An-Najah National University

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Bachelor degree in Electrical Engineering

Graduation Project II

Enhanced Control Strategy for Single-Phase Grid-Tie Inverter with Repetitive Learning Controller

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Acknowledgment

With profound gratitude and respect, I am delighted to dedicate this research to my esteemed grandfather, Mr. Shafea Sabri Nofal, who has been a true source of motivation and inspiration throughout my academic journey. Every moment spent with my wonderful grandfather has left a lasting impact as he shared in the details of my scholarly path, enriching me with wisdom and unwavering support.

To my late grandfather, Mr. Youssef Mohamed Naser, who departed during my early years but left an enduring impact. Though his departure occurred early in my life, his influence remains ever-present. His wisdom and knowledge continue to inspire me, leaving behind an unforgettable legacy in my academic journey. I gratefully recall every piece of advice he offered, each guidance becoming my beacon in the pursuit of learning and progress.

Yahya Naser

Abstract

Photovoltaic (PV) power being supplied to the utility grid is becoming increasingly popular as the world's power demand continues to rise. Solid-state inverters are the key technology that enables the integration of PV systems into the grid. Inverters are used to convert the DC voltage obtained from the PV system to AC voltage, which is then fed to the grid. Hysteresis control is typically used to control the inverter to regulate the real and reactive power injected from the PV into the grid. However, in this project, the real and reactive power will be controlled using a different technique, namely the PI controller in addition to the repetitive controller. The repetitive controller will compensate for any errors introduced by the PI controller in tracking the sinusoidal reference, as shown in Figure 1.

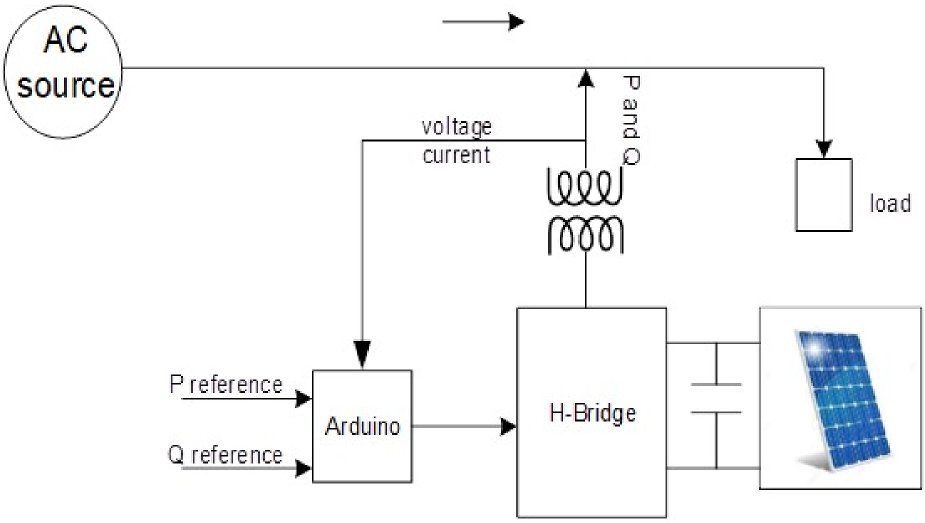

Figure 1: PV multi-level-based Grid

The project will first be simulated in MATLAB Simulink. The hardware components include a microcontroller, current, voltage sensors, H-bridge, and transformer to implement both the PI and the repetitive controllers, in addition to generating a PWM signal to the H-bridge to control the injection of real and reactive power into the grid.

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Chapter 1

Introduction

1.1 Background

An essential component of electrical engineering, a power inverter transforms direct current (DC) into alternating current (AC), in contrast with a rectifier, which performs the reverse conversion from AC to DC. The primary function of a power inverter is to optimize power transmission from a DC source, which is usually a battery or a similar power storage unit, as shown in Figure 1.1.

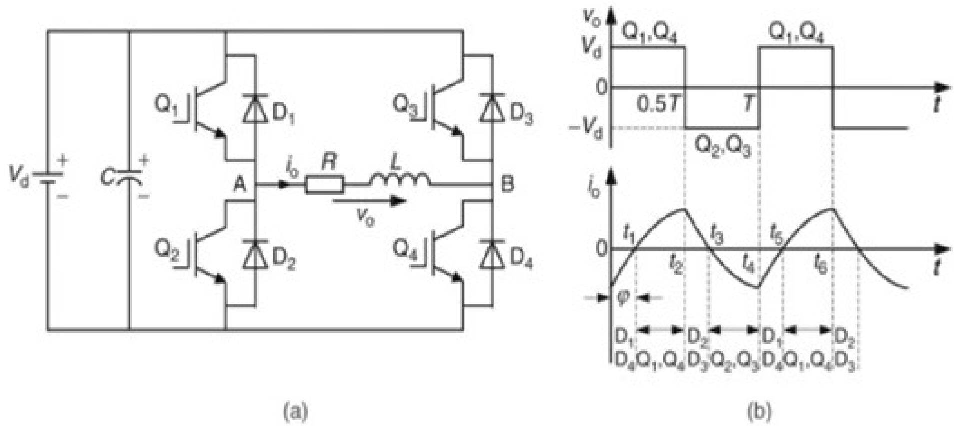

Figure 1.1: Full Bridge Inverter

Power inverters are part of the huge field of electrical engineering systems and have many functions. These devices are widely used in situations where high currents and voltages are present, and they effectively meet the electrical needs of various systems. In contrast to rectifiers, which are their predecessors, power inverters facilitate improved power flow from the DC source. Moreover, power inverters are more significant than just power conversion. They become essential tools in the delicate regulation of the flow of both active and reactive power to the grid, with a focus on power factor control.

By utilizing different control methodologies, they enhance power distribution and make sustainable contributions to grid stability. This becomes particularly important to guarantee grid reliability and efficient power delivery. Power inverters are increasingly important when they are included in photovoltaic (PV) systems. Power inverters play a crucial role in renewable energy ecosystems because they make it easier to integrate DC power from solar panels into grids that rely on AC power. PV systems and power inverters work together to provide a sustainable solution by capturing solar energy and transforming it into a format that is compatible with conventional electrical grids. Figure 2 shows a graphical representation of a PV system connected to a grid. Power inverters act as a vital link between DC and AC-dependent devices,

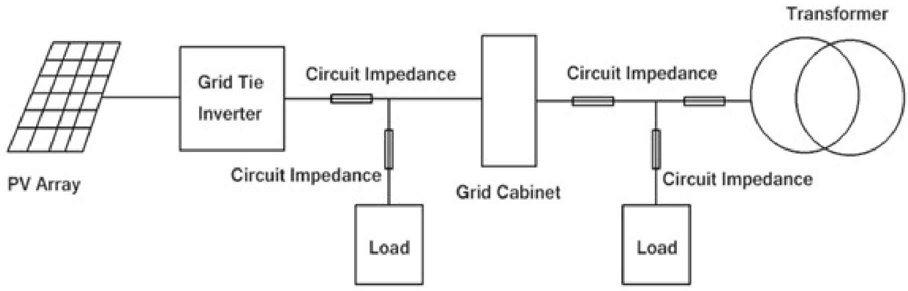

Figure 1.2: PV system connected to the grid

including those found in PV systems or traditional electrical networks. They play an essential role in maintaining the sustainability, reliability, and effectiveness of contemporary electrical infrastructure, while also making a significant contribution to the ongoing advancement of renewable energy sources.

1.2 Problem Statement

The main goal of this project is to use Pulse Width Modulation (PWM) techniques to implement a control mechanism for active and reactive power in an inverter system with constant switching frequency. Following that, the inverter's output current is transformed into a DQ axis and controlled with a Proportional-Integral (PI) controller.

When injecting both active and reactive power components into the grid simultaneously, we discovered that it can cause power losses and affect the active power and reactive power. This effect is due to a significant error that we identified in the transition from the measured current to the reference current from the output of the PI controller.

As observed injecting both active and reactive power into the grid simultaneously can lead to power losses and a negative impact on the active and reactive power. The study primarily focuses on identifying and correcting the issue that causes this effect.

This disturbance not only affects the efficiency of power transmission but also results in losses in both real and reactive power, thus having a significant impact on the overall performance of the grid.

The goal is to improve the accuracy and efficiency of power control in the inverter system, ensuring optimal power delivery to the grid.

1.3 Motivation

The study at hand is motivated by the changing landscape of energy systems and the pressing need for sustainable solutions. The researchers recognize that optimizing the power characteristics of inverters is an essential challenge in the present day of increasing energy demands and increased emphasis on environmental sustainability. The significance of this study goes beyond theoretical implications, as it looks into the practical world where advancements hold the promise of significant real-world impact.

The researchers aim to unravel the complexities that have previously limited the simple integration of renewable energy sources into mainstream power systems by investigating the intricacies of active and reactive power control in inverters. This investigation is crucial, as it can help to overcome the challenges of integrating renewable energy sources into existing power grids. By understanding how to control active and reactive power in inverters, renewable energy sources can be used more efficiently and effectively, leading to a more sustainable energy future.

Moreover, the researchers aim to provide useful perspectives that may transform the effectiveness and stability of energy conversion systems. They hope to contribute to the ongoing conversation about shaping a sustainable future for energy systems by providing a comprehensive understanding of energy systems that transcends scholarly confines. The findings of this study hold the potential to lead to changing shifts in how we harness and use power in a world

where sustainable energy solutions are no longer a choice but a necessity.
It is worth noting that the goal of this project is not only focused on academic pursuits. Instead, it seeks to lay foundations for energy systems that are not only robust but also adaptive and strong. The researchers are reacting to the worldwide appeal for creative ways to advance the cause of sustainable energy. They hope to provide a holistic perspective that can guide the evolution of sustainable energy practices on a larger scale by combining their understanding of active and reactive power control in inverters with the rapid growth of photovoltaic systems. By doing so, they aim to align their findings with the expanding domain of PV technology, which is playing a growing role in the global energy landscape.

1.4 Purpose

The purpose of this research project is to develop advanced control strategies, assess grid impact, investigate simple integration in photovoltaic systems, optimize power inverter functionality, and provide useful insight into sustainable energy practices.

