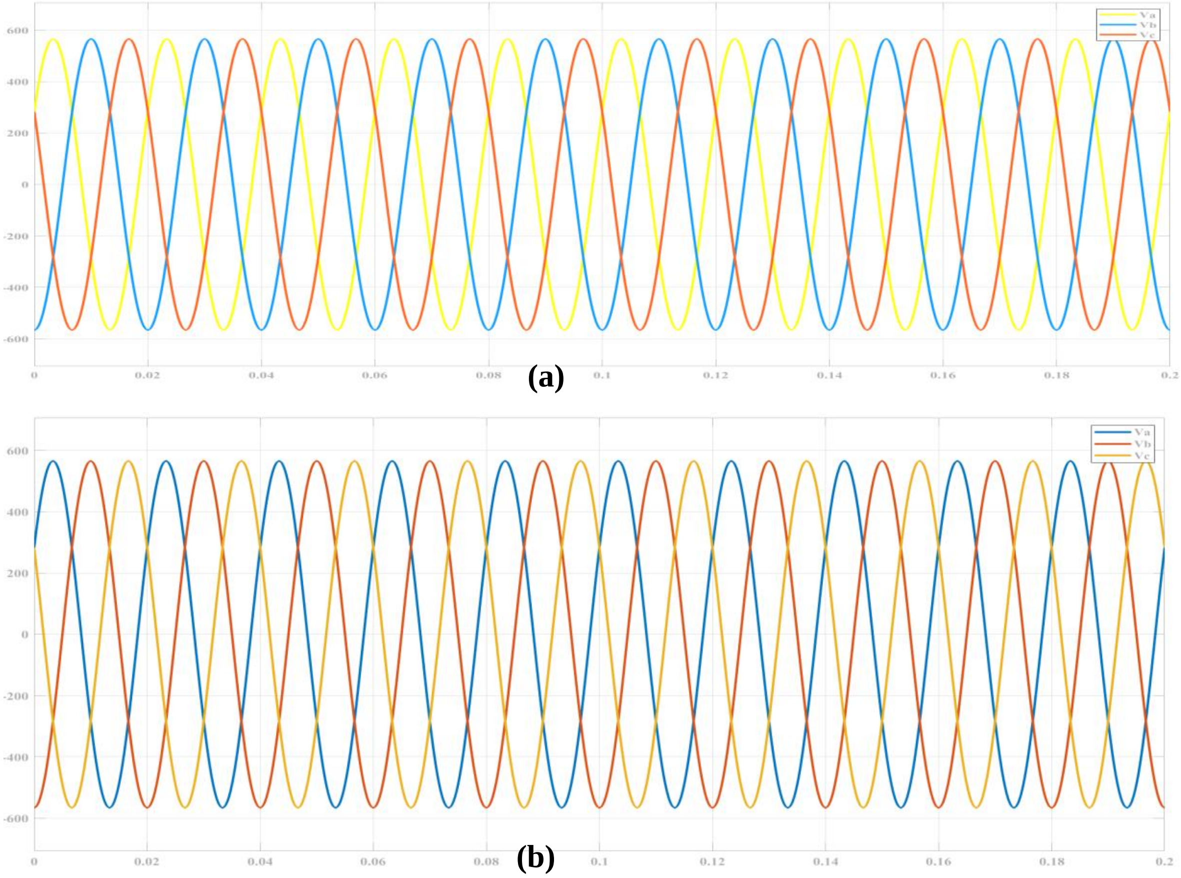



Before Model predictive control applied				After Model predictive control applied			
0 Hz	DC	3.55%	90.0°	0 Hz	DC	0.06%	270.0°
50 Hz	Fnd	100.00%	-56.7°	50 Hz	Fnd	100.00%	-60.0°
100 Hz	h2	5.91%	71.0°	100 Hz	h2	0.10%	-16.9°
150 Hz	h3	6.80%	59.8°	150 Hz	h3	0.09%	15.6°
200 Hz	h4	6.57%	42.2°	200 Hz	h4	0.09%	63.8°
250 Hz	h5	5.55%	27.0°	250 Hz	h5	0.30%	63.3°
300 Hz	h6	4.74%	17.1°	300 Hz	h6	0.15%	-19.6°
350 Hz	h7	4.02%	2.1°	350 Hz	h7	0.20%	240.9°
