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Department of Electrical Engineering

Thesis submitted for the attainment of the Academic Master's degree

processor in the loop implementation of a single phase inverter for standalone applications

Presented by:

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Academic year: 2023/2024

Dedication

To my dear parents:

Thanks to their tender encouragement and great sacrifices, they were able to provide a climate filled with love and support for the continuation of my studies. They devoted their lives to building my future, and let this work be the fruit of their countless sacrifices. No dedication can express my respect, appreciation, and deep feelings towards them. I pray to God to bless and protect them, and I hope to always be a source of pride for them.

To my dear brothers and sisters:

Who are always my source of joy and happiness, I will never find enough words to express my love for them.

To my extended family, and everyone who has helped me near or far:

Here you will find an expression of my respect and gratitude for your continuous support.

To all my friends and colleagues in studies:

I thank them for their support and assistance throughout my academic journey.

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- My supervisor CHOUDER Aissa for his support and valuable advice.
- The jury members for their suggestions and constructive criticisms.
- My family and friends for their unwavering support.

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Abbreviations

- THD: Total Harmonic Distortion
- DSP: Digital Signal Processing
- PWM: Pulse Width Modulation
- DC: Direct Current
- AC: Alternating Current
- PI: Proportional-Integral
- VSI: Voltage Source Inverters
- PR: Proportional-Resonant
- MPC: Model Predictive Control
- SM: Sliding Mode
- MG: Microgrid
- FCS: Finite Control Set
- DFT: Discrete Fourier Transform
- IEC: International Electrotechnical Commission
- CIGRE: International Council on Large Electric Systems
- CIRED: International Conference on Electricity Distribution
- MCS: Model Predictive Control
- CCS: Code Composer Studi

ملخص:

يهدف المحول ذو المرحلة الواحدة إلى تحويل التيار المستمر (DC) إلى التيار المتردد (AC) باستخدام مفاتيح إلكترونية وتقنيات تعديل عرض النبضات .(PWM) في هذا المشروع، تم إجراء المحاكاة باستخدام برنامجPSIM ، الذي يوفر بيئة مثالية لنمذجة وتحليل الدوائر الكهربائية، مما يساعد في اختبار وتحسين أداء المحول قبل التنفيذ العملي. تمت عملية التحكم باستخدام بطاقة DSP F28335للتحكم بدقة في عملية التحويل، حيث تتيح هذه البطاقة تنفيذ خوارزميات التحكم في الوقت الحقيقي، مما يعزز جودة وكفاءة الموجة الناتجة.

Abstract:

The single-phase inverter aims to convert Direct Current (DC) into Alternating Current (AC) using electronic switches and Pulse Width Modulation (PWM) techniques. In this project, simulations were conducted using the PSIM software, which provides an ideal environment for modeling and analyzing electrical circuits, aiding in testing and improving the performance of the inverter before practical implementation. The control process was carried out using the DSP F28335 card to precisely manage the conversion process, as this card allows for the implementation of real-time control algorithms, thereby enhancing the quality and efficiency of the output waveform.

Résumé:

L'onduleur monophasé vise à convertir le courant continu (DC) en courant alternatif (AC) en utilisant des interrupteurs électroniques et des techniques de modulation de largeur d'impulsion (PWM). Dans ce projet, des simulations ont été réalisées en utilisant le logiciel PSIM, qui offre un environnement idéal pour la modélisation et l'analyse des circuits électriques, aidant ainsi à tester et à améliorer les performances de l'onduleur avant la mise en œuvre pratique. Le processus de contrôle a été effectué en utilisant la carte DSP F28335 pour gérer avec précision le processus de conversion, car cette carte permet la mise en œuvre d'algorithmes de contrôle en temps réel, améliorant ainsi la qualité et l'efficacité de la forme d'onde de sortie.

General introduction

The applications of electronics were long limited to high-frequency techniques. The possibilities of application were constrained by the lack of reliability of the available electronic components. This reliability was insufficient given the requirements of new applications in the industrial domain. It was only with the development of special electronic components with higher reliability and tighter tolerances that new techniques could be considered, giving rise to a new branch of electronics called power electronics [1].

At present, this discipline of electrical engineering encompasses vast and diverse areas of application for powers covering a wide range, from a few watts to several hundred megawatts.

Voltage inverters can be controlled using several types of commands. Full-wave control is the basic technique used for two-level inverters. In this case, the control signal and the desired output voltage have the same frequency. However, the latter has power limitations and a large number of troublesome harmonics.

The drawbacks of these basic controls have spurred research to explore new strategies to improve inverter performance. The most advanced technique is pulse width modulation. This strategy involves controlling the inverter at high frequency, allowing both frequency and amplitude to be varied while keeping the DC source constant.

However, the implementation of these strategies requires very costly and bulky installations and circuits. To address this, the digital solution remains the most appropriate. Indeed, the

development of digital processors has boosted research efforts and shortened the time required for implementing these controls. The applications of electronics were long limited to high-frequency techniques. The possibilities of application were constrained by the lack of reliability of the available electronic components. This reliability was insufficient given the requirements of new applications in the industrial domain. It was only with the development of special electronic components with higher reliability and tighter tolerances that new techniques could be considered, giving rise to a new branch of electronics called power electronics [1].

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The aim of this work is to implement control over single-phase DC/AC converters using PI controllers and applying them with a DSP card.

The first chapter introduces the operating principle of the single-phase converter, along with the concept of PWM and its operation method, which will aid in understanding the system. Additionally, we touch upon a general concept of Total Harmonic Distortion (THD).

In the second chapter, we delve into simulating the system and its conversion from analog to digital, highlighting the accuracy of the obtained results.

In the third chapter, we provided a concise overview of the DSP card, its operation

mechanism, and processing structure. We then discussed PIL (Processor-In-the-Loop) and proceeded to inject the code into the DSP card, conducting simulations with the DSP processing unit, and precisely discussing the outcomes

Chapter I Overview of Inverter

1. Single Phase Inverter

1.1 Introduction:

Devices with single-phase functionality in inverters play a crucial role in converting direct current (DC) to alternating current (AC). These devices have wide-ranging applications across various fields such as solar power generation systems, electric motor operation, emergency power supplies, computers, and numerous other household and industrial applications, The process of converting DC to AC is executed precisely and efficiently by the inverter. The fundamental mechanism of the inverter consists of two main stages: the DC to AC conversion stage and the output filtering stage.In the DC to AC conversion stage, electronic switches such as transistors or thyristors are used to convert DC to AC. These switches are controlled by a dedicated control unit, which manages the sequencing, timing, and modulation of these switches to generate AC with the desired frequency and voltage.In the output filtering stage, once the AC current is generated through the inverter stage, the signal is filtered to eliminate any distortion or noise. This is achieved using capacitors, LC filters, and other electronic components to purify the AC current and make it suitable for the specific application.The efficiency and performance of the inverter depend significantly on the quality of its design and the components used. Some specific applications may require additional features such as frequency and voltage control, protection against overcurrent and overvoltage, and speed control of motors.

1.2 Analysis and Synthesis of Inverters:

Throughout this chapter, we have outlined the structure of the inverter, its general operating principle, and its various variants. Additionally, we will discuss some of the application areas of inverters. Then, we focused on the general study of multi-level voltage inverters. These are widely used in medium-voltage and high-power application areas due to their numerous advantages such as power quality, electromagnetic compatibility, low switching losses, and their ability to operate at high voltage. Additionally, they allow for reducing harmonic content in the output voltage and current. In the last part of this chapter, we will address the operating principle.

In the field of power electronics, a converter is constantly interacting with other electrical systems called subsystems. The goal is to assign a specific function to the converter, controlled either by an analog card or digitally by a processor or controller. It is crucial to define and characterize this

function. The subsystems of a system intended to power a load present potential failure risks due to their sensitivity to operating conditions. Furthermore, the introduction of electro- nics into control systems offers advantages in terms of flexibility and precision of adjustment. However, as a trade-off, the signals used in electronic cards are often disturbed by the systems

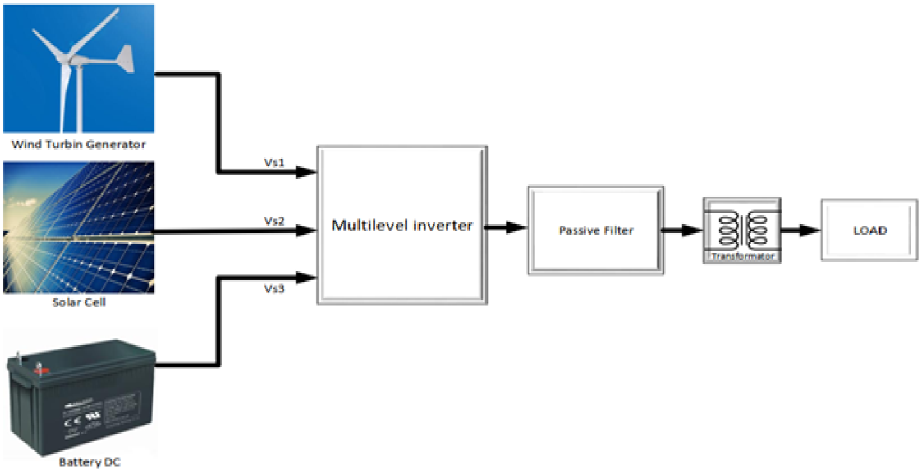

Figure (I.1). Diagram of a solar-based power generation system of multilevel inverter

1.3 Characteristics of an Invertery:

they are supposed to control (self-interference). Sometimes, the cards are subjected to exter- nal interference signals that render certain controls inoperative. Electromagnetic Compatibility (EMC) is an approach that studies the sensitivity to interference of systems. Finally, obtaining information on physical quantities crucial for understanding a system is difficult to establish

2. Synthesis Method:

One might think that only the controlled and transferred power matters, as well as the operation at the level of control signals. One would then only focus on the power components and the drivers allowing their switching control. However, designing and building reliable in- verters is no longer sufficient. Current requirements for protection, grid non-pollution, reactive power supplied by the grid, as well as filtering quality and electromagnetic compatibility, neces- sitate addressing all the constraints they introduce in the design and compliance with inverter standards in the first place. We begin by carefully examining the crucial points and means to reduce the disturbances introduced by inverters, both on the input side, i.e., the alternating current grid, and on the output side, by improving the equivalent source. This includes tech- niques such as sinusoidal absorption, passive filtering(LC type), active filtering(by inverter), as well as passive LC or transformer-based filtering methods, and active filtering with appropriate control.

2.1 State of the Art on Single-Phase inverter:

Thorough examination and presentation of the latest advancements, techniques, and re- search in the field of single-phase inverters. These devices play a crucial role in the conversion of electrical energy, transforming direct current into alternating current, and vice versa, in single-phase applications. In this state of the art, various topologies of single-phase inverters are explored, such as voltage inverters, current inverters, hybrid inverters, etc. The control methods used to ensure precise regulation of output voltage and current, as well as to gua- rantee efficient and reliable operation, are also examined. Furthermore, this state of the art highlights the current challenges and limitations encountered in the design and implementation of single-phase inverters, such as switching losses, harmonic distortion, and component sizing constraints. Proposed solutions to overcome these challenges include the use of advanced mo- dulation techniques, sophisticated control algorithms, and the integration of high-performance components.

2.2 Single-Phase inverter:

Single-phase inverters are electronic devices used to convert direct current (DC) into single- phase alternating current (AC). Their operation relies on a process of switching electronic com- ponents such as transistors and diodes. The conversion process begins with rectifying the input direct current, meaning the direct current is transformed into a pulsed signal. Then, this signal is passed through a filtering circuit that eliminates the alternating components and only allows the continuous voltage variations to pass through. Next, the inverter transistors are activated sequentially or based on a control signal to modulate the waveform of the alternating current. This is achieved by precisely controlling the duration for which each transistor is activated, thereby regulating the output voltage of the inverter. Single-phase inverters typically use pulse width modulation (PWM) or frequency modulation techniques to adjust the voltage and fre- quency of the generated alternating current. These techniques allow for controlling the output voltage by modifying the duration of the voltage pulses generated by the inverter transistors. In summary, single-phase inverters operate by converting direct current into alternating current using transistors and diodes switched in a controlled manner, allowing for precise regulation of the output voltage according to the needs of the application.

3. General Operating Principle of Single-Phase Inverters:

The operating principle of an inverter is based on switching electronics, which generates an alternating voltage waveform from a direct voltage as shown in the diagram.

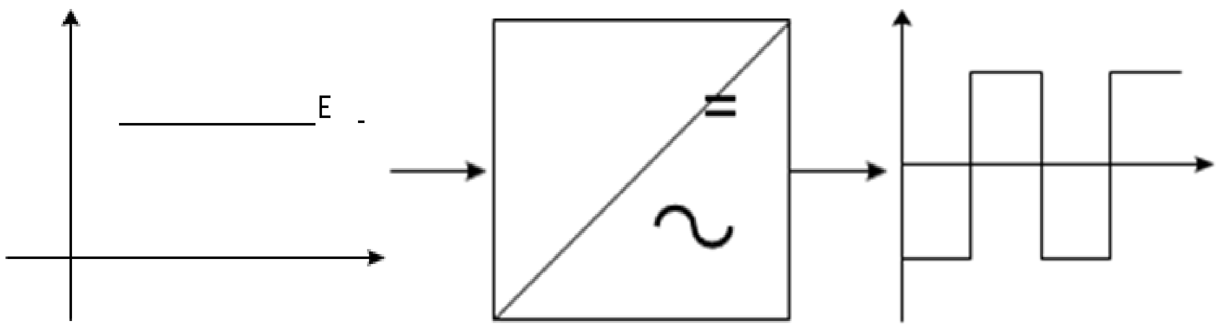

Figure (I.2): – Schematic of DC-AC Conversion

The direct use of a pair of basic switches involves adjusting the frequency and duration

of connections between the source and the output. This results in a time-based approach, leading to the use of pulse width modulation techniques. Amplitude control can be achieved either continuously by creating an adjustable source (which implies the existence of another conversion stage), or discretely by having a sufficient number of sources. When switches S1 - S4 are closed (On) and switches S2 - S3 are open (Off) for $0 < t < T/2$, a positive half- cycle U(t) = VDC is obtained, as shown in the figure. [7]

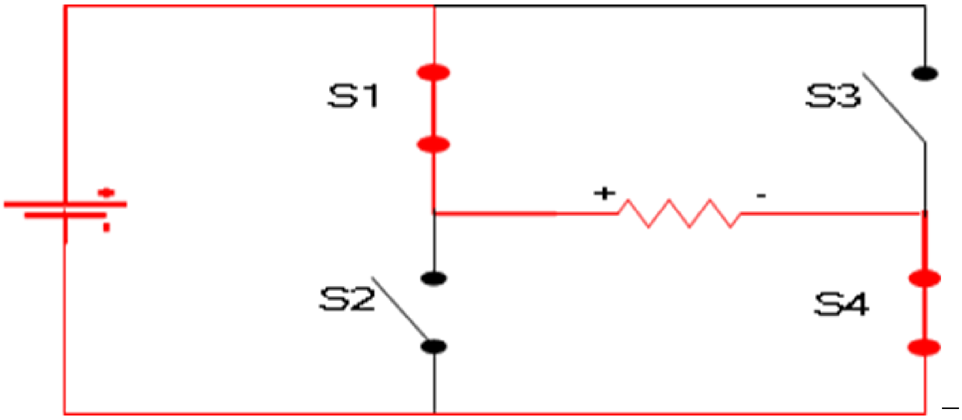

Figure (I.3): Operation of the inverter in the first half-cycle

When S1 - S4 are open (Off) and S2-S3 are closed (On) for T/2 < t < T, we obtain a negative half-cycle U(t) = -VDC as shown in Figure (I.4).

