



VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF ELECTRONICS
DEPARTMENT OF COMPUTER SCIENCE AND COMMUNICATIONS
TECHNOLOGIES

Yassir, Abbassi

**Research of Three-Phase Photovoltaic Inverter Voltage Formation
Algorithms for Inverter Embedded System**

Master's degree final work

Computer Engineering study programme, state code 6211EX051

Electronics Engineering study field

Vilnius, 2024

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Supervisor prof. Dr. Algirdas Baškys _____
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OBJECTIVES FOR MASTER'S DEGREE FINAL WORK

2024-05-27 No KTfmu-22-1684
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For student

Yassir Abbassi

Final work title: Research of Three-Phase Photovoltaic Inverter Voltage Formation Algorithms for Inverter Embedded System

The Final work must be completed by May 30, 2024
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THE OBJECTIVES:

Investigate three-phase photovoltaic inverter voltage generation algorithms for inverter embedded system using simulation, adhering the following tasks:

1. Analyze voltage generation and formation algorithms.
2. Perform the investigation of selected algorithms using simulation.
3. Based on the obtained investigation results, develop, and assess modifications to the voltage generation algorithm.

Consultants of the final degree work:

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Annotation

This master's thesis comprehensively investigates various photovoltaic inverter three-phase output voltage forming methods and voltage control algorithms, focusing on their performance in terms of transient response, voltage and current THD, adaptability, and phase correction. The investigation was performed using MATLAB/Simulink software, when photovoltaic inverter operates in off grid and on grid modes for the cases when inverter load is linear and non-linear. The majority of thesis is devoted to investigation of the inverter voltage forming method based on the Sinusoidal Pulse Width Modulation (SPWM) without output voltage feedback control and using output voltage control algorithms as closed Loop Feedback, PID PLL, and two suggested PLL simplification, Acos PLL and Atan2 PLL. Additionally, the photovoltaic inverter voltage forming method based on the Hysteresis Current Control (HCC) was investigated. Finally, the Hysteresis Voltage Control (mHVC) method, which is a suggested modification of HCC, was proposed and investigated and its advantages and drawbacks have been demonstrated.

Structure: Introduction; Photovoltaic Inverter Plant Structure; Investigation of Various Voltage Formation Algorithms; Conclusions and Suggestions; References.

Thesis consist of 80 p. text without appendixes, 63 pictures, 3 tables, 16 bibliographical entries.
Appendixes are not included.

Keywords: Photovoltaic inverter; Three-phase voltage; SPWM; Closed loop feedback; PLL; PI controller; Hysteresis control; Off grid; On grid; Linear load; Non-Linear load; MATLAB/Simulink.

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Antros pakopos studijų kompiuterių inžinerija programos magistro baigiamasis darbas

Pavadinimas Trifazių fotovoltinių keitiklių įtampos formavimo algoritmų inverterio įterptajai sistemai tyrimas

Autorius **Yassir Abbassi**

Vadovas **prof. Dr. Algirdas Baškys**

Kalba: anglų

Anotacija

Šiame magistro darbe išsamiai nagrinėjami įvairūs fotovoltinių keitiklių trifazių išėjimo įtampos formavimo būdai ir įtampos valdymo algoritmai, daugiausia dėmesio skiriant jų veikimui pereinamojo atsako, įtampos ir srovės THD, pritaikomumo ir fazių korekcijos požiūriu. Tyrimas atliktas naudojant MATLAB/Simulink programinę įrangą, kai fotovoltinis keitiklis veikia ne tinkle ir tinkle režimais, kai keitiklio apkrova yra tiesinė ir netiesinė. Didžioji dalis baigiamojo darbo skirta keitiklio įtampos formavimo metodo, pagrįsto sinusoidine impulso pločio moduliacija (SPWM) be išėjimo įtampos grįžtamojo valdymo ir naudojant išėjimo įtampos valdymo algoritmus kaip uždarojo ciklo grįžtamąjį ryšį, PID PLL ir du siūlomus PLL supaprastinimus, Acos, tyrimui. PLL ir Atan2 PLL. Be to, buvo ištirtas fotovoltinio keitiklio įtampos formavimo metodas, pagrįstas histerezės srovės valdymu (HCC). Galiausiai buvo pasiūlytas ir ištirtas histerezės įtampos valdymo (mHVC) metodas, kuris yra siūloma HCC modifikacija, ir buvo parodyti jo pranašumai ir trūkumai.

Struktūra: Įvadas; Fotovoltinės inverterio gamyklos struktūra; Įvairių įtampos formavimo algoritmų tyrimas; Išvados ir pasiūlymai; Nuorodos.

Darbo apimtis – 80 p. teksto be priedų, 63 iliustr., 3 lent., 16 bibliografinių šaltinių.

Priedai neįtraukti.

Prasminiai žodžiai: Fotovoltinis keitiklis; Trifazė įtampa; SPWM; Uždarojo ciklo grįžtamasis ryšys; PLL; PI valdiklis; histerezės valdymas; Išjungtas tinkelis; Ant tinkelio; Linijinė apkrova; Netiesinė apkrova; MATLAB/Simulink.

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IN THE FINAL DEGREE PROJECT**

2024-05-27

I declare that my Final Degree Project entitled “Research of Three-Phase Photovoltaic Inverter Voltage Formation Algorithms for Inverter Embedded System” is entirely my own work. I have clearly signaled the presence of quoted or paraphrased material and referenced all sources.

I have acknowledged appropriately any assistance I have received by the following professionals/advisers: Prof Doctor Algirdas Baškys

The academic supervisor of my Final Degree Project is prof. Dr. Algirdas Baškys.

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INTRODUCTION

With the global spotlight increasingly directed towards sustainable energy solutions, PV arrays have emerged as pivotal players in the renewable energy landscape. As the demand for clean energy intensifies, the prominence of PV arrays continues to ascend, propelled by advancements in technology and a growing environmental consciousness. The inexorable rise of renewable energies underscores the necessity for continuous research and innovation in the field—a mandate that drives the investigation and exploration of three-phase PV connected inverters.

This report delves into the intricate realm of PV arrays and the diverse designs of inverters that harness their potential. Within the first chapter, a comprehensive examination unfolds, elucidating the multifaceted nature of PV arrays and delving into the intricacies of inverter designs. Central to this exploration is an in-depth analysis of various 3-phase inverter output voltage forming methods, ranging from Pulse Width Modulation PWM to Programmed Harmonic Elimination Switching and SRF Control, drawing upon a rich tapestry of literature to illuminate their functionalities and applications.

Transitioning seamlessly into the second chapter, the focus shifts towards the simulation of different 3-phase voltage forming methodologies for PV inverters, utilizing Simulink as the primary tool for investigation. Each simulated control system undergoes meticulous scrutiny, with an array of parameters including AC output waveform, Total Harmonic Distortion levels, and technical complexity subjected to rigorous evaluation. Within this crucible of simulation, advantages and limitations of each control system are brought to light, offering invaluable insights into their efficacy and feasibility.

The investigation results presented in this report represent the culmination of exhaustive testing and refinement. When confronted with unexpected behavior, a systematic approach is adopted, wherein key parameters and component layouts are methodically adjusted to isolate and troubleshoot the underlying issues. Countless iterations have been undertaken, with only a select few voltage formation algorithms—such as but not limited to Sinusoidal PWM, Closed Feedback Loop PWM, and Simplified Phase Locked Loop—emerging triumphant from the crucible of simulation. Each iteration, whether propelled by theoretical analysis or borne out of empirical experimentation, stands as a testament to the symbiotic relationship between scholarly knowledge and personal endeavor.

Concluding with the third chapter, the report navigates through a synthesis of findings and offers insightful recommendations for future endeavors. Here, the culmination of Chapter 2's exploration is distilled into succinct reflections, providing a roadmap for further research and development in the realm of three-phase PV connected inverters. In essence, this report serves not only as a testament to the current state of the art but also as a catalyst for future innovation, driving the perpetual evolution of renewable energy technologies.

Research objectives:

Aim – The aim of the master’s thesis is to investigate three-phase photovoltaic inverter voltage generation algorithms for inverter embedded systems using simulation.

Tasks:

1. Analyze the voltage generation problem of the three-phase photovoltaic inverter and the algorithms used for three-phase voltage formation.
2. Perform the investigation of selected algorithms using simulation.
3. Based on the obtained investigation results, develop your own modification of the three-phase voltage generation algorithm for the photovoltaic inverter and investigate it using simulation.

1. Photovoltaic Inverter Plant Structure

1.1. Photovoltaic Panels

The electrical power in photovoltaic power plant is produced by the photovoltaic (PV) array, which is constructed by many PV panels in series and parallel. PV array V-I characteristics do not depend only on the hardware used, but also on environmental variables such as solar irradiance and temperature. Solar irradiance serves as the primary source of energy for photovoltaic cells. However, factors such as cloud cover, time of the year, and time of day can influence its availability. Subsequently, the generated power from PV panels is influenced by both the availability of solar irradiance and the voltage applied to the panel's terminals, considering the impact of the panel's construction on its current output.

Temperature: PV panels are sensitive to changes in temperature, and their current and power output is inversely related to temperature. As the temperature of the panel increases, its current and power output tends to decrease (Figure 1). This effect is primarily due to the temperature dependence of the panel's semiconductor materials. Higher temperatures can lead to increased electron-hole recombination and higher internal resistance, resulting in reduced current flow and lower power output.

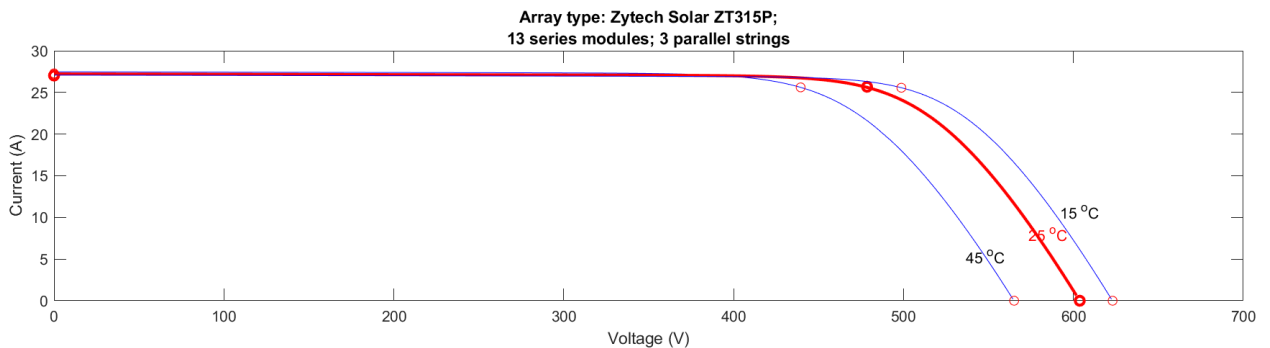


Figure 1: Simulink Generated Plot of Example PV Array I-V Characteristics at Different Operating Temperatures

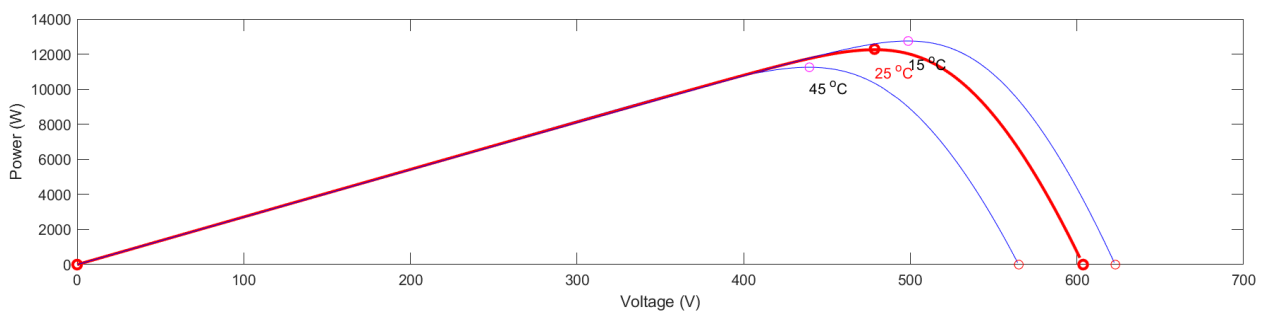


Figure 2: Simulink Generated Plot of Example PV Array P-V Characteristics at Different Operating Temperatures

Solar Irradiance: Solar irradiance, which represents the intensity of sunlight, has a direct impact on the power output of PV panels. Higher levels of solar irradiance result in increased current (Figure 3), and consequently, increased power output (Figure 4). When the irradiance levels are high, more photons strike the panel's surface, creating a larger number of electron-hole pairs and generating a higher current. The relationship between solar irradiance and current is typically linear within a certain range. As the irradiance decreases, the current generated by the PV panel also decreases proportionally, leading to lower power output.

The primary focus is on extracting the maximum available power (Figure 4). Consequently, the dominant control strategies for PV farms are derived from Maximum Power Point Tracking (MPPT) techniques. The objective of MPPT in PV farms is to generate a DC voltage reference that, when applied to the PV module, enables the extraction of maximum power corresponding to the prevailing solar irradiance conditions [1].

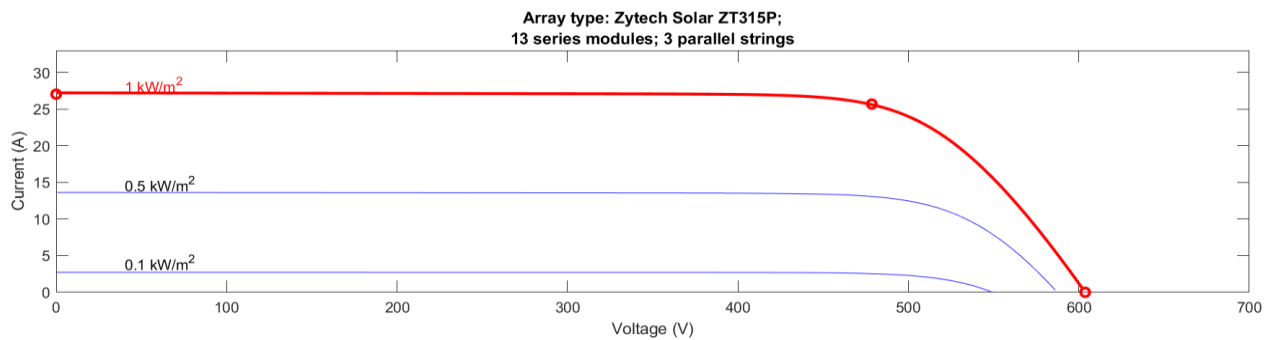


Figure 3: Simulink Generated Plot of Example PV Array I-V Characteristics at Different Irradiance Levels

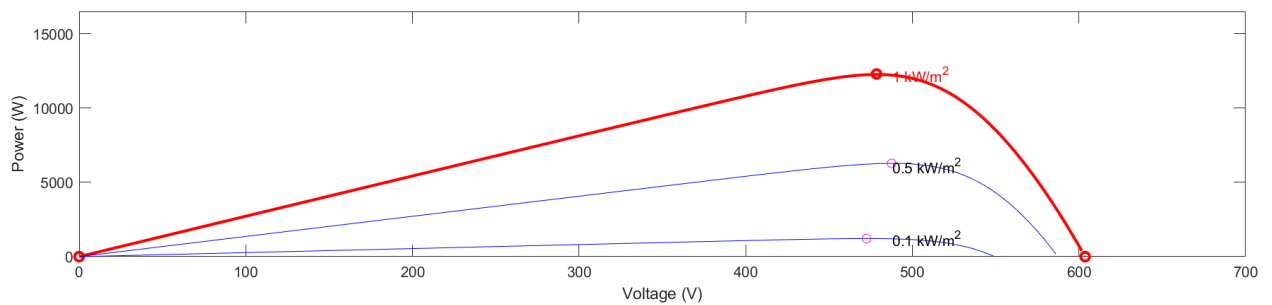


Figure 4: Simulink Generated Plot of Example PV Array P-V Characteristics at Different Irradiance Levels

The ideal operation (Max Power) of PV arrays is shown in Figure 4 as circular points on the I-V or P-V (Power Voltage) curves, where irradiance is at 1000W/m² and temperature at 25 °C.

1.2. Components of a PV Plant

The most popular components of photovoltaic inverter circuits are shown in Figure 5, which includes solar array, DC-DC converter with MPPT controller, DC-Link, Three-phase inverter, RLs filter and a grid or load [2]. The 3-phase inverter converts the DC generated by the PV array into AC that can be fed into the electrical grid or used for local consumption.

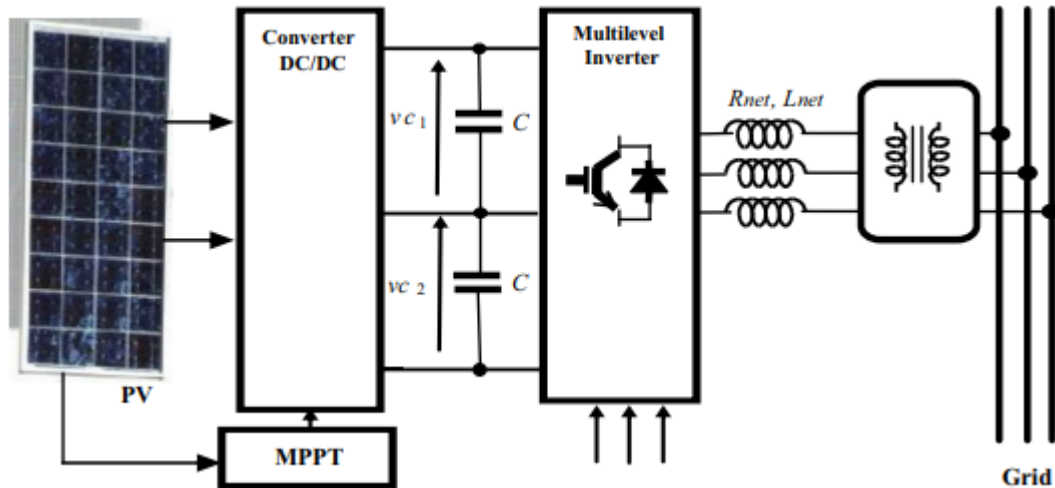


Figure 5: Block Diagram of PV Power Plant [2]

DC-DC Conversion

In PV systems, a DC-DC converter is employed between the input stage and the inverter stage. This converter helps regulate and optimize the DC voltage and current levels for efficient power conversion. The DC-DC converter may use various topologies, such as buck, boost, or buck-boost, to step up or step down the DC voltage as needed.

Output Filtering

The inverter produces pulsed AC voltage where pulse duration is modulated by the sinus law with grid frequency (such as 50 Hz). The frequency of pulsed AC voltage (carrier frequency) must be much higher than the grid frequency to guarantee low distortions of sinus voltage that is obtained after filtering using low-pass filter. Low-pass filter is implemented using components such as inductors, and capacitors. These components help suppress high frequency switching noise and ensure compliance with grid connection standards and regulations.

MPPT Controller

The output of the PV array is not stable, because of variations of irradiance, temperatures, shadows, weather conditions, and even degradation of panels. Many electronic components are included in the PV circuits to control and maintain a stable DC output of the PV array such as charge controllers, MPPTs, linear current boosters [3]. But regarding the inverter applications, only MPPTs are of interest here.

Achieving maximum power operation poses a challenge because it necessitates that the system load can utilize all available power from the PV system consistently. This implies that the system load should be at its maximum capacity when the PV system output is at its peak. Furthermore, the system load must be able to rapidly adjust itself when cloud cover appears or dissipates. The I-V characteristic of the ideal load will intersect the collection of maximum power points on the I-V characteristics of the PV array under different levels of illumination [3].

Inverter Topologies

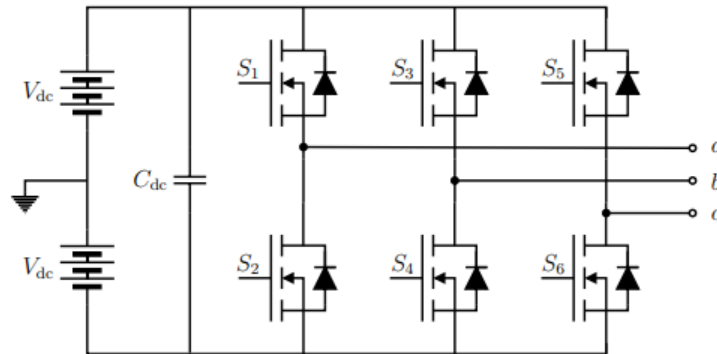


Figure 6: Circuit Diagram of 2-Level Inverter [4]

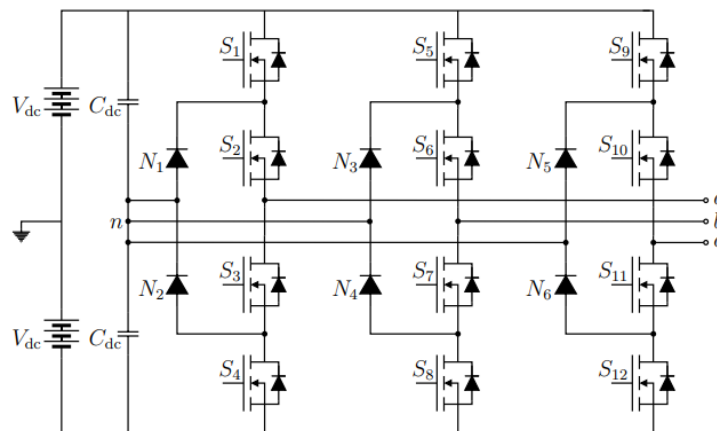


Figure 7: Circuit Diagram of 3-Level Inverter (NPC Inverter) [4]

Two-Level Inverter

The circuit diagram of two-level inverter is presented in Figure 6. It is called a "two-level" inverter because it has two voltage levels in its output waveform. In a two-level inverter, the output waveform switches between two voltage levels: the positive DC voltage and the negative DC voltage [2]. This results in a stepped approximation of a sinusoidal waveform. Two-level inverters are simple in design and widely used in various applications.

Neutral-Point Clamped Inverter

On the other hand, an NPC inverter, also known as a three-level inverter (Figure 7), is a more advanced type of inverter that provides a higher-quality output waveform compared to a two-level inverter. It achieves this by using additional switching states and voltage levels. An NPC inverter divides the DC voltage source into three levels: positive, negative, and a neutral point or midpoint voltage level. By using additional switches and capacitors, the NPC inverter can create a staircase waveform with a closer approximation to a sinusoidal waveform. This results in reduced harmonic distortion and improved output quality.

However, three-level inverter includes twice more switches (12 switches) as compared to two-level inverter (6 switches, Figure 6), therefore its self-cost is much higher. Consequently, the domestic photovoltaic power plants usually are based on two-level inverters. For this reason, this master thesis voltage formation algorithm investigation is based on the two-level inverter.

1.3. Literature Review of PV Inverter Voltage Formation Algorithms

1.3.1. PWM Technique for AC Voltage Formation

Pulse Width Modulation (PWM) is a commonly used technique in inverters to generate an AC output voltage with desired characteristics. PWM is used to convert a DC voltage produced by the PV system into an AC output voltage. The process involves switching the DC input voltage on and off at a high frequency (carrier frequency), typically in the range of several kilohertz to several tens of kilohertz.