400 Hz	h8	2.81%	-7.0°	400 Hz	h8	0.07%	175.6°
450 Hz	h9	1.79%	-1.1°	450 Hz	h9	0.06%	-72.4°
500 Hz	h10	1.52%	17.1°	500 Hz	h10	0.09%	10.6°
550 Hz	h11	1.79%	20.3°	550 Hz	h11	0.04%	-74.0°
600 Hz	h12	1.73%	19.9°	600 Hz	h12	0.04%	-7.8°
650 Hz	h13	1.79%	22.8°	650 Hz	h13	0.04%	3.4°

Table 9: Total Harmonic Distortion

THD Parameter	Before MPC	After MPC
THD (%)	12.07%	4.02%

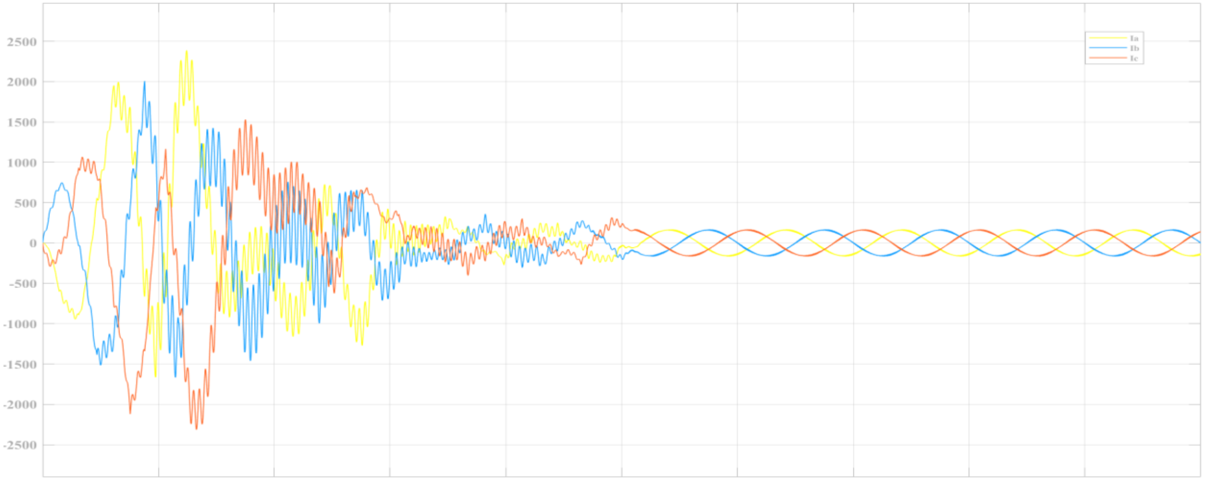
The reduction in THD signifies improved power quality, minimizing potential disturbances in the mini-grid.