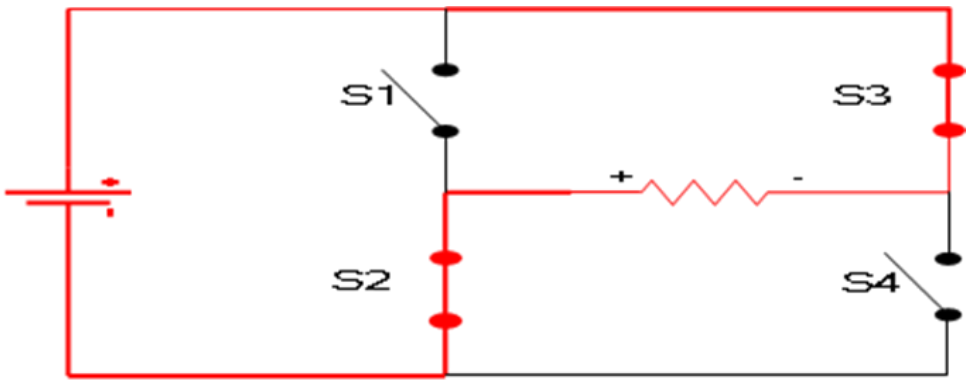

Figure (I.4): – Inverter Operation in Second Half

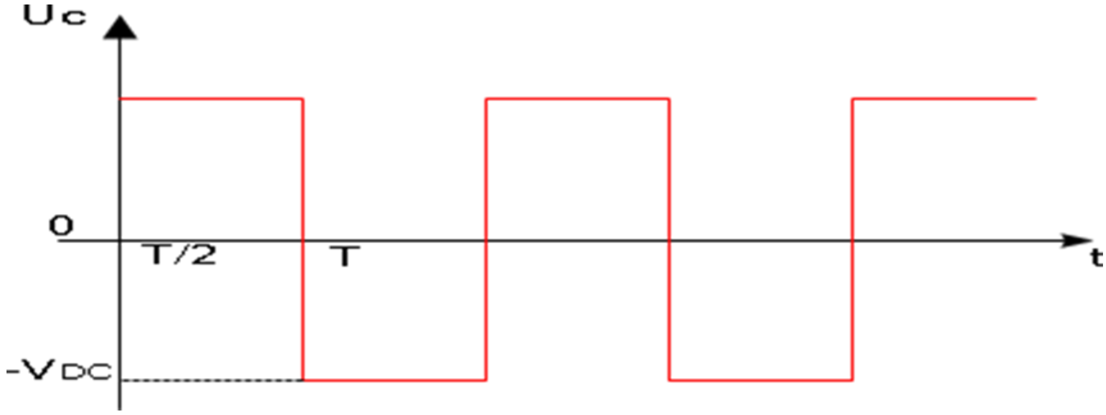

Figure (I.5): Complete signal of the inverter

3.1 Voltage Control in Single-Phase Inverters:

Figure I.5 depicts the schematic of the inverter system. The rectifier or battery provides the direct current power supply for the inverter. The fundamental voltage amplitude and output frequency of the alternating current are managed by the inverter.

When powered by inverters, alternating current loads with variable or constant voltage requirements at their input terminals must have their output voltage precisely adjusted to meet the load's needs. For example, if the inverter powers an induction motor or another magnetic circuit, the voltage/frequency ratio at the output terminals of the inverter must remain constant. By doing so, the magnetic circuit of the device powered by the inverter,

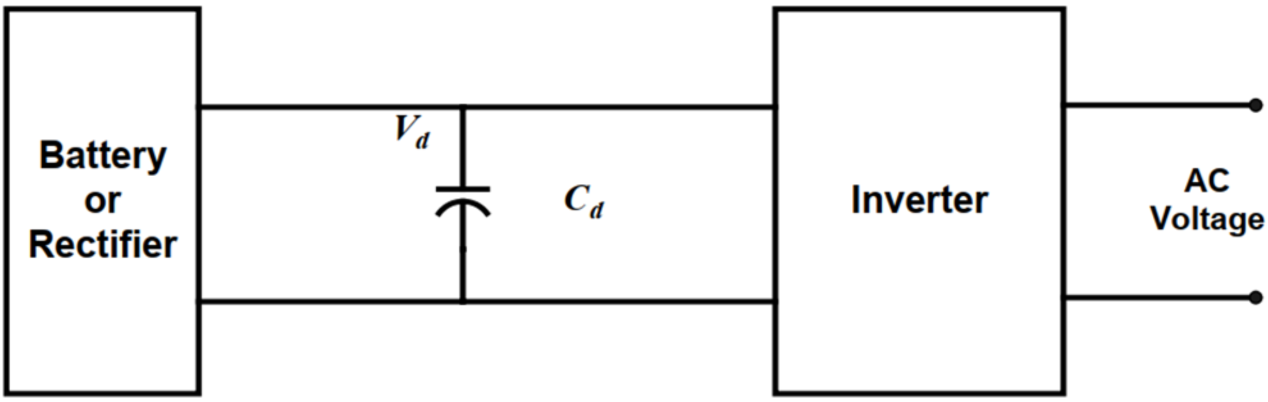

Figure (I.6): Schematic for Inverter System

3.2 Pulse Width Modulation Control:

It is possible to maintain a constant fundamental magnitude of the output voltage of an inverter by internally controlling it; no external control circuit is necessary. The most efficient way to accomplish this is through Pulse Width Modulation

The inverter utilizes a control system called Pulse Width Modulation, or PWM. In this design, a fixed input voltage powers the inverter, and the durations of activation and deacti- vation of the inverter components are adjusted to provide regulated alternating voltage. The advantages of the PWM control scheme are :

- Voltage output control can be achieved without the addition of external components.

- Pulse Width Modulation (PWM) minimizes lower-order harmonics, while higher-order harmonics can be eliminated using a filter.

The drawback of this scheme is that the switching devices used in the inverter are expensive as they need to have low switching times; however, pulse width modulation devices are very popular in all industrial equipment. Pulse width modulation techniques are characterized by pulses of constant amplitude with different duty cycles for each period. The width of these pulses is modulated to achieve control of the inverter output voltage and reduce its harmonic content. There are different pulse width modulation techniques that essentially differ in the harmonic content of their respective output voltages, so the choice of a particular pulse width modulation technique depends on the allowable harmonic content in the inverter output voltage.

4. Advanced Control Techniques for Single-Phase Inverter Systems Utilizing Pulse Width Modulation (PWM):

In single-phase inverter control, Pulse Width Modulation (PWM) technology is utilized to convert electrical power derived from a DC source into AC power. This is achieved by controlling the width of the pulses sent to the electrical devices connected to the inverter.

When employing PWM in single-phase inverter control, variable-width pulses (pulse dura- tion) are generated to control the voltage or current generated at the output. The width of the pulses is determined based on a reference signal such as a square or triangular wave. For example, the pulse width can be adjusted so that the ratio of the pulse-on time to the total period of the cycle (frequency cycle) is proportional to the desired reference values.

By using PWM technology, precise control of the generated AC voltage or current can be achieved, allowing electrical devices to operate with high efficiency and accuracy. The type of control and strategy used in PWM depends on specific application requirements and de- sired performance, including common strategies such as Sinusoidal Pulse Width Modulation (SPWM), which aims to generate AC signals resembling sinusoidal waves. [1]

$$S_{11} = V_{OUT} = \frac{V_D}{2} \quad 1.1$$

$$S_{11} = V_{OUT} = -\frac{V_D}{2} \quad 1.2$$

4.1 Pulse-Width-Modulation (PWM):

Pulse-width modulation (PWM) : offers a means of reducing the load current's overall harmonic distortion.

- The power stage is not changing, but the switching control change.

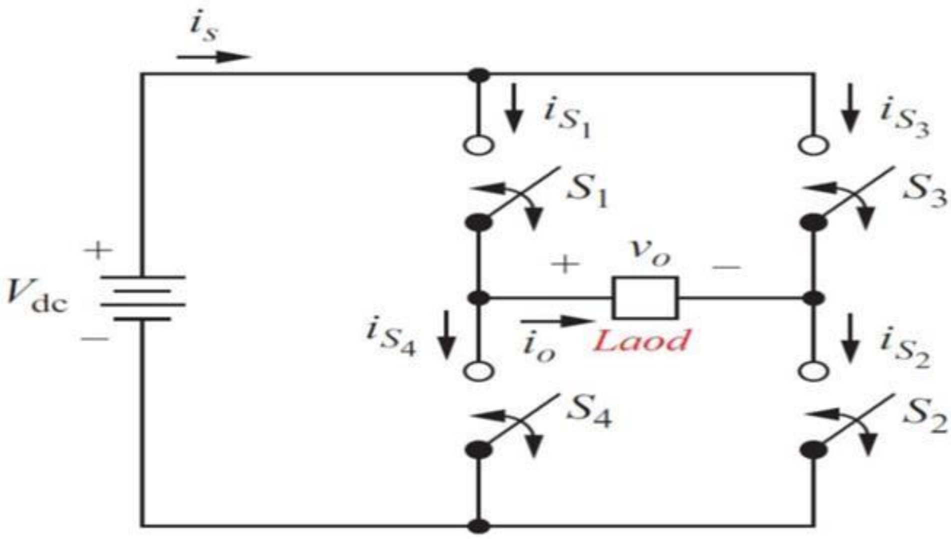

Figure (I.7): Basic inverter circuit [1]

4.2 Bipolar Switching:

The intersections of these two signals—a symmetric fixed frequency signal and a triangle waveform—are used to determine which way to switch

a) S3 and S4 come on when the triangle waveform exceeds the sine waveform. In actuality, the load receives a negative voltage throughout this period.

b) S1 and S2 come on when the Sine waveform exceeds the triangle waveform. In actuality, the load receives a positive voltage during this period.

c) The output voltage can be either positive or negative, therefore it is called. [1]

$$\text{if } Vsine > Vtri \Rightarrow S1\ S2: ON \Rightarrow Vo = Vinv \qquad 1.3$$

$$\text{if } Vsine > Vtri \Rightarrow S3\ S4{:}\ ON \Rightarrow Vo = -Vinv \qquad 1.4$$

- The output voltage has a very significant harmonic and does not appear to be sinusoidal. Actually, it is made up of both the fundamental and harmonic frequencies.

- The undesired harmonics are very high Frequencies. [1]

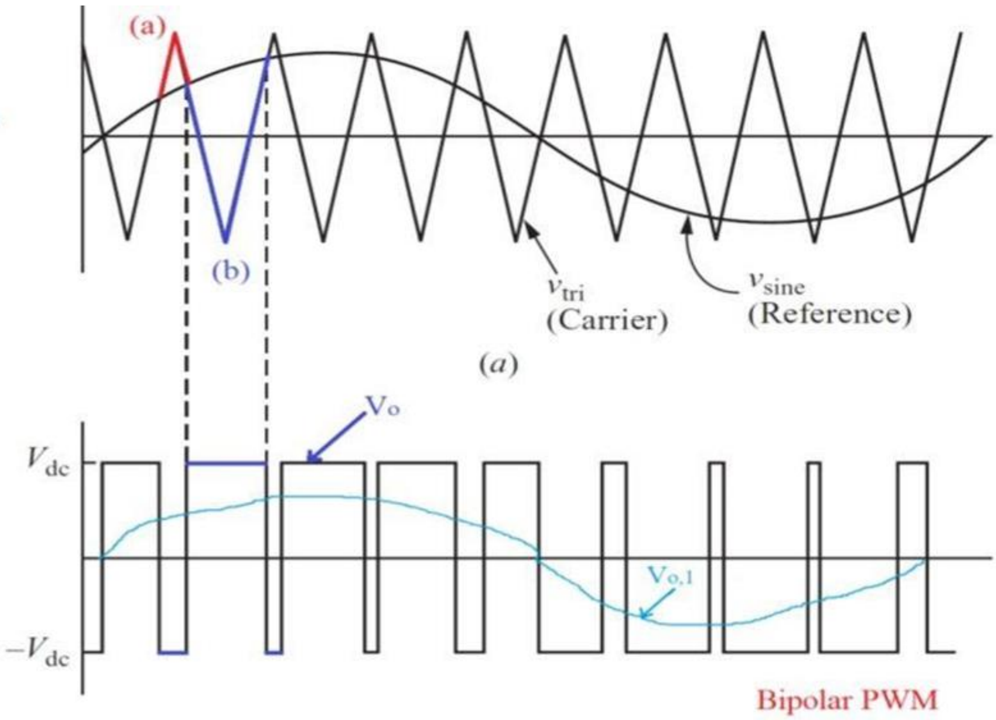

Figure (I.8): Bipolar pulse-width modulation. (a) Sinusoidal reference and triangular carrier; (b) Output voltage. [1]

4.3 Unipolar Switching:

Instead of switching between high and low as in bipolar switching, the output of a unipolar switching system for pulse-width modulation is switched either from high to zero or from low to zero.

