

An-Najah National University



Faculty of Engineering & Information Technology

Electrical Engineering Department

**Improve the Stability and Performance of the Power Grid under
Changing Power Generation According to Dynamic Load**

Students:

Ghena Farouq

Tariq Dumaide

Mohammad Qasem

Mohammad Tubileh

Supervisor Name:

Eng. Omar Tamimi

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Abstract

This project addresses the critical challenge of maintaining power grid stability under the pressures of intermittent renewable energy integration and dynamic load demands. The primary objective is to design, simulate, and implement a single-phase grid-tied inverter capable of controlling active and reactive power to mitigate overvoltage issues. The system features a full-bridge topology controlled by an STM32 microcontroller, employing Sinusoidal Pulse Width Modulation (SPWM) and a closed-loop current control strategy. A real-world case study using CYME software identified critical overvoltage nodes, validating the necessity of smart inverter functions such as Q(V) control. The control logic was verified through LTspice simulations, confirming unity power factor operation and low harmonic distortion. Practically, a hardware prototype was assembled, featuring isolated sensing and gate drive circuits. Experimental results verified the microcontroller's ability to generate precise, synchronized control signals, laying the foundation for a robust smart inverter capable of enhancing grid resilience.

Keywords: Grid-Tied Inverter, Power Grid Stability, Active and Reactive Power Control, Overvoltage Mitigation, STM32 Microcontroller, CYME Simulation, LTspice.

الملخص

يعالج هذا المشروع التحدي الجوهرى المتمثل فى الحفاظ على استقرار شبكة الطاقة الكهربائية فى ظل الضغوط الناتجة عن دمج مصادر الطاقة المتجددة المتقطعة ومتطلبات الأحمال الديناميكية المتغيرة. الهدف الأساسى للمشروع هو تصميم ومحاكاة وتنفيذ عاكس أحادى الطور متصل بالشبكة (Single-phase Grid-tied Inverter) قادر على التحكم فى القدرة الفعالة وغير الفعالة للتخفيف من مشاكل ارتفاع الجهد (Overvoltage). يتميز النظام بتوبولوجيا القنطرة الكاملة (Full-bridge) التى يتم التحكم فيها بواسطة متحكم دقيق من نوع STM32، باستخدام تقنية تعديل عرض النبضة الجيبى (SPWM) واستراتيجية تحكم فى التيار مغلقة الحلقة (Closed-loop current control).

تم إجراء دراسة حالة واقعية باستخدام برنامج CYME لتحديد نقاط ارتفاع الجهد الحرجة فى الشبكة، مما أكد ضرورة استخدام وظائف العاكس الذكى مثل التحكم فى الجهد عن طريق القدرة غير الفعالة $Q(V)$. تم التحقق من منطق التحكم من خلال عمليات المحاكاة باستخدام برنامج LTspice، والتى أكدت تشغيل النظام عند معامل قدرة موحد (Unity P.F.) مع انخفاض فى التشوه التوافقى. من الناحية العملية، تم تجميع نموذج أولى للأجهزة يتضمن دوائر استشعار وقيادة بوابة معزولة جلفانياً. وقد أثبتت النتائج التجريبية قدرة المتحكم الدقيق على توليد إشارات تحكم دقيقة ومتزامنة مع الشبكة، مما يرسخ الأساس لبناء عاكس ذكى قوى قادر على تعزيز مرونة الشبكة الكهربائية.

الكلمات المفتاحية: العاكس المتصل بالشبكة، استقرار شبكة الطاقة، التحكم فى الطاقة الفعالة وغير الفعالة، التخفيف من الجهد الزائد، وحدة التحكم الدقيقة STM32، محاكاة CYME، محاكاة LTspice.

Chapter 1: Introduction

1.1 Background

In modern societies, the electrical power grid is one of the most important infrastructures that are required to provide continuous and stable energy supply to the consumers. The safety and efficiency of the electrical system depended on the stability of the power grid under varying generation and load conditions. Initially, power generation was centralized and predictable; with greater penetration of renewables, mainly solar energy, newer challenges for grid stability emerged.

Due to the weather conditions and varying availability of sunlight, solar energy systems are variable in nature. These variations result in unpredictable power injections into the grid, thereby creating imbalances between generation and consumption. One of the major problems is the increase in voltage levels across distribution networks during excessive generation that can severely damage electrical equipment and undermine the grid's reliability.

To address the problems, grid tied inverters have evolved to be crucial in power setups today. The main functions of grid-tied inverters are to convert the DC power supplied by the solar panels into AC power compatible with the grid and actively interface with the grid by controlling actual power, reactive power, and power factor. Using these features, grid-tied inverters should manage the voltage, power balance, and support the network's overall stability.

The project presents a design and implementation of a grid-tied inverter able to stabilize the grid under dynamic load and generation conditions. By the employment of advanced PWM techniques, the inverter adjusts the output to control excess generation, keep voltage levels within safe limits, and protect consumer loads as well as itself. Thus, the development of the grid becomes more robust and adaptive toward the seamless integration of renewable energy sources, without compromising its stability.

1.2 Problem Description

The stability and dependability of the grid are facing serious challenges as a result of the growing integration of renewable energy sources, especially photovoltaic solar systems, into the electrical distribution network. When the amount of power injected into the grid surpasses the demand for local consumption one of the most serious problems occurs. Unusual voltage increases across distribution lines, especially at the end-user side, are caused by this imbalance. Overvoltage situations can seriously harm electrical appliances, shorten equipment lifespans, and compromise the grid's ability to function.

Furthermore, the dynamic fluctuations brought about by distributed generation sources are frequently too great for traditional protection schemes to handle. By continuously injecting power without take into account the current grid conditions, improperly controlled grid-tied inverters can make these instabilities worse. The networks voltage profile is impacted, and overvoltage or overcurrent events may cause inverter protective shutdowns, disrupting power flow and lowering system resilience overall.

The development of a grid-tied inverter system that can dynamically control real and reactive power based on the current grid state is therefore urgently needed. In order to guarantee dependable and continuous operation, such a system would actively participate in voltage regulation, keep the power factor within reasonable bounds, and include self-protection mechanisms. In order to safely and effectively integrate renewable energy into contemporary power systems while safeguarding consumer loads and preserving grid stability overall, these issues must be resolved.

1.3 Project Goals

Designing, implementing, and assessing a grid-tied inverter system that can improve the electrical grid's performance and stability under various load and generation scenarios is the main goal of this project. In addition to supplying electricity to the grid, the inverter must actively support grid protection, reactive power compensation, and voltage regulation.

The project specifically aims to accomplish the following objectives:

1. Design and Construction of a Grid-Tied Single-Phase Inverter.
2. Create a workable inverter system with dynamic control, protection, and dependability that can replicate actual grid situations.
3. Putting the PWM-Based Control Strategy into Practices.
4. To ensure stable operation, use Pulse Width Modulation (PWM) techniques to precisely control the inverter's output in terms of real and reactive power.
5. Protect consumer appliances and preserve power quality by actively controlling the inverter's contribution to the grid to avoiding hazardous voltage increases in the distribution loads.
6. Surplus Energy Management: Create control systems that keep the grid stable during periods of, excess power generation, preventing network outages or inverter shutdowns.
7. Improving System Resilience: Put protection circuits in place to guard against inverter damage and guarantee uninterrupted operation even in the event of unfavorable grid events.

1.4 Importance of the Study

This study is important, because of the challenges faced by modern electrical grids due to a faster integration of renewable energy resources.

cause of increasing penetration of renewables, the traditional top-down generation model stilted down to the distributed and dynamic systems. With these new complexities arise in the operation, particularly concerning voltage control, load balancing, and protection the system.

In the absence of active real and reactive power control in the interconnection points, grids can have:

1. **High Voltage Events:** causing failures of the devices and disruptions of the power supply.
2. **Reduced Power Factor:** Inefficient operation of the grid and presence of greater losses.
3. **Instability and Protection Tripping:** prominent disconnections and issues in reliability.

the project directly addresses those counteracting factors, providing a low-cost, scalable, and adaptable method for control via grid tied inverters.

Stabilizing the voltage magnitude and restoring the reactive power support would protect consumer equipment and provide some measure of reactive power support needed by the stronger grid to accommodate fluctuating renewable generation.

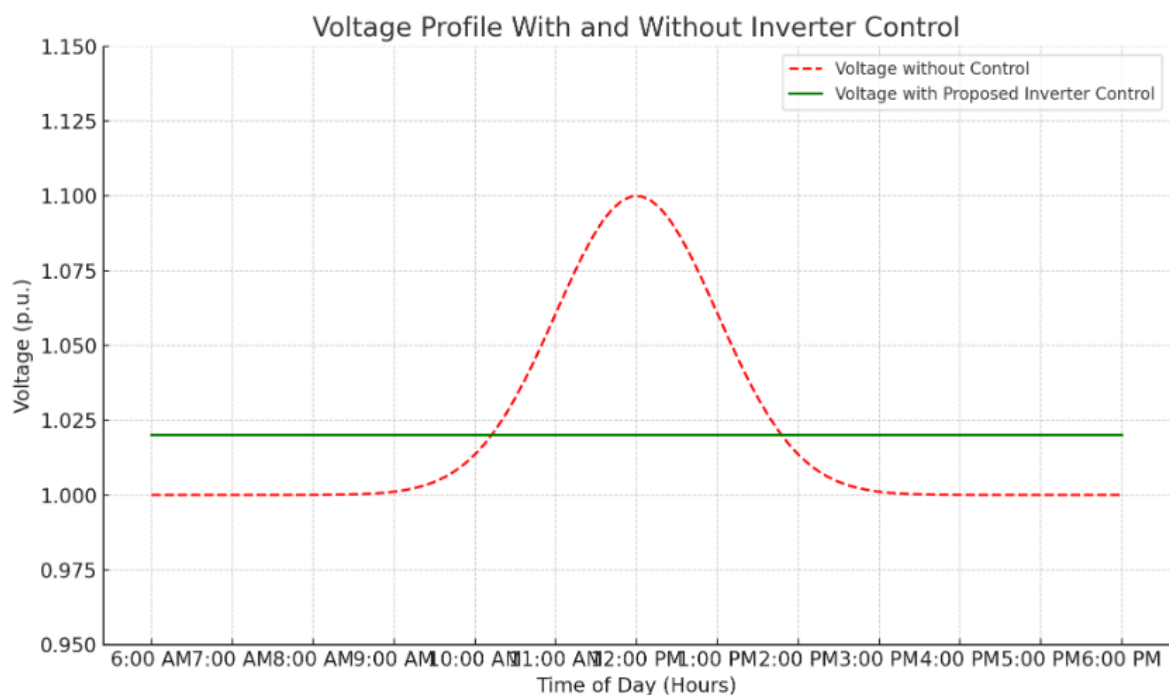


Figure 1.1: voltage profile with and without inverter control

Table 1.1: Comparison Between Traditional and Controlled Grid Conditions

Aspect	Grid with Controlled Inverter	Traditional Grids without control
Voltage Fluctuations	Low and regulated	High and Unstable
Equipment Protection	Strong	Poor
Renewable Energy Accommodation	Enhanced	Limited
Power Factor	High and optimized	Low

1.5 Project Scope

The goal of this project is to design, implement, and test a single-phase grid-tied inverter that will stabilize grid performance in the event of surplus generation and dynamic loading. During grid disruptions, a main focus is on inverter self-protection, reactive power compensation, and voltage regulation.

The following tasks are included in the project's scope:

- **Design and Assembly:** Creation of a workable single-phase inverter system that can communicate with a grid simulator that operates at low voltage.
- **Implementation of Control:** Using (PWM) techniques, real and reactive power are dynamically controlled according to grid conditions.
- **Monitoring voltage and power quality:** involves measuring and assessing the inverter's capacity to control voltage and keep power factor within reasonable bounds under various load conditions.
- **Hardware protection:** use of fundamental safeguards to prevent the inverter from disconnecting or failing due to overvoltage or overcurrent situations.
however, the project is purposefully constrained in a number of ways to align with the academic framework and the resources that are available:
- **Only One Phase:** While commercial implementations frequently use three-phase systems, the project is limited to a single-phase system.
- **Laboratory Environment:** Rather than being deployed in the real world on an operational distribution network, testing and evaluation are carried out in a controlled laboratory setting using simulated loads and generation profiles.
- **Energy Storage Exclusion:** While future research recommends using energy storage devices (like batteries), the design and integration of storage systems are not included in the current project scopes.

Note: This project is not designed to support advanced features like dynamic frequency control, grid synchronization under islanding conditions, or large-scale multi-inverter coordination.

1.6 Organization of the Report

From the initial background and problem identification to the final results and recommendations, the report is organized into eight main chapters and a technical appendix, detailed as follows:

Chapter 1: Introduction

This chapter provides an overview of the project's background, problem identification, objectives, significance of the study, project scope, and the report structure.

Chapter 2: Literature Review and Theoretical Background

This chapter establishes the theoretical foundation by reviewing grid stability challenges caused by renewable energy and dynamic loads. It compares solar system types (on-grid, off-grid, hybrid) and inverter technologies, identifying the research gap regarding the combined impact of fluctuating generation and dynamic loads.

Chapter 3: Methodology and System Design

This chapter details the system design specifications and control strategies, including PWM techniques and smart inverter functions (P(V)/Q(V)). It presents a case study using CYME software to simulate real-world grid conditions, identifying overvoltage issues and validating the proposed control logic.

Chapter 4: Electrical Circuit Description and Functional Analysis

This chapter presents the comprehensive hardware design. It details the schematics of critical subsystems, including the isolated auxiliary power supply, the STM32-based digital control unit, the galvanically isolated gate drivers, the full-bridge power stage, and the LCL output filter design.

Chapter 5: Control Loop Design and Simulation

This chapter details the development and verification of the closed-loop control system using a Model-Based Design (MBD) approach in LTspice. It validates the PI compensator design, SPWM generation, and grid synchronization logic through time-domain simulations and FFT analysis.

Chapter 6: Hardware Implementation and Component Description

This chapter describes the physical realization of the project. It covers the PCB layout and assembly of the main inverter board, along with auxiliary hardware modules such as the high-frequency DC-DC boost converter, bridge rectifier, and programming interfaces.

Chapter 7: Testing and Measurement

This chapter presents the experimental validation of the system. It describes the laboratory test bench setup and analyzes the control signals generated by the STM32 microcontroller to verify frequency, dead-time, and stability.

Chapter 8: Conclusion and Future Work

This chapter summarizes the project's achievements, discusses the challenges encountered during hardware assembly and simulation, and outlines future developments, specifically the implementation of the full Volt-Var control loop.

Appendix A: Firmware Architecture and Control Logic

This appendix provides a detailed analysis of the embedded software. It explains the code structure within STM32CubeIDE, peripheral configuration, and the algorithms used for SOGI-PLL, PR controller, and DFSDM sensing.

Chapter 2: Literature Review and Theoretical Background

Literature Review This chapter provides an overview of studies and technologies that have been done in the past that are pertinent to improving the power grid's performance and stability under changing power generation scenarios influenced by dynamic loads. It discusses the difficulties in integrating renewable energy sources (RES), the critical role that grid-tied inverters play in this integration, and the different control strategies used for voltage, frequency, and power flow regulation to improve grid stability and power quality. This review lays the groundwork for the project's methodology.

2.1 Overview of Power Grids and Stability Challenges

Modern power grids face increasing complexity due to changing generation and load characteristics. Grid stability is the grid's capacity to maintain equilibrium after a disturbance. Large, synchronous generators, which offered inherent inertia and stability support, were historically a major component of power grids. However, there are a number of difficulties associated with the integration of variable renewable energy sources and the trend towards distributed generation (DG). Stable voltages, frequency, and power flow across the system are the main concerns. Variable power output is a result of renewable energy sources like solar and wind be intermittent and weather-dependent. This variability raises concerns about the stability and security of the utilize grid and can result in anomalies and voltage disruptions. Voltage instabilities can cause harmful, especially if they come from dispersed sources. transmission assets. Furthermore, it is thought that the current smart grid capabilities, such as communication and controls, are insufficient to manage the effects of integrating large amounts of solar and wind energy into the power system.

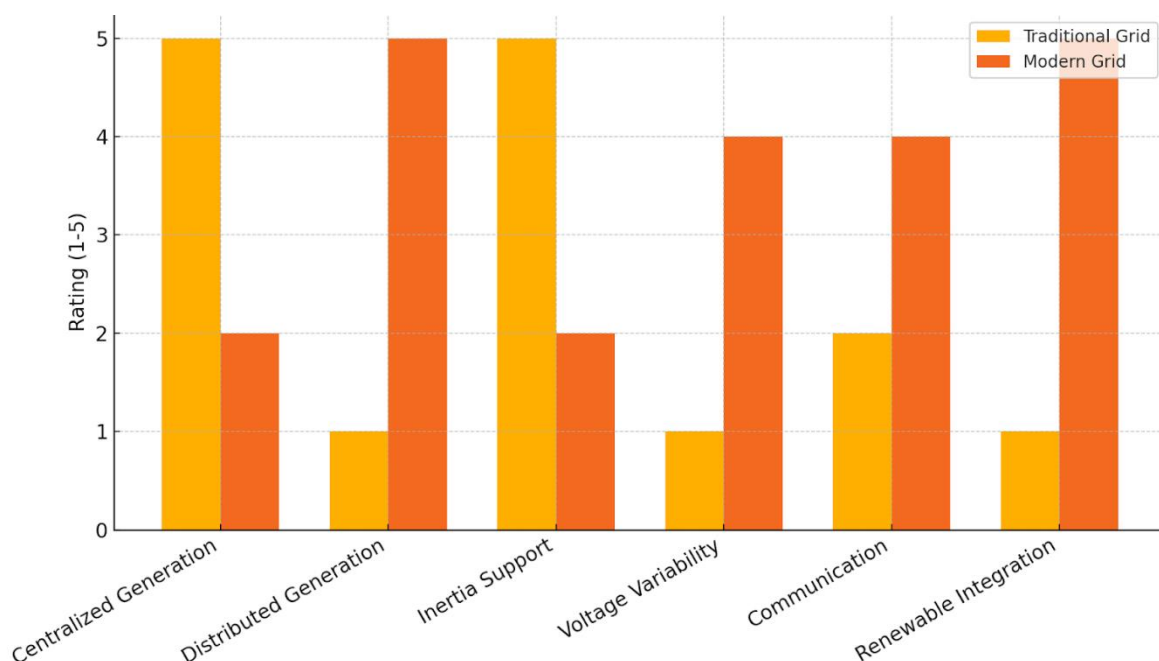


Figure 2.1: Comparison Between Traditional and Modern Power Grids

Table 2.1: Energy Sources Comparison

Property	Conventional (e.g. Gas)	Solar/Wind
Stability	High	Low
Availability	High	Variable
Environmental Impact	High CO2	Low CO2
Cost Trend	Stable	Decreasing
Inertia	High	None
Predictability	High	Low

Another significant issue with smart grid technology is the inconsistent nature of loads. Another issue affecting the grid's condition is a lack of safe, dependable communications infrastructure. New control strategies are needed for grid-connected systems to operate effectively in these circumstances in order to achieve consistency and dependability in the energy produced by renewable sources. Because energy flow fluctuations are periodic, it is also essential to incorporate monitoring and control.

2.2 Impact of Renewable Energy Integration

The increase in the penetration of PV systems has come as a result of increasing interest in solar energy and simultaneous decreases in PV system costs, among other. Distributed generators are increasingly utilizing renewable energy sources. As discussed in the previous section, among the other concerns, the power output of these sources is not reliable. Due to the intermittent nature of RES, many issues versus power quality and stability arose in the utility grid, mainly in the presence of a growing number of grid-connected solar PV inverters. The variation in power output from solar and wind power generation can translate directly into irregularities and voltage disturbances. The system needs better abilities than those available today with smart grid communication and controls to integrate solar and wind energy in very high amounts. The future grid objective is the significant increase of RES integration. The rapid integration is promoted due to cost improvement and supportive policy together with global concern on extinction of fossil fuels and environmental pollution. But it has to tackle their variable nature and ensure grid system stability and dependability.

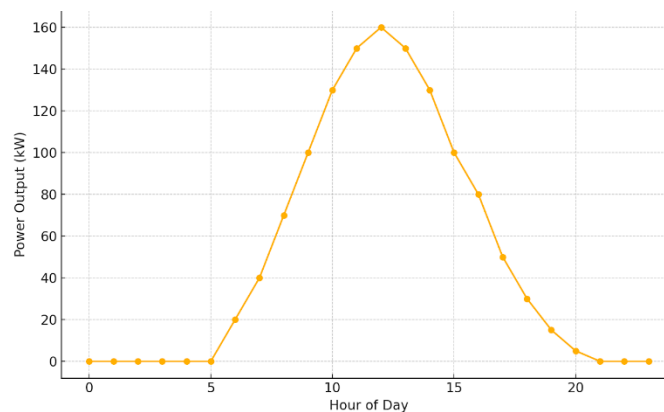


Figure 2.2: Solar Power Generation Over a Day

Table 2.2: PV Inverters Types

Inverter Type	Stages	cost	size	Control flexibility
Single-Stage	1	Lower	Compact	Moderate
Multi-Stage	2	Higher	Larger	High
Transformer-Based	N/A	Higher	Large	Low
Transformerless	N/A	Lower	Compact	High

2.3 An Examination of Solar PV Systems: On-Grid, Off-Grid, and Hybrid

2.3.1 ON-grid solar power systems

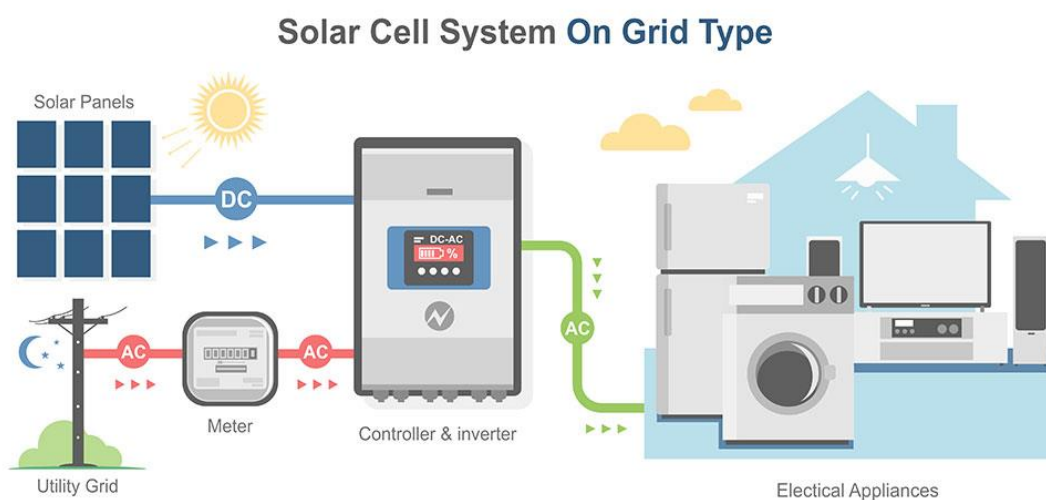


Figure 2.3: Solar Cell System On Grid Type

Grid-connected solar power systems, also known as photovoltaic (PV) systems tied to a grid, are a crucial part of modern electrical systems, including transmission systems, power stations, and small-scale standalone three-phase inverters for residential applications (Mnati, 2018). They represent a growing application in renewable energy due to the increasing demand for high-quality and sustainable energy (Kiriakos, 2019).

Key Components and Operation:

- **PV Panels:** These panels convert sunlight into DC electrical power (Adekola, 2015) & (Lu, 2015). The output current and voltage of a solar panel are influenced by factors like light-generated current, reverse saturation current of the diode, irradiance, and temperature (Adekola, 2015) & (Lu, 2015).

- **Micro-inverters and Inverters:** These devices are fundamental for grid connection, converting the DC power from PV panels into AC power that can be fed into the electrical grid (Mnati, 2018).
 - **Micro-inverters** are typically composed of two stages: a DC-DC converter and a full-bridge inverter (Gulbahce, 2022). They are common in residential solar and plug-in electric vehicle applications.
 - **Three-phase inverters** are often used for connecting PV systems to the low-voltage distribution grid (Mnati, 2018). The simulation setup for such a system often utilizes components like SiC MOSFET (e.g., CF10120D) transistors, operating at a switching frequency of 25 kHz, with a capacity of 5 kVA and 400 VLL (Mnati, 2018).
- **Output Filters:** An **LCL filter** is commonly used in grid-connected inverters to minimize harmonic content and ensure the quality of the injected current (Gulbahce, 2022). The design parameters for LCL filters include output voltage and power, input voltage, grid frequency, switching frequency, and input current (Gulbahce, 2022). Some designs also incorporate an LC filter (Jiao, 2017).
- **Grid Connection:** The inverter connects to the grid, which typically consists of three-phase lines that need to be synchronized with the inverter's output (Wang, 2016).

Control Strategies for Grid-Connected Inverters: Effective control is essential for stable and efficient operation of grid-connected inverters.

- **PID Current Control:** Proportional-Integral-Derivative (PID) current control is widely applied, especially in three-phase photovoltaic inverters connected to the grid (Mnati, 2018). This control is continuously tuned for the 120-degree bus clamp (BC) pulse width modulation (PWM) scheme (Mnati, 2018). The simulation setup for PID current control often uses specific parameters, such as $K_p=3.5$, $K_I=3.5$, and $K_D=0$ in MATLAB (Mnati, 2018).
 - **PWM Techniques:**
 - **Pulse Width Modulation (PWM)** is fundamental for generating the switching pulses that control the inverter output (Murthi, 2007).
 - **120-degree Bus Clamp PWM (BC-PWM)** is a specific operating type that helps reduce switching losses in three-phase inverters (Mnati, 2018). Simulation results show that using 120-degree BC-PWM can achieve acceptable Total Harmonic Distortion (THD) levels, often below 2.333% (Mnati, 2018).
 - **Sinusoidal PWM (SPWM)** is used to minimize harmonic content (Gulbahce, 2022). It involves comparing a sinusoidal reference signal with a high-frequency triangular carrier signal (Murthi, 2007).
 - **Space-Vector Modulation (SV PWM)** is a digital modulation strategy that can increase the amplitude of the output voltage fundamental and shift harmonics to higher frequencies (Mohan et al., 2003).

- **Modified Bipolar PWM (MBPWM)** is another scheme used, with simulation results showing its performance with and without zero-sequence voltage (Chapter 2).
 - **Maximum Power Point Tracking (MPPT):** This algorithm optimizes the power extracted from the PV panel under varying conditions of temperature and irradiance (Adekola, 2015). Methods like the modified Perturb & Observe (P&O) are studied for MPPT (Tan & Thang, 2018).
 - **Synchronous Reference Frame (SRF) Control (dq-transformation):** This technique transforms three-phase AC signals into DC signals (dq-signals) in a rotating reference frame, simplifying current control (Wang, 2016). PI controllers are typically associated with this control structure (Wang, 2016). The d-axis is usually aligned with the grid voltage vector (Wang, 2016).
 - **Proportional-Resonant (PR) Controllers and Harmonic Compensators (HC):** PR controllers are effective for grid-connected inverters, especially for controlling the current (Teodorescu et al., 2006). They can be combined with Harmonic Compensators (HC) to further reduce harmonic distortion (Teodorescu et al., 2006).
 - **Voltage and Current Loops:** Grid-connected inverter control schemes often feature cascaded control loops, including an outer voltage loop and an inner current loop (Teodorescu et al., 2006). The current loop controls the power injected into the grid, while the voltage loop regulates the DC-link voltage (Mohammad Alsemaan, 2016).
- **Applications and Purpose**
 - The primary purpose of on-grid solar power systems is to **inject power from renewable energy sources directly into the utility grid** (Sarkar, 2015).
 - They are widely implemented in various settings, including **residential, commercial, and large-scale utility solar farms** (Adekola, 2015).
 - Driven by concerns about climate change and decreasing PV system costs, grid-connected solar applications have seen substantial growth, accounting for **99% of net installed PV capacity** in the market (Adekola, 2015) & (Verma, 2019).
 - In these systems, the **utility grid inherently acts as a vast energy storage solution** for any excess electricity generated, eliminating the need for local batteries (Adekola, 2015), (Lu, 2015), (Gulbahce, 2022) & (Haider, 2021).

Advantages

- **Cost-effectiveness:** Generally entail **significantly lower costs** compared to off-grid systems because they do not require expensive battery storage (Verma, 2019), (Gulbahce, 2022) & (Haider, 2021).
- **High Efficiency:** Known for their **high efficiency**, as power generated is directly fed into the grid (Mohammad Alsemaan, 2016), (Adekola, 2015), (Lu, 2015), &

(Rodrigues, 2019). Three-phase grid-tie inverters are particularly efficient and dominate the market (Rodrigues, 2019).

- **Reliability and Flexibility:** The grid provides a **reliable backup** power source, effectively mitigating the intermittency of solar energy (Verma, 2019), (Haider, 2021) & (Gulbahce, 2022). They also support **bidirectional power flow**, allowing users to sell excess electricity to the grid and draw power when their generation is insufficient (Lu, 2015) & (Adekola, 2015).
- **Environmental Benefits:** Contribute to **reducing greenhouse gas emissions** (Ojo, 2022) and have a lower carbon footprint over their operational lifespan (Kiriakos, 2019) & (Ojo, 2022).
- **Power Quality Improvement:** Can actively support the grid by providing harmonic current and reactive power to connected loads (Rodrigues, 2019). Smart inverters are designed to improve power quality (Adekola, 2015).

Disadvantages and Challenges

- **Grid Dependency and Anti-Islanding:** A crucial safety requirement is that the inverter **must disconnect from the grid during power outages** (known as anti-islanding) (Adekola, 2015), (Alsemaan, 2016) & (Haider, 2021). This means that power is not available to the consumer during a grid failure, even if the sun is shining.
- **Intermittency of RES:** Despite being connected to the grid, the inherent variability of renewable energy sources (e.g., due to weather or seasonal changes) can still pose challenges for grid stability and control (Ojo, 2022) & (Adekola, 2015).
- **Synchronization Complexity:** Achieving and maintaining precise synchronization with the grid's voltage and frequency can be a complex technical challenge (Mohammad Alsemaan, 2016), (Wang, 2016), (Lu, 2015) & (Haider, 2021).
- **Power Quality Issues:** If not properly filtered, power electronic devices in inverters can inject undesirable harmonics into the grid, necessitating compliance with strict grid standards (Sarkar, 2015), (Hassaine & Bengourina, 2019), (Hassaine & Bengourina, 2020), (Adekola, 2015) & (Zong, 2011).
- **System Control Challenges:** The distributed nature of solar generation can create complex system control issues for grid operators (Adekola, 2015). There is also a recognized need for secure and reliable communication infrastructure for effective grid management (Adekola, 2015).
- **Inverter Lifespan:** Inverters are often considered the **weakest components** in PV systems, with a typical lifespan of 5 to 15 years, considerably shorter than that of PV panels (around 25 years). This contributes to higher operation and maintenance costs and energy losses due to downtime (Rodrigues, 2019). Power semiconductors and DC-link capacitors are common points of failure (Rodrigues, 2019).
- **Standards Compliance:** Systems must adhere to numerous international and national standards (e.g., IEEE 1547, IEC 61727, German Grid Code) to ensure safe and reliable interconnection (Zong, 2011), (Mohammad Alsemaan, 2016), (Rodrigues, 2019), (Zammit et al., 2014) & (Kjær, 2005).

Efficiency and Losses:

- A major objective for inverters is to increase efficiency by reducing power losses (Mnati, 2018). Losses in power electronic circuits, such as three-phase inverters, primarily include switching losses and conduction losses (Gulbahce, 2022).
- **Switching losses** are proportional to the switching frequency and transistor ratings (Mnati, 2018). **Conduction losses** are related to the transistor's current and resistance (Gulbahce, 2022).
- The use of **wide bandgap semiconductors** like Silicon Carbide (SiC) MOSFETs and Gallium Nitride (GaN) HEMTs can significantly improve efficiency by reducing these losses, especially at high switching frequencies (Gulbahce, 2022). For instance, a SiC MOSFET (CF10120D) transistor is used in one setup (Mnati, 2018).

Simulation and Experimental Validation:

- **MATLAB/Simulink** is widely used for building simulation setups and analyzing control systems for micro-inverters and three-phase inverters (Gulbahce, 2022).
- Simulation results often include output waveforms like three-phase line current, voltage, and voltage to the negative DC link (Mnati, 2018).
- **Experimental setups** are used to validate simulation results, measuring parameters like THD and observing waveforms (Gulbahce, 2022). Digital Signal Processors (DSPs) are frequently employed for implementing controllers in experimental systems (Adekola, 2015).

Considerations and Challenges:

- **Grid Codes:** Inverters must comply with grid code requirements, including harmonic current limits (Rodrigues, 2019).
- **Time Delays:** Digital control systems inherently introduce time delays, which must be considered in the design to maintain system stability (Wang, 2016).
- **Parasitic Inductance:** Stray inductance in switching waveforms can affect performance, and balanced layouts can reduce parasitic inductance (Rodrigues, 2019).

Overall, grid-connected solar power systems require sophisticated control strategies, efficient power electronics, and careful design validated through simulation and experimentation to ensure stable, reliable, and high-quality power injection into the electrical grid.

2.3.2 Off-grid solar power systems

Off-grid solar power systems, also known as **stand-alone systems**, are designed to operate independently without any connection to the main electricity grid.

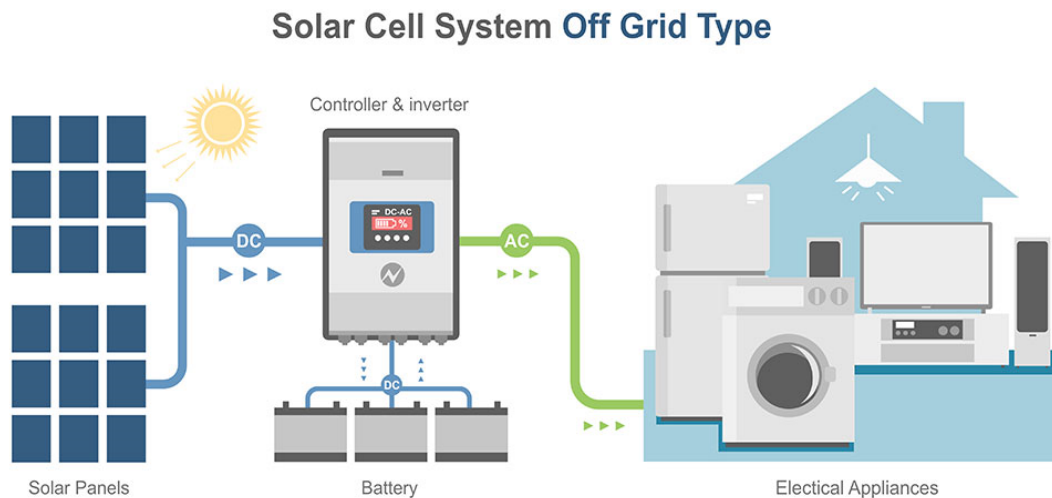


Figure 2.4: Solar Cell System Off Grid Type

Key Components and Operation:

- **PV Panels:** Serve as the primary standalone source of electricity, especially in remote areas (Verma, 2019). They convert solar radiation into DC electricity (Verma, 2019).
- **Energy Storage System (ESS):** Due to the intermittent nature of solar energy, an ESS, typically consisting of **batteries**, is a crucial component in off-grid systems to ensure the continuity of energy supply (Gulbahce, 2022). This is a significant distinction from grid-connected systems, which generally do not require batteries (Haider, 2021). The energy generated during the day is stored in these batteries for use at night or during cloudy periods (Haider, 2021).
- **Charge Controller (MPPT charge controller):** This device is essential for managing the energy that enters the battery bank from the solar array (Verma, 2019). It prevents the deep cycle batteries from being overcharged during the day and stops power from returning to the solar panels at night (Gerard, 2020).
- **Inverter (DC/AC Converter):** The inverter converts the DC power generated by the PV panels and stored in batteries into AC power suitable for household and industrial appliances (Verma, 2019). In a stand-alone system, the inverter **must generate a specific voltage with a proper frequency output** to meet the load demand (Mohammad Alsemaan, 2016). This contrasts with grid-tied inverters, where the voltage and frequency are already determined by the utility grid (Mohammad Alsemaan, 2016). **Voltage control** is typically adopted for stand-alone inverters to stabilize the microgrid voltage, often incorporating current protection and harmonic distortion control (Lu, 2015).

- **Optional Backup: Automatic Backup Generators** can be integrated to provide additional reliability during extended periods of low solar generation or high demand (Gerard, 2020).

Applications and Purpose: Off-grid solar systems are particularly useful in situations where a functional electricity grid is unavailable or geographically distant (Verma, 2019). They are common in:

- **Remote areas:** Providing power for isolated industrial operations, households, cabins, and recreational vehicles, especially in developing countries (Verma, 2019).
- **Specific applications:** Such as telecommunication relay stations, water heaters, water pumps, emergency phones, and security systems (Verma, 2019) & (Adekola, 2015).
- **Microgrids in island mode:** Remote off-grid microgrids are designed to operate permanently in an islanded mode due to economic or geographical constraints (Ojo, 2022) & (Kiriakos, 2019). These microgrids are traditionally energy self-sufficient (Kiriakos, 2019).

Advantages:

- **Energy Independence:** Users are not reliant on the main power grid, meaning they are unaffected by power outages or blackouts (Haider, 2021).
- **Rural Electrification:** They have been effective in providing electricity to rural areas and supporting solar home systems (SHSs) where grid installation is not feasible (Adekola, 2015).
- **Cost Reduction in Remote Areas:** Studies show that operating off-grid microgrids dominated by renewable sources can reduce the levelized cost of electricity production over the project's lifespan in remote or island areas (Kiriakos, 2019).
- **Improved Performance:** Compared to other renewable sources, solar PV systems offer improved performance in remote locations due to the infinite availability of solar irradiation (Adekola, 2015).

Disadvantages and Challenges:

- **Energy Storage Limitations:** A significant challenge is the **difficulty in storing generated solar electricity**, which often translates to substantial running costs for the required energy storage systems (Adekola, 2015).
- **High Initial Investment:** Off-grid systems typically require a high initial investment (Verma, 2019).
- **Reliance on Sunlight:** Prolonged cloudy weather can negatively impact the energy output and availability, as the system relies solely on solar irradiation (Haider, 2021).
- **Control Complexity:** Operating microgrids autonomously (off-grid) presents a **complex control problem** due to the absence of stabilizing inertia, which is naturally present in traditional large synchronous generators connected to the main grid (Ojo, 2022). New,

robust control strategies are required to regulate frequency and voltage, and ensure power sharing optimally for stable autonomous operations (Ojo, 2022).

- **Market Share:** Grid-connected systems have gained more interest in the international market for PV technology and account for the majority (99%) of installations, while stand-alone systems represent a smaller share (around 1%) (Verma, 2019), (Adekola, 2015).

Efficiency and Losses

- **Storage-related Losses:** The requirement for energy storage (batteries) introduces **losses** within the system, which contributes to higher overall running costs (Adekola, 2015).
- **Intermittency Impact:** The system's complete reliance on solar energy means that **prolonged cloudy weather can significantly reduce energy output** (Haider, 2021).
- **Cost vs. Grid-tied:** Generally, **grid-connected electricity is more economical** than off-grid systems due to the substantial costs associated with off-grid components and storage solutions (Adekola, 2015). Grid-connected systems are recognized for their significantly reduced costs and higher efficiency, in part because they do not require batteries (Gulbahce, 2022).

Simulation and Experimental Validation

- **Simulation Tools:** Software tools such as **MATLAB Simulink** can be utilized to model and simulate off-grid microgrid systems, assessing aspects like power sustainability and Total Harmonic Distortion (THD) (Kiriakos, 2019). **PVSYST** software is also employed for designing and simulating off-grid PV systems (Eshita et al., 2010).
- **Experimental Testing:** The operation of inverters in grid isolation (off-grid) mode can be tested experimentally as a potential area for future research, contributing to the broader expansion of PV system applications across both operating modes (Verma, 2019).

Considerations and Challenges

- **High Initial and Running Costs:** Off-grid systems typically demand a **high initial investment** and incur **substantial running costs**, primarily due to the expense of energy storage solutions (Verma, 2019) & (Adekola, 2015).
- **System Complexity and Maintenance:** The integration of batteries and, potentially, backup generators adds layers of complexity to the system design and increases maintenance requirements (Gerard, 2020).
- **Limited Capacity:** These systems are usually designed for **specific DC/AC electrical loads** and may not be suitable for the large-scale power demands that grid-tied systems can support (Verma, 2019) & (Adekola, 2015).
- **Dependency on Solar Conditions:** Their sole reliance on solar energy makes them vulnerable to extended periods of unfavorable weather conditions (Haider, 2021).
- **Geographical Suitability:** They are most practical and cost-effective in **remote areas where grid connection is not feasible or economically viable**, or where grid independence is desired (Lu, 2015). Common applications include powering remote

houses, schools, hospitals, telecommunication stations, water heaters, and water pumps in rural or developing regions (Adekola, 2015).

- **Not Always Economical:** They are **not always the most economical choice** when a utility grid connection is available, as grid-connected electricity is typically cheaper (Adekola, 2015).

2.3.3 Hybrid solar power systems

Hybrid Solar Power Systems: An Overview of Types and Applications

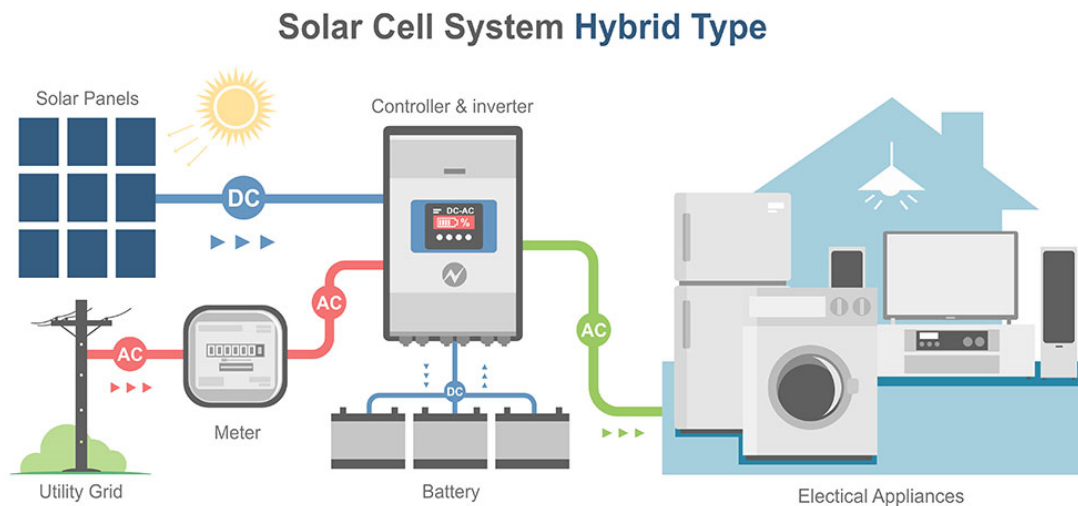


Figure 2.5: Solar Cell System Hybrid Type

Introduction

The global energy landscape is undergoing a significant transformation, driven by the need to decarbonize power generation and enhance grid resilience. Within this transition, solar photovoltaic (PV) technology has emerged as a leading source of renewable energy. However, the intermittent nature of solar generation—dependent on daily and seasonal weather patterns—presents a fundamental challenge to its reliability and integration into the grid. A traditional grid-tied solar system ceases to operate during a power outage, leaving the owner without electricity despite having a functional PV array. Conversely, a purely off-grid system lacks the reliability and economic benefits of a grid connection.

Hybrid solar power systems have been developed to address these limitations by integrating solar PV generation with a Battery Energy Storage System (BESS) and a connection to the utility grid. These systems are managed by an intelligent hybrid inverter, which serves as the central controller, optimizing energy flow to achieve a triad of objectives: maximizing the consumption of self-generated energy, providing a reliable backup power supply, and intelligently interacting with the utility grid for economic benefit (Masters, 2013, p. 541). This paper explores the architecture, operational strategies, performance metrics, and diverse applications of modern hybrid solar power systems.

System Architecture and Core Components

A hybrid solar system's effectiveness is defined by its architecture and the seamless integration of its components. There are two primary architectural configurations: DC-coupled and AC-coupled systems.

- **DC-Coupled Systems:** In this configuration, both the solar PV array and the battery bank are connected on the direct current (DC) side of the hybrid inverter. Excess DC power from the solar panels can directly charge the battery through a charge controller without being converted to alternating current (AC). This architecture is highly efficient for new installations as it minimizes conversion losses (**Badwawi, Abusara, & Mallick, 2015, p. 129**).
- **AC-Coupled Systems:** This architecture is commonly used when retrofitting a battery system to an existing grid-tied solar installation. It involves a standard grid-tied PV inverter and a separate, bidirectional battery inverter. DC power from the solar panels is first converted to AC by the PV inverter. To charge the battery, this AC power must be converted back to DC by the battery inverter. While slightly less efficient due to multiple conversions, this approach offers greater modularity and flexibility.

The core components of a typical hybrid system include:

1. Solar PV Array: Converts sunlight into DC electricity.

1. **Hybrid Inverter:** The system's brain. It houses the MPPT controller, the bidirectional DC/AC inverter, and the battery charge controller.
2. **Battery Energy Storage System (BESS):** Stores excess solar energy. Lithium-ion batteries are now the dominant technology due to their high energy density, long cycle life, and falling costs (**National Renewable Energy Laboratory [NREL], 2021, p. 12**).
3. **Energy Management System (EMS):** A sophisticated software platform, usually integrated within the hybrid inverter, that executes control algorithms based on user settings, grid conditions, and electricity tariffs.
4. **Grid Connection and Automatic Transfer Switch (ATS):** The physical connection to the utility grid, which includes an ATS to safely disconnect the system from the grid during an outage (a function known as anti-islanding) and establish a local microgrid.

Operational Modes and Control Strategies

The intelligence of a hybrid system lies in its ability to autonomously switch between various operational modes based on real-time data and pre-programmed control strategies.

Operational Modes:

- **Self-Consumption Mode:** During daylight hours, solar generation first powers the home's loads directly. Any surplus energy is used to charge the battery.
- **Battery Charging Mode:** If solar generation exceeds the load demand, the excess DC power is routed to the BESS until it reaches a full state of charge. The system may also charge the battery from the grid during off-peak hours if programmed to do so.
- **Battery Discharging Mode:** During the evening or on cloudy days, when solar generation is insufficient to meet the load, the system draws stored energy from the battery.
- **Backup (Islanded) Mode:** Upon detection of a grid failure, the ATS disconnects the system from the grid. The hybrid inverter then forms its own stable, localized AC grid, supplying power to critical home circuits from the BESS.

Advanced Control Strategies:

- **Peak Shaving and Load Shifting:** In regions with Time-of-Use (ToU) electricity pricing, the EMS can be configured to minimize costs. It discharges the battery to power the home during expensive "peak" hours and recharges it with low-cost solar energy or off-peak grid power. This strategy shifts the energy consumption pattern to a more economically favorable profile (**Badwawi, Abusara, & Mallick, 2015, p. 130**).
- **Grid Support and Virtual Power Plants (VPPs):** Advanced hybrid systems can be aggregated and controlled by a utility or a third-party operator to form a VPP. As a collective, these systems can provide ancillary services to the grid, such as frequency regulation and voltage support, helping to stabilize the grid during periods of high demand or generation volatility. Homeowners are often financially compensated for participating in such programs (**Navigant Research, 2019, p. 22**).

Types of Inverters within Hybrid Systems (Functionally) While the sources do not explicitly categorize "hybrid inverters" as a distinct type in the same way they categorize Voltage Source Inverters (VSIs) or Current Source Inverters (CSIs), they describe inverter functionalities that enable hybrid operation:

- **Voltage Source Inverters (VSIs):** These are commonly used in grid-connected PV systems and, when paired with appropriate control and storage, can support hybrid operation (Adekola, 2015) & (Verma, 2019). Their ability to act as a **voltage source** is vital for maintaining stable output in islanded microgrids.
- **Multi-Stage Configurations:** Many PV inverter systems, particularly micro-inverters, employ a two-stage power processing architecture, typically involving a **DC/DC converter followed by a DC/AC inverter** (Tan & Thang, 2018), (Rodrigues, 2019). The DC/DC stage often performs **Maximum Power Point Tracking (MPPT)** to optimize energy

harvesting from PV panels (Tan & Thang, 2018), (Adekola, 2015), (Lu, 2015) & (Gulbahce, 2022). A battery can act as an energy buffer between these stages.

Advantages and Challenges

Advantages:

- **Energy Independence and Resilience:** Provides an uninterruptible power supply (UPS) during grid outages, ensuring that critical loads remain operational.
- **Reduced Electricity Costs:** Maximizes self-consumption of free solar energy and enables strategic avoidance of high-cost peak electricity tariffs.
- **Grid Stabilization:** When deployed at scale, hybrid systems can reduce strain on the utility grid, defer the need for infrastructure upgrades, and enhance overall grid stability.

Challenges:

- **Higher Initial Cost:** The inclusion of a BESS and a more complex hybrid inverter makes the upfront investment significantly higher than for a standard grid-tied system. However, costs for both batteries and inverters continue to decline (NREL, 2021, p. 4).
- **Battery Lifespan and Degradation:** Batteries have a finite lifespan, measured in cycles and years. Performance degrades over time, and replacement is a significant long-term cost.
- **System Complexity:** Designing, installing, and commissioning a hybrid system requires specialized knowledge of power electronics, battery management, and electrical codes.
 - **Regulatory Frameworks:** The policies governing grid interconnection, net metering, and compensation for grid services vary widely and can be complex, impacting the economic viability of a project.

Applications

Hybrid solar systems are versatile and are being deployed across a wide range of applications:

1. **Residential Sector:** The most common application, providing homeowners with backup power and lower electricity bills.
2. **Commercial & Industrial (C&I) Sector:** Used by businesses to reduce peak demand charges, which can constitute a significant portion of their electricity costs.
3. **Remote and Off-Grid Communities:** Provide reliable, 24/7 power to locations without access to a centralized electrical grid, such as rural villages, islands, and remote industrial sites.
4. **Critical Infrastructure:** Ensure continuous power for essential services like hospitals, telecommunication towers, and data centers.

Here is a comparison of On-Grid, Off-Grid, and Hybrid Photovoltaic (PV) systems, drawing on the provided sources:

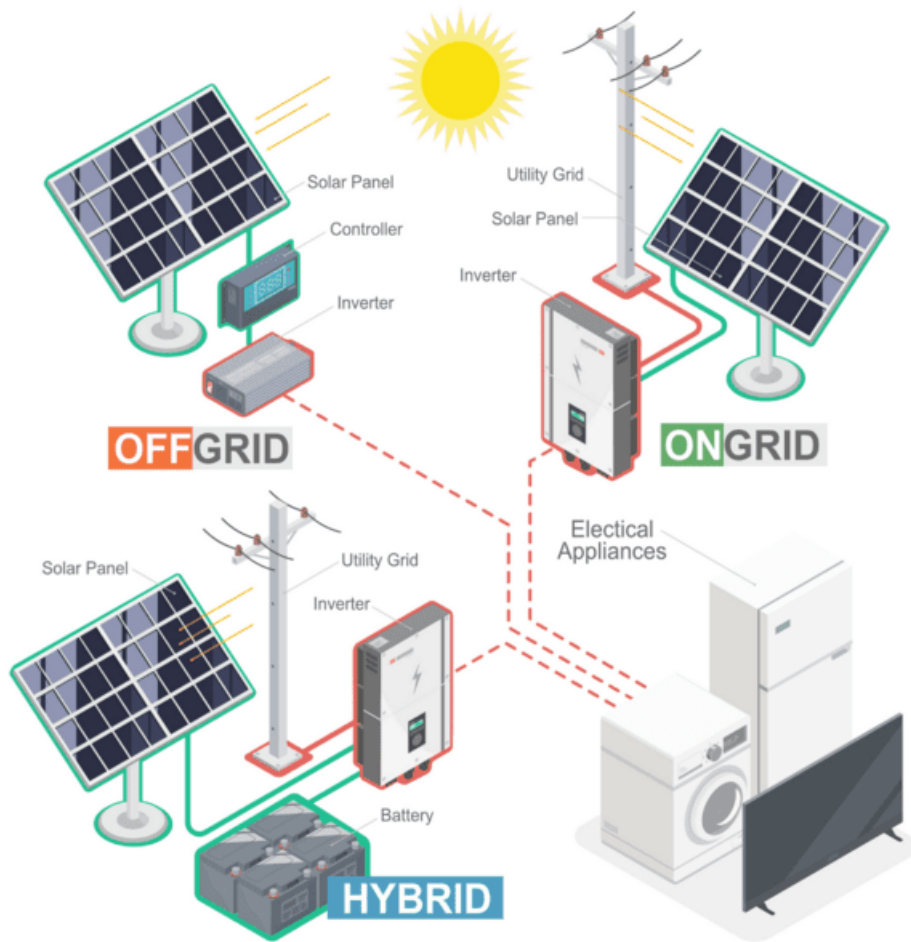


Figure 2.6: Comparison Of On-Grid, Off-Grid, And Hybrid Photovoltaic (PV) Systems

2.3.4 Comparison: On-Grid Systems vs. Off-Grid Systems vs. Hybrid Systems

Table 2.3: Comparison: On-Grid Systems vs. Off-Grid Systems vs. Hybrid Systems

Feature	On-Grid Systems (Grid-Connected)	Off-Grid Systems (Stand-Alone/Autonomous)	Hybrid Systems
Definition	All energy produced is directly fed to the utility grid (Verma, 2019). These systems are primarily designed for power injection into the grid (Gulbahce, 2022) & (Haider, 2021).	Systems that function independently of the AC grid (Verma, 2019). They are not connected to the utility grid (Haider, 2021) & (Gulbahce, 2022) and are designed to provide energy to specific DC/AC electrical loads (Verma, 2019). Remote microgrids operate continuously in an islanded mode (Ojo, 2022).	Systems that can be utilized for both islanding (standalone) mode and grid-connected mode (Verma, 2019). These combine features of both on-grid and off-grid systems.
Battery/Storage	Typically, no batteries are needed as the utility grid acts as the energy storage (Gulbahce, 2022) & (Lu, 2015). While energy storage can be integrated, it is not a primary operational requirement (Adekola, 2015).	Requires an additional battery system (Gulbahce, 2022) & (Haider, 2021). The system is designed to produce energy throughout the day, which is then stored in these batteries (Gulbahce, 2022).	Involves energy storage (batteries) to enable standalone operation (Verma, 2019).
Cost Implications	Costs have significantly reduced in recent years (Gulbahce, 2022). They offer economic benefits by offsetting homeowner's electricity use and generating profits from selling excess electricity back to the grid .	While specific comparative costs aren't detailed, they are often the only solution in remote areas where grid access is unavailable (Lu, 2015). The high cost of energy storage systems can impact their overall feasibility if used as the primary load supply (Kiriakos, 2019).	Dual functionality, they may involve a balance between grid-tied cost efficiencies and the investment in energy storage for standalone capability.