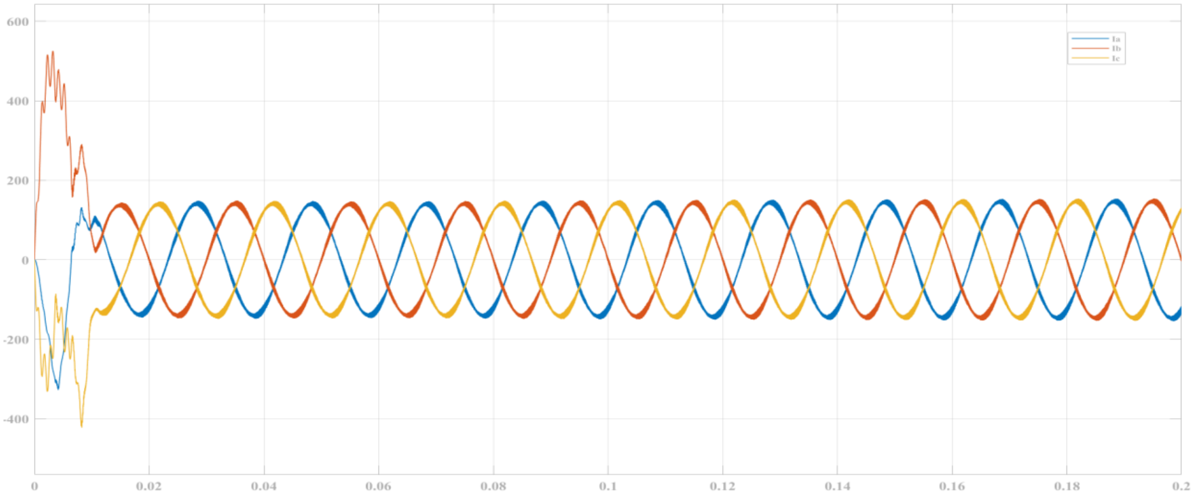
(a)

(b)

Figure 19: Before Mini-grid Output voltage (a) and Before Mini-grid Output voltage (b)



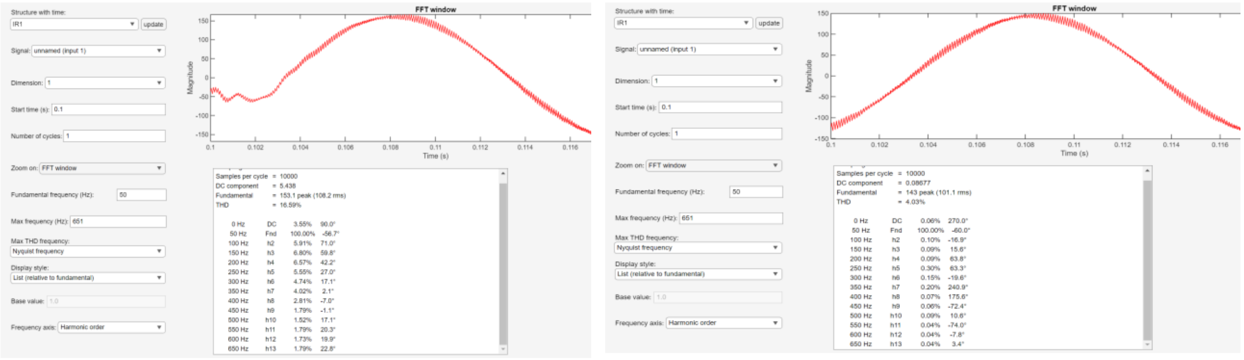
(a)



(b)

Figure 20: Before Mini-grid Output current (a) and after Mini-grid Output current (b)

The overall system response of the Nyankorogoma mini-grid is illustrated in Figure 20 (a) and (b). Prior to the implementation of Model Predictive Control (MPC), the system exhibits a settling time of 0.1 seconds, which is significantly improved to 0.01 seconds after MPC is applied. To analyze the power quality enhancement, both current waveforms from Figure 20 were processed using a Fast Fourier Transform (FFT) analysis window. The results of this analysis, presented in Figure 21 and Table 9, demonstrate a notable reduction in harmonic distortion, highlighting the effectiveness of MPC in improving system stability and power quality.