1.5 Report Structure

This report delves into power inverter systems and their integration with photovoltaic systems in an organized manner. It starts with an introduction that sets the context, defines the problem, and outlines the objectives. A comprehensive literature review provides an overview by examining the current research and methodologies.
The main section of the report provides detailed analyses of the research methodology used, offering insights into advanced control techniques, integration strategies, and optimization methods. It presents research on sustainability, reliability, and efficiency in grid operations.
The report concludes with practical insights and recommendations that highlight the importance of the research in guiding future developments in the field of renewable energy practices. Essentially, it serves as a guide for understanding the constantly evolving landscape of power inverter systems.

1.6 Earlier Coursework

Our project has benefited greatly from the diverse range of courses offered in our program. Several of these courses have played a significant role in advancing our project by aiding in the design and analysis of our study's outcomes. These courses are directly aligned with the core concepts explored in our research. By leveraging the knowledge gained from these courses, we have made substantial progress in our project, utilizing a comprehensive understanding of the subject matter. The curriculum has effectively equipped us to tackle the challenges associated with designing and studying the results of our project, ensuring a well-rounded and informed approach.

The course that significantly contributed to our project was "Electrical Machines Drives," which played a crucial role in our understanding of vector control and the design and implementation of PI controllers. This course provided us with the necessary knowledge and skills to effectively control electrical machines using vector control techniques. The concepts and techniques we learned were directly applicable to our project, enabling us to design and drive the electrical machine with precision using vector control. Through this course, we gained a deep understanding of system dynamics, control algorithms, and the practical implementation of PI controllers for vector control. Applying vector control and well-designed PI controllers, we were able to achieve the desired performance and efficiency in our project. The invaluable insights gained from the "Electrical Machines Drives" course greatly influenced the success of our study.

The "Power Electronics" course was a vital component of our project, providing practical applications of electrical and electronic elements. It specifically focused on inverters, which are essential in photovoltaic (PV) systems. Through this course, we gained a deep understanding of inverters and their control. This knowledge enabled us to comprehend the relationships between different project components and optimize their performance. The insights gained from the course played a crucial role in the successful design and implementation of inverters, ensuring efficient power generation and integration within our PV system.

The "Electrical Engineering Systems Modelling using MATLAB" course was instrumental in our project's control aspect. It provided us with the skills to model and simulate control systems using MATLAB, enabling us to design and optimize control algorithms for our photovoltaic (PV) system. By leveraging MATLAB's simulation capabilities, we were able to analyze and fine-tune the performance of the control system, ensuring efficient power regulation and grid integration. This course played a crucial role in enhancing our understanding and proficiency in control system modeling and optimization.

The "Control Systems" course, focusing on PI, PD, and PID controllers, was pivotal in our project's control aspect. Through this course, we gained a deep understanding of control system principles and techniques, specifically about power regulation. We learned how to design and implement control algorithms using PI, PD, and PID controllers to precisely regulate parameters such as real power (P) and reactive power (Q) in our photovoltaic (PV) system. This knowledge allowed us to optimize the system's performance, ensuring efficient power conversion and seamless integration with the grid. The insights gained from the "Control Systems" course greatly influenced our approach to control design, enabling us to achieve precise and reliable control of our PV system.

The "Critical Thinking and Research Skills" course has been indispensable in refining our analytical and scholarly capabilities. Focused on cultivating critical thinking and research methodologies, this course equipped us with the essential skills to conduct systematic scientific inquiries. A notable aspect of the course was our immersion in the art of crafting rigorous scientific research and mastery of LATEX coding for document preparation. The acquired critical thinking skills have allowed us to approach problems analytically, while proficiency in LATEX coding has enabled us to communicate our research outcomes with precision and professionalism. These skills, gained through the course, have seamlessly integrated into our project work, enhancing the quality of our research reports and contributing significantly to the project's success.

Chapter 2

Literature Review

The rise in renewable energy sources like solar and wind power integrating into the grid necessitates advanced control strategies for single-phase grid-tied inverters.
This chapter discusses a literature review of all aspects related to active and reactive power control in general and controllers in particular.

2.1 History

During the 1950s, power inverters were still in the developmental stage. Engineers utilized basic pulse width modulation (PWM) techniques to produce square waveforms with different duty cycles to regulate output voltage[1]. However, this approach had its limitations in terms of control accuracy and operational efficiency. To address these challenges, certain inverter designs incorporate mechanical control mechanisms. For example, rotating components such as commutators were employed to manage the switching sequence of the inverter bridge. While effective, this mechanical intervention resulted in larger dimensions and reduced efficiency.
After the 1950s, there was a significant advancement in inverter technology with the introduction of thyristors. These semiconductor switches brought about a fundamental change in how inverter control systems functioned, moving away from mechanical control methods and towards more flexible and efficient systems. Pulse Width Modulation (PWM) techniques based on thyristors became the new standard, replacing the limitations of earlier mechanical control methods. As the use of inverters expanded, reducing harmonic distortion in the output waveform became more critical. Advanced PWM techniques, such as sinusoidal PWM and space-vector modulation, were created to address this challenge[2]. These advanced methods not only tackled the issue of harmonic distortion but also greatly improved the accuracy and quality of the output waveform.
In the latter part of the 20th century, specifically from the 1980s to the 2000s, inverter technology underwent a significant transformation. The introduction of microprocessor control

brought about a paradigm shift[3], enabling the application of advanced control algorithms. Proportional-integral (PI) controllers and advanced dead-time compensation techniques were notable improvements that enhanced output voltage regulation and system stability[4]. This marked a departure from conventional methodologies, ushering in a phase characterized by heightened precision and control.

The introduction of digital signal processors (DSPs) further augmented control capabilities by enabling real-time implementation of intricate control algorithms[5]. This was exemplified by the adoption of model-predictive control (MPC) for optimal inverter performance[6]. This technological advancement represented a significant amplification of computational power, transcending previous limitations. At the same time, multi-level inverters such as H-bridge and neutral-point-clamped topologies became more popular. These inverters were designed to achieve elevated voltage outputs while concurrently mitigating harmonic distortion, requiring specialized control strategies. The coordination of the synchronized switching of multiple inverter legs became a focal point in realizing the potential of multi-level inverters.

Inverter technology has evolved significantly to keep up with the changing energy landscape. Grid-interactive inverters (GIIs) are now widely used in distributed solar power generation[7]. Advanced control algorithms with grid-interactive features like anti-islanding protection and reactive power support ensure reliable and efficient performance. Intelligent control, which uses AI and machine learning, enhances fault tolerance and enables predictive maintenance[8]. Wireless communication and smart grids facilitate real-time monitoring and control of GIIs, contributing to efficient energy management and grid resiliency. These advancements are making inverter systems more efficient, adaptable, and integrated into modern energy infrastructures[9].

2.2 Controllers

A controller is a sophisticated device that analyzes an input signal from a measured process variable and compares it against a predetermined control point value, also known as a set point or reference point. It then calculates the precise amount of output signal required by the final control element to take corrective action within a control loop.

2.2.1 PID Control

PID control is a feature of most Trerice electronic controllers. PID combines the proportional, integral, and derivative functions into a single unit.

- **Proportional (P)**—Proportional control works by measuring the difference between the desired set point and the actual value and then sending a corrective signal that is proportional to that difference. The width of the proportional band determines the strength of the corrective signal. If the proportional band is narrow, a small error will result in a large corrective action, while a wider proportional band will result in a smaller corrective action for the same amount of error.
- **Integral (I)**—Integral control responds to the duration of the deviation from the set point by sending a corrective signal. The corrective signal increases with the duration of the error.
- **Derivative (D)**— Derivative control reacts to the speed at which the deviation is changing. The corrective signal will be proportional to the rate of change within the process.

It's worth noting that different types of controllers relate the input of a controller (known as "error") to the output (known as an "actuating signal") in various ways. The most commonly used controller type is the proportional-integral-derivative (PID) controller, which uses proportional (P), integral (I), and derivative (D) controls to establish the relationship between error and actuating signal. Alternatively, PID controllers can also combine these controls to relate errors to the actuating signal.

Proportional-Integral (PI) Controller

A commonly used control system is the PI control system, which operates through feedback. It merges proportional action and integral action but omits the derivative action present in the PID system. Compared to I-only control, PI control delivers a faster response time by incorporating proportional action. It averts system oscillation and can restore the system to its set point. Nevertheless, it can be up to 50
PI-control correlates the controller output to the error and the integral of the error.
This PI-control behavior is mathematically illustrated in Equation 9.2.4

$$c(t) = K_c(e(t) + \frac{1}{T_i}\int e(t), dt) + C \tag{2.1}$$

Where

- $c(t)$ is the controller output,
- K_c is the controller gain,
- T_i is the integral time,
- $e(t)$ is the error, and
- C is the initial value of the controller

In this equation, the integral time is the time required for the I-only portion of the controller to match the control provided by the P-only part of the controller.

Proportional-Derivative (PD) Controller

Another type of control mechanism is the PD-control system, which is a combination of feedforward and feedback controls. Unlike the PID system, it lacks integral control. The PD-control system operates on both current process conditions and predicted process conditions. In this system, the control output is a linear combination of the error signal and its derivative. PD-control provides a damping effect on fluctuation similar to the proportional control and predicts process errors similar to the derivative control.

PD-control correlates the controller output to the error and the derivative of the error. This PD-control behavior is mathematically illustrated in Equation (2.2)

$$c(t) = K_c(e(t) + T_d\frac{de}{dt}) + C \tag{2.2}$$

Where

- $c(t)$ is the controller output,
- K_c is the controller gain,
- T_d is derivative time,
- $e(t)$ is the error, and
- C is the initial value of the controller

According to the equation, the PD controller can be viewed as a simplified PID controller that lacks an integral component. Alternatively, one may think of it as a fusion of P-only and D-only control equations. The D-only control anticipates the error to achieve greater stability in the closed-loop system. Nevertheless, P-D control is not widely employed since it is devoid of the integral term, which plays a crucial role in error reduction during steady-state operation.

Proportional-Integral-Derivative (PID) Controller

The PID control method is a powerful combination of three distinct control techniques that work together to achieve superior performance. With P-only control, response time is faster, while integral and derivative controllers work to eliminate or significantly reduce offset errors. The I-control is responsible for removing any remaining offset errors, while the D-control anticipates disturbances by measuring changes in error. When all three are utilized, the PID controller offers greater response and accuracy compared to each controller individually. Nevertheless, due to their higher costs, PID controllers are reserved for situations where accuracy and stability are of the utmost importance.