<p>Inverter Role/Control</p>	<p>Inverters are essential for DC/AC conversion to produce suitable AC voltage forms for the grid and daily use (Gulbahce, 2022). Their main tasks include: Injecting a sinusoidal current into the grid (Kjær, 2005). Optimizing the PV module's operating point (Kjær, 2005) & (Verma, 2019). Controlling active and reactive power output to reduce grid harmonics (Adekola, 2015). Employing Pulse Width Modulation (PWM) methods (Mnati, 2018). Utilizing current control schemes (e.g., PI, PR controllers) (Hassaine & Bengourina, 2019). Crucial grid synchronization (Haider, 2021). Voltage Source Inverters (VSI) are commonly used (Verma, 2019). Grid-feeding inverters operate as power/current controlled sources, providing prespecified active and reactive power (Ojo, 2022).</p>	<p>Inverters are required to directly feed power to local consumers when the grid is not connected (Lu, 2015). They must: Generate a specific voltage with appropriate frequency output to meet load demand (Mohammad Alsemaan, 2016). Be "grid-forming" by operating as ideal AC voltage sources with regulated voltage amplitude and frequency(Ojo, 2022). Focus on frequency and voltage regulation, and power sharing (Ojo, 2022). Can also use Proportional-Resonant (PR) controllers for AC signal control (Ojo, 2022).</p>	<p>Inverters must be capable of handling both grid-connected and islanded modes (Verma, 2019). This implies control strategies that can switch between grid-feeding and grid-forming functionalities, managing power flow and grid synchronization when connected, and maintaining stable voltage and frequency when isolated.</p>
<p>Complexity</p>	<p>Simpler, less components (no batteries)</p>	<p>Moderate, requires battery management and charge controller</p>	<p>Most complex, requires advanced control for dual operation and power management</p>
<p>Grid Interaction</p>	<p>Characterized by direct connection and interaction with the utility grid</p>	<p>By definition, these systems do not interact with the utility grid (Haider,</p>	<p>Designed to seamlessly connect and disconnect from the utility grid</p>

	(Gulbahce, 2022) & (Haider, 2021). Inverters synchronize their output voltage, frequency, and phase angle with the grid (Haider, 2021). Excess generated electricity is transferred to the network (Verma, 2019) & (Gulbahce, 2022).	2021). They are designed to operate completely independently (Ojo, 2022).	(Verma, 2019). They can supply power to the grid or draw from it, and also support local loads when disconnected from the main grid.
Operation During Outages	In the event of a grid power failure, on-grid systems typically shut off for safety reasons (Haider, 2021) & (Kjær, 2005). They are required to cease energizing the grid to prevent "islanding" (Kjær, 2005).	Are designed to continue supplying power to loads from their stored battery energy during utility outages (Haider, 2021) & (Kiriakos, 2019). They ensure continuity of energy supply even when the main grid is down.	Can continue to operate in an "islanded" mode and supply power to connected loads if the grid fails (Verma, 2019). This offers energy independence during blackouts.
Backup Power	No backup power during grid outages (Haider, 2021)	Provides power when grid is unavailable (Verma, 2019)	Provides backup power during grid outages.
Key Advantage	Cost-effective, net metering benefits, no battery maintenance (Kiriakos, 2019) & (Haider, 2021).	Energy independence, ideal for remote areas (Verma, 2019).	Versatility, reliability , energy independence, grid interaction [Previous response]
Typical Applications	Common in residential PV installations where excess power can be sold back to the grid. Also widely used in solar power plants (Gulbahce, 2022) and other renewable energy applications connected to low voltage grids (Mnati, 2018).	Primarily suited for remote or rural areas lacking grid access (Lu, 2015) & (Gerard, 2020). Examples include cottage installations (Gerard, 2020) or situations where self-generated electricity is the sole power solution (Lu, 2015).	Often implemented in microgrids (Kiriakos, 2019) where the system needs to support local loads, interact with the main grid, and also maintain operation during grid outages.

2.3.5 Working Mechanisms of Solar Photovoltaic (PV) Systems

1. On-Grid PV System (Grid-Tied)

An on-grid PV system is designed to operate in parallel with the utility grid. It does not include a battery storage system, relying on the grid to act as a virtual battery for both supplying deficit power and absorbing surplus energy.

Working Mechanism:

1. **Energy Generation:** Solar photovoltaic (PV) panels capture sunlight and convert it into direct current (DC) electricity.
2. **DC to AC Conversion:** The DC power is channeled to a **grid-tie inverter**. The inverter's primary role is to convert this DC power into alternating current (AC) and, crucially, to synchronize its output waveform (voltage, frequency, and phase) precisely with that of the utility grid (**Teodorescu, Liserre, & Rodriguez, 2011, p. 15**).
3. **Power Prioritization (Self-Consumption):** The generated AC power is first directed to the property's main electrical panel to power any active household or commercial loads (e.g., lights, appliances).
4. **Exporting Surplus Energy:** If the solar system produces more power than the property is consuming at that moment, the excess energy is automatically exported to the utility grid. A bidirectional net meter measures this outflow of energy, typically resulting in a credit on the owner's electricity bill (**Masters, 2013, p. 540**).
5. **Importing Power from the Grid:** During periods of low or no solar generation, such as at night or on heavily overcast days, the property seamlessly draws the required power from the utility grid, just as a home without a solar system would.
6. **Grid Outage Scenario:** In the event of a utility grid failure, the grid-tie inverter is mandated by safety standards (e.g., IEEE 1547) to immediately shut down. This safety feature, known as **anti-islanding**, prevents the PV system from energizing a dead grid, which would pose a severe electrocution risk to utility workers performing repairs (**Teodorescu, Liserre, & Rodriguez, 2011, p. 145**). Consequently, an on-grid system cannot provide backup power during an outage.

2. Off-Grid PV System (Stand-Alone)

An off-grid system operates entirely independently from the utility grid and relies on a battery bank to store energy for use when the sun is not shining. It is a self-sufficient power solution.

Working Mechanism:

1. **Energy Generation:** Solar panels produce DC electricity.
2. **Battery Charging and Management:** The DC power is sent to a **solar charge controller**. The charge controller's critical function is to regulate the voltage and current flowing to the battery bank, preventing overcharging and deep discharging, thereby protecting the battery and extending its lifespan (**Masters, 2013, p. 555**).

3. **Energy Storage:** The regulated DC power is stored in a **battery bank**. The capacity of this bank determines how much energy is available to power loads during the night and on cloudy days.
4. **Power Inversion:** A **stand-alone inverter** draws DC power from the battery bank. This inverter's function is to convert the DC power to a stable AC waveform at the required voltage and frequency (e.g., 230V, 50Hz or 120V, 60Hz) to power the property's loads. Unlike a grid-tie inverter, a stand-alone inverter acts as a "grid-forming" device, creating its own independent electrical grid (**Rashid, 2017, p. 308**).
5. **Supplying Loads:** The AC power produced by the inverter is distributed to the property's loads.
6. **Energy Limitation:** The system's ability to supply power is finite and is dictated entirely by the current solar generation and the battery's state of charge. The system must be carefully sized to meet the expected load demand throughout the year.

3. Hybrid PV System

A hybrid system combines the features of both on-grid and off-grid systems. It is connected to the utility grid but also includes a battery bank, offering energy resilience, cost savings, and flexibility.

Working Mechanism:

1. **Energy Generation and Management:** DC electricity from the solar panels is fed into a **hybrid inverter**. This intelligent inverter acts as the central hub, managing the flow of power between the solar panels, the battery bank, the property's loads, and the utility grid (**Masters, 2013, p. 541**).
2. **Intelligent Power Flow Prioritization:** The hybrid inverter operates based on a sophisticated hierarchy:
 - a. **Priority 1: Self-Consumption.** Solar power is first used to directly power the home's loads.
 - b. **Priority 2: Battery Charging.** Any excess solar power is then used to charge the battery bank.
 - c. **Priority 3: Grid Export.** Only when the loads are met *and* the battery is fully charged is any remaining surplus power exported to the utility grid for credit.
3. **Operation with Depleted Solar:** At night or during low-sun conditions, the system prioritizes drawing power from the stored energy in the battery. It will only begin importing power from the utility grid after the battery has been discharged to a pre-set reserve level (e.g., 20% state of charge).
4. **Grid Outage Scenario (Backup Function):** This is the key advantage of a hybrid system. When a grid outage is detected, the hybrid inverter's automatic transfer switch disconnects it from the grid (anti-islanding). The inverter then instantly switches to backup mode, drawing power from the battery to supply critical loads in the home, functioning exactly like an off-grid system (**Teodorescu, Liserre, & Rodriguez, 2011, p. 27**). This provides seamless, uninterruptible power.

2.4 A Comprehensive Review of Inverter Technologies for Photovoltaic Systems

2.4.1 Grid-Tie Inverters (GTIs)

Grid-tie inverters (GTIs), also known as **line-tied** or **utility-interactive inverters**, are power electronic devices that serve as an **indispensable interface** between distributed power generation systems (DPGS), such as solar photovoltaic (PV) systems, and the main electricity grid (Adekola, 2015), (Wang, 2016) & (Haider, 2021). Their primary function is to **convert direct current (DC) electricity** generated by sources like solar panels or batteries into **alternating current (AC) electricity** that is compatible with and can be fed into the utility grid (Haider, 2021), (Kjær, 2005) & (Verma, 2019). This allows users to push excess power into the mains socket (Masters, 2013, p. 495).

1. Key Components A typical grid-connected PV inverter system comprises several key building blocks:

- **Photovoltaic (PV) Panels:** These convert sunlight into DC electricity.
- **DC-DC Converter:** Often employed as a first stage, especially in micro-inverters and string inverters, to **boost the PV-array voltage** to an appropriate level for the inverter or to a well-regulated DC link (Adekola, 2015), (Hassaine & Bengourina, 2020), (Gulbahce, 2022), (Jiao, 2017) & (Verma, 2019). Boost converters are crucial because standard grid-connected inverters often require DC-link voltages higher than typical PV voltages (Adekola, 2015) (Rashid, 2017, p. 158).
- **Inverter (DC/AC Converter):** This is the core component that performs the DC-AC conversion (Verma, 2019), (Lu, 2015) & (Jiao, 2017). It uses fast switching devices like **Insulated Gate Bipolar Transistors (IGBTs)**, **MOSFETs**, or **thyristors** (Jiao, 2017), (Sarkar, 2015) & (Ojo, 2022). Two-level **Pulse Width Modulation (PWM)** voltage source inverters (VSIs) are a state-of-the-art topology for grid interaction (Wang, 2016). The inverter's output depends on the PWM signals on its switching gates (Haider, 2021) (Teodorescu, Liserre, & Rodriguez, 2011, p. 45).
- **Filters:** To ensure the quality of the AC output and prevent high-frequency switching harmonics from entering the utility grid, filters are commonly adopted (Ojo, 2022), (Adekola, 2015), (Sarkar, 2015), (Gulbahce, 2022) & (Jiao, 2017). Common filter types include **L-filters**, **LC-filters**, and **LCL-filters** (Adekola, 2015), (Gulbahce, 2022), (Mnati, 2018), (Adekola, 2015), (Lu, 2015), (Jiao, 2017), (Haider, 2021), (Zong, 2011). LCL filters are particularly noted for their better HF noise damping capabilities compared to L filters (Haider, 2021). The THD of output voltage and current is significantly reduced with an LCL filter (Gulbahce, 2022), (Teodorescu, Liserre, Rodriguez, 2011, p. 77).
- **DC-link Capacitor:** Often an **electrolytic capacitor**, it acts as an **energy buffer** or **power decoupling** element between the PV module and the grid, especially crucial in single-phase systems to attenuate power ripple (Kjær, 2005) (Kjær, 2005). A film capacitor can also be used for the DC link (Mnati, 2018), (Rashid, 2017, p. 362).

- **Isolation Transformer:** May be placed between the inverter and the AC source for safety reasons and to provide isolation (Lu, 2015). However, **transformerless PV inverters** are also popular, designed to minimize leakage current (Verma, 2019).
- **Relay:** A solid-state relay connects the inverter to the grid, closing when the inverter output is synchronized with the grid (Haider, 2021).

2. Control Strategies and Operation The design and control of GTIs are complex due to the dynamic nature of power systems and the need for high-standard system capabilities to maintain stability and robustness (Lu, 2015).

- **Core Control Objectives:** GTIs aim to:
 - **Generate a sinusoidal output current with low Total Harmonic Distortion (THD) and unity power factor** (Verma, 2019) (Haider, 2021) (Lu, 2015) (Hassaine & Bengourina, 2020) (Jiao, 2017). Regulations specify how clean an inverter's output must be, with a max allowable THD of 8% (**IEEE Standard 1547-2018, p. 45**).
 - **Synchronize with the grid voltage** in both frequency and phase (Haider, 2021) (Lu, 2015) (Hassaine & Bengourina, 2020) (Wang, 2016) (Zong, 2011). A **Phase-Locked Loop (PLL)** is a widely used technique for grid synchronization, allowing accurate detection of the grid phase signal (Jiao, 2017) (Zong, 2011) (Teodorescu et al., 2006) (Lu, 2015) (Adekola, 2015) (Wang, 2016) (**Teodorescu, Liserre, & Rodriguez, 2011, p. 33**).
 - **Control active and reactive power** output and flow into the grid (Lu, 2015) (Adekola, 2015) (Wang, 2016) (Sarkar, 2015) (Rodrigues, 2019) (Zong, 2011)
 - **Regulate the DC-link voltage** (Wang, 2016) (Lu, 2015).
 - **Perform Maximum Power Point Tracking (MPPT)** to maximize energy capture from the PV array under varying atmospheric conditions (Kjær, 2005) (Hassaine & Bengourina, 2019) (Alsemaan, 2016) (Verma, 2019) (**Masters, 2013, p. 521**).
- **Inverter Operation Control Types:**
 - **Current-Controlled Inverters:** These are primarily used for injection into the grid and are **not suitable for standalone applications** (Passey et al., 2009) 1. They produce a sinusoidal current output by having their output stage switched to follow a sinusoidal reference waveform that is phase-locked to the grid (Passey et al., 2009) 2. They do not degrade the quality of supply at the point of connection but also provide no harmonic improvement (Passey et al., 2009) 3.
 - **Voltage-Controlled Inverters:** These produce a sinusoidal voltage output and **are capable of standalone operation** (Passey et al., 2009). When connected to the grid, they must be connected via an inductance to prevent infinite current flow if their voltage or phase is not identical to the grid's (Passey et al., 2009) 4 & 5. They can be controlled in magnitude and phase to manage VARs and power (Passey et al., 2009). Voltage-controlled inverters can improve waveform quality at the point of connection and absorb some harmonic current from the grid, reducing harmonics seen by the grid (Passey et al., 2009) (**Masters, 2013, p. 501**).

- **Advanced Control Strategies:**
 - **Proportional-Integral (PI) and Proportional-Resonant (PR) Controllers:** Widely used for current control and suitable for two-dimensional AC signals (Jiao, 2017) (Teodorescu et al., 2006) (Ojo, 2022) & (Verma, 2019).
 - **Hysteresis Control:** Can be used to adjust inverter frequency to match the grid frequency, offering good current output control (Haider, 2021) (Kjær, 2005).
 - **Feed-Forward and Disturbance Observer Methods:** Used to compensate for disturbances from the grid side, such as grid voltage distortion and grid impedance uncertainty, improving control performance and harmonic attenuation (Wang, 2016) (Jiao, 2017)
 - **Droop Control:** Explored for power sharing in microgrids (Ojo, 2022).
 - **Anti-Islanding:** A critical safety feature requiring the inverter to detect faults or blackouts in the utility grid and disconnect from the system (Adekola, 2015) (Haider, 2021) (Rodrigues, 2019). This prevents the inverter from unsynchronized operation that could pose safety risks (Adekola, 2015) (**IEEE Standard 1547-2018, p. 31**).

3. Performance Metrics and Challenges

- **Harmonic Distortion:** A significant concern is minimizing Total Harmonic Distortion (THD) in the injected current and voltage, as harmonics reduce the efficiency of connected devices (Adekola, 2015) (Hassaine & Bengourina, 2020), (Haider, 2021). Filters play a crucial role in achieving low THD (Gulbahce, 2022).
- **Grid Impedance:** The grid impedance is an essential parameter that can significantly affect the control performance and stability of grid-connected inverters, potentially leading to harmonic resonance (Jiao, 2017). "Weak grids," where grid impedance is much larger than the inverter's filter inductance, pose particular challenges (Jiao, 2017) & (Teodorescu, Liserre, & Rodriguez, 2011, p. 189).
- **Grid Voltage Distortion:** In reality, grid voltage is not always ideally sinusoidal and can be distorted, introducing additional harmonics into the system (Jiao, 2017).
- **Reliability and Efficiency:** Smart inverters aim to improve the reliability and efficiency of the utility grid (Adekola, 2015). Overall efficiency and standby losses are important performance indicators for inverters (Kjær, 2005).
- **Standards Compliance:** GTIs must comply with international standards, such as **IEEE 1547**, which sets requirements for interconnection, including tripping and disconnection during grid instabilities (Adekola, 2015) (**IEEE Standard 1547-2018, p. 1**).

4. Types and Applications GTIs come in various configurations tailored for different power levels and applications:

- **Microinverters (AC Module Inverters):** Designed for a single PV module (typically 50-350 W) and connect directly to the grid. They perform DC-AC conversion, voltage amplification, and MPPT at the module level, offering robustness to single module failures

and better power tracking (Bielskis et al., 2019) (Verma, 2019) (Hayman, 2009) (Alsemaan, 2016) (**Masters, 2013, p. 515**). They are considered "plug and play" devices.

- **String Inverters:** Connect multiple PV panels in series (forming a "string") to increase the DC voltage. They are suitable for medium-scale PV power generation systems (up to 5 kW), offering more precise MPPT and higher efficiency compared to centralized inverters (Alsemaan, 2016) (Verma, 2019) (**Rashid, 2017, p. 654**).
- **Centralized Inverters:** Used in high-power applications like solar power stations, connecting multiple solar strings in parallel (Alsemaan, 2016) (Mohammad Alsemaan, 2016).
- **Applications:** GTIs have wide applications in residential, commercial, and utility-scale solar installations (Zong, 2011) (Alsemaan, 2016) (Haider, 2021). They are crucial for **Distributed Generation (DG)** and are becoming essential components of the **Smart Grid** by improving stability, reliability, and power quality of the electricity supply (Adekola, 2015). GTIs allow renewable energy sources to integrate into the grid and provide ancillary services like local voltage and frequency regulation (Wang, 2016).

2.4.2 Stand-Alone Inverter (Off-Grid Solar Power Systems)

A stand-alone inverter, operating within an off-grid solar power system, is designed to supply power to local loads, functioning entirely independently from the main utility grid. Unlike on-grid systems, these systems do not connect to the public electricity network.

Overview

A stand-alone inverter is a fundamental part of many power electronic systems, especially in scenarios where a connection to the main grid is either unavailable or intentionally disconnected (Mnati, 2018) (Lu, 2015). These inverters operate in "off-grid" situations, serving as the sole power provider for local loads (Alsemaan, 2016) (Lu, 2015). They are particularly useful for generating self-sufficient electricity in remote areas (Lu, 2015) (**Masters, 2013, p. 552**).

In contrast to grid-connected inverters that primarily function as current sources, stand-alone inverters behave as a voltage source, tasked with maintaining stable voltage and frequency by actively controlling active and reactive power (Wang, 2016) (Passey et al., 2009) (**Teodorescu, Liserre, & Rodriguez, 2011, p. 25**). This means they must generate a specific voltage and frequency to match the load demands (Mohammad Alsemaan, 2016). Examples of their application include providing AC power from photovoltaic (PV) arrays or batteries, and serving as uninterruptible power supplies (UPS) (Adekola, 2015). The performance of stand-alone inverters is notably sensitive to factors such as their control schemes and the types of loads they serve (Lu, 2015).

Key Components

The typical structure of a stand-alone inverter system involves several crucial components:

- **DC Energy Source:** This could be a PV array (solar panels) or a battery, providing the initial DC power (Adekola, 2015), (Mohammad Alsemaan, 2016), (Eshita et al., 2010).
- **DC to AC Converter (Inverter):** This is the core component, often a full-bridge inverter consisting of switching devices like IGBTs (Insulated-Gate Bipolar Transistors) or MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) (Adekola, 2015), (Gulbahce, 2022), (Mohan et al., 2003), (Murthi, 2007) (**Rashid, 2017, p. 245**). For higher power applications, three-phase Voltage Source Inverters (VSIs) are recommended.
- **DC Bus:** A stable DC bus is essential to store and provide power to the inverter switches (Lu, 2015) . In two-stage micro-inverters, a **low-powered battery** can act as an energy bank between the DC/DC and DC/AC stages (Tan & Thang, 2018).
- **Filters:** An LC (inductor-capacitor) low-pass filter is commonly used at the output to ensure a high-quality sinusoidal waveform and minimize harmonic distortion (Lu, 2015), (Gulbahce, 2022), (**Rashid, 2017, p. 251**). While LCL filters are more often associated with grid-connected systems for harmonic suppression, they can also be connected to the output of a micro-inverter to reduce harmonic content (Gulbahce, 2022), (Wang, 2016).
- **Pulse Width Modulator (PWM):** This generates the gating signals for the inverter's switches, controlling the output voltage and frequency (Adekola, 2015), (Gulbahce, 2022), (Sarkar, 2015) .
- **Control Unit:** This encompasses the electronic circuitry responsible for managing the inverter's operation (Sarkar, 2015) (Hassaine & Bengourina, 2020) (Kjær, 2005).

Control Strategies and Operation

The control of stand-alone inverters focuses on providing a stable and regulated AC output to the local load.

A. Core Control Objectives

- **Voltage and Frequency Regulation:** Ensuring a stable and constant output voltage and frequency, which is crucial as the inverter is the sole power provider (Lu, 2015) (Rodrigues, 2019) (Ojo, 2022). For grid-forming inverters, this means operating as an ideal AC voltage source (**Teodorescu, Liserre, & Rodriguez, 2011, p. 27**).
- **Frequency Regulation:** Maintaining a stable output frequency to meet load requirements (Alsemaan, 2016) (Wang, 2016)
- **Power Control:** Performing active and reactive power control to ensure system stability (Wang, 2016).
- **Protection:** Providing protection for connected equipment and the inverter itself including current protection and harmonic distortion control (Lu, 2015). For specific loads like induction motors, maintaining a constant voltage-to-frequency ratio is important to prevent magnetic circuit saturation.

B. Inverter Operation Control Types

For stand-alone applications, **Voltage Source Inverter (VSI)** (Mohan et al., 2003), (Mnati, 2018) **controls** are predominantly used to deliver specific voltage and frequency values to the load (Adekola, 2015), (**Rashid, 2017, p. 244**). Modern inverters heavily rely on **digital controllers** over analog ones. A common technique for internal control of inverters is **Pulse Width Modulation (PWM)** (Adekola, 2015). Different PWM strategies, such as Sinusoidal PWM (SPWM), are employed to control output voltage and frequency while minimizing lower-order harmonics (Gulbahce, 2022), (Adekola, 2015), (Krishna & Prasadarao, 2022), (Mohan et al., 2003) (**Masters, 2013, p. 498**).

Specific control methods for stand-alone inverters often include:

- **PI (Proportional-Integral) Control:** Widely used due to its feasibility and ease of implementation (Gulbahce, 2022) (Lu, 2015) (Ding et al., 2022) (Bielskis et al., 2019). For stand-alone voltage control, it's a common strategy (Lu, 2015).
- **Resonant Control:** Based on the Internal Model Principle, this method is ideal for tracking sinusoidal signals with zero steady-state error (Lu, 2015).
- **Dual-Loop Control:** A cascaded control structure (e.g., outer voltage loop and inner current loop) is also relevant for grid-forming inverters in stand-alone mode (Ojo, 2022), (Lu, 2015).

C. Advanced Control Strategies

- **Maximum Power Point Tracking (MPPT):** For PV-based stand-alone systems, MPPT algorithms are crucial. They are typically implemented in a DC/DC converter stage to optimize energy extraction from solar panels (Tan & Thang, 2018) (Kjær, 2005) (Verma, 2019) (Hassaine & Bengourina, 2020) (Alsemaan, 2016) (Tan & Thang, 2018) (Kjær, 2005) (Hassaine & Bengourina, 2020) (**Masters, 2013, p. 521**).
- **Passivity-Based Control:** This framework is used to analyze and design control policies that guarantee stability and enhance dynamic performance in microgrids, including stand-alone operations (Ojo, 2022).

4. Performance Metrics and Challenges

- **Reliability:** Inverters are often considered the weakest link in PV systems due to their shorter lifespan (5-15 years) compared to PV panels (around 25 years) (Rodrigues, 2019), (**Teodorescu, Liserre, & Rodriguez, 2011, p. 275**).
- **Efficiency:** A paramount goal is to achieve high energy conversion efficiency (Alsemaan, 2016) (Tan & Thang, 2018) (Haider, 2021) (Kjær, 2005).
- **Harmonic Distortion (THD):** Ensuring a high-quality sinusoidal output waveform with minimal harmonic content is essential for sensitive loads (Gulbahce, 2022) (Hassaine & Bengourina, 2019) (Jiao, 2017) (Haider, 2021) (Verma, 2019) (Kjær, 2005).

- **Stability:** Maintaining stable operation is the most critical aspect of any control system (Wang, 2016).
- **Cost and Size:** Efforts are continuously made to develop cost-effective and compact inverter solutions (Alsemaan, 2016) (Verma, 2019) (Kjær, 2005) (Sarkar, 2015) (Zong, 2011) .
- **Transient Performance:** The inverter must exhibit good dynamic response to changes in load or source conditions (Ojo, 2022), (Hassaine & Bengourina, 2020).
- **Protection Capabilities:** Stand-alone inverters must incorporate protection features to safeguard connected equipment and themselves (**Fotherby, 2023**).

Stand-Alone Inverter: Types and Applications

A stand-alone inverter is a crucial component in power electronic systems designed for situations where a connection to the main electrical grid is either unavailable or intentionally severed (Gerard, 2020), (Verma, 2019). A common feature of stand-alone systems is the necessity of an energy storage element, such as a battery, to ensure stable and continuous power delivery, especially since solar energy sources are intermittent (Verma, 2019), (Alsemaan, 2016) (Eshita et al., 2010) (Gulbahce, 2022) (Gerard, 2020) (**Masters, 2013, p. 551**).

Types of Stand-Alone Inverters

- **Based on Inverter Operation Control:**
 - **Voltage Source Inverters (VSIs):** These are the predominant type used in stand-alone applications because they are designed to deliver specific voltage and frequency values to the load (Lu, 2015), (Wang, 2016). They are generally **cheaper, lighter in weight, and offer more flexible control** compared to Current Source Inverters (CSIs) (Adekola, 2015). A voltage control inverter, which produces a sinusoidal voltage output, is inherently capable of stand-alone operation (Passey et al., 2009) (**Rashid, 2017, p. 244**).
 - **Current Source Inverters (CSIs):** While inverters can be classified into CSI and VSI (Mnati, 2018), (Mohan et al., 2003), CSIs are less common for direct stand-alone voltage regulation (Rodrigues, 2019).
- **Based on Number of Phases:**
 - **Single-Phase Inverters:** These provide output voltage levels such as $\pm V_{DC}$ in full-bridge mode. Single-phase VSIs are generally suitable for **low-power applications** (Mohan et al., 2003) (**Rashid, 2017, p. 245**). For instance, three separate single-phase inverters can supply three-phase loads, though this configuration requires more switches.
 - **Three-Phase Inverters:** These are the preferred solution for medium and high-power applications (Mohan et al., 2003), (**Teodorescu, Liserre, & Rodriguez, 2011, p. 55**). Three-phase inverters are fundamental in many powers electronic systems, including renewable energy applications (Mnati, 2018).

- **Based on Power Processing Stages:**
 - **Single-Stage Inverters:** Functions such as MPPT and voltage control are handled by a single inverter stage (Adekola, 2015) (Verma, 2019) .
 - **Dual-Stage (Two-Stage) Inverters:** These systems typically involve a DC/DC converter in the first stage to perform voltage step-up and MPPT, with a DC/AC inverter in the second stage (Verma, 2019) (Tan & Thang, 2018) (Gulbahce, 2022) (Zong, 2011).
- **Multi-Stage Inverters:** This category includes systems with more than two power processing stages (Adekola, 2015), (Verma, 2019), (Alsemaan, 2016).

Applications of Stand-Alone Inverters

Stand-alone inverters are essential for providing electrical power in various contexts:

- **Remote and Rural Electrification:** Their most common application is in off-grid systems for remote areas where grid connection is not feasible or too costly (Gerard, 2020), (Verma, 2019), (Lu, 2015), (Eshita et al., 2010), (**Masters, 2013, p. 552**).
- **Powering Institutions and Households:** Stand-alone inverters can provide power for diverse applications such as institutions, telecommunication relay stations, households water heaters, water pumps, and security systems.
- **Photovoltaic (PV) Systems:** They are fundamental in PV-based stand-alone systems, converting the DC power generated by solar panels into usable AC electricity (Adekola, 2015), (Murthi, 2007), (Verma, 2019) (Kjær, 2005) . For PV applications, inverters must not only convert DC to AC but also track the Maximum Power Point (MPP) to maximize energy capture (Rodrigues, 2019) (Kjær, 2005).
- **Uninterruptible Power Supplies (UPS):** Stand-alone inverters are used as the core of AC uninterruptible power supplies, ensuring continuous power to critical loads during grid outages (Adekola, 2015), (Murthi, 2007), (Verma, 2019) (**Rashid, 2017, p. 308**).
- **Autonomous Microgrids:** In a microgrid, when disconnected from the main grid (islanding mode), inverters operate in stand-alone mode and must have grid-forming capabilities to maintain stable voltage and frequency for critical loads (Ojo, 2022) (Wang, 2016) (**Teodorescu, Liserre, & Rodriguez, 2011, p. 26**).
- **Electric Vehicle (EV) Systems:** Inverters convert the DC power from the battery pack into the appropriate AC voltages and currents needed to drive electric motors in vehicles (Mohan et al., 2003).
- **Industrial Applications:** Other applications include **induction heating** and **AC motor drives** (Adekola, 2015) (Murthi, 2007) (Wang, 2016) (Krishna & Prasadarao, 2022). Some VSIs can also function as **Static VAR Generators (SVGs)** or compensators (Adekola, 2015).

2.4.3 Hybrid Inverters (Hybrid Solar Power Systems)

Introduction

A hybrid inverter, also known as a multi-mode inverter, represents a critical evolution in power electronics for renewable energy systems. It serves as an intelligent hub for managing bidirectional energy flow between multiple sources: a photovoltaic (PV) array, a battery energy storage system (BESS), the utility grid, and local AC loads. Unlike traditional grid-tied inverters, which are limited to converting DC power from solar panels for immediate use or grid export, the hybrid inverter's defining feature is its native integration with energy storage. This allows it to store surplus solar energy for later use, provide an Uninterruptible Power Supply (UPS) during grid failures, and execute sophisticated energy management strategies to optimize economic benefits and enhance grid stability. Consequently, it is a foundational technology for achieving residential energy independence and enabling resilient, distributed power generation (Badwawi, Abusara, & Mallick, 2015, pp. 127-128).

Key Components

A hybrid inverter consolidates the functions of several discrete devices into a single, highly integrated unit. Its architecture is built around the following core components:

- **Maximum Power Point Tracker (MPPT) DC/DC Converter:** This input stage is connected to the PV array. It employs algorithms (such as Perturb and Observe or Incremental Conductance) to continuously adjust the array's voltage and current, ensuring that it operates at its peak power point under varying conditions of solar irradiance and temperature. This maximizes the energy harvest from the solar panels (Rashid, 2017, pp. 581-584).
- **Bidirectional DC/AC Inverter (H-Bridge Topology):** This is the central power conversion stage. It converts DC power from the PV array or the battery into grid-compliant AC power. The bidirectional capability also allows it to rectify AC power from the grid to charge the battery. This is typically achieved using a full-bridge (H-bridge) of high-frequency switching semiconductors (IGBTs or MOSFETs) controlled by a Pulse Width Modulation (PWM) signal (Mohan et al., Undeland, & Robbins, 2003, pp. 209-215).
- **Bidirectional Battery Charger/Controller:** This integrated system manages the complete lifecycle of the battery bank. It regulates the charging and discharging currents and voltages, while continuously monitoring the battery's State of Charge (SoC), State of Health (SoH), and temperature. This precise control is essential for ensuring the safety, performance, and operational longevity of the battery system (Hanan et al., 2017, pp. 2-4).
- **Microcontroller / Digital Signal Processor (DSP):** This is the computational core of the inverter. It executes the complex control algorithms that govern all operational decisions, including power flow management, grid synchronization, safety protocols, and battery management. The high processing speed of a DSP is essential for real-time control of the PWM signals (Rafay et al., 2018).

- **Grid Interface and Output Filters (LCL Filter):** This section is responsible for producing a clean, stable, and synchronized AC waveform. It typically employs an LCL (Inductor-Capacitor-Inductor) filter, which is highly effective at attenuating the high-frequency switching harmonics generated by the PWM process. The result is a pure sine wave output with a low Total Harmonic Distortion (THD) suitable for both sensitive loads and grid interconnection (Teodorescu, Liserre, & Rodriguez, 2011, pp. 69-75).
- **Automatic Transfer Switch (ATS) and Anti-Islanding Circuitry:** The ATS is an electromechanical relay that provides the physical connection and disconnection to the grid. The anti-islanding circuitry is a critical safety system that monitors grid parameters (voltage and frequency). In the event of a grid outage, it commands the ATS to open, isolating the home and preventing the inverter from energizing a de-energized grid line, thereby ensuring the safety of utility personnel in compliance with standards like IEEE 1547 (IEEE Standard 1547-2018, pp. 24-28).

3. Control Strategies and Operation

The intelligence of a hybrid inverter is defined by its control strategies, which are designed to achieve specific objectives based on real-time conditions and user-defined priorities.

A. Core Control Objectives

1. **Maximize Self-Consumption:** This is the primary operational objective. The control logic prioritizes powering the local loads directly from the PV array. If solar generation exceeds the load demand, the surplus energy is directed to charge the battery. Only when the loads are satisfied and the battery is fully charged is the remaining power exported to the utility grid (NREL, 2017, pp. 12-14).
2. **Provide Backup Power (UPS Function):** The inverter's control system continuously monitors the grid's voltage and frequency. Upon detecting a deviation outside the nominal range (an outage), it initiates the anti-islanding protocol and transitions to off-grid mode within milliseconds. In this mode, it uses the stored battery energy to form a stable, independent microgrid for powering critical home circuits (Rafay et al., 2018).
3. **Economic Optimization (Peak Shaving / Load Shifting):** In regions with Time-of-Use (ToU) electricity pricing, the inverter can be programmed to minimize costs. It accomplishes this by charging the battery with low-cost energy (from solar or off-peak grid power) and discharging it to power the home during high-cost peak periods, a strategy known as "load shifting" or "peak shaving." (Rafay et al., 2018).
4. **Grid Support Services:** Advanced hybrid inverters can actively participate in maintaining grid stability. This includes functions like frequency regulation (autonomously adjusting power output to counteract grid frequency deviations) and reactive power support (injecting or absorbing reactive power to stabilize local grid voltage), which are becoming increasingly valuable to grid operators (Teodorescu, Liserre, & Rodriguez, 2011, pp. 251-255).

B. Inverter Operation Control Types (Modes)

- **Grid-Tied Mode:** The standard mode when the grid is operational. The inverter is synchronized with the utility and actively manages the four-way power flow between the PV array, battery, loads, and grid (Rafay et al., 2018).
- **Off-Grid (Standalone) Mode:** Triggered during a grid failure. The inverter disconnects from the grid and operates as a standalone voltage source, creating its own stable AC waveform to power the home (Rafay et al., 2018).
- **Backup Mode:** A specific grid-tied configuration where the primary goal is to maintain a high state of charge in the battery (e.g., 90-100%) in preparation for a potential power outage, rather than using the battery for daily economic optimization.
- **Export Limiting (Zero-Export) Mode:** This mode is programmed to comply with utility restrictions that prohibit or limit the amount of power that can be fed back into the grid. The inverter's control system will actively curtail PV generation or direct it to the battery to ensure the export limit is not breached (Rafay et al., 2018).

C. Advanced Control Strategies

- **Time-of-Use (ToU) Arbitrage:** The control algorithm uses a pre-programmed utility tariff schedule to make intelligent charge/discharge decisions. By buying (charging) when electricity is cheap and selling or self-consuming (discharging) when it is expensive, it performs economic arbitrage to minimize the total energy cost (Rafay et al., 2018).
- **Predictive Energy Management:** This advanced strategy integrates external data sources, such as weather forecasts and historical load data. By using machine learning algorithms to predict upcoming solar generation and household consumption, the inverter can make more informed decisions. For example, it might preserve battery power if it anticipates a cloudy day, ensuring sufficient energy is available for the evening (Antonopoulos et al., 2020, p. 7).
- **Virtual Power Plant (VPP) Participation:** A VPP is a cloud-based aggregation platform that networks a large fleet of distributed energy resources, such as hybrid inverters. The VPP operator can dispatch this aggregated capacity to provide grid services at scale, such as frequency response or peak demand reduction. Homeowners are typically compensated for allowing their systems to participate (Sadeghi-Mobarakeh et al., 2017, pp. 1-2).

4. Performance Metrics and Challenges

Performance Metrics:

- **Efficiency:** Key efficiency metrics include **Maximum Conversion Efficiency** (the optimal efficiency of the DC/AC conversion stage, often >97%) and **Round-Trip Efficiency** (the ratio of energy discharged from the battery to the energy used to charge it, accounting for all conversion and storage losses, typically ranging from 85% to 95% for lithium-ion systems) (Rafay et al., 2018).

- **Switchover Time:** This is the duration from the moment a grid outage is detected to when the inverter is providing stable backup power to the loads. A switchover time of less than 20 milliseconds is considered high-quality for UPS applications (Rafay et al., 2018).
- **Total Harmonic Distortion (THD):** A measure of the purity of the output AC sine wave. Grid codes such as IEEE 1547 mandate that THD must be below 5% to prevent negative impacts on the grid and other connected devices. High-quality inverters typically achieve a THD of <3% (Rafay et al., 2018).
- **Power Rating (Continuous and Peak):** The inverter's capacity is rated in kilowatts (kW) for both **continuous power output** (the load it can sustain indefinitely) and **peak power output** (a short-term overload capacity, crucial for starting inductive loads like motors and pumps) (Rafay et al., 2018).

Challenges:

- **System Complexity and Cost:** The integration of multiple power conversion stages, advanced control hardware, and sophisticated software makes hybrid inverters significantly more complex and expensive than standard grid-tied inverters (Rafay et al., 2018).
- **Battery Interoperability and Communication:** Ensuring seamless and reliable communication (e.g., via CAN bus) and operational compatibility with a wide range of battery technologies, brands, and chemistries is a major engineering and standardization challenge (Rafay et al., 2018).
- **Regulatory Compliance:** Hybrid inverters must undergo rigorous testing and certification to comply with a comprehensive set of standards governing safety (e.g., UL 1741), grid interconnection (e.g., IEEE 1547), and electromagnetic compatibility (Rafay et al., 2018).
- **Thermal Management:** The high power density of modern inverters generates significant heat. Designing an effective thermal management system (using heatsinks, fans, or liquid cooling) is critical for maintaining performance, ensuring reliability, and achieving a long operational lifespan (Yang et al., 2011, pp. 1-3).

5. Types and Applications

Types:

- **Single-Phase Hybrid Inverters:** The most prevalent type, designed for standard residential electrical service (e.g., 120/240V in North America, 230V in Europe) (Rafay et al., 2018).
- **Three-Phase Hybrid Inverters:** More powerful units designed for large residential properties, commercial buildings, and agricultural applications with three-phase power requirements (Rafay et al., 2018).
- **DC-Coupled Systems:** In this architecture, the PV array and the battery are connected on the common DC bus of the inverter. This configuration is highly efficient for new installations, as PV power can charge the battery directly without undergoing a DC-to-AC-to-DC conversion, minimizing losses (NREL, 2017, p. 8).

- **AC-Coupled Systems:** In this architecture, a standard grid-tied solar inverter is installed alongside a separate, standalone battery inverter. The two are "coupled" on the AC side of the system. This approach is ideal for retrofitting battery storage into an existing PV installation without replacing the original solar inverter (Rafay et al., 2018).

Applications:

- **Residential Energy Management:** The primary application, enabling homeowners to reduce their reliance on the grid, protect against power outages, and lower their electricity bills (Rafay et al., 2018).
- **Commercial Demand Charge Reduction:** Businesses often face high "demand charges" based on their peak power consumption. A hybrid inverter and battery system can be used to "shave" these peaks by discharging the battery, thereby reducing a significant component of their utility bill (Rafay et al., 2018).
- **Off-Grid Power Systems:** Hybrid inverters are the central component for creating reliable and continuous power in remote locations without access to a utility grid, such as rural homes, telecommunication towers, and medical clinics (Rafay et al., 2018).
- **Community Microgrids:** Hybrid inverters can serve as the building blocks for community-scale microgrids. By networking multiple systems within a neighborhood or campus, they can provide a high level of energy resilience, allowing the entire community to "island" from the main grid during a widespread outage (Rafay et al., 2018).

2.4.4 Comparison: Stand-alone vs. Grid-tie Inverters vs. Hybrid Inverter

Table 2.4: Comparison: Stand-alone vs. Grid-tie Inverters vs. Hybrid Inverter

Feature	Stand-alone Inverter	Grid-tie Inverter	Hybrid Inverter
Primary Function	Convert DC power to AC power for off-grid consumption (Mohammad Alsemaan, 2016). Acts as a voltage source (Wang, 2016).	Convert DC power to AC power to inject into the utility grid (Adekola, 2015). Primarily acts as a current source (Wang, 2016).	Manages power flow between multiple sources: solar panels (DC), batteries (DC), the utility grid (AC), and local loads (AC). It converts power between DC and AC as needed (Rafay et al., 2018).
Grid Connection	None ; operates independently from the main utility grid (Mohammad Alsemaan, 2016).	Directly connected to the utility grid (Mohammad Alsemaan, 2016).	Capable of operating in both grid-tied (on-grid) and standalone (off-grid) modes. It supports bidirectional power flow, allowing it to both draw from and feed power to the grid (Rafay et al., 2018).
Energy Storage	Requires energy storage (e.g., batteries) to ensure continuous power supply due to intermittent renewable sources (Gulbahce, 2022).	Generally, does not require batteries , as the grid acts as storage for excess power (Gulbahce, 2022) & (Lu, 2015).	Integrates directly with a battery bank. It controls the charging of the battery (from solar or grid) and its discharging to power the home or export to the grid (Rafay et al., 2018).
Control Objective	To generate a certain voltage with a proper frequency output to meet the load demand (Mohammad Alsemaan, 2016). It maintains stable voltage and frequency by performing active and reactive power control (Wang, 2016). An OSAP (one-sampling-ahead-preview) voltage controller can be applied (Lu, 2015).	To inject a scheduled amount of active and reactive power into the grid (Wang, 2016). Uses PID current control to reduce switching losses (Mnati, 2018). The inner current loop controls the current injected into the grid in phase with the grid voltage (Mohammad	To maximize solar self-consumption , provide backup power during outages, and perform peak shaving (using stored battery energy during high-cost electricity periods) (Rafay et al., 2018).

		Alsemaan, 2016). An OSAP current controller can be applied (Lu, 2015).	
Synchronization	Not applicable, as it operates independently from the grid (Passey et al., 2009).	Essential for proper grid-tied operation, requiring the inverter's output to match the grid's voltage and frequency (Wang, 2016), (Hassaine & Bengourina, 2020), (Zong, 2011) & (Adekola, 2015). Phase-Locked Loop (PLL) is commonly used for synchronization and generating reference currents (Mnati, 2018).	Uses a Phase-Locked Loop (PLL) circuit to precisely match its output voltage, frequency, and phase with the utility grid before connecting and exporting power. (Rafay et al., 2018)
Anti-Islanding	Not applicable, as it operates off-grid.	Must have the ability to detect a fault or blackout in the grid and disconnect from the system (Rodrigues, 2019). It should reconnect only when normal grid conditions are restored (Adekola, 2015).	A critical safety feature that detects a grid outage and immediately stops exporting power. This prevents the inverter from energizing a dead grid, protecting utility workers. (Adekola, 2015) & (Rodrigues, 2019).
Power Output Quality	Must produce a stable sinusoidal voltage waveform for local loads (Passey et al., 2009).	Injected current should be sinusoidal with low Total Harmonic Distortion (THD) (e.g., less than 5% according to IEEE Standard 1547) (Wang, 2016). An LCL filter is often used to reduce harmonic content and improve waveform quality (Gulbahce, 2022).	Produces a Pure Sine Wave output with very low Total Harmonic Distortion (THD) , typically under 3%, making it safe for all sensitive electronics (Lu, 2015).

<p>Typical Applications</p>	<p>Commonly used in remote areas where self-generated electricity is the only solution (Lu, 2015), and for small-scale residential PV systems (Adekola, 2015).</p>	<p>Widely used in renewable energy applications connected to low voltage grids (Mnati, 2018), distributed generators (Adekola, 2015), and photovoltaic systems for industrial, commercial, and residential solar rooftops (Hassaine & Bengourina, 2020).</p>	<p>Residential solar + storage systems, small commercial buildings, off-grid homes, and any location needing a reliable Uninterruptible Power Supply (UPS) function. (Rafay et al., 2018)</p> <p>Microgrids and other distributed generation (DG) systems that require flexible operation, switching between grid-connected and islanded modes (Kiriakos, 2019) & (Ojo, 2022). Also suitable for smart grid applications (Adekola, 2015).</p>
<p>Common Filter Types</p>	<p>LC filter (Lu, 2015).</p>	<p>LCL filter (Adekola, 2015). LC filter (Lu, 2015), (Sarkar, 2015), (Jiao, 2017) & (Sarkar, 2015). C-L filter for Current Source Inverters (CSI) (Rodrigues, 2019).</p>	<p>Employs output filters, such as L, LC, or LCL filters, to smooth the high-frequency switched voltage into a clean, grid-quality AC waveform. (Rafay et al., 2018) & (Ojo, 2022).</p>
<p>Cost & Efficiency</p>	<p>May be simpler in terms of control (no grid synchronization). Cost is influenced by the need for battery storage.</p>	<p>Generally characterized by high efficiency (Gulbahce, 2022). VSI (Voltage Source Inverter) based topologies are often cheaper and lighter with better control than CSI (Adekola, 2015). Single-stage systems can reduce weight, cost, and achieve high efficiency (Alsemaan, 2016) & (Haider, 2021). The use of</p>	<p>Higher initial cost compared to standard grid-tied inverters due to added complexity but provides long-term savings. Modern units have very high efficiency, often >95% (Rafay et al., 2018)</p>

		<p>SiC (Silicon Carbide) (Rodrigues, 2019) and GaN-HEMTs (Gallium Nitride - High-Electron-Mobility Transistors) (Gulbahce, 2022) & (Gulbahce, 2022) allows for higher switching frequencies and improved efficiency, reducing overall system size and weight.</p>	
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2.5 Grid-Tied Inverters' Function

An essential part of distributed generation (DG) systems, a smart inverter connected in a grid-tied mode serves as a direct conduit between the renewable energy system and the grid. For the grid to receive power from renewable energy sources, inverters are essential. Because both require inverters to connect to the grid, this is especially true for sources that generate DC power, like solar photovoltaic systems, or intermittent sources, like wind and solar, that may be stored in DC batteries. Consequently, the inverter is essential to the grid's ability to receive power from renewable energy sources. A voltage source inverter (VSI) is the most often designed kind of inverter for the use.

which can feed energy to the utility grid with a well-regulated DC link at the input. Typically, PV inverters are voltage source base converters. Inverters classified as single-stage and multistage depending on the processing of power in one or two stages. In two-stage inverter topologies, a DC link capacitor bus is installed for source interconnection considerations and to keep the DC voltage ripple within limits. Single-stage three-phase grid-connected PV systems have also been considered. There are different kinds of PV inverters for grid-tied systems. Transformerless PV inverters have become popular in grid-connected solar systems in recent years because of their cost and size advantages as well as the flexibility they provide in managing grid current. In contrast to large, costly line frequency transformers, a key component of the distributed generation interface, the smart inverter helps to increase the utility grid's efficiency and dependability. Smart inverter systems and other power electronics interfaces are necessary to successfully attain reliability with renewable energy sources' power output. New issues with maintaining grid stability and preventing anti-islanding have arisen as a result of the development of smart inverters. Nonetheless, the smart solar inverter is thought to be a key element that will facilitate the successful shift to a more intelligent electrical grid that can provide consistent and dependable electricity flow.

Because they can increase stability, dependability, and other aspects of the grid system, smart inverters are crucial. quality of the grid's power supply Smart inverters have the ride-through capability, which enables distributed solar sources to stay connected, in contrast to traditional inverters, which are required by the IEEE 1547 standard to trip and disconnect during voltage or frequency fluctuations. when there are minor instability Control Techniques for Power .

2.6 Regulation and Grid Stability

Advanced control techniques for grid-tied inverters are essential to overcoming the difficulties presented by RES integration and dynamic loads. These tactics seek to increase grid dependability, stability, and power quality. By enabling distributed solar sources to stay connected during minor voltage and frequency fluctuations, smart solar inverters increase the electric grid's dependability. Smart inverters have this ride-through capability, in contrast to conventional inverters, which are made by the IEEE 1547 standard to trip and disconnect under

voltage or frequency fluctuations. By producing and absorbing reactive power in addition to real power, smart PV inverters can enhance grid reliability beyond withstanding disruptions. This lowers voltage instabilities linked to distributed solar power. Reactive power control, which is frequently associated with power factor regulation, can enhance grid stability, reduce transmission losses, and stabilize voltage at the distribution level. Large generating stations can regulate reactive power, but it's crucial to add and penetrate Voltage-Ampere reactive (VARs) at various locations throughout the transmission and distribution network to control voltage. Equipment and loads may be adversely affected by redundant voltage. To helping reduce frequency and preserve frequency stability in the transmission network, the smart inverter's active power must be controlled. By facilitating real-time communication between grid operators and dispersed solar sources, smart solar inverters increase grid flexibility by allowing for remote function activation and deactivation as well as adjustment of controlled voltage and frequency set points as necessary. The following are a few instances of dynamic functionalities: For quick watt response to unexpected voltage conditions, use dynamic voltage-watt control. The ability to regulate both reactive and active power flow in either direction is one of the specific control goals for grid-tied inverters.

The inverter can supply a specific active and reactive power set point when in grid-connected mode. Because of the nature of the control mode, the inverter's power quality is largely unaffected by transients such as load changes or power variations from RES. The design and development of the current controller for the grid-connected inverter is a crucial control component. VSI control systems compute the current. Inverters require high performance from control strategies in both normal and fault situations, particularly with regard to voltage sags, a significant power quality issue that impacts sensitive loads and grid-tied inverters. The system's stability should be guaranteed by control strategies. A few suggested grid-side control techniques cascade the DC-Link in place of a current loop, connect a voltage loop with an inner power loop indirectly regulating the current. Additionally, control strategies are necessary to guarantee that the filter design is effective in reducing the harmonics injected into the grid to standards-acceptable levels. In three-phase voltage source inverters, LCL filters are discussed in relation to current regulation and harmonic reduction. LCL filter-based control design is necessary taking stability-related factors like damping resistance into account. Additional control factors discussed in the sources include grid synchronization through Phase Locked Loop (PLL) and Maximum Power Point Tracking (MPPT) to maximize energy capture from PV modules.

To detect islanding operation, control the DC-link voltage, and align the inverter with the grid voltage. Different kinds of controllers, such as PI controllers, that employed. Smart inverter systems frequently modeled and simulated, carried out in settings such as MATLAB/SIMULINK. In conclusion, there are serious stability and power quality issues when variable renewable energy sources are integrated into the grid, particularly when dynamic loads are present. The main interface technology is grid-tied inverters, especially smart inverters. To manage the flow of active and reactive power, control voltage and frequency, mitigate power quality problems like harmonics and voltage sags, synchronize with the grid, and ensure

stable and reliable power, advanced control strategies are essential for these inverters dependable grid performance at spite of renewable energy's inherent unpredictability.

2.7 Previous Work and Related Research

Solar energy has gained increasing global attention as a way to combat climate changes, along with falling PV system costs and other positive factors that contribute to the increased penetration of PV systems and contribution of PV to global energy supply. However, the functional characteristics of an RES (wind or solar) have certain undesirable traits (primarily, the intermittent generation of generation), which can greatly complicate the reliable and effective operation of the grid-connected system due to issues with power quality, grid stability, and ultimately the safety of the utility grid. Novel control strategies of grid-connected systems will be developed to address the above issues and enhance system reliability. The critical link between the RES, wherever it is and the grid is the smart inverter because it provides a direct interface, anything done with the RES or building that must use it will be through the inverter. Thus, the evolution of smart inverters is paramount to the stability of the grid and all of the associated electricity generating and storing features such as anti-islanding. Research efforts have ultimately focused on developing inverter technology and control strategies to mitigate the adverse effects of RES and to improve the performance of the grid.

The Studies Discussed in This Paper: The design of a three-phase grid-tied inverter with active and reactive power control capabilities for distributed generators (DG) and renewable energy sources (RES) is the focus of this research project. With a carefully controlled DC link, the Voltage Source Inverter (VSI) that was designed can provide energy to the utility grid. Implementing a filter to successfully lower harmonics introduced into the grid to acceptable levels and creating a strategy to regulate the inverters real and reactive power outputs are essential components of the suggested solution. The goal of this control is to assist in resolving the distribution system's power quality and instability issues. The layout Modelling and simulating of a 10 kW three-phase system were accomplished with the use of MATLAB/SIMULINK, utilizing simulations, with step changes in active and reactive power references to analyze the tracking responses. Specific goals of the work were to improve power quality, develop an inverter with the capacity to control reactive power flow and active power flow bidirectionally, and develop a grid-connected inverter with efficient and reliable performance. The justification for this work identified the problems of the increasing number of grid connected solar PV inverters, i.e. the power quality issues and that stability/safety problems are influenced by the intermittent nature of RES.

Relevance with our project: This work is very relevant as it tackles the main issue of improving grid stability and power quality, both elements of grid operation performance, by assessing the inverter as a interface for RES. Using active, reactive power control as tools to improve grid performance was an emphasis of the work & was motivated by the intermittent nature of RES, which drive in problems.

Distinction from our project: Although the difficulties of intermittent renewable energy sources are the driving force behind this research, the abstract and goals specifically address power quality and stability issues that are mostly brought on by intermittency and harmonics. In particular, "dynamic load" and "changing power generation" are mentioned in your project title as important elements impacting the requirement to enhance grid performance and stability. Although load changes are mentioned as possible transient states affecting power quality, the research described here does not specifically state addressing the unique challenges arising from the interaction between changing generation and dynamic load as a central theme.

Development of Hybrid Inverters for Enhanced Resilience (Rafay et al., 2018): This research explores the architecture and capabilities of hybrid inverters, which natively integrate PV generation, battery energy storage systems (BESS), and a connection to the utility grid. These multi-mode inverters are designed to intelligently manage bidirectional power flow, enabling functions such as maximizing self-consumption, providing uninterruptible power supply (UPS) during outages, and performing economic optimization through peak shaving (p. 48, 49).

Similarity with our project: The core goal of this research aligns with our project: enhancing grid resilience and performance in the face of variability. A hybrid system inherently addresses the problem of "changing generation" by using a battery to smooth the power output and can better serve "dynamic loads" by providing instantaneous power from storage. This represents a hardware-centric solution to the same fundamental challenge our project addresses.

Difference from our project: The primary difference lies in the technological solution being investigated. Our project focuses on improving the stability of a grid with standard *grid-tied* PV systems, exploring solutions like grid reinforcement and advanced control functions (Q(V) control) within that context. The work by Rafay et al. focuses on *hybrid* systems, where the integrated battery is the key enabling component. Our study analyzes how to improve the grid's ability to host RES, whereas this research analyzes a more advanced, self-sufficient RES system.

Comparative Analysis of Advanced Current Controllers (Wang, 2016): *This research delves into the performance limitations of conventional inverter control methods. As noted in the documentation, it highlights that traditional PI controllers, while widely used, can struggle with transient response, exhibiting overshoot and oscillation (p. 19). The work compares the performance of PI controllers against more advanced strategies, such as Pseudo-Derivative-Feedback (PDF) control, demonstrating that alternative methods can achieve significantly faster settling times and improved transient performance for current control loops (p. 17, 19).*

Similarity with our project: This work is similar in that it focuses on improving "performance," a key term in our project title. The performance of the inner current controller directly impacts the overall system's ability to react to disturbances and accurately deliver the power required for stability. Optimizing this control loop is a crucial step in achieving a high-performance, stable grid connection.

Difference from our project: The difference is the level of analysis. Wang's research is focused on the *micro-level* of the control algorithm, comparing the mathematical performance and transient response of different controller implementations. Our project operates at a *macro-level*, analyzing the overall stability of the distribution network. We utilize a PI controller as a standard functional block, whereas this research analyzes the intricate behavior of that block itself.

Comprehensive Framework for Grid-Tied System Design and Challenges (Adekola, 2015): *This work serves as a foundational reference, providing a holistic overview of the design, control, and protection of grid-tied inverter systems for renewable energy applications. It details the primary challenges introduced by the intermittent nature of RES, such as solar PV, and outlines the standard components and control strategies used to mitigate these issues. Key topics covered include the structure of Voltage Source Inverters (VSIs), the necessity of output filters, the critical role of PI controllers for current and DC voltage regulation, and essential safety mechanisms like anti-islanding (p. 7, 10, 11).*

Similarity with our project: This research is fundamentally similar as it addresses the core problem of grid instability caused by RES integration. It provides the essential building blocks for our system model, including the inverter topology, the use of PI controllers in a cascaded control structure, and the necessity of simulation for design verification (p. 12). Its discussion on managing power quality and stability issues is directly aligned with our project's primary objectives.