Structure with time: IR1
Signal: unnamed (input 1)
Dimension: 1
Start time (s): 0.1
Number of cycles: 1
Zoom on: FFT window
Fundamental frequency (Hz): 50
Max frequency (Hz): 651
Max THD frequency: Nyquist frequency
Display style: List (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

```
Samples per cycle  =  10000
DC component       =  5.438
Fundamental        =  153.1 peak (108.2 rms)
THD                =  16.59%

     0 Hz      DC      3.55%    90.0°
    50 Hz     Fnd    100.00%   -56.7°
   100 Hz      h2      5.91%    71.0°
   150 Hz      h3      6.80%    59.8°
   200 Hz      h4      6.57%    42.2°
   250 Hz      h5      5.55%    27.0°
   300 Hz      h6      4.74%    17.1°
   350 Hz      h7      4.02%     2.1°
   400 Hz      h8      2.81%    -7.0°
   450 Hz      h9      1.79%    -1.1°
   500 Hz     h10      1.52%    17.1°
   550 Hz     h11      1.79%    20.3°
   600 Hz     h12      1.73%    19.9°
   650 Hz     h13      1.79%    22.8°
```

Structure with time: IR1
Signal: unnamed (input 1)
Dimension: 1
Start time (s): 0.1
Number of cycles: 1
Zoom on: FFT window
Fundamental frequency (Hz): 50
Max frequency (Hz): 651
Max THD frequency: Nyquist frequency
Display style: List (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

```
Samples per cycle  =  10000
DC component       =  0.08677
Fundamental        =  143 peak (101.1 rms)
THD                =  4.03%

     0 Hz      DC      0.06%   270.0°
    50 Hz     Fnd    100.00%   -60.0°
   100 Hz      h2      0.10%   -16.9°
   150 Hz      h3      0.09%    15.6°
   200 Hz      h4      0.09%    63.8°
   250 Hz      h5      0.30%    63.3°
   300 Hz      h6      0.15%   -19.6°
   350 Hz      h7      0.20%   240.9°
   400 Hz      h8      0.07%   175.6°
   450 Hz      h9      0.06%   -72.4°
   500 Hz     h10      0.09%    10.6°
   550 Hz     h11      0.04%   -74.0°
   600 Hz     h12      0.04%    -7.8°
   650 Hz     h13      0.04%     3.4°
```

(a)

(b)

Figure 21:FFT Analysis Before and After MPC Implementation

5.3 Power Quality Improvement

The implementation of Model Predictive Control (MPC) significantly improved the voltage and frequency stability of the mini-grid. Prior to MPC application, the voltage waveform exhibited noticeable fluctuations, contributing to power quality issues. However, after integrating MPC, the system demonstrated enhanced voltage regulation with reduced distortions, as illustrated in Figure 19. The predictive control mechanism effectively adjusted the switching of the boost converter, ensuring consistent voltage output despite variations in solar irradiance. Additionally, frequency deviations were minimized, leading to a more stable and reliable power supply. These improvements underscore the effectiveness of MPC in mitigating the challenges associated with renewable energy integration into mini-grids.

Table 9: Power Quality before and after MPC on Boost

Performance Metric	Before MPC	After MPC
Voltage Stability (V)	220–240	230 (Stable)
Frequency Stability (Hz)	49.2–50.8	49.8–50.2

The MPC strategy effectively reduces voltage fluctuations and frequency deviations, ensuring a steady power supply to consumers.

5.4 Comparative Analysis (Before and After MPC Implementation)

The implementation of Model Predictive Control (MPC) has demonstrated a significant enhancement in power quality and system stability. The voltage output remains consistently regulated at 230V, effectively mitigating fluctuations caused by variations in solar irradiance. This ensures a stable and reliable power supply, preventing voltage drops or surges that could otherwise impact the performance of electrical appliances and industrial equipment. Additionally, MPC has substantially reduced Total Harmonic Distortion (THD), lowering it from 12.07% to 4.02%. This reduction minimizes electrical noise, enhances power efficiency, and prevents excessive heating, ultimately prolonging the lifespan of connected devices.