PID control correlates the controller output to the error, the integral of the error, and the derivative of the error. This PID-control behavior is mathematically illustrated in Equation 6

$$c(t) = K_c(e(t) + \frac{1}{T_i}\int e(t), dt + T_d\frac{de}{dt}) + C \tag{2.3}$$

Where

- $c(t)$ is the controller output,
- K_c is the controller gain,
- T_d is derivative time,
- T_i is the integral time,
- $e(t)$ is the error, and
- C is the initial value of the controller

The equation above shows that PID control combines three types of control: proportional, integral, and derivative. In this equation, the gain is multiplied by all three terms because, in PID control, the gain affects all three actions. However, because PID control uses derivative control, it is not suitable for processes with a lot of noise. This is because the noise would interfere with the predictive, feedforward aspect of the control.

2.2.2 Repetitive Control

The Repetitive Control (RC) strategy is designed to achieve zero steady-state error when tracking or rejecting periodic references or disturbances[10]. It relies on the Internal Model Principle (IMP)[11], which integrates the reference or disturbance generator into the control loop. This technique has proven to be effective in a range of applications, including power electronics and mechatronic systems.

Periodical Signal Generator

The periodic signal generator, i.e., the internal model, is the most relevant element in an RC system, and it is composed of a dynamic system that can generate the desired periodic signal[12]. Figure 2.1 contains a generic block scheme composed of a positive feedback system, which allows the construction of the most relevant periodical signal generators used in RC.

$$I(z) = \frac{U_r(z)}{E(z)} = \frac{\sigma H(z)W(z)}{1 - \sigma H(z)W(z)} \tag{2.4}$$

Where $\sigma = -1, 1, W(z)$ is the time delay function, and $H(z)$ is a low-pass filter introduced to improve the system robustness.

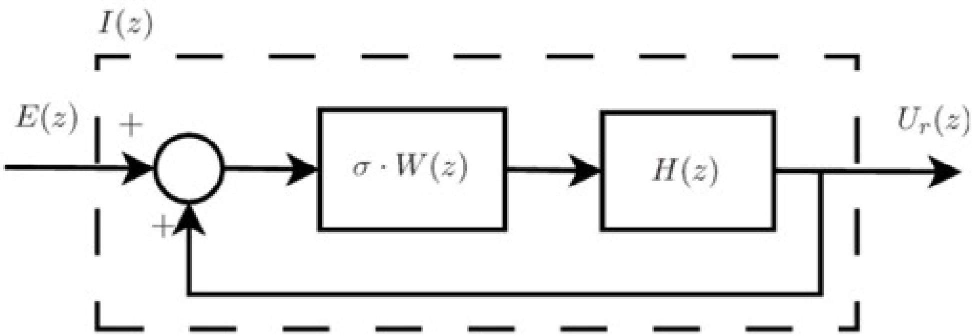

Figure 2.1: Generic periodical signal generator[12]

2.3 Constraints and Limitations

The designing and building of this project have certain limitations and constraints that are set out.

2.3.1 Constraints

- **Computational complexity**

Implementing advanced control algorithms, such as Repetitive Learning Controllers (RLCs), can be computationally demanding for resource-constrained systems like smaller inverters. Careful consideration of hardware limitations and optimization techniques is required.

- **Tuning complexities**

Choosing and tuning control parameters for optimal performance is challenging and requires expertise. Online or automatic techniques are being developed to address this.

- **Harmonic distortion**

Eliminating harmonics can be difficult for controllers, particularly in complex systems. Measures for additional filtering are necessary as harmonics can still impact grid stability.

- **Sensor limitations**

The accuracy and reliability of sensors used for feedback can greatly impact the overall performance of the control strategy. Issues such as sensor noise and calibration problems can introduce errors, such as those arising from voltage sensors and current sensors.

- **Cost considerations**

Adding advanced control algorithms and extra hardware components could increase the overall cost of the inverter system, so it's important to balance performance with cost-effectiveness.

2.3.2 Limitations

- **Dynamic grid conditions**

Although advanced control strategies can adapt to dynamic grid conditions, unexpected disturbances or abrupt changes in voltage or frequency can still pose challenges. Further research is needed to improve robustness in such situations.

- **Limited scalability**

Adapting control strategies for diverse applications may require further development, as some strategies may not scale easily for larger or more complex inverter systems.

- **Integration with other systems**

Optimal grid stability and efficiency require seamless integration of advanced control strategies with other grid management systems and communication protocols, necessitating ongoing research and collaboration.

Chapter 3

Methodology

The methodology chapter of our research project outlines the systematic approach and procedures undertaken to achieve the objectives of studying and implementing the control strategies for the single-phase grid-tie inverter, as depicted in Figure 3.1. The chapter describes the experimental setup and the steps involved in implementing and evaluating the control strategies.

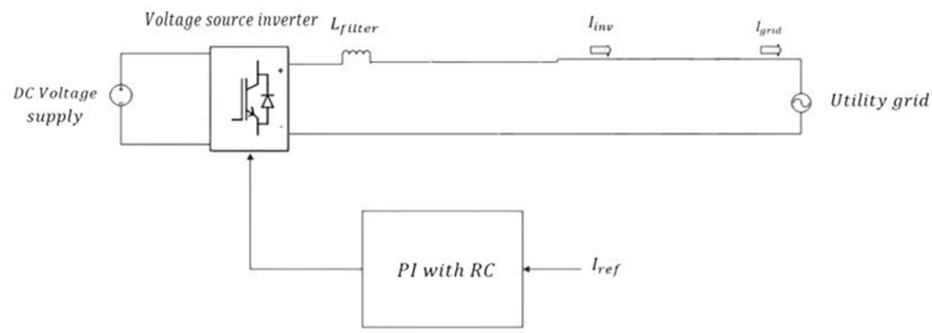

Figure 3.1: Methodology for Control Strategy Implementation

3.1 PV System

The PV system serves as the primary energy source in conventional solar power systems. However, for our investigation, we will replace the PV system with a battery-equivalent circuit. This substitution is motivated by the need to simulate secondary energy storage systems and explore the behavior of a battery-based power system in our specific project context. To begin, we designed and configured the experimental setup, consisting of a single-phase grid-tie inverter connected to a battery system.

The battery system was used as a substitute for the PV system to replicate the behavior and characteristics of the photovoltaic array. The equivalent circuit for the battery system was developed, considering the voltage and current characteristics of the PV system.

3.2 Single phase grid-connected inverter

Single-phase grid-connected inverters require the inverter, the grid, and the load as its three main parts. Figure 3.2 shows the DC voltage supply that is utilized to provide the voltage that will be sent to the voltage source inverter. For delivery into the electric grid, VSI transforms DC voltage into AC voltage. For synchronization between the inverter and the grid, this

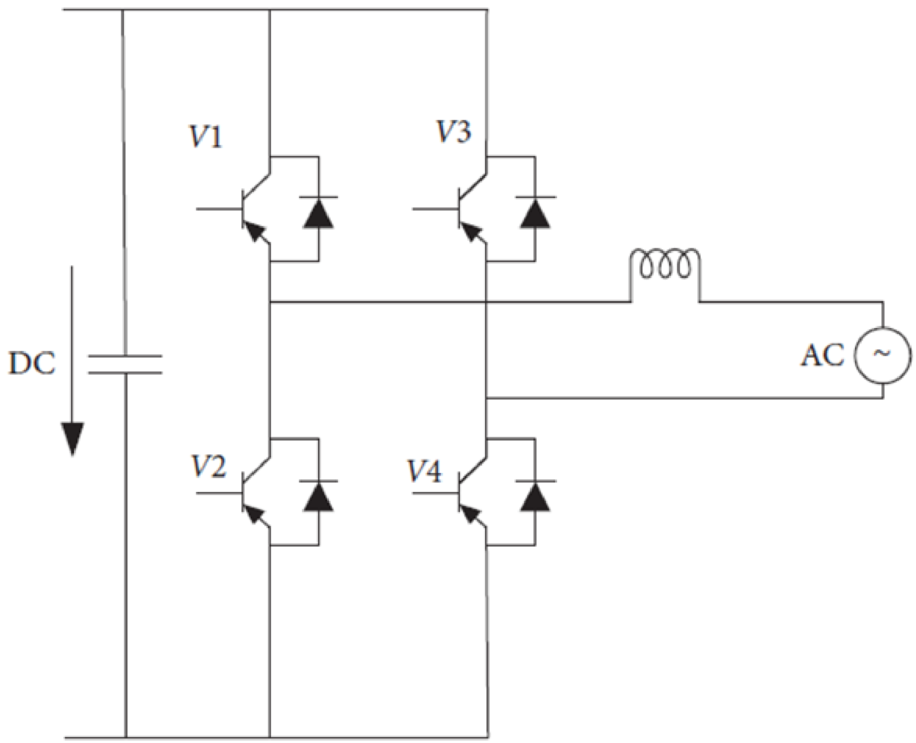

Figure 3.2: Full-bridge inverter circuit with AC

project does not require the Phase-Locked-Loop (PLL) method. This is because the reference voltage is directly taken from the grid voltage whereas the reference current is taken from the output current of the inverter. This method is more robust and constructive compared to conventional reference signal generation as this method can minimize cost and lessen the number of components such as PLL. Note that the desired voltage waveform must be obtained first to control the current waveform. The main circuit of the single-phase grid-connected inverter is