In PWM, the width or duration of the pulses in a fixed period is modulated by the sinus law to obtain the sinus shape AC voltage in the output of the inverter. There are various methods developed for the forming of PWM control signals for the transistors of inverter switches. One of popular principles for the generation of PWM signals for the control of switches is so called sinus PWM (SPWM). It involves comparing a reference signal (sinusoidal waveform representing the desired AC voltage) with a triangular waveform (carrier signal) of a higher frequency. The resulting comparison generates a PWM pulse train with varying widths, which acts as the control signals for the switch transistors of the inverter. The width of each pulse is determined based on the instantaneous values of the reference and carrier signals.

Figure 8 presents the MATLAB/Simulink model diagram, which implements the SPWM control signal logic.

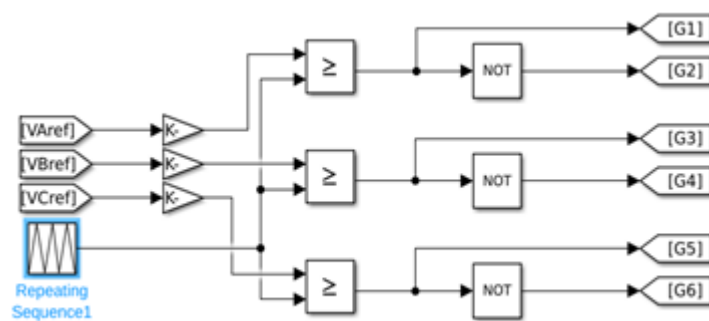


Figure 8: Simulink Implementation of a SPWM Control Signal Logic.

The switching devices (such as IGBTs) in the inverter are controlled by these pulse signals in figure 8 (G1, G2...). Every pulse provided to the gate turns the transistor switch on, allowing the flow of current from the DC input to the output. When the pulse is inactive, the switch is turned off, cutting off the current flow. The amplitude of the inverter AC output

voltage is controlled by adjusting the duty cycle of the pulses. A wider pulse results in a higher amplitude, while a narrower pulse corresponds to a lower amplitude. This process allows precise control of the output voltage amplitude.

1.3.2. Square-Wave method in Three-Phase Inverter

The square-wave method for three-phase inverters involves generating an output voltage with a square wave shape. This method eliminates the need for continuous switching of the inverter's switches, as they only switch at the phase frequency. This significantly reduces power losses in the switches. However, the trade-off is a high total harmonic distortion (THD) in the output.

In square-wave mode, the inverter cannot directly control the magnitude of the output AC voltage. To regulate the output voltage, the input DC voltage must be adjusted. By varying the input voltage, the magnitude of the output voltage can be controlled.

It is worth noting that the square-wave pulse switching scheme is largely obsolete and is primarily found in older thyristor-based inverters [4]. Modern inverters typically use more advanced methods to achieve better performance and lower harmonic distortion.

1.3.3. Programmed Harmonic Elimination Switching

Programmed Harmonic Elimination Switching is a technique that combines the principles of square wave switching and Pulse Width Modulation (PWM) to simultaneously control the fundamental output voltage and eliminate specific harmonics from the output waveform [5].

By integrating square-wave switching and PWM, this technique allows for precise control over the magnitude and shape of the fundamental output voltage. In real-time operation, Programmed Harmonic Elimination Switching (PHES) works by utilizing pre-computed and pre-optimized switching patterns to control the inverter's output waveform. Here's a general overview of how the technique works in real-time:

- **Pre-computation and optimization:** The switching angles or patterns required for harmonic elimination are determined through an offline optimization process. These optimized patterns are calculated based on the desired harmonic elimination and voltage control objectives.
- **Look-up table (LUT) generation:** The optimized switching patterns are stored in a look-up table, which maps the modulation depth (usually determined by the control algorithm) to the corresponding set of switching angles. The LUT contains pre-determined switching angles for different modulation depths.
- **Real-time operation:** During real-time operation, the control algorithm calculates the modulation index based on the desired output voltage and other control parameters. The modulation index determines the appropriate modulation depth for the inverter.

Switching angle selection: Using the modulation index as an input, the control algorithm retrieves the corresponding set of switching angles from the LUT. These switching angles are then used to generate the switching signals for the inverter.

1.3.4. Synchronous Reference Frame (SRF Technique)

Synchronous Reference Frame method enables precise forming of current or voltage in synchronization with a reference frame, typically the fundamental frequency of the AC system.

In SRF Control, the AC system is typically transformed into a rotating reference frame, known as the synchronous reference frame or dq-frame. This reference frame rotates at the same frequency as the AC system's fundamental frequency. The dq-frame consists of two orthogonal axes: the d-axis and the q-axis. The d-axis is aligned with the instantaneous value of the AC system's voltage or current waveform, while the q-axis is perpendicular to the d-axis. The goal of SRF Control is to control the current or voltage in this rotating reference frame.

SRF technique relies on mathematical transformations, such as Clarke-Park transformation, to convert the AC system's three-phase quantities into their respective dq-frame components. First, the current or voltage of each line (A, B, and C) are transformed into an Alpha-Beta-Zero components by Clarke Transformation, which is a conversion of three-phase quantities into a two-coordinate reference frame. It is important to know that the component Zero is not used in the park transformation.

$$\alpha = \frac{1}{3} (2A - B - C) \quad 1.1 [6]$$

$$\beta = \frac{1}{\sqrt{3}} * (B - C) \quad 1.2 [6]$$

$$component_{zero} = A + B + C \quad 1.3$$

Park Transformation takes as inputs, the components α and β , and the phase angle θ between the three-phase quantity (current or voltage) and a reference value from the grid or power source. The output values of this transformation are:

$$d = \alpha * \cos \theta + \beta * \sin \theta \quad 1.4 [6]$$

$$q = \alpha * -\sin \theta + \beta * \cos \theta \quad 1.5 [6]$$

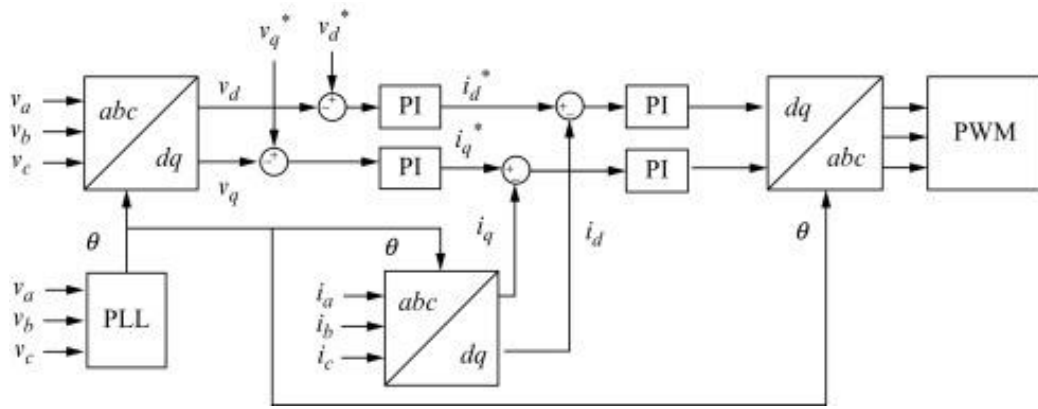


Figure 9: Dual-loop control in SRF Technique [6]

By controlling the current or voltage in the dq-frame, it becomes easier to implement various control strategies, such as PI (Proportional-Integral) controllers or model-based control algorithms (Figure 9). These control strategies can be utilized for tasks like regulating the current or voltage, compensating for reactive power, or implementing advanced control techniques such as grid synchronization or power factor correction [7].

2. Investigation of Various PV Inverter Voltage Formation Algorithms

The investigation of photovoltaic inverters was conducted using MATLAB/Simulink software. The study focused on inverters utilizing the sinusoidal PWM (SPWM) voltage forming method, employing the following three-phase voltage control algorithms: No loop SPWM, Closed Feedback Loop control and Phase Locked Loop (PLL) control. Additionally, Hysteresis control techniques were examined as a voltage forming method.

Waveforms of the output voltages were obtained, and the total harmonic distortion (THD) for each method was evaluated. The investigation covered scenarios where the photovoltaic inverter operates in isolated (island) mode and grid-connected mode, under both linear and non-linear loads.

A modification of the hysteresis control method, aimed at simplifying the structure of the low-pass filter, was proposed, and analyzed. As well as simplified PLL methods which are not mainstream but were suggested and tweaked as potential alternatives for PLL.

2.1. Simulink Models of PV Array and Load

2.1.1. PV Array Model

Simulink offers a diverse range of PV array models sourced from the National Renewable Energy Laboratory (NREL) System Advisor Model (2018), providing users with reliable and validated simulations. For consistency across all subsequent simulations, this thesis utilizes the Zytech Solar ZT315P PV array module preset (Figure 10). Each module can generate a maximum power of 315.1 *W*, with corresponding current and voltage values at maximum power of 8.56 *A* and 36.81 *V*, respectively.

To meet the requirements of high voltage and sufficient current for the load, the PV system needs to output approximately 478.53 *V* and 25.68 *A*. Achieving this necessitates configuring the system with 3 parallel strings and 13 series-connected modules for each Zytech Solar ZT315P module. The Simulink model of investigated photovoltaic system is presented in Figure 10.

The environmental conditions are standardized at 1000 irradiance and 25 °C temperature, ensuring optimal operation of the PV array without the need for MPPT.

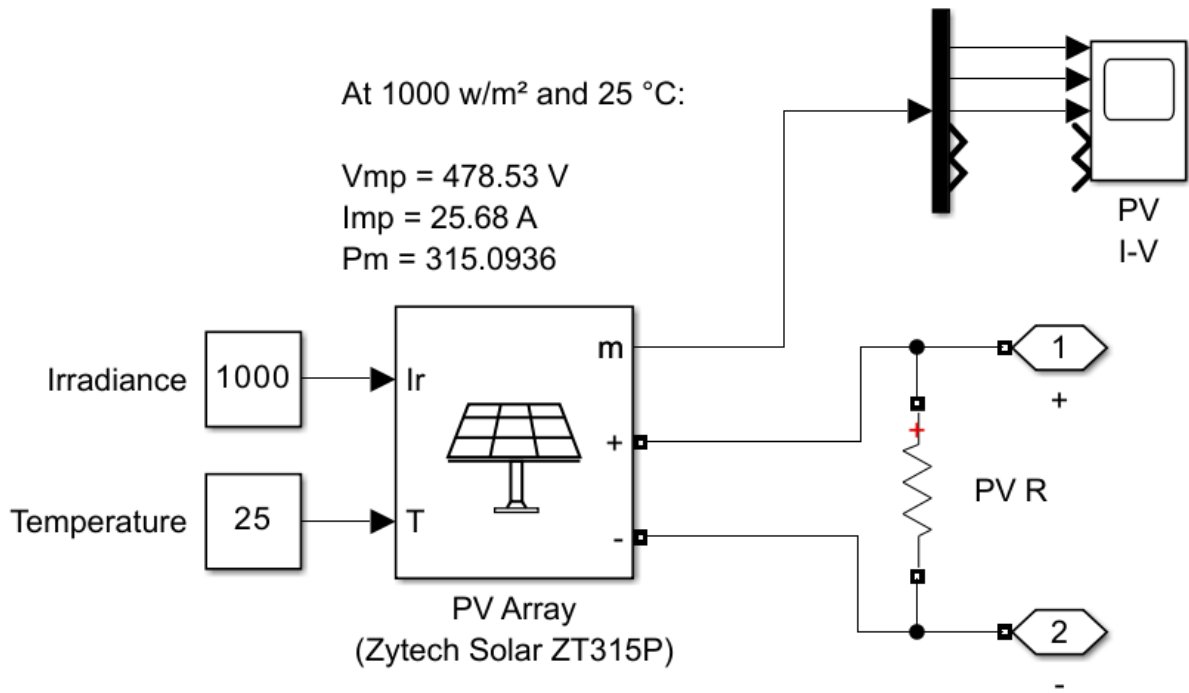


Figure 10: Circuit Diagram of PV Array in Simulink Model

While certain components such as inverters, low pass filters, and converters may reduce the power rating of the system, the extent of this reduction depends on the specific design choices made. However, the simulation allows for flexibility in adjusting the PV system to lower current and voltage values based on the voltage formation algorithm employed.

To maintain maximum power voltage and current input for the subsequent circuitry, a resistor with a value of 18.6 Ω is connected in parallel with the PV array. Additionally, a capacitance serves as a DC-Link, ensuring uninterrupted power supply within the system. This configuration helps optimize the performance and reliability of the PV system during simulation studies.

2.1.2. Types of Loads Investigated

The simulations are conducted in island mode, where each algorithm undergoes testing in both grid-connected and isolated conditions. Figure 11 shows the Simulink circuit diagram model composed of all the different types of loads.

During isolation, the inverter output is subjected to two distinct loads. First, the resistive linear load shown in Figure 12, and secondly, a three-phase rectifier bridge loaded by resistive load as a nonlinear load (Figure 13). Subsequently, the performance of the system under each load type is evaluated. The obtained results are then compared, allowing for the identification of any disparities or inefficiencies. Based on these comparisons, enhancements are proposed or implemented to optimize system performance and address any observed

shortcomings. This iterative process ensures that the algorithms are robust and adaptable across various operating conditions, ultimately leading to improved overall system effectiveness.

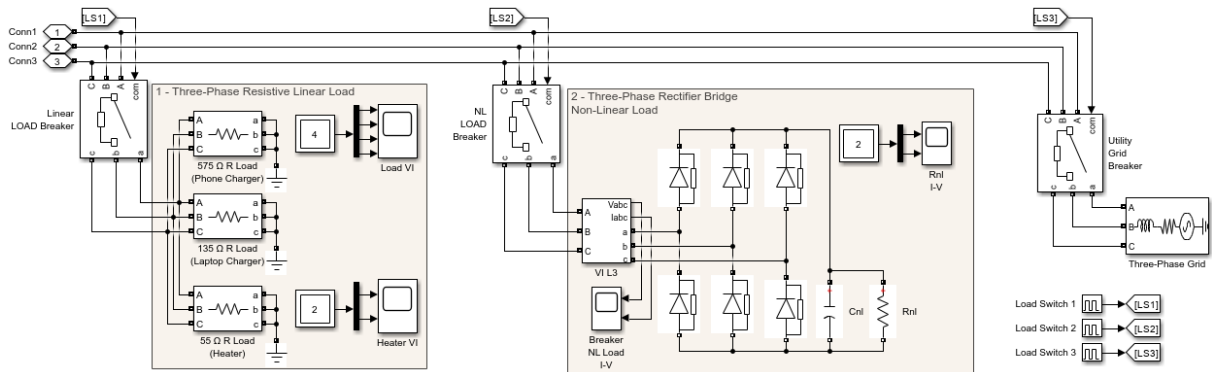


Figure 11: Circuit Diagram of the Load Block used in the Simulink Models

The V-I measurements are taken for the load and before the load as well, to sniff the changes in waveforms all around the load.

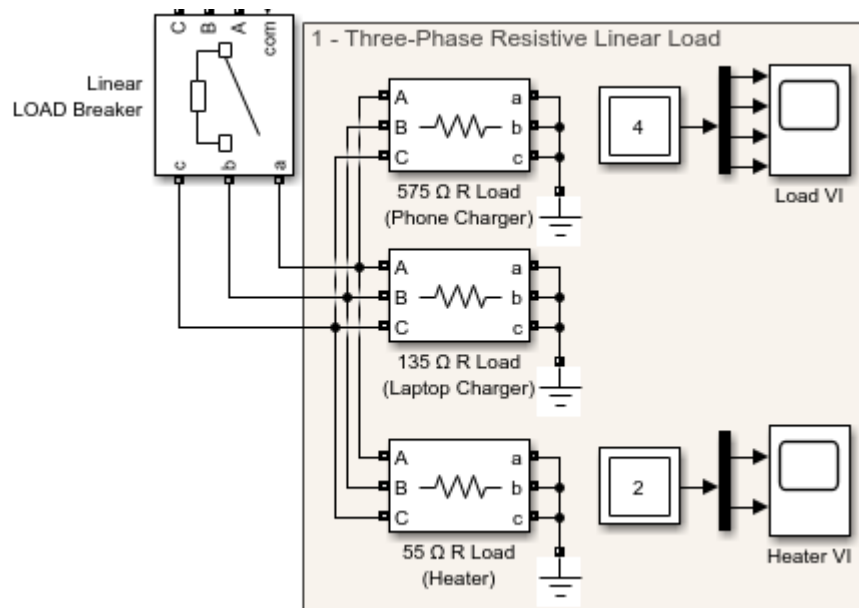


Figure 12: Circuit Diagram of Linear Load Block

The resistive linear load in figure 12, emulating typical home appliances, is simplified to consist solely of resistances, devoid of capacitance or inductance components. The primary focus of the simulations is to assess the ability of voltage forming techniques to produce three-phase AC voltage with low THD and the desired amplitude. Thus, the inclusion of inductance or capacitance warrants specialized consideration.

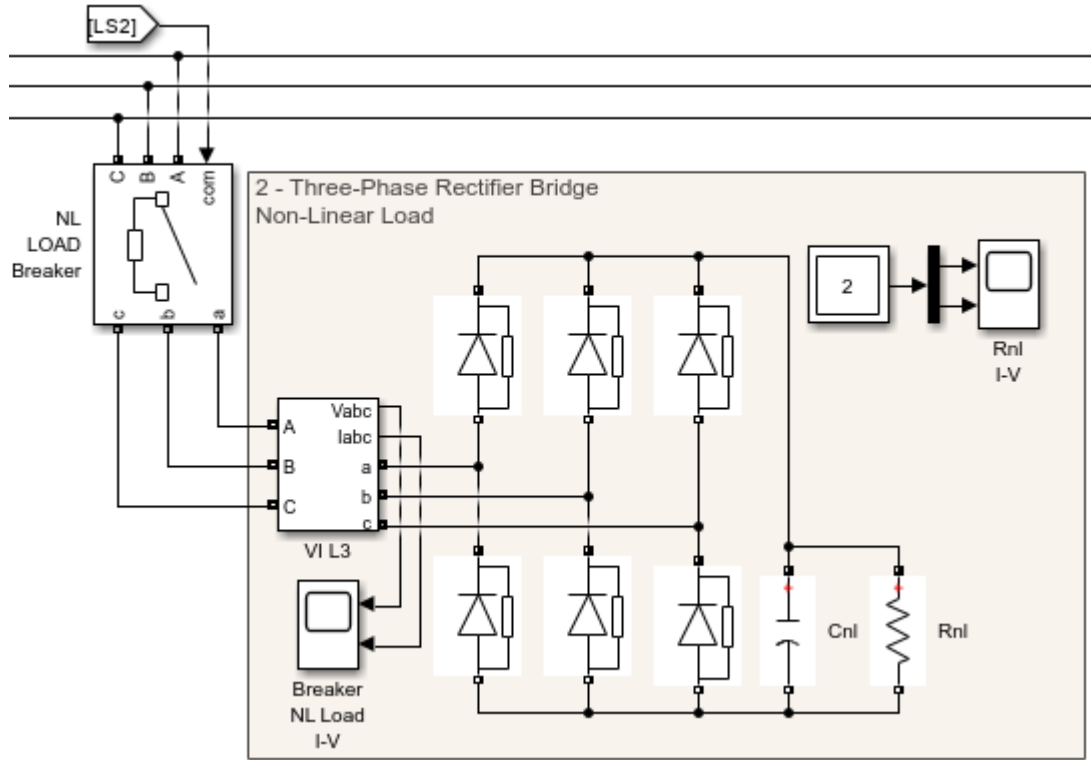


Figure 13: Circuit Diagram of Nonlinear Load Block

Conversely, the nonlinear load represents a three-phase full rectifier bridge, incorporating diodes and a smoothing capacitor, as shown in figure 13.

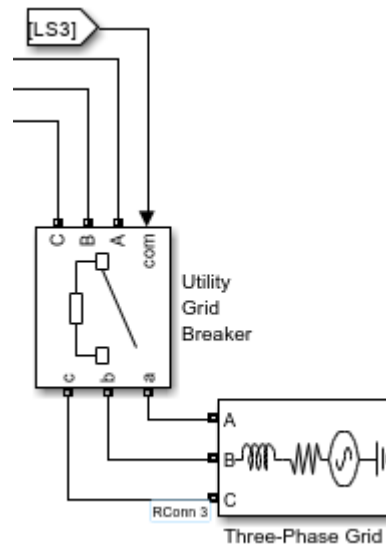


Figure 14: Grid-Connected Load Block

In Simulink, the three-phase grid block in figure 14 serves as a utility grid counterpart. It is configured with a source frequency of 50 Hz and a V_{RMS} of 340 V , with a phase angle of 0° degrees for line A. These settings emulate typical grid conditions, facilitating realistic

simulation scenarios and enabling accurate evaluation of the system's performance under normal operating conditions.

2.1.3. Total Harmonic Distortion Standards

The IEEE standard that governs the maximum THD of voltage and current for PV connected inverters is IEEE Std 519-2014, titled "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems." The IEEE Std 519-2014 defines the Point of Common Coupling (PCC) as a point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be, connected. The PCC is a point located upstream of the considered installation [8].

According to IEEE Std 519-2014:

- **Voltage THD:** The Total Harmonic Distortion of voltage at the PCC should not exceed 5% for general systems. Individual harmonic components should be limited to 3% of the fundamental frequency voltage [8].
- **Current THD:** For current, the TDD, which is the current distortion in relation to the maximum demand load current (15 or 30 minutes demand), should be less than 5% for systems with a ratio of short-circuit current to load current (I_{sc}/I_L) less than 20 [8].

These limits ensure that the harmonic distortion does not adversely affect the performance and reliability of the power system and its components. PV inverters, when connected to the grid, must comply with these harmonic limits to ensure they do not introduce excessive distortion that could impact the stability and efficiency of the power network.