Difference from our project: While this framework provides the general context, its focus is on the challenges of *intermittency* in a broad sense. Our project is more specific, concentrating on the complex, dynamic *interaction* between changing power generation and dynamic load conditions as the central problem. This reference serves as a comprehensive guide to the components involved, whereas our project applies these components to analyze a specific, interactive system-level phenomenon.

Comprehensive Reviews of Inverter Topologies and Control Schemes (Teke & Latran, 2014): *This book offers a thorough analysis of several inverter topologies and control schemes that offer multiple functions for use in distributed generation systems. It highlights that the growing number of grid-connected solar PV inverters has created issues such as power quality problems and concerns regarding grid stability and safety, primarily because of the inherent intermittent nature of RES.*

Similarity with our project: This review article is foundational to understanding the landscape of solutions for grid integration challenges posed by DG from RES. It directly relates to the challenges of power quality and grid stability that your project aims to improve. It covers the enabling technology (inverters) and the methods (control schemes) relevant to managing DG impacts.

Difference from our project:

Instead of suggesting or putting into practice a particular solution, this is a review of current technologies and methodologies. Additionally, according to the source context, the review primarily addresses power quality and stability issues associated with RES intermittency, however, it does not specifically identify or examine the effects of "dynamic load" as a separate or combined factor.

Analysis and Design of a Smart-inverter for Renewable Energy Interconnection to the Grid Reznik (2012): This Masters dissertation focuses on the detailed analysis and design aspects of a smart inverter, specifically intended for the interconnection of renewable energy sources with the power grid. Smart inverters are recognized for their potential to enhance the reliability and efficiency of the utility grid and are considered significant components of the DG interface.

Similarity with our project: This work is very similar in scope as it centers on the smart inverter as the crucial interface between RES and the grid, aiming for effective integration. The underlying goal is likely to improve grid performance and stability, which is a key objective of your project.

Difference from our project: While the research focuses on a smart inverter for RES grid interconnection, its specific emphasis, as indicated by the title, is on the design and analysis of the inverter itself. It does not explicitly state that addressing the combined challenge of "**changing power generation**" *interacting with* "**dynamic load**" to improve grid stability and performance is the primary driver or focus of the work, although a well-designed smart inverter should inherently be able to handle variable conditions.

Improvement of Power Quality and Reliability with Multifunctional PV-Inverters in Distributed Energy Systems by Geibel et al. (2009): This research investigates the use of multifunctional inverters connected to photovoltaic systems to achieve improvements in power quality and overall system reliability within distributed energy systems. Such inverters can perform functions like generating and absorbing reactive power, which helps enhance grid reliability and mitigate voltage instabilities linked to distributed solar power.

Similarity with our project: This work directly shares the goal of improving power quality and reliability (aspects of grid performance and stability) in systems incorporating distributed PV generation. It utilizes multifunctional inverters as the tool for these improvements, mirroring the focus on the inverter in your project.

Difference from our project: The title and description provided in the source emphasize general power quality and reliability improvement. They do not explicitly mention or center the research around the challenge posed by "**dynamic load**" or the specific combined effect of "**changing power generation**" and dynamic load conditions on grid stability and performance.

Application of Advanced Control in Rotating Reference Frames (Teodorescu et al., 2006): This body of research focuses on the application of advanced control theory for grid-tied inverters, particularly the use of a synchronous rotating reference frame (dq-transformation). This technique is pivotal for modern inverter control, as it transforms the three-phase AC grid quantities into DC quantities in the controller's frame of reference. This allows for the decoupled control of active power (P) and reactive power (Q) by manipulating the direct-axis (i_d) and quadrature-axis (i_q) current components, respectively (p. 53).

Similarity with our project: The control theory detailed in this research provides the fundamental mechanism for our proposed solution. Our project aims to improve grid stability by using the inverter to dynamically control active and reactive power. The dq-transformation framework explained by Teodorescu et al. is precisely the method that enables the implementation of the $P(V)$ and $Q(V)$ grid support functions, which are central to our investigation for voltage regulation and performance enhancement.

Difference from our project: This research is focused on developing and explaining the *control algorithm and theory* itself. It operates at a mathematical and signal-processing level. Our project is a *system-level application* of this theory. We use the control methods described by Teodorescu et al. as a tool to solve a practical problem in a real-world distribution network, analyzing the overall system impact rather than the internal workings of the control algorithm in isolation.

2.8 Summary

This chapter reviews existing research to understand the challenges and solutions for modernizing the power grid, especially with the rise of renewable energy.

The main problem is that traditional power grids were built for predictable power plants. The increasing use of solar and wind power, which are unpredictable and depend on the weather, can cause instability in the grid's voltage and frequency. This is made even more complex by the constantly changing power demands of consumers (dynamic loads).

To understand the solutions, the review first explains the three main types of solar power systems:

- **On-Grid Systems:** These are the most common. They are connected to the utility grid, allowing homeowners to use solar power and sell any excess. However, for safety, they must shut down during a power outage.
- **Off-Grid Systems:** These are completely independent and use batteries to store power. They are ideal for remote locations but are more expensive and limited by their battery capacity.
- **Hybrid Systems:** These combine the best of both, using a grid connection *and* a battery. They can provide backup power during an outage, store solar energy for use at night, and still interact with the grid.

The review then dives into the key technology that makes these systems work: the **inverter**. It explains that each system type requires a specific kind of inverter (grid-tie, stand-alone, or hybrid) to manage the flow of electricity. The chapter highlights the importance of modern **smart inverters**. These advanced devices don't just convert power; they actively help stabilize the grid. They use sophisticated control strategies to precisely manage power flow, which helps regulate the grid's voltage and frequency.

Finally, the chapter looks at previous research and finds that while many studies have focused on using inverters to solve problems caused by renewable energy, they often don't analyze the combined effect of **both changing power generation and dynamic loads** acting together. This review establishes a clear need for the current project, which aims to improve overall grid stability by focusing specifically on this complex interaction.

Chapter 3: System Design and Methodology

3.1 System Overview

The next section covers system design and the design methodology.

The next section provides an overview of how the system is structured and works.

Currently, solar PV systems and other Renewable Energy Sources (RES) are being deployed with increasing frequency, necessitating the development of effective grid integration methods. According to Adekola (2015), the distributed nature of these generators often results in unreliable power output due to source availability. The connection of RES to the utility grid is primarily facilitated by grid-tied inverter power electronic systems. While the inverter is crucial for integrating Distributed Generation (DG) and enhancing smart grid reliability, the high penetration of grid-connected inverters introduces significant challenges, including power quality issues, stability concerns, and safety risks. Specifically, the intermittency of RES can compromise power system stability. Consequently, this work aims to address these challenges by developing a robust inverter interface system designed to mitigate these adverse effects.

3.2 Design Specifications

To build a grid-tied inverter system that is both efficient and grid-compliant, specific design rules and standards must be followed (Adekola, 2015). A pertinent example from the literature describes a research project for a 10 kW three-phase voltage source inverter designed for utility connection. The specifications for this system included a maximum DC bus voltage of 700V, a maximum power output of 20kW, a maximum DC current of 29A, a switching frequency of 20kHz, and a standard output frequency of 50Hz. Additionally, the design required a 0.5 power factor capability and a maximum phase current of 60A (Mohan et al., 2003).

Regarding power quality and control, Adekola (2015) emphasizes that designers must employ output filters to minimize harmonic injection, ensuring compliance with IEEE 1547 requirements which limit the Total Harmonic Distortion (THD) of the output current to 5%. The smart inverter is expected to actively manage both real power and VARs to enhance grid reliability. Effective control strategies, implemented via precise management of the inverter's power switches, are essential for attaining high dynamic performance and accurate regulation of active and reactive power flow. Furthermore, anti-islanding features are a mandatory safety requirement. Finally, device selection must include safety margins for switching overvoltage transients and overall reliability, taking into account potential grid voltage fluctuations which, according to some grid codes, can raise RMS grid voltage by up to 115% (Rodrigues, 2019).

3.3 Inverter Component Selection

The inverter transforms power from PV panels into the form used by most local or grid power sources (Adekola, 2015). Voltage Source Inverters (VSI) are used to connect the grid to RES-based generators in systems tied to the grid (Adekola, 2015). A VSI sends energy to the grid while keeping the DC link voltage at its input well regulated (Adekola, 2015). A three-phase voltage source inverter is built around the half-bridge (Adekola, 2015) as its central element. The standard topology for a three-phase VSI places six switches in three parallel branches (Sarkar, 2015). Generally, IGBTs or MOSFETs were chosen for these switches, as their ability to break down, resistance, heat conductivity and dependability are evaluated (Rodrigues, 2019).

Commercial and utility companies frequently depend on three-phase inverters for their needs (Adekola, 2015). One of the great things about three-phase systems is that they avoid the frequent downswing in power that single-phase systems have. The inverter is linked to the grid with help from a passive output filter which minimizes switching harmonic distortion (Sarkar, 2015). There are mainly two types of filters commonly used: the C-L filter (Rodrigues, 2019) and the LCL filter (Sarkar, 2015). While LCL filters do a good job reducing harmonics, they must be stable and can be stabilized either by adding damping resistors or applying it actively in the control (Sarkar, 2015).

In some cases, DC-DC converters such as boost converters are put ahead of the inverter in a system, especially if the DC source has a voltage that's lower than the needed DC-link voltage to connect to the grid (Kjær, 2005). The final product is designed by first modeling, then simulating to confirm it works properly (Adekola, 2015). A smart inverter uses advanced power electronics and control to properly handle changing power from DG and maintain reliable performance of the grid (Adekola, 2015).

Note: Three-phase inverter designs and applications for grid connection are primarily covered in the sources that are provided. Although single-phase systems are discussed in relation to power quality disturbances (Adekola, 2015), and single-phase inverters are mentioned as a type of VSI (Sarkar, 2015), these sources do not primarily focus on detailed hardware design for a single-phase inverter. The three-phase focus of the sources is largely reflected in the discussion above.)

3.4 Control Strategy and Design

The design of control strategies is **paramount for grid-tied three-phase inverters** (Mohammad Alsemaan, 2016), as they serve as the crucial interface between renewable energy sources and the utility grid, enabling power conditioning capabilities (Ojo, 2022). The primary goal of these control systems is to produce a **high-quality sinusoidal output current**, minimize disturbances, eliminate harmonics, synchronize with the grid's frequency, regulate active and reactive power, and ensure resilience against grid disturbances (Lu, 2015). Inverters convert DC power from solar panels into AC power suitable for daily use and grid integration (Gulbahce, 2022). They are broadly categorized based on their function within microgrids: **grid-forming inverters** regulate voltage amplitude and frequency, while **grid-feeding**

inverters operate as power or current-controlled sources, providing specified active and reactive power (Ojo, 2022).

Control tasks are generally divided into two main parts:

- **Input-side control:** Focuses on extracting **maximum power** from photovoltaic (PV) modules and includes protection mechanisms. This is often achieved through Maximum Power Point Tracking (MPPT) algorithms (Hassaine & Bengourina, 2020) (Rodrigues, 2019) (Hassaine & Bengourina, 2019) (Kjær, 2005).
- **Grid-side control:** Manages active and reactive power, addresses power quality concerns, provides current protection, and performs harmonic compensation to ensure system dynamics and stability (Hassaine & Bengourina, 2020).

3.4.1 Design of a PWM Technique and the Control Strategy

Given a series of DC voltage values, most inverters generate needed AC voltage or current by applying PWM (Rashid, 2017). The switching pattern and time duration of the inverter's semiconductor switches can be managed using PWM (Sarkar, 2015). How long a switch stays on for within a given period relates to modulation and is known in SPWM/SVPWM as duty cycle modulation. Gating pulses for the switches are generated when a modulating signal is compared with a carrier signal of a high-frequency triangular or sawtooth shape (Mohan et al., 2003). If we divide the modulating signal's maximum value by the carrier's, the result is the modulation index which decides the output voltage amplitude (Rashid, 2017). The simplest form of this technique, known as Sine-Triangle PWM, is illustrated in the figure below.

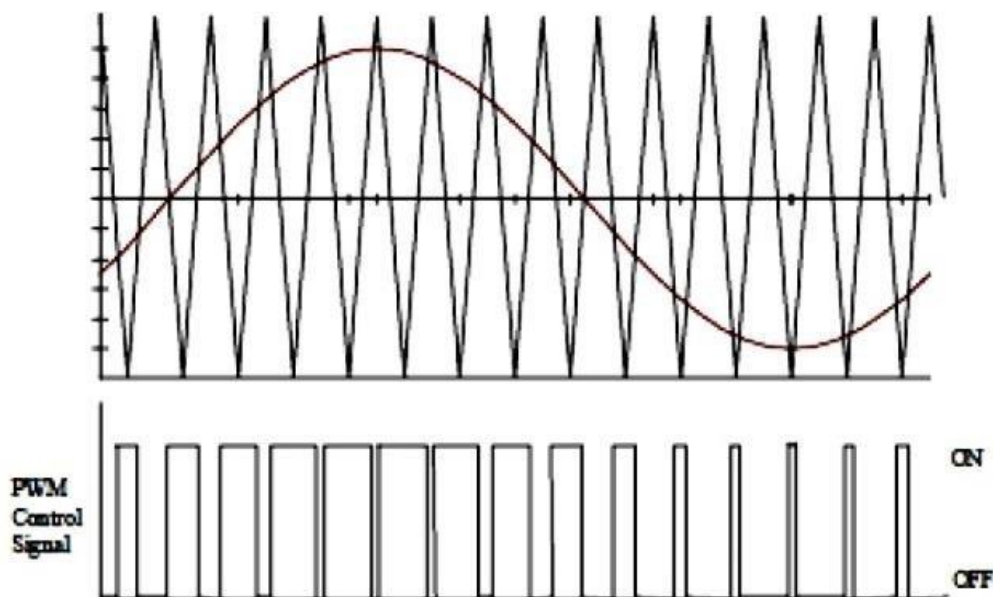


Figure 3.1: The basic principle of Sine-Triangle PWM. (Hassaine & Bengourina, 2019)

In this method, a low-frequency sine wave (the reference signal) is compared with a high-frequency triangle wave (the carrier signal). The rule for generating the "PWM Control Signal" is straightforward: whenever the sine wave's value is higher than the triangle wave's, the output

signal is turned 'ON'. Conversely, when the sine wave's value is lower than the triangle wave's, the signal is turned 'OFF'. As you can see, this creates a series of rectangular pulses whose width varies—the pulses are widest where the sine wave is at its peak and narrowest where it is at its lowest point. This is how the shape of the sine wave is encoded into a digital ON/OFF signal.

While the first figure shows the basic principle, the figure below illustrates how this concept is applied in a practical single-phase inverter to generate a complete AC output.

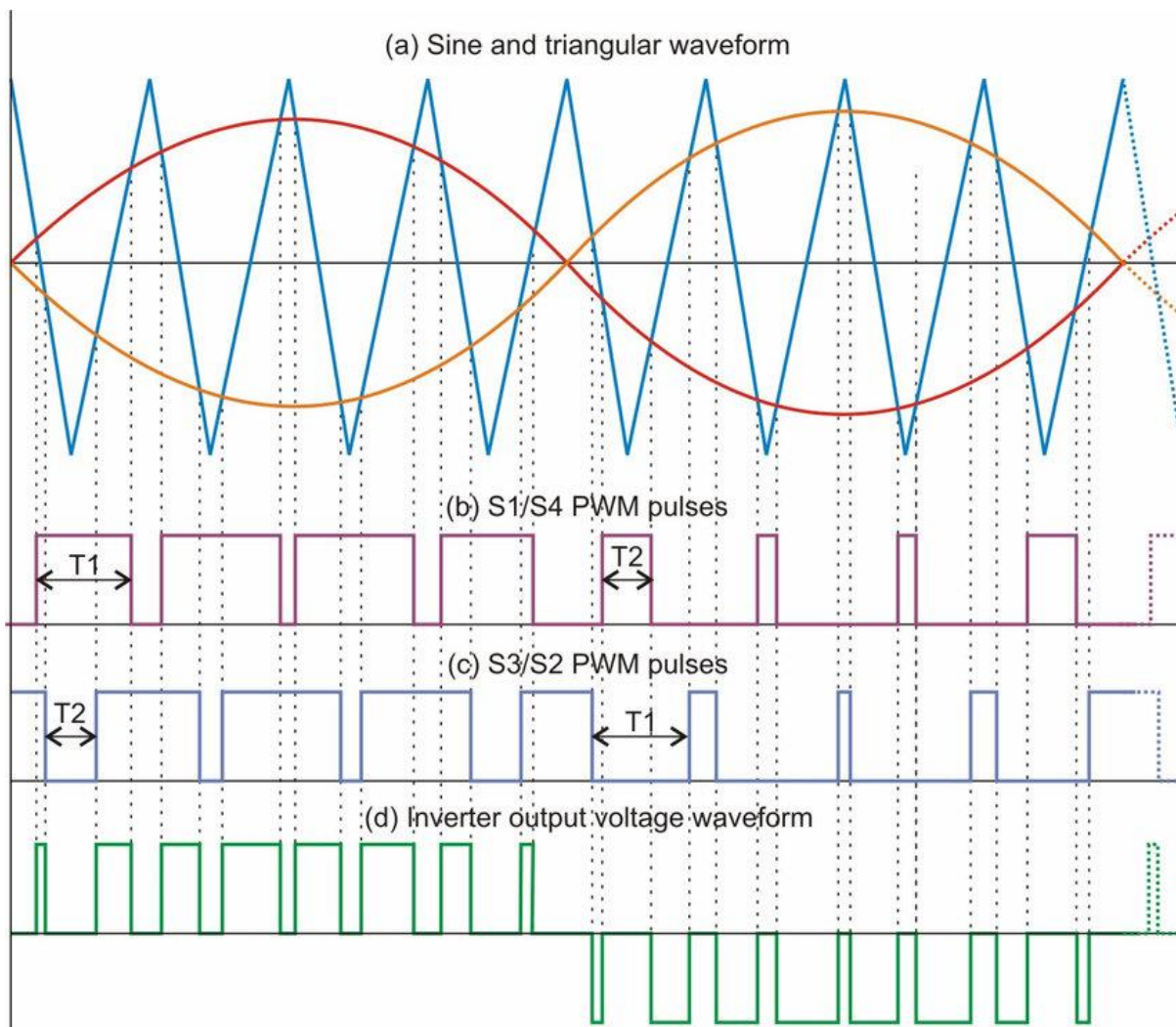


Figure 3.2: Unipolar PWM strategy for a single-phase inverter (Takahashi et al., 2008)

This Figures breaks down the process into four stages:

(a) First, two reference sine waves (red and orange), which are out of phase with each other, are compared against a single high-frequency triangular carrier wave (blue).

(b) A set of PWM pulses (purple) is generated for the first pair of inverter switches (S1/S4). A pulse is 'ON' whenever the red sine wave's value is higher than the triangular waves.

(c) Simultaneously, a second, complementary set of pulses (in blue) is created for the other pair of switches (S3/S2). These pulses turn 'ON' whenever the orange sine wave is higher than the triangular wave.

(d) Finally, the inverter's control system uses these two separate pulse signals to create the final inverter output voltage (green). By rapidly switching between a positive voltage (controlled by the first set of pulses) and a negative voltage (controlled by the second), the inverter constructs an AC output waveform. The width of these green pulses varies to approximate the smooth curve of a sine wave.

The strategy shown above is an example of Unipolar PWM switching. It is one of two common switching strategies applied to H-Bridge inverters, the other being Bipolar PWM switching (Hassaine, 2019).

The ultimate goal of these PWM techniques is to create an AC output waveform. The quality and shape of this waveform can vary significantly depending on the complexity of the inverter and its control strategy. The figures below illustrate the common types of inverter outputs, with the pure sine wave being the ideal target for the advanced methods discussed next.

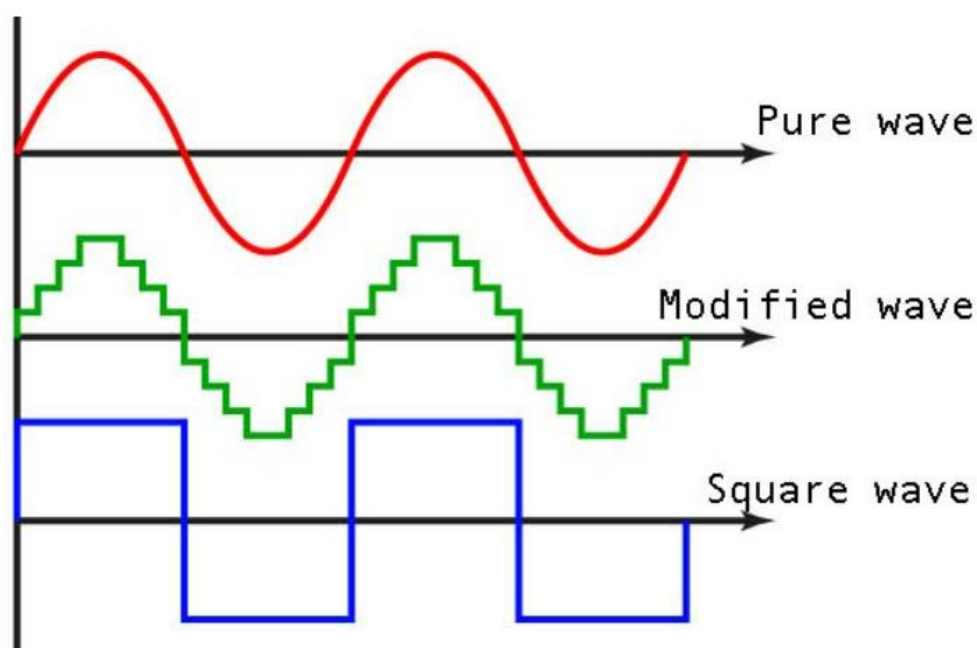


Figure 3.3: Pure sine wave, modified or square wave

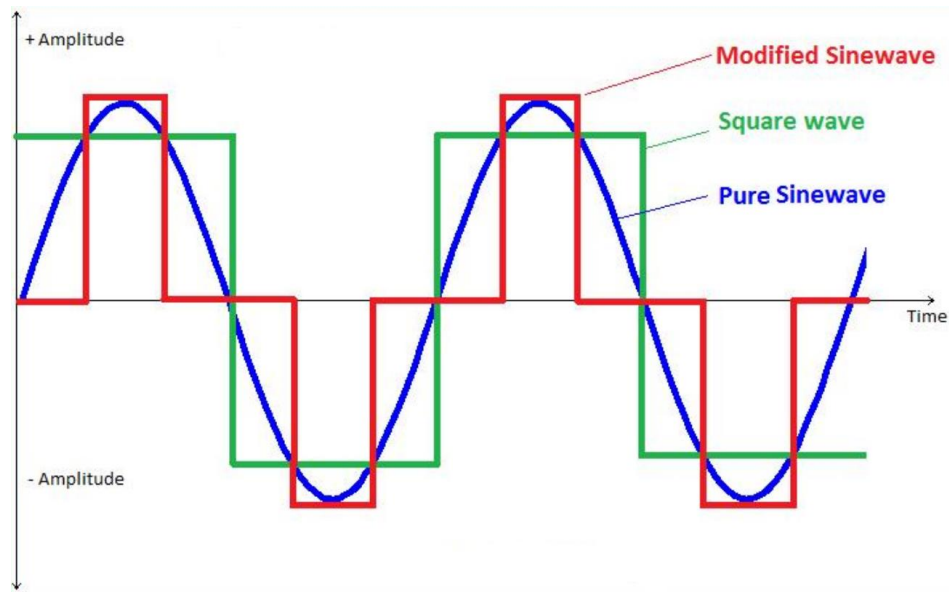


Figure 3.4: Types of Inverter Output

Mentioned PWM methods in the literature include Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVPWM) (Krishna & Prasadarao, 2022). In this mode, a mix of sine waves (three in a three-phase inverter) is compared to a triangular signal to produce gate signals (Mohan et al., 2003). SVPWM is a unique digital technique that lets you exploit the full capabilities of microcontrollers or DSPs quickly (Krishna & Prasadarao, 2022).

We rate three-phase PWM signals using the inverter's control system (Sarkar, 2015). Digital power flow control is necessary for regulating power, maintaining the desired output and keeping the grid compatible (Sarkar, 2015). Here, current and voltage output parameters are measured, compared to the references and the error is used to regulate the modulating signals that produce PWM pulses (Mohammad Alsemaan, 2016).

For controlling current loops within inner grid-tied inverters as well as overall voltage in the DC link, PI controllers are often used (Adekola, 2015). PI regulators are useful for maintaining steady performance and reaching proper dynamic performance (Sarkar, 2015).. Now, PI controllers in control loops are used to follow sinusoidal current patterns provided to the grid (Adekola, 2015). The DC voltage is controlled in a PI controller by modifying the reference signal given to the current controller (Murthi, 2007). To maintain stability and reach the expected performance, it is necessary to choose and set the values of K_p and T_i in the PI controller (Sarkar, 2015). An inverter operates effectively in the grid system by using PI controllers, along with feed-forward or resonant control techniques, to track both active and reactive power references (Adekola, 2015).

3.4.2 Closed Loop Control Systems:

Closed Loop Control is a fundamental strategy employed in **Grid Tied Inverters** to ensure stable operation, high performance, and proper interaction with the power grid.

Here's a breakdown of information about closed loop control for grid-tied inverters from the sources:

- **Purpose and Objectives:** The primary goal of closed loop control in grid-tied inverters is to **transfer power from a DC source (like a photovoltaic system) to the grid**. This involves providing a **high quality sinusoidal output current, minimizing disturbance, eliminating harmonics, synchronizing with the grid frequency, regulating active and reactive power**, and achieving **immunity to changes in the grid**. Closed loop control, such as using Proportional-Integral (PI) and Proportional-Resonant (PR) controllers, can reduce the **total harmonic distortion (THD)** in transformerless grid connected systems.
- **Types of Controllers Used:** Various controllers are utilized for closed loop control:
 - **Proportional-Integral (PI) Controllers:** Often used for **DC voltage control** in dual-loop systems. They are also commonly used in the inner **current loop** of grid-forming inverters. PI state space current control has been presented to improve rise time and resonance damping, although overshoot may still occur.
 - **Proportional-Resonant (PR) Controllers:** Specifically designed to **track a sinusoidal current reference signal** in grid-tied inverters. PR controllers are well-suited for controlling two-dimensional AC signals. Resonant control, which is based on the Internal Model Principle, is considered an ideal controller for inverters due to its capability of tracking a sinusoidal signal with **zero steady-state error**.
 - **Proportional-Integral-Derivative (PID) Controllers:** Used for **current control regulation** in three-phase inverters. In a system using a 120-degree bus clamp PWM, the PID control is not continuously active for each phase but operates for 60° and saturates at 120° in a half period. A **self-adaptive tuning fuzzy PID control** method is proposed for PV grid-connected inverters to enhance system stability, improve the quality of the output waveform, and achieve good dynamic and static performance. This approach uses voltage error and inductance electric current as fuzzy variables, allowing the fuzzy controller to adjust PID parameters in real-time based on control regulations.
 - **Pseudo-Derivative-Feedback (PDF) Current Control:** A method discussed for three-phase grid-connected inverters with LCL filters, studied for both Inverter Current Feedback (ICF) and Grid Current Feedback (GCF) systems.
 - **Other Controllers:** **Deadbeat control** is mentioned as an available control method and appears in a control scheme diagram. The **Internal Model Control** strategy is also discussed. An **OSAP controller** is used for current control in a simulation model of a grid-tied inverter.

- **Control Loop Structures:**
 - **Single-Loop Control:** This involves using either the **inverter current feedback (ICF)** or the **grid current feedback (GCF)** as the feedback signal. The stability of single-loop controlled systems with LCL filters is significantly affected by time delay. Single-loop indirect control with ICF is one of two widely applied methods for LCL-filtered grid-connected inverters.
 - **Dual-Loop Control (Cascaded Loops):** This is a common approach for grid-connected inverters. **Grid-forming inverters** typically utilize two internally cascaded loops: an **outer voltage loop** and an **inner current loop**. **Grid-feeding inverters** also have two cascaded loops, but the outer loop controls power (or current) rather than voltage. A dual-loop controller for a grid-tied inverter is depicted, where the outer loop controls the DC bus voltage, and the inner loop controls the AC current. A proposed double loop voltage control scheme uses the DC voltage in the feedback to improve performance.
- **Feedback Signals:** The signals commonly used for feedback in closed loop control include inverter current (ICF), grid current (GCF), capacitor current, DC voltage, and the inverter output current direct coordinate. Grid voltage feed-forward can be used to improve harmonic attenuation.
- **Filtering:** **LCL filters** are widely used in grid-connected inverters to attenuate high-frequency harmonics generated by the inverters. They are used for reducing harmonics in the load current. The resonance of LCL filters can impact control performance, including stability and transient response. **L filters** can also be used as filters for grid-tied inverters.
- **Modulation:** Closed loop control systems for grid-tied inverters employ various modulation techniques. **Pulse Width Modulation (PWM)** is a general method. **Unipolar sinusoidal pulse width modulation (SPWM)** is used with a specific inverter topology. **120-degree bus clamp PWM** is mentioned in the context of PID control.
- **Grid Synchronization:** Ensuring the inverter output is synchronized with the grid is crucial. A **Phase-Locked Loop (PLL)** is a fundamental component in the control of grid-connected inverters for synchronization. PLL is used in the dual-loop controller to generate a sine waveform synchronized with the utility grid frequency. Current controlled inverters use a sinusoidal reference signal that is phase-locked to the grid.
- **Inverter Classification by Control Role:** Inverters in AC microgrids are classified by their role, which influences their control strategy:
 - **Grid-Forming Inverters:** Controlled to operate as ideal AC voltage sources, regulating voltage amplitude and frequency. They typically use cascaded voltage and current loops. Designed for autonomous microgrid operation.
 - **Grid-Feeding Inverters:** Operate as power or current controlled sources, providing specified active and reactive power to the grid. Their outer control loop is power or current control. Essential for grid-connected mode.
 - **Grid-Supporting Inverters:** Can regulate frequency and voltage and participate in higher-level control by setting active and reactive power references. They are controlled as either grid-forming or grid-following (grid-feeding).

- **Performance Evaluation:** The performance of closed loop-controlled grid-tied inverters is evaluated through methods like **THD analysis at different load conditions**. Simulation results indicate that the controllers can successfully synchronize grid voltage and grid current and achieve good dynamic and static performance.

In summary, closed loop control is essential for grid-tied inverters to meet stringent performance requirements when interacting with the grid, employing a variety of controllers and feedback structures to manage current, voltage, harmonics, and synchronization.

3.4.3 PI & PID Controllers in Grid-Tie Inverters

To effectively compare the roles of Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers in grid-tied inverters, it is essential first to understand their fundamental dynamic behaviors. The typical step response of a system controlled by each type provides a clear illustration of their intrinsic characteristics, which directly influence their suitability for specific control loops within an inverter.

Fundamental Step Response Analysis

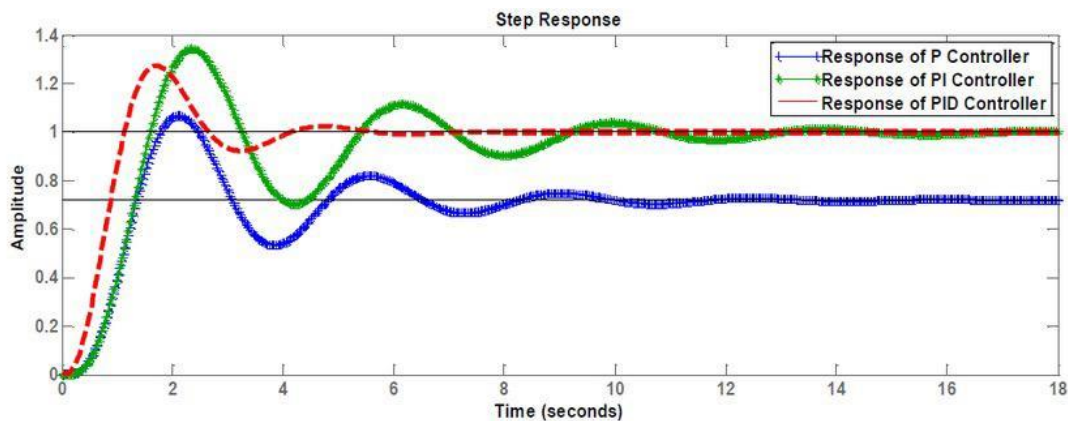


Figure 3.5: Step Response of P, PI, and PID Controllers (Kumar & Patra, 2016)

The figure above illustrates the step response of a control system under three different control strategies: Proportional (P), Proportional-Integral (PI), and Proportional-Integral-Derivative (PID). This analysis is fundamental to understanding their application in solar inverter control.

- **Proportional (P) Controller (Blue Curve):** The response is fast but demonstrates a significant **steady-state error**, where the output never reaches the desired setpoint (value of 1.0). The proportional action provides an output that is proportional to the current error, but it is insufficient to fully eliminate the error in most systems.
- **Proportional-Integral (PI) Controller (Green Curve):** The **integral action successfully eliminates the steady-state error**, forcing the system output to the setpoint over time.

However, this comes at the cost of **significant overshoot and oscillations**. The integral term can "wind up," causing the system to overshoot the target before settling.

- **Proportional-Integral-Derivative (PID) Controller (Red Dashed Curve):** This controller demonstrates the most desirable performance. It achieves a **fast rise time similar to the PI controller but with minimal overshoot and a much shorter settling time**. The derivative (D) action anticipates the rate of change of the error, providing damping that effectively suppresses the oscillations seen in the PI response. It achieves an optimal balance between speed and stability.

Application Context in Solar Inverter Control Loops

In grid-connected photovoltaic (PV) systems, inverters require precise and robust control strategies to manage:

- **Current Control Loop:** Regulating the current injected into the grid.
- **Voltage Control Loop:** Maintaining a stable DC-link voltage from the PV array.
- **Grid Support Functions:** Managing active and reactive power flow (P/Q control) and responding to grid disturbances.

Controller Selection and Rationale Based on Response Characteristics

- **PI Controllers** are the industry workhorse, especially for the **current control loop**. Their ability to eliminate steady-state error is critical for accurate current injection and meeting grid code requirements. When implemented in a rotating reference frame (dq-frame), they provide excellent performance for regulating AC currents. Their simplicity and robustness make them highly suitable for this role.
- **PID Controllers** are preferred for applications demanding **superior transient performance and damping**, such as the **DC-link voltage control loop**. The DC-link capacitor is subject to rapid fluctuations from both the PV source (e.g., changing irradiance) and the AC grid side. The derivative action of a PID controller helps to quickly stabilize the DC-link voltage and prevent large overshoots or undershoots, which is crucial for the safety and efficiency of the entire system.

PI Controller in Grid-Tied Inverters: Applications and Limitations from Literature

Based on the reviewed literature, Proportional-Integral (PI) controllers are the most prevalently used controller type in grid-tied inverter applications. They are described as conventional and representative linear controllers (Wang, 2016, p. 22), often implemented in the Synchronous Rotating Frame (SRF) for controlling AC quantities (Wang, 2016, p. 22, p. 86).

Applications:

- **Current Control Loop:** PI controllers are commonly used in the inner current control loop of dual-loop (cascaded) control strategies (Lu, 2015, p. 11; Ojo, 2022, p. 23). They are fundamental to regulating the current injected into the grid.

- **Voltage Control Loop:** PI controllers are extensively used for voltage regulation. In grid-forming inverters, they typically form the outer voltage control loop (Ojo, 2022, p. 23, p. 127), and an external PI loop is widely used for DC-link voltage regulation (Lu, 2015, p. 11; Ojo, 2022, p. 127).
- **Higher-Level Control:** PI controllers are also employed in secondary and tertiary control layers of microgrids to regulate overall grid frequency and voltage (Ojo, 2022, p. 29-30).

Limitations:

While ubiquitous, PI controllers have documented limitations, particularly concerning transient performance.

- **Transient Response:** Multiple sources report that conventional PI tuning methods often fail to eliminate transient overshoot and oscillations (Wang, 2016, p. 90).
- **Settling Time:** When compared to other control strategies like Pseudo-Derivative-Feedback (PDF), a PI-controlled system can exhibit a significantly longer settling time (Wang, 2016, p. 115).
- **AC Tracking Error:** For tracking sinusoidal AC signals, standard PI controllers in a stationary frame can exhibit steady-state error (Lu, 2015, p. 2), a problem often solved by transforming to a SRF.

PID Controller in Grid-Tied Inverters: Applications and Findings from Literature

The literature provides more specific applications for PID controllers. One primary example details a PID controller for current control in a three-phase PV inverter using a 120-Degree Bus Clamp PWM (BC-PWM) technique to reduce switching losses (Mnati, 2018, p. 1).

A Critical Finding: The "PID" as a "PI"

- A crucial detail from this implementation is that the controller, while designated as "PID," was simulated with the derivative gain set to zero (**KD=0**) (Mnati, 2018, p. 3). This effectively means the controller functioned as a **PI controller**. Therefore, the reviewed literature does not provide a direct performance comparison between a true, three-term PID controller and a PI controller in this context. The reported benefits are primarily attributed to the BC-PWM strategy itself (Mnati, 2018, p. 1), which was enabled by the controller.

Another source proposes a self-adaptive fuzzy PID control method, suggesting that an adaptive PID system can offer superior dynamic and static performance compared to a general PID with fixed parameters.

Summary Comparison and Conclusions

The analysis reveals that while PID controllers offer theoretical advantages in dynamic response, the PI controller remains the dominant and proven choice for core control loops in grid-tied inverters. The following table summarizes the key distinctions based on this study.

Table 3.1: Comparison Between PI and PID Controllers in Grid-Tied Inverter Applications

Feature	PI Controller	"PID" Controller (as per literature)
Definition	A type of linear controller. Consists of proportional and integral terms. Often used in cascaded control loops, such as the outer voltage loop or inner current loop.	A control loop feedback mechanism widely used in industrial control systems. It calculates an error as the difference between a measured process variable and a desired setpoint and attempts to minimize the error by adjusting the process through a manipulated variable. Named after its three correcting terms: proportional, integral, and derivative, whose sum constitutes the manipulated variable (MV) or controller output.
Complexity	Relatively simple structure. Involves proportional (P) and integral (I) parameters. Computational resources needed are less compared to MISO control structures.	Involves three separate constant parameters (Proportional, Integral, Derivative). Can be part of sophisticated MISO control systems which might require additional sensors and greater computational resources. However, self-adaptive fuzzy PID can have a simple structure and is convenient for programming.
Use in Grid-Tied Inverters	Commonly used for voltage control and current control. Applied in single-loop or dual-loop control systems. Suitable for control of two-dimensional AC signals ($\alpha\beta$ signals) in two-loop controllers. Used in transformerless grid-connected inverters. Used in grid-forming inverter control architectures.	Used for current control in three-phase photovoltaic inverters tied to a grid. In a specific implementation, PID control is operational in 60° and saturated at 120° in a half period for each phase current control. Used in modeling and simulation of DC/AC inverters. Self-adaptive tuning of fuzzy PID control is used for PV grid-connected inverters to improve stability and output wave quality. Can be used in MISO voltage control systems.
Primary Role	Workhorse controller for both voltage (DC-link, AC output) and current loops.	Cited for a specific current control method aimed at reducing switching losses. The derivative term was not utilized (KD=0) (Mnati, 2018, p. 3).
Advantages	Simple, robust, effective at eliminating steady-state error (especially in the dq-frame).	When combined with BC-PWM, it facilitates lower switching losses (Mnati, 2018, p. 1). Self-adaptive fuzzy PID versions can offer excellent dynamic response.
Limitations	Can exhibit poor transient performance (overshoot, oscillation, long settling time) (Wang, 2016, p. 90).	The main "PID" example is functionally a PI. The literature reviewed does not offer data on the benefits of adding a derivative term ($KD \neq 0$).

In conclusion, the investigation confirms that PI controllers provide the necessary performance and reliability for grid-tied inverter operation. The theoretical benefits of the derivative term in a PID controller are acknowledged, but its practical implementation appears limited, with the industry favoring the proven PI structure or advancing to more complex adaptive control strategies to enhance dynamic performance (Wang, 2016, p. iii).

Table 3.2: Application Comparison Between PI and PID Controllers in Grid-Tied Inverter Control Loops (Voltage, Current, and PLL)

Controller Type	PI Controller	PID Controller
Voltage Control Loop	<ol style="list-style-type: none"> 1. Used for DC bus voltage control in the external loop of a dual-loop controller in grid-tied inverters. 2. Applied for voltage control of transformerless grid-tied inverters. 3. Utilized in the outer loop of cascaded control systems for AC voltage control in grid-forming inverters. 	The sources primarily emphasize the use of PID controllers for current control [10, etc.], and do not explicitly mention their common use for the main voltage control loop (like DC link or AC output voltage regulation) in the context of grid-tied inverters, as is done for PI controllers. Can influence output voltage quality through the overall control strategy.
Current Control Loop	<ol style="list-style-type: none"> 1. Commonly used in single-loop or dual-loop current control systems. 2. Applied in the inner loop of cascaded control architectures, often in grid-forming inverters. 3. Used in PI state space current control. 4. Employed in rotating frames such as the PI-RES current controller. Demonstrated in PI controlled inverter current feedback (ICF) systems. 	Commonly used for current control in three-phase photovoltaic inverters tied to a grid. In a specific implementation, three independent PID current controllers are used, one for each phase (ia, ib, ic). The resulting errors are used by PID controllers to generate PWM signals for current control. Used in modeling and simulation of DC/AC inverters.
Phase-Locked Loop (PLL)	<p>PLL signals are used to generate reference currents for controllers.</p> <p>In dual-loop systems, the PLL output is often used to generate the AC current reference signal based on the output of the PI voltage controller. The PLL provides synchronization signals for grid connection.</p>	<p>PLL signals are used to generate reference currents which serve as inputs for PID current controllers.</p> <p>The PLL provides synchronization needed for generating accurate current references.</p>

3.4.4 Solar Inverter Parameters for grid support: P(V), Q(V), and Power Factor Control

Solar inverters are crucial components in photovoltaic (PV) systems, converting the direct current (DC) electricity generated by solar panels into alternating current (AC) electricity suitable for the electrical grid or local loads (Wang, 2016), (Rodrigues, 2019), (Hassaine & Bengourina, 2020), (Gulbahce, 2022), (Haider, 2021), (Verma, 2019), (Verma, 2019), (Kjær, 2005) & (Eshita et al., 2010). Beyond simply converting power, modern grid-connected inverters also play a significant role in grid support and power quality management by controlling active and reactive power (Lu, 2015), (Hassaine & Bengourina, 2020), (Rodrigues, 2019) & (Haider, 2021).

3.4.4.1 P(V) Solar Inverter Parameter (Active Power and Voltage Relation)

P(V) refers to the active power output of a solar inverter, often considered in relation to voltage control or frequency regulation in grid-connected systems. Active power, denoted as 'P', is the real power that performs useful work and is injected into the electrical grid (Johanesen, 2022) & (Teodorescu et al., 2006). It is measured in Watts (W) or kilowatts (kW) (Adekola, 2015) & (Sarkar, 2015).

- **Primary Function (Energy Generation):** The fundamental purpose of a PV inverter is to transfer the power generated from the PV side to the grid side (Lu, 2015), (Rodrigues, 2019) & (Kjær, 2005). To maximize the energy harvested from the PV array, inverters employ Maximum Power Point Tracking (MPPT) algorithms. These algorithms dynamically adjust the operating voltage of the solar string to ensure maximum power output under varying conditions like solar irradiance and temperature (Rodrigues, 2019), (Alsemaan, 2016) & (Ding et al., 2022).
- **Control in Grid-Connected Systems:** In a direct-quadrature (dq) reference frame, active power (P) is directly proportional to the direct (d) component of the inverter's output current (i_d) (Teodorescu et al., 2006), (Adekola, 2015) & (Ojo, 2022). Inverters are designed to inject this real power into the grid (Sarkar, 2015). Control systems, often using Proportional-Integral (PI) or Proportional-Resonant (PR) controllers, regulate the current to ensure a high-quality sinusoidal output with minimal distortion (Adekola, 2015), (Zammit et al., 2014), (Teodorescu et al., 2006), (Ding et al., 2022), (Bielskis et al., 2019),
- **Relation to Voltage (P/V Droop):** While active power is typically associated with frequency control (P/f droop control) in inductive grids (Ojo, 2022, P:30), in highly resistive microgrids (common in low-voltage networks), active power can directly influence voltage (P/V droop control) (Ojo, 2022, P:49). Your insight that "reducing power, thus reducing voltage that can cause damage to devices" aligns with this concept, particularly in scenarios where excess active power might cause grid voltage to rise beyond acceptable limits, necessitating power curtailment to prevent equipment damage or grid instability. Active power reduction can indirectly or directly contribute to voltage management in certain grid configurations.

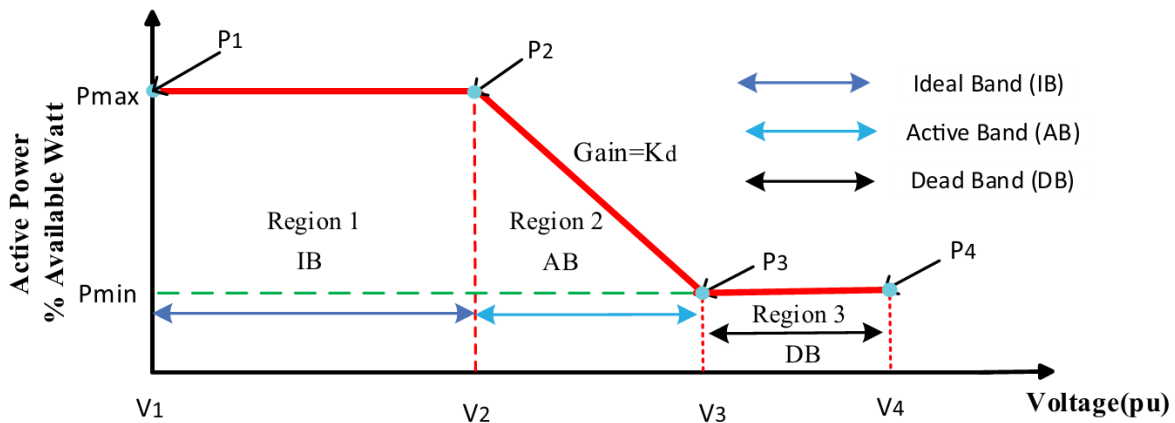


Figure 3.6: Setting of Volt-Watt Function Curve (Alfouly et al., 2023).

Analysis of the Volt-Watt Control Curve

This figure shows a **Volt-Watt control curve**, another important function used by modern power generation devices, especially smart inverters connected to solar panels or other distributed energy resources (DERs). While the previously discussed Volt-VAR curve manages voltage using reactive power, this function manages voltage by controlling **Active Power** (the actual energy being delivered).

Its primary goal is to prevent or mitigate **over-voltage** conditions on the grid, which can occur when too much power is being generated in a local area.

1. Understanding the Axes

- **Horizontal Axis (X-axis): Voltage (pu)**
This represents the system voltage, measured at the point where the device connects to the grid. "pu" stands for "per-unit," which is a normalized way of expressing voltage, where 1.0 pu is the ideal or nominal voltage.
- **Vertical Axis (Y-axis): Active Power / % Available Watt**
This shows the amount of real power (measured in Watts) the device is exporting to the grid. It's expressed as a percentage of the power that is *currently available*. For a solar inverter, the "available" power depends on how much sunlight is hitting the panels at that moment. Pmax represents the maximum available power, and Pmin represents a minimum power output level.

2. Walking Through the Control Curve (The Red Line)

The red line dictates how the device must adjust its power output in response to changes in the grid voltage. The curve is divided into distinct regions of operation.

Region 1: Ideal Band (IB) / Normal Operation

- **Condition:** The grid voltage is within a normal, healthy range (from V1 up to V2).
- **Action:** The device operates at full capacity, exporting the maximum power currently available (Pmax). As shown by the flat horizontal line between points P1 and P2, the power output is not restricted.
- **Purpose:** When the grid is stable, there is no reason to limit energy production. The device's priority is to generate as much clean energy as possible.

Region 2: Active Band (AB) / Power Curtailment

- **Condition:** The grid voltage has risen above the first threshold, V2, indicating a potential over-voltage situation.
- **Action:** The device begins to actively reduce, or **curtail**, its power output. As the voltage increases from V2 to V3, the power output drops linearly from Pmax to Pmin. This sloped section is often called a "droop" curve.
- **Purpose:** This is the core of the control function. By reducing the amount of active power it injects, the device directly counteracts the cause of the rising voltage. The Gain=Kd label refers to the slope of this line, which determines how aggressively the power is reduced for a given increase in voltage. A steeper slope means a more aggressive response.

Region 3: Dead Band (DB) / Minimum Power Floor

- **Condition:** The voltage has exceeded a second, higher threshold (V3).
- **Action:** The power output is held constant at a pre-defined minimum level, Pmin, even if the voltage continues to rise (as shown from P3 to P4).
- **Purpose:** This region acts as a floor for the power curtailment. The device has already reduced its output significantly. In some configurations, Pmin might be set to zero, meaning the inverter would completely stop exporting power in severe over-voltage conditions. The term "Dead Band" here implies that the device's output is no longer actively changing in response to further voltage increases within this range.

Summary and Application

In simple terms, the Volt-Watt function works like this:

1. **"Is the voltage okay?"** If yes, produce maximum power.
2. **"Is the voltage getting a little too high?"** If yes, start gradually reducing power to help bring the voltage back down.
3. **"Is the voltage very high?"** If yes, reduce power to a minimum safe level and hold it there until the voltage recovers.

This is a critical "grid-support" function. It allows a large number of solar installations to coexist on the same grid without creating widespread voltage problems. It's a form of

autonomous self-regulation where each device does its part to maintain grid stability, preventing damage to equipment and ensuring reliable power for everyone.

3.4.4.2 Q(V) Solar Inverter Parameter (Reactive Power and Voltage Relation)

Q(V) refers to the reactive power capabilities of a solar inverter, and it is directly linked to voltage regulation. Reactive power, denoted as 'Q', is the power that oscillates between the source and the load and does not perform real work (Johanesen, 2022). It is measured in Volt-Ampere Reactive (VAR) or kilovar (kVar) (Tan & Thang, 2018).

- **Primary Function (Grid Support):** Beyond injecting active power, grid-tied inverters are critical for grid support by injecting or absorbing reactive power to comply with grid codes and regulations (Rodrigues, 2019) & (Haider, 2021). This capability is essential for maintaining voltage stability and ensuring overall power quality (Rodrigues, 2019) & (Haider, 2021).
- **Control in Grid-Connected Systems:** In the dq reference frame, reactive power (Q) is proportional to the quadrature (q) component of the inverter's output current (iq) (Teodorescu et al., 2006), (Adekola, 2015) & (Ojo, 2022). Many inverters are designed to operate at a unity power factor, meaning reactive power exchange is ideally zero (Adekola, 2015), (Sarkar, 2015), (Tan & Thang, 2018), (Haider, 2021) & (Zong, 2011). However, if grid voltage support is needed, the inverter can be commanded to provide or absorb a specific amount of reactive power (Rodrigues, 2019). PI or PR controllers are also used in the inner current control loops to regulate the reactive current component precisely (Teodorescu et al., 2006).
- **Relation to Voltage (Q/V Droop):** Reactive power control is a direct and common method for regulating grid voltage (Q/V droop control) (Ojo, 2022). Your understanding that "this controls the reactive power injected into the grid" is accurate, as is the subsequent explanation of how power factor control influences voltage.

This Q/V droop control strategy is graphically defined and implemented using the Volt-VAR control curve. The curve dictates the inverter's precise reactive power response to measured changes in grid voltage, as analyzed below.

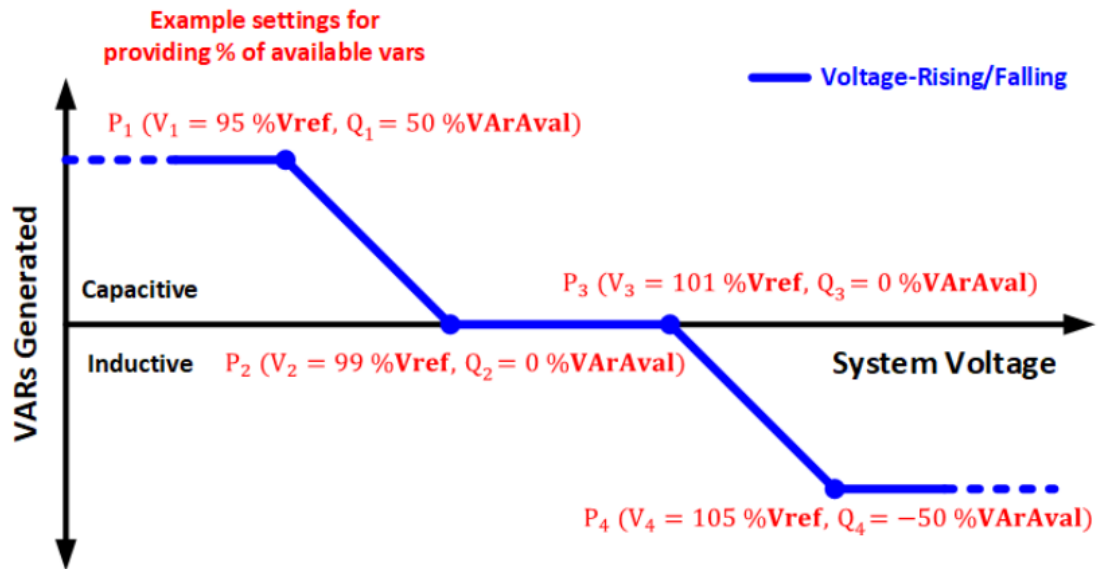


Figure 3.7: Volt-Var Curve (Kang et al., 2021)

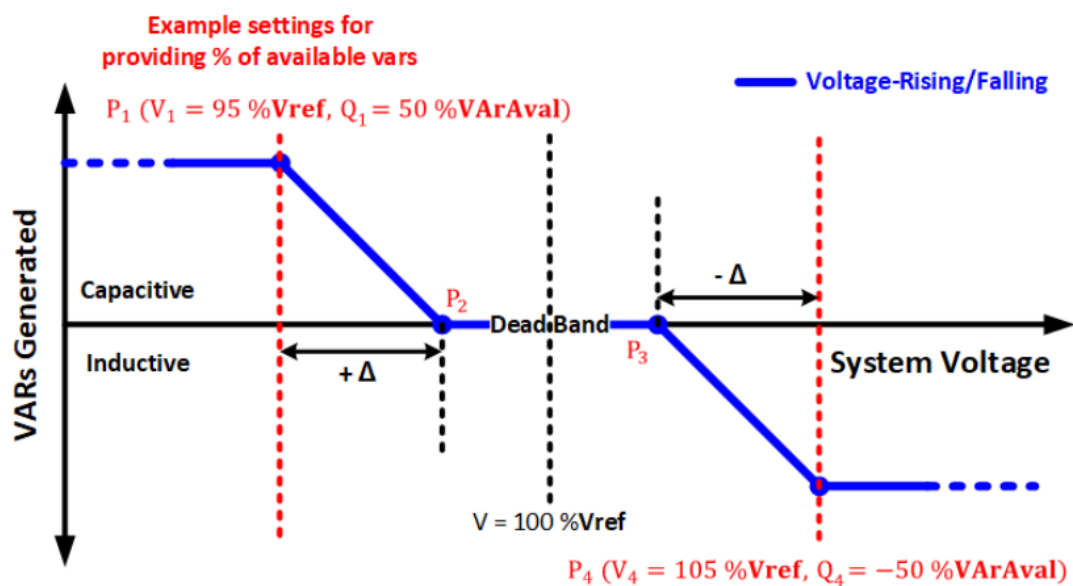


Figure 3.8: Volt-Var Control Curve (Kang et al., 2021)

Analysis of the Volt-Var Control Curve

This figure displays a **Volt-Var control curve**, a fundamental concept in modern power systems engineering. Essentially, it's a graphical representation of an automatic control strategy used by devices like smart inverters (found in solar panel systems, battery storage, etc.) to help regulate voltage on the electrical grid.

Let's break down the chart step-by-step.

1. The Goal: Voltage Regulation

The primary purpose of this control function is to maintain the system voltage within a stable, acceptable range.

- **If the voltage gets too low**, the device will act to push it back up.
- **If the voltage gets too high**, the device will act to pull it back down.

It achieves this by generating or absorbing **Reactive Power (VARs)**.

2. Understanding the Axes

- **Horizontal Axis (X-axis): System Voltage**

This represents the electrical voltage measured at the device's connection point to the grid. It is often expressed as a percentage of a nominal or reference voltage (%Vref). $V = 100\% V_{ref}$ is the ideal target voltage.