Furthermore, the application of MPC has improved frequency stability, maintaining it within an optimal range of 49.8–50.2 Hz. This minimizes the risk of power interruptions and ensures a reliable supply for end users. Stable frequency is essential for preventing operational malfunctions in sensitive equipment and maintaining the overall performance of the mini-grid. Beyond voltage and frequency regulation, MPC optimizes energy flow by dynamically adjusting power distribution. This leads to a reduction in energy losses, enhancing overall system efficiency and reliability. The optimization process ensures that available energy is utilized effectively, thereby maximizing the benefits of integrating solar power into the Nyankorogoma mini-grid.

5.5 Discussion on Practical Implications

The findings validate that integrating solar PV into the Nyankorogoma Hydro Mini-Grid with MPC enhances power reliability and quality. The reduced voltage and frequency fluctuations minimize power outages, benefiting consumers. Additionally, the lower THD levels improve equipment lifespan and operational efficiency.

6. Conclusion and Recommendations

6.1. Conclusion

This research successfully implemented Model Predictive Control (MPC) for integrating solar power into the Nyankorogoma hydro mini-grid, demonstrating its effectiveness in enhancing power quality and reliability. The MATLAB/Simulink simulations confirmed that the MPC-based control strategy stabilized voltage fluctuations, optimized energy flow, and significantly reduced Total Harmonic Distortion (THD) from 12.07% to 4.02%. By dynamically adjusting control actions based on predictive algorithms, the mini-grid maintained a more stable voltage of 230V and a frequency range of 49.8–50.2 Hz, reducing power losses and improving overall system stability.

One of the key challenges addressed in this study was the inefficient dissipation of excess hydro-generated energy in dump loads. The integration of solar power through MPC allowed for better utilization of this energy, redirecting it for productive use and improving system efficiency. Comparative FFT analysis before and after MPC implementation revealed a significant reduction in harmonic distortion, improving waveform quality. Additionally, the hybrid solar-hydro approach increased the mini-grid's capacity to serve more consumers while maintaining voltage and frequency stability, demonstrating its potential for broader application in rural electrification projects.

Overall, this research contributes to the advancement of predictive control in renewable energy systems by showcasing the benefits of MPC in managing hybrid mini-grids. The findings provide a foundation for future work in optimizing mini-grid efficiency through advanced control strategies, particularly in regions where reliable renewable energy integration is essential for rural development.

6.2 Recommendations

Based on the findings of this research, several recommendations can be made for future work and practical implementation to enhance the effectiveness and scalability of the proposed Model Predictive Control (MPC) strategy. While the study successfully validated the MPC strategy through simulations, real-world implementation is necessary to assess its performance under practical operating conditions. A pilot project at the Nyankorogoma mini-grid would help evaluate real-time energy management, system adaptability, and long-term stability. Testing in actual field conditions would provide insights into operational challenges and necessary refinements for better system performance.

To further enhance energy reliability, integrating battery storage into the mini-grid should be considered. Batteries would help store excess solar energy during peak generation periods and supply power during low generation times, improving overall system efficiency and reducing dependence on hydro power alone. This hybrid energy storage approach would ensure a more balanced and uninterrupted power supply.

A detailed cost-benefit analysis should be performed to assess the economic viability of implementing MPC-based control in rural mini-grids. The study should consider installation costs, operational savings, and potential revenue generation from improved power availability. Understanding the financial feasibility would help determine the scalability and attractiveness of the approach for large-scale deployment.

Given the positive results obtained in simulations, the proposed approach should be tested on other mini-grids in Rwanda and similar regions. Different environmental conditions, load profiles, and grid structures should be studied to determine the general applicability of MPC for hybrid renewable energy systems. Expanding the research to diverse settings would provide valuable insights into its adaptability and performance in various mini-grid configurations.