Switch controls for one unipolar switching method are shown in Fig (I.7) as follows:

- if Vseni > Vtri S1 : ON
- if Vseni < Vtri S4 : ON

- if -Vseni <V triS2 : ON
- if -Vseni > Vtri S3 : ON

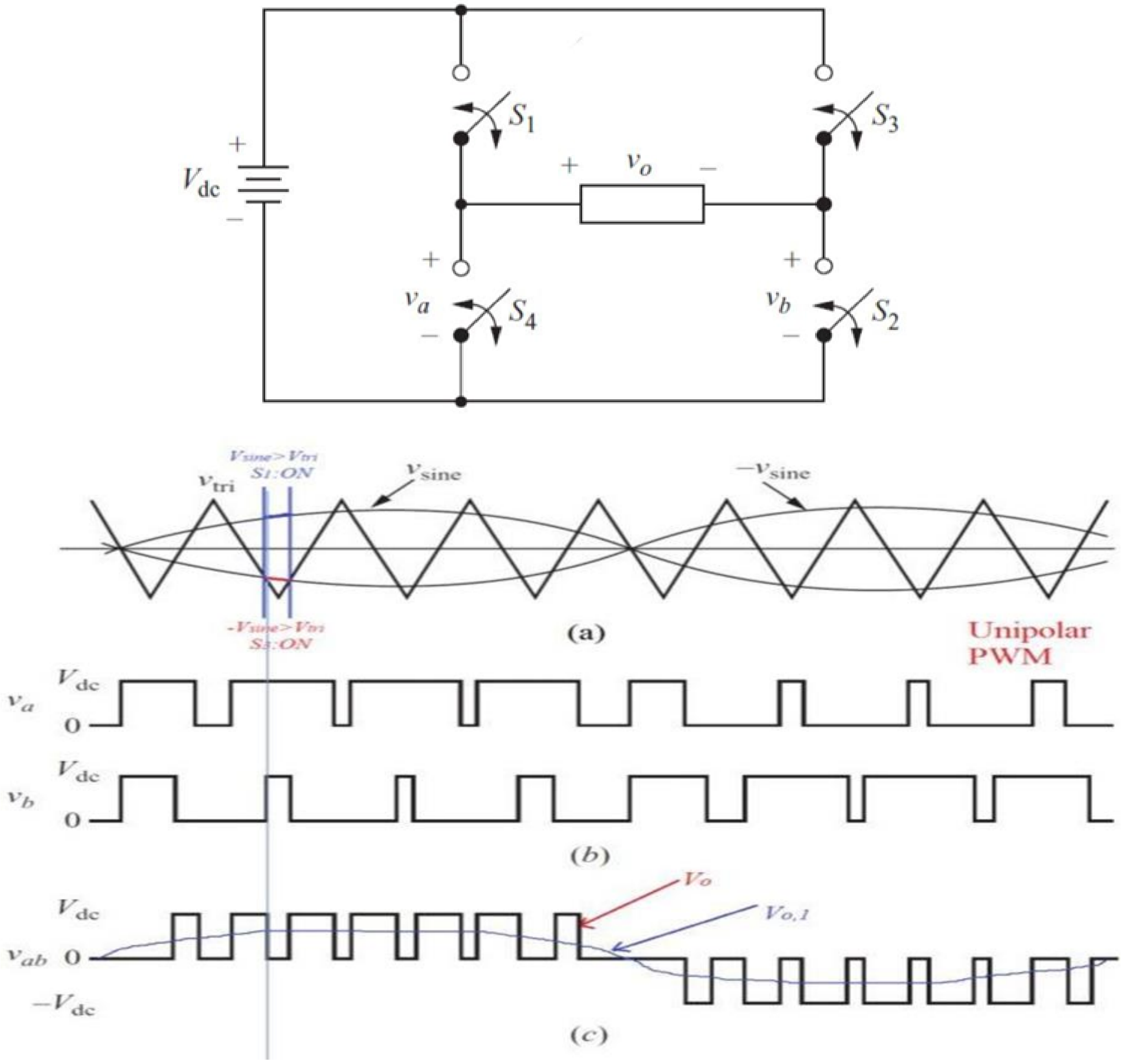

Figure (I.9): Unipolar PWM

(a) Reference and carrier signals; (b) Bridge voltages va and vb; (c) Output voltage. [1]

- This is known as Unipolar because switching occurs between zero and +Vdc when the reference is positive, and when the
- Reference is negative, while -Vdc and zero are the switching voltages.

4.4 Definitions:

Frequency Modulation Ratio (mf):

$$mf = \frac{f_{carrier}}{f_{refere}} = \frac{f_{tri}}{v_{sine}}$$

Amplitude Modulation Ratio (ma):

$$ma = \frac{v_{ref}}{v_{carrier}} = \frac{v_{sine}}{v_{tri}}$$

- The output voltage V1's basic frequency amplitude is linearly proportional to ma if ma is less than 1. In other words, V1=maVdc.
- Ma controls the amplitude of the PWM output's basic frequency. This matters when dealing with an unregulated DC supply voltage since the value of Ma can be changed to provide a constant-amplitude output by adjusting for changes in the dc supply voltage

You can adjust the ma to alter the output's amplitude. The output amplitude grows with ma, but not linearly, if ma is bigger than 1.[1]

5. Duty cycle:

The duty cycle specifies the ratio of the duration in the high state (t H) of a signal to the period (T). It is often denoted by the Greek letter: α (alpha).

less t

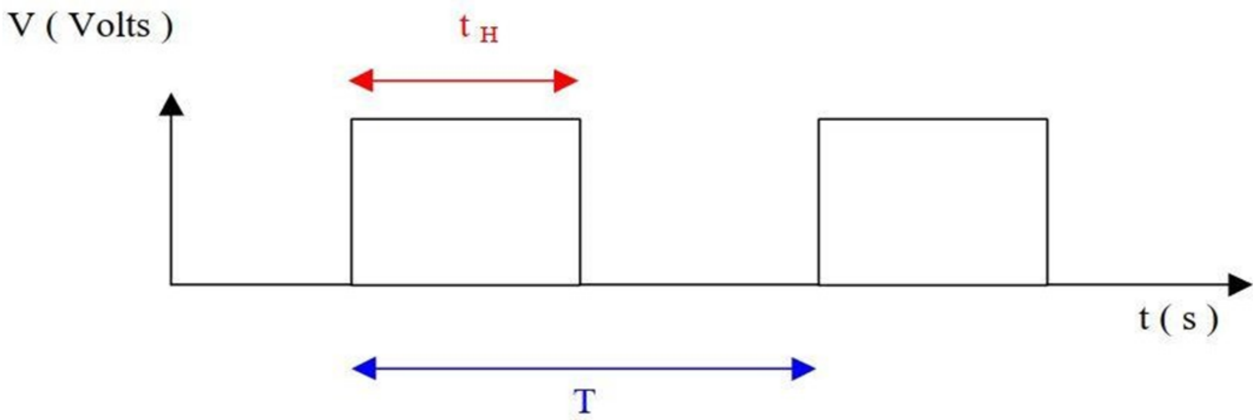

Figure (I.10) : Duty cycle

a = t H / T

6.Total Harmonic Distortion (THD) in Electrical Engineering:

The quality of electrical systems is deteriorated due to increased harmonic distortion, which is primarily caused by the extensive use of power electronic systems and other nonlinear loads. As a result, it is crucial that power distribution firms take sufficient care to report on the quality of their electrical product [8-9].

Nonlinear loads, such as the power electronic converters found in adjustable speed drives, switched-mode computer power supply, and energy -saving lights and interface converters that connect renewable energy sources to the electrical grid. Power converters have an impact on the rise in harmonic distortion when they are connected to the grid because they drive the increase in harmonic and interharmonic content by producing and consuming energy at frequencies different than the system's fundamental frequency [10,11]. The study produced by the combined CIGRE/CIRED Working Group

examines the potential effects of new technologies on the quality of the supply of energy on both the demand side and the system itself. Along with summarizing opinions on fresh approaches to measurement and mitigation, this paper offers significant conclusions and recommendations. High-frequency switching circuits included in electronic converters cause distortion over the traditional 2 kHz harmonic frequency region, moving it to the 0-150 kHz range. According to International Electrotechnical Commission (IEC).

regulations, this vast frequency range is typically separated between low frequencies, or harmonics, between 0 Hz and the 40th harmonic (from 0 to 2 kHz, for 50 Hz networks), and high frequencies, or supra-harmonics (from 2 kHz to 150 kHz). In this broad range, the behavior of disturbances in voltage and current is not uniform in terms of frequency or time [19, 20]. As an illustration, low-frequency possess a greater range of amplitudes and frequencies. Consequently, for each recorded frequency range, proper time-frequency analysis techniques with suitable sampling windows should be applied. Often, the high-frequency spectra have a wideband nature. On the other hand, discrete or narrowband components (harmonics components) at multiples of the power system frequency or at distinct frequencies predominate in lower frequency spectra.

Subharmonics and interharmonics. Another feature of low-frequency distortions is that they tend to spread throughout the network, while high-frequency distortions primarily move within the building [12].

Both at low and high frequencies, harmonics and interharmonics can cause unwanted effects such flicker, equipment overheating, increased network losses, interference in communications systems, and mistakes in control systems and digital meters [10,13,14]. Furthermore, interharmonics cause a shift in the waveform's periodicity.

the ensuing issues as a result of measuring processes based on the Discrete Fourier Transform (DFT) becoming desynchronized [15].

To accurately assess the quality of the power provided, it is crucial to analyze the harmonic and interharmonic distortion not only in the electrical network but also in the power electronic converter outputs. Given the importance of electrical energy in all social interactions, techniques for

evaluating the quality of it [16–17]. Measurement standards are even more important in light of the variety of current measurement techniques since they help to standardize and compare measurements across various equipment and enable the drawing of more trustworthy conclusions [18] One of the most significant measurement indices utilized in these standards to assess power system quality systematically and similarly is total harmonic distortion (THD), which contributes to higher power system quality and lower distortion levels. Since the fundamental component is typically the one that predominates in signals, THD is the percentage of signal energy difference from the fundamental component.

power systems, in particular the voltage one.

Although there are other power quality indices that measure waveform distortion, like power factor, individual harmonic measurement, etc., it should be noted that THD distortion factor is the only one mentioned in international and European standards for renewable energy systems, like grid-connected photovoltaic systems.

how much harmonic pollution there is. Furthermore, a large number of the commercial quality testing devices available today only measure the THD factor; they do not account for total interharmonic distortion or measure in high frequency ranges. Therefore, it is convenient to examine which of the distortion factors that are now defined is best suited for harmonic detection. as well as interharmonic pollution in electrical systems. Improving the performance of the power system under investigation starts with accurately assessing the distortion variables that determine the power quality.

In order to demonstrate how the new definitions improve our understanding of the harmonic and interharmonic distortion caused by power devices like inverters, this paper will review the various distortion factors that have been defined in the literature and in standards. Consequently, this study examines distortion variables that

measure harmonic distortion in signals that are produced by power electronic equipment, which have a wider frequency range and a higher interharmonic content. This allows them to measure distortion in signals more appropriately than those specified in the standards, which are more suited for measuring distortion in network signals. Additional instances of the use of distortion rates are also provided, encompassing educational research

on the caliber of the signals examined and the regulations on the way control over the distortion produced by loads or users and the modification of the signal by converters.

Conclusion:

In conclusion, the concept of single-phase inverter was reviewed, including its working prin- ciple and various designs. A comprehensive overview of common applications, features, and potential drawbacks of this type of inverters was provided. Current studies and research in this field were also discussed, along with the challenges facing its development and performance enhancement. A deep understanding of these fundamentals will be crucial for exploring and implementing various control strategies in single-phase inverters. Attention will also be direc- ted towards potential future research areas and expected technological advancements in this field

Chapter II

MODELLING AND CONTROL OF VOLTAGE SOURCE INVERTERS (VSI)

Introduction:

In the realm of power electronics, Voltage Source Inverters (VSIs) represent a cornerstone technology, bridging the gap between DC and AC power systems. Their versatility and efficiency make them indispensable in various applications, from renewable energy integration to industrial drives. One pivotal aspect of VSI operation is the control method employed to regulate output parameters such as voltage and frequency. Among these methods, the Proportional-Integral (PI) control stands out for its robustness and effectiveness. The PI controller adjusts output characteristics by continuously monitoring error signals, thereby ensuring stable and precise performance under diverse operating conditions. This academic exploration delves into the operational principles of VSIs and elucidates the intricacies of PI control, aiming to provide a comprehensive understanding of this vital technology in modern power systems.

For the purpose of creating inner control for microgrid systems, numerous control strategies have been devised. These include proportional-resonant (PR) control techniques [112–114], traditional linear control systems with one or more PI feedback/feedforward loops [4], and sophisticated control strategies like Model Predictive Control (MPC) [115] and Sliding Mode control (SM) [116], among others. The implementation of the inner controller for single-phase VSI based on proportional-integral (PI) control techniques is covered in paper [117]. To enhance the output voltage tracking feature of paralleled single-phase droop-controlled inverters, a multi-loop resonant controller is proposed in [118]. In [119], the inner loop of an islanded microgrid is equipped with a Finite Control Set-Model Predictive Control (FCS-MPC) technique to monitor the voltage reference. Effective voltage tracking has been made possible by this control method.

To lessen the effect of VSIs' internal impedance on the performance of the system control, the output voltage control scheme design should guarantee that each VSI module functions as a reliable voltage source. In this context, the following part presents the modeling, analysis, and tuning process of the inner voltage and current controller for a single-phase VSI.

1. Modeling and analysis of the inner control loops for single-phase VSI:

This part presents the modeling of the inverter with an LC filter and develops the suggested control technique. Furthermore, the system's closed-loop model is derived, including the control technique under consideration. Additionally, this section adopts a guideline for the controller parameter tweaking.

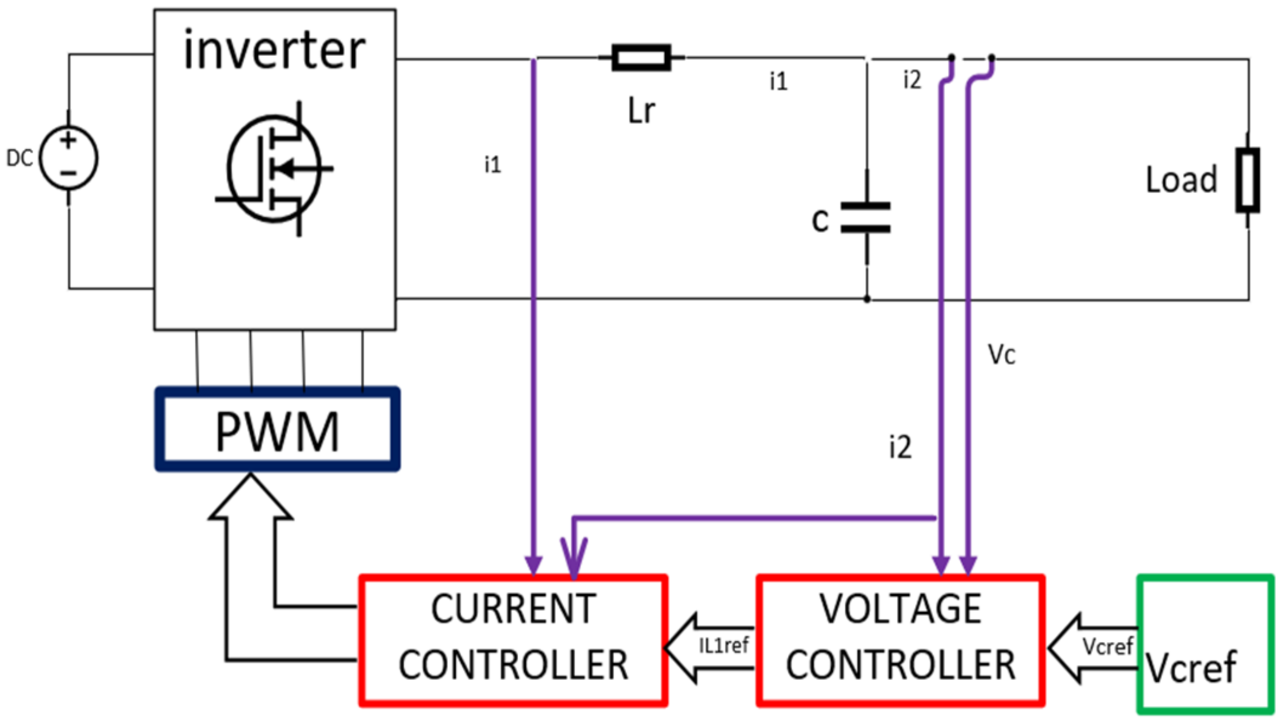

Figure (II.1): Schematic of the inner controller-based primary control for a single-phase VSI,
voltage source inverters.

1.1 Modeling of the LC-filtered VSI :

According to Figure (I.9), the mathematical formulation of the single-phase inverter VSI

with LC filter can be given as follow It ensures that the sum of the voltages across the inverter,

the load, and the capacitor is zero in the circuit.

$$v_{inv} - v_l - v_c = 0 \qquad 1.1$$

It establishes the relationship between the voltages across the inverter, the load, and the

capacitor in the circuit.

$$v_l = v_{inv} - v_c \qquad 1.2$$

Differential equation representing the rate of change of current in the inductor with respect to time Laplace transform:

$$l\frac{d_{i1}}{dt} = v_{inv} - r_{i1} \qquad 1.3$$

1.2 Laplace transform currents:

$$lsI_1(s) = v_{inv}(s) - r1I_1(s) - r1I1(s) - v_c \qquad 1.4$$

The Laplace transform of the first equation relates the Laplace transform of the current through the inductor to the Laplace transforms of the voltages across the inverter, the resistor, and the capacitor.