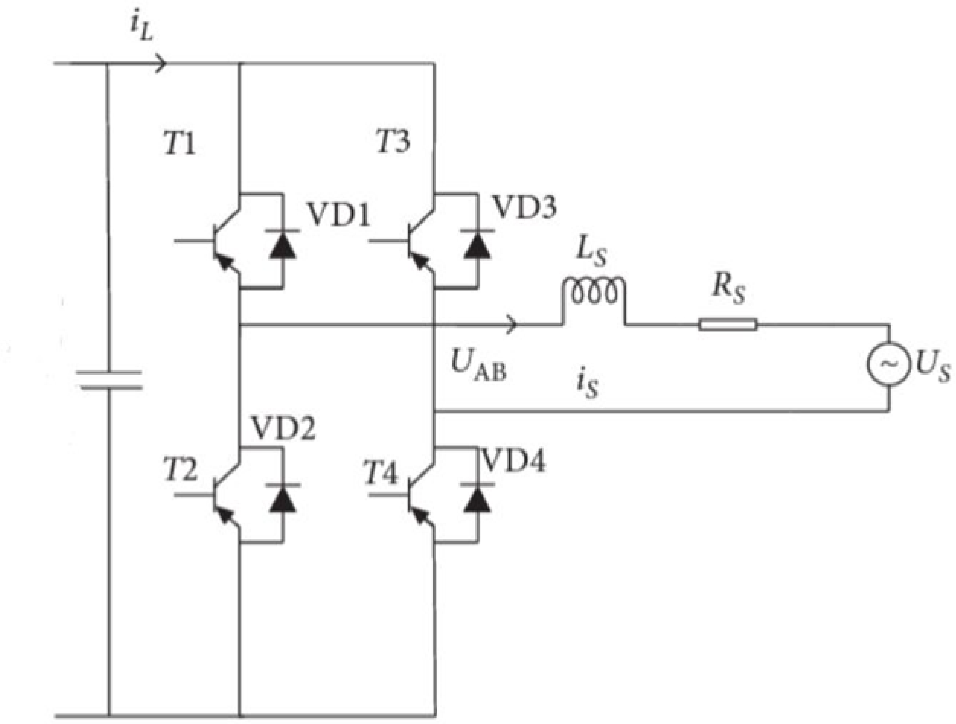

Figure 3.3: The main circuit of single phase

shown in Figure 3.3, which is a voltage-type full-bridge circuit composed of four IGBTs and continuous current diodes in reverse parallel. $T_1 - T_4$ is the IGBT, $V_{D1} - V_{D4}$ is the continuous current diode, L_s is the filter inductance on one side of the power grid, and Rs is the parasitic resistance of the filter inductance. U_s and U_{dc} are the corresponding AC power supply and DC power supply, respectively.

According to Figure 3.3, we can obtain the flowing equation:

$$L_s = \frac{di_s}{dt} = U_{AB} - U_s - R_s i_s \tag{3.1}$$

Then, we have

$$\frac{i_s(s)}{U_{AB}(s) - U_s(s)} = \frac{1}{R_s + L_s s} \tag{3.2}$$

3.2.1 α β transformation for single phase inverter

The alpha-beta transformation is a mathematical transformation that is used to convert a single-phase voltage signal into a rotating reference frame. This transformation is used in single-phase inverters to control the output voltage and current.

The alpha-beta transformation is defined by the following equations:

$$\alpha = cos(\omega t) + jsin(\omega t) \tag{3.3}$$

$$\beta = cos(\omega t - 90) + jsin(\omega t - 90) \tag{3.4}$$

where ω is the angular frequency of the voltage signal.

The alpha-beta transformation can be used to convert a single-phase signal into a two-phase signal using the following transformation matrix:

$$T = \begin{bmatrix} \alpha & \beta \end{bmatrix} \tag{3.5}$$

The resulting two-phase signal is given by:

$$\begin{bmatrix} V_\alpha & V_\beta \end{bmatrix} = T \begin{bmatrix} V \end{bmatrix} \tag{3.6}$$

Where V is the single-phase signal as shown in Figure 3.4

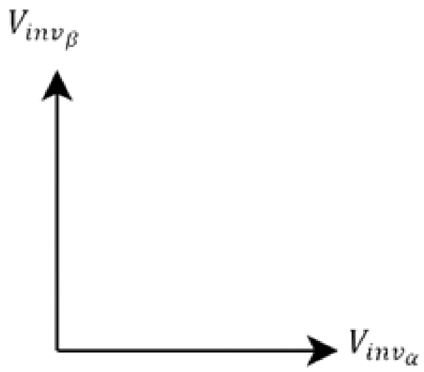

Figure 3.4: Alpha-Betta Transformation Axis

3.2.2 PQ Theory for single phase

In the context of power analysis and control, the P-Q theory for single-phase systems can be described using the alpha-beta transformation.
So now we need to determine the reference current in the alpha direction using the given expression:

$$i_{inv_{\alpha_{ref}}} = \frac{P_{ref} * V_{inv_\alpha} + Q_{ref} * V_{inv_\beta}}{V_{inv_\alpha}^2 + V_{inv_\beta}^2} \tag{3.7}$$

3.3 Proportional-Integral controller

PI controller is often employed to regulate and maintain a desired current level in a system. The PI controller takes into account the error between the desired reference current and the actual measured current to determine the appropriate control signal.
The proportional component of the PI controller responds to the instantaneous error between the reference current and the measured current. As shown in Figure 3.6, the block diagram for a PI controller multiplies the error signal by the proportional gain (K_p) to generate an output that is directly proportional to this error. The proportional gain determines the strength of this response. A higher proportional gain results in a more significant correction applied to the system based on the magnitude of the error. The following equations can be used to calculate

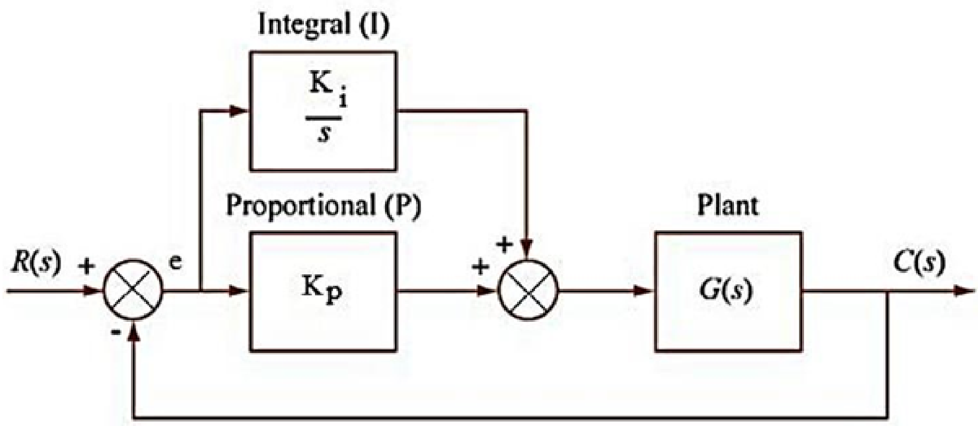

Figure 3.5: Block Diagram of PI Controller for Current Control

the proportional and integral control actions:

$$Proportional control action = k_p * Error \tag{3.8}$$

$$Integral control action = k_i * \int Error \tag{3.9}$$

where:

- k_p **is the proportional gain**
- k_i **is the integral gain**

The proportional gain and the integral gain are two tuning parameters that can be adjusted to improve the system's performance. The proportional gain controls the system's response to changes in the setpoint. The integral gain controls the system's ability to eliminate steady-state errors.
In the current controller, a comparison is made between the alpha signal and the alpha reference. The purpose is to detect the error resulting from the phase shift between the controller's output and the reference signal.

3.4 Repetitive Learning Controller

Repetitive control is a control method used to track or reject periodic signals, and it is derived from the internal model principle (IMP). The merit of the IMP lies in its ability to incorporate the generator of externally controlled signals within a stable closed-loop control system. This allows for adjustment without steady-state error and suppression of periodic interference.
when the system reaches a state of zero steady-state error, as shown in the figure representing the internal model of the repetitive controller, the input to the controller becomes zero. However, both the reference signal and the feedback signal persist, and the periodic disturbance follows the original dynamic characteristics. Nevertheless, the controller maintains its function of generating an appropriate control signal to enable continuous system adjustment without static error. This highlights the crucial role of the controller as a structural model capable of accurately reflecting and processing external signals in achieving zero steady-state error.

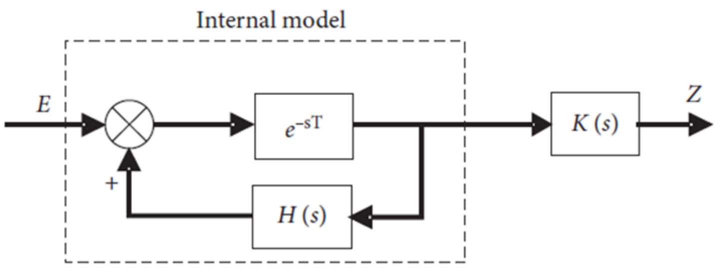

Figure 3.6: Internal Model Structure for Repetitive Control

A low-pass filter $H(s)$ is usually used to improve the robustness of controlled systems, although it may reduce the gains in these specific frequencies. is set as a second-order Butterworth filter in this paper by designing its cut-off frequency. The compensator is utilized to retain system stability when the internal model is added to the closed-loop system. Thus, the transfer function of RC is described by:

$$RC(s) = \frac{Z(s)}{E(s)} = \frac{e^{-sT}}{1 - H(s)e^{-sT}} \tag{3.10}$$

when employed in conjunction with a PI controller, a repetitive control strategy becomes a control technique specifically designed to minimize the tracking error resulting from periodic disturbances or signals within a system. As shown in Figure 3.7, the integration of a PI controller and a repetitive control scheme enables accurate tracking of a reference signal despite the presence of repetitive inputs. This combination ensures robust performance in the face of periodic disturbances, enhancing the system's ability to maintain precise tracking.

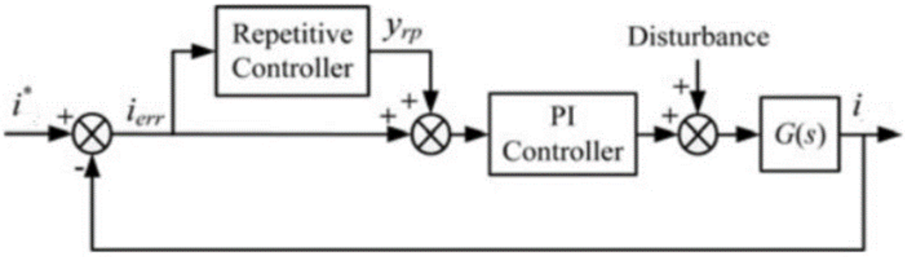

Figure 3.7: Integrated Control Scheme: Repetitive Controller and PI Controller

3.5 Design and Results

3.5.1 Simulation design

Figure 3.9 below represents the simulation design, which is focused on evaluating the performance of a repetitive control system in effectively rejecting periodic disturbances and precisely tracking reference signals. The objective of this design is to assess the system's ability to mitigate the effects of periodic disturbances and achieve accurate tracking of desired reference signals.