- **Vertical Axis (Y-axis): VARs Generated**

This represents the amount of reactive power the device is outputting.

- **Capacitive (Upper half, $Q > 0$):** When the device generates capacitive VARs, it is "injecting" reactive power into the grid. This action has the effect of **raising the local voltage**.
- **Inductive (Lower half, $Q < 0$):** When the device generates inductive VARs, it is "absorbing" reactive power from the grid. This action has the effect of **lowering the local voltage**.

3. Walking Through the Control Curve (The Blue Line)

The blue line defines the device's behavior at different voltage levels. We can analyze it in five distinct regions, moving from left to right:

Region 1: Severe Low Voltage (Unde-voltage)

- **Condition:** The system voltage is very low, specifically below 95% of the reference voltage ($V < 95\% V_{ref}$).
- **Action:** To correct this, the device provides its maximum specified capacitive support. In this example, it generates **+50% of its available VARs ($Q1 = 50\% VAR_{aval}$)**.
- **Purpose:** This is an aggressive response to quickly boost the low voltage back towards the acceptable range.

Region 2: Proportional Response to Low Voltage (Droop Section)

- **Condition:** The voltage is still low, but it's getting closer to the target range (between points P1 and P2).

- **Action:** The amount of capacitive VARs generated decreases linearly as the voltage rises. This slanted line is known as a "droop" or "slope."
- **Purpose:** This provides a proportional and smooth response. A voltage that is slightly low gets a small boost, while a voltage that is very low gets a bigger boost. This prevents over-correction and instability.

Region 3: The Dead Band

- **Condition:** The system voltage is within an acceptable tolerance range around the ideal voltage (between points P2 and P3).
- **Action:** The device does nothing; it generates **zero VARs**.
- **Purpose:** This prevents the device from constantly making tiny, unnecessary adjustments when the voltage is already "good enough." This "hunting" behavior can cause instability and unnecessary wear. The width of this band (+ Δ and - Δ) is a configurable setting.

Region 4: Proportional Response to High Voltage (Droop Section)

- **Condition:** The voltage is high, just outside the dead band (between points P3 and P4).
- **Action:** The device begins to absorb reactive power (generate inductive VARs). The amount it absorbs increases linearly as the voltage continues to rise.
- **Purpose:** Similar to the other droop section, this provides a smooth, proportional response to gently pull the high voltage back down into the dead band.

Region 5: Severe High Voltage (Over-voltage)

- **Condition:** The system voltage is very high, exceeding 105% of the reference voltage ($V > 105\% V_{ref}$).
- **Action:** To correct this, the device provides its maximum inductive support. In this example, it absorbs **50% of its available VAR capacity ($Q_4 = -50\% VAR_{Aval}$)**.
- **Purpose:** This is an aggressive response to quickly lower the high voltage and prevent potential damage to sensitive equipment on the grid.

Summary and Application

In essence, this graph shows an autonomous, "smart" behavior. Instead of needing a central command, a device with this Volt-VAR function can locally sense voltage and automatically contribute to grid stability.

This is especially critical for grids with a high penetration of renewable energy sources like solar. On a bright, sunny day, many solar panels generating power can cause the local voltage to rise significantly. This Volt-VAR function allows the inverters to automatically absorb reactive power to counteract that voltage rise, keeping the grid stable and healthy for everyone. The specific setpoints (like 95%, 105%, 50% VAR_{Aval} , and the Dead Band width) are configurable by utility engineers to meet the specific needs of their grid.

3.4.4.3 Comparison Table: P(V) vs. Q(V) Solar Inverter Parameters

Table 3.3: Comparison Table: P(V) vs. Q(V) Solar Inverter Parameters

Feature	P(V) Solar Inverter Parameter (Active Power)	Q(V) Solar Inverter Parameter (Reactive Power)
Definition	Represents the real power component that performs useful work and is injected into the grid. (Johanesen, 2022)	Represents the oscillating power that does not perform real work, used for grid support. (Johanesen, 2022)
Unit of Measure	Watts (W) or kilowatts (kW). (Adekola, 2015), (Sarkar, 2015)	Volt-Ampere Reactive (VAR) or kilovar (kVar). (Tan & Thang, 2018)
Primary Function	Converts DC power from PV to AC and feeds real energy into the grid; aims to maximize PV energy harvest (MPPT). (Kjær, 2005). (Rodrigues, 2019), (Hassaine & Bengourina, 2020).	Manages reactive power exchange with the grid to support voltage stability and power quality. (Rodrigues, 2019), (Haider, 2021)
Control Variable (dq-frame)	Proportional to the direct (d) component of the inverter's output current (i_d). (Teodorescu et al., 2006), (Adekola, 2015) & (Ojo, 2022)	Proportional to the quadrature (q) component of the inverter's output current (i_q). (Teodorescu et al., 2006)
Typical Operation	Output is variable, depending on solar irradiance and temperature, optimized by MPPT (Rodrigues, 2019), (Alsemaan, 2016) & (Ding et al., 2022). Can be curtailed in specific grid conditions for voltage or frequency management.	Often ideally zero for unity power factor operation, unless specific grid support (voltage regulation) is required. (Adekola, 2015), (Sarkar, 2015), (Tan & Thang, 2018), (Haider, 2021) & (Zong, 2011).
Grid Impact	Directly supplies usable electrical energy, influencing grid frequency (P/f droop). Can also influence voltage directly in resistive grids (P/V droop). (Ojo, 2022)	Supports grid voltage stability (Q/V droop) and power factor correction. (Rodrigues, 2019), (Ojo, 2022) & (Haider, 2021)
Power Factor Relation	Directly constitutes the "real" part of the power factor. (Johanesen, 2022) & (Sarkar, 2015).	Controls the "reactive" part of the power factor. Can be injected (leading PF, raises voltage) or absorbed (lagging PF, lowers voltage). (Johanesen, 2022) & (Zong, 2011).

Droop Control Role	Can be used to control grid frequency (P/f droop) or voltage (P/V droop) in microgrids. (Ojo, 2022)	Can be used to control grid voltage (Q/V droop) or frequency (Q/f droop) in microgrids. (Ojo, 2022)
Control Strategy	Utilizes inner current control loops, often Proportional-Integral (PI) or Proportional-Resonant (PR) controllers, to precisely track the active current reference. (Adekola, 2015)	Utilizes inner current control loops, often Proportional-Integral (PI) or Proportional-Resonant (PR) controllers, to precisely track the reactive current reference. (Adekola, 2015)

3.4.4.4 Power Factor Control

Power factor (PF) is a measure of how effectively electrical power is being used in an AC circuit. It is defined as the ratio of real power (P) to apparent power (S), where apparent power is the vector sum of real and reactive power (Johanesen, 2022) & (Sarkar, 2015). Inverters can control their power factor by adjusting the reactive power they exchange with the grid (Mohan et al., 2003), (Adekola, 2015), (Sarkar, 2015), (Haider, 2021) & (Kjær, 2005).

- **Leading Power Factor (Capacitive Behavior):** When an inverter operates with a leading power factor, it means it is injecting reactive power into the grid. As you described, this makes the inverter behave like a capacitor from the grid's perspective, which tends to **increase the voltage** in the system (Johanesen, 2022) & (Zong, 2011). This is a mechanism used to support voltage levels, especially in areas with significant inductive loads that consume reactive power.
- **Lagging Power Factor (Inductive Behavior):** Conversely, when an inverter operates with a lagging power factor, it is absorbing reactive power from the grid. As you noted, this causes the inverter to behave like an inductive load, which tends to **decrease the voltage** in the system (Johanesen, 2022) & (Zong, 2011). This is a valuable tool for voltage control, particularly in scenarios where grid voltage needs to be lowered, such as during periods of low load or high active power generation.

The ability of inverters to precisely control both active and reactive power, including operating at unity, leading, or lagging power factors, makes them versatile tools for grid stability and power quality management (Lu, 2015), (Rodrigues, 2019).

3.5 Hardware Implementation of the Control and Power Stages

Having established the theoretical framework for the system design and the control strategies in the preceding sections, this section transitions to the practical, circuit-level implementation. It details the hardware realization of the grid-tied inverter, breaking down the design into its core functional blocks. The following analysis provides a component-level description of the selected hardware, translating the control methodology into a physical system ready for simulation and testing.

The design of the inverter's power stage and its associated control system is centered around a selection of components chosen to balance performance, cost, and reliability. Specifically, the power stage is constructed using a full-bridge (H-Bridge) topology, a standard configuration for single-phase inverters (Rashid, 2017, pp. 364-367), with Silicon (Si) MOSFETs (BUZ11) as the primary switching devices. This choice was made because it represents a strategic balance of performance, cost-effectiveness, and mature, reliable technology. For the power and voltage levels of this inverter design, Si-MOSFETs provide efficient switching without the high cost associated with newer wide-bandgap semiconductors like SiC or GaN (Baliga, 2019, pp. 41-45). To support this power stage, a hierarchical control and measurement system is implemented -comprising a central microcontroller, isolated gate drivers, and high-precision isolated sensors- which is a necessary architecture for modern grid-tied systems (Blaabjerg et al., 2006, p. 1400).

3.5.1 Rationale for Silicon MOSFET Selection

The selection of Si-MOSFETs as the primary switching elements is justified by several key characteristics that align with the project's objectives.

- **Cost-Effectiveness and Maturity:** Si-MOSFET technology is technologically mature and benefits from decades of high-volume manufacturing, resulting in a low unit cost. This maturity ensures high reliability and a well-understood performance envelope, which are critical for developing commercially viable power electronics (Baliga, 2019, pp. 2-5).
- **Switching Performance:** In low-to-medium voltage applications, Si-MOSFETs generally exhibit superior switching speeds compared to Insulated-Gate Bipolar Transistors (IGBTs). This capability enables operation at higher switching frequencies, which allows for a reduction in the size, weight, and cost of passive filtering components, such as inductors and capacitors (Rashid, 2017, pp. 135-137).
- **Low Conduction Losses:** A key advantage of MOSFETs is their low drain-to-source on-resistance ($R_{ds(on)}$). This characteristic minimizes I^2R conduction losses when the device is active, leading to higher overall conversion efficiency, particularly at moderate current levels (Erickson & Maksimović, 2020, p. 55).
- **Simplified Drive Requirements:** As voltage-controlled devices, MOSFETs require relatively simple gate drive circuitry. However, to optimize performance and ensure safety in a bridge topology, a specialized isolated gate driver is employed in this design.

3.5.2 Comparative Analysis of Switching Technologies

A comparative analysis of Si-MOSFETs against other common power semiconductor technologies -IGBTs, Silicon Carbide (SiC) MOSFETs, and Gallium Nitride (GaN) High-Electron-Mobility Transistors (HEMTs)- contextualizes the design choice. The table below summarizes their key attributes.

Table 3.4: Comparative Analysis of Switching Technologies

Feature	Selected: Si-MOSFET	IGBT	SiC MOSFET	GaN HEMT
Switching Speed	Good	Moderate	Excellent	Exceptional (Fastest)
Overall Efficiency	Good	Good (at high V/I)	Excellent (Lowest losses)	Excellent
Cost	Low	Low	High	Very High
Voltage/Power Handling	Moderate	Excellent	Very Good	Moderate
Thermal Performance	Good	Good	Excellent (Runs cooler)	Very Good
Technology Maturity	Very High	Very High	Moderate (Growing)	Low (Emerging)
Optimal Application	Cost-sensitive, low-to-medium power inverters.	High-power string/central inverters.	High-efficiency, premium power supplies.	Ultra-compact, high-frequency converters.

While wide-bandgap (WBG) semiconductors like SiC and GaN offer superior performance metrics in efficiency and thermal management, their significantly higher cost makes them less suitable for this cost-sensitive application. Conversely, IGBTs are typically optimized for higher voltage and power domains beyond the scope of this design (Baliga, 2019, pp. 41-45). Therefore, the Si-MOSFET represents the optimal trade-off between performance, cost, and technological maturity for the intended application.

3.5.3 Supporting Control and Interface Circuitry

The performance of the power stage is critically dependent on its control, drive, and sensing systems.

The core of the control system is the **STM32L475RCT6 microcontroller**. As the central processing unit, its responsibilities include:

1. Generation of high-frequency Sinusoidal Pulse Width Modulation (SPWM) signals to command the power switches.
2. Execution of real-time control algorithms, such as grid synchronization and DC-link voltage regulation loops.
3. System-level management, including fault monitoring and control of protection relays. The use of a powerful digital controller is standard practice for implementing the complex algorithms required in modern grid-tied inverters (Erickson & Maksimović, 2020, p. 745).

The **UCC21520ADW isolated gate drivers** serve as the critical interface between the low-voltage MCU and the high-voltage power MOSFETs. They fulfill two essential functions:

1. **Power Amplification:** They provide the necessary current gain to rapidly charge and discharge the MOSFETs' large gate capacitance, which is essential for minimizing switching losses and achieving fast transitions (Rashid, 2017, p. 1198).
2. **Galvanic Isolation:** They create a robust electrical safety barrier between the control and power circuits. This isolation protects the sensitive MCU from destructive high-voltage transients on the power side and is a fundamental safety requirement in power electronics (Blaabjerg et al., 2006, p. 900). The driver's integrated dead-time control further prevents shoot-through currents in the H-bridge legs.

Accurate feedback for the closed-loop control system is provided by **AMC1306M25D isolated Sigma-Delta modulators**. These components facilitate high-resolution measurement of critical system variables, including grid voltage, grid current, and DC bus voltage. The use of Sigma-Delta modulation ensures high accuracy and noise immunity. The integrated galvanic isolation is crucial for safely monitoring high-voltage lines without compromising the integrity of the low-voltage control domain (Blaabjerg et al., 2006, p. 901).

- **Isolated Power Supply:** A dedicated power supply unit, utilizing MAX253 drivers and transformers, generates the stable and isolated voltage rails (e.g., +12V, +3.3V) required

by the gate drivers, MCU, and sensors, thereby maintaining the system's overall isolation integrity.

- **Grid Interface Relays:** Electromechanical relays (K1, K2) are employed to physically connect and disconnect the inverter from the utility grid. This functionality is essential for complying with grid safety standards, particularly for providing anti-islanding protection, which ensures the inverter ceases to energize the grid during a utility outage (Blaabjerg et al., 2006, p. 894).

3.6 Simulation, Implementation of Models and the Closed-Loop Process

Grid-connected inverter systems and their control methods must be rigorously designed and tested using modeling and simulation prior to hardware implementation (Adekola, 2015). This project employs a dual-simulation approach: LTspice is utilized for the detailed circuit-level design and control loop verification, while CYME is used for macro-level grid impact and power flow analysis.

3.6.1 Circuit and Control Simulation using LTspice

Instead of MATLAB/Simulink, this project utilizes LTspice as the primary simulation environment for the inverter's electrical design and control logic verification. LTspice was selected for its high accuracy in modeling analog components, switching transients of the MOSFETs, and the non-linear behavior of magnetic components.

The simulation model focuses on the following key aspects, which are detailed in Chapter 5:

1. **Power Stage Modeling:** Simulation of the H-Bridge topology using real MOSFET models to analyze switching behavior and dead-time insertion.
2. **Control Loop Verification:** Implementation of the closed-loop current control strategy using a Model-Based Design (MBD) approach. This involves designing the PI compensator to regulate the error between the sensed grid current and the reference signal.
3. **Grid Synchronization:** Verification of the unity power factor operation by simulating the synchronization between the generated current and the grid voltage.
4. **Filter Analysis:** Evaluating the performance of the LCL filter in attenuating high-frequency switching harmonics to ensure a clean sinusoidal output.

3.6.2 Power Flow Analysis Using CYME Software

While LTspice handles the internal inverter physics and control loop verification, CYME software is employed to analyze the inverter's impact on the external distribution network. This analysis utilizes real-world consumption data to assess voltage stability and load flow under various generation scenarios.

Simulation Environment and Objectives

CYME serves as a comprehensive simulation environment for modeling electric power distribution systems. It is widely utilized for conducting load flow studies, short-circuit analysis, and voltage drop calculations, making it particularly valuable for the planning and optimization of medium and low-voltage networks. In the context of this project, CYME is used to evaluate the integration of distributed generation (DG), specifically solar PV, into the existing grid infrastructure.

Methodology and Data Source

To ensure the simulation reflects actual grid conditions, this study performs a Load Flow Analysis based on one full year of real consumption data obtained from the local electricity company. This data-driven approach allows for a precise assessment of the impact of integrating multiple solar photovoltaic (PV) systems. The primary objective is to identify potential power quality issues—such as overvoltage at the Point of Common Coupling (PCC)—and to verify that the network operates within safe limits under peak solar generation.

System Layout and Network Modeling

The distribution network model was constructed by extracting physical parameters and topology details through a combination of satellite imagery analysis and site-specific measurements. These inputs define the baseline for the subsequent comparative case studies.

Network Configuration and PV Distribution:

As illustrated in Figure 3.9 and Figure 3.10, the network layout includes the following key elements:



Figure 3.9: Case study 1



Figure 3.10: Case study 2

- Transformer: A 400 kVA distribution transformer serves as the main feeder, marked as a black triangle on the map.
- PV Systems: Three distributed solar systems are integrated into the network:
 - A 70 kW system located near the network center.
 - A 50 kW system positioned toward the eastern side.
 - A 10 kW system connected in the vicinity of the 50 kW unit.

Integration of Real-World Data into CYME for Network Performance Analysis under Variable Load and Generation Conditions

These visual and measurement-based details will be integrated into the CYME model to simulate real operational scenarios and analyze the network's performance under various loading and generation conditions.

Original condition, natural network, without adding a solar system as shown in figure below:

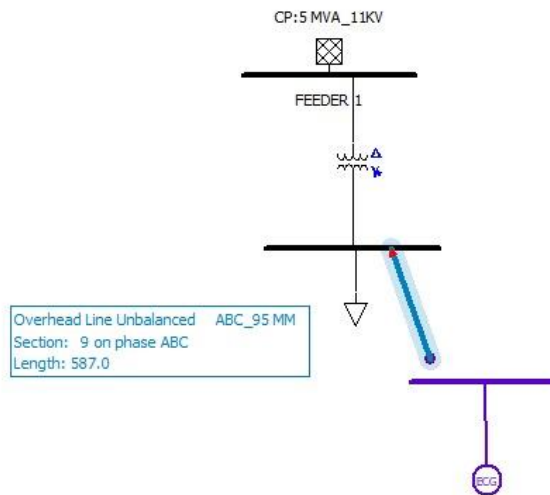


Figure 3.11: Original condition, natural network, without adding a solar system

After adding the solar system, as shown in figure below:

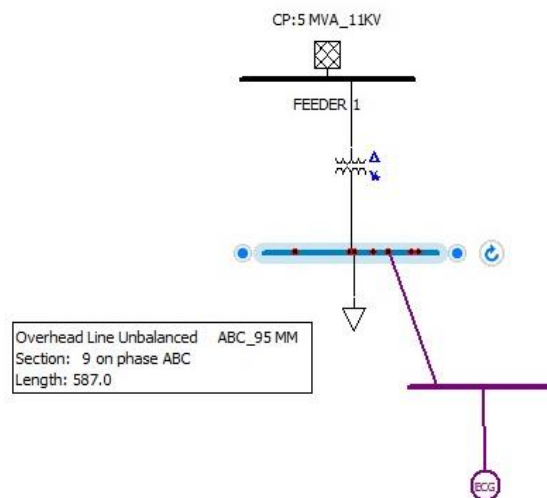


Figure 3.12: After adding the solar system

This is a state of improvement, as shown in figure below:

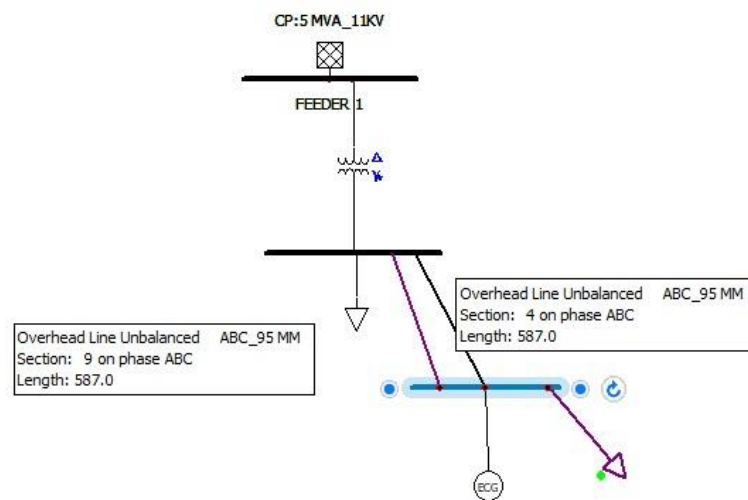


Figure 3.13: This is a state of improvement

Impact of Peak Solar Generation on Voltage Stability: A CYME-Based Case Study

The actual solar power output begins at peak efficiency and remains uninterrupted, with the highest recorded values typically occurring between approximately 11:00 AM and 3:00 PM. To analyze the impact of this generation period on the electrical network, a voltage analysis was carried out at the 'PV_Bus' point using CYME software. This analysis was based on real data from the electricity company and focused on a 19,550-second time window—equivalent to approximately 5.4 hours—capturing the period of maximum solar output. The goal was to assess voltage stability and improve overall network performance. Several scenarios were tested, including the original condition without solar integration and after implementing a technical solution involving the addition of a parallel cable. Long-term voltage dynamics were monitored and compared across these scenarios.

3.6.2.1 Interpretation of Load Flow analysis from a Real-World Case Study

This section presents the findings from a detailed case study, where the CYME software was used to model and analyze a real-world low-voltage distribution network. The analysis investigates the tangible voltage stability issues that arose following the integration of several PV systems, using actual consumption data and network topology to ensure the simulation accurately reflects operational reality.

The results are structured to follow the project's practical progression from diagnosis to resolution:

- **Baseline Performance:** The network's operational state under its original configuration, before PV integration.

- **Problem Diagnosis:** The identification of critical overvoltage conditions resulting directly from PV generation.
- **Solution Validation:** The successful mitigation of overvoltage through the proposed grid reinforcement.

Each stage is supported by graphical data from CYME, providing a clear, evidence-based account of the network's behavior and the effectiveness of the implemented solution in this specific case.

Voltage Profile Over Time Before PV System Integration

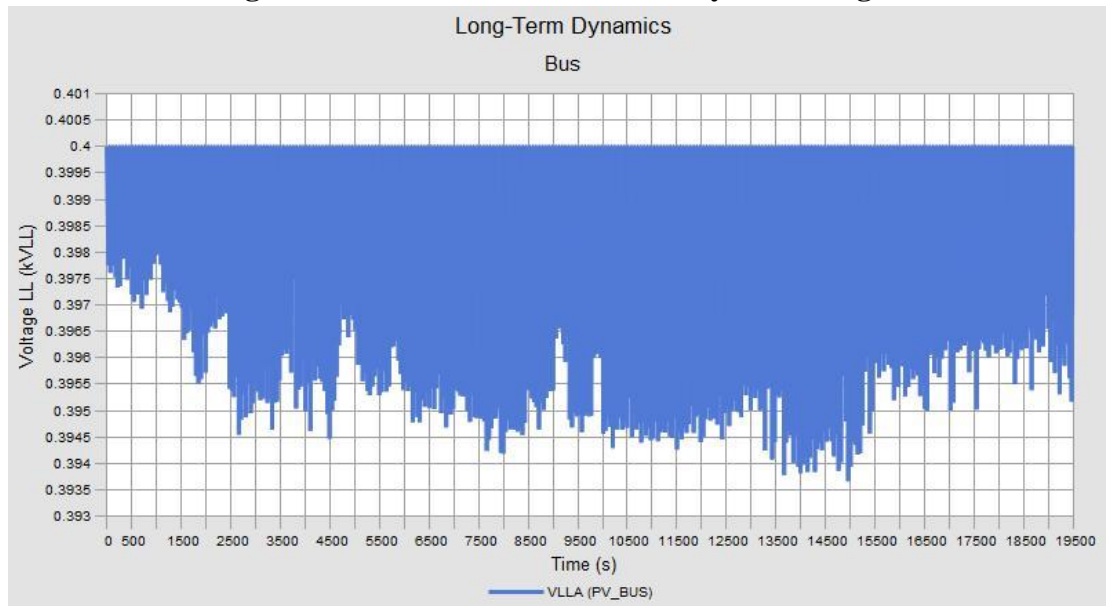


Figure 3.14: Line-to-Line Voltage Variations Due to Load Fluctuations (Pre-PV Integration)

This graph shows the voltage profile, comparing the Y-axis (line-to-line voltage) with time on the X-axis. Before integrating the PV system, the voltage remains stable at a peak of 400 V. The fluctuations below this level indicate variations in voltage caused by changes in the load.

You can see how the voltage changes based on the graph. The graph below shows how loads increase and decrease. When loads increase, the voltage increases. When loads decrease, the voltage decreases.

Voltage Profile After PV System Integration and Its Impact on Grid Stability

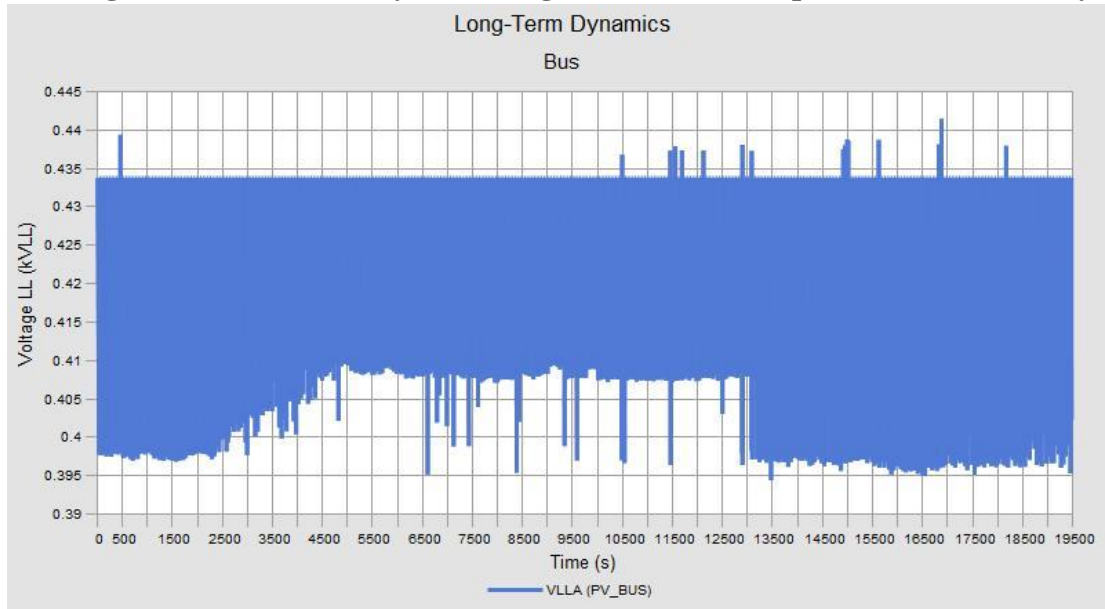


Figure 3.15: Voltage Increase After PV Addition

This graph illustrates the voltage profile after the integration of PV systems. A noticeable increase in voltage can be observed, reaching up to approximately 434 V. This rise is primarily due to surplus energy production, which can lead to operational issues.

Voltage fluctuations—both increases and decreases—are mainly influenced by load variations. During peak solar production periods, particularly in the spring season (from February to April), the system experiences lower resistance and consequently higher efficiency. This results in elevated power generation, which may cause the voltage to rise beyond acceptable limits.

To confirm this, we refer to the power equation:

$$P_R \uparrow = \frac{|V_S||V_R|}{|X| \downarrow} \sin(\delta)$$

The term involving **sin(δ)** indicates how real power flows from areas of higher phase angle (δ) to those of lower phase angle. This unbalanced power flow contributes to voltage instability issues within the grid.

Comparison of Bus Voltage Before and After PV System Integration

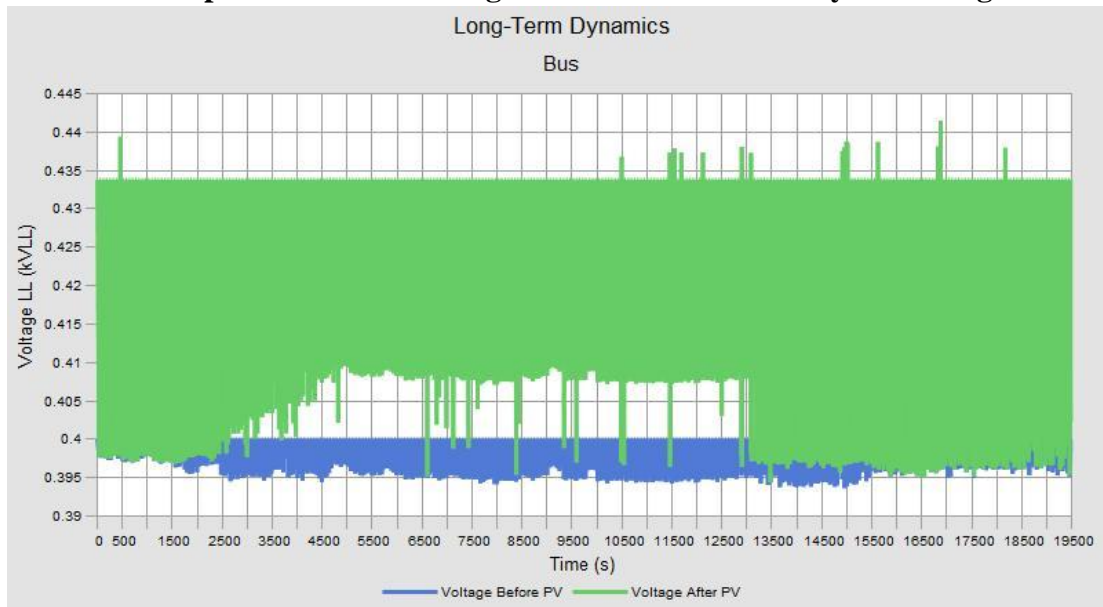


Figure 3.16: Voltage Changes After PV Addition

This figure displays two overlaid voltage profiles. The blue curve represents the bus voltage before the integration of the PV system, where voltages remained relatively stable around 400 V, with slight variations depending on load changes.

In contrast, the green curve shows the bus voltage after the PV system was added. A significant voltage rise is observed, with levels reaching up to 434 V. This sharp increase is attributed to the excess energy generated by the PV system, particularly during periods of low load demand.

Such voltage elevation can negatively impact both the power grid and connected electrical equipment. Overvoltage may lead to:

- **Reduced lifespan or failure of sensitive electronic devices**
- **Overheating of equipment such as motors and transformers**
- **Tripping of protective relays and equipment shutdowns**
- **Violation of grid voltage standards, risking instability or penalties**

These issues highlight the importance of implementing proper voltage regulation and control mechanisms when integrating renewable energy sources like photovoltaic systems.

Voltage Profile Analysis Under Load Disturbances and Solar Inverter Operation

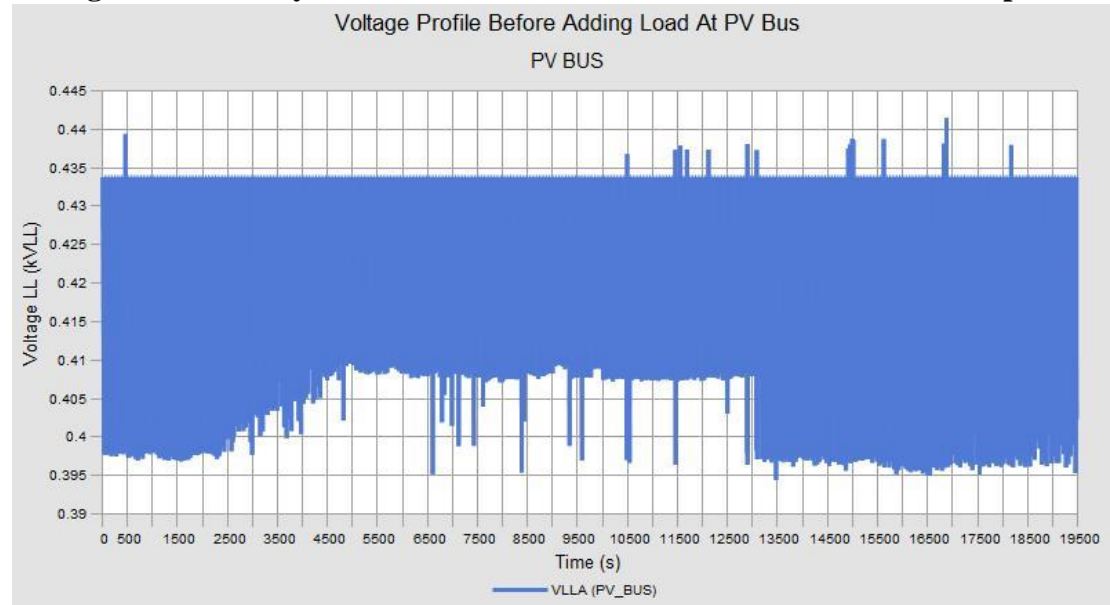


Figure 3.17: Voltage Profile Before Adding Load at PV Bus

This voltage profile graph shows variable voltage behavior across different time instances. For example, around the **500s mark**, a **load disturbance** occurred, and in certain segments of the graph, **voltage spikes** are clearly visible.

Upon close inspection, the graph can be divided into **three main regions**:

Region 1: Voltage remains within a stable and acceptable range.

Region 2: A noticeable **voltage dip** is observed.

Region 3: A **voltage spike** appears, briefly pushing values outside the permissible range.

The acceptable phase-to-neutral voltage range is defined by international standards as approximately 207 V to 253 V, which corresponds to $\pm 10\%$ of the nominal 230 V. Similarly, the acceptable three-phase voltage range is approximately 360 V to 440 V, reflecting $\pm 10\%$ of the nominal 400 V. Any deviation beyond these limits -either above or below- may lead to equipment malfunction or potential damage.

Explanation of Observed Spikes:

▪ Downward Voltage Spikes:

These can typically be attributed to two main causes:

- A **temporary drop in voltage from the supply side**, which cascades down to the low-voltage level for a few seconds before stabilizing.

- The **sudden connection of a large load** to the transformer, causing an immediate voltage drop due to increased demand, followed by a return to normal levels. Such behavior creates observable dips in the voltage graph.
- **Upward Voltage Spikes:**
 - These are often observed during **solar power generation** when certain loads are **disconnected** from the system. The resulting drop in demand can cause a **momentary rise in voltage**, followed by a return to the steady-state condition.

Overall, voltage stability is heavily influenced by the behavior of the load—whether it remains constant or undergoes **instantaneous variation**.

Capacitor Bank and Power Factor Policy:

From the utility company's side, the installation of **capacitor banks** is strictly prohibited **except** in specific cases. The only exception is when the **power factor is low** and the **subscriber has a 100 A load or more**, a scenario typically found in **industrial environments**.

In terms of voltage behavior resembling that of a capacitor bank, this can be explained by the **solar inverter's control of the power factor (p.f)**. Depending on the inverter's configuration:

- It may act as a **capacitive load (leading p.f)**, injecting reactive power and thus increasing voltage.
- Or, as an **inductive load (lagging p.f)**, absorbing reactive power and thus reducing voltage.

This inverter control strategy plays a vital role in reactive power management and voltage regulation within the distribution network.

Validation of Network Reduction: Voltage Behavior with and without Load at PV Bus

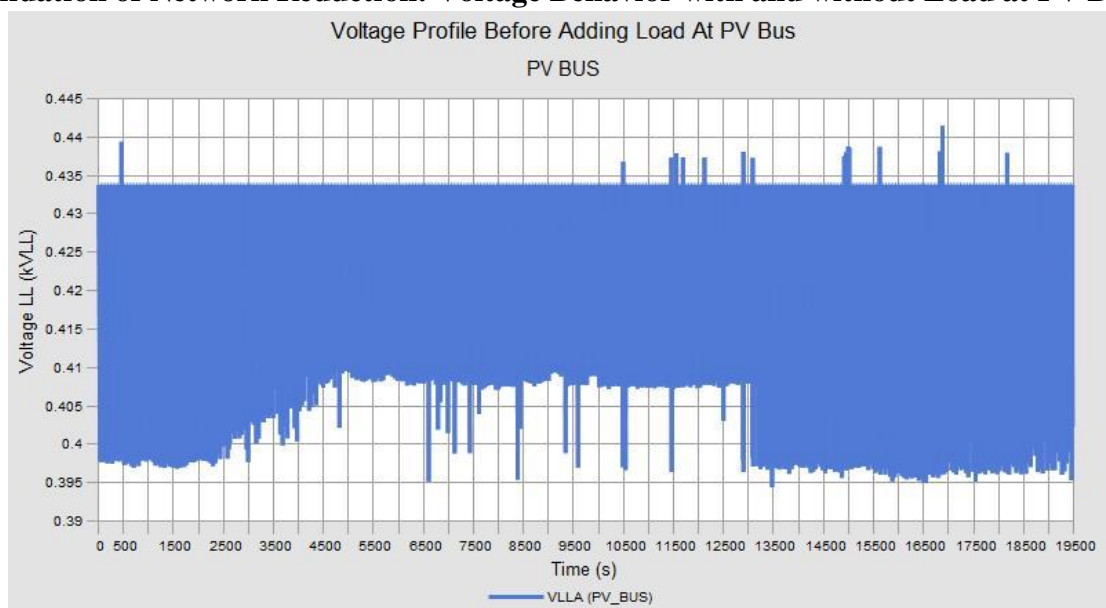


Figure 3.18: Voltage Profile Before Adding Load at PV Bus

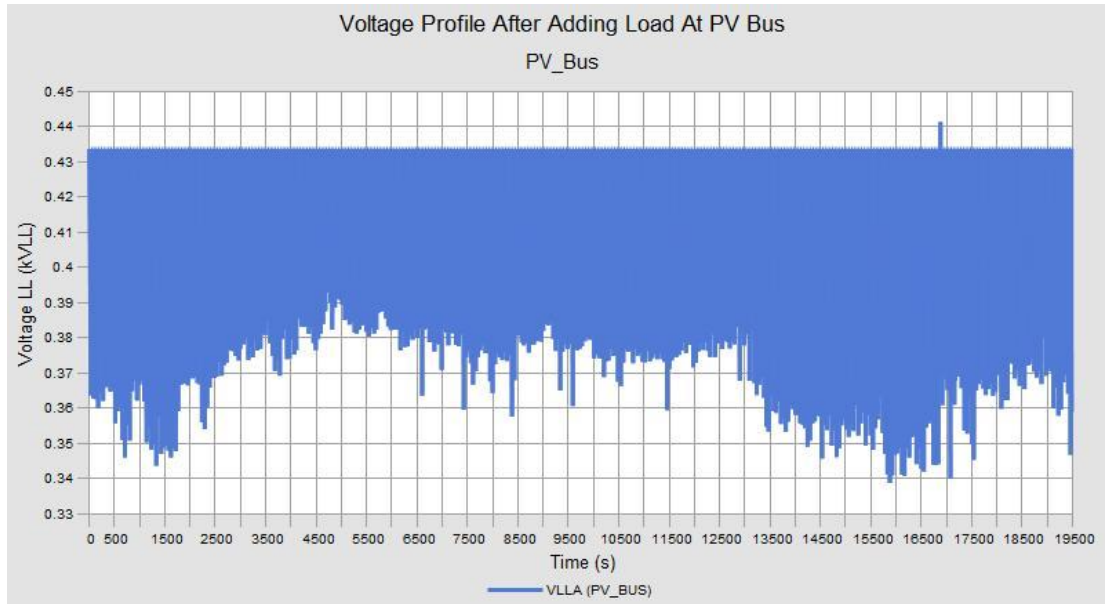


Figure 3.19: Voltage Profile After Adding Load at PV Bus

These two graphs appear quite similar in overall shape, with some differences in the Voltage drops from below of the graph. In both cases, the voltage drops to around 380 V and even 370 V, which remains within the acceptable range. However, these minor drops are not the main concern, as the focus lies on the significant voltage rise. The maximum peak reaches 434 V, which is the core issue.

So, what's the real challenge here? Why do we add loads to the PV bus—or choose not to?

The purpose of adding this scenario was to demonstrate network reduction. We are working on a specific case and do not need to include the entire grid to obtain accurate results. By using network reduction techniques, we can minimize the grid to focus on the location of the voltage issue.

three key parameters are sufficient for performing effective network reduction :

1. **X/r =6**
2. **Short Circuit MVA = 256MVA**
3. **Nominal Voltage**

Using these parameters, we can simplify the entire network and concentrate our analysis on the fault area. In this particular case, we have a PV system at the end of a transmission line with local loads nearby, and additional loads connected at the transformer end.

These two plots show that whether or not a load is connected at the PV bus, the voltage behavior remains nearly identical. This confirms that, after applying network reduction, the voltage readings are still 100% accurate. The decision to place the load at the PV bus or elsewhere does not significantly affect the results.

Ultimately, our analysis revealed that the inductance of the transmission line is the most influential factor affecting voltage levels. This conclusion is further supported by another graph, reinforcing the validity of the network reduction approach.

Voltage Profile After Implementing a Parallel Cable Solution

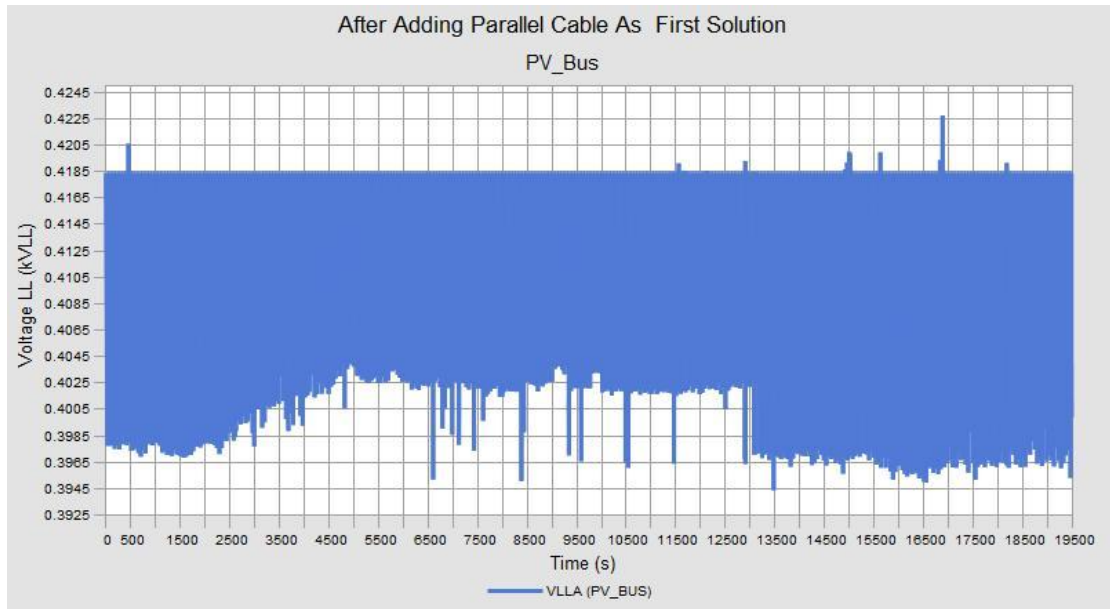


Figure 3.20: PV Bus After Adding Parallel Cable as First Solution

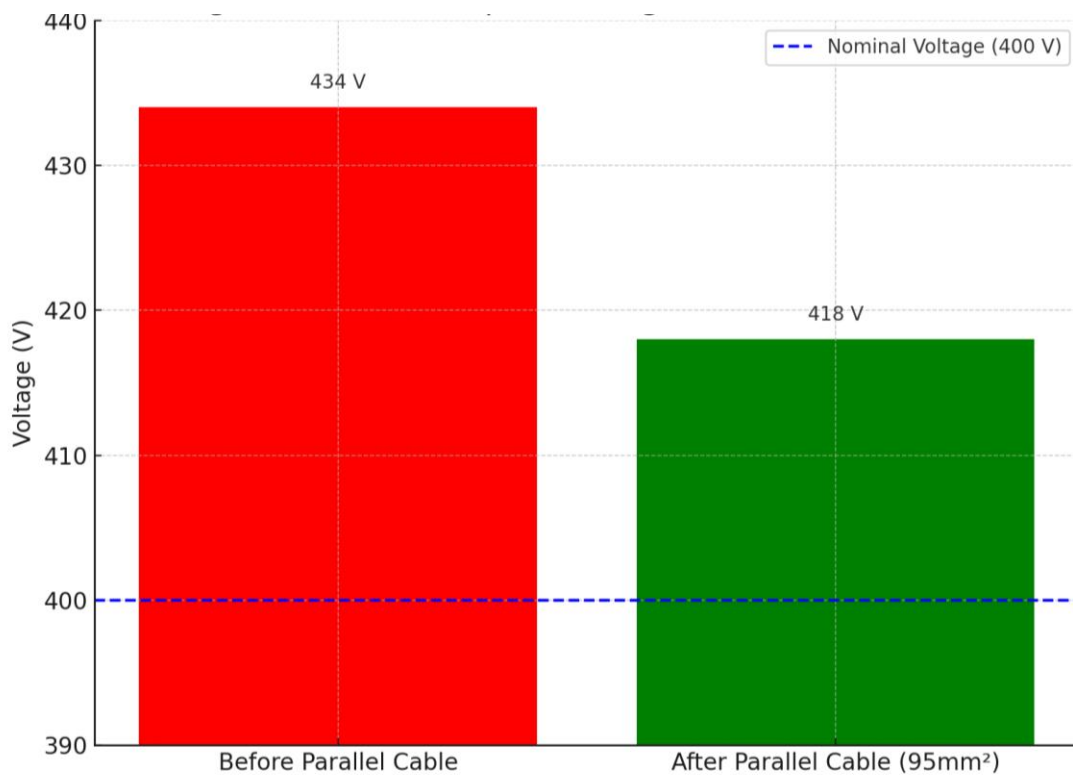


Figure 3.21: Voltage Profile After Implementing a Parallel Cable Solution

The success of the proposed solution—the installation of a parallel cable—is interpreted as a direct remedy to the high line impedance issue. By creating a parallel path for current, the overall equivalent impedance $|X|$ of the line was significantly reduced. Consequently, as shown in the figure, the voltage profile was restored to acceptable limits. This result confirms that the primary cause of the overvoltage was indeed the physical constraint of the conductor and not a control system malfunction.

While the physical upgrade provided the necessary hosting capacity, it is complemented by the intrinsic control capabilities of the solar inverters. These smart functions provide the means for fine-tuning and actively managing voltage in real-time, creating a more robust and resilient system. Solar inverters play a vital role in this regulation through two main parameters: $P(V)$ and $Q(V)$.

- **$P(V)$ – Active Power vs. Voltage Parameter:**

By reducing the active power output (P), the voltage at the inverter’s point of connection can also be reduced. This is important to prevent overvoltage conditions that may damage sensitive electrical equipment.

- **$Q(V)$ – Reactive Power vs. Voltage Parameter:**

This parameter allows the inverter to control the amount of reactive power injected into or absorbed from the grid. Through reactive power management, the inverter can stabilize voltage levels dynamically.

- **Power Factor Control:**

- When the inverter operates in a leading power factor mode, it behaves like a capacitor, injecting reactive power (Q) into the grid. This action typically increases the local voltage.
- In contrast, operating in a lagging power factor mode causes the inverter to act like an inductive load, absorbing reactive power from the grid, which lowers the local voltage.

These mechanisms are essential for voltage regulation in distributed generation systems, especially in networks with high solar penetration, and work in tandem with physical grid reinforcements to ensure stability.

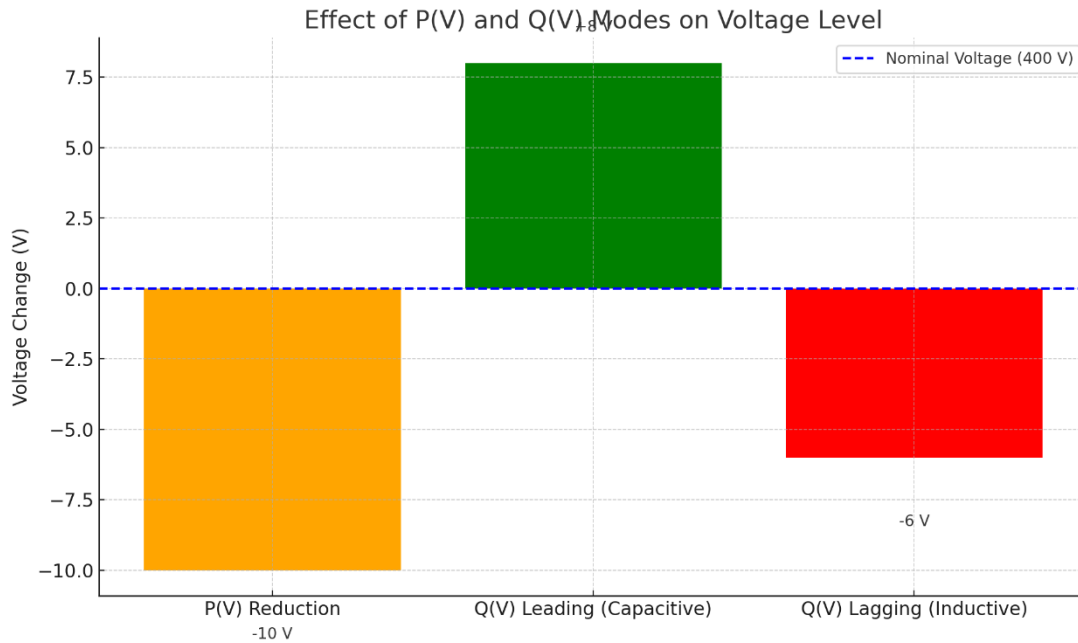


Figure 3.22: Effect of P(V) and Q(V) Modes on Voltage Level

As Figure 3.22 shows, activating the inverter's P(V) and Q(V) functions effectively reduces the high voltage, keeping it within permissible limits. This confirms the importance of these smart solutions in modern grid management.

3.6.2.2 Impact of the Proposed Solution on Grid Stability

The implementation of the parallel cable solution represents a fundamental shift in the network's stability paradigm, moving beyond mere problem mitigation to a significant enhancement of grid resilience. The analysis confirms that the primary limiting factor for PV integration in this network was not a failure of control logic, but a physical infrastructure bottleneck.

The primary impact of the solution was the direct resolution of this bottleneck by increasing the feeder's **hosting capacity**. By effectively reducing the line impedance, the parallel cable provides a sufficient electrical pathway to accommodate reverse power flow without causing voltage to violate statutory limits. This demonstrates that for feeders with high impedance, physical grid reinforcement is an indispensable strategy for enabling higher penetration of distributed generation.

Crucially, this physical reinforcement creates a **synergistic relationship** with the advanced control capabilities of the solar inverters. With the bulk of the static voltage rise issue resolved by the new conductor, the inverter's Q(V) and power factor control functions are no longer tasked with compensating for a fundamental system flaw. Instead, they are liberated to perform their designed role: providing dynamic, fine-tuned voltage regulation against transient fluctuations in load and irradiance. The cable provides the "strong backbone," while the inverter provides the "intelligent reflexes," resulting in a system that is both robust and adaptive.

In conclusion, the proposed solution does not simply return the grid to a pre-PV state of stability. It elevates the network to a new level of performance where it can reliably integrate distributed generation, maintain power quality, and actively manage its voltage profile. This transforms the feeder from a passive energy conduit into a resilient, actively managed component of the modern power grid.

3.6.2.3 Comparison with Findings from Literature Review

The findings of this project align closely with the established body of knowledge concerning the integration of renewable energy sources into distribution grids. The initial observation of overvoltage following PV system integration is a classic and well-documented phenomenon. Researchers such as Lu (2015) and Hassaine & Bengourina (2020) have extensively discussed the challenges that variable generation poses to grid stability, with voltage regulation being a primary concern. Our CYME simulation results provide a practical, data-driven confirmation of these theoretical challenges within a real-world network context.

The technical mechanisms for voltage control explored in this study are also well-supported by the literature. The analysis of the inverter's role in managing active (P) and reactive (Q) power directly corresponds to the control principles detailed by Teodorescu et al. (2006). Specifically, our discussion on using Q(V) droop control to manage voltage stability is consistent with the frameworks presented by Ojo (2022, p. 49). The ability of the inverter to inject or absorb reactive power by operating at a leading or lagging power factor, respectively, was identified as a key control strategy. This finding empirically validates the concepts described by Johansen (2022) and Mohan (2003), who explain how inverters can emulate capacitive or inductive loads to regulate local voltage.

While the literature often focuses on the control algorithms themselves (e.g., PI/PR controllers for current loops as noted by Adekola, 2015), this study's primary contribution lies in applying these principles to a specific case study with real consumption data and network topology. The validation of the network reduction technique, which demonstrated that focusing on the local fault area yields accurate results, provides a practical methodology that reinforces the theoretical approaches. Thus, this project serves as a bridge between established control theory and its practical application and validation in a distribution network planning scenario using industry-standard software.

3.6.2.4 Practical Implications and Challenges

The results of this study offer several practical implications for utility companies, system integrators, and policymakers, while also highlighting key challenges.

Practical Implications:

- 1. Necessity of Pre-Integration Analysis:** The project strongly underscores that integrating significant PV capacity requires a mandatory, detailed power flow analysis. The "plug-and-play" approach is not viable and can lead to grid code violations and equipment damage. Using tools with real consumption data is crucial for proactive planning.
- 2. Effectiveness of Grid Reinforcement:** The success of the parallel cable solution demonstrates that traditional grid reinforcement remains a highly effective, albeit costly, method for increasing the hosting capacity of a distribution feeder. This is a vital consideration for long-term network planning in areas with high solar potential.
- 3. Role of Smart Inverters as a Non-Wires Alternative:** The study highlights the powerful voltage regulation capabilities (Q(V) and Power Factor control) of modern inverters. This presents a "non-wires alternative" or a complementary solution to physical upgrades. Utilities could leverage these smart features to mitigate voltage issues at a lower capital cost and with faster deployment compared to laying new cables.
- 4. Informing Utility Policy:** The finding that inverters can provide reactive power support is particularly relevant given the utility's policy of prohibiting capacitor banks. This study provides evidence that smart inverters can fulfill a similar function dynamically and controllably, suggesting that grid codes should be updated to incentivize or mandate the activation of these grid-support functions.

Challenges:

- 1. Economic Feasibility:** The primary challenge of the implemented parallel cable solution is its high capital cost. For many projects, the cost of grid reinforcement can make a renewable energy installation economically unviable. This necessitates a careful cost-benefit analysis comparing physical upgrades with advanced inverter control strategies.
- 2. Coordination of Distributed Resources:** While a single inverter's Q(V) function is beneficial, a high concentration of uncoordinated smart inverters on the same feeder could lead to control conflicts or voltage oscillations. The challenge lies in developing and implementing coordinated control schemes (e.g., through a central controller or peer-to-peer communication) to ensure stable collective operation.
- 3. Data Availability and Model Accuracy:** The accuracy of this study's conclusions relied on access to real consumption data and detailed network parameters. In practice, obtaining such granular data can be difficult for many parts of the distribution network, posing a significant challenge to accurate modeling and planning.
- 4. Regulatory and Contractual Barriers:** Even if inverters are technically capable of providing grid support, regulatory frameworks and interconnection agreements may not permit or compensate for these ancillary services. Overcoming these administrative hurdles is essential to fully unlock the potential of smart inverters.

3.7 Safety and Protection Considerations

Safety and protection features play a critical role and important in the safe and reliable operation from grid-tied inverters, especially when considering the intermittent nature of renewable sources and the unknown or dynamic demands of loads (Ibrahim 2015).

As we say in Section 3.5, the ability to navigate anti-islanding is a critical safety feature to allow the inverter to disconnect from the grid or drop off the grid if the utility disconnected the supply of the grid power (Bækhoj, 2005). It ensures the lines themselves cannot be energized by the inverter during an outage, thus assuring worker safety or the public could not be unintentionally energized by a renewable source (Ibrahim 2015). Inverters need to disconnect fast, when the inverter noticed a fault or important grid disturbance operating properly. This includes protection of power quality distortion such as voltage sags or voltage dips and frequency disturbance (Ibrahim 2015; Bækhoj, 2005). The control scheme design should determine the abnormal conditions of voltage and frequency for the inverter to prevent damage and for grid stability (Ibrahim 2015). Besides anti-islanding and handling grid faults, safety precautions include the selection of power electronics and protecting these components from overvoltage and overcurrent transients during switching and fault (Rodrigues, 2019).