2.2. Voltage Formation Using No Feedback Loop Sinusoidal Pulse Width Modulation (SPWM)

2.2.1. Case 1: Linear Resistive Load

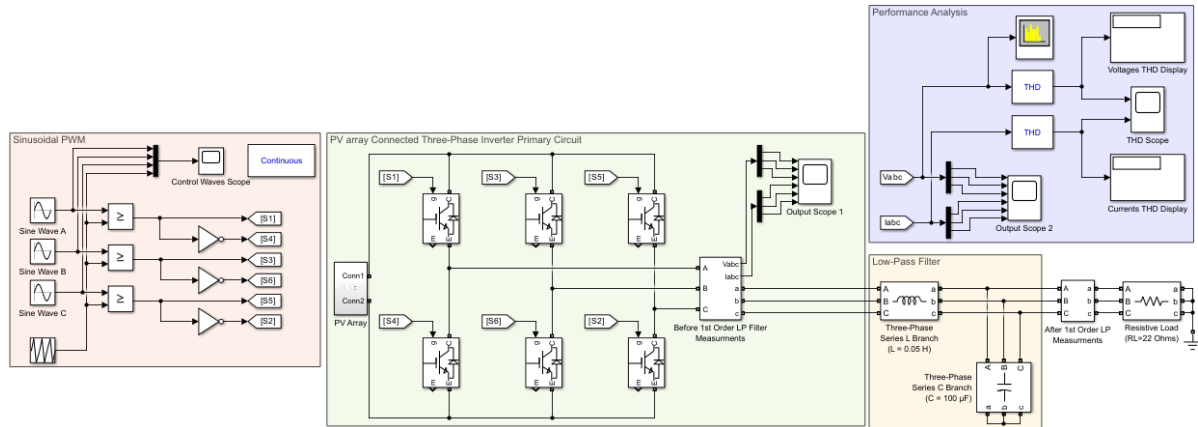


Figure 15: SPWM Controlled Three-Phase Inverter Simulink Model (Resistive Load Case)

Circuit diagram of the Simulink model of photovoltaic inverter implementing SPWM voltage forming method loaded by the linear load is presented in Figure 15. The figure above showcases 4 main blocks:

- **PV array Connected Three-Phase Inverter:** Composed of a PV array, an IGBT bridge and an optional scope for measuring signals before applying a low-pass filter. The PV array is operating at an optimal temperature of $T = 25^{\circ}\text{C}$, and have an irradiance input of $I_r = 10^3 \text{ W/m}^2$, which will be the default parameters for all the simulations implementing a PV array for this investigation. The IGBT bridge has 6 transistors, for a 2-level three-phase inverter.

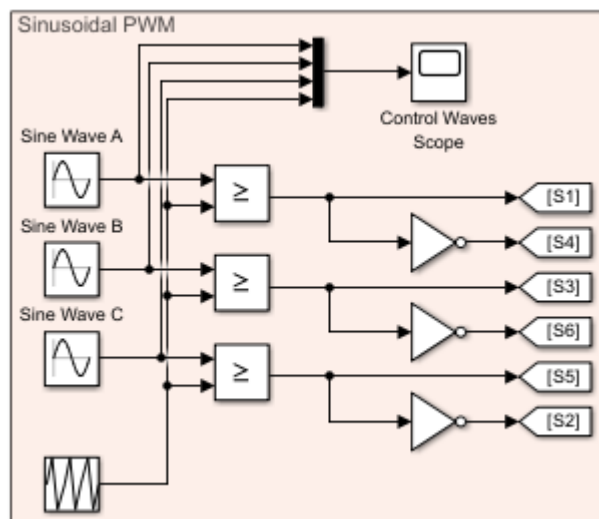


Figure 16: Simulink Diagram of SPWM Control Signal Generation Block

- Sinusoidal PWM circuit (Figure 16): The control circuit of this design utilizes the SPWM technique. The carrier signal is triangular with a frequency of $f_c = \frac{10^4}{1.5} = 6666.67 \text{ Hz}$. The reference signals are sinusoidal signals with a frequency of $f_r = 50 \text{ Hz} = 100\pi/s$.

2.2.2. Simulation Results

Each sinusoidal reference signal controls 2 distinct and unique IGBTs. If one is in operation mode, the opposite is off. The following table displays each reference signal with its corresponding transistors:

Table 1: Reference Signals and their Respective Controlled Transistor Gates

Reference Signal	Controlled IGBTs	Corresponding Output Phase
Signal A	S1 & S4	Phase A
Signal B	S3 & S6	Phase B
Signal C	S2 & S5	Phase C

Switching the states of transistors consists of comparing the sinusoidal signal and the carrier signal, which is an operation carried by relational operators. If the reference signal is greater than the carrier signal, the directly connected transistor is activated. The second transistor's input is driven by the relational operator via an inverter, resulting in an operational mode that is complementary to its counterpart, like the case between S1 and S4.

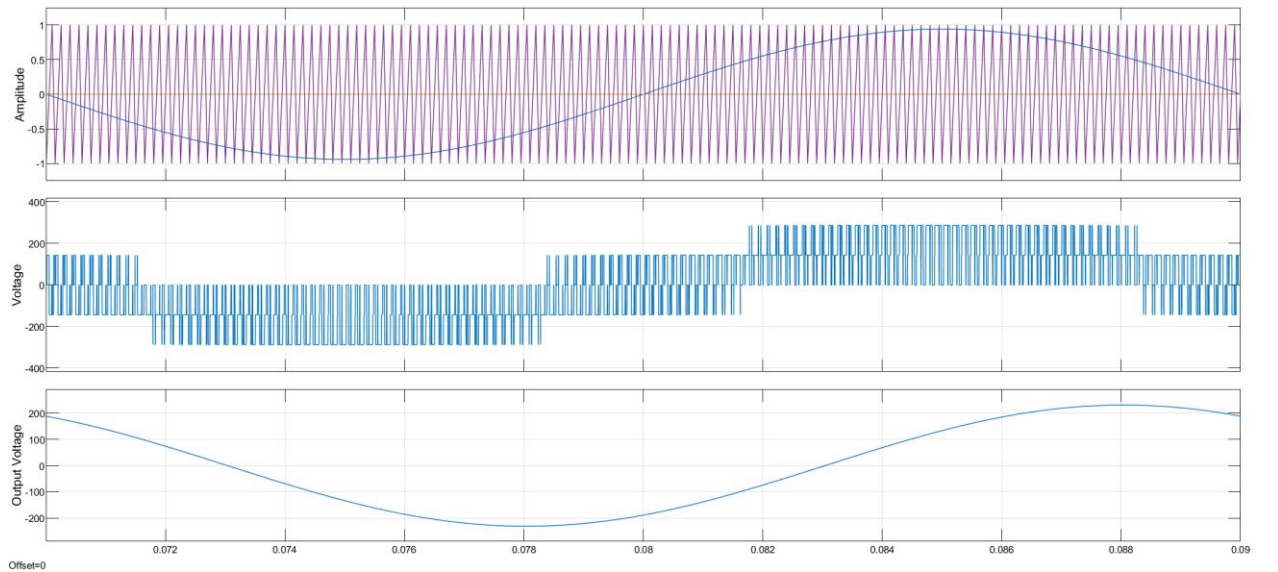


Figure 17: (Upper) Line A Reference and Carrier Signals, (Middle) Line A Output Voltage, (Lower) and the Line A Filtered Output Voltage

The first graph of figure 17 is the cross-over of the carrier and reference signal A. The maximum amplitude of the sinusoidal signal is 0.94. This value guarantees the filtered Line A voltage to oscillate between 230V and -230V.

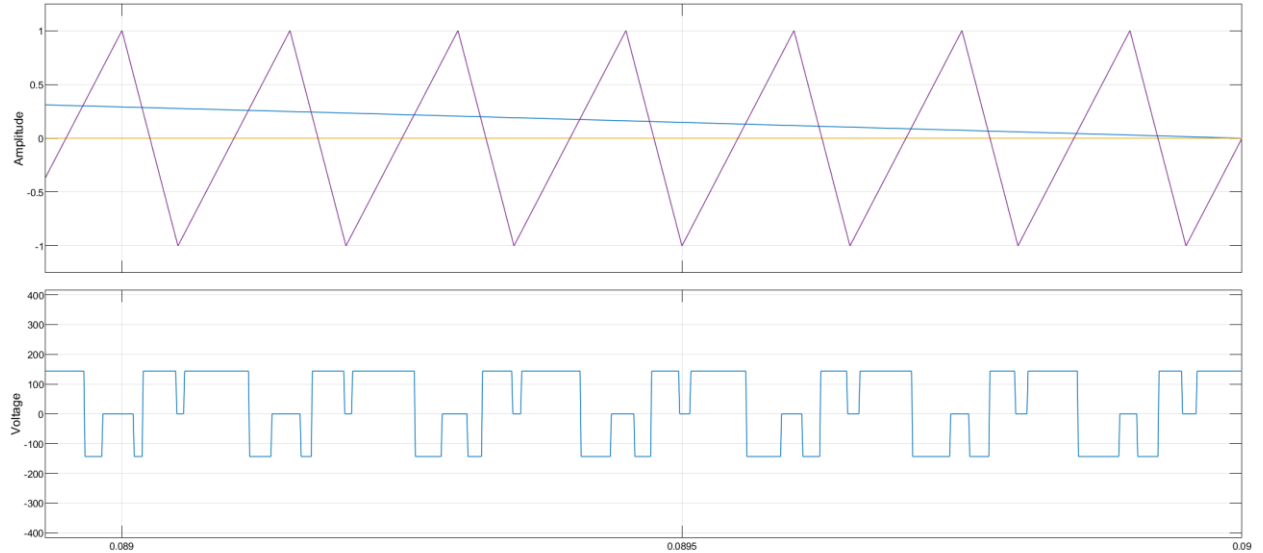


Figure 18: Zoom-In on Figure 17: (Upper) Line A Reference and Carrier Signals, (Bottom) Line A Output Voltage

The objective of the SPWM technique is to generate an inverter voltage output represented as a square wave signal. A square wave alternates between its peak and trough values. Nevertheless, as depicted in figure 18, numerous ripples are evident during the intervals between the peak and trough voltage periods. Consequently, the inverter output voltage manifests as a square wave oscillating between the peak, trough, and zero values. In the real-world application, ripples may occur due to factors such as switching losses in the inverter circuit, non-ideal characteristics of electronic components, and limitations in the resolution of the modulation process. These imperfections result in additional frequencies or variations in the waveform, creating ripples around the desired waveform.

The Low-Pass Filter at the output of inverter mitigates high-frequency harmonics and ensures a smoother and more sinusoidal output voltage waveform. This filter configuration typically consists of a capacitance connected in parallel with the load and an inductance connected in series. The capacitor serves to provide a low impedance path for high-frequency components, allowing them to be bypassed to the ground, while the inductor impedes the flow of high-frequency currents, thereby attenuating the higher frequency components. The combination of the capacitor and inductor forms a resonant circuit that effectively filters out the undesired harmonics.

Eventually, the reference test resistive load, a type of electrical load that consists of a resistor of $R_{load} = 22\Omega$. It simulates resistive elements, such as resistors or heating elements, which convert electrical energy into heat. In a resistive load, the relationship between voltage, current, and resistance complies with Ohm's Law, $V = R * I$.

For a purely resistive load, the voltage and current are in phase, meaning they reach their peaks and troughs simultaneously in an alternating current system. Moreover, the power dissipated in a resistive load is proportional to the square of the current passing through it, and it is given by the formula $P = I^2 R$, where P is power, I is current, and R is resistance.

Result Analysis

Filtered Output Voltage and Current

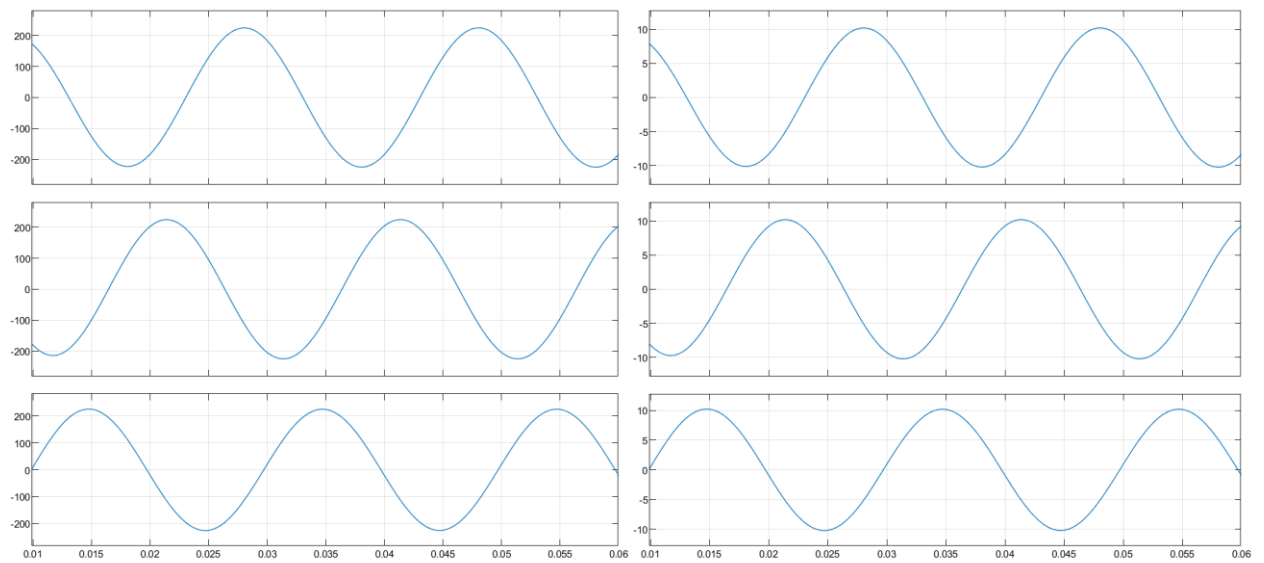


Figure 19: Inverter Output Voltage (Left) and Current (Right) Using SPWM (Linear Load)

The Simulink simulation results in an output voltage and current with very little percentage of ripples (Figure 19) and a low THD (Figure 20). Both the voltage and current are in phase given the use of resistive load for the simulation. The output voltage is around 225 V, while the current is around 10.22 A. The design aimed for a 230 V across all phases, furthermore, the voltage signals of each phase may differ up to 0.9 V.

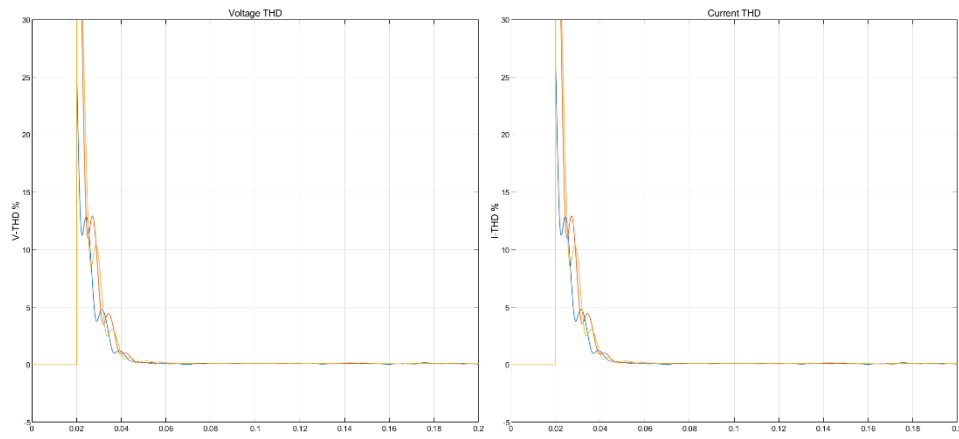


Figure 20: Output Voltage and Current THD % Using SPWM (Linear Load)

The simulation has proved the performance of SPWM in generating a sinusoidal output signal with low THD levels as shown in figure 20. The downside of SPWM is that it has no flexibility over the parameters of the modulation. Many factors contribute to the wrong output signals, therefore, using SPWM alone is not enough to guarantee stable desired voltages and currents across all the phases.

2.2.3. Case 2: Load Switching

The load test includes simulations of different types of loads, as well as tweaks to the simulation parameters.

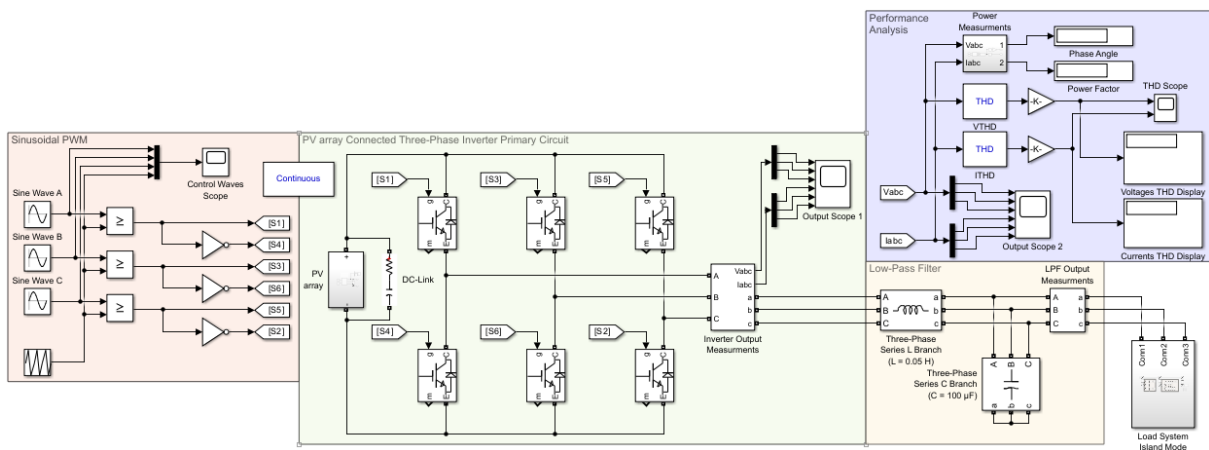


Figure 21: SPWM Controlled Three-Phase Inverter Simulink Model (Island Mode Load)

Each load simulation takes 100 ms of the total period of the simulation. The simulation runs for 300 ms for three different loads, Linear, Non-linear, and Grid-Connected.

Linear Load (Resistive Load)

When a SPWM inverter is connected to a purely linear load composed of resistive elements, it exhibits exemplary performance regarding harmonic distortion (as illustrated in figure 22 and 23):

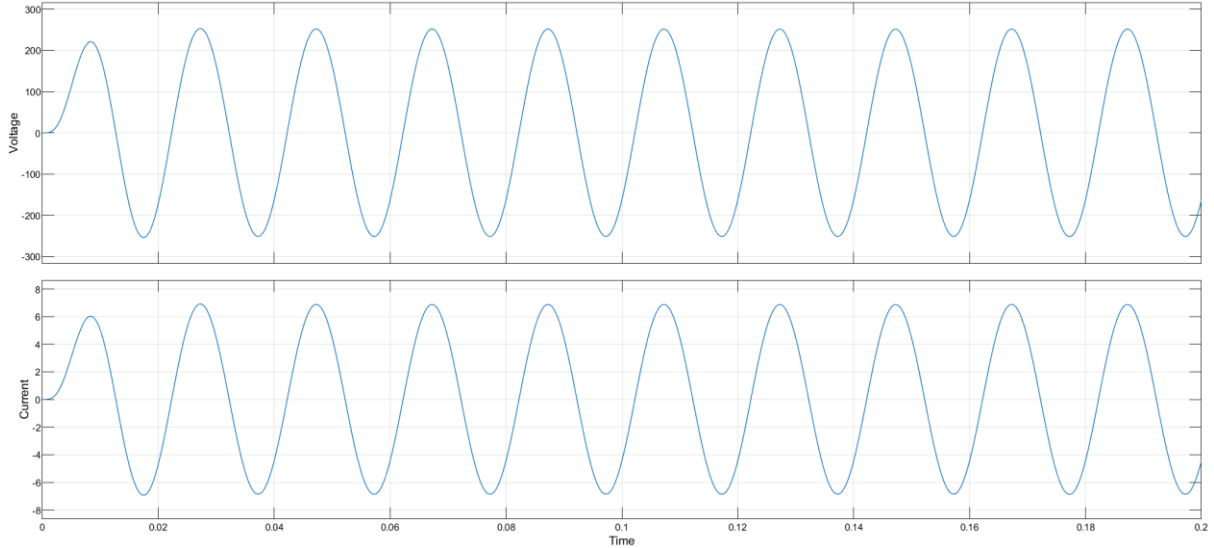


Figure 22: Inverter Output Voltage and Current of Linear Load Test Using SPWM

Voltage THD: The voltage THD remains exceedingly low, falling below 0.003%. This indicates that the output voltage waveform is almost a perfect sinusoid, showcasing the efficiency of SPWM in minimizing voltage distortion for linear loads.

Current THD: The current THD remains stable at around 1%. This slight distortion in current is expected even in ideal conditions but is still within acceptable limits, ensuring the current waveform is nearly sinusoidal.

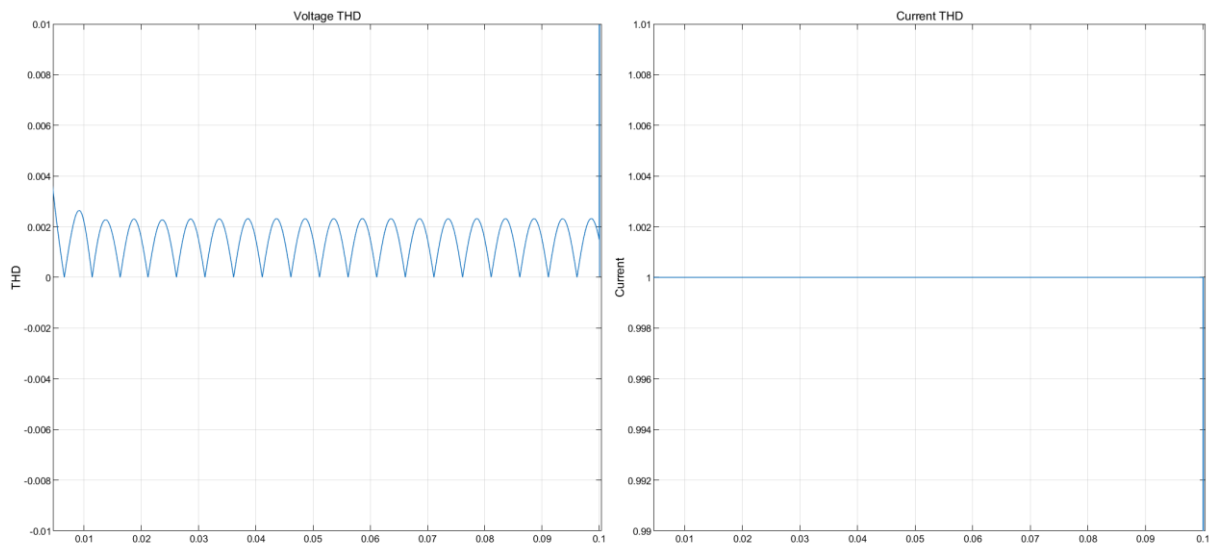


Figure 23: Output Voltage and Current THD % of Linear Load Test Using SPWM

This minimal distortion underscores SPWM's effectiveness in generating clean power for linear loads, thereby ensuring high power quality and efficient energy transfer.