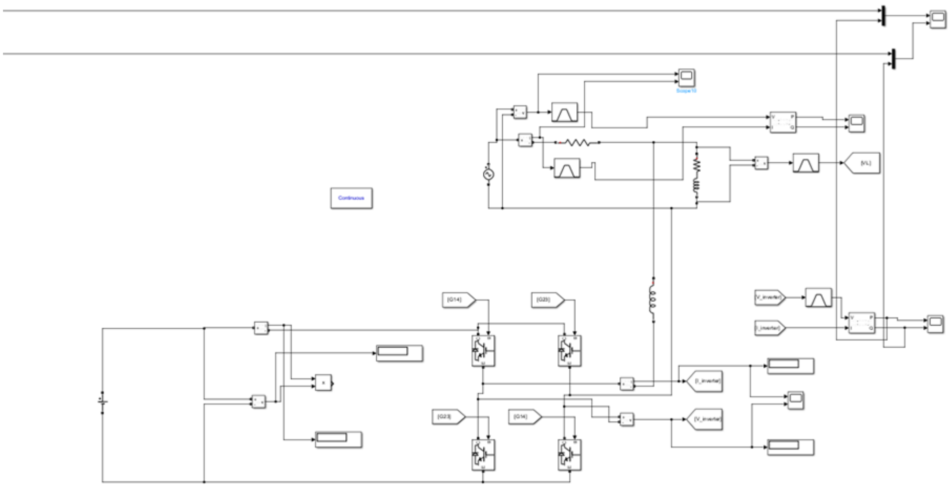

Figure 3.8: Simulation Design for Evaluating Repetitive Control Performance

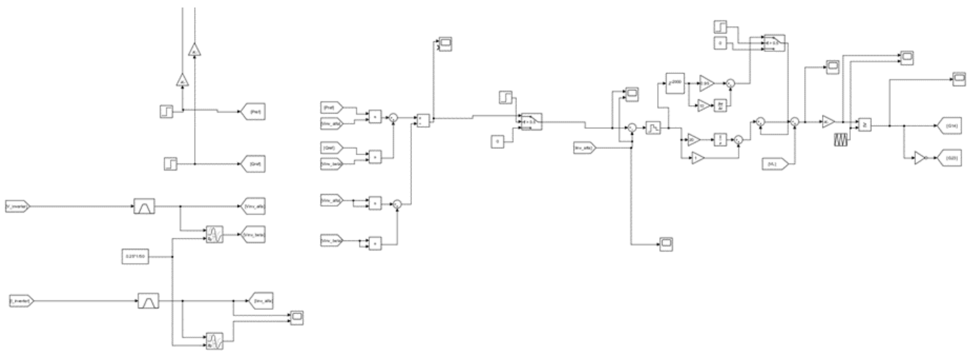

Figure 3.9: Simulation Design for Evaluating Repetitive Control Performance

System components

- **Battery**

  The system includes a battery component with a voltage rating of 230V, which serves as a vital element in the simulation design. The battery represents an equivalent component of the PV system used in the simulation. It plays a crucial role in energy storage and management within the system.

- **Single-phase grid-tied inverter**

  The single-phase grid-tied inverter in the simulation plays a critical role in converting the 400V DC power from the battery into synchronized AC power for the utility grid. It utilizes advanced control algorithms to efficiently convert the battery's DC power to AC power, ensuring effective power transfer and grid synchronization. The simulation also incorporates measurements of current and voltage to assess the inverter's performance and its impact on power generation and grid interaction. By monitoring and regulating these parameters, the inverter maintains stable operation and optimizes power flow.

- α β **Transform**

  The simulation includes the transformation of the voltage and current signals of the inverter into the alpha-beta reference frame. This transformation simplifies control algorithms and enables independent regulation of active power and reactive power. By utilizing the alpha-beta reference frame, the simulation evaluates the effectiveness of controlling these power components, ensuring efficient energy flow and power quality in the system. The incorporation of the alpha-beta transformation allows for assessing active power and reactive power control, voltage regulation, and overall system performance.

- **Repetitive Controller**

  Incorporated into the simulation is a repetitive controller component, which serves the purpose of minimizing tracking errors arising from periodic disturbances. The repetitive controller operates alongside the existing control system, continuously generating a compensating signal to effectively reduce tracking errors. To optimize its performance, the parameters of the repetitive controller undergo a trial-and-error process within the simulation. The primary objective is to achieve accurate tracking of reference signals by effectively mitigating the impact of periodic disturbances on the system.

  As shown in Figure 3.10, it is noteworthy that the samples in the simulation are shifted by 2000 samples to accommodate the inherent delay and align the compensating signal appropriately.

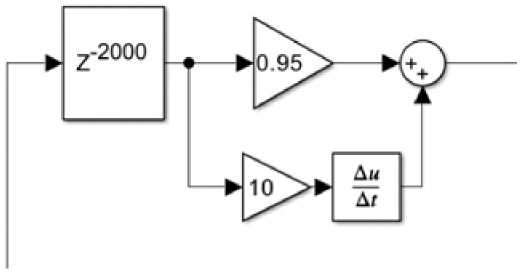

Figure 3.10: Sample Shift for Delay Compensation

- **PI Controller**

  The PI controller, as shown in Figure 3.11, plays a critical role in the simulation, facilitating precise regulation of the system's output. Through a trial-and-error process, the parameters of the PI controller are meticulously tuned to achieve optimal system performance. The controller continuously adjusts its output using proportional and integral terms, based on the error between the desired setpoint and the measured output. This iterative parameter tuning, as illustrated in the figure, ensures system stability, rapid response, and accurate tracking of the setpoint. Incorporating the PI controller and its parameter-tuning process into the simulation allows for a visual representation of the controller's impact on the system's output regulation.

$$k_i = 20 \; k_p = 1$$

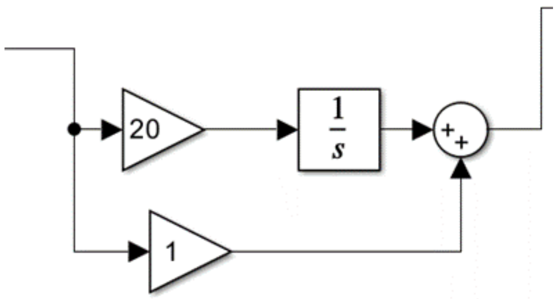

Figure 3.11: PI Controller Integration and Parameter Tuning in the Simulation

- **Pulse Width Modulation**

  In the simulation, as shown in Figure 3.12, the output of the PI controller is fed into a comparator to generate pulse width modulation (PWM) signals. These PWM signals, as depicted in the figure, control the behavior of the inverter by adjusting the width of the pulses. Through pulse width modulation, the PWM signals regulate the inverter's output voltage and frequency, ensuring proper synchronization with the utility grid and accurate power delivery. The inclusion of the comparator and PWM generation, as shown in the figure, allows for an evaluation of the control signal's effectiveness in controlling the inverter's behavior. Additionally, the PWM signals in the simulation operate at a switching frequency of 5 kHz, as indicated in the figure. This specific switching frequency, as depicted in the figure, determines how rapidly the inverter's power devices switch on and off. By incorporating this 5 kHz switching frequency in the simulation, as shown in the figure, the behavior of the inverter accurately reflects high-speed switching characteristics, allowing for an assessment of its impact on the system's performance.

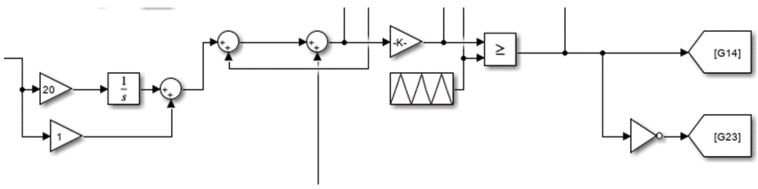

Figure 3.12: Block Diagram of PWM Generation for Inverter Control

Simulation results and discussion

Parameters	Value
Grid phase voltage (V)	230
DC side voltage (V)	400
Switching frequency $f_s(kHz)$	5
Filter inductance $L_s(mH)$	1.5
Input voltage frequency $f(Hz)$	50

Table 3.1: The simulation parameters

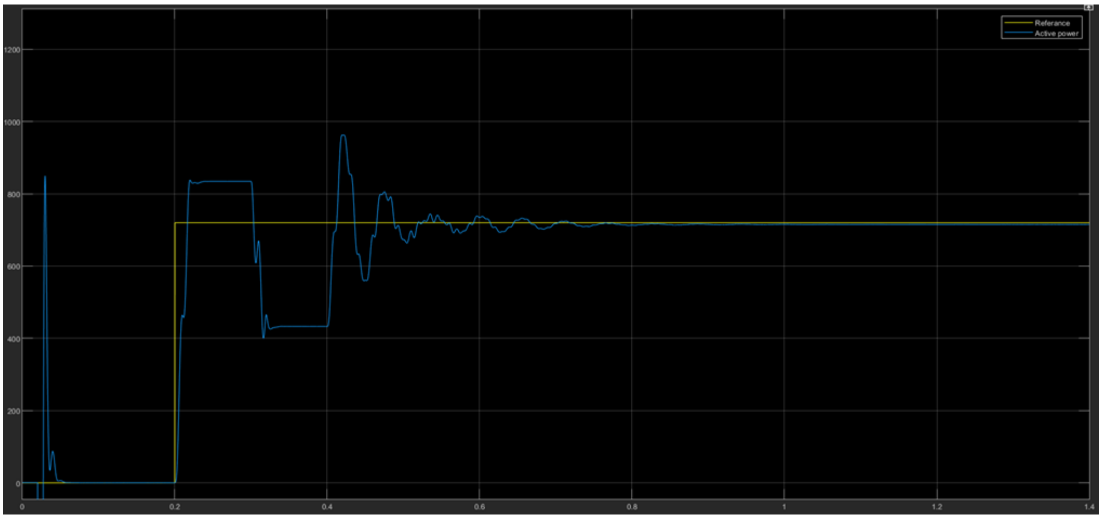

Figure 3.13: Comparison of Error and Real Power Before and After Repetitive Controller Operation.