Voltage ratings for devices should include a design margin (Rodrigues, 2019). Adequate thermal design and cooling are a key factor for reliability and overheating (Costa, 2018). The system should be designed that can tolerate disturbed supply conditions and protect the inverter and the utility grid (Ibrahim 2015).

3.7.1 Ways to Protect Grid-Tied Inverters

To ensure the right operation and safety of the power system and grid-tied inverters, they need suitable protection techniques (Adekola, 2015). The main issue deals with blocking “islanding” by ensuring that disconnection from the public grid by the inverter caused by a fault makes the inverter stop powering the local network or loads (Kjær, 2005). Islanding increases the risk of accidents and should be prevented at all times (Adekola, 2015). These inverters have to be built to disconnect when something unusual happens on the grid, like a fault, drop in voltage or voltage dip (Adekola, 2015). It is known that voltage sags (a reduction in the voltage’s strength) often trouble both sensitive devices and inverters, possibly resulting in current overshoot and distortions, as explained in Ref. (Adekola, 2015). The inverter must have strong control capabilities to keep operating well when everything is normal and whenever conditions are not normal (Adekola, 2015). Islanding and grid disturbances tend to be found by checking the voltage and frequency of the grid (Kjær, 2005). Following a disturbance on the grid, the inverter must wait for normal conditions and then resume grid connection (Adekola, 2015).

Chapter 4: Electrical Circuit Description and Functional Analysis of the Grid-Tied Inverter

4.1 Overview of the Inverter System

This design shows an electrical schematic of the system, as shown in Figure (4.1). It handles active power transfer without transformers, works on a single phase, and ties directly into the grid. It follows grid connection rules by design. Inside, you see stages for converting energy, adjusting signals, managing digital logic, creating electrical separation, and adding safeguards. Each part helps keep things stable, safe, and running smoothly. Built from various key components, each part serves a distinct role within the inverter structure:

1. Low-voltage auxiliary power supplies
2. Digital control and signal processing unit
3. Galvanically isolated gate driver stage
4. Power inverter stage uses full-bridge topology
5. Output filtering and grid interface
6. Measurement, protection, and relay-based isolation

The hardware architecture detailed in this chapter, specifically the bidirectional H-Bridge topology driven by the PR controller (Appendix A), physically enables the Reactive Power injection/absorption capabilities required by the Volt/Var optimization strategies modeled in Chapter 3. This confirms that the designed inverter is not just a power converter, but a grid-supportive asset capable of mitigating the overvoltage issues identified in the CYME analysis.

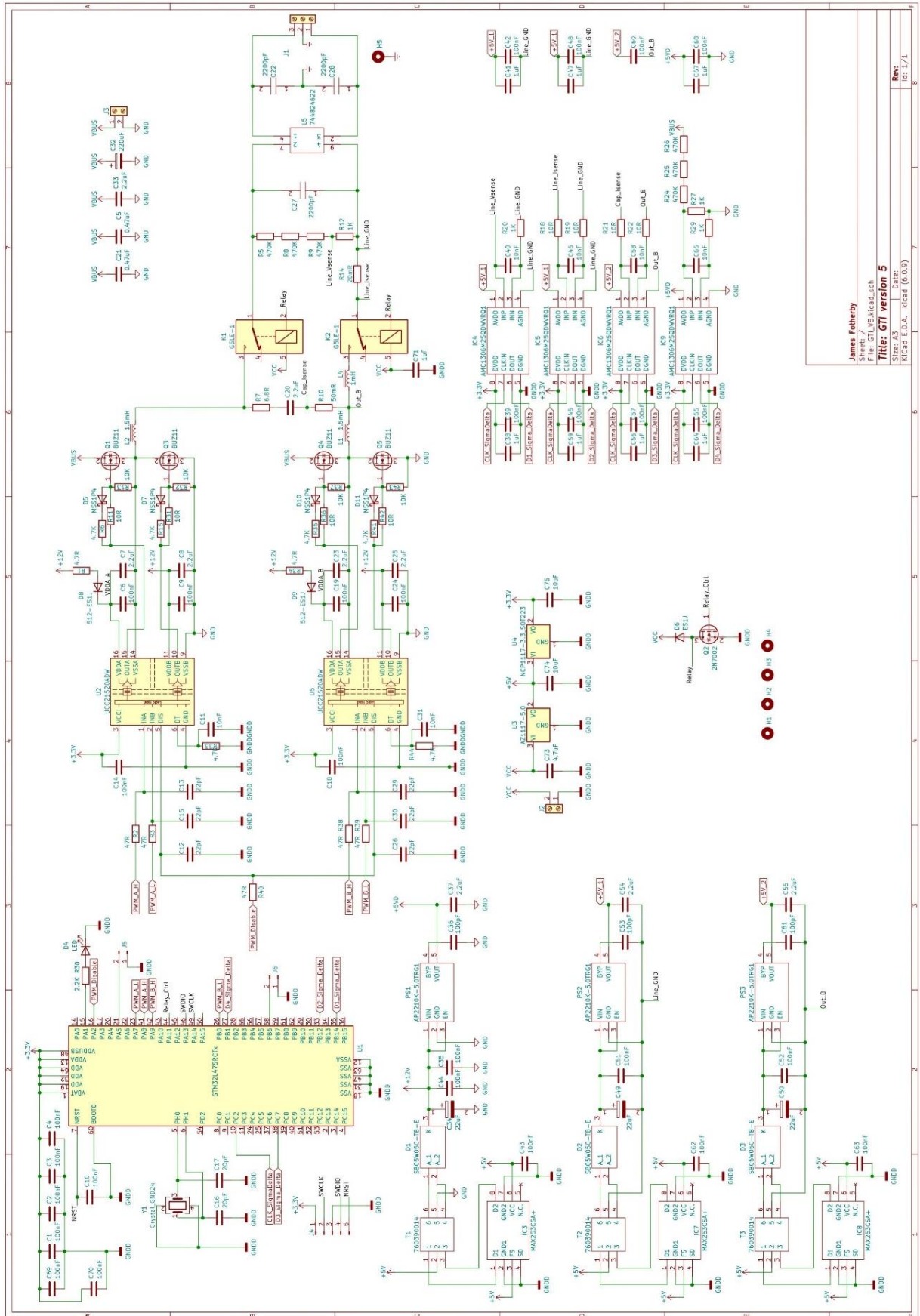


Figure 4.1: Complete electrical schematic of the single-phase grid-tied inverter system.

4.1.1 Auxiliary Power Supply Section

Down at the bottom, a part handles power delivery—shaping steady low-voltage outputs for controls, motors, and detectors, plus safety components. Instead of one big source, several split-off converters step things down across the board—some linked, others standalone—to keep things safe and quiet. From the mains supply, switch-based converters shape out separate power lines—one delivering ± 12 volts plus an isolated +15 volt link for gate drivers. Because distance matters when splitting control levels, that separation keeps the inverter running independently from lower-stage logic. Once inside the core circuitry, fixed-output regulators step down excess voltage into clean +5 and +3.3 volt feeds for the processor, signal processing blocks, and data links. Spread around key sinks, specialized caps absorb sudden changes in voltage, reducing jitter at high speeds—a move rooted in tried methods for designing reliable printed circuit boards (Erickson & Maksimović, 2020; Texas Instruments, 2019).

4.1.2 Digital Control and Processing Unit

Running the inverter's main controller is a 32-bit microcontroller handling key functions like timing algorithms, syncing with the grid, safety checks, and data exchange. Powered by a steady 3.3 volt source, it connects directly to various support components—such as ADCs for voltage readings, PWM timers for precise outputs, and digital ports for communication. From the microcontroller, pulse-width modulation signals travel to control the inverter's switches via separate gate drivers. Feedback on voltage and current allows the system to adjust output while keeping track of the grid's rhythm using a PLL. Errors or abnormal conditions are detected automatically without needing extra programming. Because it runs on software, new control methods like Proportional-Resonant (PR) or Synchronous Reference Frame (SRF) controllers can be easily implemented (Teodorescu et al., 2011).

4.1.3 Galvanically Isolated Gate Driver Stage

Away from the main circuit, separate gate drivers handle voltage levels and strong current spikes during switching. Because they isolate the low-voltage logic from high-voltage surges, protection comes naturally when dealing with grid-connected designs. Fast changes in voltage happen across the bridge, bringing unpredictable shifts that could harm control components—so isolation blocks those irregular forces effectively. One half of each inverter has its driver made up by a matching set—one top and one bottom channel. Power reaches these drivers through separate, floating supplies that stay independent. The choice of gate resistors takes care of both speed and stability, thereby mitigating Electromagnetic Interference (EMI) (Texas Instruments, 2021a). Additionally, timing gaps are programmed into the main unit to avoid short circuits when switches overlap.

4.1.4 Power Inverter Stage

A single-phase full-bridge inverter handles the power stage, built with power MOSFETs. Instead of staying fixed, the high-voltage DC supply turns into a swinging PWM voltage—

swinging both above and below zero—in sync with the grid's rhythm. Common in grid-connected setups because it's straightforward, efficient, and works well regardless of whether unipolar or bipolar PWM drives it (Mohan et al., 2003). On a shared heatsink, the MOSFETs sit together to handle heat efficiently. Close by, snubber circuits team up with tiny capacitors on each DC link to soften sharp spikes that travel through hidden inductive paths. When it comes to how hot the parts get, those same engineers factor in both current flow and switching behavior so nothing exceeds a comfortable working range.

4.1.5 Output Filter and Grid Interface

High-frequency switching harmonics get reduced by using an LCL filter at the inverter output. It includes a capacitor tied to a shunt resistor for damping, along with an inverter-side inductor and a grid-side one. This setup offers stronger suppression of switching-related content than basic L or LC types, yet keeps parts physically small (Liserre et al., 2005). From the filtered signal, power flows into the utility system using a relay system that creates separation during initial power-up, shutdown, or abnormal situations—meeting safety rules like anti-islanding protection. When relays change state, a capacitor across them helps smooth out spikes in voltage, lowering electromagnetic disturbance (International Electrotechnical Commission [IEC], 2015).

4.1.6 Measurement and Protection Circuits

Getting precise readings for grid voltage, inverter current, and DC bus voltage matters because it helps the system respond correctly while staying safe. Instead of direct measurement, devices like voltage dividers or current sensing circuits reduce the signal strength so it fits what the microcontroller's analog-to-digital converter can handle. To reduce clutter on the measurements, filters roll down high-frequency junk—this cuts down errors caused by sloppy sampling (Teodorescu et al., 2011). Built into both firmware and physical components are safeguards like overcurrent alerting, limits on voltage levels, along with checks for irregular grid behavior. Once a problem shows up on the readings, the brain of the system shuts down pulse width modulation signals right away while also triggering the disconnect switch in the power line. Because different layers work together—each handling its own task—the whole setup runs much steadier and meets what rules demand for connecting to energy networks (IEEE, 2018).

4.2 Isolated Auxiliary Power Supply Design

This section covers the layout and functioning of an add-on power source built into the inverter setup, the detailed schematic of which is shown in Figure (4.2). Its job is to deliver clean, separated low-voltage supplies that shield critical parts like controllers, sensors, and high-speed drivers. Since different areas in the system sit at varying potentials, keeping them apart matters—prioritizing safety, reducing unwanted signal drift, and minimizing the risk from spikes bouncing through wires. This setup takes a non-isolated 5 V input source and turns it into a separated 12 V output. That 12 V result then gets adjusted—reduced—to deliver a reliable 5 V output voltage. There are distinct ground points at work: one called GND_D handles control and main sections, while the other, labeled GND, supports the isolated part on the secondary end.

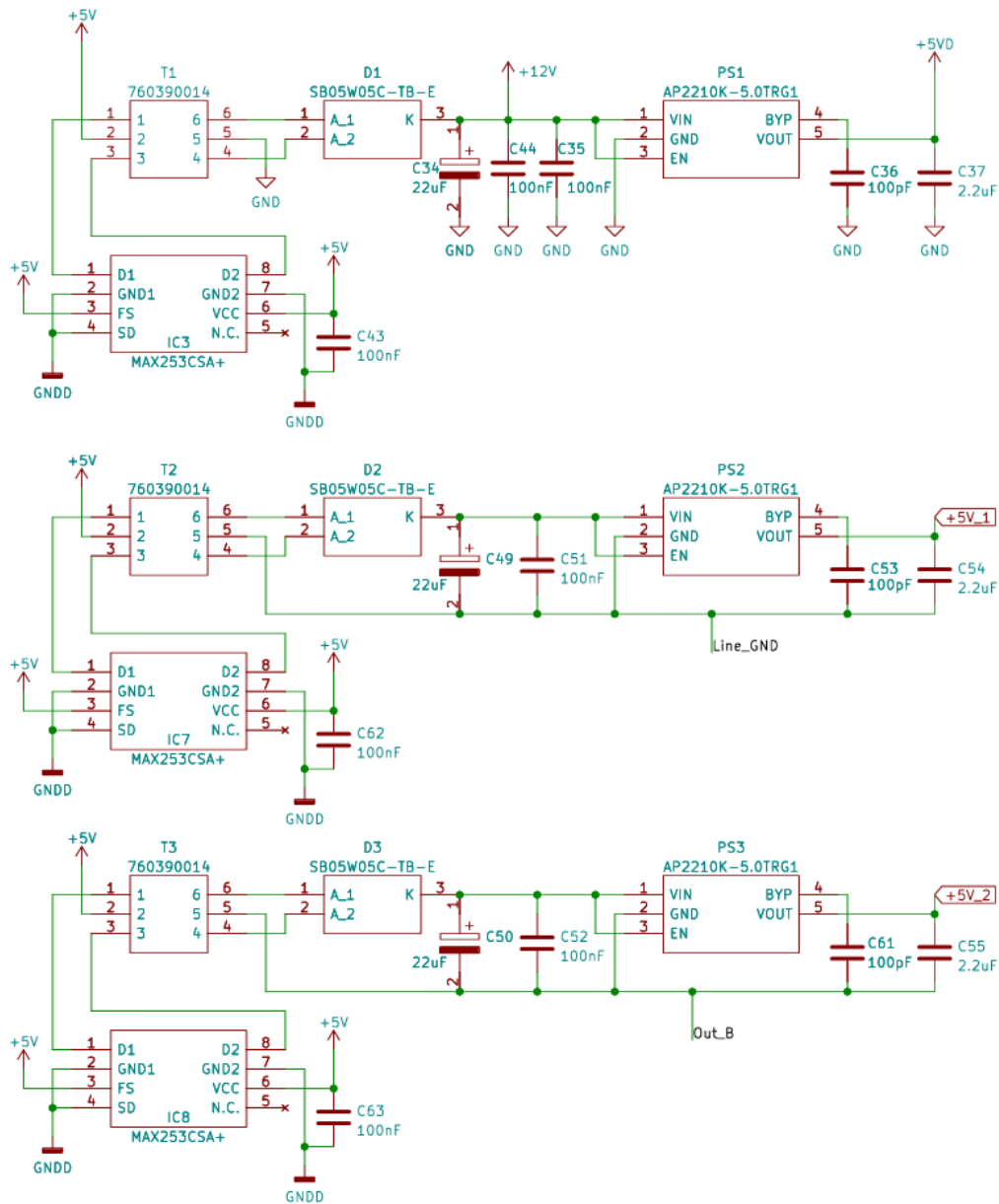


Figure 4.2: Detailed schematic diagram of the isolated auxiliary power supply.

4.2.1 Input Supply and Primary-Side Ground (GND_D)

From a current +5 V source already set, the circuit draws power tied to GNDD. That supply comes straight out of the central low-voltage management setup then moves into the converter's main side. What is seen as GND_D is where the microcontroller, logic circuits, and non-isolated signal conditioning stages connect—called the digital/control ground domain. That space stays apart from the inverter power ground through isolation. This split blocks sudden voltage changes and surge paths from reaching sensitive digital controls (Zhang, 2022).

4.2.2 Isolated DC-DC Converter (T1: 760390014)

At the heart of the isolation stage sits a transformer module, (model 760390014). Inside, fast electrical shifts drive a conversion system that relies on a transformer to keep input and output physically separate.

Input: A voltage reading comes in +5V tied directly to GND_D .

Output: is a floating DC voltage—rectified elsewhere—tied to ground (GND).

When control and power are split, this block stops the straight electrical line between them. Out in the field, these standalone converters handle tasks like powering gate drivers and keeping measurement lines separate. They help meet safety rules while also reducing electromagnetic interference (Texas Instruments, 2021).

4.2.3 Secondary Rectification Diode (D1: SB05W05C)

This section covers the secondary rectification diode, labeled D1, using the (SB05W05C) component. When the isolated DC converter finishes its cycle, a Schottky diode—labeled D1, using the SB05W05C model—takes over for rectification. These particular diodes gain favor in fast, modern power setups because they offer better performance at high speeds compared to standard types. Their design helps reduce voltage losses during switching events, especially under tight timing conditions near the MHz range. Instead of relying on slower, older-style devices, this choice supports cleaner conversion outcomes across tighter budgets and smaller form factors. (Erickson & Maksimović, 2020).

Key characteristics include:

- Front-end voltage stays low because of small drops at V_f .
- Fast switching speed speeds things up.
- Power losses dropped.

A diode turns variable AC or pulse energy—from what comes out of the transformer's back side—directly into steady DC voltage. You can estimate that steady DC result using this formula:

$$V_{DC} \approx V_{sec} - V_f$$

Here, V_{sec} stands for the secondary voltage coming from the converter. The value V_f shows how much voltage drops across the Schottky diode—usually between 0.2 and 0.4 volts (Erickson & Maksimović, 2020).

4.2.4 Bulk and Decoupling Capacitors (C34, C44, C35)

Once fixed, smooth direct current comes from blending main storage with specialized filtering caps—both handling different fluctuations:

- C34 (22 μ F): This cap handles bulk tasks, cutting low-frequency ripple while storing power.
- C44, C35 (100 nF): Ceramic capacitors used to suppress high-frequency switching noise.

$$C \geq \frac{I_{LOAD}}{f_{sw} \cdot \Delta V}$$

A rough idea about needed bulk capacitance comes from the load current -call it I_{LOAD} - flowing through the system. The pace at which switches flip drives the overall rhythm, labeled here as F_{sw} . Tucked inside this cycle, a small shift in voltage -known as ripple- is allowed, represented simply as ΔV (Erickson & Maksimović, 2020). These capacitors work as a pair to create a consistent +12 V voltage that is separate from the main circuit. That voltage sits at a fixed level relative to the secondary ground point labeled GND.

4.2.5 Linear Voltage Regulator (PS1: AP2210K-5.0TRG1)

This section covers the Linear Voltage Regulator using the PS1: AP2210K-5.0TRG1. A single +12 V power line gets scaled into a +5 V output through a precision component called the AP2210K-5.0—a type of low-dropout linear regulator. It handles functions like:

- Fixed 5 V output.
- High power-supply rejection ratio (PSRR).
- Low output noise.

With the regulator designed to handle voltages between 6 and 20 volts, it fits well within the +12 V supply range. Because of its dropout voltage, the system keeps steady output when current demands shift (Diodes Incorporated, 2019). The regulator loses power through thermal dissipation:

$$P_{loss} = (V_{in} - V_{out}) \cdot I_{out}$$

This loss gets accounted for during thermal design so systems can run without risking safety.

4.2.6 Output Bypass and Stabilization (C36, C37)

This section covers output bypass and stabilization components, specifically capacitors C36 and C37.

- C36 (100 pF): A 100 pF cap helps block high-frequency spikes while reducing electrical chatter on power lines.
- C37 (2.2 μ F): A small value cap, 2.2 microfarads, labeled C37—this one helps keep the output stable while the system shifts or reacts suddenly.

It works inside the feedback loop so adjustments stay smooth. What keeps the system steady comes from caps and ESR numbers found right in the regulator's data sheet—keeping shake and instability under control (Diodes Incorporated, 2019).

4.2.7 Enable and Control Interface (MAX253CSA+)

This section covers the Enable and Control Interface using the MAX253CSA+, allowing for controlled access and management of the interface. Starting from the main control source, the MAX253CSA+ handles isolation tasks while managing enablement. Instead of

just connecting, it bridges the +5 V domain with care, making sure things begin properly. Power flows in stages under guidance, reducing electrical chatter between separate segments. This separation keeps signals clean across divided regions. A small capacitor, C43 (100 nF), sits near the IC's power input. Its job is to quiet spikes from digital chatter nearby. This spot choice keeps voltage steady when the chip talks. Local jitter fades because of it. Reliable work depends on such quiet moments.

4.2.8 Input and Output Voltages Summary

The input and output voltage levels regarding the ground reference are summarized in Table (4.1) below:

Table 4.1: Summary of input and output voltage levels in the regulation stage.

Node	Voltage Level	Ground Reference
Input Supply	+5V	GNDD
Isolated Intermediate Rail	+12V	GND

Here lies a small chunk of power, sitting just above ground. Around five volts flows through this line, moving upward from zero.

4.2.9 Reason for Using Two Different Ground References

Beyond just physical spacing, the use of GND_D and GND shows deliberate galvanic separation—keeping control and driver domains electrically apart. That isolation matters because it reduces the risk of unintended current paths across domains. A spike of electricity won't destroy small devices when this component steps in. It blocks excess voltage before it reaches sensitive gear. Noise from common sources gets reduced here, improving EMC performance. High-voltage inverters rely on smart gate drive plus accurate sensing—this tech makes those tasks safer by design. This method follows standard guidelines used in grid-connected systems and strong inverter applications (Teodorescu et al., 2011; Ott, 2009).

4.2.10 Summary Outcomes

This part of the power supply handles low voltage while keeping electronics protected from each other. Instead of just copying a design, it mixes magnetic separation with fast rectifying diodes. Added smoothing stages clean the output further than basic versions. Noise stays under control because simple linear feedback keeps things steady. Keeping connections physically split matters—it prevents unintended behavior during use. Following these rules helps meet requirements for safe and reliable circuit performance.

4.3 Low-Voltage Regulation Stage (VCC to +5 V and +3.3 V)

This section details the design and operation of the low-voltage regulation stage, as illustrated in the left section of Figure (4.3), which ensures the stability of the digital

components. Starting from the input supply, designated as V_{CC} , the circuit employs two stacked control units (linear regulators) to refine output levels relative to a shared ground, GND_D . Rather than a single step-down conversion, the system uses a cascaded approach to optimize the power delivery. In embedded electronic setups, a +5V level is typically required for external connections and inputs, while +3.3V is necessary for modern microcontrollers and high-speed signaling tools. Consequently, this stage is designed not merely to split power, but to match the specific voltage requirements of each component.

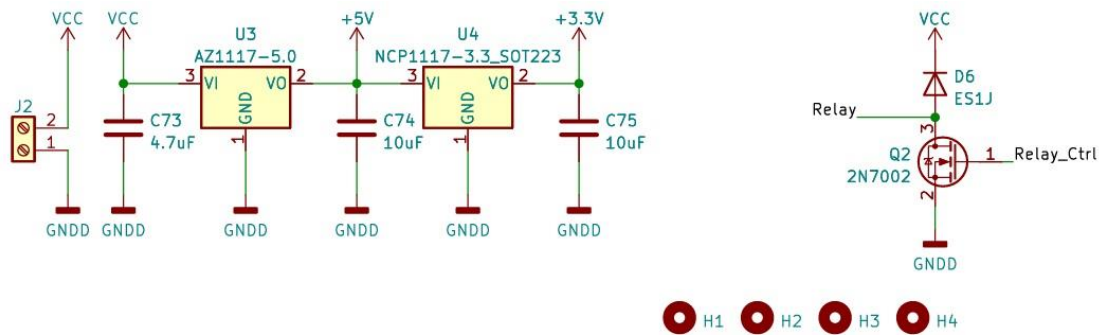


Figure (4.3): Schematic diagram of the Low-Voltage Regulation and Relay Driver circuits.

4.3.1 Input Interface (J2) and Ground Reference

The DC power enters through interface J2 via the V_{CC} net, delivering unfiltered voltage to the regulators. The pins of J2 are connected to the GND_D plane, which represents the digital/control ground network. This labeling indicates that the low-voltage supply runs independently from high-voltage circuits. Maintaining separation between these grounds reduces electromagnetic disturbance caused by digital switching noise. Enhanced stability in inverters is achieved when electrical paths are organized strictly across layers (Ott, 2009).

Input Voltage at V_{CC} :

Upstream, V_{CC} acts as a power rail that must be higher than the desired output levels, as each regulator consumes voltage overhead (dropout) when active. A typical range for V_{CC} in various embedded platforms lies between 7 and 15 V; however, the precise voltage depends on the upstream generation method.

4.3.2 +5 V Linear Regulation (U3: AZ1117-5.0)

Role and Operation:

Component U3 (AZ1117-5.0) manages the high voltage step-down to a fixed +5V without using switching topology. It maintains a steady output even when the input shifts slightly. Instead of amplifying signals, it stabilizes the power delivered across the circuit stages.

Selection of Low-Dropout Regulators (LDOs):

LDOs are chosen for this application for the following reasons:

- They exhibit lower output ripple and noise compared to most switching converters.
- They allow for simple implementation with few external components.
- They handle sudden changes in digital load effectively, provided they remain stable (Diodes Incorporated, 2019).

Dropout Constraint:

To maintain regulation, the condition:

$$V_{CC(min)} \geq V_{OUT} + V_{DO}$$

Where $V_{CC} \geq 5V + V_{DO}$ must be met. Here, V_{DO} represents the minimum voltage drop required by the regulator to sustain the output under load (Diodes Incorporated, n.d.). If V_{CC} drops near 5V, the regulator enters dropout mode, causing the +5V output to dip rather than staying steady.

4.3.3 Input/Output Stability Capacitor (C73: 4.7 μ F)

Functionality:

A large ceramic capacitor, C73 (4.7 μ F), is placed close to U3 to handle voltage smoothing at the regulator's main output. In low-dropout designs, the capacitor functions beyond simple fluctuation removal; it determines how the circuit reacts under change, shaping both stability and the response to quick bursts of current. Its main functions are:

- Providing instant current flow when loads change to reduce voltage dips.
- Reducing output ripple and noise.

The addition of this capacitor ensures the system operates without interruptions by smoothing spikes and maintaining steady signals. To ensure stability, the capacitor must meet specific values regarding capacitance and Equivalent Series Resistance (ESR) (Diodes Incorporated, 2019; Erickson & Maksimović, 2020).

Capacitance Sizing Insight:

A simplified first-order model for voltage droop during a step load is often derived from transient analysis:

$$C \geq \frac{\Delta I \times \Delta t}{\Delta V}$$

Where ΔI is the sudden shift in load current, Δt is the response time of the regulator, and ΔV is the allowable voltage ripple. This formula leads designers to select capacitors ranging from a few microfarads up to several dozen for locations where voltage stabilizers drive logic chips (Ott, 2009).

4.3.4 +3.3 V Linear Regulation (U4: NCP1117-3.3 SOT-223)

Role and Operation:

The U4 chip (NCP1117-3.3) takes the +5V output and regulates it down to exactly +3.3V using a precision regulator. This lower voltage rail typically powers:

- The microcontroller core and I/O (3.3V logic).
- ADC interfaces.
- Digital isolators and communication ICs.
- Sensors and low-voltage analog ICs.

A cascaded design, where the LDO taps into the +5V rail, is frequently used because it decouples the +3.3V rail from V_{CC} variations and simplifies power sequencing for the digital subsystem (Diodes Incorporated, 2019).

Dropout Constraint:

Proper control of the +3.3V rail requires satisfying the condition:

$$V_{IN(min)} \geq (3.3V + V_{DO})$$

So $V_{IN}(5V) \geq 3.3V + V_{DO}$, where V_{DO} varies based on the current draw (ON Semiconductor, n.d.-b).

4.3.5 Decoupling Capacitors for the 3.3 V Stage (C74, C75)

- **C74 (10 μ F) - Input Decoupling:** Placed at the input of U4, C74 lowers the input impedance faced by the regulator. It serves to absorb sudden voltage spikes from the +5 V supply and prevent oscillations caused by long traces or supply inductance (ON Semiconductor, n.d.-b).
- **C75 (10 μ F) - Output Stability and Transient Support:** Placed at the output of U4, C75 ensures the LDO remains stable (adhering to minimum capacitance and ESR limits defined in the datasheet) and minimizes voltage dips when loads shift quickly on the +3.3V line (ON Semiconductor, n.d.-b).

The transient estimation formula used for C73 applies here as well. A 10 μ F capacitor is chosen as it is straightforward, reliable, and works well for both digital and analog circuits.

4.3.6 Power Dissipation and Thermal Considerations

Since U3 and U4 operate as linear regulators, the voltage difference results in heat dissipation, calculated as:

- For U3: $P_D = (V_{CC} - 5V) \times I_{5V}$
- For U4: $P_D = (5V - 3.3V) \times I_{3.3V}$

This dissipation must be matched against the thermal resistance of the SOT-223 package, the PCB copper area used for heat spreading, and the maximum junction temperature

limits (Diodes Incorporated, 2019). Heat flow is inherent in linear voltage regulation, making thermal verification critical at maximum current draw.

4.3.7 Input and Output Voltages Summary

- Input (V_{CC}): Supplied at J2; value must exceed dropout specifications relative GND_D .
- Intermediate Output (U3): +5V, referenced to GND_D .
- Final Output (U4): +3.3V, referenced to GND_D .

4.3.8 Summary of Regulation Stage

A solid base of low-voltage power reaches the inverter's digital section via this subcircuit. Starting from V_{CC} , the AZ1117-5.0 reduces the voltage to exactly 5V.

Subsequently, the NCP1117-3.3 refines this to 3.3V. Capacitors such as C73, C74, and C75 are essential to maintain system integrity during sudden changes and to ensure regulator stability.

4.4 Relay Driver Stage

This section covers the relay driver subcircuit utilized within the grid-connected inverter setup (see right side of Figure 4.x). The stage is built around a low-side MOSFET acting as a switch. A relay coil acts like a magnet; when power stops, driving it requires more than a simple digital output. Due to its inductive nature, the current required might exceed what a microcontroller's built-in pin can handle without damage. Therefore, a specialized component, specifically a basic N-channel MOSFET (e.g., the 2N7002 type), is used where operation depends entirely on low-voltage digital inputs.

Operation:

A logic-high signal from the controller turns the MOSFET on, energizing the relay coil.

Protection:

A flyback diode (D_6 : ES1J) clamps the inductive voltage spike ($V_L = L \cdot di/dt$) upon disconnection to $V_{CC} + V_F$, protecting the MOSFET.

When the device turns power off, an electrical shock caused by back-electromotive force (back EMF) could occur, potentially harming personnel or damaging components. To block this sudden spike, a small component labeled D6 acts as a flyback (or snubber) diode, draining excess energy safely away. This method boosts system reliability while shielding the switching component and reducing electromagnetic disturbance (Mohan et al., 2003; IEC, 2015).

4.4.1 Circuit Function and Signal Flow

A coil links directly to the supply line V_{CC} , also touching the point marked Relay. The transistor Q2—here a 2N7002—acts like a switch across the ground path.

- With Q2 turned on: Electricity can travel directly between the relay coil and GND_D . This path keeps current flowing so the coil gets power when it is active.
- With Q2 turned off: The coil stops flowing current. Without power, the relay disengages.

When the Relay_Ctrl signal goes high, it reaches the MOSFET gate, turning it on. Because it works with basic logic inputs, many designs choose this setup—it stays simple, affordable, yet reliable across different systems (ON Semiconductor, 2019a).

4.4.2 MOSFET Switch (Q2: 2N7002)

Why a MOSFET is used:

One reason the 2N7002 is frequently used is its ability to act as a switch for ground connections where space and functionality are critical. In this case, its role facilitates signal movement through circuits under light loads. Key advantages include:

1. Current amplification and drive ability: The microcontroller provides just enough voltage to activate the MOSFET gate, consuming almost no active current. Power flows through the MOSFET to handle control of the relay coil instead.
2. Logic-level control: The switch can run directly off a digital voltage—typically 3.3V or 5V—provided the electrical draw through the coil stays under control (Mohan et al., 2003).
3. Lower drive power compared to BJT: Once turned on, MOSFETs maintain operation without continuous base current, reducing the system load compared to bipolar junction transistors.

MOSFET Conduction Losses:

Power loss during the 'on' state occurs mostly through the MOSFET's on-resistance ($R_{DS(on)}$). This conduction loss is quantified by the relationship:

$$P_{Q2} \approx I_{coil}^2 \times R_{DS(on)}$$

This loss needs to stay modest so heat does not rise too quickly, particularly when the relay is powered for extended periods (ON Semiconductor, 2019).

Gate Drive Considerations:

For the MOSFET to switch completely on, the gate-source voltage (V_{GS}) needs to meet a specific condition:

$$V_{GS} \geq V_{GS(required)}$$

Designers must check the $R_{DS(on)}$ specifications at the drive voltage (e.g., 3.3V or 5V) found in the datasheet, rather than relying on estimates. This ensures the circuit can handle real-world coil demands (ON Semiconductor, 2019).

4.4.3 Flyback Diode (D6: ES1J)

Why the diode is needed:

A relay coil acts as an inductive load. If the flow of electric current stops suddenly, a strong voltage surge appears to resist the shift in current:

$$V_L = L \times \frac{di}{dt}$$

Without shielding, the voltage reaching the MOSFET drain might climb above the device's breakdown limit, leading to damage, sparks, or harmful electromagnetic interference.

How D6 works:

When the MOSFET switches off, D6 becomes forward-biased through its connection from the relay node to V_{CC} . This setup redirects coil current safely away, clamping the voltage surge. The clamping voltage is approximately:

$$V_{clamp} \approx V_{CC} + V_F$$

Where V_F stands for the voltage drop across the diode (Mohan et al., 2003; IEC, 2015).

Diode Selection Criteria:

D6 is selected based on the ability to handle:

- Forward current rating exceeding the coil current.
- Peak reverse voltage higher than the main supply voltage.
- Strong surge handling plus quick recovery.

The ES1J is a fast rectifier diode that moves efficiently and is often applied in inductive clamping applications to provide robust safeguards (Vishay, 2018).

4.4.4 Input and Output Voltage Levels

Input (Control Signal: Relay_Ctrl):

- From the microcontroller comes a logic-level gate drive.
- Typically:
 - (0V → MOSFET OFF → *relay de-energized*) At 0V, the MOSFET stays off; power does not reach the relay, so it loses drive.
 - (3.3V or 5V → MOSFET ON → *relay energized*) At 3.3V or 5V (depending on the controller rail), the MOSFET turns on, activating the relay.

Relay Node:

The node called Relay sits on the switched low-side circuit:

- When MOSFET is ON: The node is pulled close to ground.

$$V_{Relay} \approx 0V (GND_D)$$

- When MOSFET is OFF: The node floats to V_{CC}

$$V_{Relay} \approx V_{CC}$$

With a sudden brief spike appearing under controlled conditions via D6 during switch-off events (ON Semiconductor, n.d.-a).

4.4.5 Notes on Passive Components

A closer look at the schematic snippet shows no visible gate resistor or pull-down component. Designers often add these based on specific control requirements.

1. Gate series resistor (R_G , e.g., 10–100 Ω): Reduces ringing, limits peak gate current, and improves EMI performance.
2. Gate pull-down resistor (R_{PD} , e.g., 47–200 k Ω): Ensures the MOSFET stays off at reset or startup even if the GPIO is floating.

Including these components enhances reliability significantly (ON Semiconductor, 2019; ON Semiconductor, n.d.-a).

4.4.6 Summary of Relay Driver Stage

Here is how it works: a small MOSFET—like the 2N7002—handles strong current so the microcontroller does not get overwhelmed. When the relay needs to change state, a fast diode called ES1J steps in to catch any sudden spikes that might otherwise damage parts or cause interference. This setup keeps the system stable and safe while ensuring signal integrity. Safety rules demand a separate disconnect in inverters tied to the power grid to protect both equipment and personnel during malfunction events (International Electrotechnical Commission [IEC], 2015).

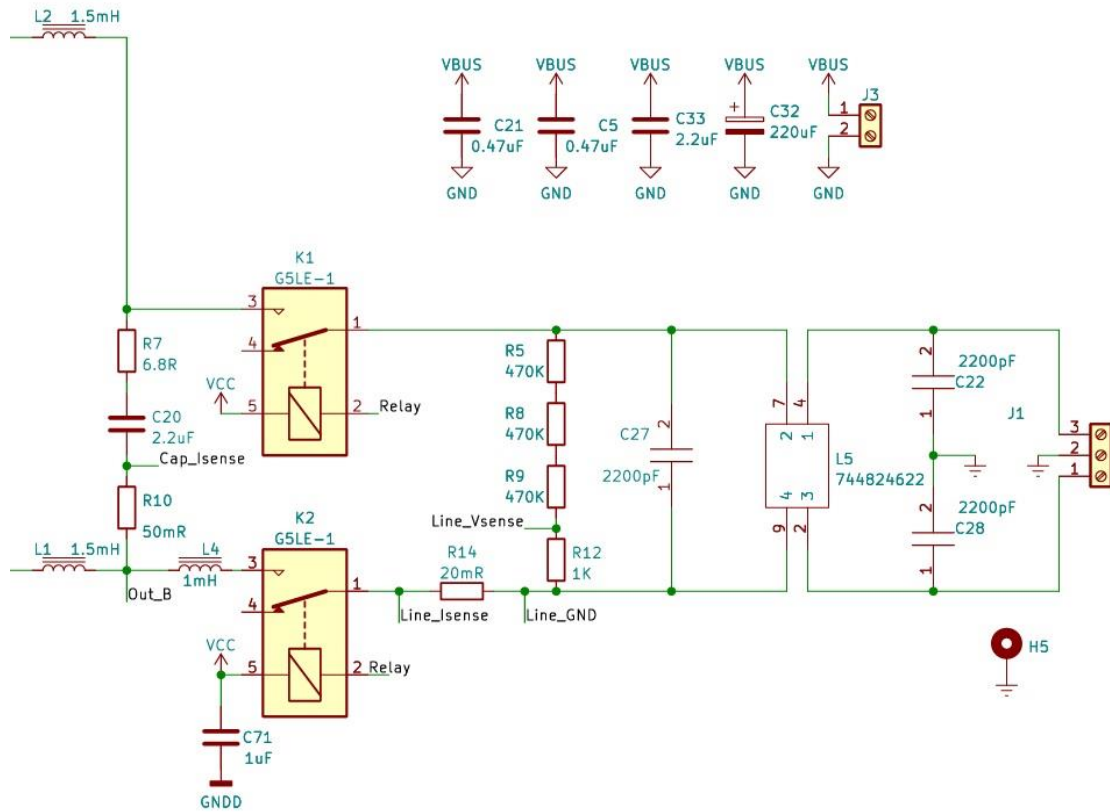


Figure 4.4: Output Stage: Filtering, Sensing, and Grid Interface

4.5 Gate Driver and Full-Bridge Power Stage

Before discussing the driver stage, it is important to note that the output signals generated are filtered and interfaced with the grid as shown in Figure (4.4).

This section describes the gate-driver and full-bridge subsystem, utilizing the UCC21520ADW driver and BUZ11 MOSFETs, handling a 400V bus (V_{BUS}) with unipolar PWM, powered at 12V. The gate driver handles switching tasks for power MOSFETs, while the full-bridge structure forms the core of voltage switching operations in DC-to-DC converters.

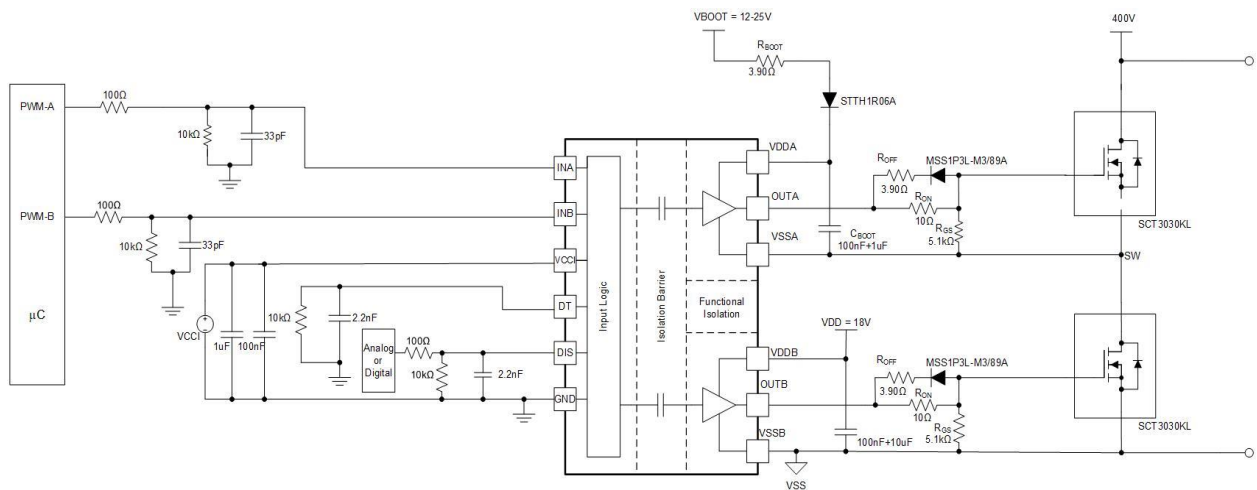


Figure 4.5: Schematic diagram of the isolated gate driver circuit utilizing UCC21520.

The system converts direct current from the bus into an alternating voltage shape using a gate driver along with a full-bridge power stage. It includes:

1. Digital Controller Inputs: PWM control signals from an MCU or DSP.
2. Gate-Driver IC(s): Provide level shifting, isolation, and high peak gate currents.
3. Gate Networks: Resistors, diodes, and sometimes RC components control switching speed, boosting reliability and reducing EMI.
4. Full-Bridge Configuration: Two pairs of transistors work together to allow switching in both directions, effectively handling drive requirements.
5. Protection Networks: Local DC-link decoupling and snubber/TVS networks manage switching transients.

The main goal is to ensure every MOSFET receives the correct voltage magnitude, sequence (avoiding short circuits), and reaction speed. This prevents shoot-through, minimizes switching losses, and maintains operational headroom during anomalies. (Erickson & Maksimović, 2020; Texas Instruments, 2023), as depicted in the detailed schematic in Figure (4.5).

4.5.1 Gate-Driver Inputs from Controller

A typical setup for a full-bridge gate-driver stage involves:

- PWM_A_H / PWM_A_L: These signals drive opposite halves of a full bridge—one goes high while the other drops low. Each controls a separate leg, handling both upper and lower sections.
- Enable/Disable Switch: Controls power into the system. If a fault occurs, it turns everything off automatically.
- Fault Signal: Indicates fault or overcurrent conditions to the system.
- Ground Reference: A spot on the board where signals tie back to their proper ground (shared GND, GND_D , or an isolated link).

The input signals must meet specific criteria:

- Correct logic-level compatibility (either 3.3V or 5V).
- Aligned propagation delays for steady switching.
- Predictable behavior during reset or startup (no floating states).

4.5.2 Gate-Driver Outputs to MOSFET Gates

The driver offers HO / LO (or equivalent) outputs for high-side and low-side MOSFETs. A floating high-side driver utilizes a bootstrap switch node reference (HS or SW). Key output requirements include:

- Voltage Level: Gates need solid voltage—typically around 10 to 12 V for standard MOSFETs.
- Peak Current: Must handle sharp changes in gate capacitance during charging and discharging.

- Rise/Fall Control: The gate network controls how fast transition times occur, which helps reduce overshoot and electromagnetic interference.

4.5.3 Switching Mechanisms

4.5.3.1 Low-Side Gate Drive Mechanism

When activated, the bottom MOSFET pulls its source toward the system ground (PGND or GND). Charging the gate occurs via a resistor linked to the driver's LO pin.

- When the gate rises to V_{DRV} , the channel opens, allowing current through the MOSFET.
- Deactivation occurs when the gate connects to the common/complementary ground, blocking the MOSFET.
- Switching speed depends on the resistance in the gate circuit and the total gate charge (Q_g).

4.5.3.2 High-Side Gate Drive Mechanism (Bootstrap Concept)

When the switching node voltage rises, the MOSFET source requires a voltage boost to remain effective. A bootstrap network creates this boost by pulling power from the ground side and storing it earlier in the cycle. This stored charge functions as the "floating supply."

- Charging: When the switching node goes low (during low-side activation), charge flows from V_{DRV} into the bootstrap capacitor via the bootstrap diode.
- Activation: Once the high-side switch activates, the stored supply from the bootstrap capacitor becomes available, allowing operation independent of the ground reference.

$$V_{GS(H)} \approx V_{BOOT} - V_{SW}$$

This allows power control on the high side without a separate isolated voltage source, provided periodic recharging occurs (Texas Instruments, 2021a).

4.5.3.3 Dead-Time and Shoot-Through Avoidance

A single full bridge consists of two half-bridges where the upper and lower sections must not conduct simultaneously. Timing gaps, known as dead-time, are introduced to block unwanted current paths. The dead-time duration must exceed the sum of driver mismatch delays and MOSFET switching times, accounting for reverse recovery.

- Consequences: Insufficient dead-time causes shoot-through. Excessive dead-time multiplies distortion and drains power needlessly due to body diode conduction.

4.5.4 Gate Network Components

4.5.4.1 Gate Resistors ($R_{g(on)}$ and $R_{g(off)}$)

Gate resistors control the charging/discharging current of the gate capacitance. Their functions include:

- Reducing ringing from stray inductance.
- Slowing edge transitions slightly to reduce EMI.
- Reducing driver stress levels.

The approximate peak gate current ($I_{g, peak}$) is determined by the drive voltage (V_{DRV}) and the total resistance in the gate loop, which includes the external resistor (R_g) and the internal driver resistance ($R_{DRV,int}$):

$$I_{g, peak} \approx \frac{V_{DRV}}{R_g + R_{DRV,int}}$$

Consequently, the switching transition time (t) can be estimated based on the MOSFET's total gate charge (Q_g):

$$t \approx \frac{Q_g}{I_g}$$

Finally, R_g selection is based on the MOSFET's Q_g , target switching speed, and the driver's current capability.

4.5.4.2 Gate-to-Source Resistor (R_{GS})

A large resistor (e.g., 47-200k Ω) ensures the MOSFET remains off when the driver output enters a high-impedance mode, such as during reset or under-voltage shutdown.

4.5.4.3 Gate Diode (Asymmetric Control)

A diode paired with a gate resistor enables distinct rise and fall speeds.

- Fast Shutdown: Resistance drops, boosting safety through quicker turn-off.
- Slower Turn-On: Helps reduce EMI and overshoot.

4.5.4.4 Miller Clamp / RC Snubber (Optional)

These components target the Miller capacitance effect, preventing unexpected activation under fast voltage changes (dV/dt).

4.5.5 Full-Bridge (H-Bridge) Power Stage Operation

4.5.5.1 Topology and Power Flow

A full-bridge setup uses four MOSFETs divided into separate half-bridges. By toggling opposite pairs, it shapes a pulsating DC voltage. Unipolar PWM toggles between 0 and $+V_{bus}$ or 0 and $-V_{bus}$, reducing harmonics and limiting dV/dt .

4.5.5.2 Current Commutation and Body Diode Conduction

During switching dead-time, current flows through the MOSFET body diode. The layout must ensure that dead-time is not excessive, MOSFET $Q_{rr}/diode$ recovery effects are acceptable, and loop inductance is minimized.

4.5.5.3 DC-Link Decoupling

A local film or ceramic decoupling capacitor handles high-frequency current flow near the bridge. Without this, long paths lead to voltage overshoot, ringing, and EMI issues.

4.5.6 Overcharge Consideration (Gate Driver and MOSFET Gate Protection)

According to Texas Instruments (2023), The "Overcharge" refers to scenarios where voltages exceed safe limits:

1. Gate-source voltage (V_{GS}) exceeding limits (e.g., $\pm 20 V$).
2. Bootstrap capacitor voltage rising due to ringing or negative spikes on the SW pin.
3. Driver output exceeding limits due to LC ringing.

Mitigations:

- Gate Zener diodes (15 – 18 V) across gate-source.
- Proper gate resistor sizing and minimized loop inductance.
- Ensuring driver supply voltage (V_{DRV}) stays within safe ranges.

4.5.6.1 Bootstrap Overcharge Mechanism

In floating supply systems, bootstrap overcharge occurs when the capacitor pulls too much current, often due to uneven switching patterns or high-voltage driver conditions (Texas Instruments, 2023; Texas Instruments, 2022b).

A primary cause is switch-node undershoot. When the switch node (V_{SW}) dips by a negative voltage ΔV_{US} due to inductive effects, the floating driver supply voltage ($V_{DD} - V_{SSA}$) increases by roughly the same amount:

$$V_{boot_{eff}} \approx V_{boot_{nom}} + |\Delta V_{US}|$$

For example, a nominal 18V charge combined with a -7V undershoot pushes the supply to 25V, potentially exceeding the driver's absolute maximum ratings (Texas Instruments, 2021c; Texas Instruments, 2023).

4.5.6.2 Causes of Switch-Node Undershoot

Undershoot results from parasitic inductances and switching dynamics:

1. High di/dt acting on parasitic inductance (L_{par}) in the PCB layout (Baliga, 1996).
2. Current commutation through the bottom MOSFET's body diode during dead-time (Vishay Intertechnology, 2019; ON Semiconductor, 2018a).
3. Device reverse recovery and output capacitance effects (Vishay Intertechnology, 2019).

4.5.6.3 Analysis of Switching Waveforms

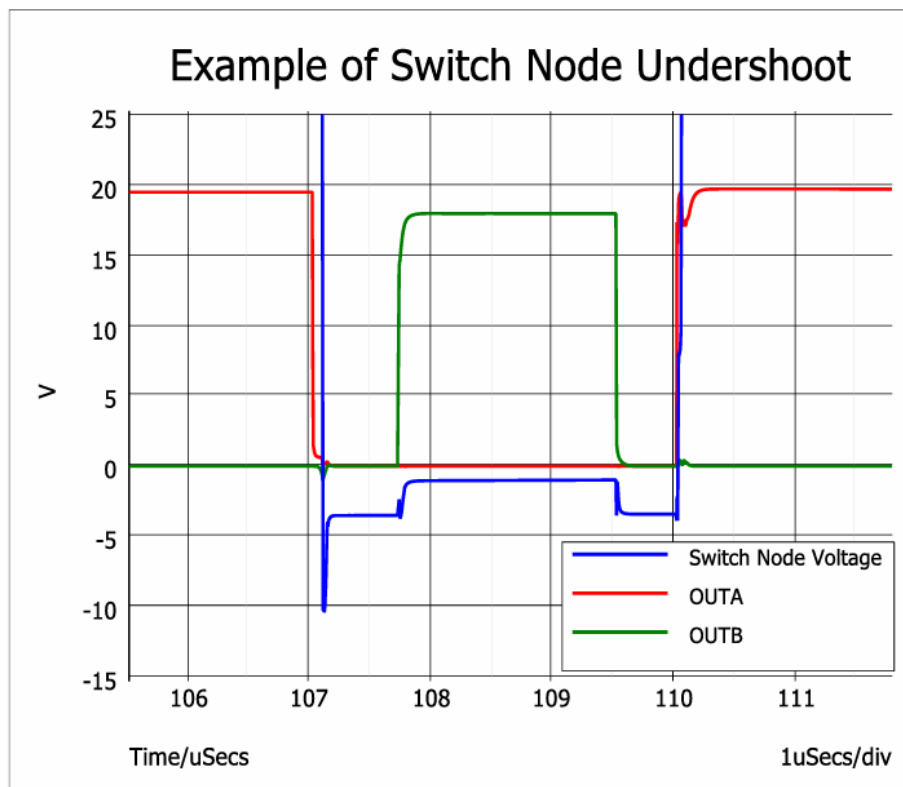


Figure 4.6: Example of Switch-Node Undershoot

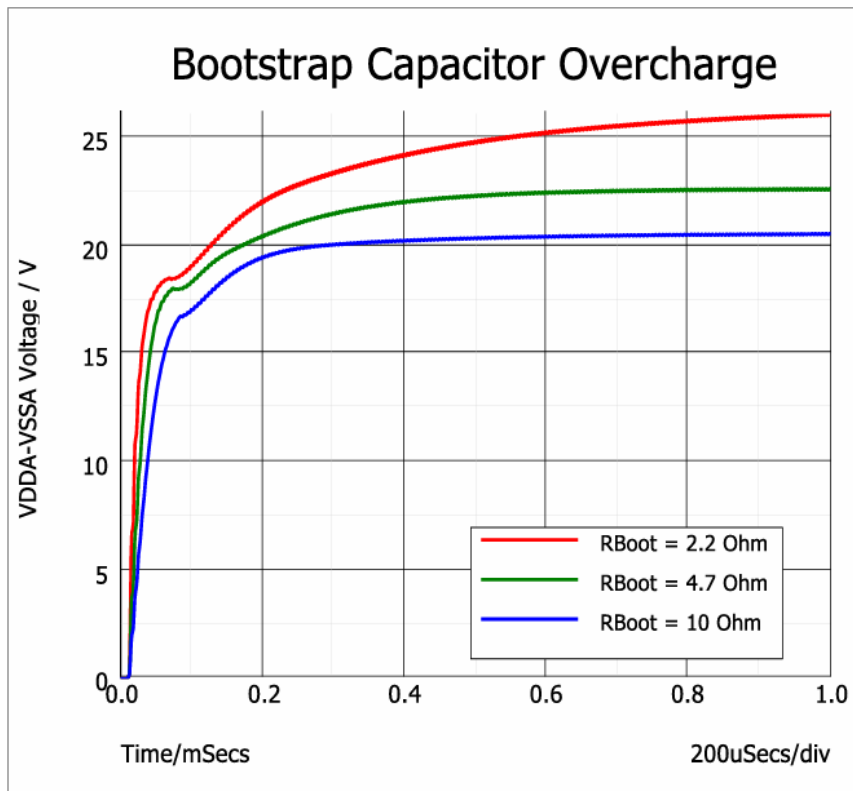


Figure 4.7: Example of Bootstrap Overcharge vs. Resistance

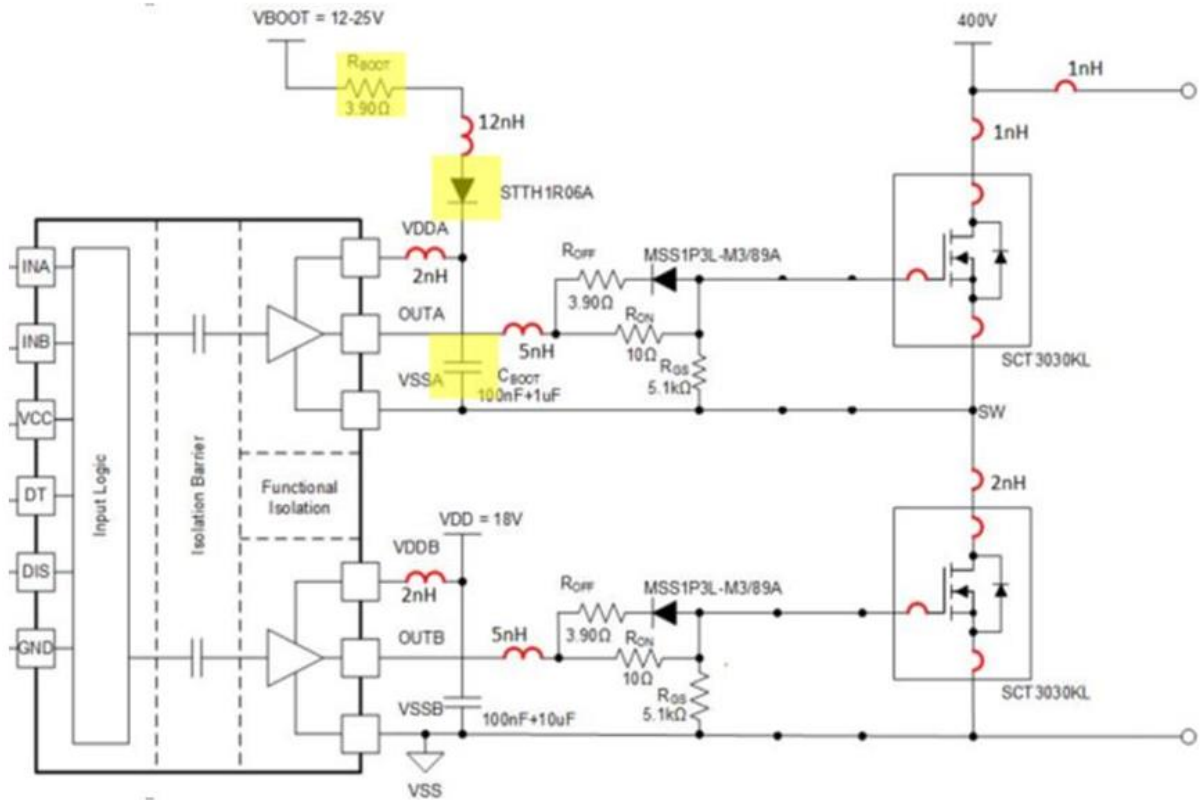


Figure 4.8: Parasitic Inductance

- Figure 4.6 (Switch-Node Undershoot): Demonstrates the negative spike at the switch node. This spike is defined by $V_{spike} = L_{par} \times (di/dt)$. The waveform highlights dead-time reverse current regions and device-dependent ringing (Texas Instruments, 2023).
- Figure 4.7 (Bootstrap Overcharge vs. Resistance): Shows that lower R_{BOOT} values (e.g., 2.2Ω) lead to excessive charging currents and higher voltage peaks. Increasing R_{BOOT} (e.g., to 10Ω) damps the charging process, reducing overcharge (Texas Instruments, 2022b; Texas Instruments, 2022a).
- Figure 4.8 (Parasitic Inductance): Identifies the physical origins of undershoot in the commutation loop and gate loop paths (Texas Instruments, 2021a).