Laplace transform of the current through the inductor is determined by the Laplace transform of the voltage difference between the inverter and the capacitor, taking into account the resistance and inductance of the circuit.

$$I1(s) = \frac{1}{r_1 + ls}(v_{inv} - v_c) \qquad 1.5$$

This equation describes how the rate of change of the voltage across the capacitor (V_c) with respect to time (t) equals the difference between the currents flowing into and out of the capacitor, represented as (I1(t)) and (I2(t)) respectively.

1.3 Laplace transform voltage :

The Laplace transform of the given equation represents how the Laplace transform of the voltage across the capacitor (Vc(s)) is related to the Laplace transforms of the currents (I1(s)) and (I2(s)).

$$CsV_C(s) = I1(s) - I2(s) \qquad 1.6$$

relationship between the Laplace transform of the voltage across the capacitor and the Laplace

transforms of the currents flowing into and out of the capacitor, considering the capacitance of the

capacitor.

$$v_c(s) = \frac{1}{Cs}\big(I1(s) - I2(s)\big) \qquad 1.7$$

$$\begin{cases} I1(s) = \dfrac{1}{r1 + ls}(v_{inv}(s) - v_c(s)) \\ v_c(s) = \dfrac{1}{Cs}(I1(s) - I2(s)) \end{cases} \qquad 1.8$$

Therefore Laplace transform

$$G_i = \frac{1}{r1 + ls} \quad 1.9$$

$$G_v = \frac{1}{Cs} \quad 1.10$$

Accordingly, the schematic diagram of the averaged model of an inverter with LC filter in s-
domain can be obtained as shown in Figure (II.4) The system model, as shown, includes the model of
the filter inductor and capacitor. It is worth to note that the big symbols define the average values
of the corresponding variable.

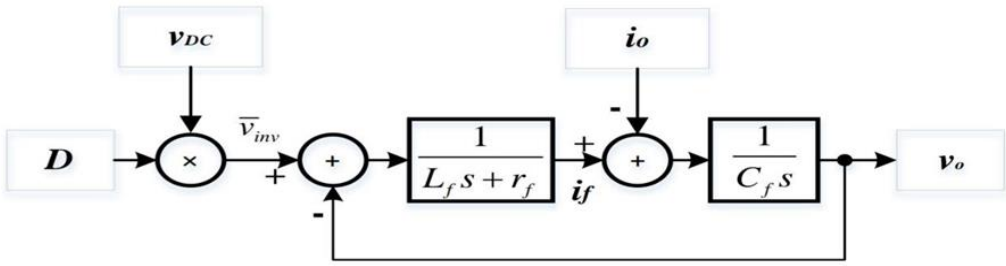

Figure (II.4). Block diagram of the LC-filtered VSI average model. VSI,voltage source inverters.

where i1, i2, and if represent the output voltage and current of the LC-filtered inverter side
and the inductor filter current, respectively, and Vinv is the average value of the inverter side's
output voltage. The filter capacitor's resistance and inductance are defined by Cy, rs, and Ls,
respectively. D is a switching action that is dependent on the state of the two switches, Q1-Q3
and Q2-Q4, which have values that fall between [-1,1] .

As previously mentioned, a PI controller is introduced for voltage and current regulation.

In the current loop, the measured current i is compared to the reference current iref, where

the obtained current error is presented to the PI controller. In the current controller loop, the
measured current is compared to the corresponding reference, as shown in Fig. The obtained
current error is presented to a proportional controller pI. generate the average value of the
output voltage reference of the inverter side, , in corporation with the output voltage vo. Then, the expression of the current compensator can be written as follows :

$$v_{invref} = C_i(s)\left(il_{ref} - il\right) + v_c \qquad 1.11$$

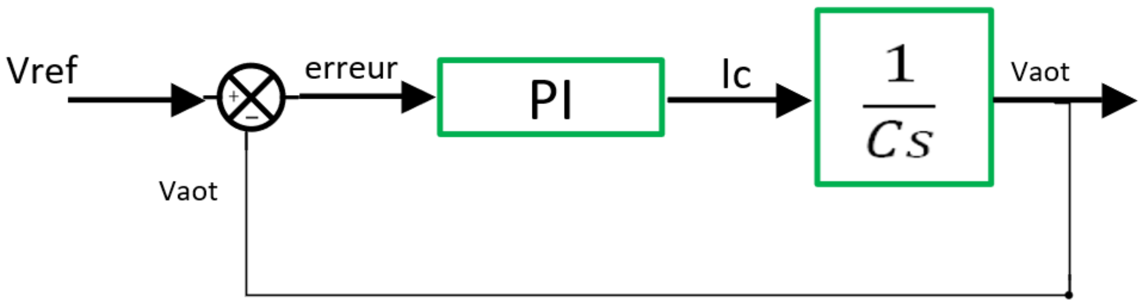

Figure (II.2): VCL voltage controller loop.

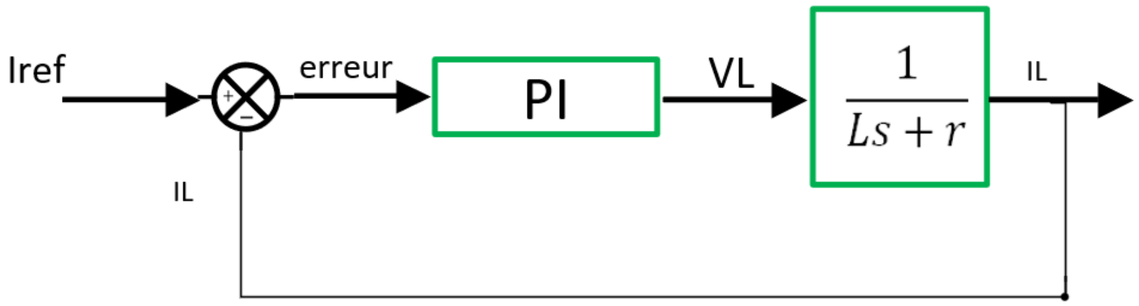

Figure (II.3): CCL current controller loop

$$C_i(s) = k_{pi} + \frac{k_i}{s} \qquad 1.12$$

where Cv(s) is the transfer function of a PI controller, which canbe written as follows :

$$Il_{1ref} = C_v\left(v_{cref} - v_c\right) - k_p v_{cref} + \mathrm{I}l2 \qquad 1.13$$

function of the PI controller which can be defined as follows:

$$C_v = k_{pv} + \frac{k_{iv}}{s} \qquad 1.14$$

3.2.2 Control design and parameters tuning :

3.2.2.1. CLTFi :

$$GiBF = \frac{C_i \times G_i}{1 + C_i \times Gi} \qquad 2.1$$

After calculating the direct relationship we obtain.

$$GiBF = \frac{\frac{sk_{pi} + k_i}{ls^2 + sr1}}{1 + \frac{sk_{pi} + k_i}{ls^2 + sr1}} \qquad 2.2$$

$$GiBF = \frac{sk_{pi} + k_i}{ls^2 + sr1 + sk_{pi} + k_i} \qquad 2.3$$

To match the general relationship of the PI controller we divide by L.

$$GiBF = \frac{\frac{sk_{pi}}{l} + \frac{k_i}{l}}{s^2 + \frac{sr1}{l} + \frac{k_i}{l}} \qquad 2.4$$

In order to obtain values **kp, ki**

$$Gi = \frac{\omega i^2}{s^2 + 2\zeta\omega i s + \omega i^2} \qquad 2.5$$

We perform tuning to obtain the relationship between Kpi and Kii.

$$Gi = \frac{\omega i^2}{s^2 + 2\zeta\omega i s + \ \omega i^2} = \frac{\frac{sk_{pi}}{l} + \frac{k_{pi}}{l}}{s^2 + \left(\frac{r1 + k_{pi}}{l}\right)s + \frac{k_i}{l}} \qquad 2.6$$

By matching the two relationships, we obtain

$$k_{pi} = 2\zeta\omega i l - r1 \qquad 2.7$$

$$k_{ii} = \omega i^2 l1 \qquad 2.8$$

3.2.3 CLTFv :

$$GvBF = \frac{C_v \times G_v}{1 + C_v \times G_v} \quad 3.1$$

$$C_v \times G_v = \frac{sk_{pv} + k_i}{Cs^2} \quad 3.2$$

After calculating the direct relationship, we obtain.

$$GvBF = \frac{sk_p + k_i}{1 + \frac{sk_p + k_i}{Cs^2}} \quad 3.3$$

To match the general relationship of the PI controller, we divide by C.

$$GvBF = \frac{\frac{sk_{pv}}{C} + \frac{ki}{C}}{s^2 + \frac{sk_p}{C} + \frac{k_i}{C}} \quad 3.4$$

$$GvBF = \frac{\omega i^2}{s^2 + 2\zeta\omega v s + \omega i^2} = \frac{\frac{sk_{pv}}{C} + \frac{k_i}{C}}{s^2 + \frac{sk_p}{C} + \frac{k_i}{C}} \quad 3.5$$

We perform tuning to obtain the relationship between Kpv and Kiv.

$$k_{pv} = 2\zeta\omega v C \quad 3.6$$

$$k_{iv} = \omega i^2 C \quad 3.7$$

After numerical compensation, we obtain: PI

1.4 controller current:

$$k_{pi} = 34.5377 \quad 3.8$$

$$k_{ii} = 3.1583\text{e} + 005 \quad 3.9$$

Voltage controller :

$$k_{pv} = 0.0409 \quad 3.10$$

$$k_{iv} = 36.3201 \quad 3.11$$

2. Simulation inverter single phasi :

After completing the computational processes and system modeling, the next step in eva- luation and analysis is simulation. Simulation is a crucial step in understanding the behavior and expected performance of the system under various conditions and variables. Through si- mulation, we can assess how the system responds to different signals and conditions, and verify the design and implementation of the system.

This report will review the simulation results obtained using the PSIM software. We will analyze the system's performance under different conditions and track its response to changes in references and various conditions. This simulation provides an opportunity to improve design and control, and enhance our understanding of the system's behavior in different contexts.

2.1 Inner voltage and current control loops :

The purpose of the inner control loop is to keep the system stable while adjusting the inverter output voltage to the required voltage reference, which is supplied by the droop control. As shown in Fig(II.5), this control scheme consists of voltage and current control loops. The most often used method in these loops to regulate the inductor and capacitor voltage is the classical PI regulator to provide quick transient response and to maintain current in each DG unit [4], [5]. But for the MG's performance, the inner control loop architecture is crucial. Various methods have been used to control the voltage sensing interface in an islanded microgrid. For instance, in [6], a proportional resonant (PR) controller for paralleled single-phase droop- controlled systems was modified at the fundamental frequency The idea behind inverters was to enhance the output voltage-tracking functionality. Furthermore, an MCS-MPC technique-based inner loop voltage controller method was devised in [11] with the goal of eliminating steady state error and enhancing reference tracking. Additionally, paper has advanced. Additionally, sliding mode technique has been devised in [21] for the inner loop to improve non-overshoot transient performance in islanded MG and reference tracking speed

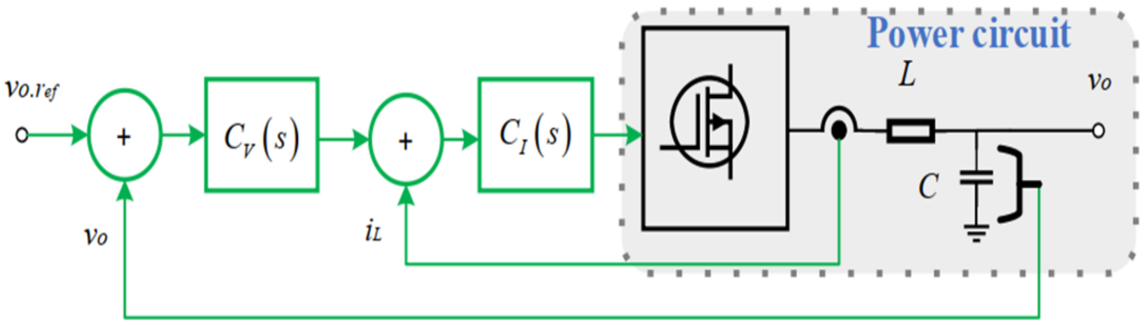

Figure (II.5): Diagram of double-loop control of the output voltage[25].

On the other hand, system stability analysis and performance improvement depend on the modeling and tuning processes of the inner control loops. Numerous works, including those pu- blished in [22] and [23–24], have been offered in the literature study with regard to the modeling and design of the inner control.On the other hand, system stability analysis and performance improvement depend on the modeling and tuning processes of the inner control loops The re- viewed review leads one to the general conclusion that all developed approaches aim to address the main problems associated with droop-based control, such as inaccurate load sharing, poor transient response, instability issues caused by sudden load perturbation, and improving power sharing performance even under highly harmonic distortions resulting from nonlinear opera- ting conditions. In this context, the creation and architecture of an enhanced primary control scheme, It is crucial to have knowledge of the estimate unit, power calculation block, and virtual impedance control loops because they can provide precise power sharing, a significant stability margin, quick transient response, and intrinsic control of harmonic components appropriate for highly distorted nonlinear loads. The current thesis centers on this idea.

3. Introduction to the software used in experiments PSIM :

PSIM is a powerful simulation software known for several distinctive features that set it apart from others

- Intuitive User Interface : PSIM offers an intuitive and user-friendly interface, allowing users to easily build and analyze circuits without requiring extensive prior knowledge in electrical analysis.
- Versatile Modeling Capabilities : PSIM can model a wide range of electrical circuits and power systems including transformers, motors, inverters, three-phase transformers, solar systems, and more.

- Dynamic Analysis Support : PSIM enables users to analyze circuit behavior over time, providing a deeper understanding of the effects of changes on circuits and systems.
- Frequency Domain Analysis : PSIM can be used to analyze circuits and systems at different frequencies, allowing users to understand the frequency's impact on system performance.

In terms of accuracy and reliability, PSIM's simulation results are typically close to practical results when accurate models are used and correct inputs are provided. However, discrepancies may occur due to estimation in the model or other factors such as noise and device errors in real-world applications.

4. After system modeling :

After simulating in the following image the inverter single phase analog and LC filter,control was achieved using a PI controller as shown below.