Figure 3.13 presented provides a comparative analysis of the error prior to 0.4s, representing the period before the operation of the repetitive controller, and the subsequent behavior. It is evident from the figure that the error is noticeably minimized once the repetitive controller becomes active. Furthermore, the figure also demonstrates the impact of the repetitive controller on real power. By incorporating the repetitive control strategy, the real power is effectively regulated and maintained within desirable levels, contributing to enhanced system performance and improved power quality.

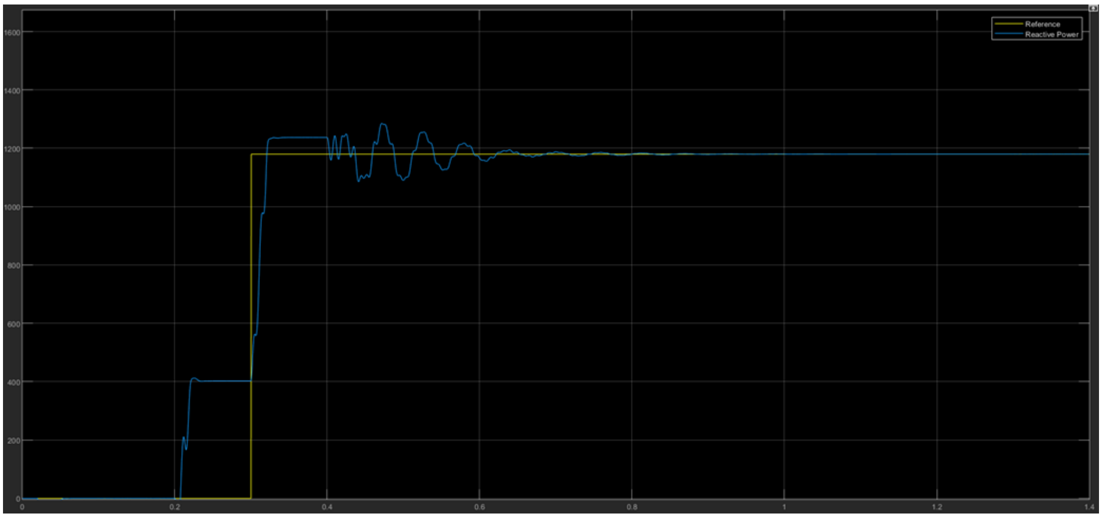

Figure 3.14: : Comparative Analysis of Reactive Power Improvement and Error Minimization with Repetitive Controller Operation.

Additionally, Figure 3.14 reveals a similar trend in the improvement of reactive power after 0.4s, coinciding with the activation of the repetitive controller. The reduction in error is evident, showcasing the effectiveness of the repetitive controller in minimizing deviations and optimizing the system's reactive power dynamics. This highlights the role of the repetitive controller in achieving precise control and regulation of reactive power, contributing to enhanced system stability and power quality.

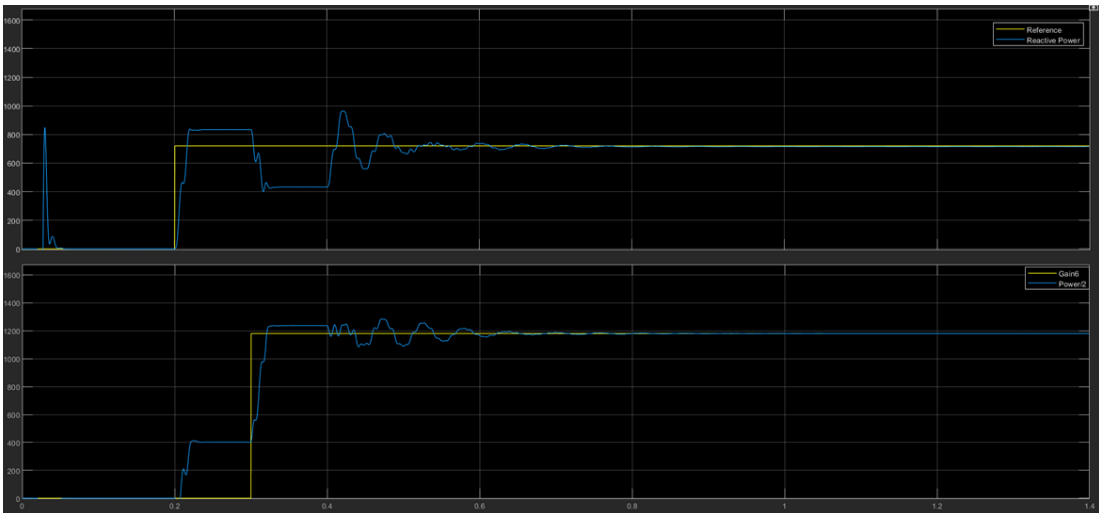

Figure 3.15: Active and Reactive Power Injection and its Impact

Figure3.15 illustrates the behavior of active and reactive power injection in the system. At 0.25s, when we inject real power, it has an impact on the reactive power as well. Similarly, when we inject reactive power, it affects the active power. However, after 0.4s, the repetitive controller starts operating and significantly reduces this mutual effect. As a result, the deviation in both active and reactive power is minimized, leading to improved power quality and stability in the system. Additionally, it is important to note that the integration of the repetitive controller effectively mitigates the unwanted interactions between active and reactive power, allowing for more precise control and better regulation of power flow. This highlights the significance of utilizing the repetitive controller in minimizing the influence of injected power on both active and reactive components, ensuring optimal system performance and power delivery.

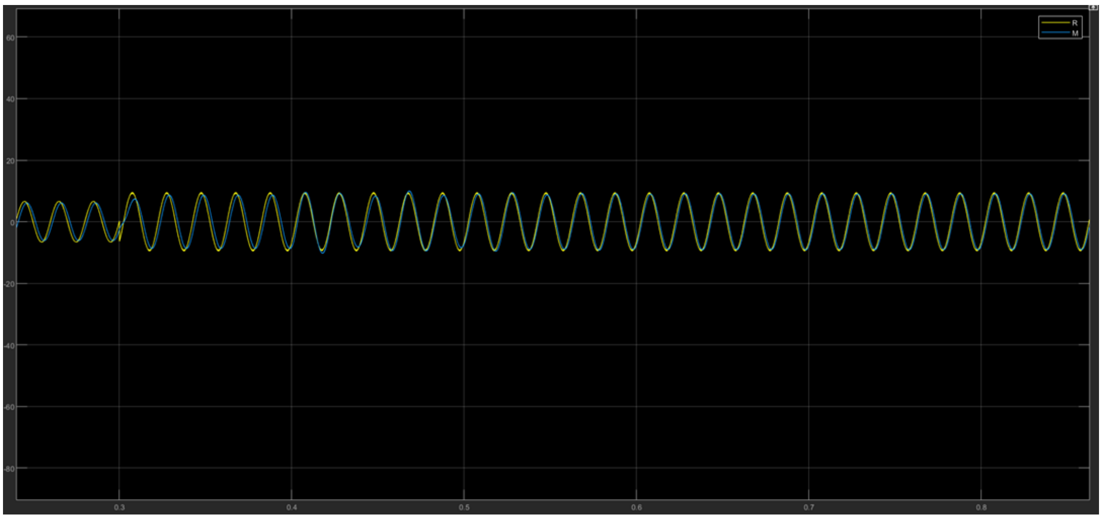
Figure 3.16: Alignment of Measured and Reference Currents with Minimized Phase Shift

As shown in Figure 3.16, we can observe a significant reduction in the phase shift between the measured current and the reference current. This reduction is crucial for optimizing the real and reactive power components of the system. The alignment of these currents minimizes power losses and ensures efficient power generation and consumption. Furthermore, the figure demonstrates that the samples are shifted by 2000 samples to accurately capture the alignment and synchronization of the currents, as indicated by the vertical lines in the plot. This precise alignment allows for precise control and improved system performance.

3.5.2 Hardware implementation

Parts

- **Microcontroller**
  The microcontroller selected for this project is the Arduino Mega 2560, an integral part of the open-source electronics prototyping platform known for its adaptability and user-friendly interface. Arduino boards, including the Mega 2560, are proficient in converting various inputs, such as sensor readings, into actionable outputs, like motor activation. What sets the Mega 2560 apart is its vast array of built-in libraries and the capability to seamlessly incorporate external libraries, thereby enhancing the Arduino development environment. Notably, the Mega 2560 offers PWM (Pulse Width Modulation) pins, ranging from pins 2 to 13 and pins 44 to 46. These PWM pins play a pivotal role in generating analog-like outputs through digital means. In the context of this project, precise control and modulation of analog signals are facilitated by utilizing PWM pins, specifically pins 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13, along with pins 44, 45, and 46. This capability proves instrumental in effectively interfacing with a diverse range of electronic components, such as motors or any other devices requiring adjustable analog signals.

Figure 3.17: Arduino Mega 2560

- **H–Bridge**

  The H-bridge employed in this project is the L298N, a circuit capable of driving current in either polarity, controllable through Pulse Width Modulation (PWM). With a peak current rating of 2A, well within the project's specified constraints, the L298N proves to be a highly suitable choice. As illustrated in Figure 3.18, the L298N module comprises two H-bridges. Its operation involves the reception of two input signals, In1 and In2, set in opposition to each other. This configuration results in a square wave voltage waveform across the load, which, in this particular project, is maintained at 12V. The versatility of the L298N's H-bridge design and its compatibility with PWM make it an effective component for controlling current direction and magnitude, crucial for various applications within the project's scope.