Non-Linear Load (Using Rectifier Bridge)

When the same SPWM inverter is connected to a non-linear load, such as a full rectifier bridge, the performance varies depending on the smoothing capacitor:

With Smoothing Capacitor

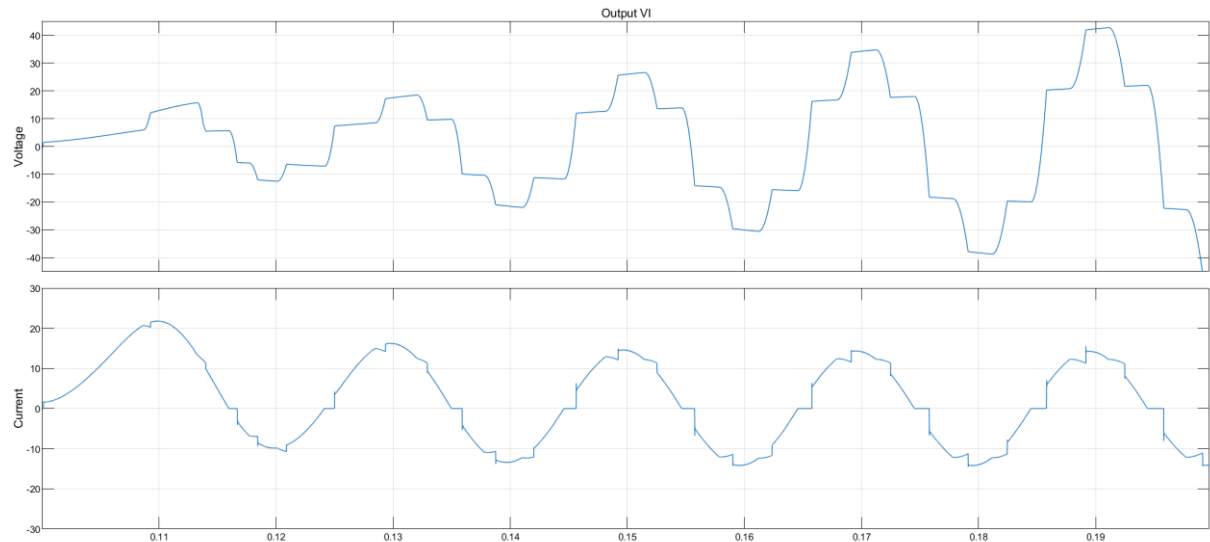


Figure 24: Inverter Output Voltage and Current of Full Bridge Test using SPWM

Figure 24 showcases harmonics on the voltage and current signals.

Voltage Output Distortion: The voltage output of the inverter becomes heavily distorted due to the non-linear characteristics of the load. The full bridge rectifier with a smoothing capacitor introduces significant harmonics into the voltage waveform, deviating substantially from a pure sine wave.

Current Waveform: Despite the severe voltage distortion, the current waveform retains a slightly better sinusoidal shape. This is due to the rectifier's operation which draws current in pulses, partially mitigating the distortion effects on the current compared to the voltage.

Voltage Level at PCC: The voltage at the Point of Common Coupling (PCC) drops significantly to around 35 volts. This voltage drop is a direct consequence of the high harmonic content and poor power factor associated with non-linear loads.

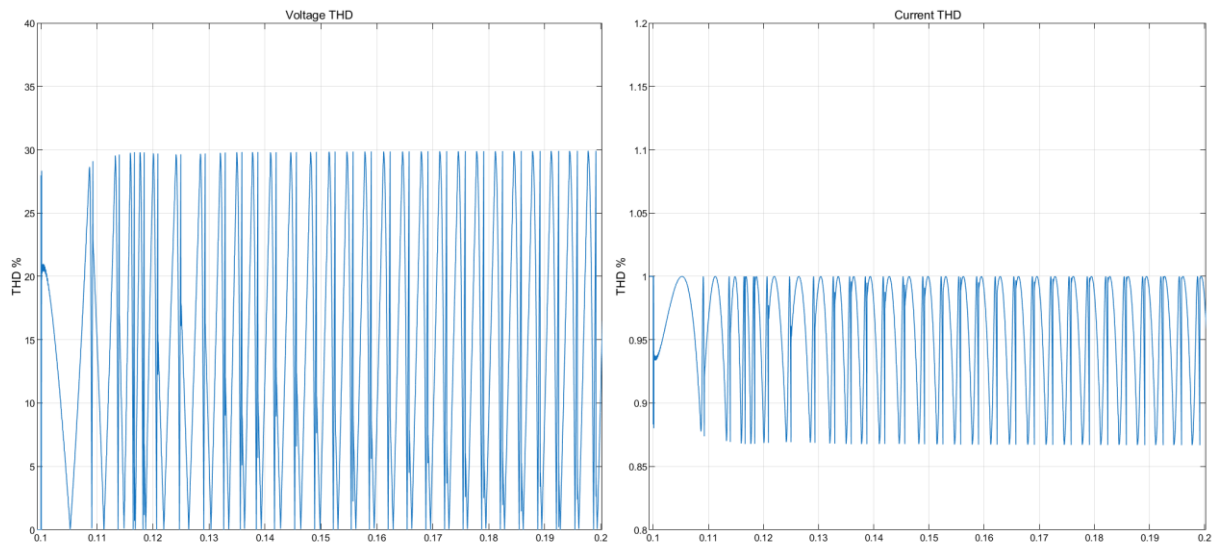


Figure 25: Output Voltage and Current THD % of Full Rectifier Bridge Test Using SPWM

Voltage THD values in figure 25 escalated dramatically, reaching up to 30%. Such high levels of distortion highlight the challenges in maintaining power quality when supplying non-linear loads with SPWM inverters. Meanwhile, the current THD oscillates between 0.85% and 1%.

Without Smoothing Capacitor

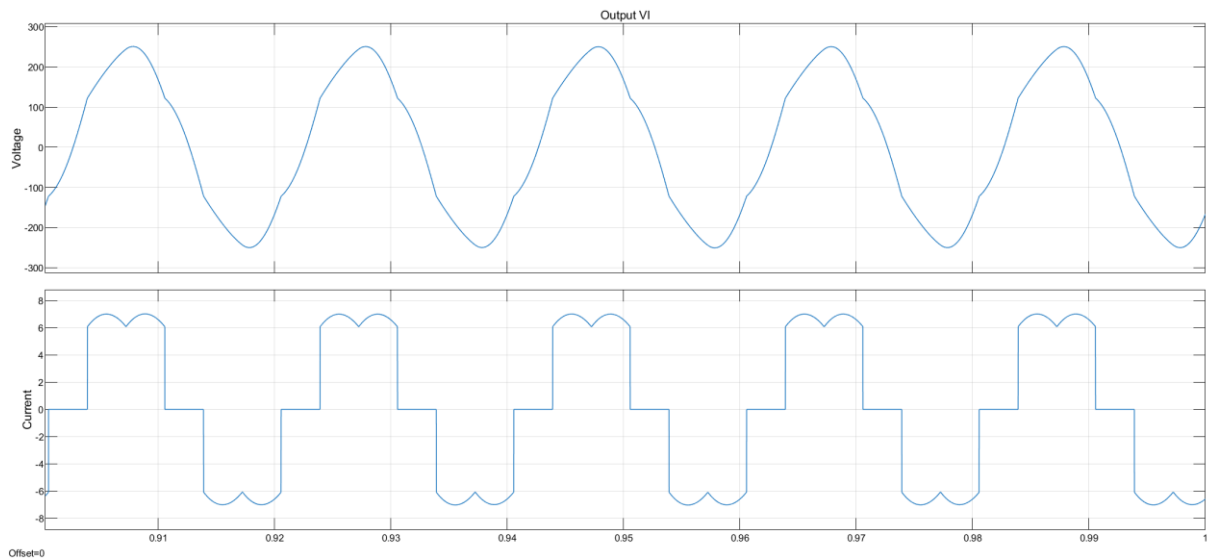


Figure 26: Inverter Output Voltage and Current of Rectifier Bridge Test Without Smoothing Capacitor Using SPWM

The situation is reversed upon removing or lowering the capacitance of the smoothing capacitor, as illustrated in figure 26. The voltage THD improves significantly, falling to around 5%. The absence or reduction of the capacitor reduces the filtering of the rectified

output, which lessens the harmonic content fed back into the inverter, thereby lowering the voltage distortion.

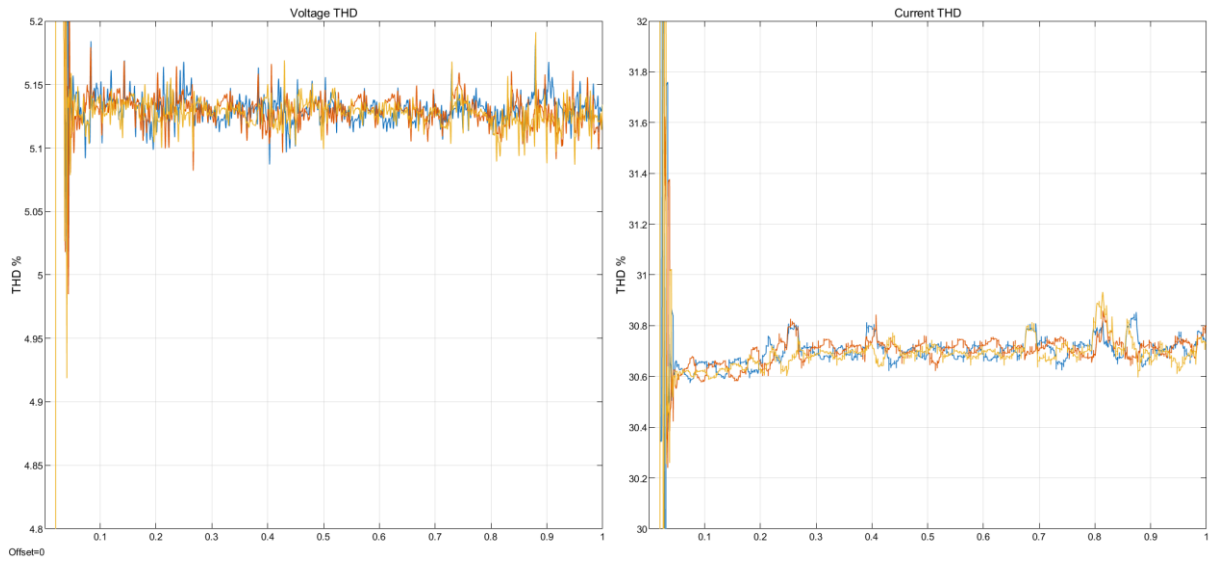


Figure 27: Output Voltage and Current THD % of Rectifier Bridge Test Without Smoothing Capacitor Using SPWM

The current waveform becomes more distorted without the capacitor since the rectifier's pulses are no longer smoothed, increasing the current THD to around 30% (Figure 27).

These results emphasize the influence of the smoothing capacitor on harmonic distortion in non-linear loads and the role it plays in the performance of SPWM inverters.

Grid-Connected Mode

In grid-connected mode, the situation further deteriorates. Both the voltage and current waveforms become extremely distorted. The interaction between the grid and the inverter's output, especially under mismatched conditions, results in severe waveform distortion.

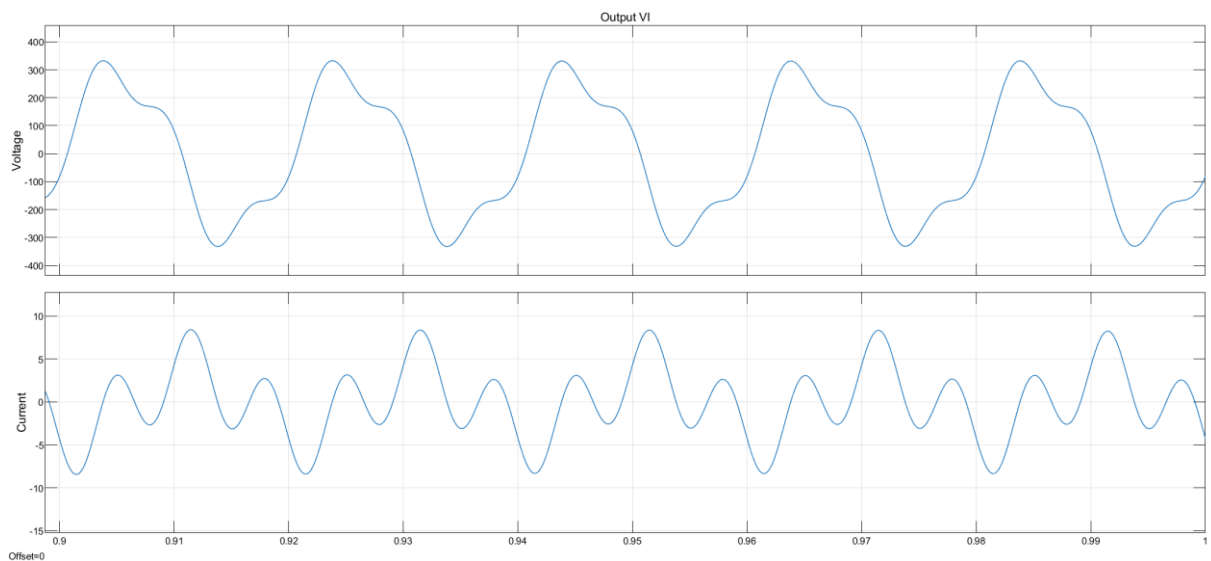


Figure 28: Inverter Output Voltage and Current of Grid-Connected Test Using SPWM

The voltage and current become uncontrollable (Figure 28), indicating a failure in synchronizing with the grid's parameters. This could be due to various factors, including phase mismatches, frequency deviations, and inadequate filtering.

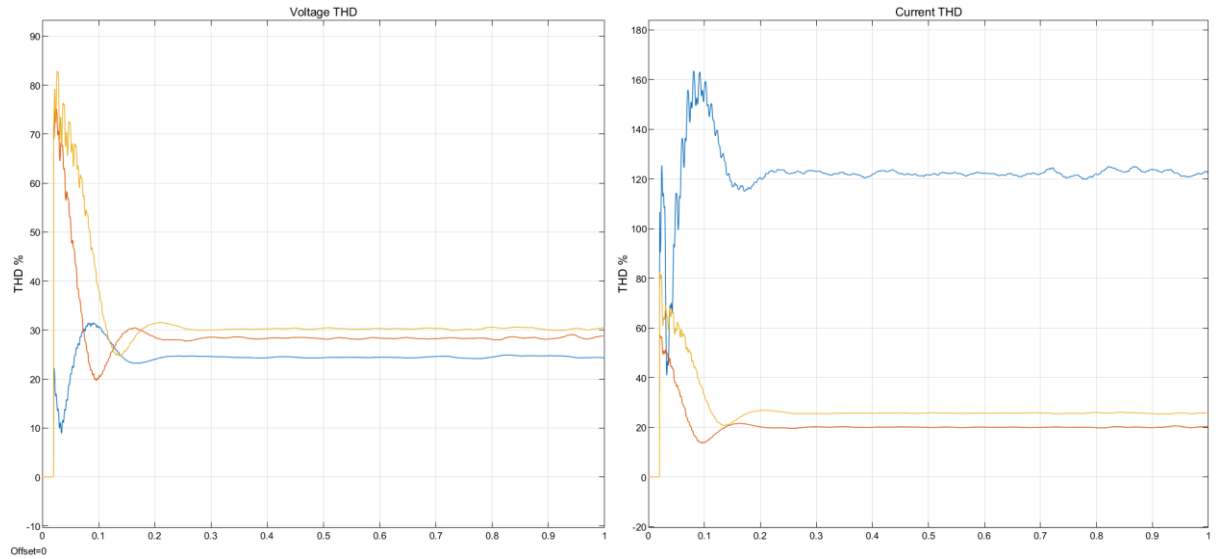


Figure 29: Output Voltage and Current THD % of Grid-Connected Test Using SPWM

The THD values for both voltage and current skyrocketed (Figure 29) implying excessively high levels of harmonic distortion. This not only affects power quality but can also cause damage to electrical equipment and reduce the efficiency of power distribution.

This scenario underscores the critical need for advanced control and synchronization mechanisms when integrating SPWM inverters with the grid. Proper filtering, harmonic compensation, and robust control algorithms are essential to manage the complexities of grid-connected operations and maintain power quality within acceptable standards.

2.2.4. Conclusion

SPWM offers several advantages and disadvantages in its application for inverter design. One of the primary benefits of SPWM is its ease of implementation and configuration, making it accessible for a variety of uses without the need for complex setups. Additionally, SPWM is highly effective in achieving very low THD for linear loads, with THD levels as low as 0.003% in both current and voltage, resulting in a highly pure sinusoidal output and ensuring high power quality.

However, SPWM has several notable drawbacks. The technique does not inherently account for variations in DC input voltage provided to the inverter, which can lead to inconsistent output and the potential for high voltage damage to the load. This lack of adaptability to changing input conditions is a significant limitation, especially in dynamic environments. Moreover, the performance of SPWM is heavily dependent on manual configuration relative to the input irradiance and temperature levels of the PV array. This need for ongoing adjustments increases the complexity of operation.

To achieve optimal performance, SPWM typically requires the inclusion of a voltage regulator. While this component helps manage output voltage levels and ensures stability, it also adds to the overall complexity and cost of the system. Furthermore, SPWM performs poorly when dealing with non-linear loads or in grid-connected modes. Non-linear loads, such as those incorporating a full rectifier bridge, introduce significant harmonic distortion that SPWM struggles to manage effectively. In grid-connected scenarios, maintaining synchronization and control can be challenging, leading to highly distorted voltage and current outputs.

In conclusion, while SPWM is beneficial for specific applications, particularly with linear loads, its limitations in adapting to dynamic input conditions, the need for manual configuration, dependence on additional voltage regulation, and poor performance with non-linear and grid-connected loads must be carefully considered. These factors limit the broader applicability of SPWM in more complex and variable environments.

2.3. Voltage Formation Using Closed Loop Sinusoidal Pulse Width Modulation (CL-SPWM)

2.3.1. Simulink Model

The circuit diagram of the Closed Loop PWM voltage forming method is presented in Figure 30. Closed loop control guarantees the accurate control of the phase and amplitude of inverter output voltage to keep the same phase with the grid phase and to provide the desired value of the output current.

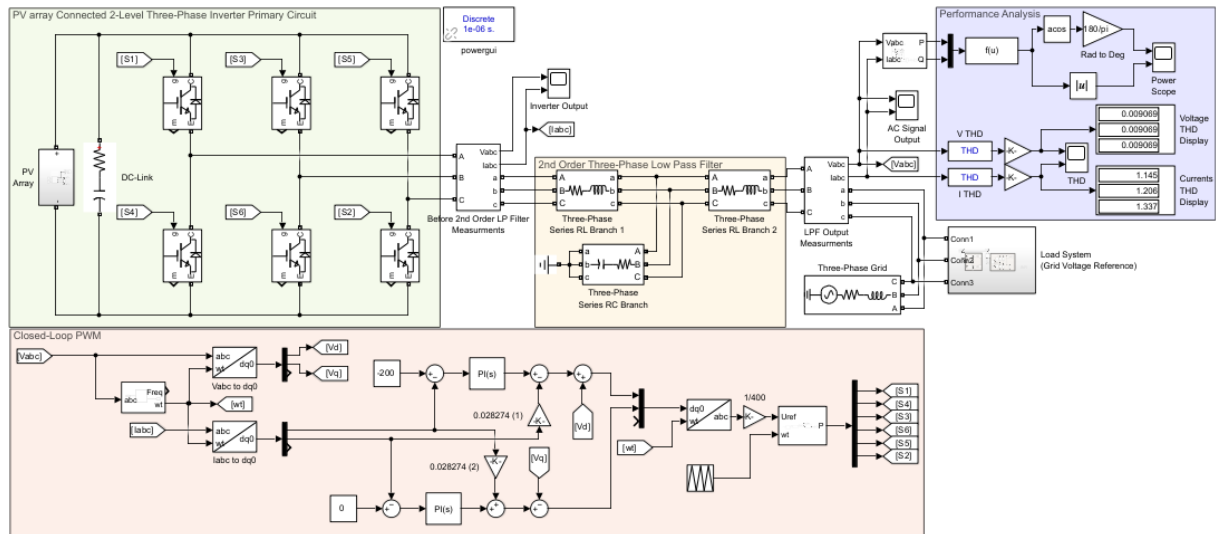


Figure 30: Closed Loop SPWM Controlled Three-Phase Inverter Simulink Model

The primary objective of this design is to drive an output AC voltage like the grid AC voltage, with a specific output current. The closed feedback loops command the inverter IGBTs to drive a desired current output, adhering to the grid specifications. The chosen output current for this design is 200 A, however, it is important to mention that the output current should adhere to the possible values the input DC voltage allow using the Closed Feedback Loop PWM.

This Simulink design is to implement a closed feedback loop Pulse Width Modulation current control system for a three-phase inverter. The design employs advanced control strategies, including Clark and Park transformations, Proportional-Integral (PI) controllers, and Inverse Clark and Park transformations, to regulate the inverter's output in response to specified reference values.

PID Controller

A Proportional-Integral-Derivative (PID) controller is a widely used type of feedback control system that is commonly employed in engineering and control applications. It is

designed to regulate a process by continuously adjusting a control output based on the error signal, which is the difference between the desired setpoint and the actual process variable.

Components of a PID Controller:

Proportional Term $P(t)$: The proportional term is directly proportional to the current error. It is calculated by multiplying the error by a proportional gain K_p . The proportional term provides immediate response to changes in the error, helping to reduce steady-state error.

Integral Term $I(t)$: The integral term is proportional to the accumulation of past errors over time. It is calculated by integrating the error over time and multiplying by the integral gain k_i . The integral term helps eliminate any accumulated steady-state error and brings the system to the setpoint.

Derivative Term $D(t)$: The derivative term is proportional to the rate of change of the error. It is calculated by taking the derivative of the error with respect to time and multiplying by the derivative gain K_d . The derivative term anticipates future error trends, providing damping and reducing overshooting.

Role of PID Controller in the Design

1. Current Control Loop (I_d)

- In the I_d control loop, the PID controller adjusts the output voltage V_d based on the error between the reference current (-200, setpoint) and the actual direct current I_d .
- The proportional term influences the immediate response to current errors.
- The integral term ensures that any steady-state error is eliminated over time.
- The derivative term provides damping to prevent overshooting and improve system stability.

2. Current Control Loop (I_q)

- In the I_q control loop, a separate PID controller adjusts the output voltage V_q based on the error between the reference current (0, setpoint) and the actual quadrature current I_q .
- Like the I_d loop, the PID controller in the I_q loop adjusts the voltage to minimize error, eliminate steady-state error, and provide damping.

3. Transfer Functions

- Both control loops have similar process/transfer functions, expressed as follows:

$$T(t) = K_p e(t) + K_i \left(\int e(t) dt \right) + K_d \frac{de(t)}{dt} \quad 2.1$$

Overall Functionality:

The PID controllers in both loops work collaboratively to dynamically adjust the voltages (V_d and V_q) to achieve the desired current responses.

The proportional, integral, and derivative terms together contribute to a robust and adaptive control system, ensuring precise and stable regulation of currents in the transformed coordinate system. The following table summarizes the impact of each term on the error:

Table 2: Impact of PID Terms on Error [9]

PID Terms	Rise Time	Settling Time	Overshoot	Steady State Error
<i>P</i>	Decrease	Small change	Increase	Decrease
<i>I</i>	Small change	Decrease	Decrease	No change
<i>D</i>	Decrease	Increase	Increase	Eliminate

In summary, the PID controllers play a crucial role in the closed-loop control system by continuously adjusting the voltages based on the error signals. This enables the system to respond to changes, eliminate steady-state errors, and maintain stability in controlling the direct and quadrature currents.

2.3.2. Circuit Components and Parameters Description

Inverter Circuit Components

- DC Voltage Source and Inverter

A two-level inverter with six IGBTs is connected to a DC voltage source.