While MPC proved effective in stabilizing power quality, further research can explore integrating artificial intelligence (AI) or machine learning techniques to enhance predictive capabilities. AI-driven control could improve decision-making by learning from historical data and dynamically adapting to unforeseen grid conditions. This advancement would make the control strategy even more robust and intelligent in managing energy flow.

By implementing these recommendations, the potential of hybrid solar-hydro mini-grids can be maximized, ensuring sustainable and reliable energy access for rural communities. This research provides a strong foundation for further advancements in predictive control strategies, contributing to the broader goal of enhancing power quality and reliability in mini-grid systems.

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Appendices

Model Predictive Control of boost converter;

```
function S = MPC_Boost(iL, Vin, Vout, iL_ref, wf)
    % Define sampling time
    Ts = 10e-6;

    L = 1e-3;   % Inductance in Henry
    RL = 0.2;   % Inductor resistance in Ohms

    % Define possible switching states (S=1 or S=0)
    States = [1; 0];

    % Initialize optimization variables
    g_op = 1e6;   % Large initial value for cost function
    n_op = 1;   % Optimal switching state index

    % Persistent variable to store previous switch state
    persistent S_old;
    if isempty(S_old)
        S_old = 0; % Initialize previous state to 0 if not set
    end

    % Loop over possible switching states to evaluate cost function
    for n = 1:2
        % Predict inductor current at next step based on system model
        iL_k1 = (Ts/L) * (Vin - iL * RL - Vout * (1 - States(n))) + iL;

        % Compute switching cost (penalizes switching transitions)
        g_sw = abs(States(n) - S_old);

        % Compute tracking cost (penalizes deviation from reference current)
```

```
        g_iL = abs(iL_ref - iL_k1);

        % Total cost function (weighted sum of tracking and switching cost)
        g = g_iL + g_sw * wf;

        % Update optimal switching state if a lower cost is found
        if g < g_op
            n_op = n;
            g_op = g;
        end
    end

    % Select optimal switching state
    S = States(n_op);

    % Store selected state for next iteration
    S_old = S;
end
```

Simulink model of the system

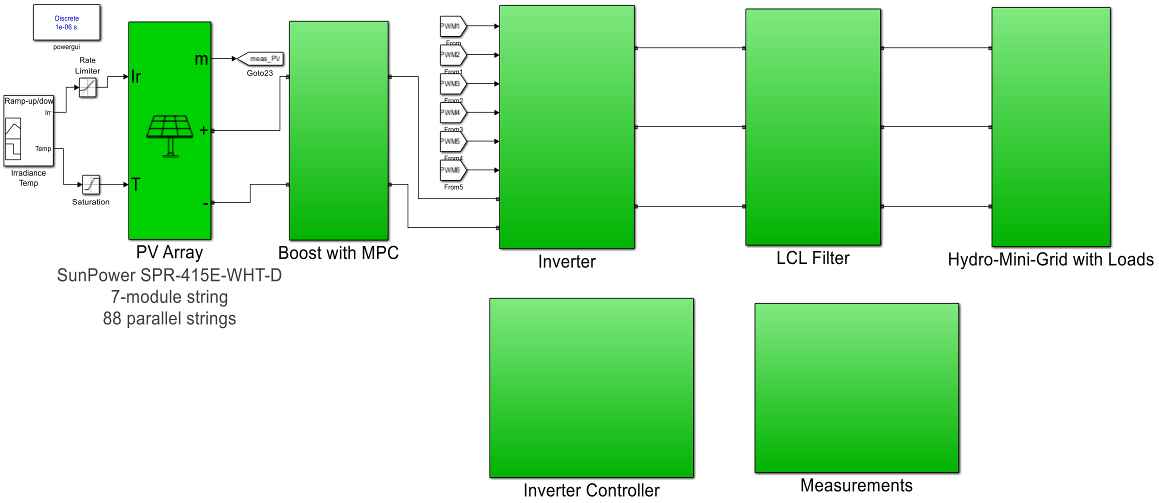

Figure 22: Simulink model of the system