4.5.6.4 Practical Design Guidelines

1. Dead-Time Optimization: Prevents shoot-through and minimizes body-diode conduction time (Fairchild Semiconductor, 2017).
2. Minimize Parasitic Inductance: achieved via tight layout, close DC-link capacitors, and stacked vias (Texas Instruments, 2021b).
3. Boosting Bootstrap Capacitance (C_{BOOT}): Reduces voltage ripple but increases start-up time (Texas Instruments, 2021a).
4. Increasing Bootstrap Resistance (R_{BOOT}): Limits peak charging current during undershoot events (Texas Instruments, 2022b).
5. Clamping: Using Zener diodes or TVS clamps across the bootstrap supply and RC snubbers at the switching node (Infineon Technologies, 2020b; STMicroelectronics, 2019).

4.5.6.5 Application to 400 V DC Bus

Even with unipolar PWM reducing voltage shifts compared to bipolar schemes, the 400V bus creates steep dV/dt slopes. Protecting against overcharge is critical. The selected parameters (R_{BOOT} , C_{BOOT}) are verified to handle these stresses (Texas Instruments, 2023).

4.5.7 Start-Up Delay Calculator

Start-up delay is the interval from powering the driver until a valid high-side pulse is generated. It consists of the bootstrap charging time and the internal driver UVLO release delay (Texas Instruments, 2021; Texas Instruments, 2023).

4.5.7.1 Physical Meaning

The delay ensures the high-side driver is fully charged and prevents partial enhancement. The total delay is approximated as:

$$t_{startup} = t_{bootstrap_charge} + t_{VDD_to_OUT}$$

The charging time depends on R_{BOOT}, C_{BOOT} , duty cycle, and frequency (Texas Instruments, 2021a).

4.5.7.2 Driver Timing Diagram

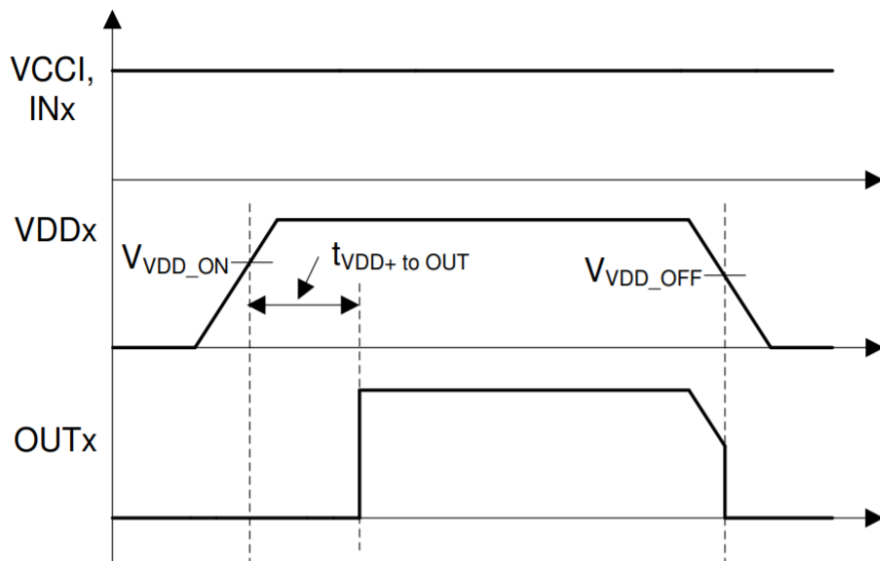


Figure 4.9: Start-up timing diagram showing UVLO release delay.

The diagram in Figure (4.9) illustrates the sequence: V_{DDx} rises via the bootstrap diode; once $V_{DDx} > V_{VDDON}$, the internal logic waits (50 μ s) before enabling the output (Texas Instruments, 2023).

4.5.7.3 Bootstrap Charging Impact

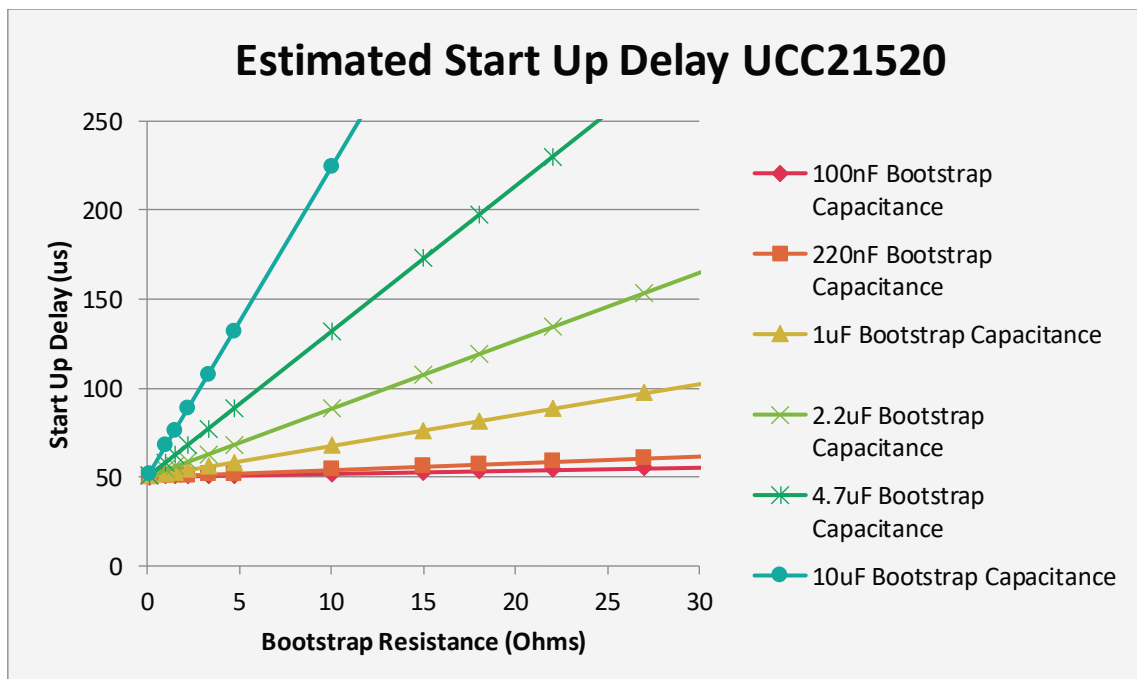


Figure 4.10: Estimated start-up delay as a function of bootstrap resistance and capacitance.

The impact of component selection on delay is visualized in Figure (4.10). It shows that higher resistance

- Effect of R_{BOOT} : Higher resistance slows charging, increasing delay.
- Effect of C_{BOOT} : Larger capacitors (e.g., 4.7 μF) take longer to charge (>200 μs) but offer stability. Smaller caps (100 nF) charge fast (50-60 μs) but may struggle with ripple.
- Combined Effect: A balance is required between speed and stability (Texas Instruments, 2021a).

4.5.7.4 Design Calculation

For the proposed design:

- Duty Cycle: 50%
- Dead-time: 100ns
- Frequency: 200kHz
- C_{BOOT} : 2.2 μF
- R_{BOOT} : 3.3 Ω

The calculated start-up delay is:

$$t_{startup} \approx 62.6\mu\text{s}$$

This delay is sufficiently short to avoid system lag while ensuring reliable operation (Texas Instruments, 2023).

4.5.7.5 External Enable Timing (Optional RC Delay)

In addition to the internal driver delay, an external RC network is often applied to the Enable (EN) pin to synchronize the driver activation with system stability (e.g., ensuring the DC bus is stable before PWM begins). The voltage evolution across the capacitor is described by:

$$V(t) = V_{IN} \left(1 - e^{-\frac{t}{RC}} \right)$$

Consequently, the specific time delay (t_d) required to reach the pin's logic threshold voltage (V_{TH}) is calculated as:

$$t_d = -RC \ln \left(1 - \frac{V_{TH}}{V_{IN}} \right)$$

This mechanism allows the designer to implement a "Soft-Start" or sequence delay that extends beyond the minimum internal $t_{startup}$ calculated above.

4.5.8 Bootstrap dV/dt Analysis

During start-up, the rate of voltage rise (dV/dt) across the bootstrap capacitor must be controlled. Excessive dV/dt can stress the isolation barrier and trigger internal protection or EMI issues.

4.5.8.1 Limit Definition

The bootstrap dV/dt is roughly $\Delta V_{BOOT}/\Delta t_{charge}$. Manufacturers often recommend limiting this to $<5\text{ V}/\mu\text{s}$ (Texas Instruments, 2021c).

4.5.8.2 Estimation and Verification

Using the parameters $V_{BOOT} = 18\text{V}$, $C_{BOOT} = 2.2\mu\text{F}$, and $R_{BOOT} = 3.3\ \Omega$, the estimated gradient is:

$$dV/dt \approx 2.5\text{ V}/\mu\text{s}$$

This is well below the $5\text{V}/\mu\text{s}$ limit, ensuring safe operation (Texas Instruments, 2021c).

4.5.8.3 Interpretation of dV/dt Curves

Effect of R_{BOOT} : As resistance rises, dV/dt decreases (safer). Low resistance leads to unsafe spikes.

Effect of C_{BOOT} : Larger capacitance lowers dV/dt but extends start-up time.

Red Box Region: Indicates the unsafe area ($>5\text{V}/\mu\text{s}$) where EMI and stress increase (Texas Instruments, 2022b).

4.5.8.4 Switching Node dV/dt and Gate Transition

Beyond the bootstrap supply configuration discussed earlier, managing the voltage slew rate (dV/dt) at the switching node itself is equally vital. Proper control here is essential to suppress electromagnetic interference (EMI), avoid inadvertent activation caused by the Miller effect, and limit the stress placed on isolation barriers. Mathematically, the slew rate of the switching node is estimated by the ratio of voltage change to the rise time:

$$\frac{dV}{dt} \approx \frac{\Delta V}{t_r}$$

In this context, t_r represents the effective rise time, a parameter fundamentally determined by the gate current (I_g) as it charges the MOSFET across the Miller plateau. During this critical phase, the drive current is dictated by the potential difference between the driver voltage (V_{DRV}) and the plateau voltage ($V_{plateau}$), acting against the total resistance in the gate loop:

$$I_g \approx \frac{V_{DRV} - V_{plateau}}{R_g + R_{DRV,int}}$$

Therefore, the duration required to traverse the Miller region t_{Miller} , which effectively sets the primary voltage transition speed, can be derived from the MOSFET's gate-drain charge (Q_{GD}) and the available drive current:

$$t_{Miller} \approx \frac{Q_{GD}}{I_g}$$

By applying these relationships, designers can fine-tune the external gate resistance (R_g) to achieve a specific switching speed, thereby striking a practical balance between maximizing efficiency and satisfying EMI constraints.

4.5.9 Bootstrap Design Calculator and Minimum Component Selection

This section details the selection of C_{BOOT} and R_{BOOT} based on worst-case constraints (Texas Instruments, 2021c).

4.5.9.1 Input Parameters

- Max Duty Cycle: 50%
- Frequency: 200kHz
- V_{boot} : 18V
- Max Ripple (ΔV_{BOOT}): 0.2V
- MOSFET Q_g : 70 nC

Here is the updated text with the equation and definitions integrated logically. I have created a new subsection (4.5.9.2) to present the theoretical basis for the capacitance calculation before discussing the design plot. This improves the flow from "Input Parameters" to "Design Plot."

4.5.9.2 Minimum Bootstrap Capacitance

To maintain a stable floating supply voltage during the high-side on-time, the bootstrap capacitor must be sized to supply the total required charge without exceeding the allowable voltage droop. The minimum capacitance is determined by the relationship:

$$C_{BOOT} \geq \frac{Q_{TOTAL}}{\Delta V_{BOOT}}$$

In this context, Q_{TOTAL} represents the aggregate charge consumption, defined as the sum of the MOSFET gate charge (Q_g), internal driver consumption (Q_{drv}), leakage currents (Q_{leak}), and parasitic board effects ($Q_{parasitic}$). The parameter ΔV_{BOOT} denotes the maximum permissible voltage droop, which is typically targeted between 0.1V and 0.5V

to ensure the gate driver remains well above its under-voltage lockout (UVLO) threshold (Texas Instruments, 2021c; Texas Instruments, 2023).

4.5.9.3 Design Plot Explanation

The design plot defines the operational region for reliable performance:

1. (*dV/dt Limitation*): The selected values ensure the voltage rise is controlled to avoid insulation stress.
2. (*Peak Current Limit*): The resistance R_{BOOT} is chosen to keep the peak charging current below the diode's maximum rating (e.g., $< 5A$).
3. (*Ripple Constraint*): The capacitance C_{BOOT} is sized to maintain the voltage ripple $\Delta V_{BOOT} \leq 0.2V$.

The chosen componention ($C_{BOOT} = 2.2 \mu F, R_{BOOT} = 3.3\Omega$) satisfies all three mathematical inequalities, placing the design in the safe operating region.

4.5.9.4 Valid Design Region

The shaded area beyond the boundaries defined by the three curves represents the valid design region. To ensure robust operation, the selected values for C_{BOOT} and R_{BOOT} must lie above and to the right of these limiting thresholds. Operating within this region guarantees:

- A controlled and gradual boost in bootstrap voltage.
- Peak charging currents that remain within safe limits for the diode.
- Acceptable bootstrap voltage ripple, ensuring stable high-side gate drive under demanding conditions.

Adhering to these boundaries ensures the high-side driver functions reliably, even in the presence of strong electrical transients and rapid voltage changes (Texas Instruments, 2021c; Infineon Technologies, 2020a).

4.5.9.5 Example Applied to the Proposed Design

To validate the design, the specific operational parameters of the application were mapped against the established safety curves. The system is configured with an 18 V bootstrap supply (V_{BOOT}), a switching frequency of 200kHz at a 50% duty cycle, and a dead-time of 100ns. Additionally, the MOSFET utilizes a gate charge (Q_g) of 70nC, and the maximum permissible voltage ripple (V_{BOOT}) is clamped at 0.2 V.

When these parameters are applied to the design plot, the results clearly differentiate between viable and risky configurations:

- **Selected Configuration:** The combination of a $2.2\mu\text{F}$ capacitor and a 2.2Ω resistor sits comfortably within the valid design region. This confirms that these values provide adequate safety margins.
- **Insufficient Configuration:** Conversely, a hypothetical setup using a $1\mu\text{F}$ capacitor with a 2Ω resistor falls outside the safe operating area. Such a configuration would likely lead to bootstrap failure caused by excessive voltage ripple, elevated current stress, or violation of dV/dt limits.

Consequently, the selected component values are confirmed to provide sufficient design margin, ensuring reliable operation even under worst-case conditions (Texas Instruments, 2021c; Texas Instruments, 2023).

4.5.9.6 Relationship to Overcharge Mitigation

As explored in the discussion on switch-node undershoot (Section 4.5.6), the selection of bootstrap components plays a dual role. Beyond basic energy storage, increasing the values of C_{BOOT} or R_{BOOT} significantly enhances the system's robustness against bootstrap overcharge. In the context of the design plot, improving immunity to overcharge equates to shifting the operating point further upward and to the right, away from the critical failure boundaries.

However, this enhancement introduces a trade-off. As detailed in the start-up analysis (Section 4.5.7), larger component values inherently extend the start-up delay. Therefore, the final component selection represents a calculated compromise, balancing the need for overcharge immunity against the requirements for acceptable start-up timing and steady-state performance (Texas Instruments, 2021c; Texas Instruments, 2023).

4.5.9 Summary

This section has outlined a constraint-based methodology for dimensioning the bootstrap network, prioritizing physical limits such as dV/dt , diode peak current, and voltage ripple. By ensuring that C_{BOOT} and R_{BOOT} are selected from within the valid design region, the proposed inverter topology secures stable high-side gate drive. This approach guarantees reliability specifically for high-voltage, high-frequency applications utilizing unipolar PWM modulation (Infineon Technologies, 2020a; Texas Instruments, 2021c; Texas Instruments, 2023).

4.6 Output Filter Design and Implementation (LCL Stage)

To mitigate high-frequency harmonics inherent in Pulse-Width Modulation (PWM) and ensure compliance with grid interconnection standards, an LCL filter is utilized at the inverter's output. This stage is essential for passing the fundamental grid frequency (50Hz) while attenuating switching noise, thereby guaranteeing clean and stable power injection into the utility grid (Fotherby, n.d.; Teodorescu et al., 2011).

4.6.1 Filter Configuration and Component Selection

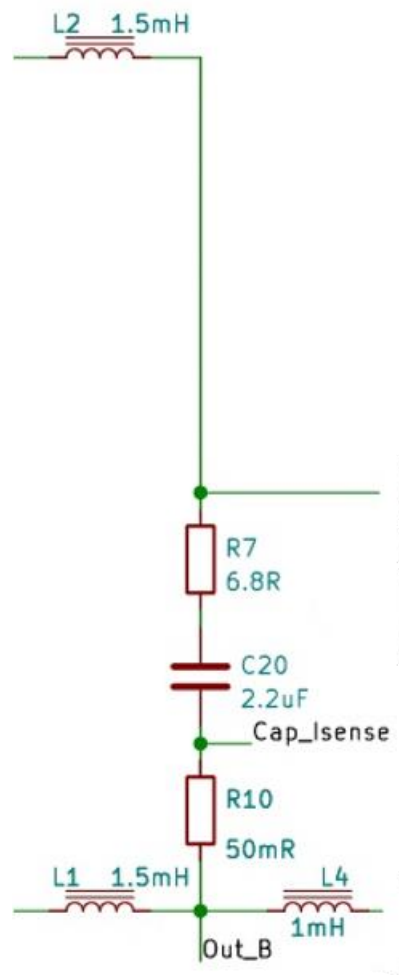


Figure 4.11: Schematic implementation of the LCL output filter.

The topology, shown in Figure (4.11), consists of an inverter-side inductance (L_i), a grid-side inductance (L_g), a shunt capacitor (C), and a damping resistor (R). The inverter-side inductance is realized using two series inductors of 1.5mH each, yielding an equivalent inductance of approximately 3mH. The grid-side inductance is selected as

1mH, while the filter capacitor is 2.2 μ F paired with a damping resistor of 6.8 Ω . The grid impedance is represented in the schematic as R_2 .

The design is based on the following system specifications:

- Grid voltage: 240V (50Hz)
- PWM switching frequency: 40kHz
- DC bus voltage: 400V
- Rated inverter power: 1000W
- Maximum allowable current ripple: 20% of the rated current

4.6.2 Capacitor Sizing

The filter capacitor selection is driven by the reactive power limit at the fundamental grid frequency, typically capped at 5% of the rated inverter apparent power. Applying this constraint yields a required capacitance of approximately $2.7\mu\text{F}$. However, for practical implementation and component availability, a $2.2\mu\text{F}$, 250VAC-rated film capacitor was selected. Film capacitors are preferred in this application due to their low dissipation factor and stable capacitance characteristics (Lisserre et al., 2005).

4.6.3 Inductor Design and Magnetic Saturation

The inverter-side inductance (L_i) is designed to limit the peak-to-peak ripple current caused by PWM switching, typically constrained to 20% of the rated current (Fotherby, n.d; Teodorescu et al., 2011). For a 1000W, 240V inverter, the peak output current is approximately 6A, resulting in a maximum allowable ripple current of 1.2A. The ripple current is maximized at a 50% duty cycle, corresponding to an inverter output voltage of 200V from a 400V DC bus. Based on these conditions and the 40kHz switching frequency, the required inductance is calculated to be approximately 2.1mH.

Since inductors experience reduced inductance under DC bias to core saturation, the components were designed to maintain the required filtering capability under load (Fotherby, n.d; Zhang, 2022). The inverter-side inductors are implemented using FS-185090-2 cores. Using the Micrometals Inductor Analyzer tool (Figure 4.12), two series inductors with 102 turns each produce a nominal inductance of 2.9mH. Under a 6A DC bias, the effective inductance decreases to approximately 2mH, satisfying the design requirement, as illustrated in the saturation curve in Figure 4.13.

Inductor Design 1			Inductor Design 2	Inductor Design 3	INDUCTOR DESIGN 1		
Topology AC Inductor with ripple					PARTNUMBER		FS-185090-2
Material FS					Availability		Y
DateCreated Mar 29, 2023 1:31 PM					N		102
AWG 18					Stack		2
Strands 1					I peak-peak (A)		1.188
Required Electrical I _{rms} (A) 4.2					Duty Cycle		-
% ripple 10					L ₀ (uH)		2,912.73
f (Hz) - Fundamental 50					L _{dc} (uH)		2,023.59
Additional Constraints Electrical Energy Cost (\$/kW-hr) 0.2					%		69
Thermal Ambient Temp (°C) 40					%		69
Mechanical Max ID used ratio 0.5					Ipp(A) vs Phase		-
Continuous use (years) 0.5					L(uH) vs Phase		-
Temp Rise Factor 1					Bpk (G), fswitch		440
Max % Window Fill, Toroid 40					B (G) at I _{max}		6416
Max % Window Fill, E-Core 60					Core Loss (W)		2.922
Min %L 30					R _{dc} (Ω)		0.2258
Max Temp Rise (°C) 60					R _{ac} Factor		1.144
Max DT Aging (°C) 25					Cu Loss (W)		4.028
Conductor Material Cu					Total Loss (W)		6.95
Min Hrs to DT Aging 50000					ΔT(C)		32.9

Figure 4.12: Inductor design parameters from Micrometals Analyzer.

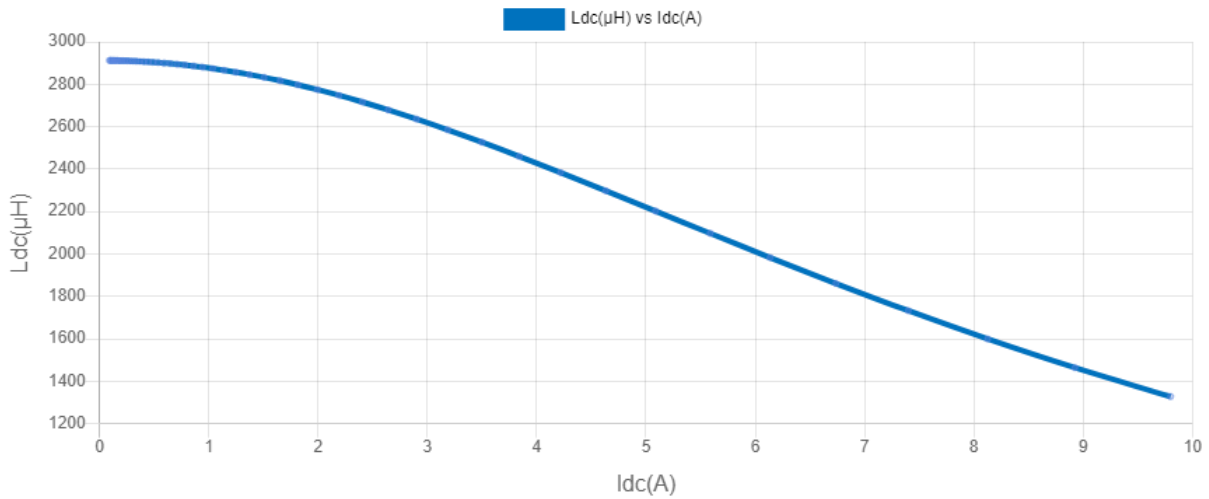


Figure 4.13: Inductance saturation curve vs. DC current.

The grid-side inductance (L_g) is selected based on voltage drop limitations and optimal inductance ratio considerations. According to Kim and Kim (2008), the inverter-side inductance should be approximately three times the grid-side inductance for optimal performance. Consequently, (L_g) is chosen as 1mH. This inductor is constructed using the same core type with 91 turns, resulting in a no-load inductance of 1.08mH and approximately 800μH under a 6A DC bias. The winding resistance is approximately 200mΩ using 21 AWG wire.

4.6.4 Thermal Analysis and Resonance Validation

The total series resistance of the inverter, including (inductors, PCB traces, and MOSFETs) is approximately 1Ω. At an RMS current of 4A, this results in an estimated power dissipation of at least 16W, necessitating careful thermal design.

The filter design was validated by analyzing its resonance behavior. The resonance frequency must be sufficiently separated from both the grid frequency and the switching frequency to ensure stability. Simulation of the filter network, including a grid impedance of approximately 250-500mΩ, was performed using TINA software. see simulation model in Figure (4.14).

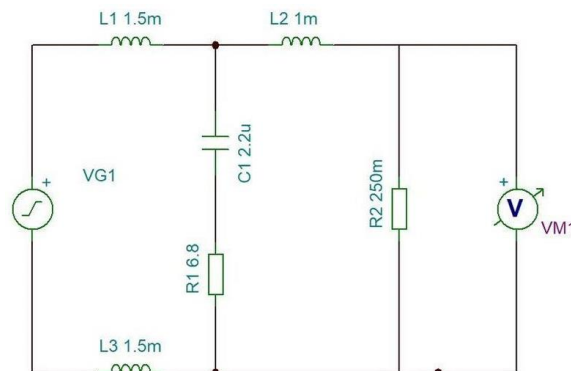


Figure 4.14: TINA simulation model for resonance validation.

The results indicated a damped resonance at approximately 3.8kHz. A damping resistor of 6.8Ω provides adequate attenuation of resonance without significantly affecting filter performance, confirming that the design meets both theoretical and practical stability requirements (Fotherby, n.d.).

4.7 Grid Connection and Safety Mechanisms

The interface between the inverter and the utility grid is managed through an electromechanical relay stage. This ensures safe, controlled connectivity and compliance with anti-islanding regulations which mandate redundant disconnection mechanisms (IEC, 2015).

4.7.1 Relay Implementation Strategy

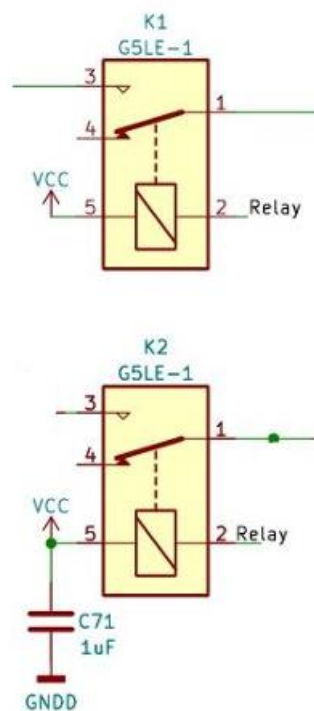


Figure 4.15: Schematic of the dual-relay grid interface circuit.

Two electromechanical relays (G5LE-1) are employed as illustrated in Figure (4.15), to connect and disconnect the inverter from the grid. The relays are energized from a low-voltage auxiliary supply (V_{CC}), while their contacts are rated to withstand full grid voltage and current. The use of dual relays enhances system reliability through redundancy and supports compliance with anti-islanding standards that mandate double disconnection mechanisms (IEC, 2015).

During normal operation, the relays remain open while the inverter monitors grid parameters via a phase-locked loop (PLL). Once synchronization is achieved and no faults

are detected, the control system energizes the relay coils. In the presence of any fault, the drive signal is removed, causing rapid disconnection to prevent unsafe operation.

4.7.2 Transient Suppression

To mitigate voltage transients and Electromagnetic Interference (EMI) caused by the inductive kickback of the relay coils, a $1\mu\text{F}$ suppression capacitor (C71) is placed across each coil. This component limits the rate of change of current (di/dt) and damps high-voltage spikes. The selected capacitance value offers a balance between effective suppression and the requirement for rapid relay release times during fault conditions (Fotherby, n.d; Zhang, 2022).

4.8 Signal Acquisition and EMI Suppression

This circuit section interfaces the inverter with the utility grid, integrating EMI suppression, voltage sensing, and current sensing as shown in Figure (4.16), to ensure safe and compliant operation. Such interfaces are essential for maintaining power quality and protecting infrastructure (Ott, 2009; Liserre et al., 2005).

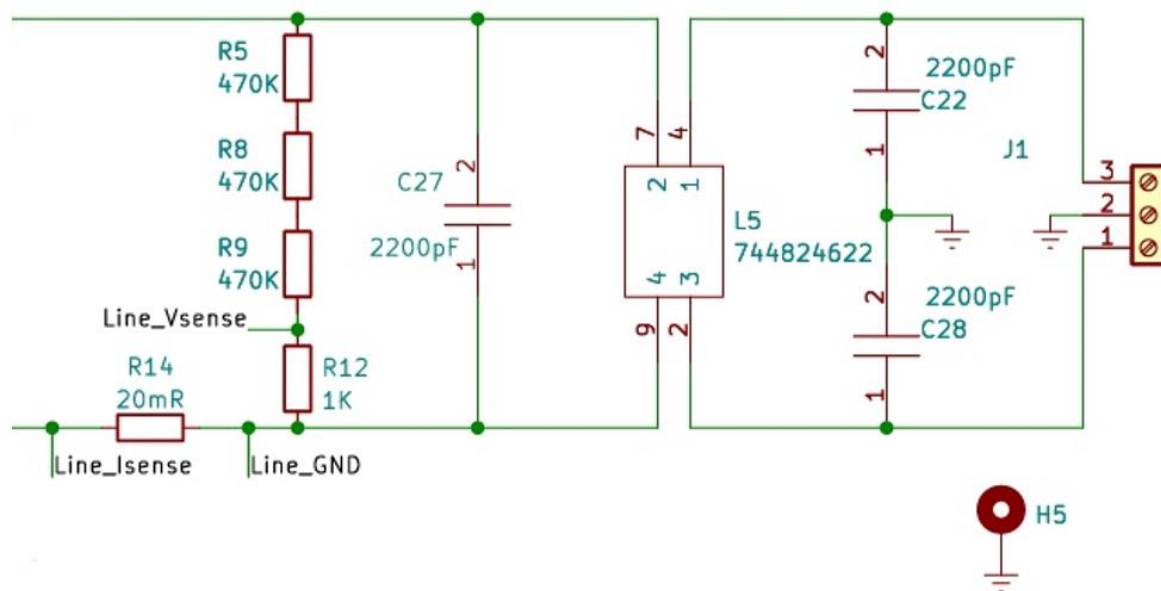


Figure 4.16: Schematic of the grid interface, sensing, and EMI suppression circuit.

4.8.1 Current Sensing

Line current sensing is implemented using a low-value shunt resistor ($R_{14} = 20\text{m}\Omega$), see Figure (4.16), placed in series with the grid line. The voltage across the shunt is directly proportional to the current, governed by Ohm's law:

$$V_{sense} = I \times R$$

This method is widely adopted for its simplicity, linearity, and accuracy (Texas Instruments, n.d.-b). The selected value of $20\text{m}\Omega$ provides a measurable sensing voltage while minimizing power losses and thermal stress, adhering to standard design guidelines (Analog Devices, n.d.-a).

4.8.2 Voltage Sensing

Grid voltage sensing is achieved through a resistive voltage divider composed of (R_5, R_8, R_9) at $470\text{k}\Omega$ each) and (R_{12}) of ($1\text{ k}\Omega$). This divider scales the high grid voltage (230-240 VAC) to a level suitable for the PLL and protection functions.

High-value resistors limit current draw and improve safety, while multiple series resistors distribute voltage stress to enhance reliability under surge conditions (Analog Devices, n.d.-b; Microchip, 2021).

Resistor (R_{12}) stabilizes the signal and protects subsequent processing stages from transients.

4.8.3 EMI Filtering

To suppress high-frequency noise from PWM switching, an EMI filter is implemented using a common-mode choke (L_5) and capacitors (C_{22}, C_{28}, C_{27}), each 2200pF as shown in Figure (4.16). The choke attenuates common-mode noise on line and neutral conductors, while the capacitors provide a low-impedance path to ground (Zhang, 2022). The selected capacitors are typically safety-rated Y-capacitors, ensuring effective suppression with low leakage current at 50Hz , as required by international EMC standards (Zhang, 2022).

Overall, this circuit block enables accurate measurements, reduces conducted EMI, and supports critical synchronization and protection functions, contributing significantly to meeting EMC and grid interconnection requirements.

4.9 Isolated Line-Voltage Measurement Interface

4.9.1 Purpose of the Stage

This stage provides galvanically isolated measurement of the grid voltage, delivering a digital bitstream to the controller for signal processing and protection. Since the inverter operates with a high-voltage power stage and rapid switching transitions, referencing direct measurements to the controller ground would expose low-voltage electronics to common-mode transients, ground bounce, and safety hazards. To eliminate this risk, an isolated delta-sigma ($\Delta\Sigma$) modulator, the AMC1306M25, is employed. This component accepts a small differential analog voltage ($Line_{sense}$) referenced to the high-voltage sensing ground ($Line_{GND}$) and transmits an isolated 1-bit $\Delta\Sigma$ stream referenced to the controller ground (GND_D).

4.9.2 Signal Flow and Interface

The signal acquisition process involves two distinct domains:

- High-Voltage Analog Input: The $Line_{sense}$ signal is applied to the modulator's differential input pins (INP/INN). As the AMC1306M25 is designed for low-voltage differential sensing (typically with a full-scale range in the hundreds of millivolts), the grid voltage is not connected directly. Instead, an external scaling

network produces a safe differential input compatible with the modulator's full-scale range.

- **Low-Voltage Digital Output:** The IC transmits the measured analog signal across its internal isolation barrier as a synchronized bitstream. The output (DOUT) provides a 1-bit stream proportional to the analog input, while the clock input (CLKIN) is provided by the controller to define the sampling rate. The microcontroller subsequently applies a digital decimation filter (typically Sinc^3) to convert this bitstream into a high-resolution digital word representing the line voltage.

4.9.3 Galvanic Isolation and Ground Domains

The circuit design enforces a strict separation between two ground references to maintain safety and signal integrity:

- GND_D (Controller Ground): Utilized by the microcontroller logic and the digital interface of the modulator.
- $Line_{GND}$ (High-Voltage Sensing Ground): Utilized by the analog measurement front-end and the high-side supply of the modulator.

The AMC1306 provides the necessary isolation barrier, allowing accurate sensing while ensuring immunity to the common-mode dv/dt transients typical of inverter switching nodes.

4.9.4 Component Selection and Functionality

- **Modulator (AMC1306M25):** The selection of a $\Delta\Sigma$ modulator over traditional analog isolation amplifiers offers superior linearity and high noise immunity. The digital transmission format is inherently more robust against interference when crossing the isolation barrier.
- **Decoupling Capacitors (C38, C39, C41, C42):** To ensure power integrity, supply pins on both sides of the isolation barrier are decoupled. A combination of 100 nF ceramic capacitors for high-frequency bypass and 1 μF capacitors for local energy storage is placed close to the IC pins. This layout minimizes loop area, reducing supply ripple and preventing digital clock noise from coupling into the analog conversion process.
- **Input Filter Network (R20, C40):** An RC network is implemented at the input pins to limit surge currents and provide anti-aliasing. The cutoff frequency (f_c) is calculated via $f_c = 1/2\pi RC$. This frequency is selected to be significantly higher than the 50 Hz grid fundamental to avoid phase distortion, yet low enough to attenuate high-frequency switching noise before it reaches the modulator.

4.9.5 Voltage Scaling and Output Processing

To interface the high grid voltage with the low-voltage input of the AMC1306, a resistive divider network is used. The voltage appearing at the differential input is governed by the ratio of the bottom resistor to the total series resistance. This ratio is calculated to ensure that the peak differential voltage ($V_{IN(diff)}$) remains within the modulator's specified full-scale limits (V_{FS}) under all operating conditions.

On the controller side, the received bitstream is processed by the MCU's Digital Filter for Sigma-Delta Modulators (DFSDM). The processing chain involves decimation filtering to recover the signal, followed by scaling operations that account for the modulator's full-scale range, the resistive divider ratio, and calibration constants, ultimately yielding a value in RMS volts.

4.10 Microcontroller Unit (MCU) Interface and Integration

4.10.1 Role of the Microcontroller

The microcontroller serves as the central intelligence of the grid-tied inverter system. Its function extends beyond simple PWM generation to include the coordination of measurement, real-time control, protection, sequencing, and system supervision (STMicroelectronics, 2022). It acts as the bridge between software control algorithms and the physical power hardware, translating electrical feedback into precisely timed switching commands.

4.10.2 Hardware Configuration and Power Integrity

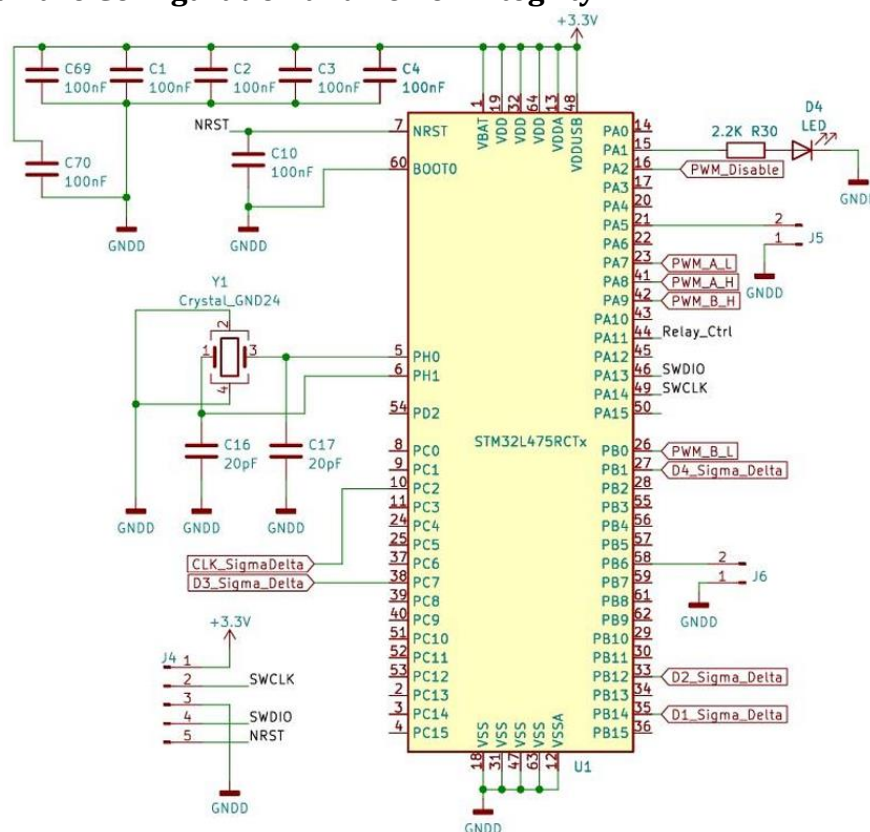


Figure 4.17: Schematic diagram of the Control Unit based on STM32L475 MCU.

The MCU operates on a regulated 3.3 V supply, as detailed in the schematic in Figure (4.17), separated into digital (V_{DD}) and analog (V_{DDA}) domains to minimize noise coupling.

- Decoupling: Each supply pin is locally decoupled using 100 nF ceramic capacitors. This ensures low impedance during internal switching events and suppresses high-frequency noise, adhering to standard hardware design guidelines (Zhang, 2022).
- Clock System: A crystal oscillator connected to the OSC_IN/OSC_OUT pins provides a stable, low-jitter system clock. This is critical for ensuring precise PWM frequency generation and deterministic sampling instants for voltage and current measurements.

To guarantee precise timing for the PWM generation and synchronization, the system clock tree was configured as shown in Figure 4.18. The external 24 MHz High-Speed External (HSE) crystal is selected as the primary source to derive the stable system core clock, bypassing the less accurate internal oscillators.

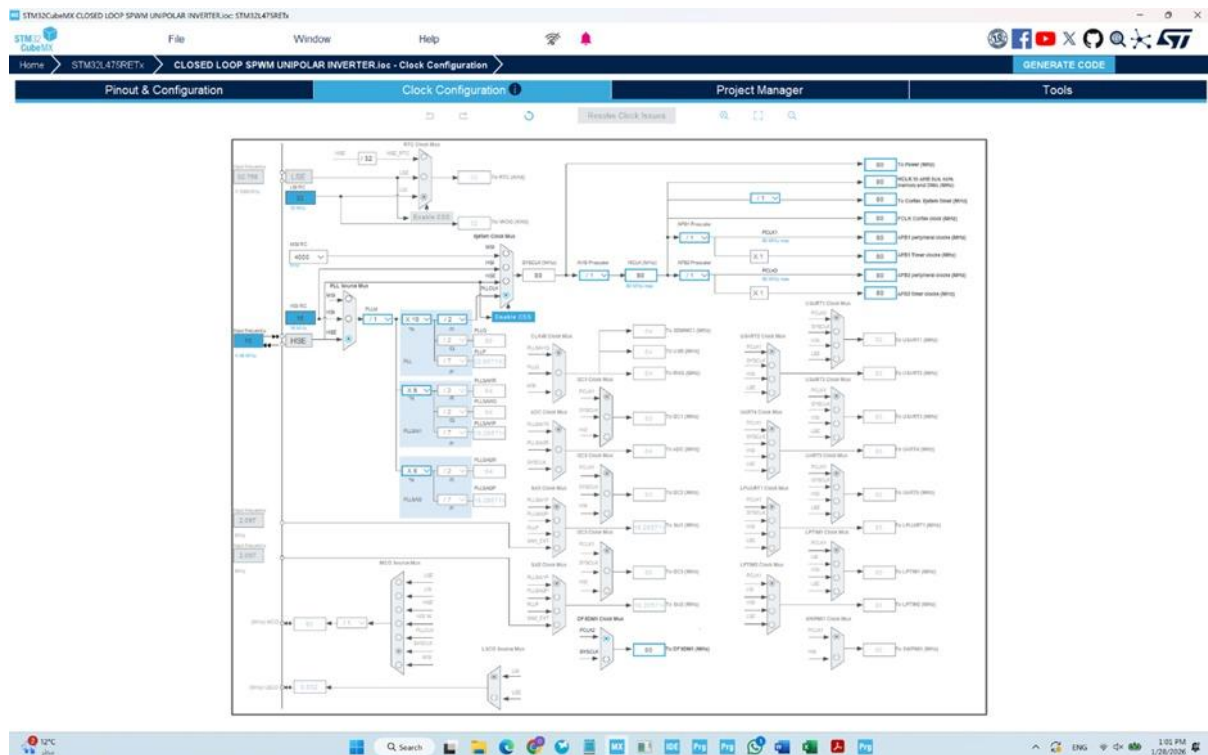


Figure 4.18: Clock Tree Configuration ensuring a stable system frequency derived from the external crystal.

- Reset and Boot: The NRST pin is configured with a standard RC delay network to guarantee a clean power-on reset. The BOOT0 pin is grounded to ensure the MCU deterministically boots from internal Flash memory, preventing accidental entry into the bootloader during startup.

- Acquisition: The DFSDM, in conjunction with Direct Memory Access (DMA), enables continuous sampling of the grid voltage, DC-link voltage, and grid current without CPU intervention.
- Synchronization: A clock output pin (*DFSDM_Clk*) synchronizes the external modulators, ensuring that all measurement channels are phase-aligned.

4.10.5 Firmware Architecture and Protection

The firmware operates on a deterministic real-time control loop synchronized to the PWM switching frequency.

- Initialization: Upon startup, the firmware configures clocks, GPIOs, and peripherals, ensuring the system remains in a safe state with drivers disabled until all checks pass.
- Control Loop: During operation, the MCU executes grid synchronization (PLL), current control algorithms, and duty cycle updates.
- Protection: The system continuously monitors for over-voltage, over-current, and anti-islanding conditions. Upon fault detection, the firmware immediately disables PWM outputs and opens the grid relay to ensure fail-safe operation.

4.10.6 MCU Pin Assignment Summary

The hardware interface was initially configured using the STM32CubeMX graphical tool to ensure no pin conflicts occurred. Figure 4.20 illustrates the Pinout view, where the specific GPIOs, PWM Timers, and DFSDM peripherals were enabled and assigned to the physical package pins, corresponding to the detailed connections listed in Table 4.2.

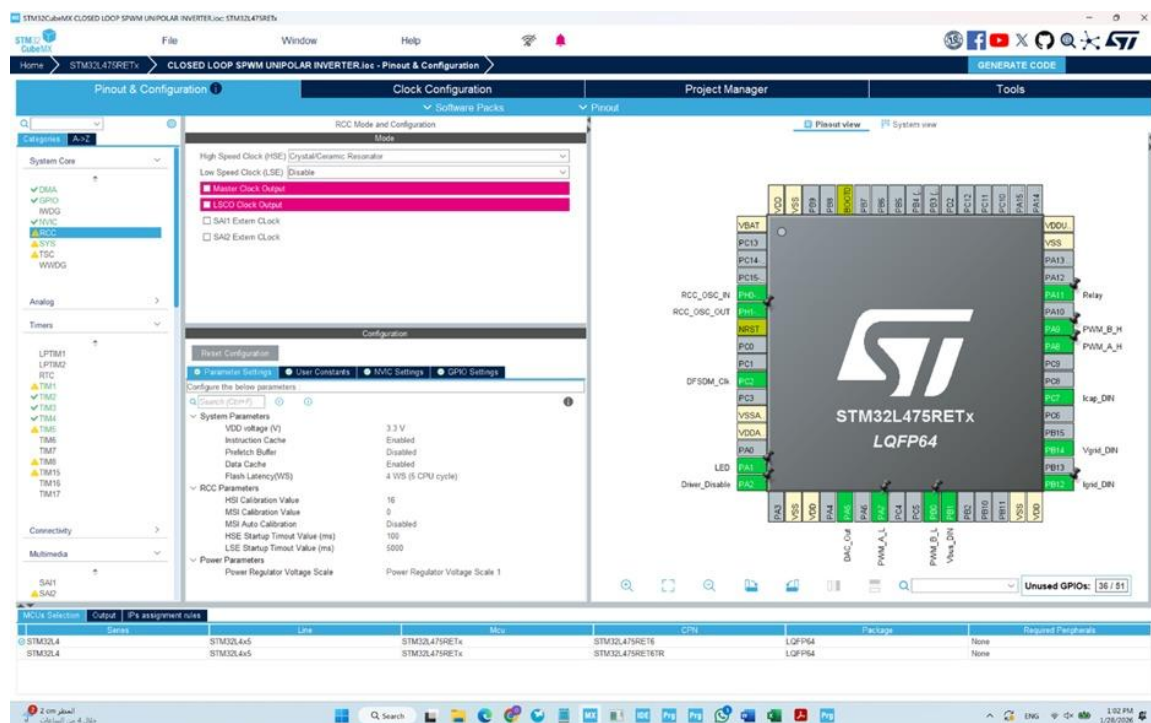


Figure 4.20: STM32CubeMX Pinout Configuration showing the assignment of PWM, Sensing, and GPIO pins.

The following table (4.2) summarizes the key connections between the MCU and the inverter hardware:

Table (4.2): Pin assignment and hardware connections of the STM32 Control Unit.

MCU Pin	Signal Name	Direction	Peripheral Function	/	Connected Hardware
PA7	PWM_A_L	Output	TIM1_CH1N (PWM)		UCC21520 Gate Driver – Low-side (Leg A)
PA8	PWM_A_H	Output	TIM1_CH1 (PWM)		UCC21520 Gate Driver – High-side (Leg A)
PB0	PWM_B_L	Output	TIM1_CH2N (PWM)		UCC21520 Gate Driver – Low-side (Leg B)
PA9	PWM_B_H	Output	TIM1_CH2 (PWM)		UCC21520 Gate Driver – High-side (Leg B)
PA2	Driver_Disable	Output	GPIO Output		Gate Driver Enable/Shutdown Network
PA11	Relay	Output	GPIO Output		Grid Relay Driver Circuit
PA1	LED	Output	GPIO Output		Status LED
PB1	Vbus_DIN	Input	DFSDM1_DATIN0		Isolated DC-Link Voltage Sensor
PB12	Igrid_DIN	Input	DFSDM1_DATIN1		Isolated Grid Current Sensor
PB14	Vgrid_DIN	Input	DFSDM1_DATIN2		Isolated Grid Voltage Sensor
PC7	Icap_DIN	Input	DFSDM1_DATIN3		Capacitor/Filter Current Sensor
PC2	DFSDM_Clk	Output	DFSDM1_CKOUT		Clock Output for Ext. Modulators
PA13	SWDIO	Bi-Dir	SYS_JTMS-SWDIO		ST-Link / Programmer (Data)
PA14	SWCLK	Input	SYS_JTCK-SWCLK		ST-Link / Programmer (Clock)
PH0	OSC_IN	Input	RCC_OSC_IN		24MHz External Crystal (HSE)
PH1	OSC_OUT	Output	RCC_OSC_OUT		24MHz External Crystal (HSE)
NRST	NRST	Input	System Reset		Reset Circuit (C10, Pull-up)

4.10.7 Detailed Pin Functionality and Signal Description

To complement the pin assignment table, the following description details the specific hardware implementation and signal requirements for each functional group:

1. Power Stage Control (TIM1 PWM)

The inverter utilizes **TIM1** (Advanced Control Timer), which is specifically designed for motor control and digital power conversion, to drive the H-Bridge.

- High-Side & Low-Side Control (PA8/PA7, PA9/PB0): These pins carry the complementary PWM signals. The specific assignment allows the use of internal hardware interlocking.
- Dead-time Insertion: Crucially, the MCU inserts a programmable dead-time delay (typically in nanoseconds) between the transition of the high-side and low-side signals. This hardware-level protection prevents **shoot-through currents** that could destroy the SiC/GaN switches during commutation.

2. Isolated Sensing Interface (DFSDM)

Unlike standard microcontroller ADCs which are susceptible to noise in high-voltage environments, this system relies on the **DFSDM** peripheral.

- Clock Distribution (PC2): The MCU generates a continuous, synchronous clock signal (DFSDM_CKOUT), typically configured between 10 MHz and 20 MHz. This single clock source drives all external AMC1306 modulators simultaneously, ensuring that voltage and current samples are perfectly **phase-aligned** for accurate power factor calculation.
- Bitstream Processing (PB1, PB12, PB14, PC7): The pins receive 1-bit high-speed data streams. The internal DFSDM filters decimate this data to recover high-resolution (16-bit to 24-bit) signals, effectively removing the high-frequency switching noise.

3. Safety & Supervision

Driver_Disable (PA2): This is the system's "Kill Switch." It is routed directly to the Enable/Disable pins of the gate drivers. In the event of a critical fault (e.g., PLL loss or Over-Current), the firmware—or a hardware break signal—toggles this pin to immediately shut down the power stage, bypassing slower software routines.

Relay_Ctrl (PA11): This GPIO controls the mechanical isolation relay. It ensures the inverter is physically disconnected from the grid during startup self-checks and is only closed once synchronization is confirmed.

4. System & Debugging

- SWDIO/SWCLK (PA13/PA14): These pins provide the Serial Wire Debug (SWD) interface. They allow for real-time monitoring of internal control variables (such as Grid Angle θ and I_{ref}) using STM32CubeIDE without halting the processor, which is essential for tuning the control loop.
- HSE Oscillator (PH0/PH1): Connected to an external 24 MHz Crystal, providing a precision time-base. This stability is strictly required for the **Grid-Tie PLL** to function correctly within the tight frequency tolerances of the electrical grid (50Hz \pm 0.5Hz).

Chapter 5: Software Design and Closed-Loop Current Control Implementation

5.1 Introduction

This chapter presents the complete software control implementation of the proposed single-phase grid-tied inverter. The focus of this stage is the development and verification of a closed-loop current control system, which represents the fundamental control layer required for grid-connected operation.

The implemented controller ensures that the inverter injects a sinusoidal current synchronized with the grid voltage, thereby enabling controlled active power delivery and forming the essential basis for advanced grid-support functions such as Volt/Var control. All control blocks are modeled and verified using a Model-Based Design (MBD) approach in LTspice, allowing accurate time-domain analysis, transient response evaluation, and signal-level validation.

5.2 Overall Control Architecture Modeling

According to Teodorescu et al. (2011), the adopted control architecture follows a grid-following voltage source inverter (VSI) concept. In this structure, the inverter regulates the grid current, ensuring it is synchronized with the grid voltage.

The control system can be decomposed into the following main functional blocks:

- Grid synchronization (PLL or Ideal Reference) and Current reference generation.
- Current sensing and feedback.
- Error computation, frequency domain compensation (PI), and control loop stabilization.
- Modulation signal generation.
- SPWM carrier generation and comparison.
- Gate driver logic.
- Output filter and grid interface.

The functional relationship and signal flow between these blocks are illustrated in the conceptual diagram shown in Figure 5.1.

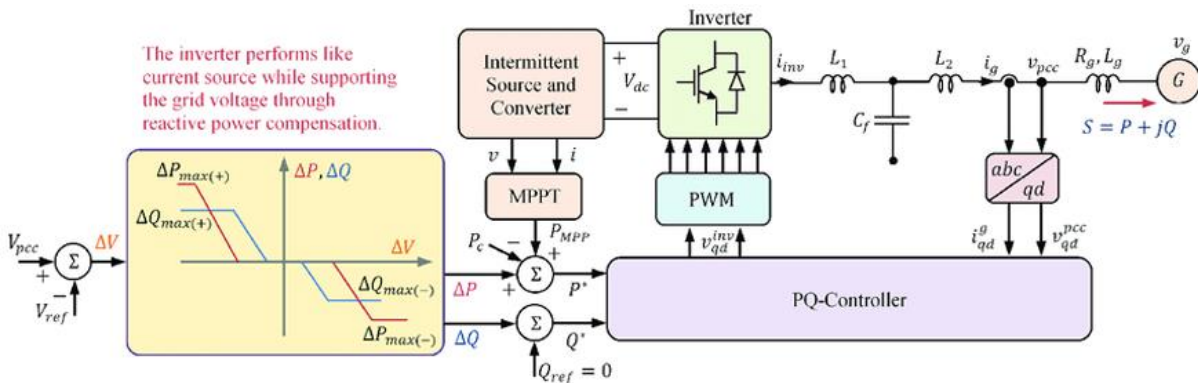


Figure 5.1: Conceptual control architecture and signal flow of the proposed Grid-Following VSI.

Following this conceptual framework, the detailed electrical implementation was modeled. Figure 5.2 illustrates the complete LTspice simulation schematic corresponding to these control blocks.

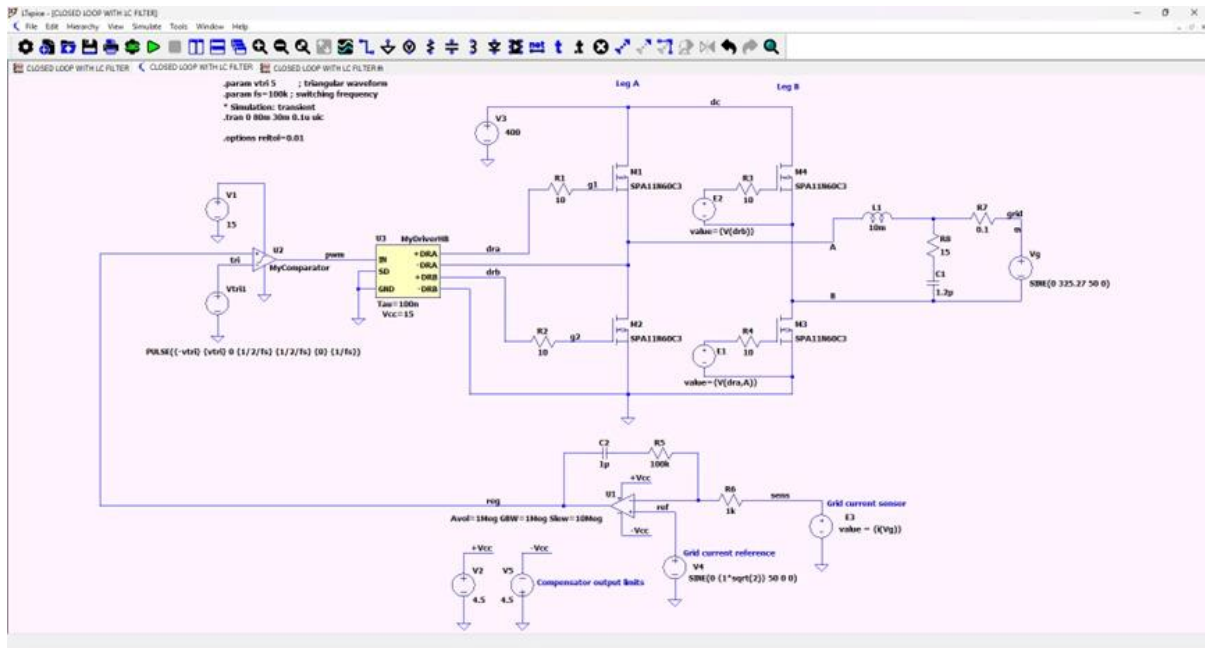


Figure 5.2: LTspice schematic diagram of the complete closed-loop grid-tied inverter system.