External pulse signals control the switching of the inverter.

- Low-Pass Filter

The inverter output undergoes filtering through a Low-Pass Filter to smooth the waveform.

- Three-Phase Source

The filtered output is connected to a three-phase source with a V_{RMS} value of 220V.

Current is measured before the Low-Pass Filter, and voltage is measured after the filter.

Closed Loop PWM Circuit

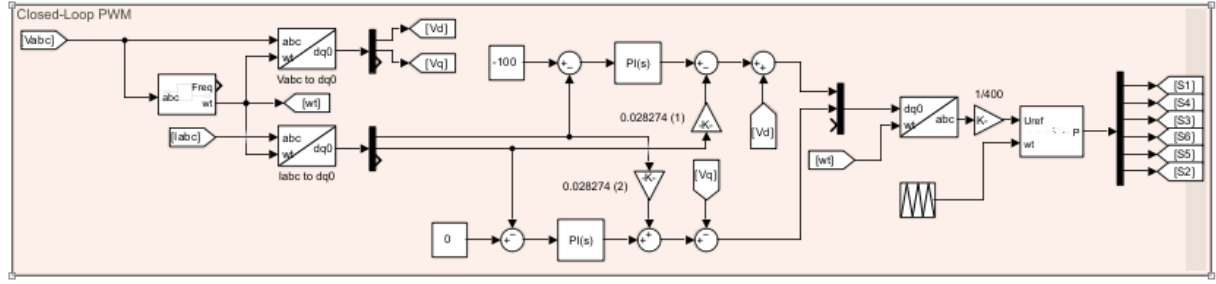


Figure 31: Simulink Diagram of Closed Loop SPWM Control

Clark and Park Transformation: Voltage and current measurements are transformed from abc to dq_0 coordinates using the "abc to dq_0 " block.

Current Control Loops: Two independent current control loops are implemented: one for the direct current component (I_d) and another for the quadrature current component I_q . The PI controllers are employed in both loops to regulate the currents based on reference values. The gain values are set manually to $K_p = 30$, and $K_I = 200$, as it provided best results for the simulation.

Current Control Loop (I_d): Incorporates feedback from I_q and V_d . It adjusts V_d based on the difference between the reference current and the actual I_d , considering the cross-coupling effect with I_q .

Current Control Loop (I_q): Incorporates feedback from I_d and V_q . It adjusts V_q based on the difference between the reference current and the actual I_q , considering the cross-coupling effect with I_d .

Inverse Clark and Park Transformation: Outputs from both control loops are combined and fed into an Inverse Clark and Park Transformation block. This block reverses the earlier coordinate transformations, bringing the system back to the abc coordinate system.

PWM Generation: The transformed signals are amplified and used as reference voltages for a PWM Generator block. The PWM generator produces switching signals for the IGBTs in the inverter, completing the feedback loop.

This Simulink design establishes a sophisticated closed-loop control system for a three-phase inverter, combining Clark and Park transformations, PI controllers, and Inverse Clark and Park transformations. The design aims to achieve precise regulation of currents and voltages, considering the interdependence introduced by the coordinate transformations. The closed-loop PWM control ensures optimal performance and responsiveness of the inverter in a three-phase electrical system.

2.3.3. Results and Analysis

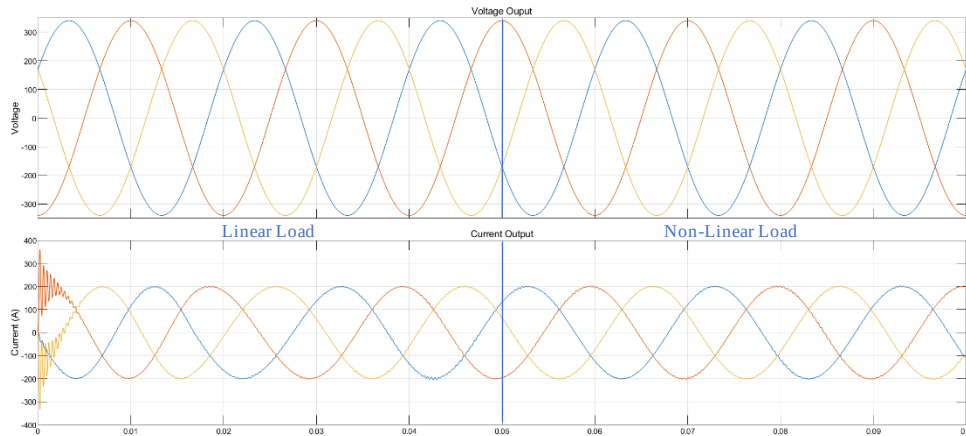


Figure 32: Output Voltage and Current Using Closed Loop SPWM

The AC output voltage in figure 32 meets the grid requirements, with each phase peaking at 340 V and a frequency of 50 Hz. The voltage signal is smooth, with no visible ripples or harmonic distortions.

In contrast, the AC current output shows high THD, with noticeable ripples in the first 5 ms of the simulation. This is due to the initial influence of the PI Controller on current control. The difference between the desired current (-200 A) and the actual current decreases over time, eventually stabilizing at 200 A for each phase. However, the AC current signal has more ripples compared to the voltage signal. The performance metrics of the design are shown in the following figure.

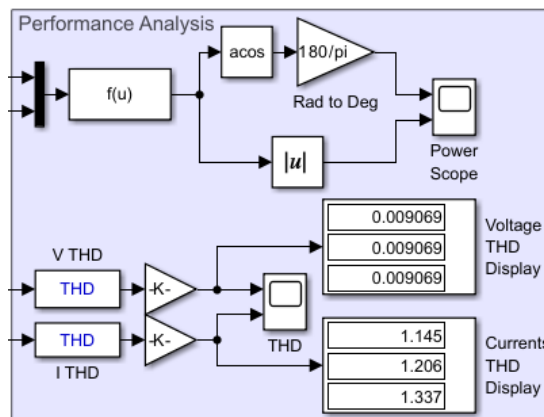


Figure 33: Performance Monitor of Closed Loop SPWM

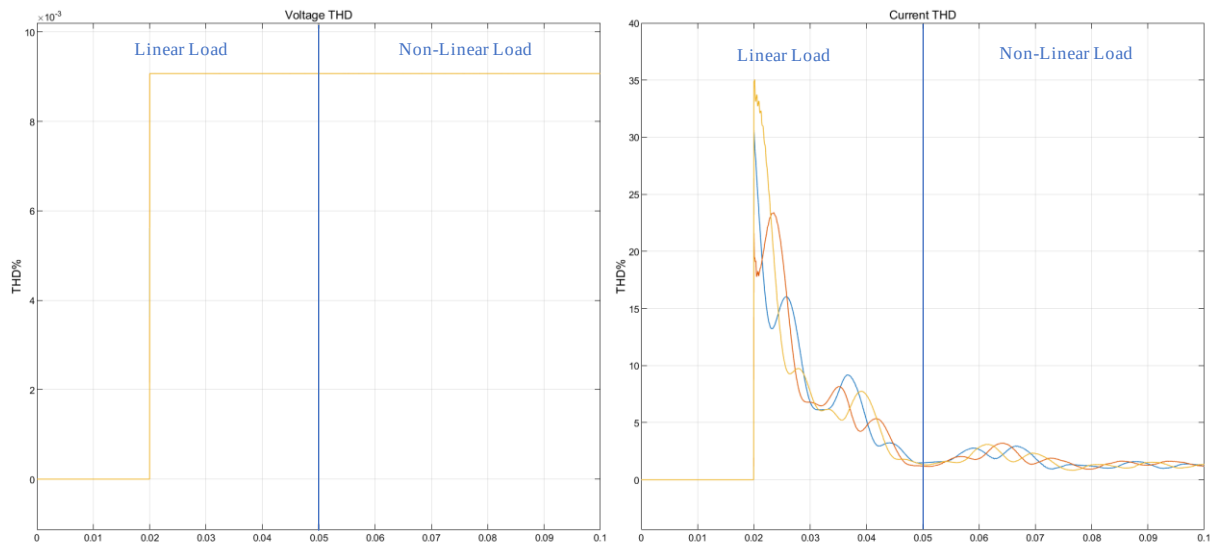


Figure 34: Output Voltage and Current THD % Using Closed Loop SPWM

Figure 34 highlights THDs of the voltage signal (THD_V) quantified at approximately 0.009069%, reflecting a nominal level of harmonic content. Conversely, the THD of the current signal THD_I skyrockets to 35% at the beginning of the simulation and, settles at 0.8% and 1.1% eventually, a range deemed relatively low and conducive to diverse power system applications.

A slight increase in current THD when switching to non-linear load occurs, but immediately reduced in the span of 40 ms.

The power factor of the system is approximated at -0.9 , accompanied by a phase angle spanning from 180° to 150° as shown in figure 35. This power factor denotes the ratio of real power to apparent power, signifying efficient power utilization in the system. The phase angle, indicative of the temporal displacement between the voltage and current waveforms, is within the anticipated range for typical inductive loads.

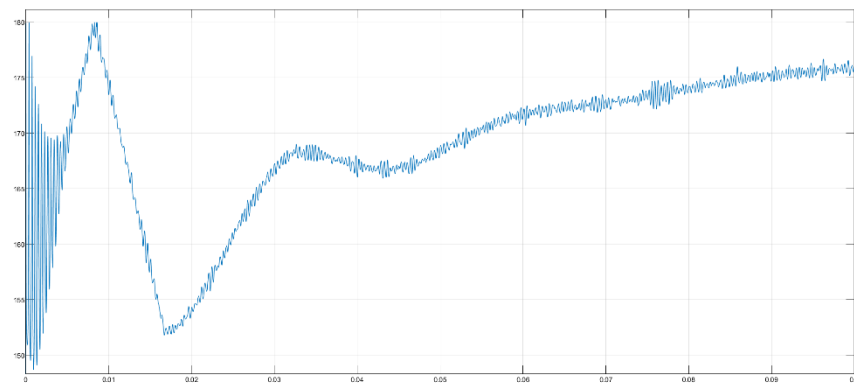


Figure 35: Phase Angle Variation between Voltage and Current During the Simulation of Closed Loop SPWM

The Power Factor (PF) is defined as the ratio of Real Power (P) to Apparent Power (S) in an electrical system. Real Power (P) represents the actual power utilized by the system for performing useful work, while Apparent Power (S) encompasses both Real Power (P) and Reactive Power (Q). Reactive Power (Q) is the portion of power that oscillates between the source and load but does not contribute to useful work. In summary, the Power Factor is a metric indicating how efficiently electrical power is converted into useful work within a system, with higher values signifying more effective power utilization.

$$P = V * I * PF \quad 2.2$$

$$S = V * I = \sqrt{P^2 + Q^2} \quad 2.3$$

$$PF = \cos(\theta) \quad 2.4$$

$$\theta = \text{phase}(V) - \text{phase}(I) \quad 2.5$$

2.4. Voltage Formation Using Phase Locked Loop SPWM

2.4.1. PLL Principle

A paramount issue of voltage formation algorithms for grid-connected three-phase inverters is ensuring synchronization with the grid voltage. A direct and effective technique to achieve this synchronization is using a PLL control system.

PLL is a feedback control system that automatically adjusts the phase of the inverter output to match the phase of a reference signal, typically the grid voltage, as illustrated in figure 36. This synchronization is crucial for the seamless integration of the inverter with the grid, ensuring that the inverter-generated AC waveform is in phase with the grid's AC waveform. By locking onto the grid frequency and phase, a PLL ensures that the inverter operates efficiently, reducing the risk of power surges, harmonics, and other disturbances that can degrade system performance.

A PLL control system consists of three main components: the Phase Detector (PD), the Loop Filter (LF), and the Voltage Controlled Oscillator (VCO) (See example in figure 37). The PD compares the phase of the input reference signal with the VCO output, generating an error signal proportional to their phase difference. The LF processes this error signal to remove noise and produce a smooth control voltage, often acting like a PID controller. The VCO adjusts its frequency based on the control voltage to minimize the phase error, aligning the output signal with the reference signal. Together, these components work in a feedback loop to maintain precise synchronization.

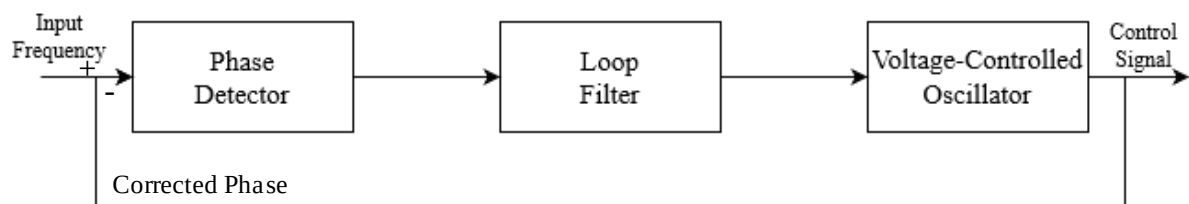


Figure 36: PLL General Components

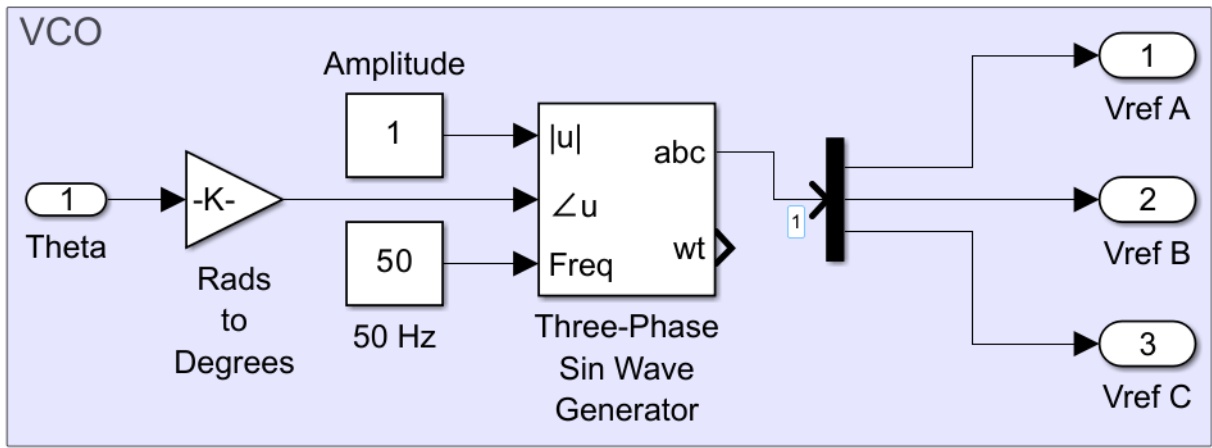


Figure 37: Voltage-Controlled Oscillator Simulink Diagram

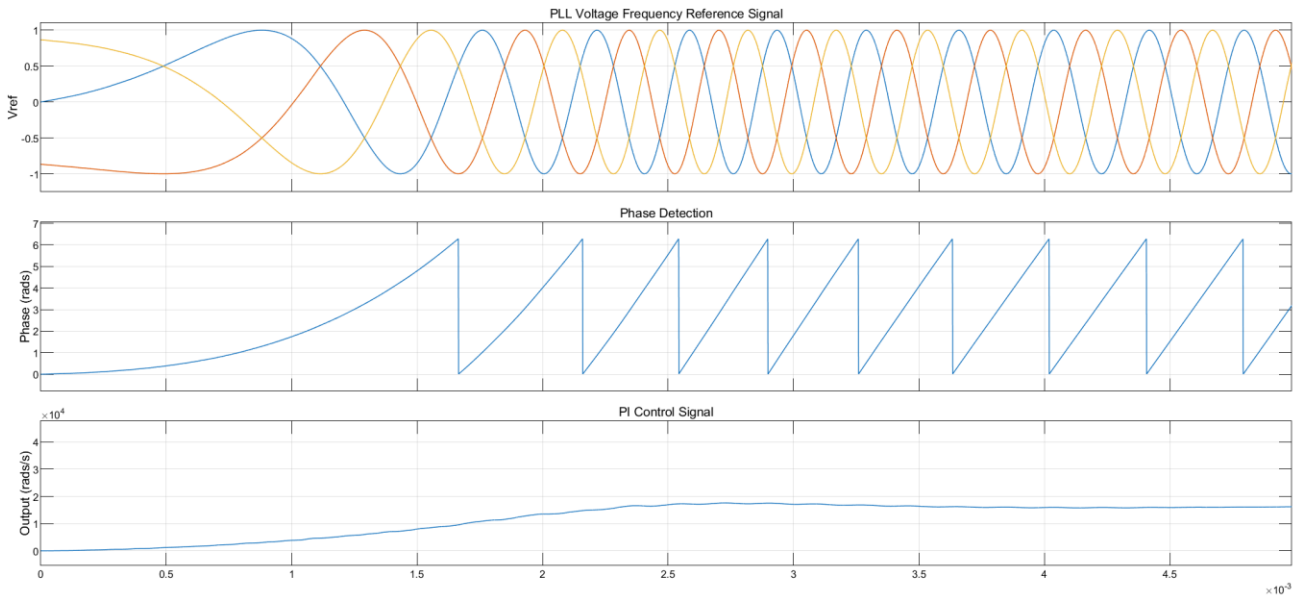


Figure 38: PLL Components Outputs (From up to bottom: VCO, Phase Detector and PI controller)

PLL systems are highly effective for maintaining synchronization within a specific frequency range as shown in figure 38, which is an example based on 50 Hz grid frequency. However, their performance degrades at higher frequencies. The primary shortcoming is that beyond a certain frequency threshold, the PLL's ability to reduce phase and frequency errors diminishes significantly. This limitation is due to the inherent bandwidth constraints of the PLL components, such as the phase detector, loop filter, and voltage-controlled oscillator VCO, which means the frequency threshold varies depending on the electrical circuit in use.

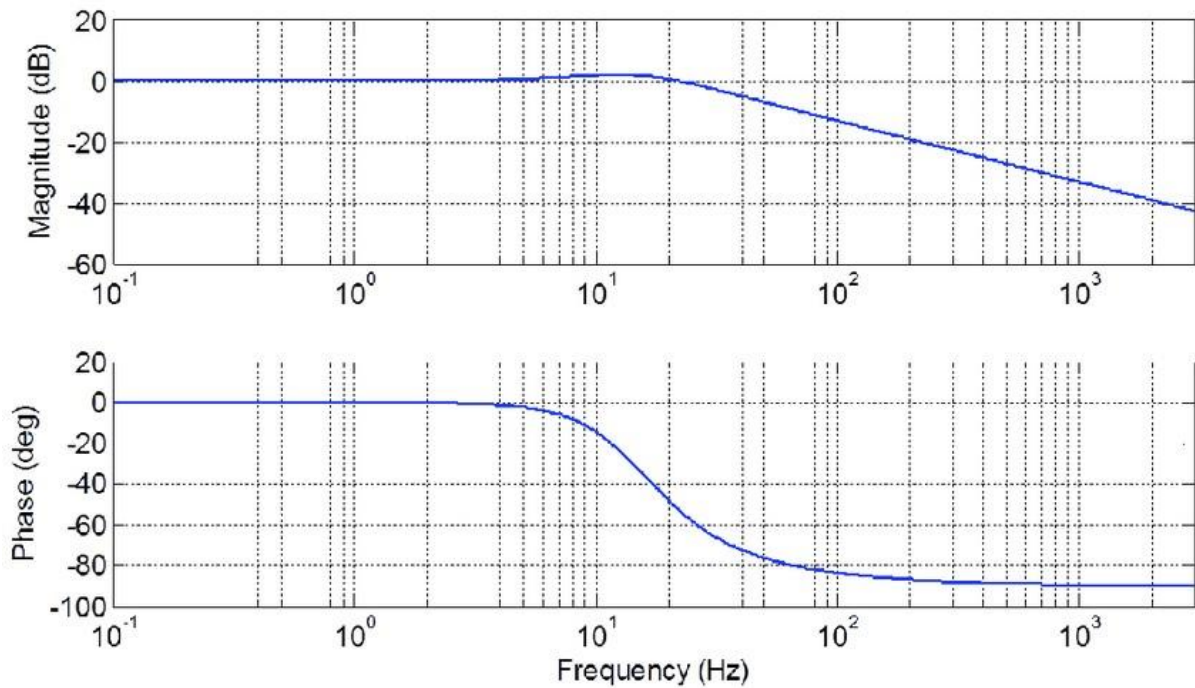


Figure 39: Example – Frequency Bode Plot of PLL [10]

The Bode plot of a PLL provides a visual representation of this limitation. Figure 39 is an example of a bode plot for PLL. In the magnitude plot, the gain typically decreases as frequency increases, indicating reduced control effectiveness. The phase plot further illustrates this by showing an increasing phase lag, approaching -90 degrees at higher frequencies. This phase lag signifies that the PLL can no longer respond swiftly enough to correct errors, leading to poor synchronization and control failure beyond the critical frequency. This critical situation in the bode plot (figure 39) highlights frequency range over which an example PLL system can effectively operate and maintain control.

PLL algorithm can be implemented in different ways. The following sector of the chapter explores three different PLL implementations, to assess their complexity and performance. The simulation provides a valuable platform for understanding and comparing their performance in various applications. By simulating these algorithms, we can gain insights into their behavior under different conditions and identify their strengths and weaknesses.

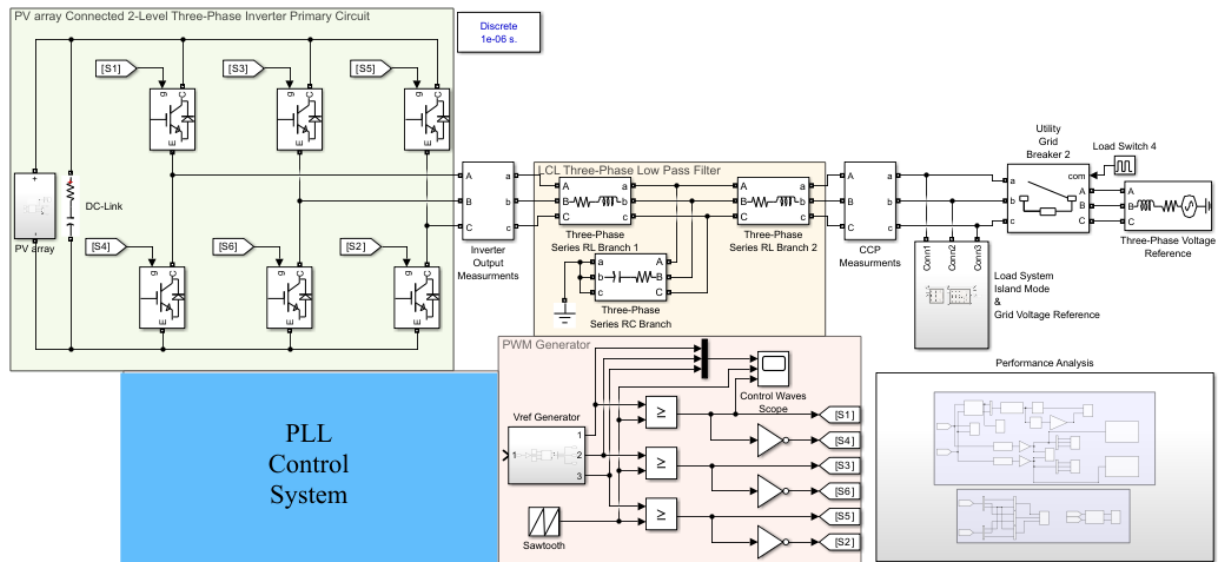


Figure 40: PLL Controlled Three-Phase Inverter Simulink Model

Figure 40 illustrates the common layout of the Simulink models used to investigate the PLL voltage formation algorithms in the following sections. The PLL Control System block marked in blue in figure 40 corresponds to the block which implements the different PLL techniques.