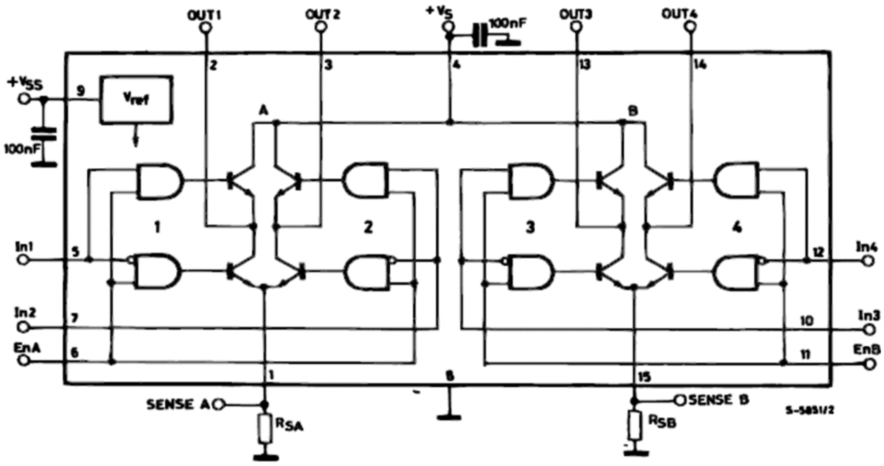

Figure 3.18: L298N H-bridge module internal structure

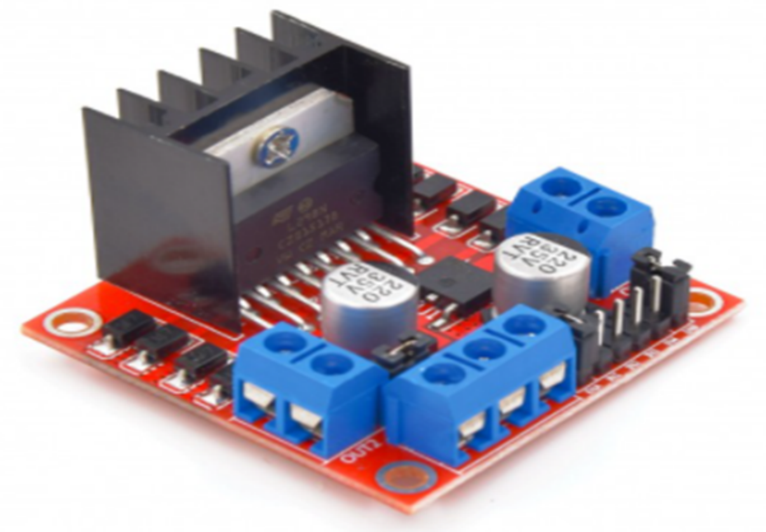

Figure 3.19: L298N H-bridge module

- **Current Transformer**

  The current sensor employed in this project is the ZMCT103C module, designed to accurately detect alternating current (AC). With its capability to measure AC up to 5A, the ZMCT103C proves to be a versatile component for current monitoring applications. The sensor outputs an analog voltage in the range of 0 to 5V, directly proportional to the current flowing through the connected wire. This analog signal can be easily interfaced with any microcontroller through an analog input port. Featuring two Phoenix terminal connectors, the ZMCT103C allows seamless integration into the circuit by connecting in series. On the opposite side, the module includes three pins: VCC and GND for powering the board, and an output pin providing the analog voltage signal. This straightforward design facilitates the integration of the ZMCT103C into the project, enabling accurate and efficient monitoring of current levels within the specified range.

Figure 3.20: ZMCT103c current sensor

- **Voltage Sensor**

  A voltage sensor is a sensor used to measure and monitor the amount of voltage on a specific element of a circuit. The module used for this project is the A01B single-phase voltage transformer shown in Figure 3.21 because of its suitable specifications (measures up to 250V AC).

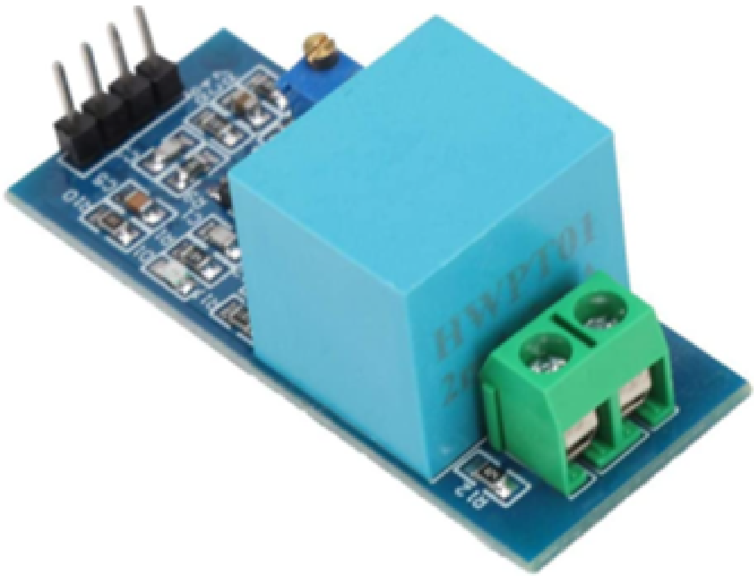

Figure 3.21: A01B voltage sensor

- **Transformer**

  A transformer is a static electrical device that transfers energy by inductive coupling between its winding circuits. Varying current in the primary winding creates a varying magnetic flux in the transformer's core and, thus, a varying magnetic flux through the secondary winding. This varying magnetic flux induces a varying electromotive force (E.M.F.) or voltage in the secondary winding. The transformer used here is a step-up transformer from 12V to 220V; it is used to step up the voltage from the output of the H-bridge to be able to deliver the appropriate voltage to meet the source voltage.

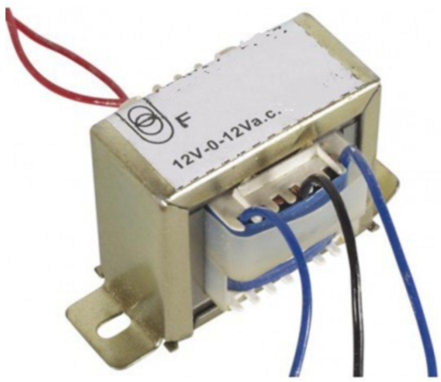

Figure 3.22: 12V–0–12V transformer

3.5.3 Hardware Hardware Design

Current Sensor and Voltage Sensor Testing

Before presuming real readings, both sensors need to be tested by connecting them, as shown in Figure 3.23.

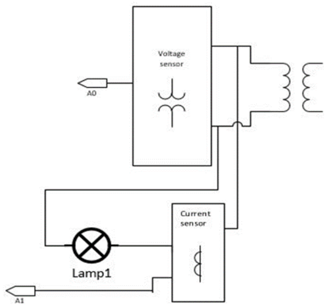

Figure 3.23: Current sensor and voltage sensor connection with an AC voltage source and a linear load

The output of both sensors was connected to analog Arduino pins to be viewed on the serial plotter, and the results in Figures 3.24 and 3.25 were obtained.

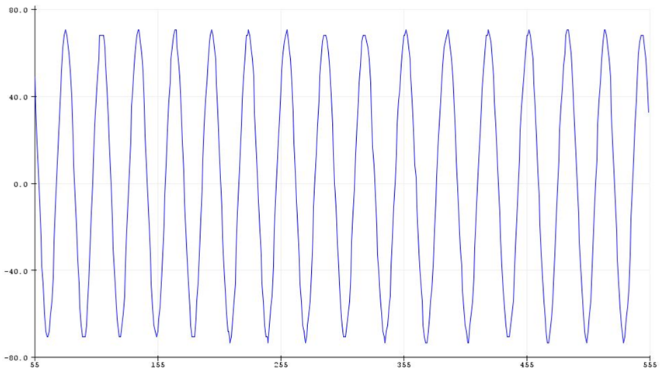

Figure 3.24: Voltage measurement

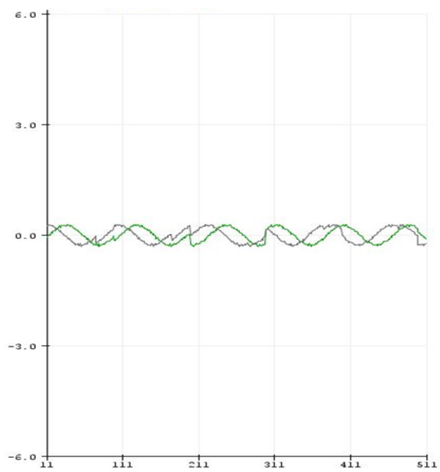

Figure 3.25: Current measurement (green) and a shifted signal achieved by code (blue)

H–Bridge Testing

The H-bridge module necessitates dual DC power sources: a 5V supply to energize the board and a 12V supply to energize the bridge component. Appropriate Arduino code was employed to furnish the requisite input signals for the bridge. To verify the correct functioning of the module, the two outputs from the H-bridge were directed into a picoscope. The observed output range was approximately [-12V, 12V], as depicted in Figure 3.26. Additionally, a PWM signal was generated and directed to the H-bridge as part of the operational setup 3.27.