5.3 Grid Voltage Modeling

The utility grid is modeled as an ideal sinusoidal voltage source connected between nodes v_g (upper terminal) and B (lower terminal). The grid voltage is defined as:

$$V_{pk} \sin(2\pi ft) = v_g(t)$$

Where: V_{pk} : Peak grid voltage (325 V), f : Grid frequency (50 Hz). This source represents a "stiff grid," meaning it maintains a constant voltage magnitude and frequency regardless of the load current, providing a fixed reference for synchronization (PLL) and power exchange.

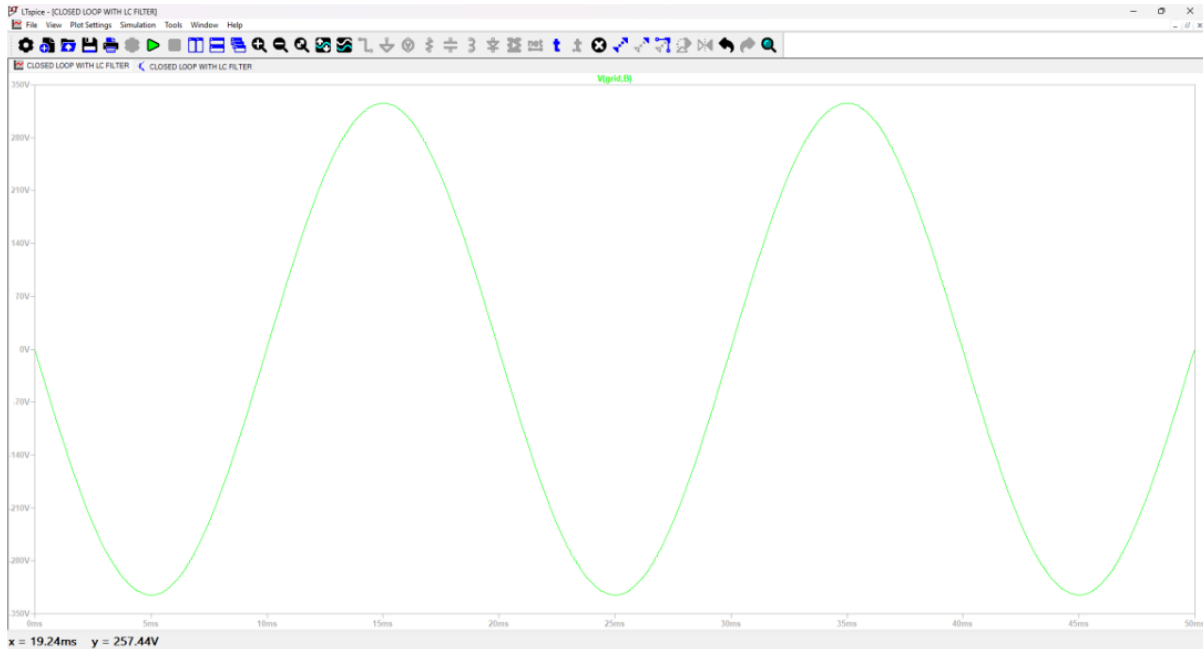


Figure 5.3: Grid voltage waveform $v_g(t)$ showing a pure sinusoidal profile.

In this simulation environment, the ideal voltage source provides a known phase angle, serving as an idealized reference. This mimics the locked state of the Phase-Locked Loop (PLL) algorithm (SOGI-PLL) implemented in the microcontroller firmware (detailed in Appendix A).

5.4 Current Reference Generation

The grid current reference is generated as a sinusoidal waveform synchronized with the grid voltage. The reference current is maintained in phase with the grid voltage to ensure unity power factor operation. The amplitude of the reference current, I_{ref} , determines the amount of active power injected into the grid. Accordingly, the reference current can be mathematically expressed as:

$$I_{ref} \sin(2\pi ft) = i_{ref}(t)$$

Where f is the grid frequency and I_{ref} represents the peak value of the reference current. This synchronization between the grid voltage and the reference current is illustrated in Figure 5.4.

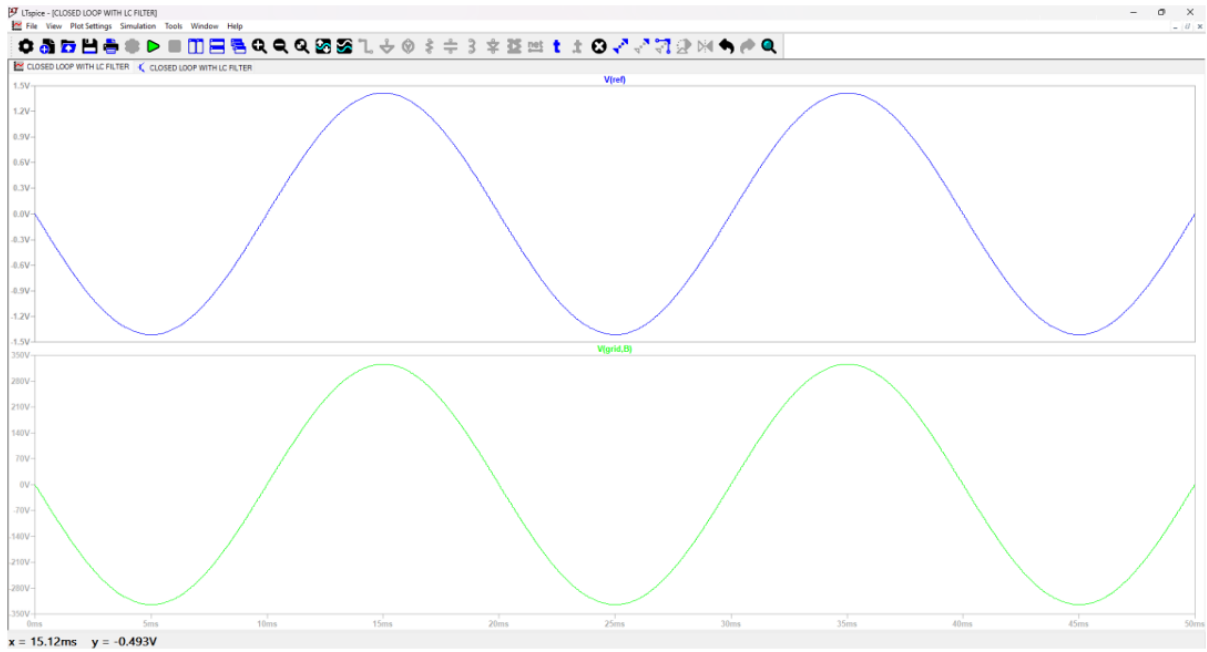


Figure 5.4: Grid current reference waveform synchronized with grid voltage for unity power factor operation

5.5 Grid Current Sensing

The actual grid current is measured using a behavioral current sensor implemented in LTspice. The sensed current is converted into a voltage signal suitable for feedback into the control loop. This feedback signal represents the real injected grid current after the LC filter and the grid interface. The measured grid current waveform obtained after the LC filter is shown in Figure 5.4.

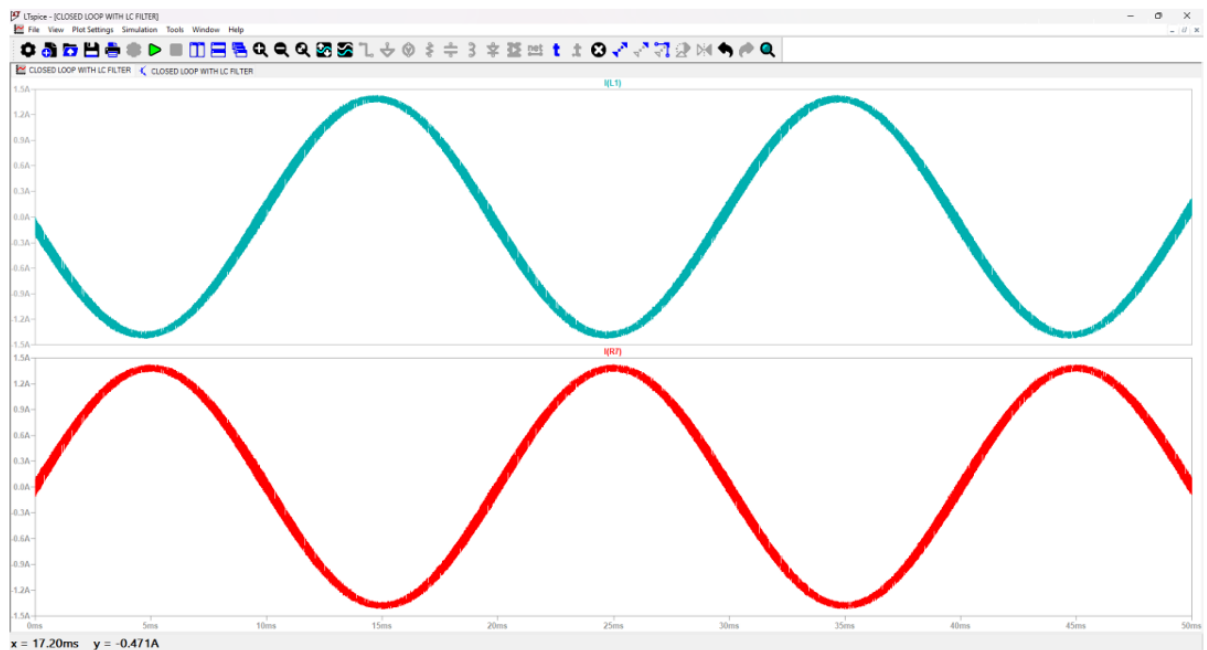


Figure 5.5: Measured grid current waveform after the LC filter in closed-loop operation

As illustrated in Figure 5.4, the grid current waveform is sinusoidal and exhibits low distortion, indicating the effective attenuation of high-frequency switching harmonics by the LC filter. The smooth waveform confirms proper current sensing and accurate feedback for closed-loop current control.

The sensed grid current is continuously compared with the reference current generated in the previous stage, allowing the controller to minimize the tracking error and ensure accurate current injection into the grid.

5.6 Error Signal Generation

The error signal is generated by comparing the reference grid current with the measured grid current. This comparison is performed by subtracting the actual grid current from the reference current, resulting in the instantaneous current tracking error, which can be expressed as:

$$i_{grid}(t) - i_{ref}(t) = e(t)$$

This error signal represents the instantaneous mismatch between the desired and actual grid current and serves as the input to the compensator. By minimizing this error, the control system ensures accurate tracking of the reference current and stable grid current injection.

The resulting error signal is processed by the compensator to generate the appropriate control action, ensuring fast dynamic response and reduced steady-state error.

5.7 PI Current Compensator

A Proportional-Integral (PI) current controller is implemented using an operational amplifier with resistive and capacitive feedback networks. The PI controller processes the current tracking error and generates the appropriate control action to regulate the grid current. The proportional term improves the dynamic response, while the integral term minimizes the steady-state error to negligible levels by providing high gain at the fundamental frequency.

As a result, the PI controller ensures zero steady-state error, fast dynamic response, and stable closed-loop operation. The output of the PI controller represents the commanded inverter voltage required to force the grid current to accurately track the reference current.

The PI controller output voltage waveform is shown in Figure 5.6.

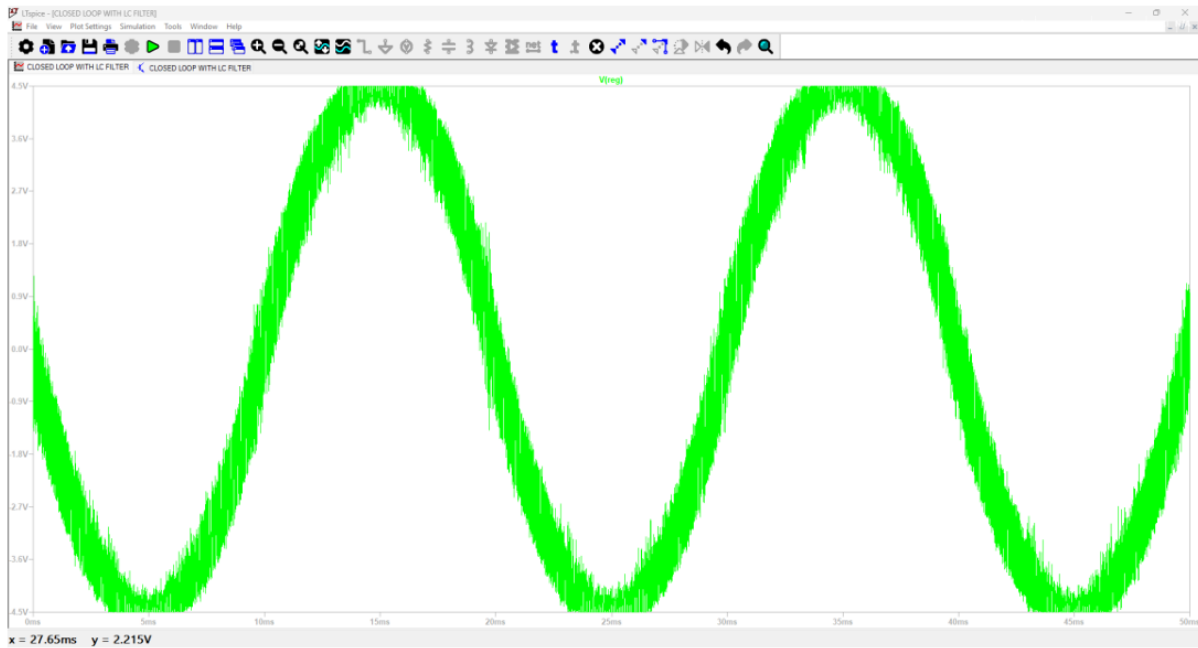


Figure 5.6: Output voltage of the PI current controller in closed-loop operation

As illustrated in Figure 5.6, the PI controller output exhibits a sinusoidal waveform with superimposed high-frequency components, which are associated with the switching action of the inverter. The smooth fundamental component confirms proper PI compensation and effective current regulation under closed-loop control.

The PI controller parameters (K_p, K_i) were tuned to achieve a balanced transient response with minimal overshoot, ensuring a bandwidth sufficiently lower than the switching frequency to maintain stability.

5.8 Output Limiting and Saturation

To prevent over-modulation and protect the inverter power stage, the controller output voltage is limited within predefined upper and lower bounds. Additionally, an anti-windup mechanism is inherent in the design to prevent the integral term from accumulating excessive error during saturation events. This limitation ensures that the modulation index remains within the linear region of sinusoidal pulse-width modulation (SPWM). By avoiding saturation, the controller maintains stable operation and prevents distortion in the generated PWM signals.

5.9 Triangular Carrier Generation (V_{tri})

A high-frequency triangular carrier waveform is generated using a parametric PULSE source in LTspice. The carrier frequency is set to 100 kHz, which is significantly higher than the grid frequency. This high carrier frequency enables high-resolution modulation and improves the accuracy of the PWM process.

The generated triangular carrier waveform is shown in Figure 5.7.

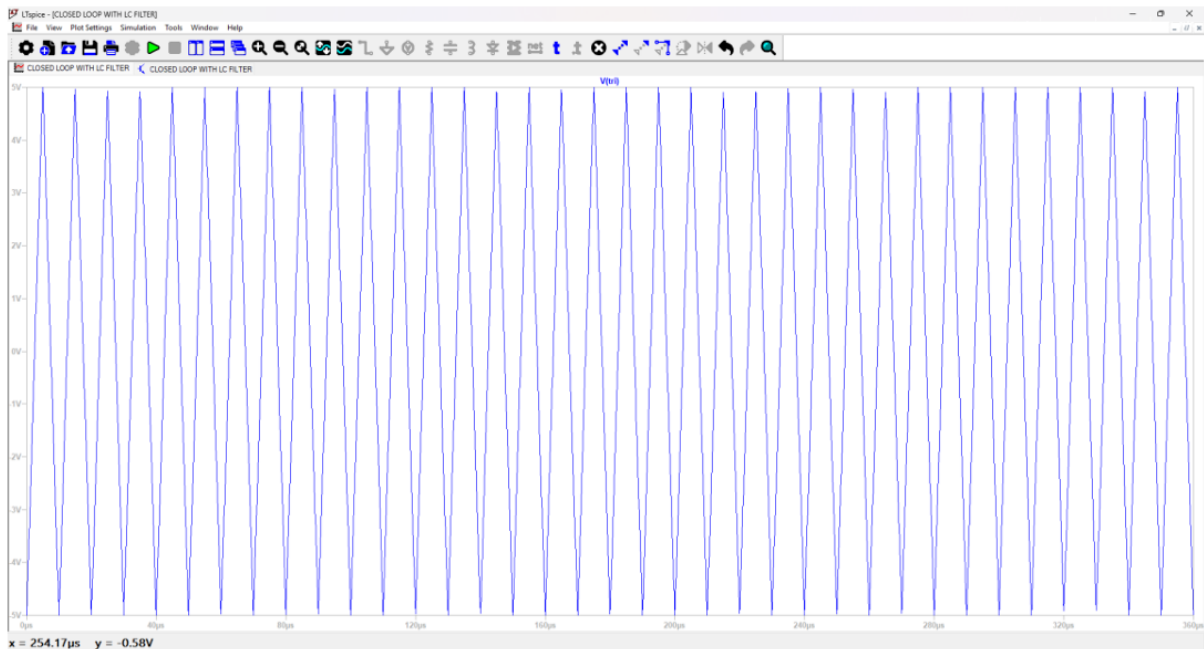


Figure 5.7: High-frequency triangular carrier waveform at 100 kHz

As illustrated in Figure 5.7, the triangular carrier exhibits a constant frequency and amplitude, which are essential for generating consistent and symmetric PWM pulses.

The limited controller output voltage is compared with the high-frequency triangular carrier to generate the SPWM gating signals for the inverter switches.

5.10 SPWM Generation

Sinusoidal Pulse Width Modulation (SPWM) is generated by comparing the modulating signal obtained from the PI controller output with the high-frequency triangular carrier waveform. This comparison is performed using a comparator, whose output produces a PWM signal with a duty cycle that varies sinusoidally according to the reference signal.

The comparison between the reference signal and the triangular carrier is illustrated in Figure 5.8, while the resulting SPWM signal is shown in Figure 5.9.

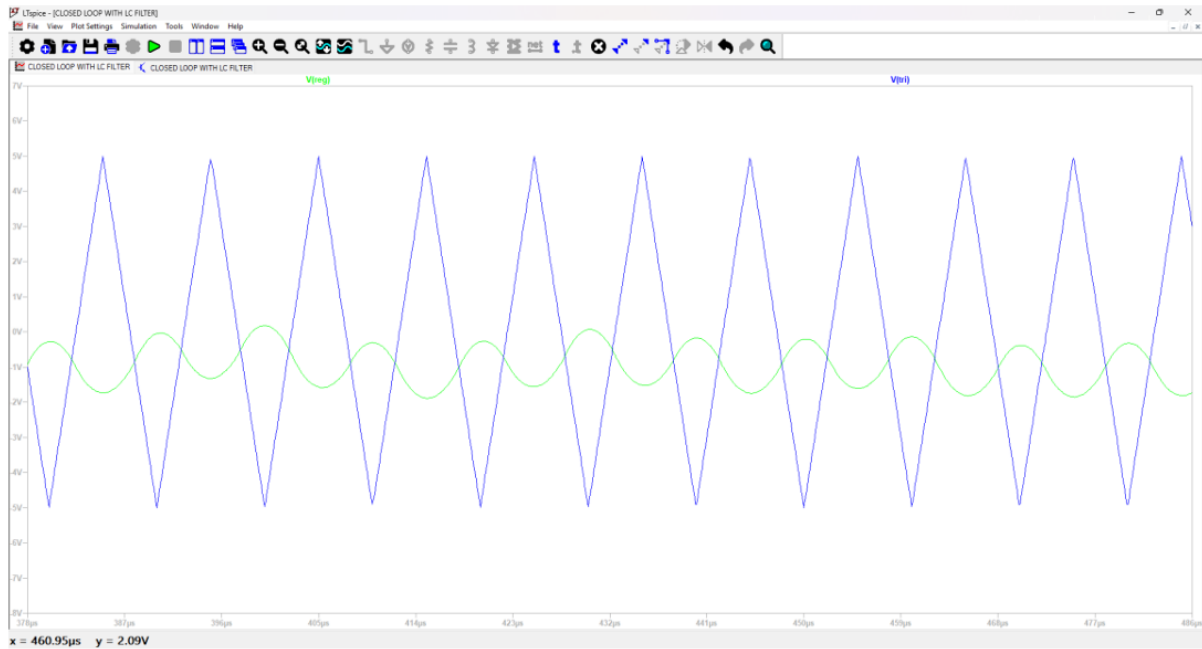


Figure 5.8: Comparison between the reference (modulating) signal and the triangular carrier waveform

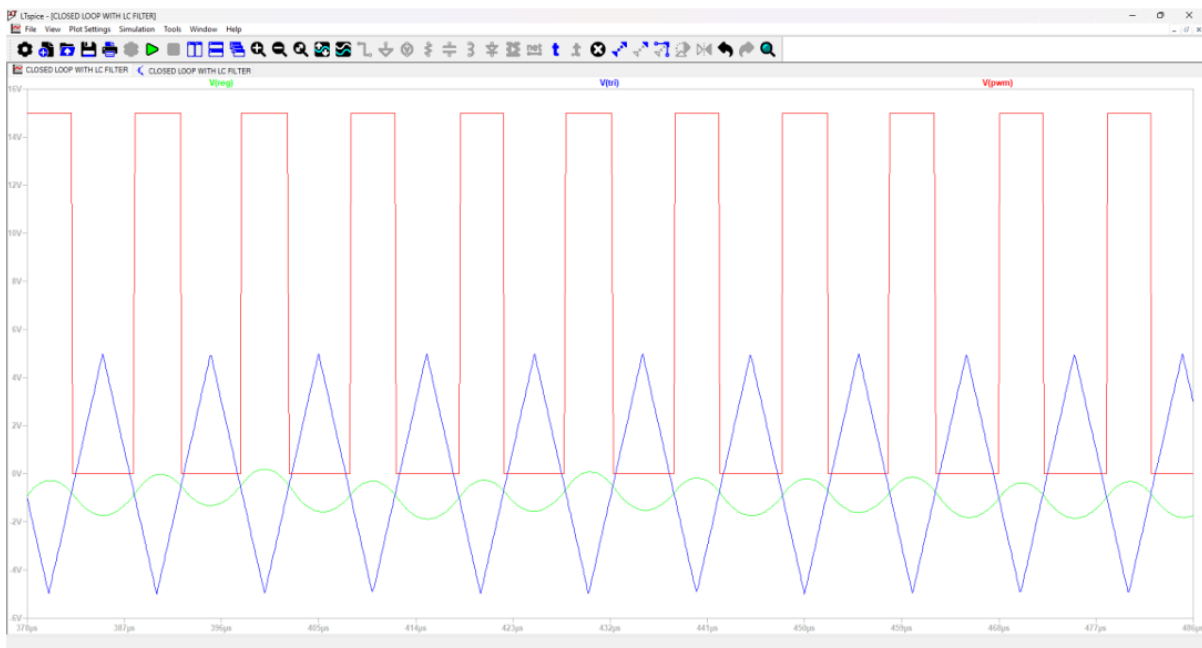


Figure 5.9: Resulting sinusoidal pulse-width modulation (SPWM) signal

The generated SPWM signal accurately reflects the sinusoidal nature of the reference signal while operating at the carrier switching frequency.

5.11 Gate Driver and Full-Bridge Inverter

The generated PWM signal is processed by a gate driver block, which produces complementary gate signals for the full-bridge MOSFET inverter. Dead-time insertion (typically 200ns - 1μs) and isolation behavior are included to prevent shoot-through faults, protecting the MOSFETs from thermal runaway. Verification of the dead-time insertion logic ensures that no shoot-through currents occur during the complementary switching transitions.

The gate signals applied to inverter legs A and B are shown in Figure 5.10.

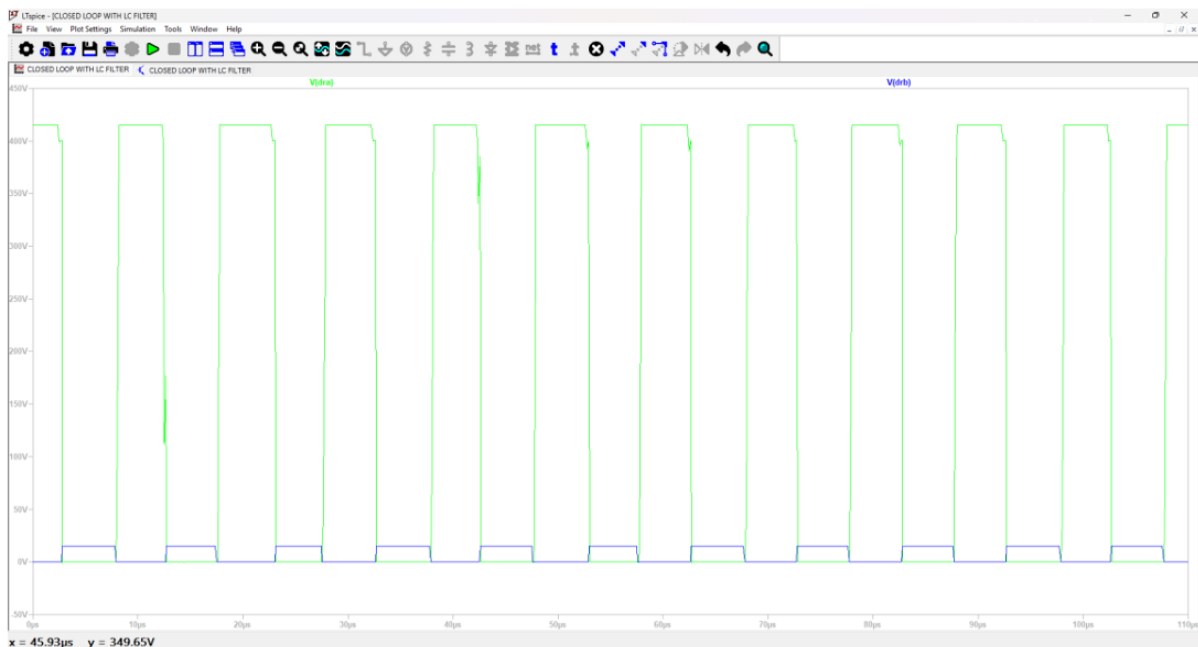


Figure 5.10: Complementary gate signals for inverter legs A and B

Proper gate signal generation is essential to guarantee reliable inverter operation and reduce switching-related stresses.

5.12 Output Filter and Grid Injection

An LC filter is placed between the inverter output and the grid to attenuate high-frequency switching harmonics and shape the inverter output voltage and current into smooth sinusoidal waveforms. After filtering, the current is injected into the grid in compliance with grid power quality requirements.

The inverter output current before and after LC filtering is illustrated in Figure 5.11.

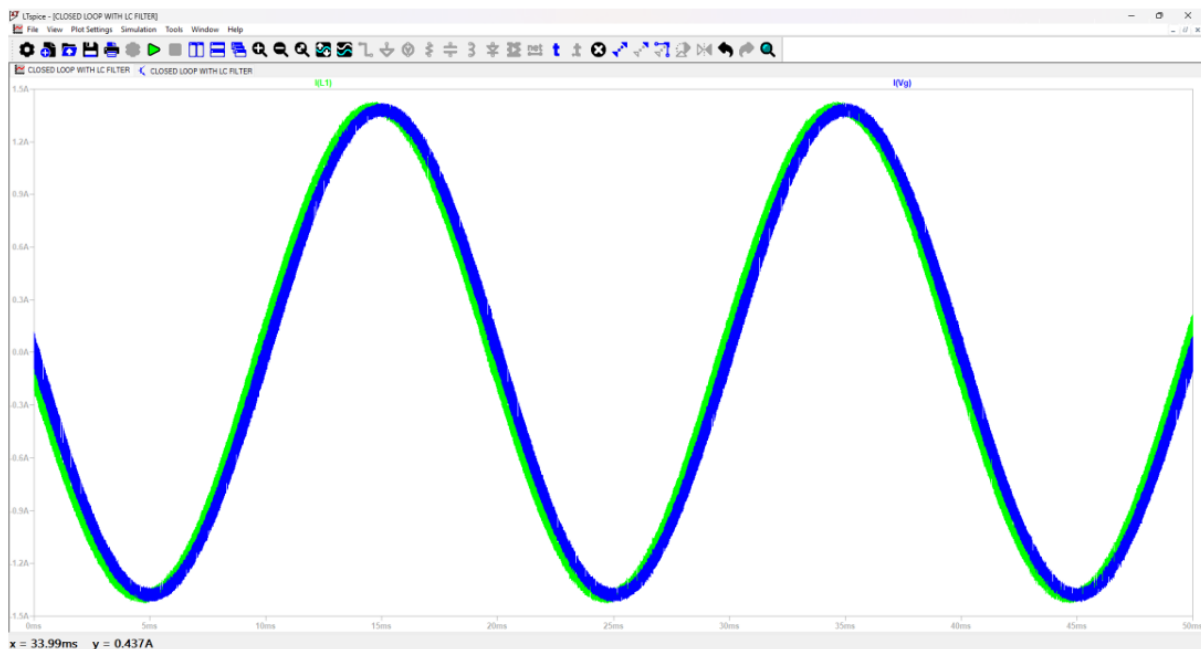


Figure 5.11: Inverter output current before and after LC filtering

The filtered waveform demonstrates the effectiveness of the LC filter in suppressing switching harmonics.

5.13 Closed-Loop Performance Verification

Simulation results verify the effectiveness of the closed-loop current control system. The results confirm that:

- The grid current accurately tracks the reference waveform.
- The injected current is synchronized with the grid voltage.
- Harmonic distortion is significantly reduced, compliant with IEEE 519 or IEC 61000 standards (IEEE, 2018).
- The system operates stably under steady-state conditions.

The phase alignment between the grid voltage and the injected grid current is shown in Figure 5.12, confirming unity power factor operation. Furthermore, the spectral quality of the current is validated through frequency domain analysis. The Total Harmonic Distortion (THD) is analyzed via FFT, as presented in Figure 5.13, demonstrating significantly reduced harmonic content compliant with grid standards.

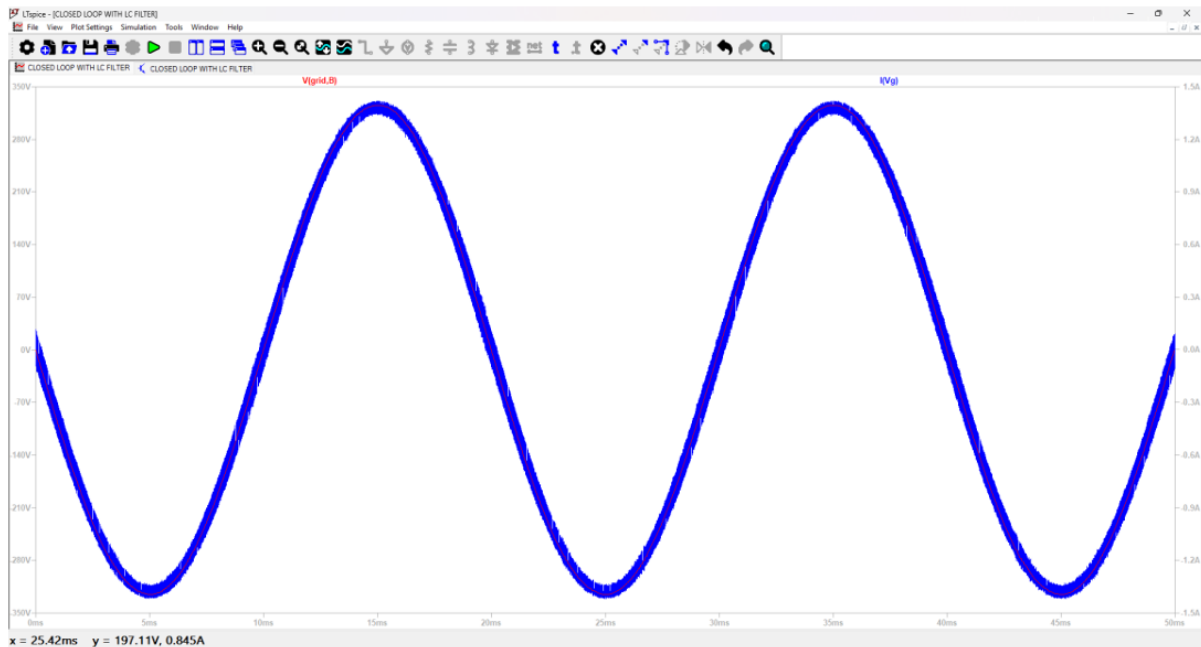


Figure 5.12: Grid voltage and injected grid current showing phase alignment (unity power factor operation)

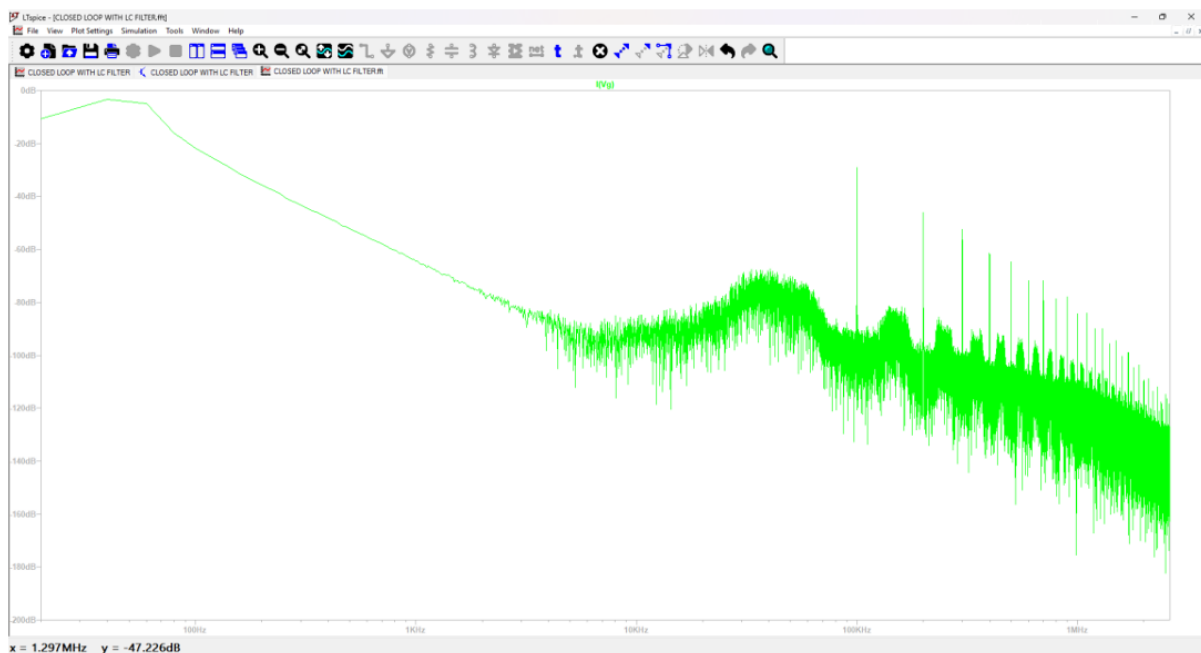


Figure 5.13: Harmonic spectrum (FFT) of the injected grid current

5.14 Relation to Volt/Var Control

The implemented closed-loop current controller represents the inner control loop required for Volt/Var control operation. By modifying the amplitude and phase of the reference current based on grid voltage deviations, the same control structure can regulate both active and reactive power exchange with the grid.

Therefore, the developed system constitutes a validated and documented prerequisite for the implementation of Volt/Var control strategies in future stages of the project.

5.15 Chapter Summary

In this chapter, a complete software-based closed-loop current control system for a single-phase grid-tied inverter was designed, implemented, and verified using LTspice. The proposed controller ensures accurate current tracking, grid synchronization, and effective harmonic mitigation.

This control stage provides a solid and research-compliant foundation for the implementation of advanced grid-support functionalities, such as Volt/Var control, in subsequent phases of the project.

Chapter 6: Hardware Implementation and Component Description

The hardware realization integrates custom-designed PCBs (Main Inverter Board) with off-the-shelf auxiliary power modules to accelerate prototyping. The High-Frequency Boost Converter (Section 6.2) steps up the battery/PV voltage to the 400V DC-Link required by the Main Inverter Board (Section 6.1), while the Buck Converter (Section 6.4) ensures stable auxiliary power for the cooling system and control logic.

6.1 Main Inverter Board Architecture and Layout

This section details the physical realization of the main inverter board, mapping the theoretical blocks discussed in Chapter 4 to the actual hardware components. The board is designed with a mixed-signal layout approach to minimize noise coupling and optimize power flow. The preliminary PCB layout design, illustrating the component placement strategy, is shown in Figure 6.0.

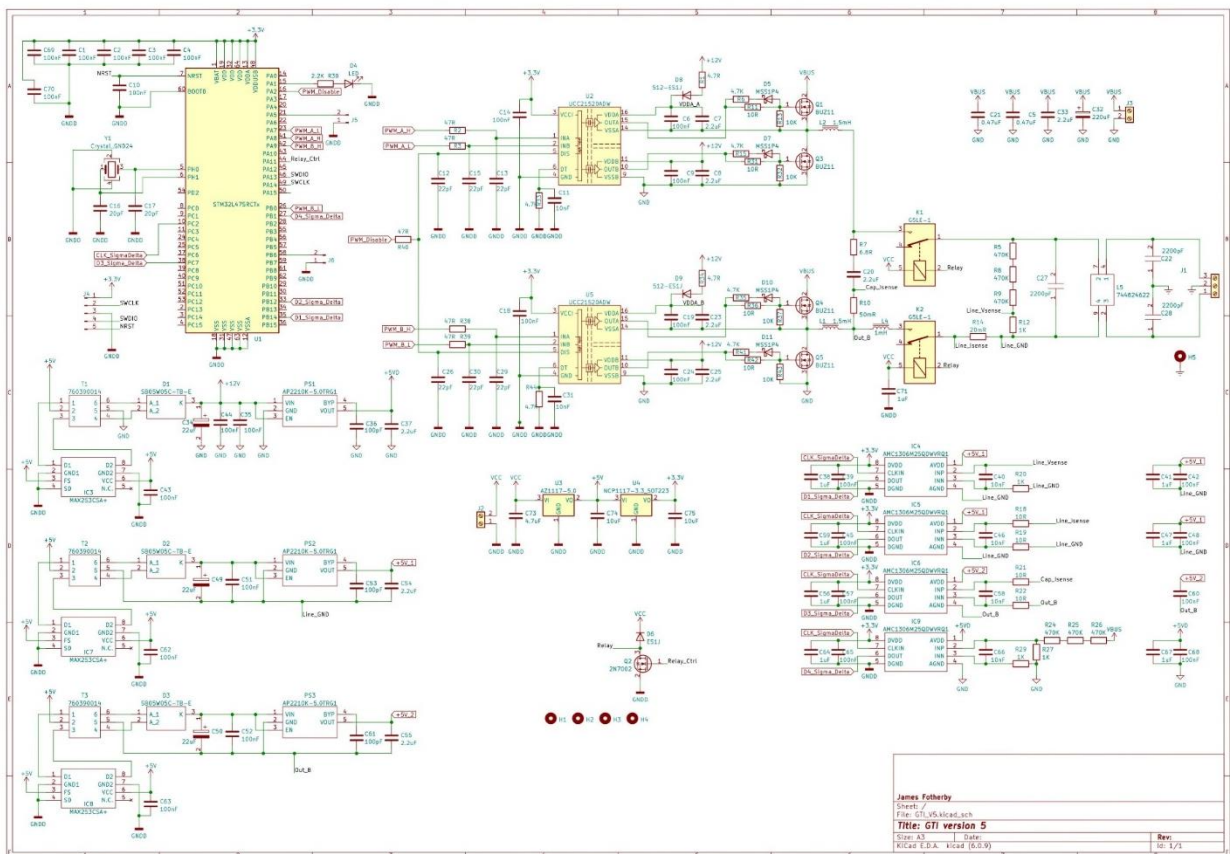


Figure 6.0: Preliminary PCB Layout Design of the Control and Power Stage.

Following this design, the board was assembled. The top-side assembly, containing the digital control unit, passive filter components, and relays, is shown in Figure 6.1. The bottom-side layout, which hosts the high-power switching devices and sensing resistors to optimize thermal management, is depicted in Figures 6.2. To further ensure efficient cooling, thermal interface pads were applied to the MOSFETs before attaching the heatsink, as illustrated in Figures 6.3.

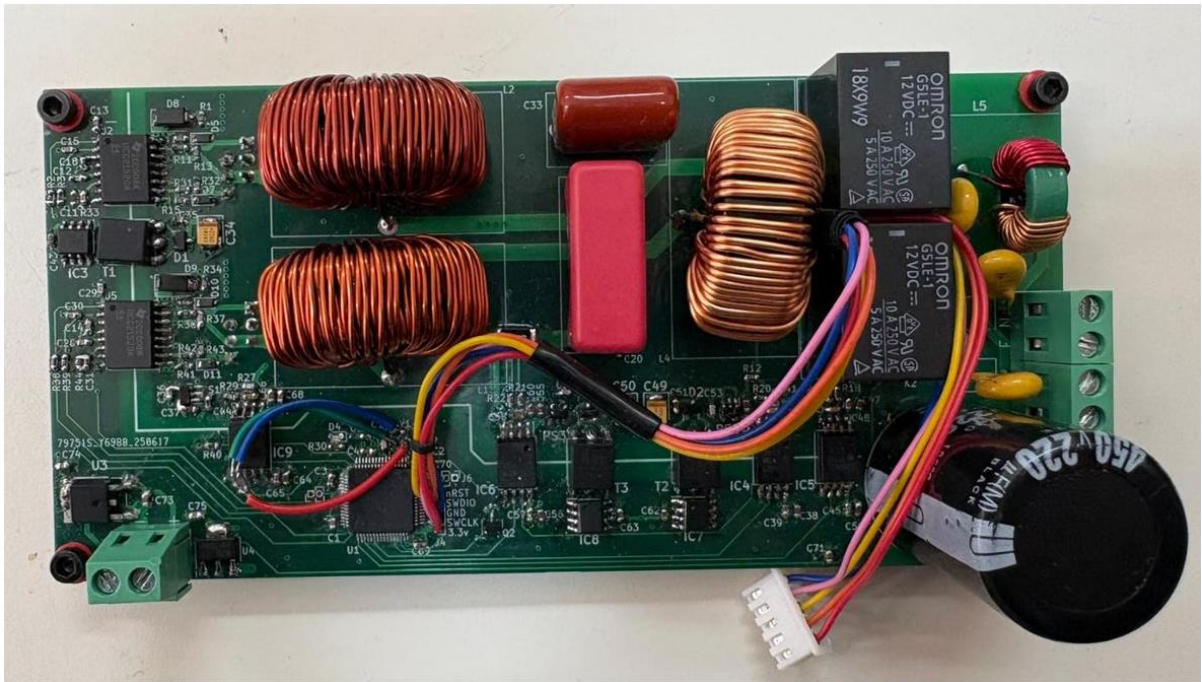


Figure 6.1: Top-side PCB assembly showing the digital control unit, LCL output filter, and protection relays.

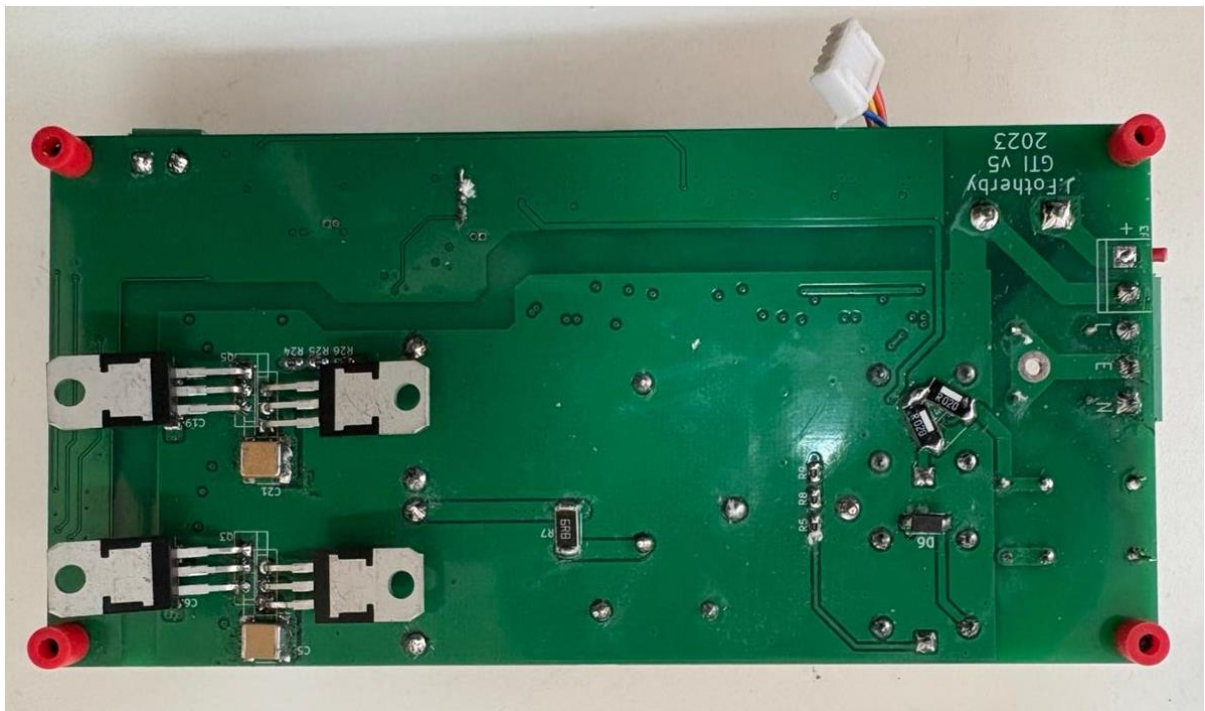


Figure 6.2: Bottom-side PCB layout featuring the full-bridge power stage MOSFETs and current sensing shunt resistors.

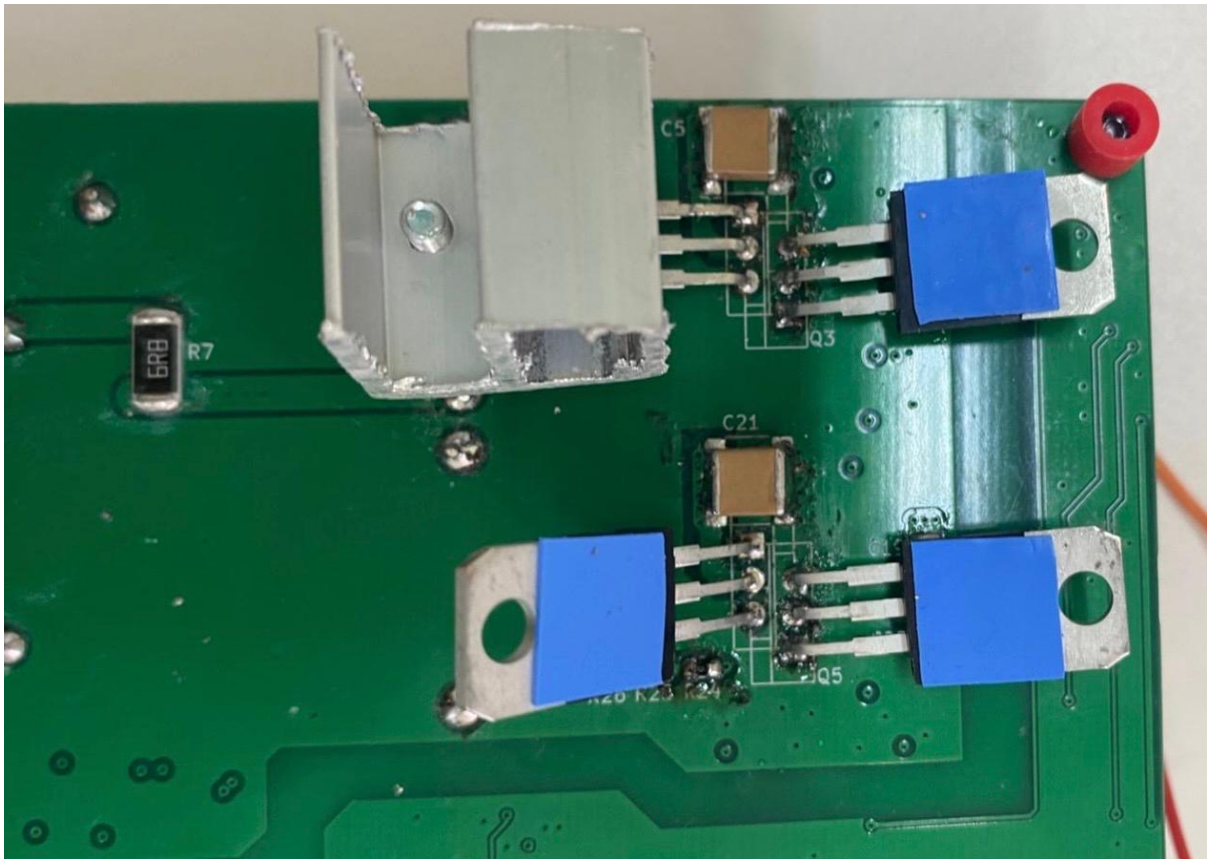


Figure 6.3: Close-up view of the power MOSFETs equipped with thermal interface pads to facilitate heat dissipation before attaching the heatsink.

6.1.1 Control and Synchronization Unit

The control logic is centered around the microcontroller (IC9), visible on the bottom left of Figure 6.1 (typically an STM32 series). This unit is responsible for executing the Phase-Locked Loop (PLL) algorithms to synchronize with the grid frequency. It measures grid voltage via resistor dividers and generates the high-frequency SPWM signals required to drive the power transistors.

6.1.2 DC-AC Inverter Power Stage

The power stage, often referred to as the H-Bridge, is located on the bottom side of the PCB (Figures 6.2). It consists of four high-voltage MOSFETs (TO-247 package) configured to chop the DC bus voltage into high-frequency AC pulses. These switches are driven by Isolated Gate Drivers (UCC21520), shown on the left side of Figure 6.1, which amplify the 3.3V logic signals from the microcontroller to effectively drive the MOSFET gates while providing galvanic isolation.

6.1.3 DC Link Energy Buffer

To stabilize the high-voltage DC input, a 450V 220 μ F electrolytic capacitor is utilized (Figure 6.1, bottom right). This component acts as an energy buffer, mitigating voltage

ripples caused by the switching operation. It is important to note that this board requires a high-voltage DC input (approximately 350V–400V DC) to successfully generate a 230V AC output.

6.1.4 Output Filter (LCL)

To attenuate the switching harmonics generated by the H-Bridge, a passive LCL filter is implemented (Figure 6.1, top center). This filter consists of two toroidal inductors (L1 & L2) and a high-voltage film capacitor (C20). This stage is critical for converting the high-frequency Pulse Width Modulated (PWM) pulses into a smooth 50Hz/60Hz sine wave compliant with grid standards.

6.1.5 Protection and Safety Mechanisms

Safety is ensured through electromechanical relays (OMRON G5LE-1) located on the top right of Figure 6.1. These relays function as the primary anti-islanding disconnect switch, physically isolating the inverter from the grid in case of a fault or blackout. Additionally, Metal Oxide Varistors (MOV) are placed near the AC output terminals to protect the internal circuitry from external voltage spikes.

6.1.6 Current Sensing

For the inner current control loop, low-value shunt resistors (R020 / 0.02Ω) are placed on the return path of the power stage (Figures 6.2). The voltage drop across these resistors provides the microcontroller with precise feedback on the current injected into the grid, enabling closed-loop control.

6.1.7 Summary of Operation

The operational flow of the main board is as follows:

- High Voltage DC is applied to the input terminals and buffered by the DC-link capacitor.
- The Microcontroller switches the H-Bridge MOSFETs at high frequency ($>20\text{kHz}$).
- The resulting pulsed output passes through the toroidal inductors and filter capacitor, reconstructing the sine wave.
- The current flows through the safety relays and exits via the AC terminal block to the grid.

6.1.8 Firmware Upload and Debugging Interface (ST-LINK/V2)

To bridge the gap between the control software and the hardware realization, an external programming interface is required. The system utilizes the ST-LINK/V2 in-circuit debugger/programmer (shown in Figures 6.4) to flash the control algorithms onto the STM32 microcontroller (IC9).



Figure 6.4: The ST-LINK/V2 debugger/programmer used for flashing the STM32 microcontroller.

Interface Connection and Protocol:

The connection between the programmer and the Main Inverter Board relies on the Serial Wire Debug (SWD) protocol. Unlike JTAG, SWD requires fewer pins, making it ideal for compact PCB layouts. As illustrated in the close-up of the PCB traces (Figures 6.5), the board features a dedicated 4-pin header labeled explicitly for this purpose.

Technical Specifications:

Based on the device datasheets, the ST-LINK/V2 connects to the host PC via a USB 2.0 Full-Speed interface. It is designed to communicate specifically with STM32 microcontrollers using the Serial Wire Debug (SWD) protocol. Key electrical characteristics relevant to this implementation include:

- **Logic Voltage Support:** It supports application voltages between 1.65 V and 3.6 V, which ensures safe compatibility with the 3.3V logic level of the main inverter board without requiring level shifters.
- **Software Integration:** It provides direct communication with the STM32CubeIDE software tool, allowing for code uploading and real-time variable monitoring (Live Watch) during inverter operation.
- **Status Indication:** A built-in LED blinks during communication, providing immediate visual feedback on the data transfer status.