2.4.2. Rotating Reference Frame PLL (DQ0)

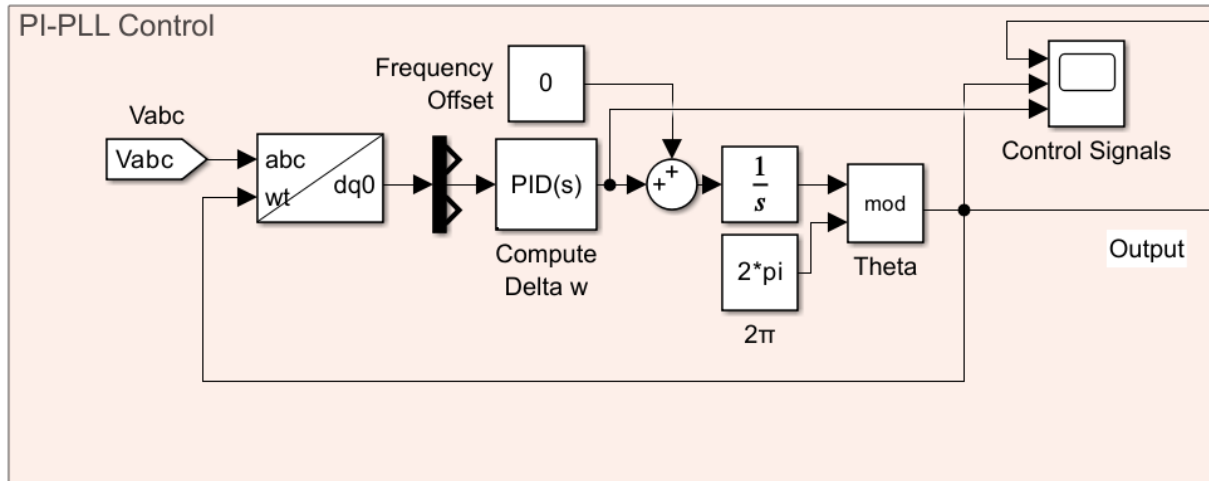


Figure 41: Simulink Diagram of PID PLL Control

This PLL method utilizes the transformation of three-phase voltages from the abc frame to the $dq0$ rotating reference frame to detect the phase accurately. The processes illustrated by figure 41 involves several key steps:

1. Transformation of V_{abc} to V_{dq0} :

The system takes the three-phase voltage V_{abc} , measured from the common coupling point (CCP), as input. These voltages are transformed to the $dq0$ frame using the following equations:

$$V_d = \frac{2}{3} \left(V_a \sin(\omega t) + V_b \sin\left(\omega t - \frac{2\pi}{3}\right) + V_c \sin\left(\omega t + \frac{2\pi}{3}\right) \right) \quad 2.6$$

$$V_d = \frac{2}{3} \left(V_a \cos(\omega t) + V_b \cos\left(\omega t - \frac{2\pi}{3}\right) + V_c \cos\left(\omega t + \frac{2\pi}{3}\right) \right) \quad 2.7$$

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) \quad 2.8$$

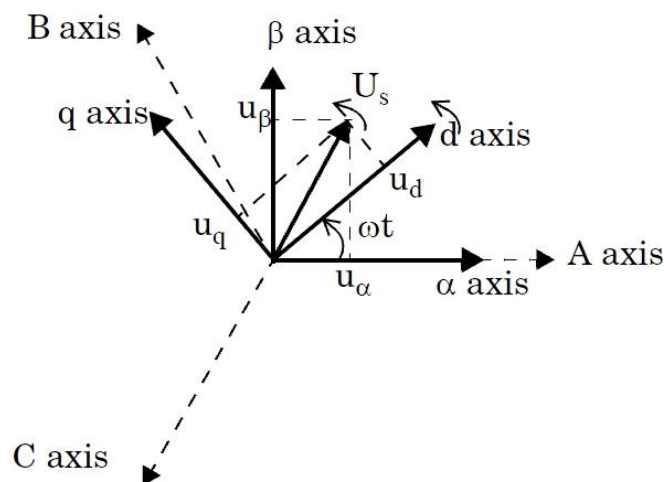


Figure 42: Example Plot of Rotating Reference Frame DQ0 [11]

V_d : Represents the direct axis component, which is aligned with the reference frame. In a perfectly synchronized system (ideal PLL operation), V_d will be a constant DC value representing the magnitude of the voltage vector.

V_q : Represents the quadrature axis component, which is orthogonal to the V_d component. In the context of PLL, V_q is used as an error signal indicating the misalignment between the reference frame and the actual phase of the voltage. The goal of the PLL is to drive V_q to zero, indicating phase alignment.

V_0 : Represents the zero-sequence component, which should be zero in a balanced system ($V_a + V_b + V_c = 0$).

2. PID Controller Processing:

The V_q component, indicative phase error, is fed into a PID controller, which minimizes V_q to zero, thus ensuring phase alignment. The PID controller is tuned automatically using Simulink Auto Tuning Function. This step ensures that the system can track the fundamental grid frequency ω_t by calculating the phase deviation ω_{err} :

$$\omega_{err} = PI_{output} \quad 2.9$$

The addition of the nominal frequency ensures that the PLL maintains synchronization with the grid's base frequency, allowing the system to correct only for deviations or drifts from this fundamental frequency.

3. Integration to Obtain Phase:

The adjusted frequency signal is then integrated to derive the phase angle:

$$\theta = \int_0^t \omega_{err} dt \quad 2.10$$

Frequency is the rate of change of phase over time. Integrating the frequency provides the cumulative phase angle, ensuring continuous phase tracking.

4. Modulo Operation and Phase Feedback:

The output of the integrator undergoes a modulo 2π operation to ensure the phase angle stays within a 0 to 2π range. This phase angle is then:

- Sent to a VCO to generate a reference signal.
- Fed back into the $dq0$ converter to update the transformation with the latest phase angle, ensuring closed-loop operation.

2.4.3. Simplified Trigonometric PLL (Acos)

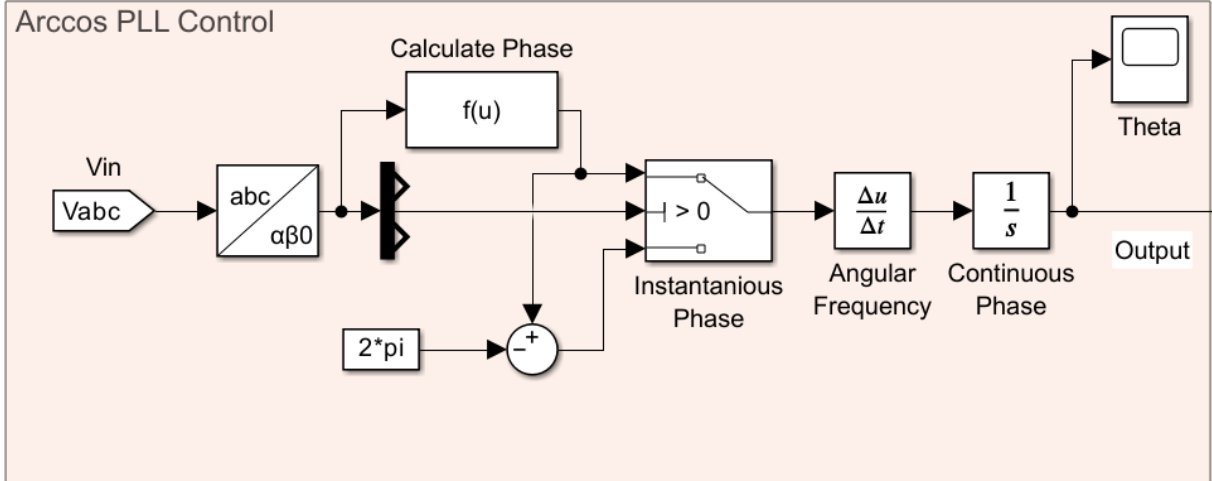


Figure 43: Simulink Diagram of Simplified Acos PLL Control

Figure 43 shows the process of using Acos PLL control using Simulink blocks. In this PLL simulation, the $\alpha\beta 0$ stationary reference frame is utilized for phase detection in three-phase voltage control. In this framework, the terms "Alpha" and "Beta" (see figure 44) represent the components of the three-phase voltage input, V_α and V_β , respectively. These terms are used to calculate the instantaneous angle θ between them using the function:

$$F(V_\alpha, V_\beta) = \cos^{-1} \left(\frac{V_\alpha}{\sqrt{(V_\alpha^2 + V_\beta^2)}} \right) \quad 2.11$$

The output $\theta(t)$ is subject to the following conditions:

$$\begin{aligned} \text{If } V_\beta < 0, \quad & \theta(t) = 2\pi - F(V_\alpha, V_\beta); \\ \text{otherwise,} \quad & \theta(t) = F(V_\alpha, V_\beta) \end{aligned}$$

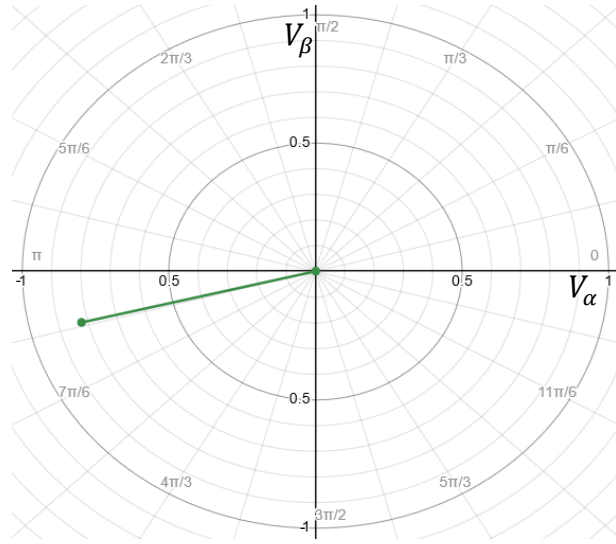


Figure 44: Example Plot of Unitary Stationary Reference Frame Alpha-Beta-Zero

To get the phase $\phi(t)$, which is the phase correction of the VCO, it is required to calculate the angular frequency $\omega(t)$ from the $\theta(t)$, then is calculated:

$$\omega(t) = \frac{\Delta\theta(t)}{\Delta t} \quad 2.12$$

$$\phi(t) = \oint \omega(t) dt \quad 2.13$$

The output condition is set to overcome the $\cos^{-1}(x)$ range output limitation. The arccosine function returns values in the range of $[0, \pi]$, corresponding to angles in the first and second quadrants. Therefore, based on V_β sign, the quadrant correction is possible, simply by adhering to the condition specified above.

This method of PLL employs a basic trigonometric approach to phase detection. It leverages the stationary Alpha-Beta-Zero reference frame to obtain 2D vector terms of the three-phase voltage signal. When applied to the three-phase voltage across the CCP, the phase represents the degree to which the frequency of the inverter AC output is not synchronized with the voltage frequency at the CCP. This phase difference is then utilized to generate the control signal for the inverter.

2.4.4. Simplified Trigonometric PLL (Atan2)

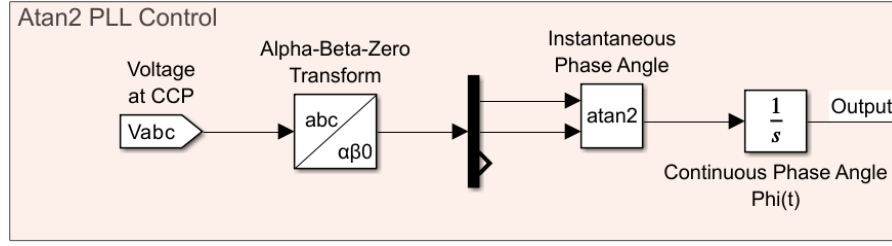


Figure 45: Simulink Diagram of Simplified Atan2 PLL Control

Another method for phase detection in PLL systems is to use $\text{atan2}(x)$ function instead of $\cos^{-1}(x)$ (see figure 45). The latter function phase quadrant correction relies entirely on the sign of V_β . In case of noise, and fluctuations, the arcos function might result in erroneous output.

In a PLL application, there are two theoretical differences between acos and atan2 : quadrant determination, and stability near $V_\beta = 0$.

Quadrant Determination:

The $\cos^{-1}(x)$ method relies entirely on the sign of V_β to determine the correct phase quadrant. In the presence of noise and fluctuations, this can lead to erroneous outputs.

In contrast, the $\text{atan2}(x)$ function inherently considers both V_α and V_β simultaneously. This dual consideration makes $\text{atan2}(x)$ more robust and reliable for accurate angle calculation, even when signals fluctuate around zero.

Improved Stability Near Zero:

The $\text{atan2}(x)$ function smoothly handles transitions through zero without requiring additional logic. This stability is crucial in maintaining accurate phase detection and synchronization.

The instantaneous phase angle θ is found using the following function:

$$\theta(t) = \text{atan2}(V_\alpha(t), V_\beta(t)) \quad 2.14$$

The following function calculates the phase correction:

$$\Theta(t) = \oint \theta(t) dt \quad 2.15$$

2.4.5. Results and Analysis

The PID PLL method has proven to be the best in terms of performance. The closed loop does not only provide better transient responses, and adaptivity along all the loads configuration, but the lowest THDs possible among its simplified counterparts.

However, A downside shared by the PLL methods is their inability to control the voltage RMS value.

In the figure 46, the PID PLL phase correction when connecting the linear loads and the non-linear loads with the grid have wider pulse width than the phase pulses of the previous load configurations.

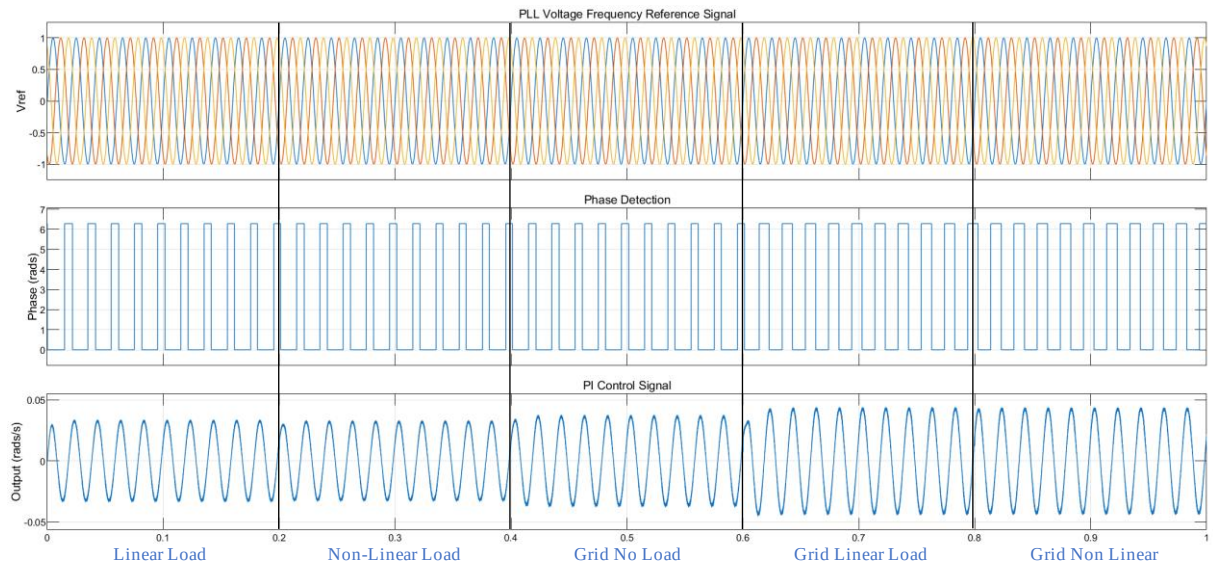


Figure 46: PID PLL Control Signals

When it comes to *atan2* PLL, the phase correction of has a half sinusoidal pulse, with similar amplitudes and widths, as illustrated in the bottom plot of figure 47. The peaks of the pulses seem to increase or decrease continuously depending on the load configuration.

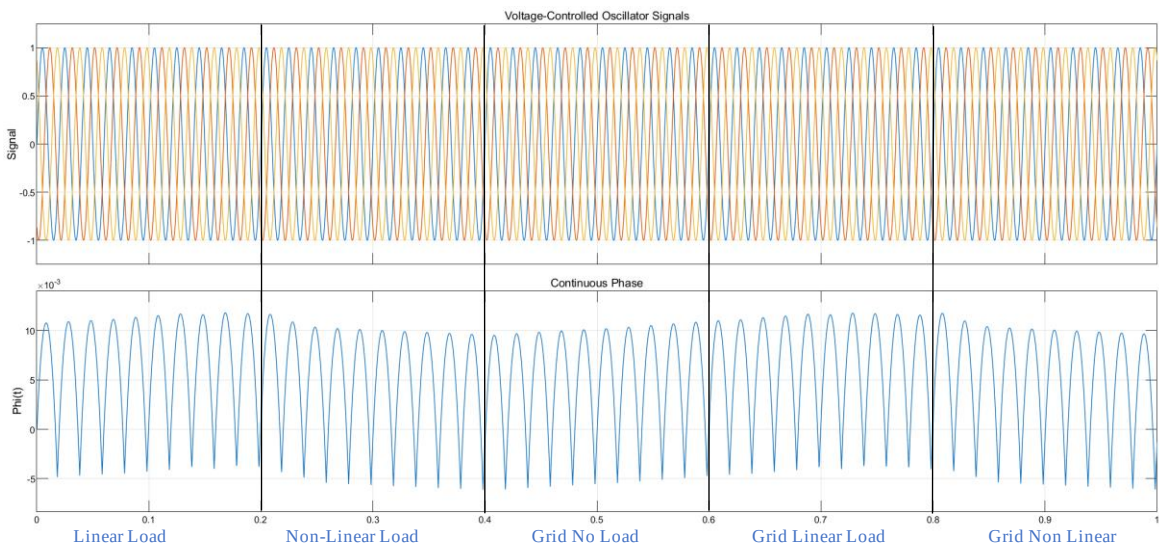


Figure 47: Atan2 PLL Control Signals

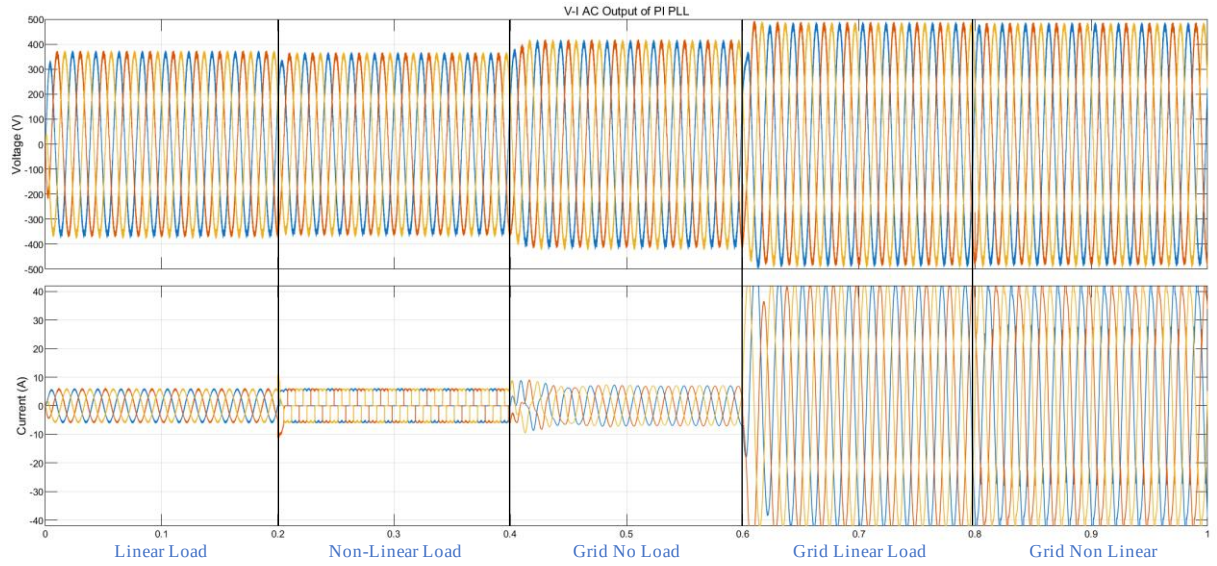


Figure 48: Inverter Output Voltage and Current Using PID PLL

Across all load configurations, the PID has optimal operating conditions three-phase voltage. Figure 48 upper plot showcases a smooth three-phase voltage. The current depends on whether the load is non-linear, and whether it is connected to the grid. This performance profile is consistent with many voltage-controlled systems studied during this work project.

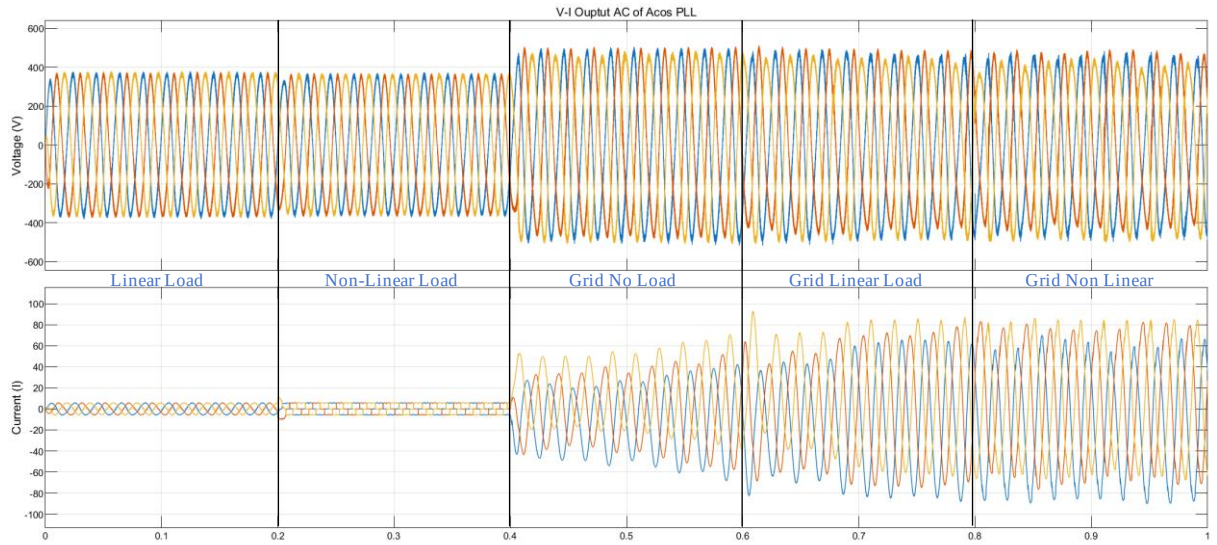


Figure 49: Inverter Output Voltage and Current Using Acos PLL

The Acos PLL has the least performance among the three simulated PLLs. Acos PLL is characterized by slow transient responses, as demonstrated in bottom plot of figure 49, when connected to the grid, and higher harmonics than the recommended values.