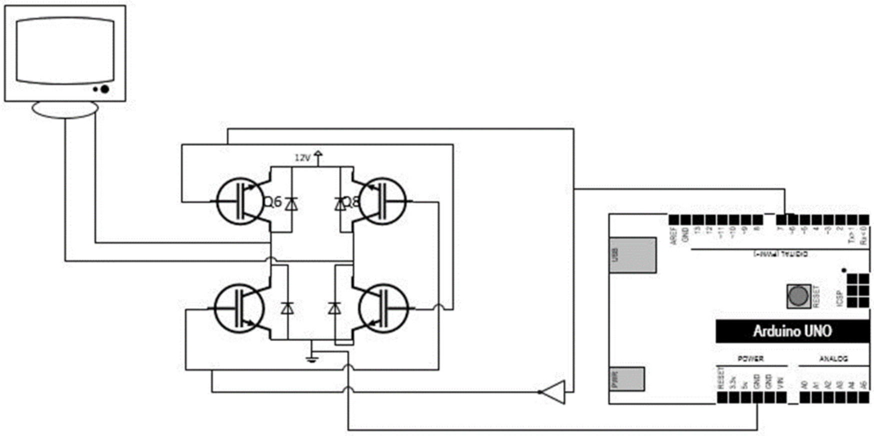

Figure 3.26: H–bridge connected with picoscope

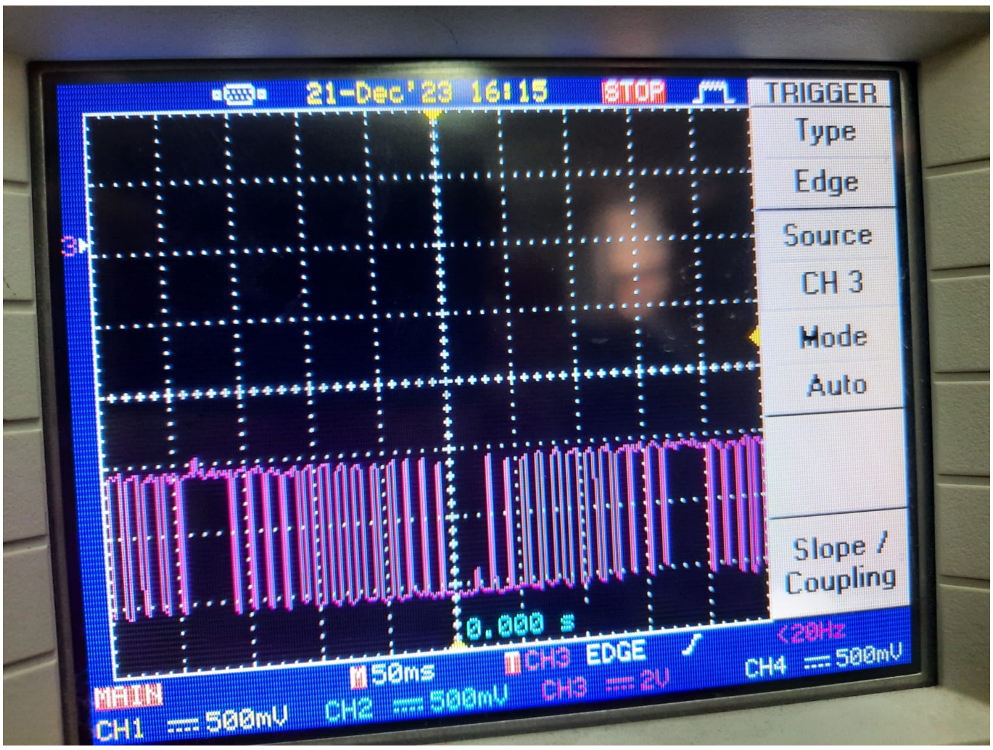

Figure 3.27: Pulse Width Modulation waves applied to the Inverter

Transforming current and voltage into an alpha-beta axis.

We configured the microcontroller to operate within an interrupt service routine (ISR), strategically optimizing its performance. Within this framework, as shown in the figures 3.28 and 3.29, we proceeded to transform the acquired voltage and current data into the alpha-beta axis. This transformation enhances precision and facilitates subsequent analysis within the designated system.

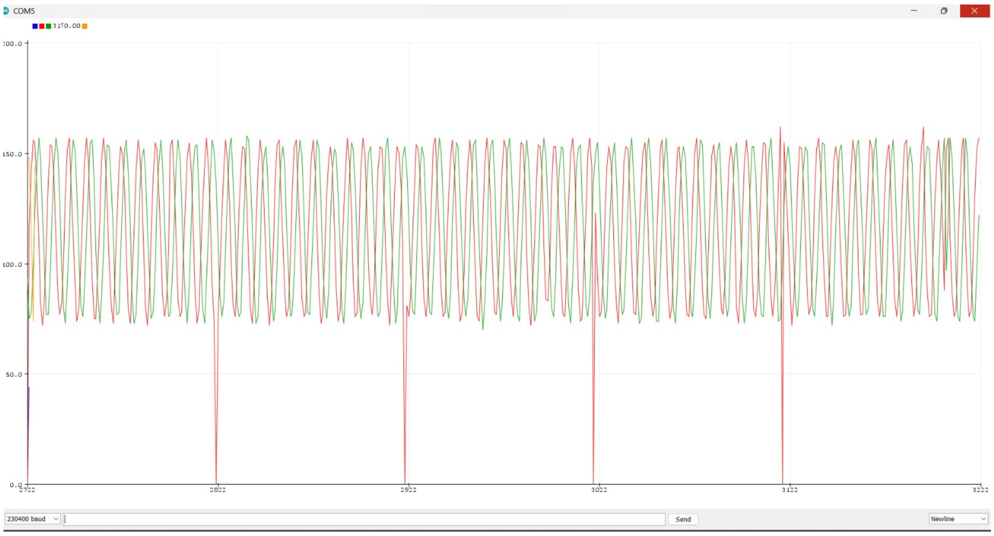

Figure 3.28: Iref alpha-beta waveforms

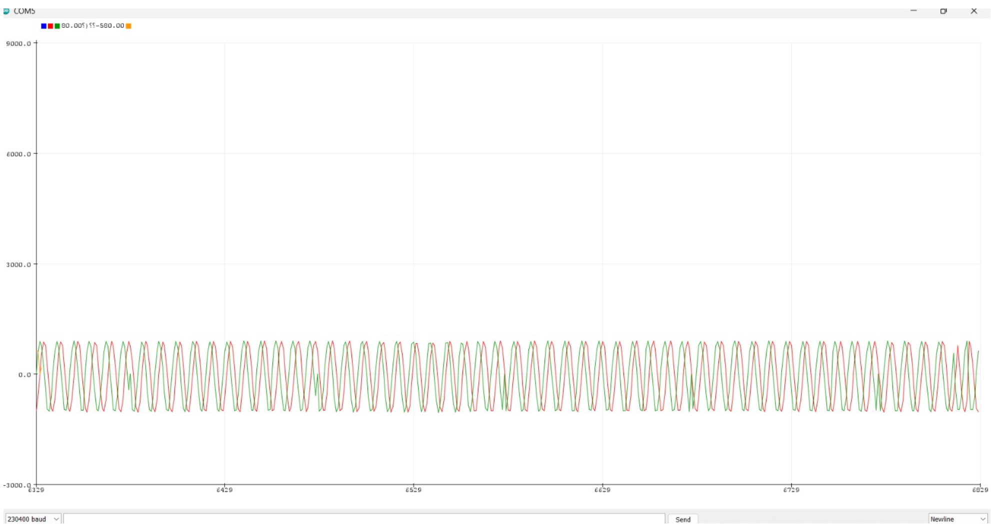

Figure 3.29: Vref alpha-beta waveforms

Regrettably, due to the prevailing war in Gaza, our project has been interrupted, and we are unable to proceed further. The challenging circumstances have restricted our time and impeded our ability to access the university workshop. Under these conditions, we must rely solely on the simulation results for the project, as physical implementation is presently unfeasible. We appreciate your understanding during these challenging times and hope for a resolution to the current situation soon.

Chapter 4

Conclusion and Discussion

4.1 Discussion

In the field of integrating photovoltaic power, inverters play a crucial role in converting the direct current (DC) voltage generated by PV systems into the alternating current (AC) voltage that is required for the grid. Previously, inverters used hysteresis to regulate real and reactive power injection. However, our project introduces a new hybrid control strategy that combines the established PI controller with a new addition: the repetitive controller. This innovative approach promises to significantly improve the efficiency and reliability of inverters, thus contributing to the advancement of photovoltaic power integration technology.

The PI controller, known for its adaptability, works with the repetitive controller to control real and reactive power in a nuanced manner. While the PI controller adjusts dynamically to changing power demand, the repetitive controller acts as a vigilant guardian, ready to compensate for any errors during the tracking of the sinusoidal reference.

The adoption of advanced control techniques indicates a significant step towards precision in our operations. This is expected to bring about substantial improvements in the quality and efficiency of our system. The PI controller, with its real-time responsiveness, facilitates our system's ability to cope with fluctuations effectively. On the other hand, the repetitive controller is an expert in error correction, ensuring prompt and effective resolution of any deviations in tracking the sinusoidal reference.

4.2 Future Work

- **Short-term future work**

In the near future, our primary objective is to prioritize the optimization and fine-tuning of our hybrid control strategy. We must conduct extensive experimental validations and simulations to gain a deeper understanding of how the PI controller and repetitive controller integration perform in real-world situations. It is imperative that we proactively address any unforeseen challenges and continue to improve the system's responsiveness. Moreover, we need to evaluate the hybrid control strategy's effectiveness in diverse environmental and grid conditions to enhance its resilience and dependability.

- **Long-term future work**

Looking towards the future, our focus will be on expanding the applications and scalability of our hybrid control strategy. This could involve adapting the approach for multi-phase systems or complex grid architectures. To meet the evolving demands of power grids, enhancing the adaptability of the PI controller and refining the learning capabilities of the repetitive controller will be essential. Additionally, exploring the integration of emerging technologies like artificial intelligence or machine learning could lead to even more sophisticated and autonomous control strategies. Ongoing research and development will be necessary to ensure our hybrid control strategy stays at the forefront of sustainable and resilient photovoltaic system integration into the grid.

4.3 Recommendations

To improve the robustness and applicability of the control system designed for a single-phase grid-tie inverter, the following recommendations are proposed:

- **Parameter Optimization**

Conduct an in-depth analysis of PI and repetitive controller parameters. Optimize systematically to fine-tune these parameters for optimal balance and peak performance across various scenarios.

- **Energy Storage Integration Trial**

Assess the impact of incorporating energy storage devices on system stability, response times, and overall reliability.

4.4 Conclusion

Our research into control strategies for single-phase grid-tie inverters represents a notable accomplishment. Not only has it resulted in achieving near-zero errors in active and reactive power control, but it has also enabled seamless injection of both powers without any interference. This dual capability holds significant practical implications beyond academic circles, particularly in scenarios where uninterrupted injection of both active and reactive power is essential. We anticipate that continued optimization of existing strategies and further research will lead to even greater improvements in the efficient and independent control of active and reactive power.

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Appendix

Table 1: Evidence Table

Study	Methodology	Magnitude of Benefit	Citation	Year
[1]	Experimental	2/5	Low	2018
[2]	Field Study	2/5	Low	2021
[6]	Simulation	3/5	High	2019
[4]	Simulation	3/5	Low	2021
[5]	Field Study	2/5	Low	2018
[10]	Simulation	4/5	Low	2018
[7]	Field Study	2/5	Low	2018
[8]	Simulation	3/5	Low	2022
[9]	Experimental	3/5	High	2020
[12]	Experimental	4/5	Low	2018