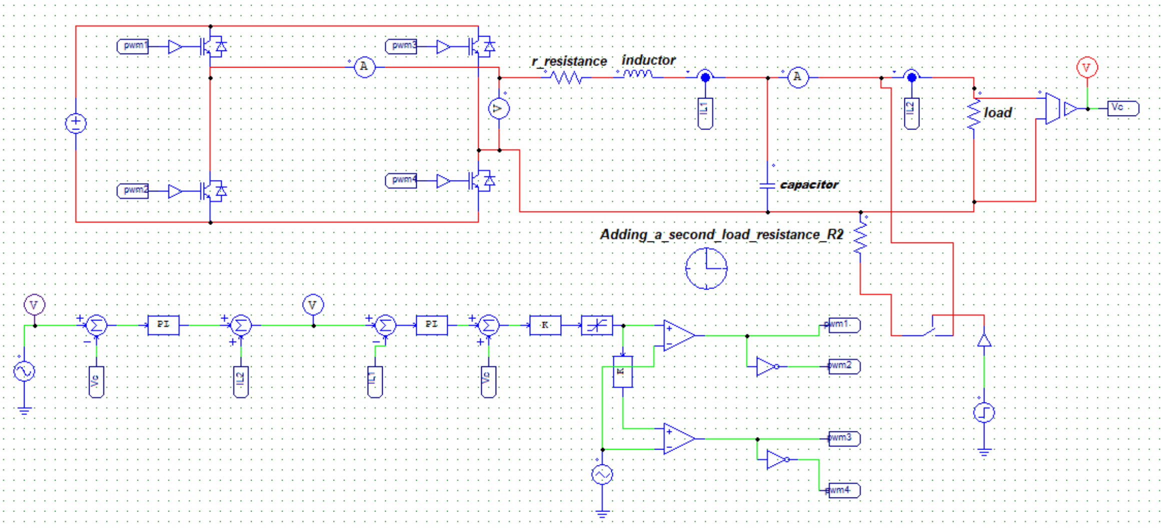

Figure (II.6): inverter single phase analog

Through the provided Figure (II.6), we observe that the red section illustrates the electronic power stage, representing a single-phase inverter and LC filter with the resistance R.

The green section represents the control part, as mentioned earlier. Two PI controllers are used as depicted in the image. The role of the first controller is in voltage control, while the second one represents the current controller. Here are the simulation results as follows

We notice that the voltage ab across the terminals of the inverter without LC is (ab) follows

From the image, we observe a significant to some extent agreement between Ich, IL, and IL ref.

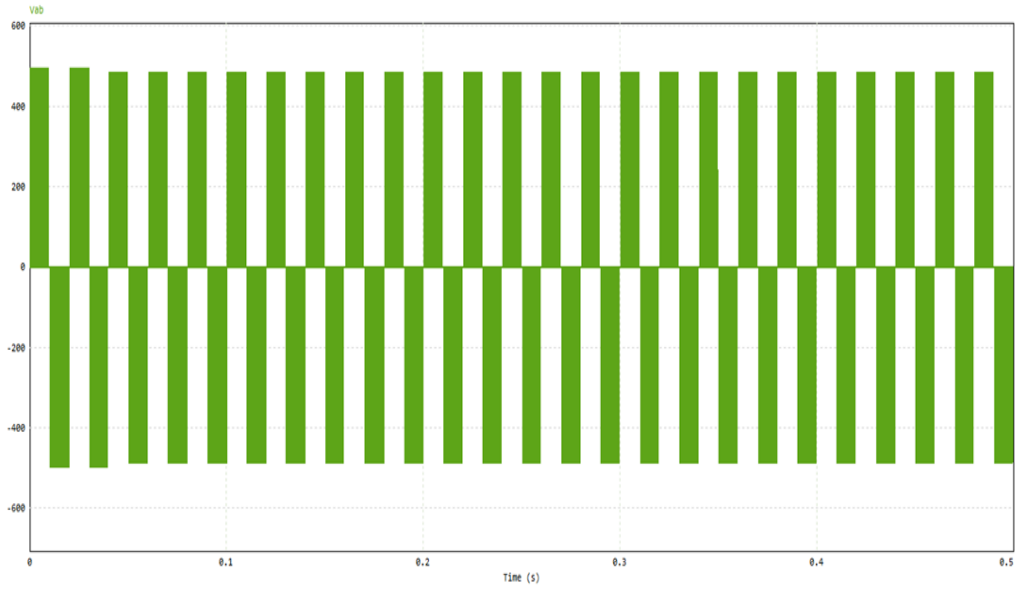

Figure (II.7): Vab inverter

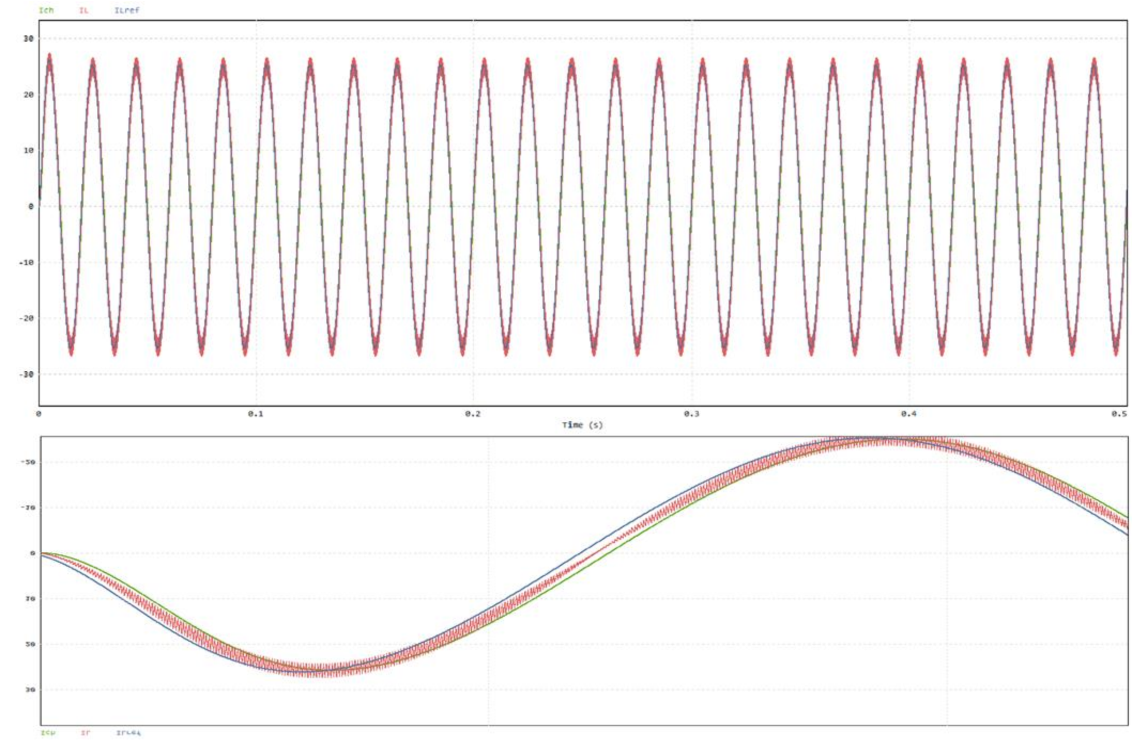

Figure (II.8): current controller

From the image, we observe a significant to some extent agreement between Ich, IL, and IL ref.

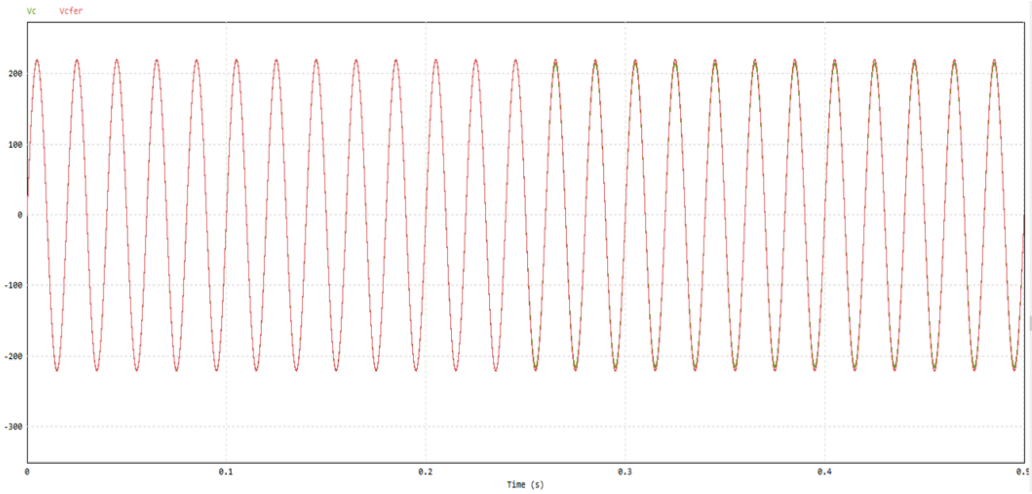

Figure (II.9): voltage Vc Vcref

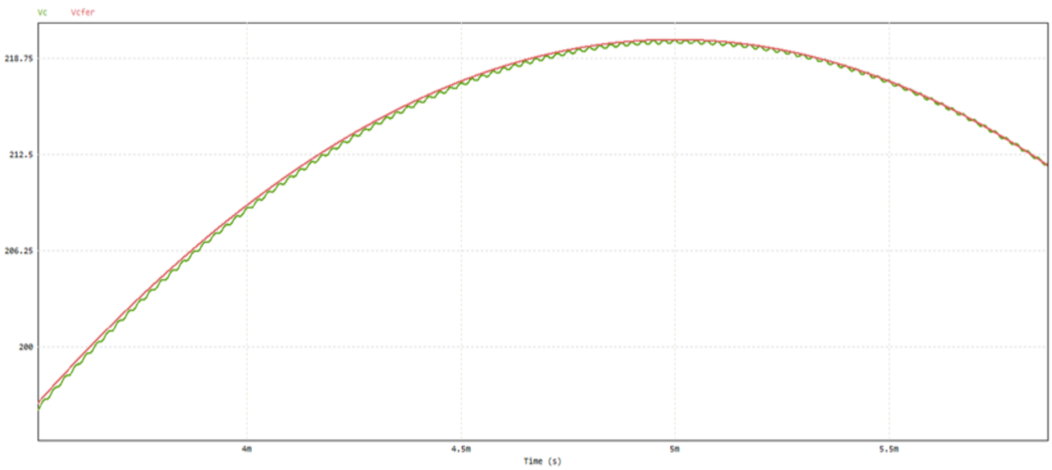

Figure (II.10): voltage Vc Vcref

To confirm the capability and effectiveness of the PI controllers, we apply a second load after a period of time and observe its effect on the voltage.
As shown in the following image

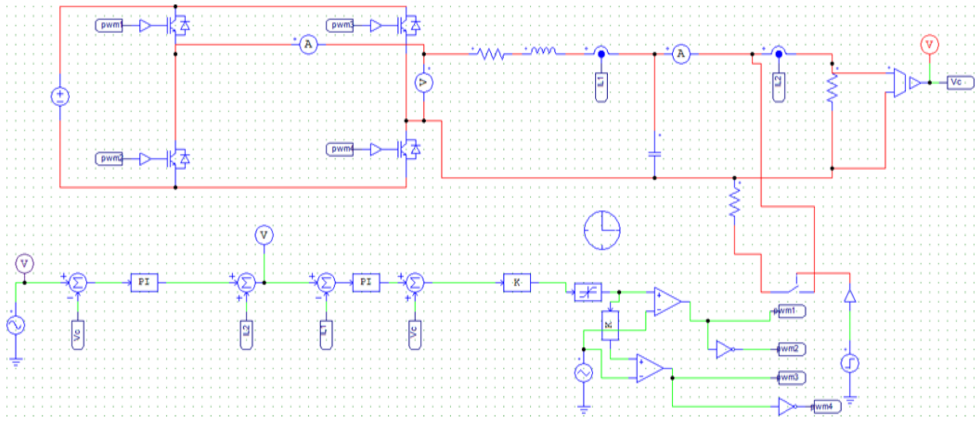

Figure (II.11): inverter single phase analog in addition R2

After zooming in on the curve at the moment of adding the second resistor R2, we observe an increase in the controller's response speed.

After adding the resistor, we observe the following simulation results

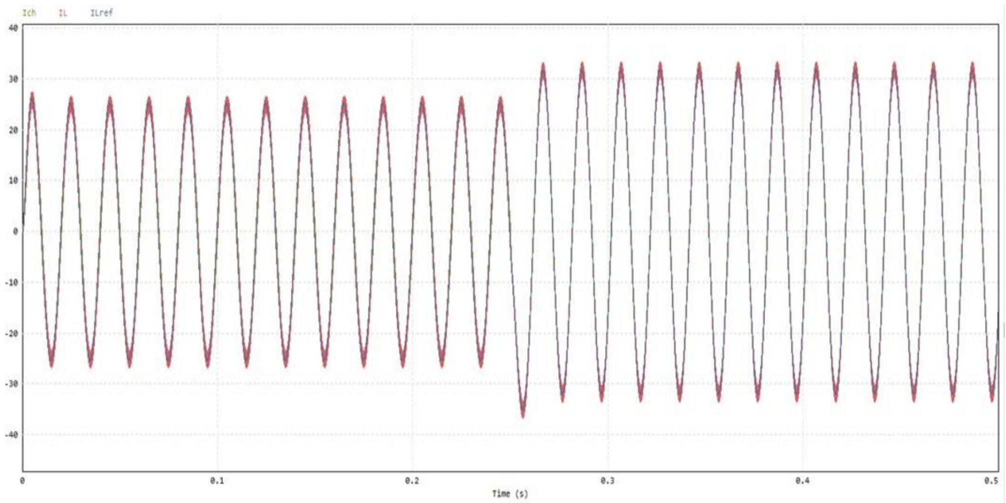

Figure (II.12): current ,Ich, IL ,ILref

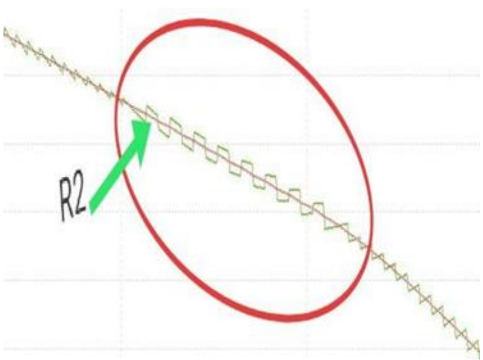

Figure (II.13): Ich in addition R2

To confirmthe capability and effectiveness of the PI controllers, we apply a voltage reduction after a period of time and observe its effect on the voltage Vc.