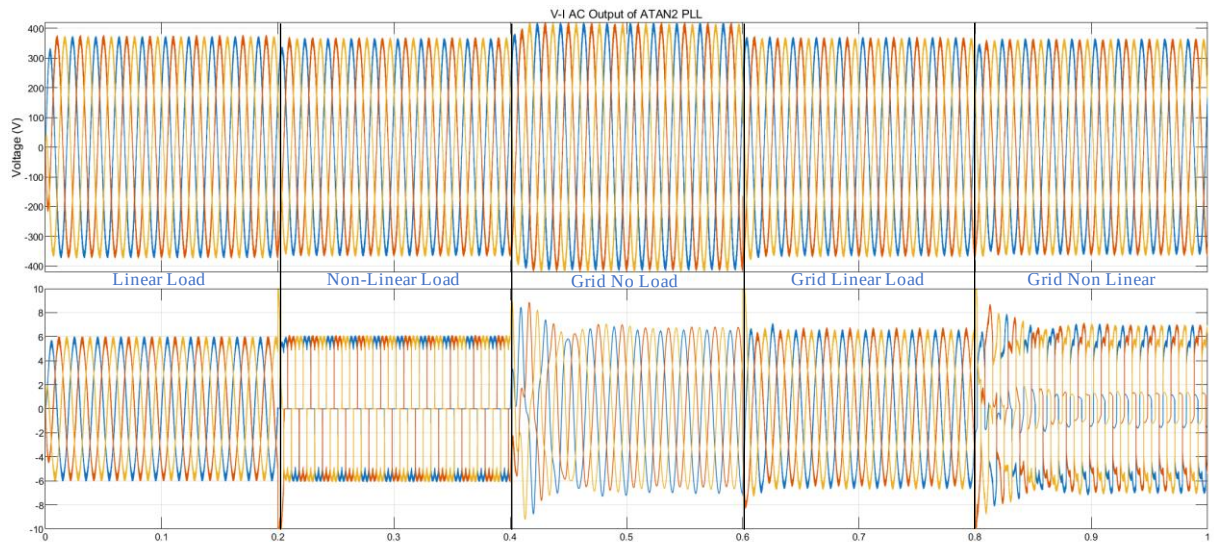


Figure 50: Inverter Output Voltage and Current Using Atan2 PLL

The Atan2 PLL improves harmonics and transient response (Compare figures 50 and 49). The Atan2 PLL could be an alternative to PID, except with the case of grid connected non-linear load, where the PID proved to work far better than Atan2 PLL. Otherwise, their performance is closely similar.

Figure 50 demonstrates how the voltage across the loads types adheres to recommended standards, but the current either has a low transient response, or high harmonics.

Comparison of THD values of All Simulated PLLs

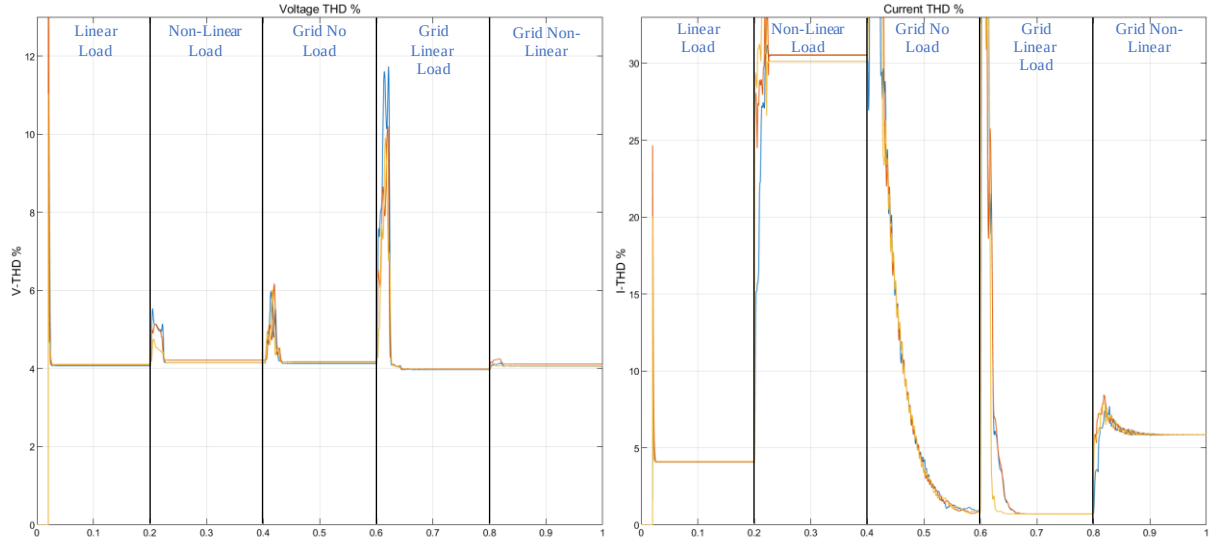


Figure 51: Output Voltage and Current THD % Using PID PLL

PID PLL ensures three-phase Voltage THD % around 4% no matter the load used (see figure 51 (left)). Current THD % performance changes with the load type, registering high THDs for non-Linear Load. However, the connection to grid immensely mitigates the harmonics for non-linear load (see figure 51 (right)).

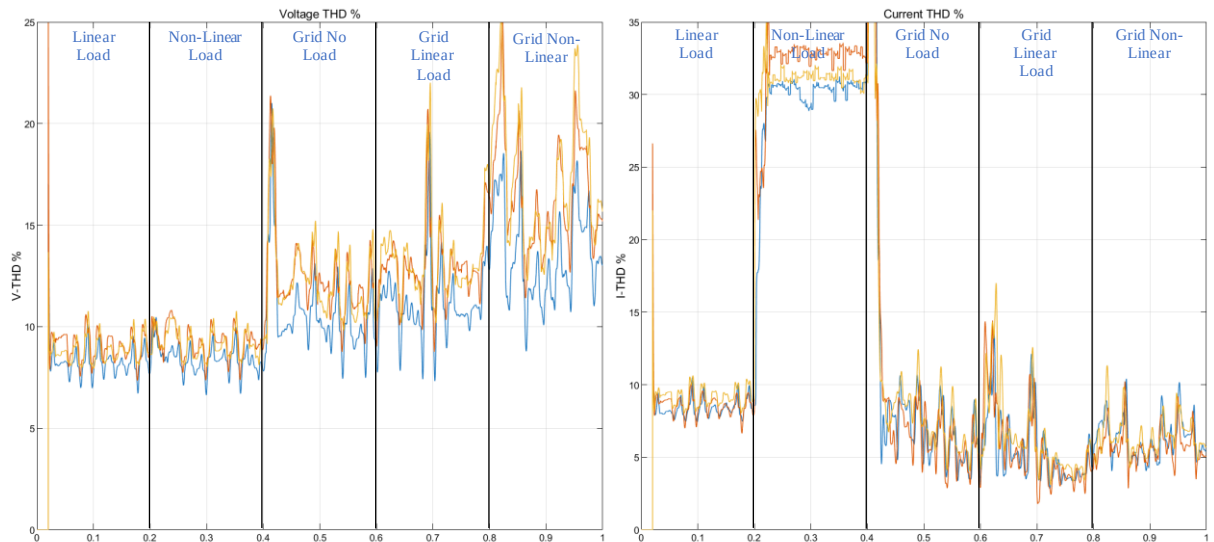


Figure 52: Output Voltage and Current THD % Using Acos PLL

The Acos PLL failed to deliver recommended voltage and current three-phase signals. Figure 52 showcases high voltage and current THDs, while current THD % are lowered when connecting to the grid. However, the THD in this case oscillates around 5%, which is not recommended.

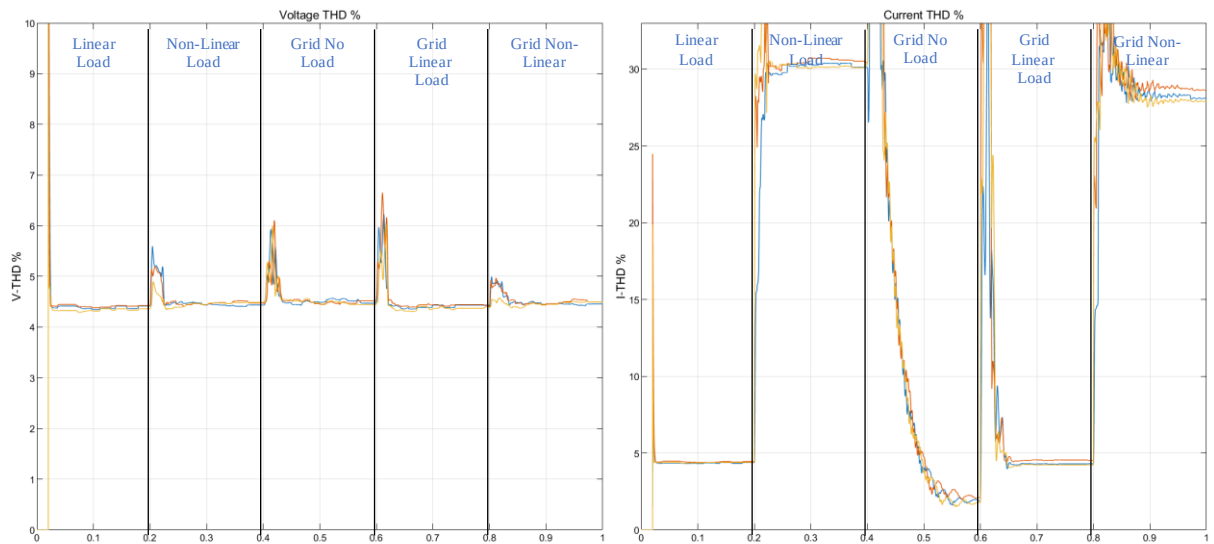


Figure 53: Output Voltage and Current THD % Using Atan2 PLL

Atan2 PLL proved to be a viable alternative to PID PLL, despite its simplicity (Compare figures 53 and 51). The performance characteristics of Atan2 are like its PID alternative, except in one load type, which is the grid connected non-linear load. The atan2 PLL registered the highest current THD % reaching to 28%.

2.4.6. Conclusion

PID:

The PID method, utilizing the abc to dq0 transformation and a PI controller, achieves the best overall performance among the three methods investigated. Key performance metrics include:

- **Transient Response:** Superior transient response, ensuring rapid adaptation to changes in load and system conditions.
- **THD:** Achieves the lowest THD, making it highly effective in maintaining signal quality.
- **Adaptability:** Performs optimally across all load configurations, both linear and non-linear, connected to the grid or standalone.
- **Phase Correction:** Exhibits reliable phase correction with wider pulse widths under different load conditions, ensuring stable operation.

Simplified Acos PLL:

The Simplified Acos PLL, using the $\alpha\beta 0$ stationary reference frame and the $\text{acos}^{-1}(x)$ function for phase detection, shows the weakest performance:

- **Transient Response:** Slow transient responses, indicating lag in adapting to changes in load and system conditions.
- **THD:** Higher harmonics compared to the PI and Atan2 PLL methods, which can degrade signal quality.
- **Phase Correction:** Less reliable phase correction, especially under varying load conditions, leading to stability issues.
- **Performance under Load:** Struggles particularly when connected to the grid, showing significant performance degradation.

Simplified Atan2 PLL:

The Simplified Atan2 PLL, which employs the $\text{atan2}(x, y)$ function for phase detection, offers a balanced performance:

- **Transient Response:** Better transient response than the Acos PLL but not as fast as the PID.
- **THD:** Improved harmonic performance over the Acos PLL, but still not as low as the PID.
- **Phase Correction:** Provides smoother and more consistent phase correction with half sinusoidal pulses, improving stability under noise and fluctuations.

- Performance under Load: Generally, performs well across various load configurations but falls short of the PID, especially with non-linear grid-connected loads.

Summary of Performance Differences:

- PID: Best performance in transient response, THD, adaptability, and phase correction, making it the preferred choice for high-performance applications.
- Acos PLL: Least effective, with slow transient response, higher THD, and unreliable phase correction, particularly unsuitable for grid-connected systems.
- Atan2 PLL: Intermediate performance, with reasonable transient response and harmonic improvement over Acos PLL, but not matching the PID's reliability and efficiency, especially under challenging load conditions.

2.5. Voltage Formation Using Hysteresis Control

Hysteresis control (HC) is a prominent method employed in the realm of power electronics, particularly in the context of three-phase inverters. Nonetheless simple in implementation, this technique serves as a robust means of regulating the output voltage and current of inverters, ensuring efficient and reliable operation across various applications, of both grid-tie and stand-alone inverters [12].

At its core, hysteresis control operates on the principle of comparison between a reference signal and the actual output. By dynamically adjusting the switching signals to the inverter's power devices based on this comparison (shown in figure below), hysteresis control effectively maintains the output within a predefined band around the reference signal. This approach offers inherent advantages such as fast response times, inherent overcurrent protection, and simplicity of implementation, making it a preferred choice for numerous real-time control applications [12].

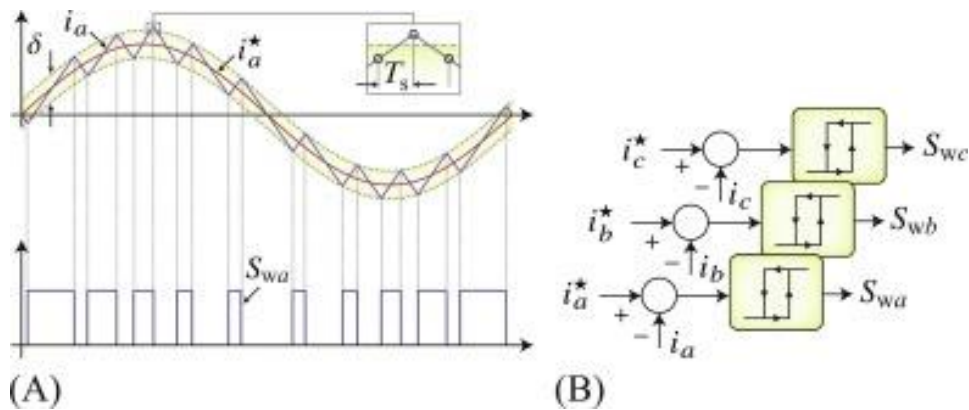


Figure 54: Hysteresis current control for a three-phase two-level power converter: (A) operation principle for line “A” and (B) block diagram. [13]

The figure 54 highlights four fundamental parameters for the HCC operation: i_a^* , i_a , δ , and S_{wa} .

i_a^* : Reference signal for optimal current waveform.

i_a : Actual signal measured at the output of the inverter.

δ : Band length, which represents the acceptable deviation of the actual signal deviates from the reference signal.

S_{wa} : The switching signal for the inverter. When the actual signal drop to the lower band, it activates the rising edge of S_{wa} .

In the domain of three-phase inverters, hysteresis control plays a pivotal role in ensuring accurate and responsive modulation of the output voltage and current waveforms. By

continuously monitoring the deviations between the desired output and the actual performance, the controller swiftly adjusts the switching states of the inverter's semiconductor devices to maintain precise control over the output parameters. HC offers advantages such as precise regulation and robustness for both output current and voltage.

However, the key to its effectiveness lies in selecting an appropriate hysteresis band, which determines the control's behavior. Classical hysteresis control employs a constant hysteresis band, resulting in variation in switching frequency over the fundamental inverter period. This variation directly impacts several aspects of the system, including filter design, semiconductor selection, current ripple, and AC voltage variation. In addition, applying HC to three-phase inverters introduces new challenges, such as the coupling between phase currents induced by interference between switching voltages among phases, especially in systems without a neutral point.

To mitigate this issue, some researchers propose decoupling hysteresis approaches or introducing a small dead zone between hysteresis bands. These strategies aim to minimize the undesirable effects of phase coupling, thus improving the overall performance and reliability of the three-phase inverter system. [12]

Control Modes Advantage of HC

HC is versatile, operating in different modes to suit diverse applications. It regulates power systems efficiently, ensuring stable output currents or voltages within predefined limits. This adaptability makes HC invaluable across industries, from renewables to industrial automation [14].

When it comes to control modes, HC has proven in many applications its robustness whether with linear or nonlinear controls.

1. **PID Control:** As described previously in the Closed-Loop Feedback PWM, PID control is a widely used linear control technique that adjusts the output of a system based on the proportional, integral, and derivative terms of the error signal. In combination with hysteresis control, PID can provide enhanced performance by fine-tuning the control response based on the system's error dynamics.
2. **Sliding Mode Control (SMC):** Sliding mode control is a nonlinear control technique that aims to drive the system states towards a predefined sliding surface, where the dynamics become simpler to control. SMC can be used alongside hysteresis control to ensure robustness against uncertainties and disturbances in the system, particularly in applications where precise tracking of reference signals is crucial. Figure 55 presents an implementation diagram of SMC.

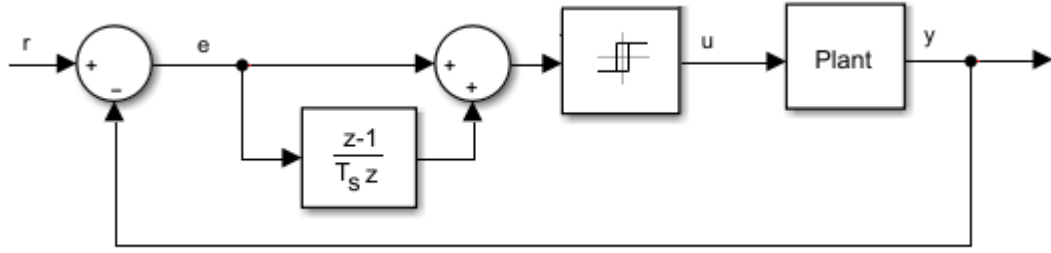


Figure 55: SMC block implements hysteresis-based sliding mode control [15]

3. **Model Predictive Control (MPC):** MPC is a sophisticated nonlinear control technique that utilizes a dynamic model of the system to predict future states and optimize control inputs over a finite time horizon. When combined with hysteresis control, MPC can offer superior performance in terms of tracking accuracy, disturbance rejection, and constraint handling, making it suitable for advanced control applications in PV systems, motor drives, and power electronics [16]. Figure 56 presents an implementation of MPC.

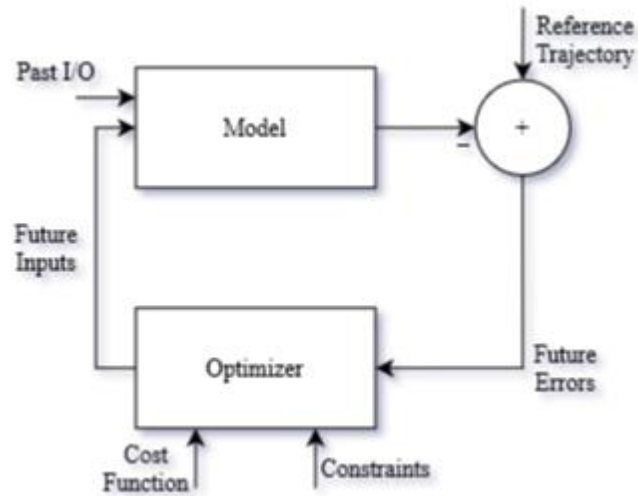


Figure 56: Basic Structure of MPC [16]

4. **Fuzzy Logic Control (FLC):** Fuzzy logic control is a nonlinear control technique that uses linguistic variables and fuzzy rules to emulate human-like decision-making processes. When integrated with hysteresis control, FLC can provide adaptive and robust control in complex and uncertain environments, where conventional control techniques may struggle to perform optimally.

Hysteresis controllers offer several advantages adaptive to the other control technique, notably [14]:

Direct Consideration of Switching Behavior: Hysteresis controllers allow for the direct consideration of the switching behavior of the power inverter during the design phase. This means that the controller can account for the specific characteristics of the inverter's switching dynamics, resulting in more accurate and tailored control strategies.

Robustness to Load Parameter Variations: Hysteresis controllers exhibit robustness to variations in load parameters. This robustness can be mathematically proven, indicating that the controller can maintain stable performance even when the load conditions change, such as variations in resistance or inductive reactance.

Almost Static Response: Hysteresis controllers achieve an almost static response, meaning that the dynamics of the control system are primarily bounded by the DC-link voltage and the actual switching frequency of the inverter. This characteristic ensures stable and predictable behavior, with minimal transient effects.

Simple Hardware Implementation: Hysteresis controllers offer the advantage of simple hardware implementation. They can be realized using logical devices, which align with the Boolean nature of the controller's input and output variables. This simplicity in hardware design enhances the feasibility and cost-effectiveness of implementing hysteresis control in practical systems.

2.5.1. Current Control (HCC)

HCC stands out as a robust and effective technique utilized in the realm of PV connected inverters. As the demand for renewable energy sources intensifies, particularly solar power derived from PV systems, the need for efficient and reliable control methodologies becomes increasingly paramount. HCC presents itself as a promising solution, offering precise regulation of output current while ensuring high power quality in PV applications.

At its core, HCC operates on the principle of comparing a reference current signal with the actual output current. By dynamically adjusting the switching signals to the inverter's power devices based on this comparison, HCC effectively maintains the output current within a predefined band around the reference signal. This approach provides inherent advantages such as fast response times, inherent overcurrent protection, and simplicity of implementation, making it an appealing choice for real-time control in PV systems.

2.5.1.1. Simulink Model

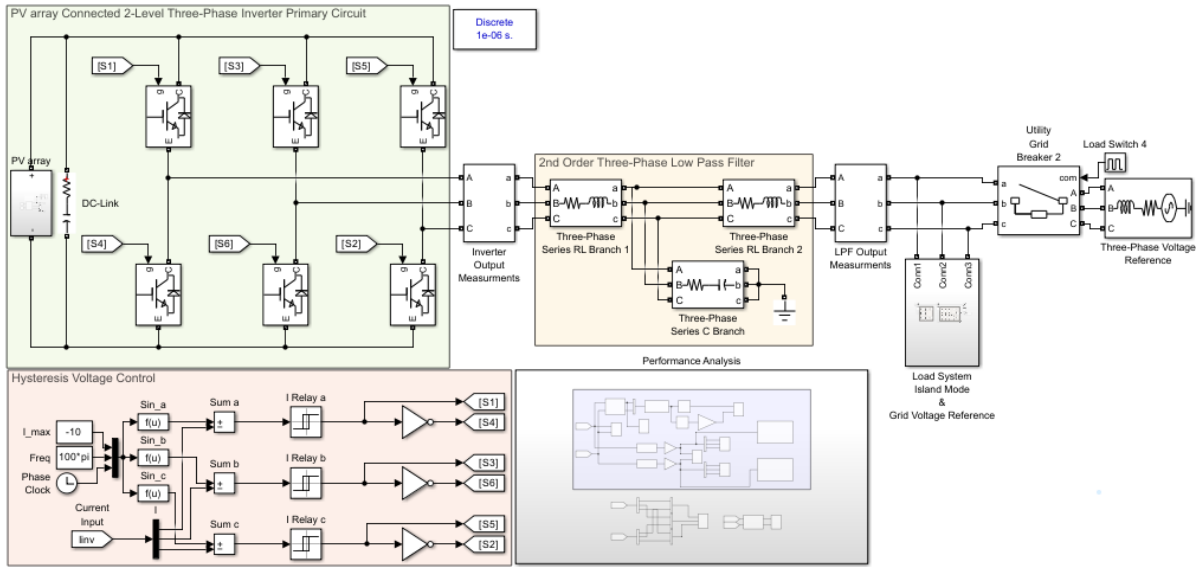


Figure 57: HCC Controlled Three-Phase Inverter Simulink Model

For the HCC simulation in Simulink (Figure 57), requires setting a value for the peak current value I_{max} of the reference signal. I_{max} value depends on the load configuration and the maximum current the PV array can generate. In this simulation, $I_{max} = 10$ A. The desired reference signal is compared to the three-phase current at the inverter output.