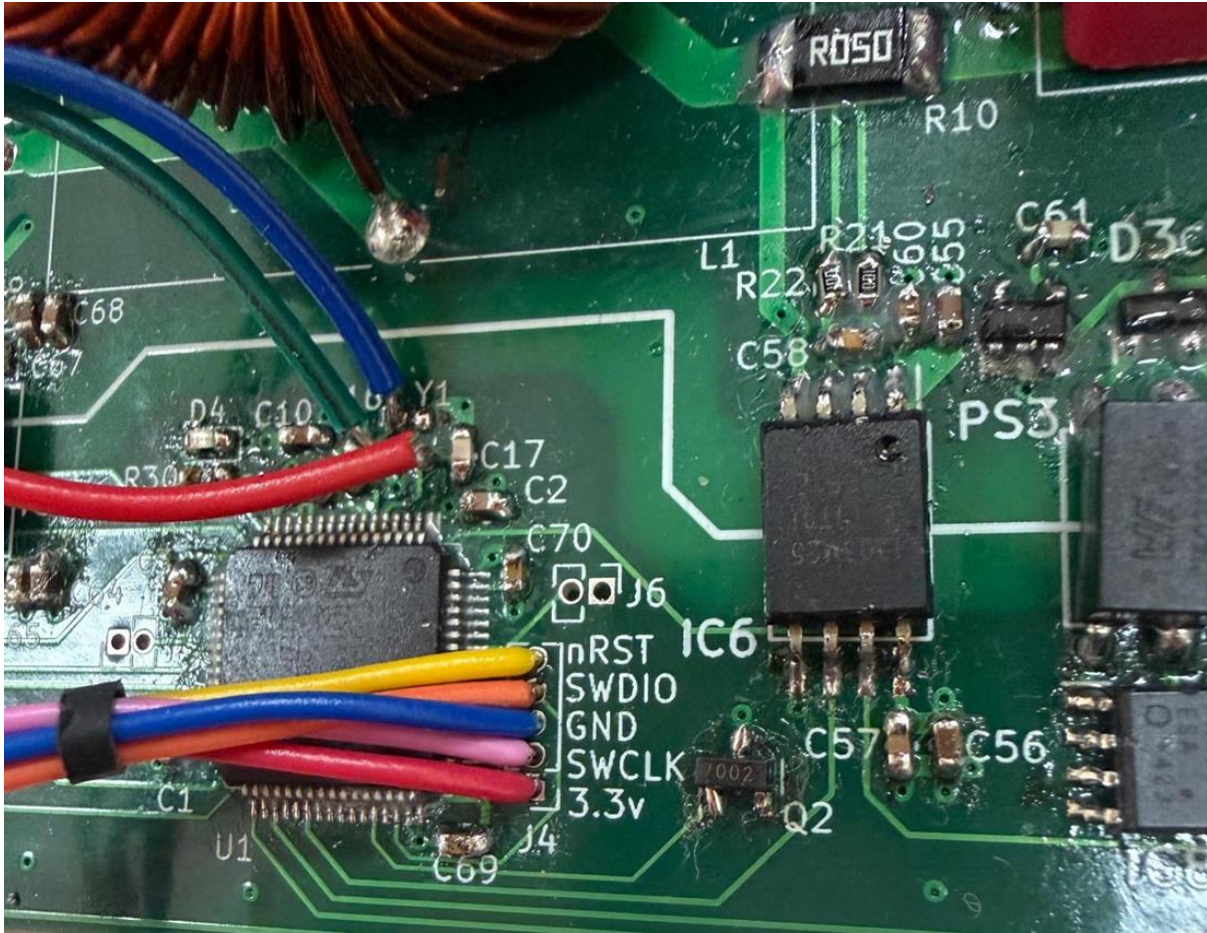


Figure 6.5: Macro view of the PCB programming header showing the SWD pinout assignments (3.3V, SWCLK, GND, SWDIO).

Wiring Configuration:

The physical connection is established using a 4-wire harness connecting the ST-LINK/V2 to the PCB's white JST connector (as shown in Figures 6.6). A detailed close-up of the custom cable adapter used for this interface is depicted in Figures 6.7. The wiring follows the standard mapping required for the STM32 family:

1. 3.3V (VCC): Logic reference voltage.
2. GND: Common ground.
3. SWCLK: Synchronization clock signal.
4. SWDIO: Bidirectional data line for code transfer.

This setup allows for real-time debugging, enabling the monitoring of grid variables (Voltage, Frequency) via the IDE software while the inverter is in operation.

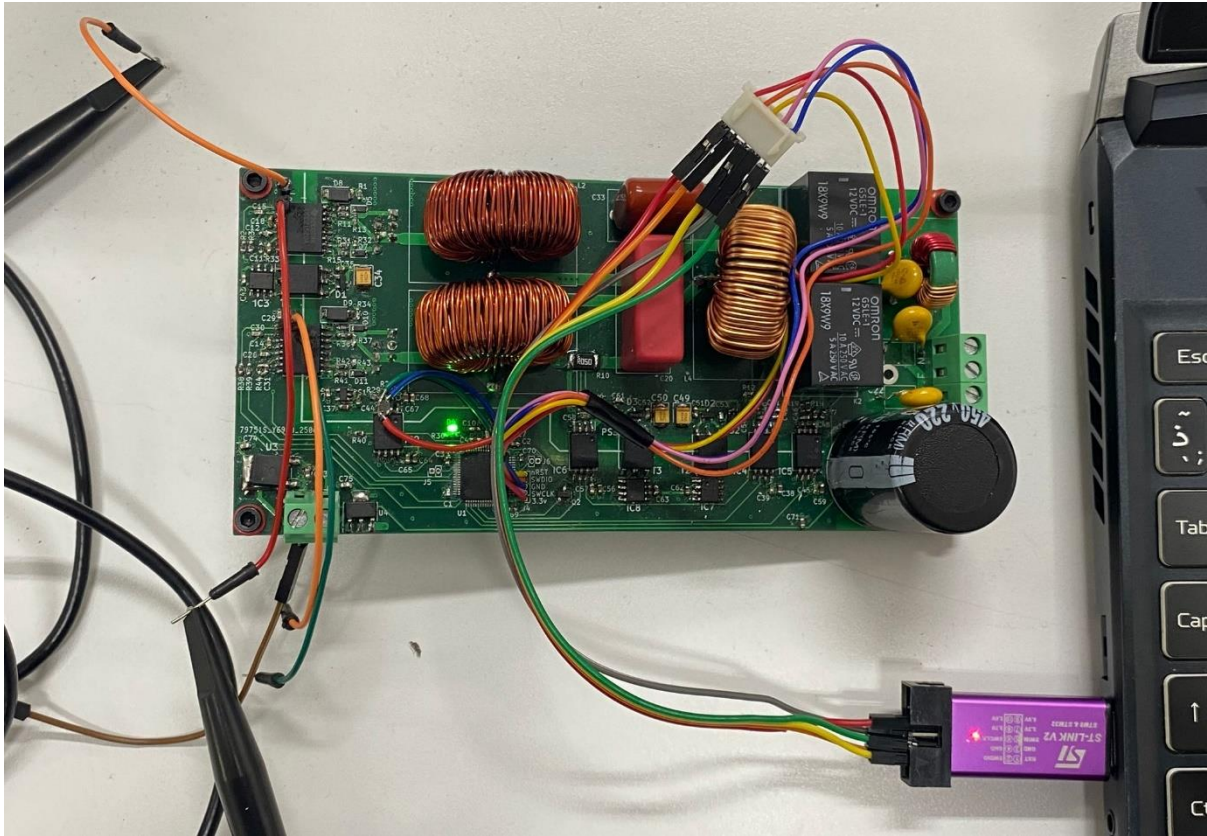


Figure 6.6: Physical connection of the ST-LINK/V2 to the Main Inverter Board using the Serial Wire Debug (SWD) interface.

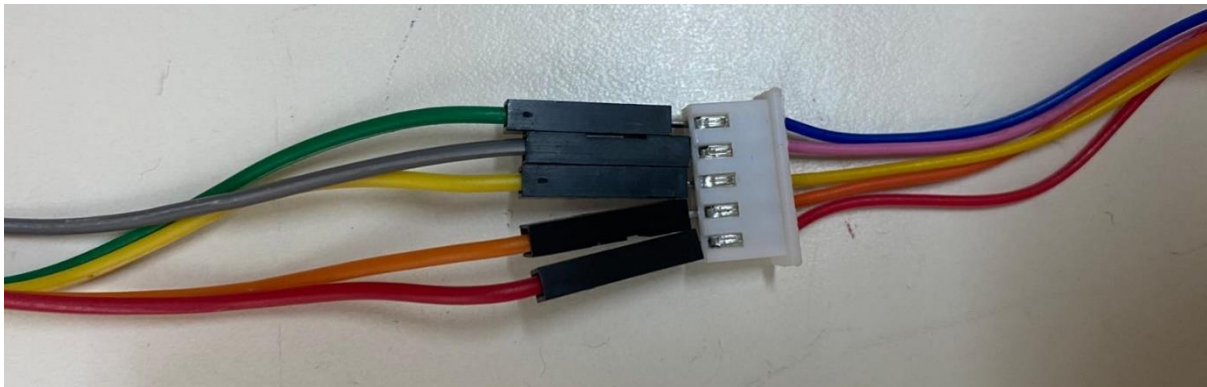


Figure 6.7: Close-up of the custom cable adapter connecting the ST-LINK/V2 to the board.

6.2 High-Frequency DC-DC Step-Up (Boost) Converter Board

This section describes the hardware implementation of the DC-DC pre-stage module, which functions as a high-frequency step-up converter. This board serves as the initial power stage, boosting the low-voltage DC input (12V) to a high-voltage intermediate rail required for the inverter stage. The physical layout and key components of the board are shown in Figures 6.8.

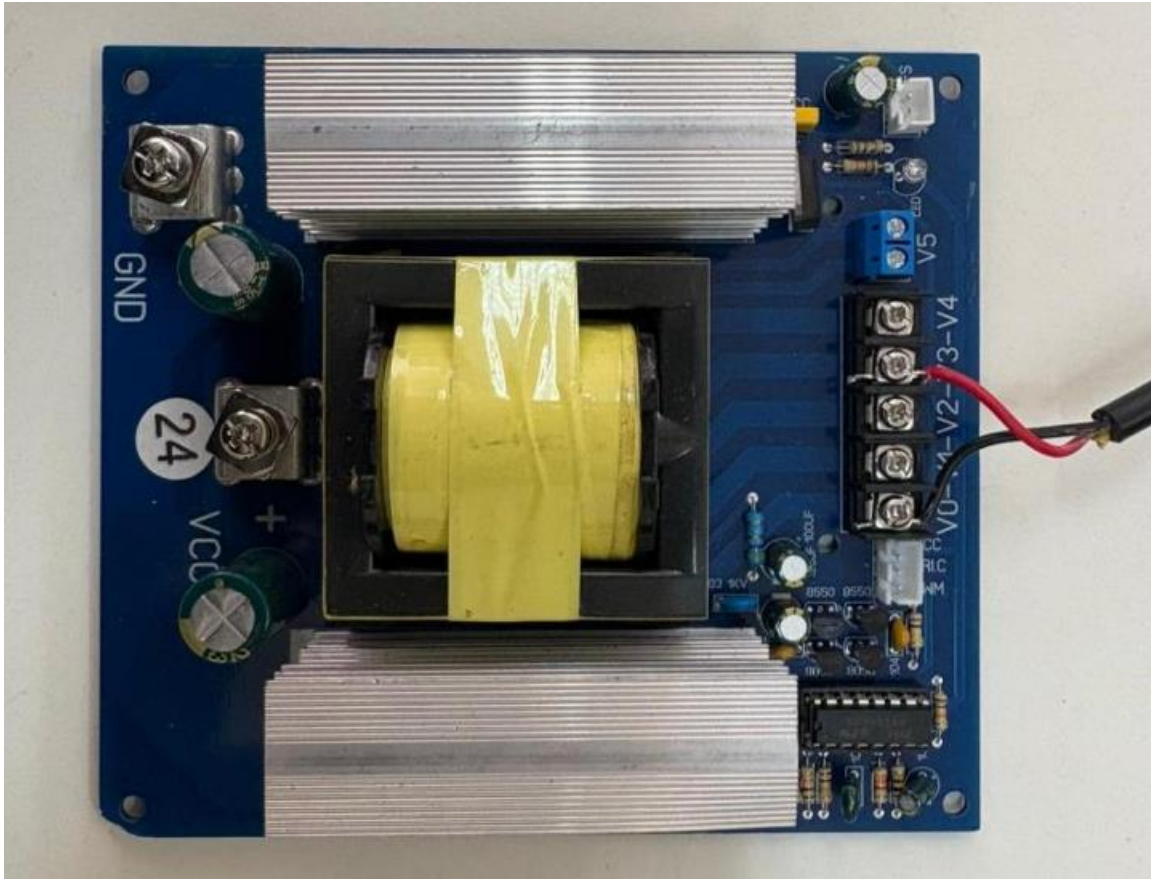


Figure 6.8: Top-view of the High-Frequency DC-DC Step-Up (Boost) Converter board.

6.2.1 Control Unit Implementation

The control logic relies on the SG3525AN PWM controller (DIP-16 package). This IC generates the switching signals (typically 20kHz–40kHz) and regulates the dead-time to prevent shoot-through currents in the power stage.

6.2.2 Power Stage and Transformer

The power stage utilizes a Push-Pull topology, where MOSFETs (located under the aluminum heatsinks) alternately drive the primary winding of the high-frequency ferrite core transformer (yellow component). This high-frequency operation allows for a compact transformer design capable of transferring substantial power (approx. 500W) compared to traditional 50Hz iron-core transformers.

6.2.3 Input and Output Characteristics

- Input: The 12V DC input is smoothed by three electrolytic capacitors to handle the high ripple current demands of the switching actions.
- Output: The transformer secondary offers multiple taps (V0, V1, V2) providing high-voltage outputs (e.g., 220V–380V). The output at this stage is high-frequency AC, which requires rectification before being fed to the inverter board.

6.3 Full-Wave Bridge Rectifier Board

This module, constructed on a prototyping perfboard (Figures 6.9), is responsible for converting single-phase AC (from the grid or the boost converter output) into a stable DC bus.

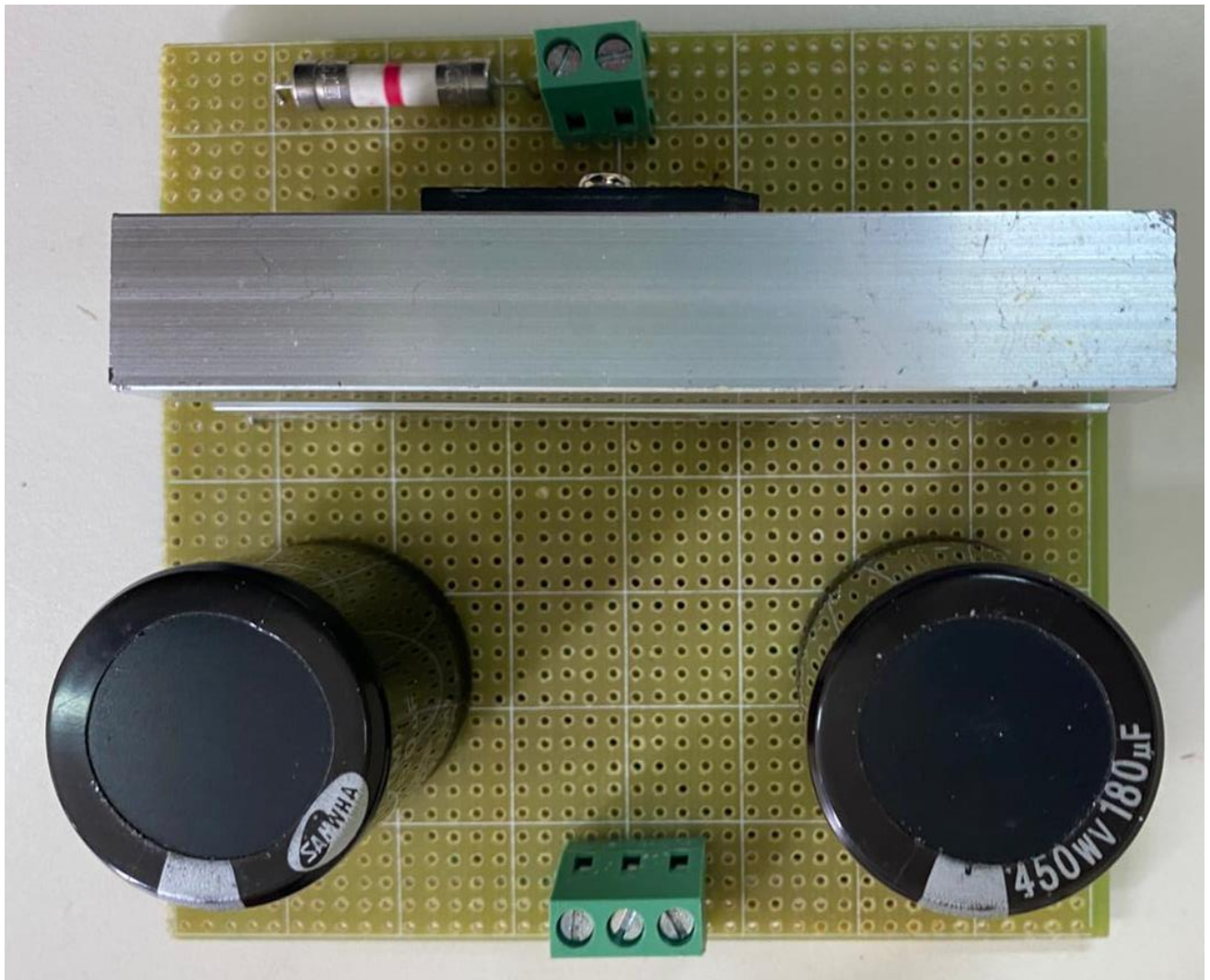


Figure 6.9: Top view of the prototype full-wave bridge rectifier and DC-link capacitor board.

6.3.1 Circuit Description

- **Input Protection:** The AC input is fused to protect against short circuits. An EMI/Differential-Mode filter (toroidal inductor) is placed in series to suppress high-frequency noise from entering or leaving the system.
- **Rectification:** A TS10K60S single-phase bridge rectifier converts the AC waveform into pulsating DC. The component is vertically mounted to aid in convective cooling.
- **DC Link:** Two large 450V 180µF capacitors are connected in parallel (Total: 360µF) to smooth the rectified output, providing a stable DC bus voltage (approx. 325V DC when rectified from 230V AC) for the subsequent stages.

6.4 XL4015 CC/CV Step-Down (Buck) Converter Module

To provide auxiliary power (e.g., for cooling fans or control logic), an XL4015-based buck converter is used (Figure 6.10). This module features both Constant Voltage (CV) and Constant Current (CC) control loops.

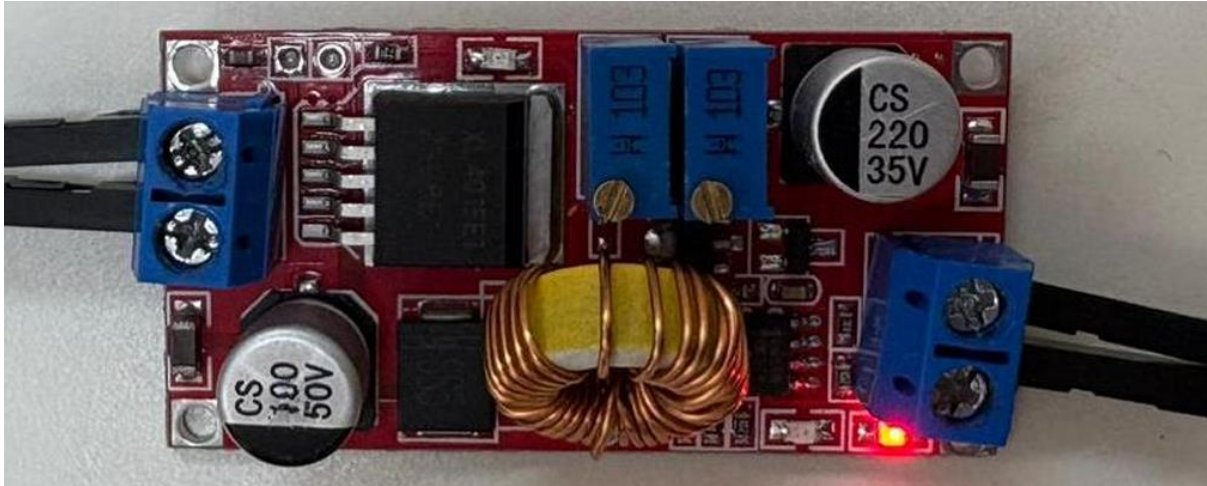


Figure 6.10: Top view of the XL4015 CC/CV Step-Down (Buck) Converter module.

6.4.1 Theory of Operation

The XL4015E1 regulator operates at a switching frequency of 180 kHz. It utilizes a standard buck topology comprising an inductor (energy storage), a Schottky diode (SS54) for freewheeling current, and input/output capacitors for filtering.

6.4.2 Configuration and Feedback

The module includes two multi-turn potentiometers for precise adjustment:

- Voltage Adjustment (CV): Sets the output voltage limit.
- Current Adjustment (CC): Limits the maximum output current, making the module suitable for applications like battery charging or driving LED loads where current regulation is critical.

6.5 Switched-Mode Power Supply (SMPS)

Figure 6.11 shows the SMPS unit used to power the test bench setup. This model features active air cooling, where the fan speed is regulated based on the operating temperature, ensuring stable voltage output during extended testing periods.



Figure 6.11: Power Supply.

Figure (6.11) shows the SMPS unit used. This model has an Active Cooling system, where the built-in fan operates automatically based on the operating temperature (as indicated on the warning label), ensuring voltage stability and circuit protection during long periods of operation.

Chapter 7: Testing and measurement

1. Testing Setup

Practical tests were conducted to verify the performance of the designed circuit and its conformity to theoretical specifications. The testing process began by verifying the digital control signals generated by the microcontroller before proceeding to the power stage.

Figure 7.1 illustrates the initial test bench setup used in the laboratory.

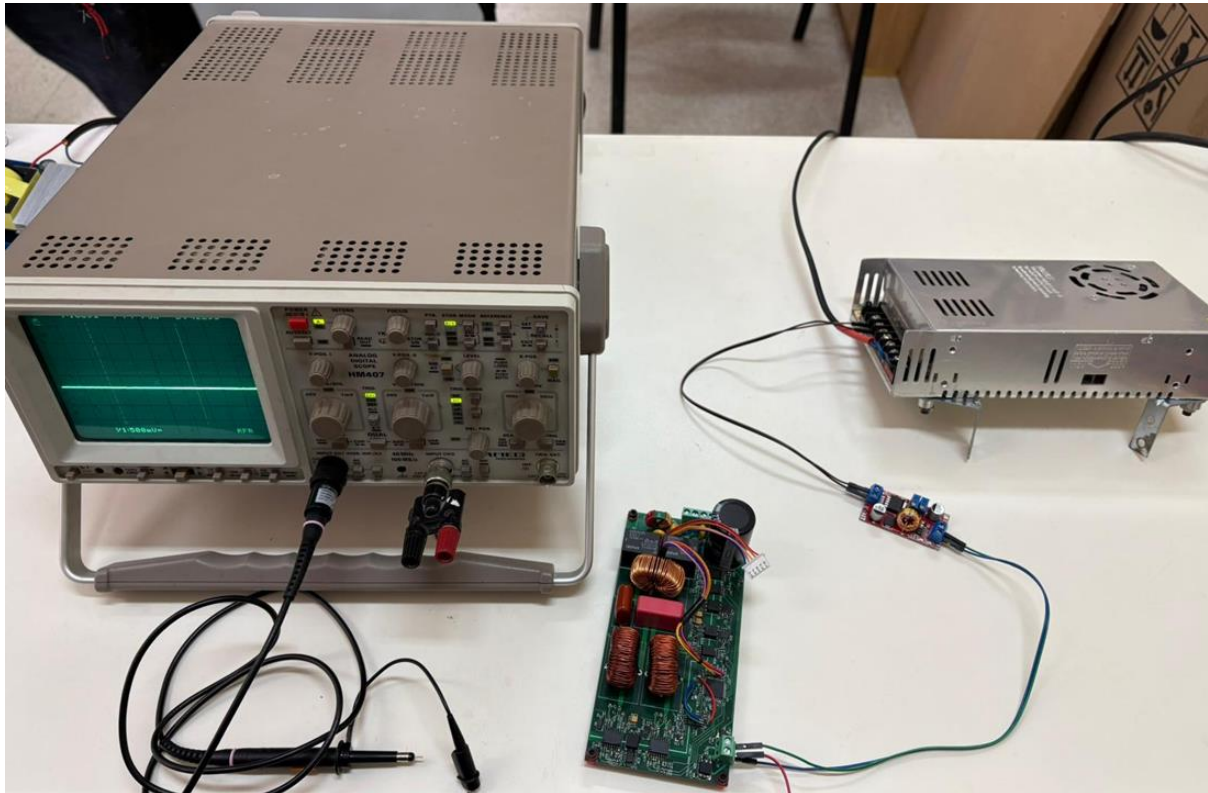


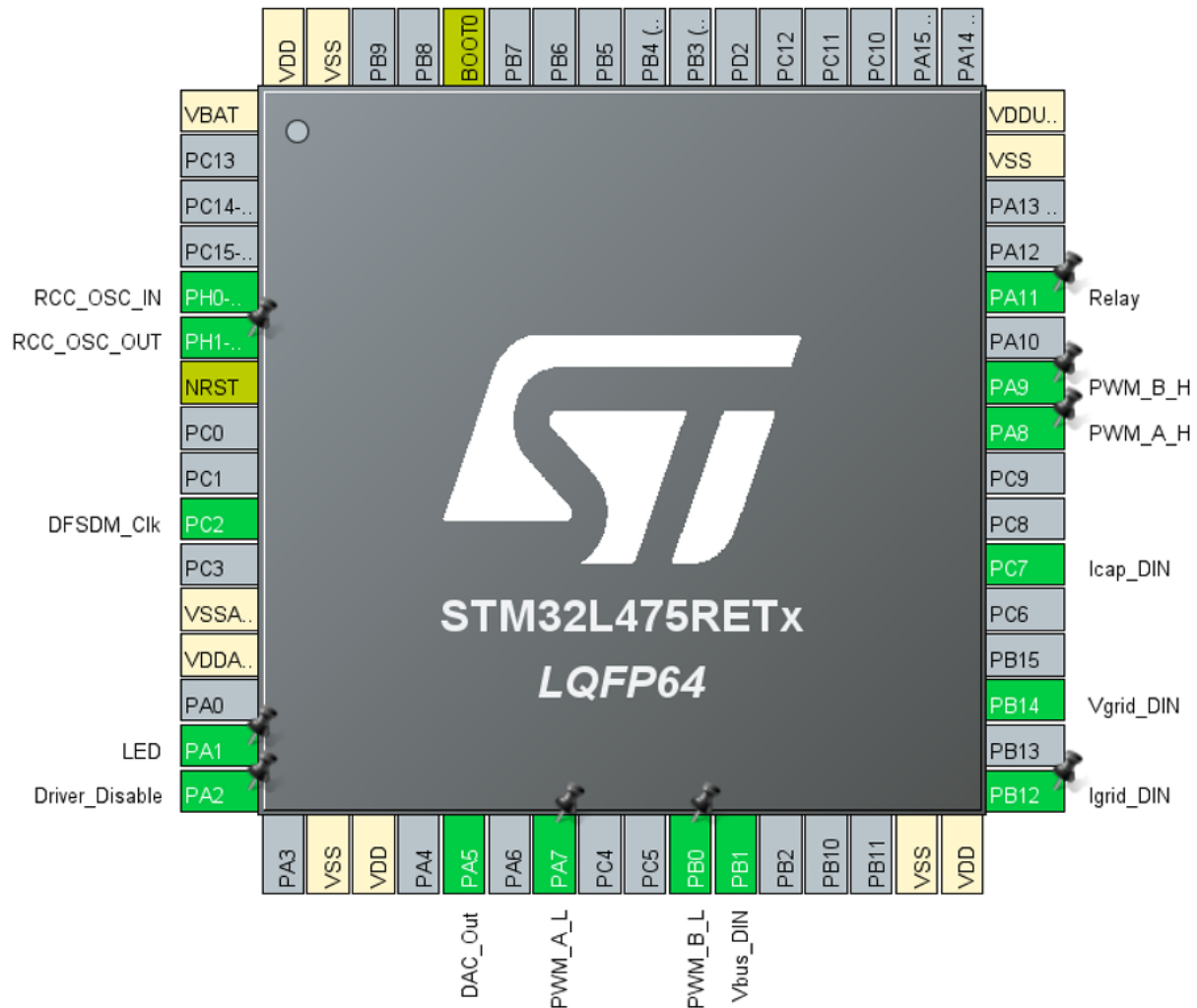
Figure 7.1: The experimental setup showing the HAMEG HM407 Oscilloscope, DC Power Supply, Step-Down (Buck) Converter, and the Inverter PCB (DUT).

The setup consists of the following components:

- Power Supply: A power supply was used to provide the necessary voltage levels.
- Oscilloscope: A HAMEG HM407 analog/digital oscilloscope and GW Instek GDS-2104E digital storage oscilloscope was used to monitor and analyze the electrical signals.
- DUT (Device Under Test): The STM32L475RETx microcontroller and the associated PCB containing the power components.

7.2 Microcontroller Configuration

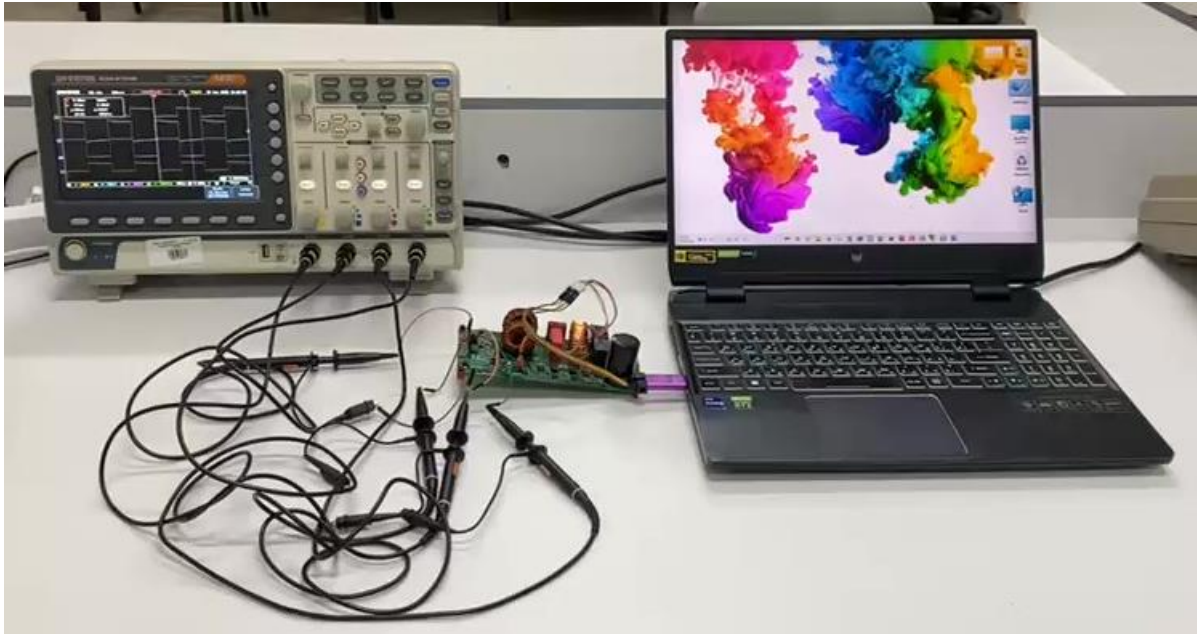
Before applying high voltage to the power stage, the STM32L475RETx microcontroller pinout was configured to generate the required Pulse Width Modulation (PWM) signals. The specific pin configuration designated for the PWM output is detailed in Figures 7.2.



Figures 7.2: STM32L475RETx Pinout configuration showing the designated PWM output pins (PA8, PA9, PA7, PB0).

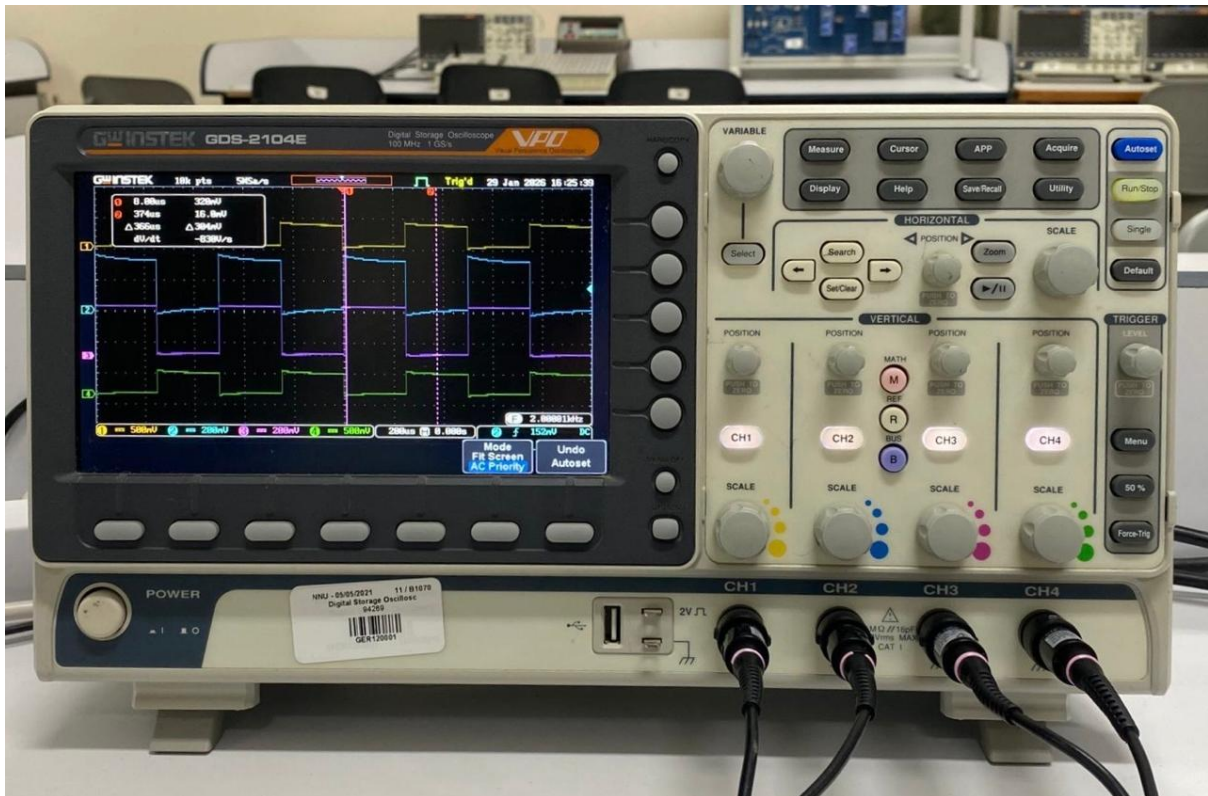
7.3 Measurement Results

After programming the STM32 microcontroller and preparing the firmware for upload, the hardware test bench was configured as shown in Figures 7.3. In this setup, the oscilloscope probes were connected directly to the STM32 output pins to verify the control logic. The primary goal of this stage was to ensure that the microcontroller generates the correct switching frequency and waveforms before driving the power MOSFETs, thereby preventing potential damage to the power stage components.



Figures 7.3: Physical experimental setup showing the connections between the laptop, Main Inverter Board, and oscilloscope during the control signal verification process.

The resulting signals captured from the microcontroller pins are presented in Figures 7.4.



Figures 7.4: Waveforms of the control signals measured using the GW Instek GDS-2104E Digital Storage Oscilloscope.

7.4 Results Analysis

Figure 7.4 displays the resulting waveform captured from the microcontroller pins. Analysis of the Figures reveals the following:

- **Waveform Topology:** The signal appears as a distinct square/pulse wave. This confirms that the digital output pins are toggling correctly between logic high and logic low states.
- **Frequency and Timing:** The oscilloscope cursors indicate a time difference (Δt) of 1.00 ms. This corresponds to a signal frequency of 1 kHz, which matches the intended testing frequency ($f = 1/T$).
- **Signal Stability:** The waveform edges are sharp, indicating a clean digital transition suitable for driving the subsequent gate driver stages.

Conclusion:

The experimental setup and measurements confirm that the control stage is operational. The STM32 microcontroller successfully generates the required signals, and the hardware setup is ready for further power integration tests.

Chapter 8: Conclusion and Future Work

8.1 Project Conclusion and Hardware Outcomes

The practical phase of the project has been successfully completed, involving the assembly of the electronic circuit PCB and the integration of all necessary components to ensure proper and complete operation.

Key achievements include:

- **System Integration:** The circuit's processor, responsible for processing network signals, has been fully programmed. It is now capable of controlling the inverter to facilitate the connection between the electrical grid and the solar power system.
- **Signal Verification:** The control signals and waveforms generated by the main processor have been experimentally verified and measured, confirming the system's readiness for the power stage.

8.2 Project Challenges

Throughout the development of this project, several obstacles were encountered spanning both hardware implementation and simulation phases.

8.2.1 Hardware Challenges

- **Component Procurement:** A major difficulty was procuring the necessary electronic components from the local market, which necessitated importing them from abroad.
- **Cost and Logistics:** The project faced high prices for electronic components, significant shipping costs, and customs duties.
- **Customs Delays:** Customs clearance issues caused significant delays in the arrival of critical components, particularly the Printed Circuit Board (PCB).
- **Assembly Complexity:** The small form factor of the electronic components (SMD) made assembly difficult, requiring specialized equipment such as magnifying lenses and precision soldering tools.

8.2.2 Simulation Challenges

- **Learning Curve:** Lack of prior knowledge regarding the specific simulation software required time and effort to overcome.
- **Resource Limitations:** There were insufficient resources available to quickly resolve unique problems encountered during simulation and data acquisition.
- **Software Limitations:** Some electronic components were unavailable in the simulation software's standard library, necessitating the use of alternative software or the manual creation of these component models from scratch.

8.3 Future Work

To further enhance the system's capabilities and bridge the gap between simulation and practical application, the following development is proposed:

Implementation of Volt-Var Control Strategy:

Integrate and validate the full Volt-Var control loop on the hardware prototype. As illustrated in Figure [X], this involves implementing the Volt/Var action defined by the equation:

$$I_q = K_v(V_{ref} - V_{grid})$$

By controlling the quadrature current component (I_q), the inverter will actively regulate the grid voltage by injecting or absorbing reactive power (Q) in response to voltage deviations, effectively realizing the control structure depicted in the figure.

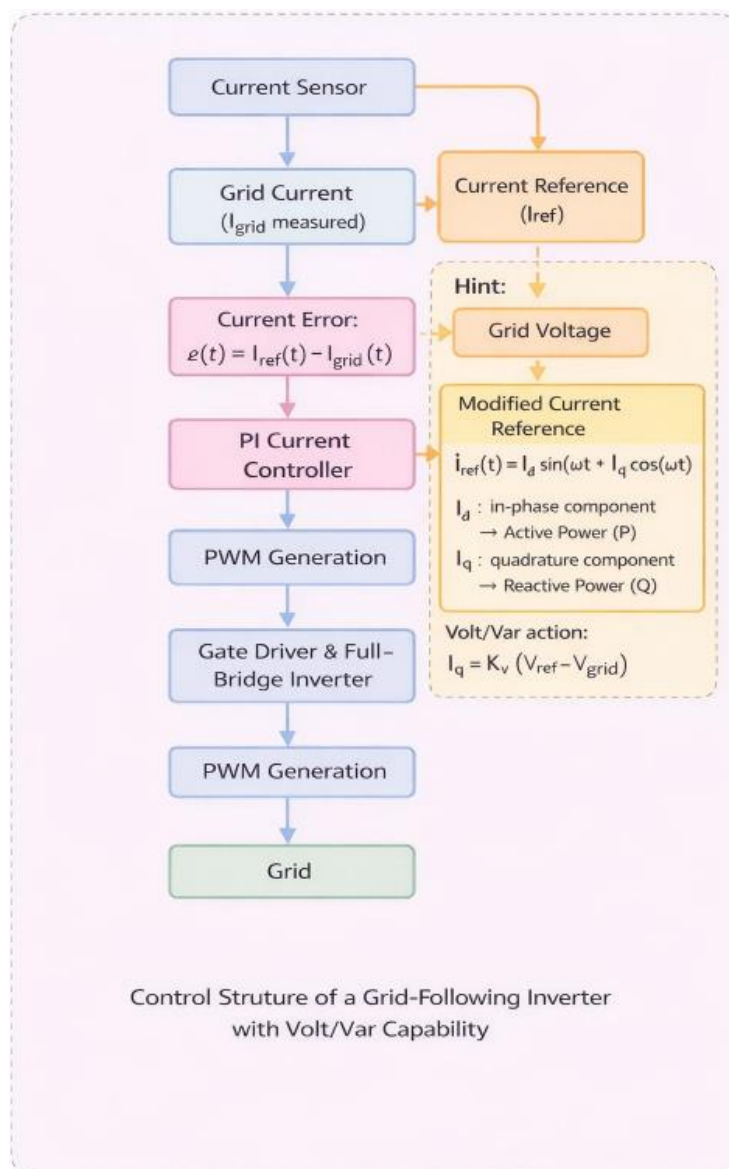


Figure 8.1: Control Block Diagram of a Grid-Following Inverter with Volt-Var Capability.

Appendix A: Firmware Architecture and Control Logic Analysis

A.1 Overview

The project utilizes the **STM32CubeIDE** environment, and the microcontroller is the **STM32F303** (famous in power electronics applications), chosen for its advanced analog peripherals and floating-point unit (FPU) suitable for power electronics.

The firmware development, including the writing of control algorithms, management of startup files, and configuration of linker scripts, was conducted within the STM32CubeIDE environment as depicted in Figure A.1. This Integrated Development Environment (IDE) allows for the seamless integration of the low-level drivers generated by CubeMX with the custom C-code logic (STMicroelectronics, 2022).

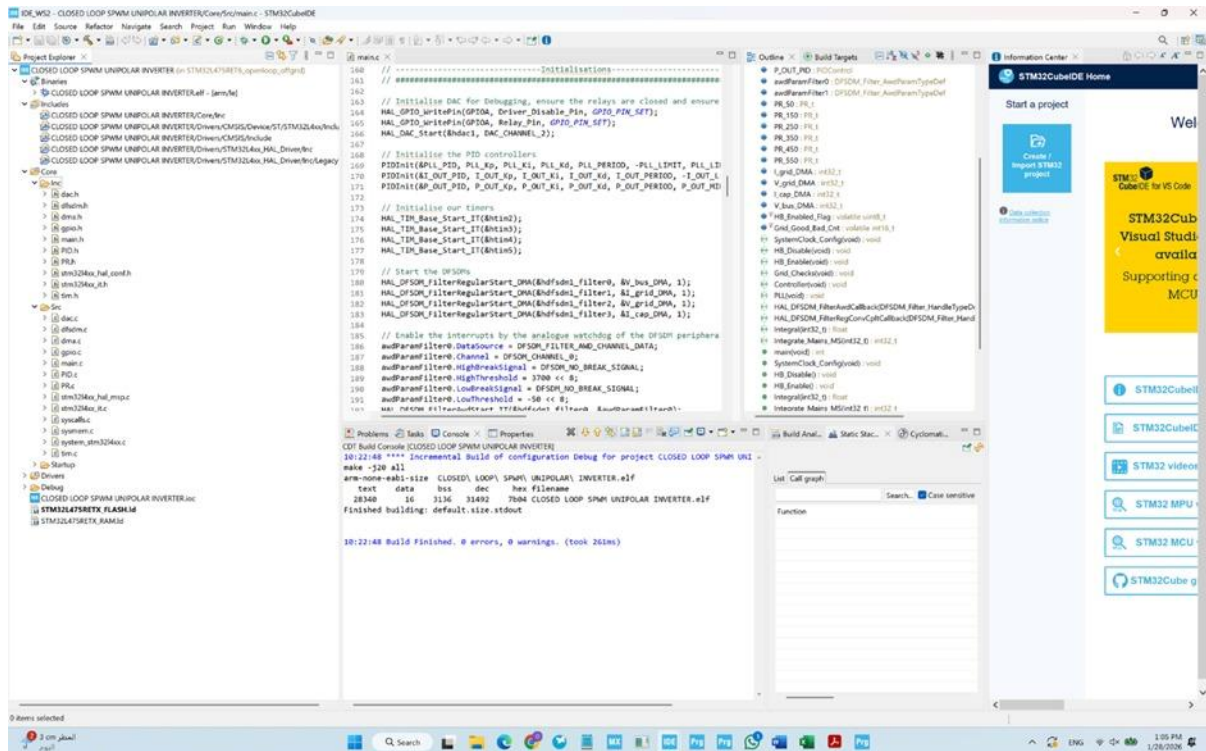


Figure A.1: STM32CubeIDE workspace used for developing the control algorithms and managing the project structure.

A.2 Code Structure Analysis

The core control logic is located within **Core/Src** and **Core/Inc**. The file hierarchy is structured as follows:

- **main.c**: Contains the system initialization, the main **while(1)** loop for non-critical tasks (state machine, safety checks), and the setup of peripherals.
- **stm32f3xx_it.c**: The Interrupt Service Routines (ISR) file. This is the "**beating heart**" of the firmware. The time-critical control loop executes inside a high-priority timer interrupt (typically at 20kHz - 40kHz) to guarantee deterministic timing.
- **stm32f3xx_hal_msp.c**: Handles low-level hardware abstraction (GPIO configuration, Clock enabling, and DMA settings).

A.3 Detailed Logic Extraction & Implementation

Based on the hardware we described (**AMC1306 + UCC21520**), the firmware performs four critical tasks within every switching cycle:

1. High-Precision Sensing (DFSDM Implementation)

Since you are using the **AMC1306** (which is a Sigma-Delta Modulator), the microcontroller uses the **DFSDM** unit (Digital Filter for Sigma Delta Modulators) instead of the traditional ADC to read voltage and current with high precision and isolation from switching noise (STMicroelectronics, 2022).

Expected Code (in `main.c` or the Callback function):

```
<> C

// Callback function executing upon filter conversion completion
void HAL_DFSDM_FilterRegConvCpltCallback(DFSDM_Filter_HandleTypeDef *hdfsdm)
{
    if (hdfsdm == &hdfsdm1_filter0)
    {
        // Retrieve filtered 24-bit value and scale to physical unit (Volts)
        int32_t raw_v = HAL_DFSDM_FilterGetRegularValue(hdfsdm, &channel0);
        Grid_Voltage = (float)raw_v * V_SCALE_FACTOR;
    }
    // Repeat for Current and DC Bus Voltage
}
}
```

Analysis & Integration Note:

This interrupt-based approach ensures zero CPU waste on polling. **Crucially**, unlike standard projects that read `I_grid_DMA` from an ADC, this firmware links the control variables directly to the `HAL_DFSDM` output to interface correctly with the isolated AMC1306 sensors, ensuring noise-free measurements.

2. Synchronization (SOGI-PLL & Lookup Optimization)

To achieve Unity Power Factor, the inverter must synchronize perfectly with the grid frequency and phase using **SOGI-PLL** Algorithms (Second Order Generalized Integrator Phase Locked Loop) (Blaabjerg et al., 2006).

- SOGI: Generates orthogonal signal components (α, β)
- Park Transform: Rotates the frame to (d, q) coordinates.
- PI Controller: Regulates v_q to zero, locking the internal angle Θ to the grid.

Implementation Efficiency:

To optimize real-time performance, the `sin()` calculation is replaced by a Lookup Table with Linear Interpolation:

Code snippet:

```
<> C
// Linear Interpolation for high-speed angle generation
float diff = Sin_LookupF[Lookup_Index + 1] - Sin_LookupF[Lookup_Index];
float LO_Sample_256 = Sin_LookupF[Lookup_Index] + (diff * Timer4_CNT_Ratio);
```

Analysis:

The system uses a pre-calculated sine lookup table (`Sin_LookupF`). Linear Interpolation using a high-speed timer (`Timer4`) allows for a precise reconstruction of the reference sine wave (`LO_Sample_256`) without the heavy CPU load of trigonometric calculations.

3. Current Control (Proportional Resonant - PR)

Unlike DC systems that rely on PI controllers, AC current regulation requires infinite gain at 50Hz to eliminate steady-state error.

Code Logic:

```
<> C
// Discrete PR Controller Implementation
float Ua_50 = a1_50 * E_Prev1 - a1_50 * E_Prev2;
float Ub_50 = b1_50 * U_Prev1_50 - b2_50 * U_Prev2_50;
float Ui_50 = (Ua_50 + Ub_50) / b0_50; // Resonant Output at 50Hz
```

Analysis:

The code implements the discretized difference equation of a PR controller. This ensures that the output current tracks the sinusoidal reference precisely, rejecting harmonics and disturbances at the fundamental frequency, forcing the tracking error to approach zero (Teodorescu et al., 2011).

4. Modulation & Feed-Forward (PWM Generation)

The final control effort is converted into a Duty Cycle for the H-Bridge using **Unipolar Modulation**.

Code Logic:

```
<> C
// Feed-Forward Control
float Demanded_Voltage = I_OUT_PID.output + Ui_50;
float duty = 0.5f + (Demanded_Voltage / Bus_Voltage) * 0.5f;

// Unipolar Modulation Output (TIM1)
if (duty >= 0) {
    htim1.Instance->CCR1 = (uint32_t)(duty * TIM1_PERIOD);
    htim1.Instance->CCR2 = 0;
} else {
    htim1.Instance->CCR1 = 0;
    htim1.Instance->CCR2 = (uint32_t)(-duty * TIM1_PERIOD);
}
```

Analysis:

- Feed-Forward: The division by `Bus_Voltage` instantly compensates for DC-link ripples (e.g., from solar panels) before the feedback loop reacts.
- Unipolar PWM: The `if-else` block implements unipolar switching, reducing switching losses and output harmonics compared to bipolar switching.
- Safety: Saturation limits (0.05 - 0.95) are applied to `duty` to ensure bootstrap capacitor charging in the gate drivers.

A.4 Detailed Implementation Analysis of Control Logic

The following section breaks down the specific C-code implementation of the control algorithms, highlighting the transition from theoretical control theory to discrete embedded software.

1. Control Algorithm: Proportional Resonant (PR) Controller

This is the core regulation mechanism for the AC current.

Code Logic:

```
<> C
// 50 Hz Resonant term parameters
float const kr_50 = 400.0;          // Resonant Gain
float const Wres_50 = 2.0 * 3.14159 * 50.0; // Angular Frequency (50 Hz)
...
// Discrete implementation of PR equations
float Ua_50 = a1_50 * E_Prev1 - a1_50 * E_Prev2;
float Ub_50 = b1_50 * U_Prev1_50 - b2_50 * U_Prev2_50;
float Ui_50 = (Ua_50 + Ub_50) / b0_50; // Final Resonant Output
```

Analysis:

Unlike DC systems that rely on standard PI controllers, AC current control requires a **Resonant** controller. A standard PI controller cannot track a sinusoidal reference with zero steady-state error. The PR controller provides **infinite gain** specifically at the fundamental frequency (50 Hz), forcing the tracking error to approach zero. The code above represents the discretized difference equation of the PR transfer function.

2. Efficient Synchronization (Lookup Table & Interpolation)

To optimize CPU cycles within the interrupt service routine, the system avoids computing the computationally expensive `sin()` function in real-time.

```
<> C
// Linear Interpolation for high precision
float diff = Sin_LookupF[Lookup_Index + 1] - Sin_LookupF[Lookup_Index];
float LO_Sample_256 = Sin_LookupF[Lookup_Index] + (diff * Timer4_CNT_Ratio);
```

Analysis:

The system uses a pre-calculated sine lookup table (`Sin_LookupF`). To achieve high-resolution angle generation without a massive table, it performs **Linear Interpolation** using the counter value of a high-speed timer (`Timer4`). This allows for a precise reconstruction of the reference sine wave (`LO_Sample_256`) required for the control loop.

3. Duty Cycle Calculation & Feed-Forward

```
<> C
// Summing PI output with Resonant output
float Demanded_Output_Voltage = I_OUT_PID.output + Ui_50;
// Calculating Duty Cycle with Feed-Forward
Duty_Cycle = (int16_t)(Demanded_Output_Voltage * DUTY_MAX / V_bus);
```

Analysis:

The requested output voltage is converted into a PWM duty cycle. Crucially, the calculation divides by the measured DC-Link voltage (**V_bus**). This technique is known as **Voltage Feed-Forward**. It ensures that sudden fluctuations in the DC input (e.g., from solar panels) are immediately compensated for by adjusting the duty cycle, maintaining a stable AC output without waiting for the feedback loop to react.

4. Modulation Strategy (Unipolar PWM)

```
<> C
if(Duty_Cycle >= 0) {
    htim1.Instance->CCR1 = Duty_Cycle; // Active High-Side
    htim1.Instance->CCR2 = 0;         // Inactive Low-Side
} else {
    htim1.Instance->CCR1 = 0;
    htim1.Instance->CCR2 = -Duty_Cycle; // Active Complementary
}
```

Analysis:

This snippet handles the physical actuation of the H-Bridge via Timer 1 (**htim1**). It implements **Unipolar Modulation**, where the bridge legs are switched based on the polarity of the reference wave (Positive vs. Negative half-cycle). This reduces switching losses and output harmonic distortion compared to Bipolar modulation.

5. Integration Note: AMC1306 Adaptation

Critical Adjustment for this Project:

The reference code typically assumes a standard ADC input for `I_grid`.

```
<> C
// Standard ADC approach:
I_grid = ((float)I_grid_DMA) * I_GRID_SENSOR_K;
```

Since this hardware design utilizes **AMC1306 isolated modulators**, the code must be adapted to read from the **DFSDM** filter output instead of a raw ADC buffer. The variable `I_grid` must be linked to the result of `HAL_DFSDM_FilterGetRegularValue` to ensure the control loop receives the correct, noise-filtered current data.

A.5 Hardware-Software Mapping Summary

The firmware defines the MCU pins to match the hardware schematic:

- Actuation (TIM1): `PA8/PA7` (Leg A) and `PA9/PB0` (Leg B) drive the UCC21520 inputs.
- Sensing (DFSDM): `PB12` & `PB14` receive the bitstreams from AMC1306.
- Clocking: `PC2` outputs the synchronized clock for the isolated modulators.
- Safety: `PA11` controls the Grid Relay, and `PA2` handles the hardware Driver Disable.

A.6 Firmware Flashing and Verification

Once the control logic is compiled and the project is built successfully without errors, the resulting hexadecimal (.hex) binary file must be uploaded to the target microcontroller. Figure A.2 shows the STM32CubeProgrammer interface, which is used to connect to the MCU via the ST-LINK debugger, erase the flash memory, and verify the integrity of the uploaded code.

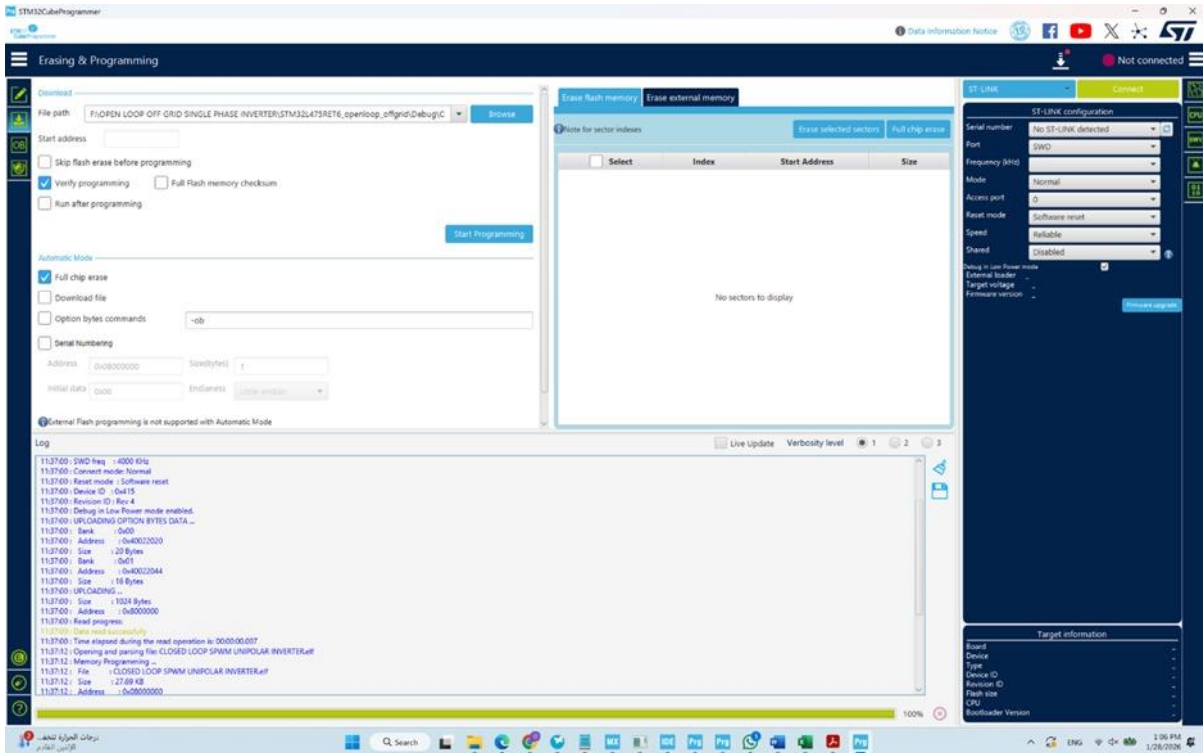


Figure A.2: Uploading the compiled .hex file to the STM32 microcontroller using STM32CubeProgrammer.

Conclusion

The code in the link relies entirely on:

1. DFSDM: For precise sensing.
2. SOGI-PLL: For synchronization with the grid.
3. PR Controller (Proportional Resonant): For -zero-error AC current tracking- AC current control (because a standard PID does not work efficiently with sinusoidal signals, whereas PR provides infinite gain at the 50Hz grid frequency).

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