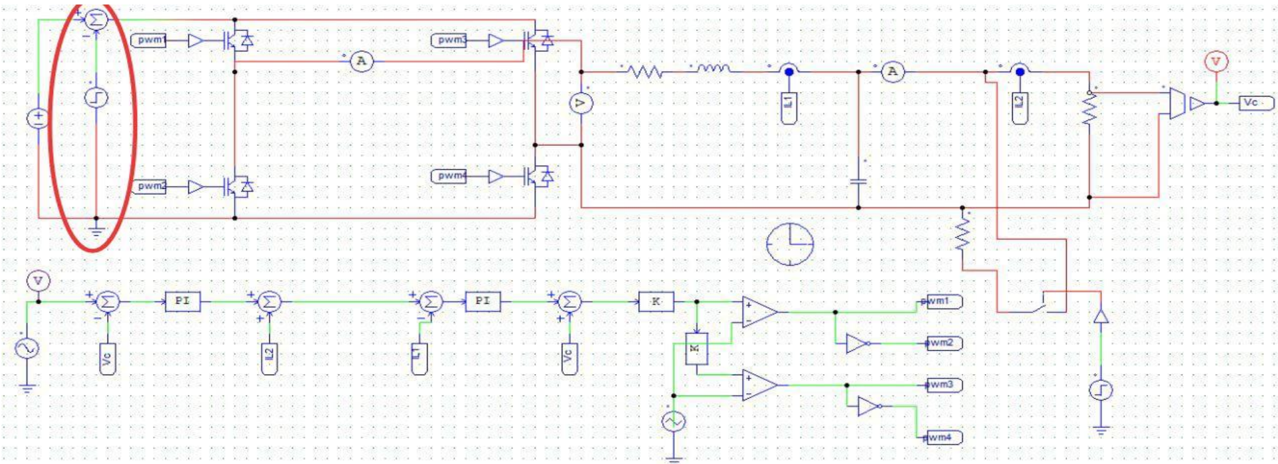

Figure (II.14): inverter single phase analog in addition step voltage source

After executing the simulation, we did not observe any significant change at the level of Vc

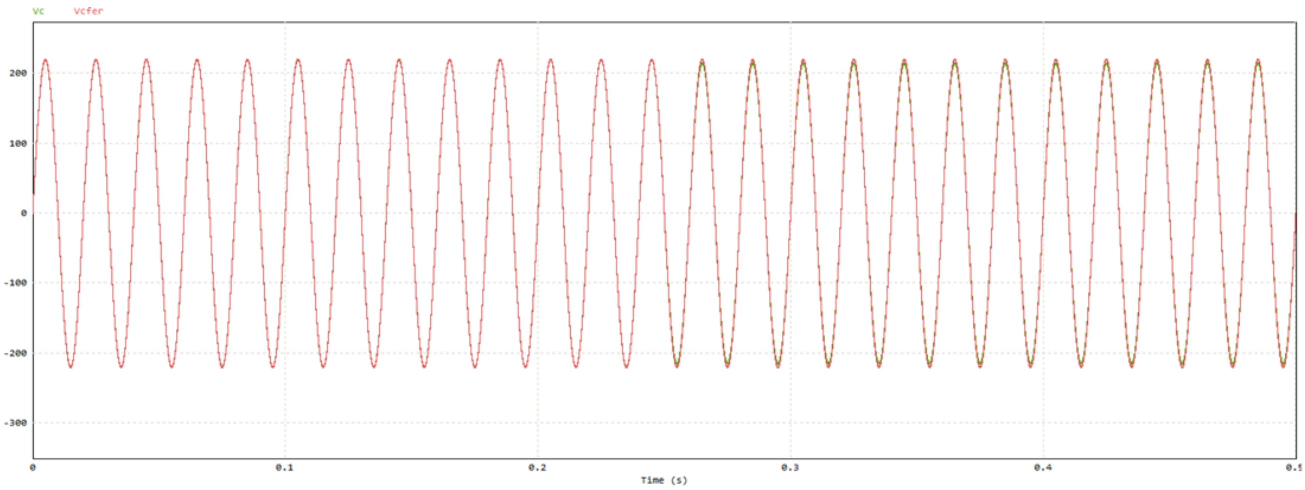

Figure (II.15): voltage Vc Vcref

conversion of simulation processes from analog control systems to digital control is considered a fundamental task in the field of electrical engineering. This importance stems from the increasing challenges faced by modern electrical systems, which demand high accuracy and efficiencyin control operations. Digital control offers a range of advantages compared to analog control, including greater precision, rapid parameter adjustments, and the ability to integrate with other control systems. In this paper, we will analyze the process of converting simulation from analog control to digital control.

In order to convert the simulation from analog control to digital, we first convert the PI controllers from analog control to digitalThe conversion process is carried out as follows :

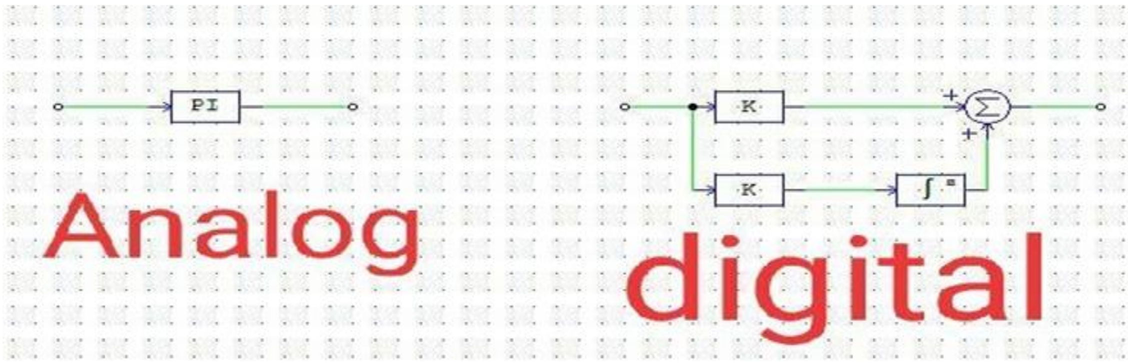

Figure (II.11): Analog and Digital Control Diagram for a Proportional-Integral (PI) Control System

The conversion process is carried out as follows:
Conversion of Proportional-Integral (PI) Control Systems between s-Domain and z-Domain Representations using Bilinear (Tustin)

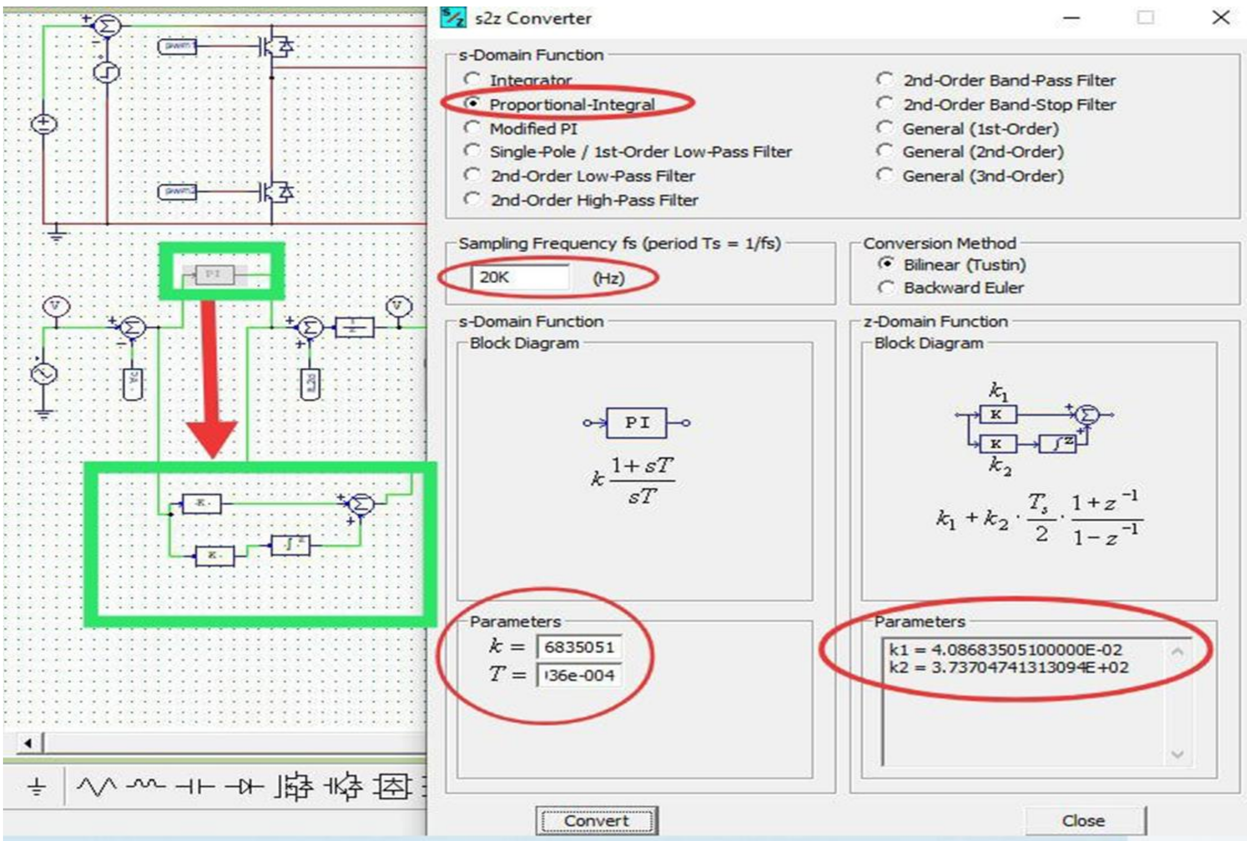

Figure (II.18): Conversion method using software psim

We then proceed to convert the inputs (Vc),(iL1),(iL2) by selecting the DSPF28335 card. Through the simulation results, it is observed that :

Amplifying a moment of pulling 1V from a DC source

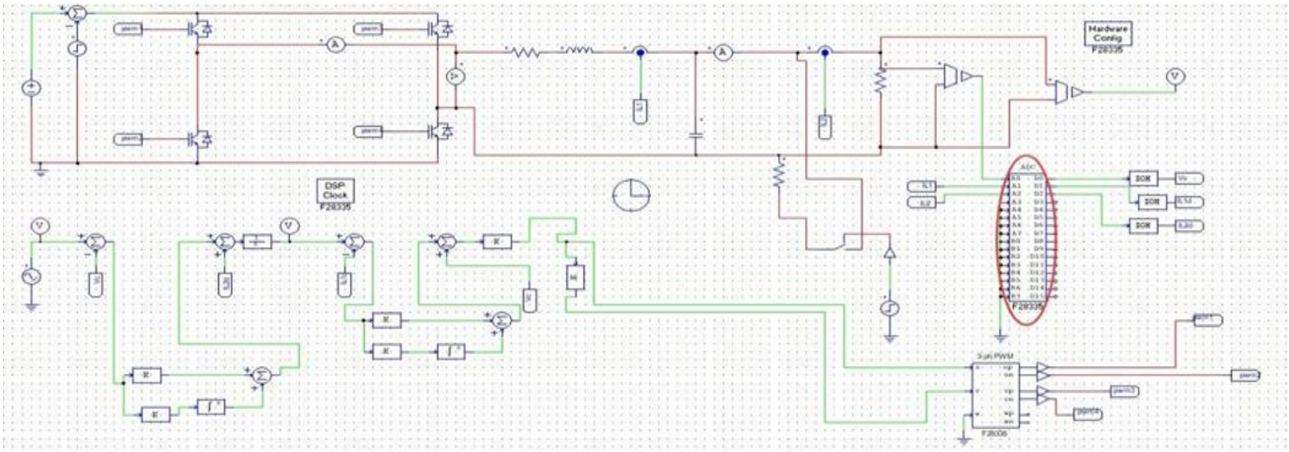

Figure (II.19): inverter digital

Through the simulation results, it is observed that:

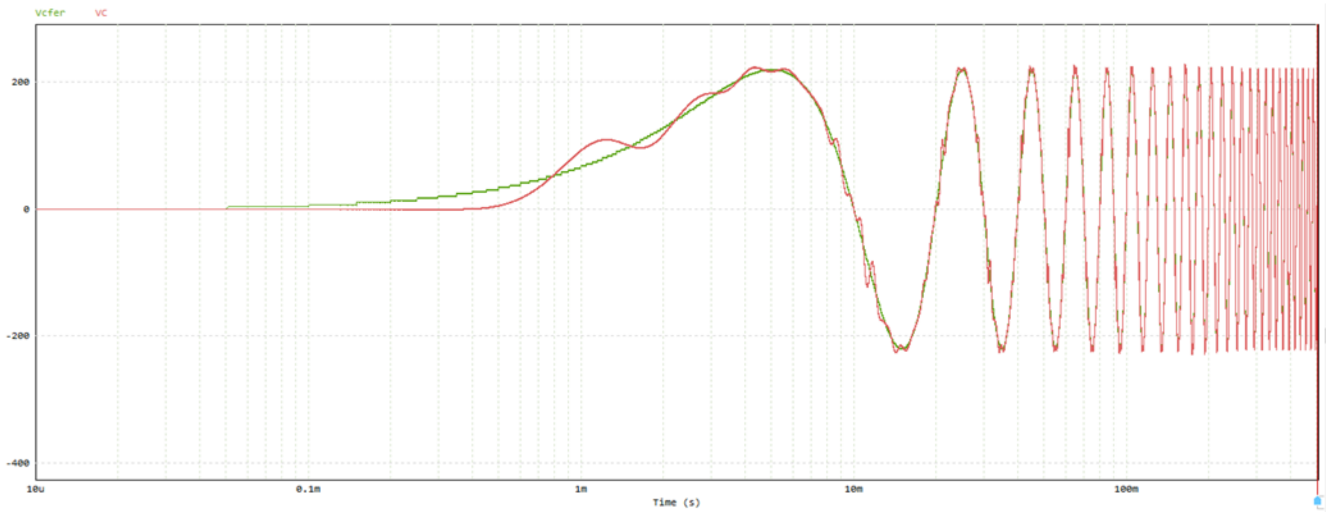

Figure (II.20): The controller's operation begins as it tracks Vc , Vcref

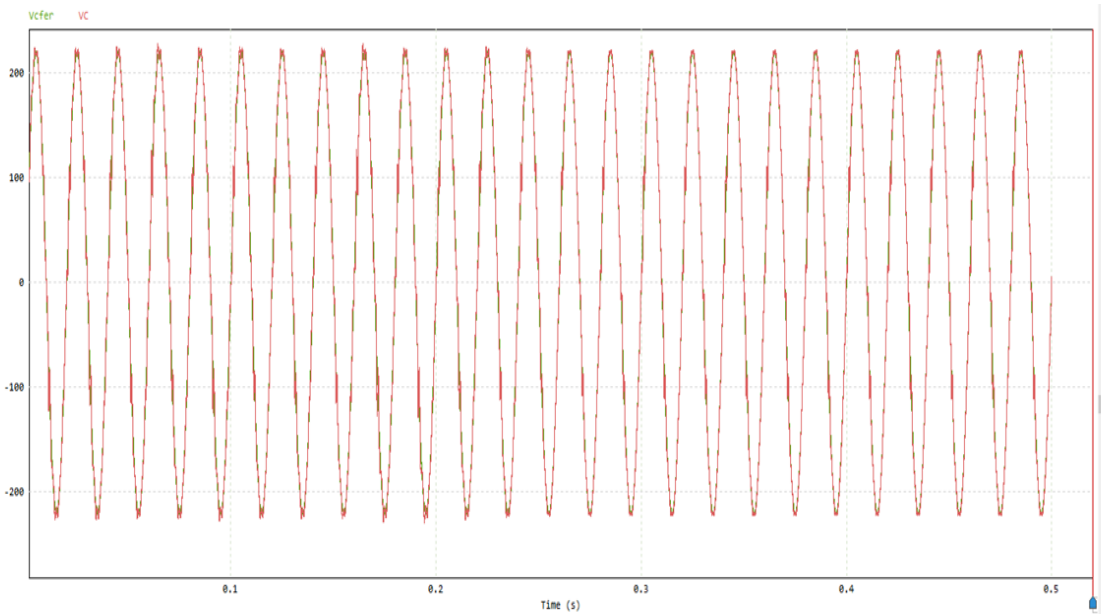

Figure (II.21): voltage Vc Vcref digtail

Amplifying a moment of pulling 1V from a DC source

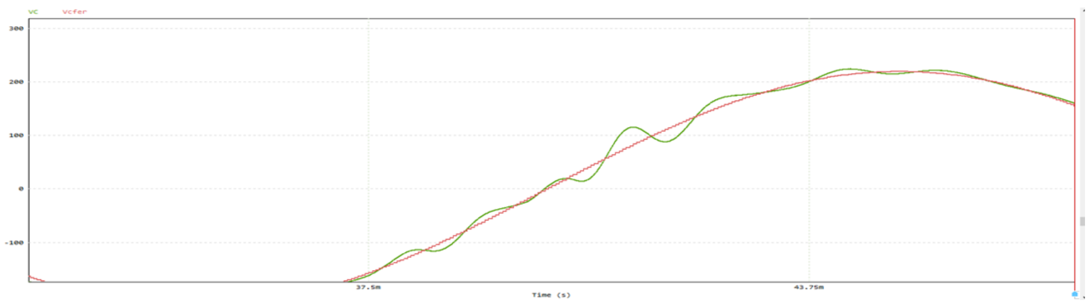

Figure (II.22): inverter single phase digtail in addition step voltage source

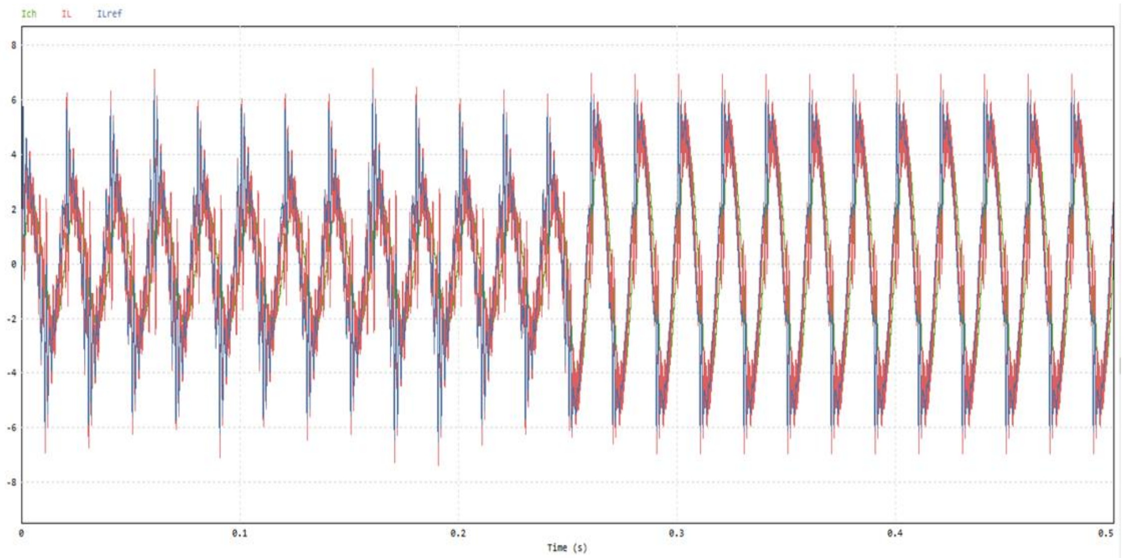

Figure (II.23): current digtail ,Ich, IL ,ILref

The obtained results demonstrate the speed response of the PI controller under different conditions.

Conclusion :

In this chapter, we focused on modeling and simulating a single-phase inverter using an analog approach with a PI controller. The primary objective was to accurately replicate the behavior of the inverter system under various operating conditions. Through meticulous calibra- tion and validation, we achieved precise results that closely matched theoretical expectations.

Our analog simulations provided valuable insights into the performance characteristics and control dynamics of the inverter. However, recognizing the increasing demand for digital control solutions in modern power systems, we embarked on the journey of transitioning from analog to digital simulations. The conversion process from analog to digital includes two fundamental stages. The first stage involved converting PI from analog to digital, followed by the next stage of converting IL1, IL2, and Vc to digital. After simulation, the results were excellent and perfectly matched the expected values.

In this chapter, we discussed in detail the operation mechanism of single-phase inverters, as well as explained PWM technology and how to control it to adjust the output values of the inverter as needed. Additionally, we addressed THD and its impact on devices consuming

Chapter III Processor in the Loop

Introduction:

Processor-In-the-Loop (PIL) simulation is a powerful technique used in the field of embed- ded systems development and control engineering. It involves integrating real-time processor hardware with simulation software to test and verify control algorithms and hardware designs. In PIL simulation, the control algorithm runs on a real processor while interacting with a si- mulated environment. This allows developers to evaluate the performance of control algorithms under realistic conditions without the need for expensive hardware prototypes. One of the key advantages of PIL simulation is its ability to bridge the gap between software development and hardware implementation. By executing the control algorithm on actual hardware, developers can uncover potential issues that may arise due to hardware constraints or limitations. Additio- nally, PIL simulation enables rapid prototyping and iterative refinement of control algorithms. Developers can quickly modify and test algorithms in a simulated environment before deploying them onto physical hardware, reducing development time and costs. Overall, Processor-In-the- Loop simulation is a valuable tool for accelerating the development and testing of embedded control systems, offering a cost-effective and efficient way to validate control algorithms and hardware designs before deployment in real-world applications.

1. The description of the card DSP F28335 :

1.1 Hardware characteristics:

1.1.1 Functional diagram:

The digital calculator F28335's functional diagram is shown in figure(III.1), while the actual image is shown in figure (III.5) :. The manufacturer's technical datasheet (Texas Instruments) is where the diagram was taken from. The different processor modules (CPU, ADC, PWM module, SARAM, etc.) as well as the connections and communication channels (buses, pins, etc.) are depicted in this diagram in blocks.The digital calculator F28335's functional diagram is shown in figure (III.1), while the actual image is shown in figure (III.5) :. The manufacturer's technical datasheet (Texas Instruments) is where the diagram was taken from. The different processor modules (CPU, ADC, PWM module, SARAM, etc.) as well as the connections and communication channels (buses, pins, etc.) are depicted in this diagram in blocks.

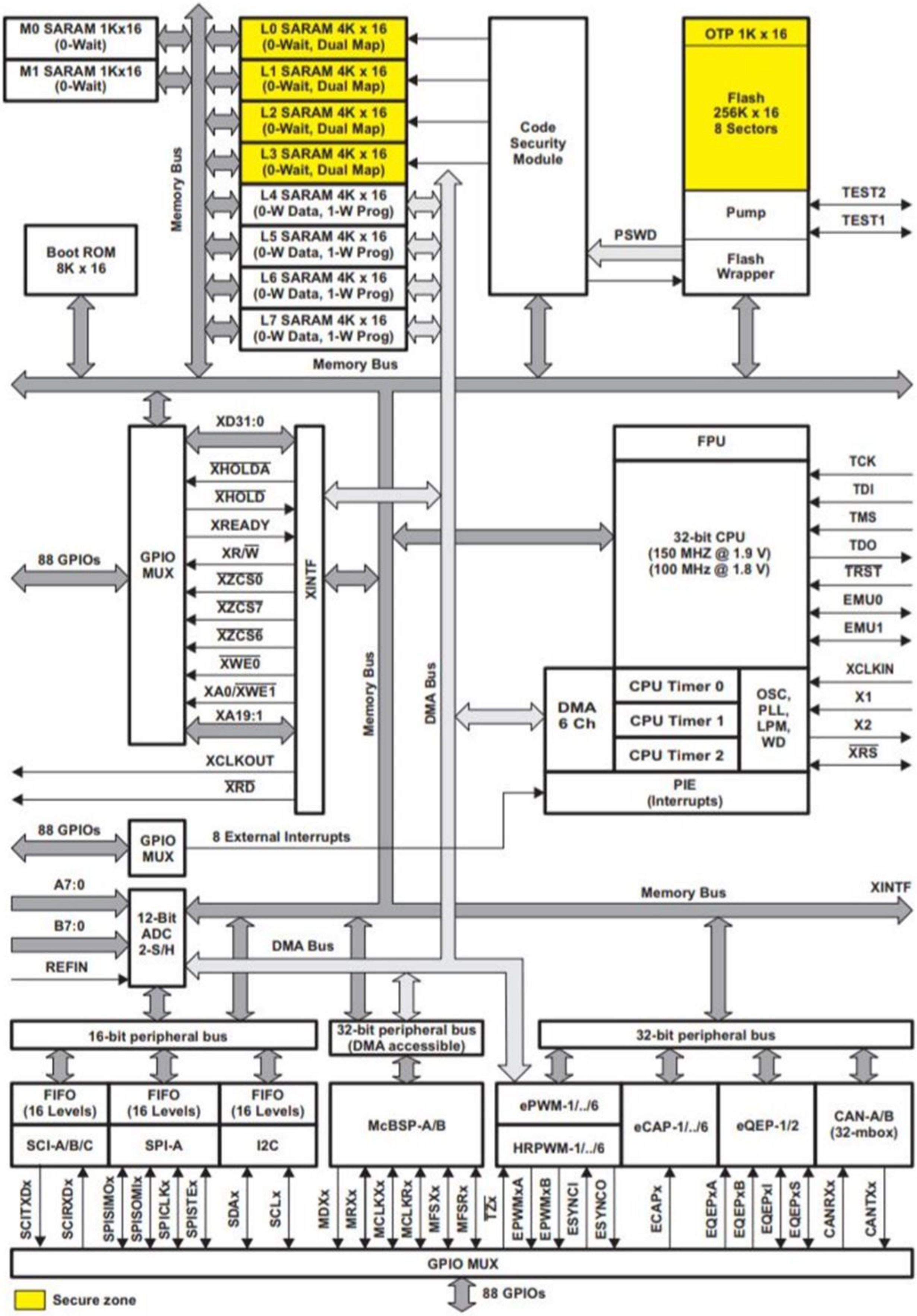

Figure (III.1): Functional diagram.

1.2 C28x CPU:

Digital signal controllers (DSC) include the F2833x (C28x+FPU) family. It's an extremely powerful C/C++ engine that enables users to create system control software using a top-tier

language. It also makes it possible to develop mathematical algorithms using C/C++. Similar to how microcontroller devices are usually used for system control activities, the device is likewise efficient for mathematical work on DSPs. In many systems, this efficiency removes the requirement for a second processor. The controller's ability to process 64-bit MAC 32*32 data allows it to efficiently handle digital resolution issues. Additionally, the device's fast interruption response and automatic backup of critical logs result in a peripheral that can handle numerous asynchronous events with little latency. The device has an eight-level protected pipeline with memory access. This pipeline enables him to execute at a high speed without requiring the usage of fast-moving memory [26].Additionally, the device's fast interruption response and automatic backup of critical logs result in a peripheral that can handle numerous asynchronous events with little latency. The device has an eight-level protected pipeline with memory access. This pipeline enables him to execute at a high speed without requiring the usage of fast-moving memory [26]. [26] : Texas Instruments Incorporated, Fiche technique, SPRS439N –JUNE 2007– REVISED OCTOBER 2016.

1.3 Memory bus (Harvard):

Multiple buses are employed to facilitate the exchange of data among memory, peripherals, and the CPU. The C28x bus architecture consists of three main buses : a program read bus, a data read bus, and a data write bus. The program read bus is equipped with 22 address lines and 32 data lines. Utilizing 32-bit data buses enables the execution of operations on 32 bits within a single cycle. The multiplexed bus architecture, commonly known as Harvard architecture, facilitates fetching instructions, reading data values, and writing data values within a single cycle.

2. Processor-In-the-Loop :

With PSIM's PIL Module, one can perform processor-in-the-loop (PIL) simulation with the power stage implemented and simulated in PSIM and the control code for the TI

DSP running on the actual DSP hardware. This tutorial describes, in step by step, how to set up and perform the PIL simulation. The process involves the following steps :

Preparing the code for PIL simulation Setting up in PSIM Setting up the hardware The circuit is a inverter singel phasi with Two PI controllers were used the first for voltage control and the second for current control, switching at 20 kHz. The unit delay block U1 represents the one-cycle delay inherent in digital control. The first step in PIL simulation is to prepare the code. The code can be either written manually by users or automatically generated by PSIM using the SimCoder, we will use the code generated by PSIM.

3. Creating Code:

The modified circuit incorporates an A/D converter following the current sensor, while replacing the carrier wave and comparator with a PWM generator, and specifying the hardware target. Both the A/D converter and

PWM generator originate from PSIM's F2833x Target library. They emulate the behavior of the A/D converter and PWM generator functions within the real F28335 DSP hardware. Below is the modified circuit, with the A/D converter and PWM generator highlighted.

As illustrated in the subsequent image.

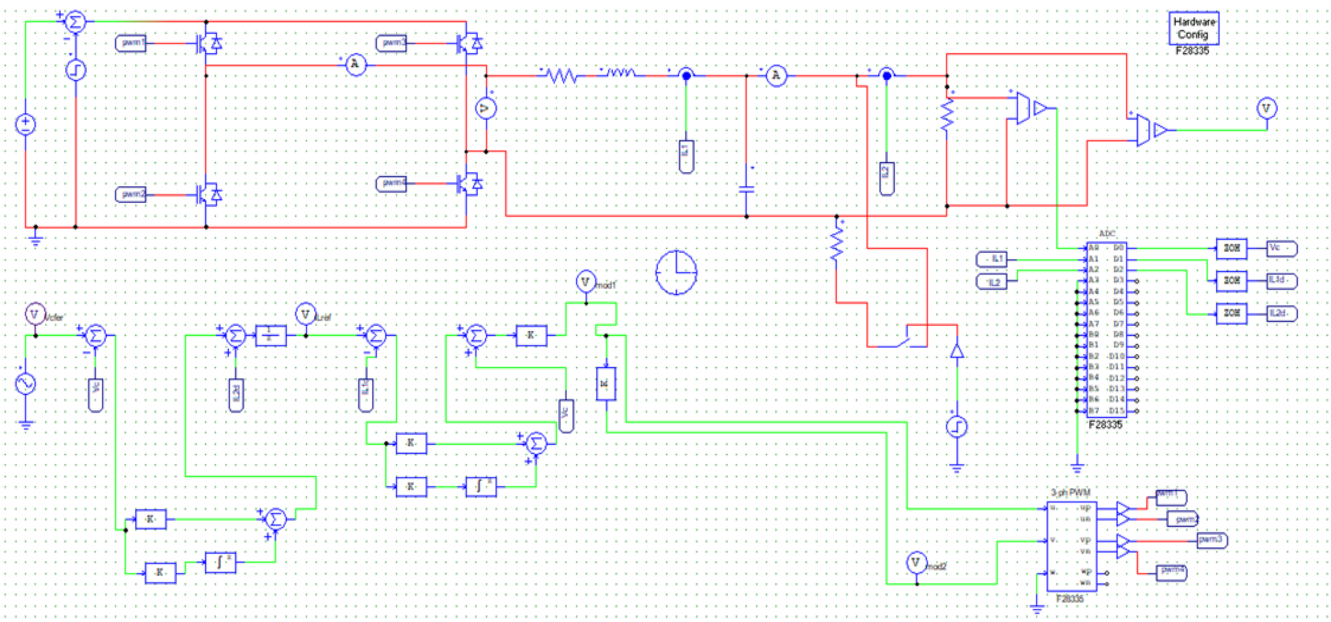

Figure (III.2): inverter singl phasi digital

PSIM can simulate this circuit and generate code automatically that is ready to run on the DSP hardware. To generate the code, in PSIM, go to Simulate Generate Code. A sub-folder inverter singel phasi (simcoder) (C code)" will be generated that contains the C code and other necessary files for Code Composer Studio (CCS). Make a copy of this sub-folder, and rename it to "inverter singel phasi (PIL) (C code)" for the modified code for PIL simulation.