Performance analysis uses three load presets:

- Island Mode: Load is linear or non-linear for 200 ms each of the simulation running time, with no grid connection.
- Direct Grid Connection: No load at the Common Coupling Point (CCP) for 200 ms.

- Loads Connected to Grid: Loads are connected along with the grid for 200 ms.

2.5.1.2. Results and Analysis

HCC performs excellently with various load types, maintaining a consistently sinusoidal AC output voltage with no apparent ripples. However, the voltage peak value varies with different load configurations, which can be a limitation in applications requiring a precise $240 V_{rms}$ output. Adjustments are needed to maintain the desired AC voltage (See figure 58).

The peak AC voltage V_{max} ranges from 380V to 480V depending on the load configuration. When the load is connected to the grid, the AC voltage stabilizes at an optimal $240 V_{rms}$.

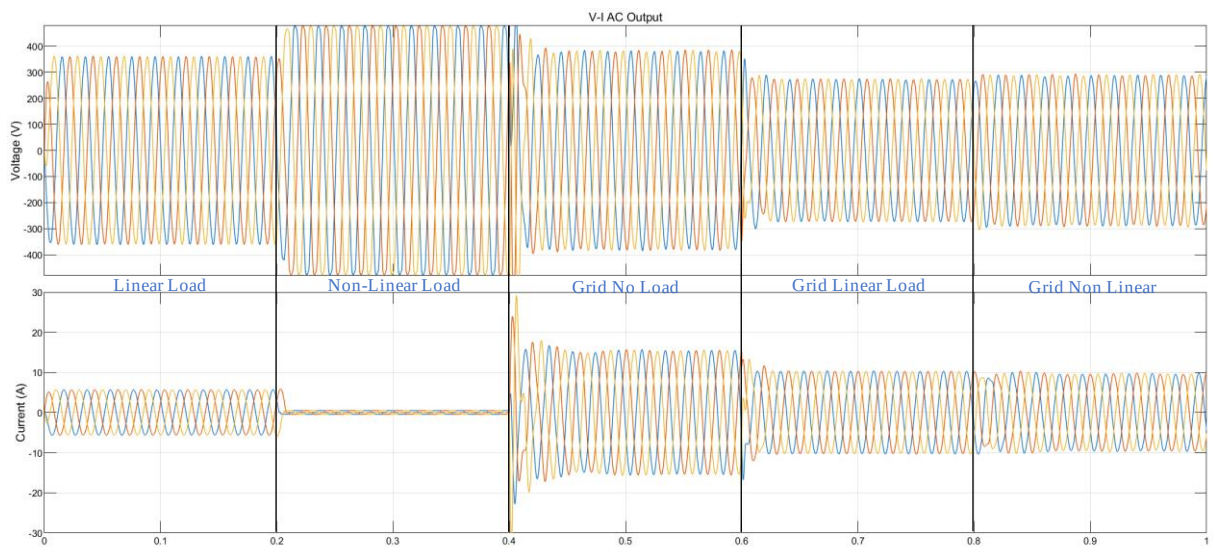


Figure 58: Inverter Output Voltage and Current Using HCC

A closer examination of the AC waveforms in figure 59 reveals that non-linear loads not connected to the grid exhibit flat peaks due to the voltage drop across diodes in the rectifier bridge. This issue is mitigated when the load is connected to the grid, which supplies additional current, reducing the diode effects. This improvement is demonstrated by the AC waveform and a reduced THD percentage when the non-linear load is connected to the grid.

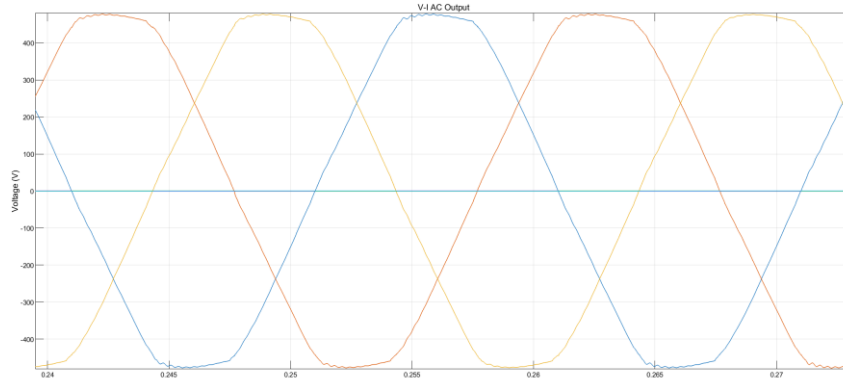


Figure 59: Zoom-In on the Voltage Curve in Figure 58 During Isolated Non-Linear Load

The three-phase current shows no significant ripples except for the isolated non-linear load, where the current appears as a stair-step signal due to the rectifier bridge effects.

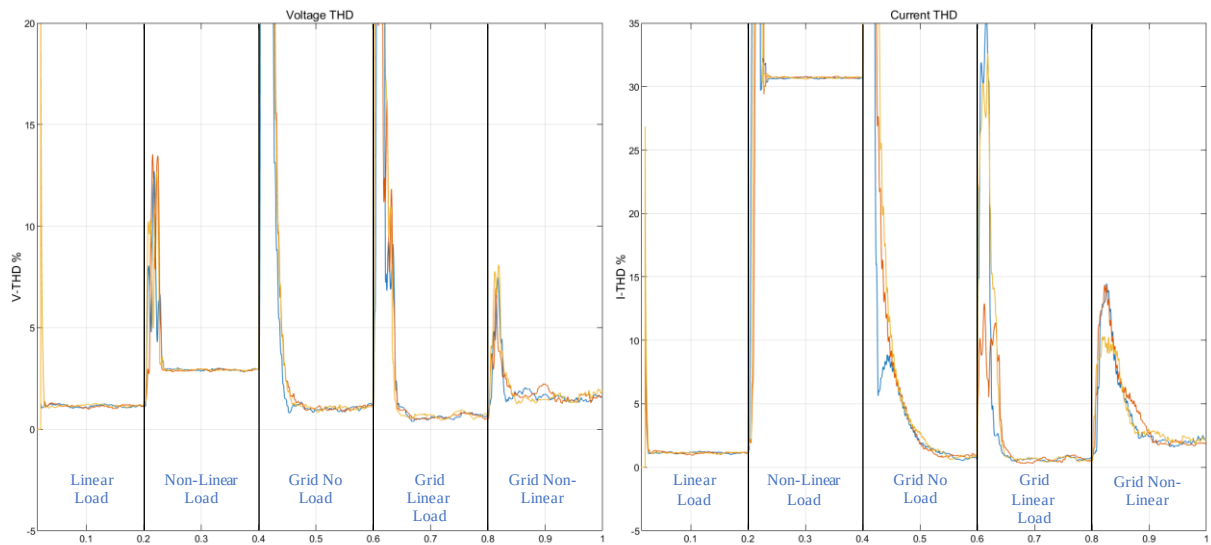


Figure 60: Output Voltage and Current THD % using HCC

The voltage THD across all loads in figure 60 remains below 5%, with an average THD of about 1.5% for most configurations. The highest voltage THD level, at 3%, occurs with the isolated non-linear load.

The current THD generally mirrors the voltage THD performance, except for the isolated non-linear load, where the current THD exceeds 30%.

During the simulation, loads are switched every 200 ms, leading to high THD levels in both current and voltage at the beginning of each interval (i.e., at 200 ms, 400 ms, 600 ms, and 800 ms). This indicates a transient response when the system is first powered on or when significant changes in electrical parameters occur. Such transient responses are common in many electrical systems, including inverters, as the system requires time to reach steady-state operation after power is applied or load conditions change.

2.5.2. Modified Hysteresis Voltage Control (mHVC)

The modification of Hysteresis Current Control method (HCC), in which instead of current, the voltage is observed has been proposed in master thesis. This method, referred to mHVC, ensures that the inverter does not exceed $V_{rms} = 240\text{ V}$, by monitoring the voltage instead of the current as it is the case in HCC. It requires changes at both the control block level and the low pass filter. Simulation results are optimal when using a simple Three-Phase Low Pass Filter based just on inductances. The inductance is connected in series between inverter output and load.

2.5.2.1. Simulink Model

The circuit diagram of the Simulink model that implements the mHVC is presented in figure 61. At the control system level, the reference signal represents the desired three-phase AC peak voltage $V_{peak} = \frac{V_{rms}}{\sqrt{2}}$ at 50 Hz. The AC voltage input, which is compared to the reference signal, is measured at the CCP.

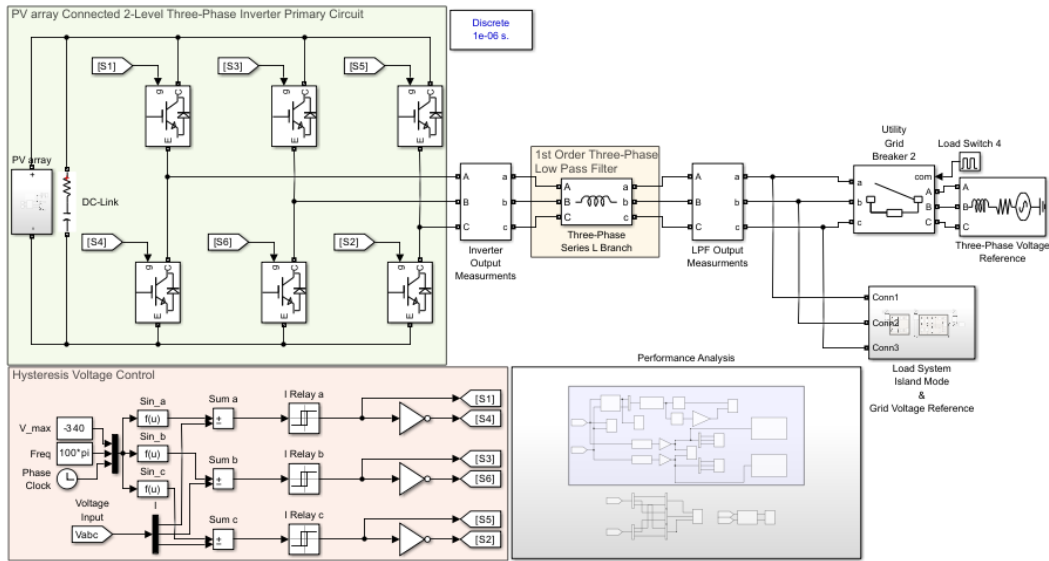


Figure 61: mHVC Controlled Three-Phase Inverter Simulink Model

The mHVC (Figure 61) ensures that the inverter does not exceed the $V_{RMS} = 240\text{ V}$, by monitoring the voltage instead of the current in HCC. It requires changes at both the control block level and the low pass filter. Simulation results are optimal when using a simple first-order inductive Three-Phase Low Pass Filter. The inductance is connected in series between the inverter and the CCP.

At the control system level, the reference signal represents the desired three-phase AC voltage of 240 V_{rms} at 50 Hz. The AC voltage input, which is compared to the reference signal, is measured at the CCP.

2.5.2.2. Analysis and Results

The mHVC operates as expected, providing a three-phase AC voltage of $V_{rms} = 240\text{ V}$ when isolated from the grid. However, mHVC fails to deliver smooth AC signals for both voltage and current when connected to a rectifier bridge load.

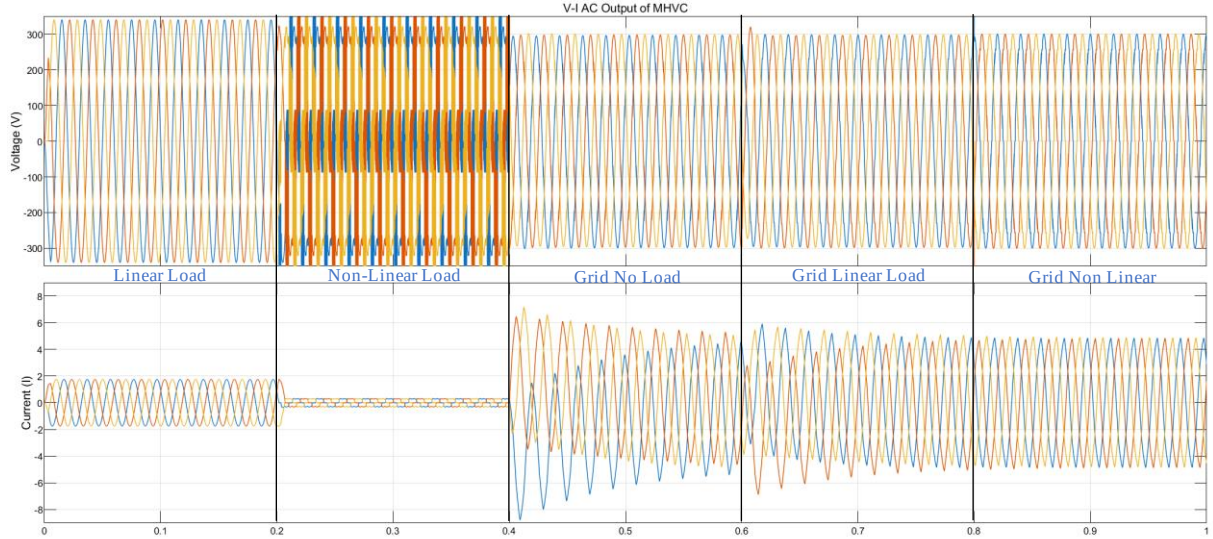


Figure 62: Inverter Output Voltage and Current Using mHVC

When connected to the grid, as shown in figure 62, the voltage is suppressed to 300V peak due to the grid's impedance. In this scenario, the current exhibits a slow transient response. The transient response improves and becomes faster when the load is connected to the grid.

The simulation demonstrates that mHVC can effectively manage non-linear loads if connected to the grid. In this case, both voltage and current have very fast transient responses, resulting in very smooth three-phase AC signals.

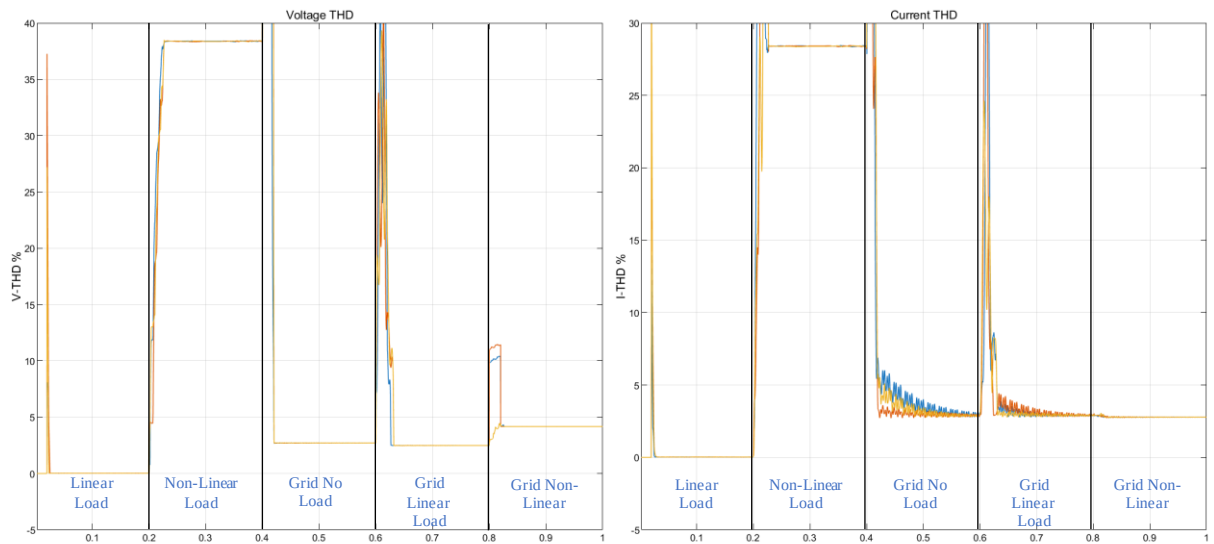


Figure 63: Output Voltage and Current THD % Using mHVC

The THDs of mHVC and HCC are similar for most load types, with THD percentages falling under 5%, indicating optimal operation (Compare figures 63 and 60).

For a non-linear load isolated from the grid, the voltage and current THDs are 37% and 27%, respectively. However, when connected to the grid, these THD percentages are significantly reduced to optimal operation conditions, with voltage THD around 4% and current THD about 2.5%.

2.5.3. Conclusion

In conclusion, Hysteresis Control offers advantages in not requiring a Closed Feedback Loop for grid connection, which reduces the complexity of the control system significantly.

- HCC demonstrates flexibility with various load types. However, it necessitates setting the current offset correctly and lacks the ability to precisely control voltage to match a specific RMS value.
- The proposed mHVC guarantees the desired V_{rms} of the three-phase AC voltage if system impedance is configured correctly. It effectively handles non-linear loads when connected to the grid, significantly reducing THD from 28% to 2%. mHVC also allows to use a simpler low-pass filter than its counterpart HCC (Compare filter presented in Figure 61 with this one provided in Figure 57). The filter in mHVC based inverter only includes inductances that are connected in series between every output of the inverter and load, while the low-pass filter used in HVC based inverter is more complex.
- The drawback of the mHVC based inverter is that it may exhibit slow transient response in current depending on control tuning and might perform poorly with non-linear loads when not connected to the grid.

3. Conclusion and Suggestions

This report provides an in-depth investigation of various photovoltaic inverter three-phase voltage forming methods and control algorithms, focusing on their performance in terms of transient response, total harmonic distortion (THD), adaptability, and phase correction. The investigation was conducted using Simulink.

The primary focus was on the inverter voltage forming method based on Sinusoidal Pulse Width Modulation (SPWM), both without output voltage feedback control and with different output voltage control algorithms. These algorithms include Closed Loop Feedback, PI PLL, Simplified Acos PLL, and Simplified Atan2 PLL.

Additionally, the study examined the photovoltaic inverter voltage forming method based on Hysteresis Current Control (HCC). A modified Hysteresis Voltage Control (mHVC) method was also proposed and analyzed, with its advantages and drawbacks clearly demonstrated.

SPWM

SPWM offers significant advantages in terms of ease of implementation and the ability to achieve very low THD for linear loads, producing high-quality sinusoidal output. However, its inability to adapt to variations in input voltage and reliance on manual configuration for optimal performance are notable drawbacks. SPWM also struggles with non-linear loads and grid-connected scenarios, limiting its applicability in dynamic and complex environments.

Closed Loop Feedback PWM

The Closed Loop Feedback PWM method exhibits excellent performance in meeting grid requirements with a smooth voltage signal and minimal harmonic distortion. It achieves low THD levels for both voltage and current signals, making it suitable for a wide range of applications. Despite a slight increase in current THD under non-linear loads, the system demonstrates robust adaptability and maintains stability, highlighting its effectiveness in dynamic conditions.

Phase-Locked Loop (PLL) Methods

Among the PLL methods investigated:

- PID: Emerges as the superior method with the best overall performance. It excels in transient response, THD reduction, adaptability, and reliable phase correction, making it the preferred choice for high-performance applications.
- Simplified Acos PLL: Shows the weakest performance, with slow transient responses, higher THD, and unreliable phase correction, particularly unsuitable for grid-connected systems.
- Simplified Atan2 PLL: Offers a balanced performance, providing reasonable transient response and improved harmonic performance over the Acos PLL. However, it does not match the reliability and efficiency of the PID, especially under challenging load conditions.

Voltage Formation based on Hysteresis Control Methods

Hysteresis Control methods demonstrate distinct advantages and limitations:

- HCC: Simplifies the control system by not requiring a Closed Feedback Loop for grid connection and offers flexibility with various load types. However, it requires precise current offset settings and lacks voltage control precision.
- Proposed mHVC: Enhances voltage regulation and effectively reduces THD when handling non-linear loads connected to the grid. It requires less configuration effort than HCC but may exhibit slow transient responses and challenges with non-linear loads in standalone configurations.

Summary

The findings of this report underscore the importance of selecting the appropriate voltage formation strategy based on the specific requirements and constraints of the application.

- ✓ No Loop SPWM is beneficial for applications requiring simple implementation and high-power quality for linear loads but is less suitable for dynamic and complex environments.
- ✓ Closed Loop Feedback SPWM and PID methods stand out for their superior performance across various metrics, offering robust solutions for both grid-connected and standalone PV inverter systems.
- ✓ Hysteresis Control methods provide flexibility and simplicity, with mHVC showing promise in voltage regulation and harmonic reduction for non-linear loads.

Overall, this report highlights the critical balance between simplicity, performance, and adaptability in the design and control of three-phase PV inverters, guiding future innovations and applications in the renewable energy sector.

Table 3: Summary of Average THD of Investigated PV Inverter Voltage Formation Algorithms

		Load Configuration				
		Linear	Non-Linear	Grid Connected No Load	Grid Connected Linear	Grid Connected Non-Linear
No Loop SPWM	V-THD	0.002 %	5.15 %	Inoperable		
	I-THD	1 %	30.8 %			
CL-SPWM	V-THD	Requires Grid for operation		Non-Tested	0.009 %	0.009 %
	I-THD				1.5 %	1.5 %
PID PLL SPWM	V-THD	4 %	4 %	4 %	4 %	4 %
	I-THD	4 %	31 %	1 %	1 %	6 %
Acos PLL SPWM	V-THD	10 %	10 %	12 %	12 %	15 %
	I-THD	9 %	33 %	8 %	5 %	7 %
Atan2 PLL SPWM	V-THD	4.5 %	4.5 %	4.5 %	4.5 %	4.5 %
	I-THD	4.5 %	30 %	2 %	4 %	28 %
HCC	V-THD	0.8 %	3 %	1 %	0.5 %	1.2 %
	I-THD	0.8 %	31 %	0.8 %	0.8 %	2.5 %
mHVC	V-THD	< 0.1%	48 %	2.5 %	2.5 %	4.5 %
	I-THD	< 0.1%	28 %	4 %	4 %	4 %

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