As depicted in the diagram, the inputs Vc, IL1, and IL2 are converted from analog to digital (A/D). Similarly, in our system, we have P1 and P2 controllers to obtain a PWM signal.

4. Modifying Code for PIL Simulation:

After the code is available (either written manually or from PSIM), the next step is to identify variables that need to interface with PSIM. A PIL block will be used as the interface. Signals from the rest of the PSIM circuit to this block will be inputs (such as measured vol-

tages/currents), and signals from this block to PSIM will be outputs (such as PWM modulation

waves). Typical input/output variables are :

Inputs : Variables after the A/D converter

Outputs : Variables before the PWM generator, and any other internal variables for dis- play/debugging purposes the input variable is the A/D converter output, and the output va- riable is the modulation signal before the PWM generator. If we wish to monitor the internal signal Verr, Verr will be an additional output variable. These variables are often in an interrupt service routine. Note that variables before the PWM generator are the output variables.

The PWM generator outputs are the actual PWM gating signals that appear at the output ports,and they cannot be sent to PSIM. The PWM gating signals need to be generated in PSIM.

Only two changes need to be made to the code :

All input/output interface variables need to be defined as global variables. Statements in the code that assign values to ADC outputs need to be commented out. This is because there is no input at the actual ADC port, and the values must come from PSIM.

4.1 Setting Up in PSIM:

To prepare the schematic for PIL simulation, first make sure that the CCS folder path is supported. If CCS is installed in the folder “c :5” for CCS v5 or “c :6” for CCS v6, nothing needs to be done since PSIM has included these two folders already. If CCS is installed in a folder other than these two folders, it needs to be added to the PSIM path by going to Options » Set Path, and add the CCS folder to PSIM Search Path. Modify the original circuit in Page 1 by removing the control circuit, except the PWM generator, and replacing it with a PIL block from the PSIM library under Elements Control PIL Module. The modified schematic file is shown as follows.

To execute the simulation, we follow the following steps.

Here is the following image illustrating the PIL module :

After injecting the code into the DSP F28335 card, all PI control systems are deleted while maintaining the outputs (Vc IL1D IL2D) by adding a PIL Block and modifying it, which we will explain after this step.

As illustrated in the above image, the PIL inputs and outputs have been defined, as shown : 3 inputs and 2 outputs. Additionally, the frequency is set to 20kHz at the three inputs.After simulating using PIL, here are the obtained results.

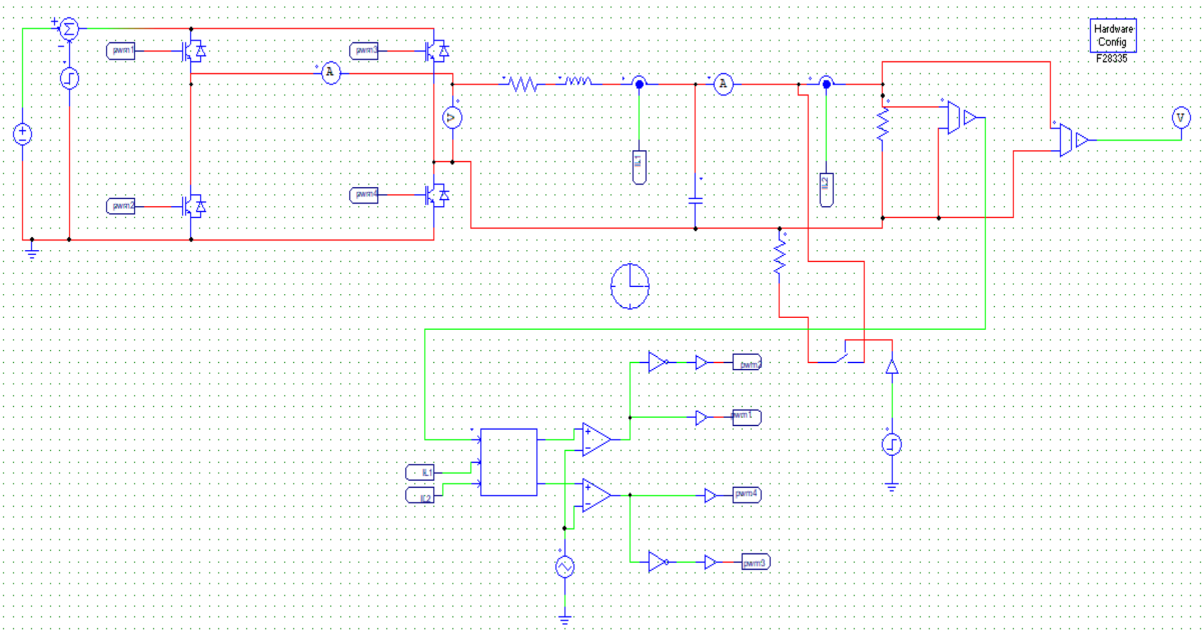

Figure (III.3): pil

After making the necessary adjustments to the PIL module as shown in the following image

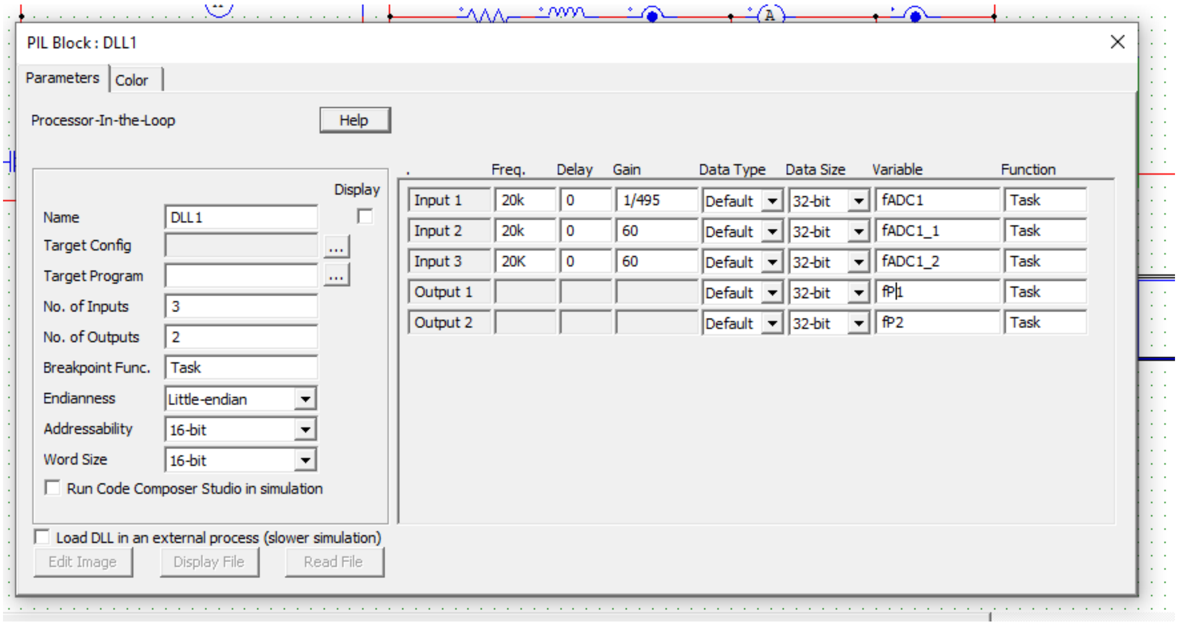

Figure (III.4): pil bocks

After installing the DSP card, we need a code injection program into the card, which is Code Composer Studio.

Here is an image of the DSP f28335 used.

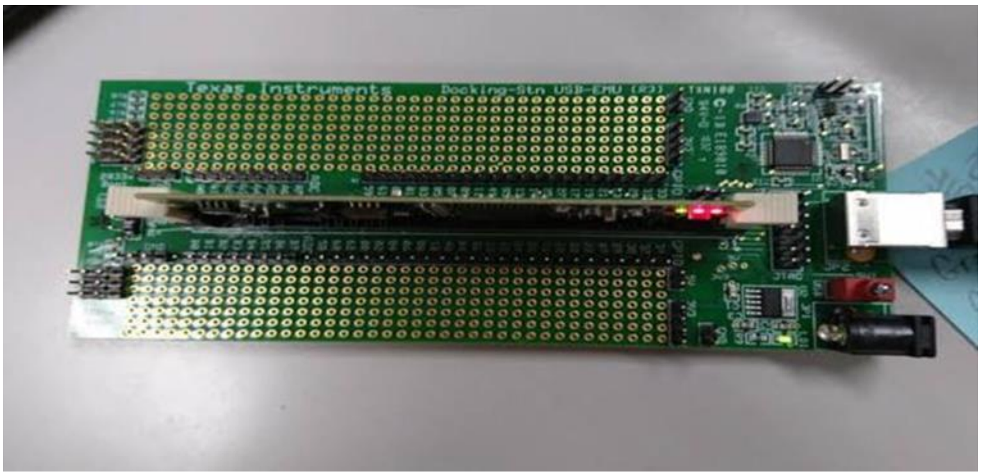

Figure (III.5): dsp f28335

Here is the following image illustrating system modeling.

The following image illustrates the output value Vc, demonstrating the precision of the res- ponse of the PI controller under practical conditions using PIL, despite the imposed variations

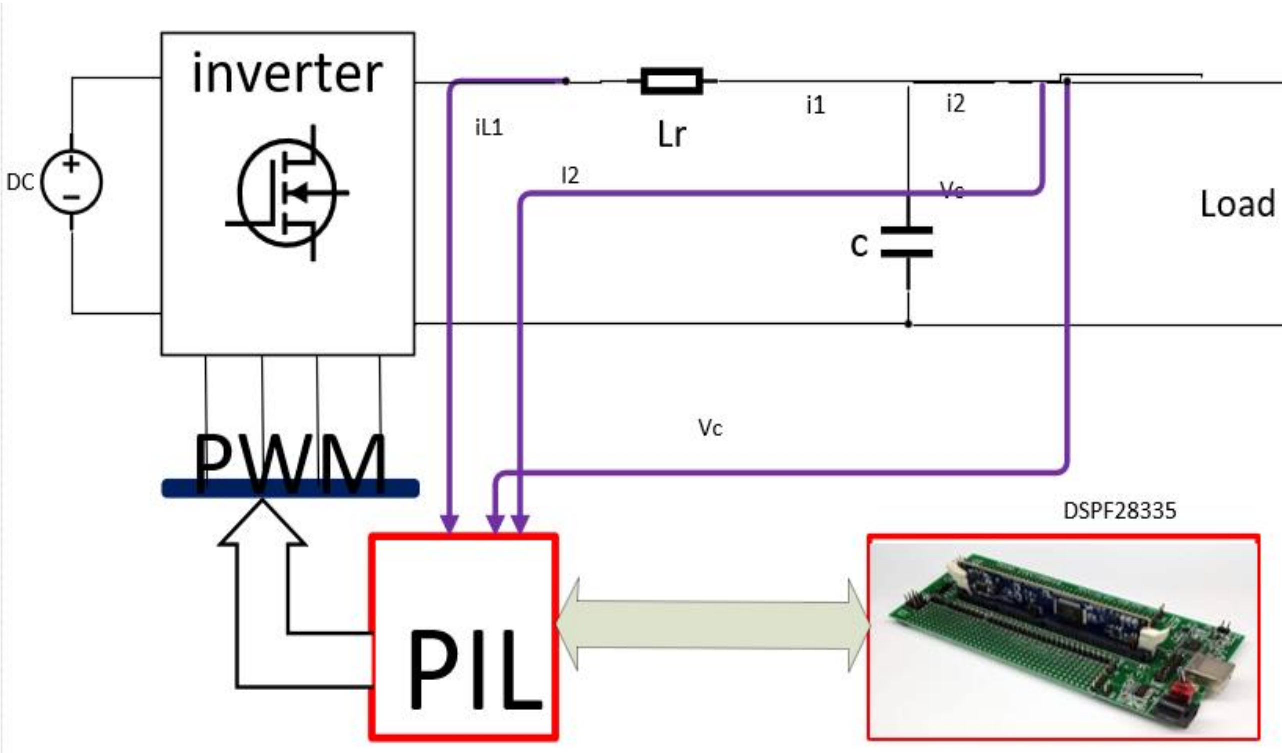

Figure (III.6): inverter singel phasi pil

After conducting the simulation, we observe the following results:

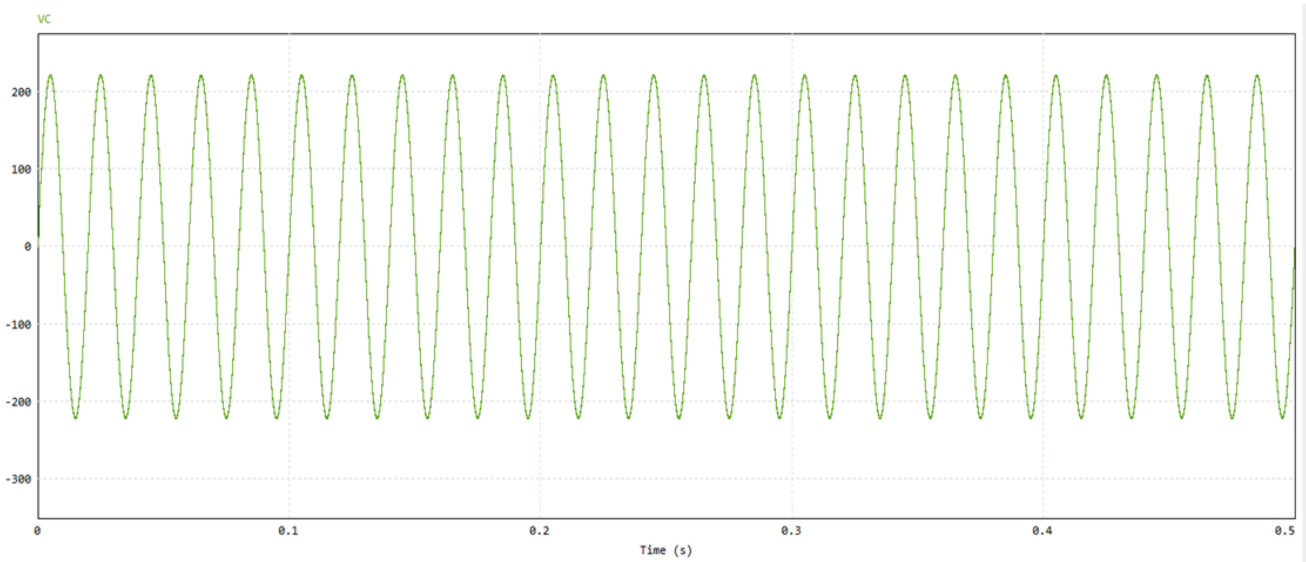

Figure (III.7): voltage Vc

The following image illustrates the output value Vc, demonstrating the precision of the response of the PI controller under practical conditions using PIL, despite the imposed variations on the system at differenttimes. For instance, a resistance R2 was added at one time, while 1V was subtracted at another time

These variations did not affect the output voltage Vc, indicating the accuracy of the PI controller's

response under operational.

Where the difference between Vc and Vcref is almost negligible, as indicated by the Total Harmonic

Distortion (THD), which we will discuss the results of later on.

Also, the current curve results were as follows.

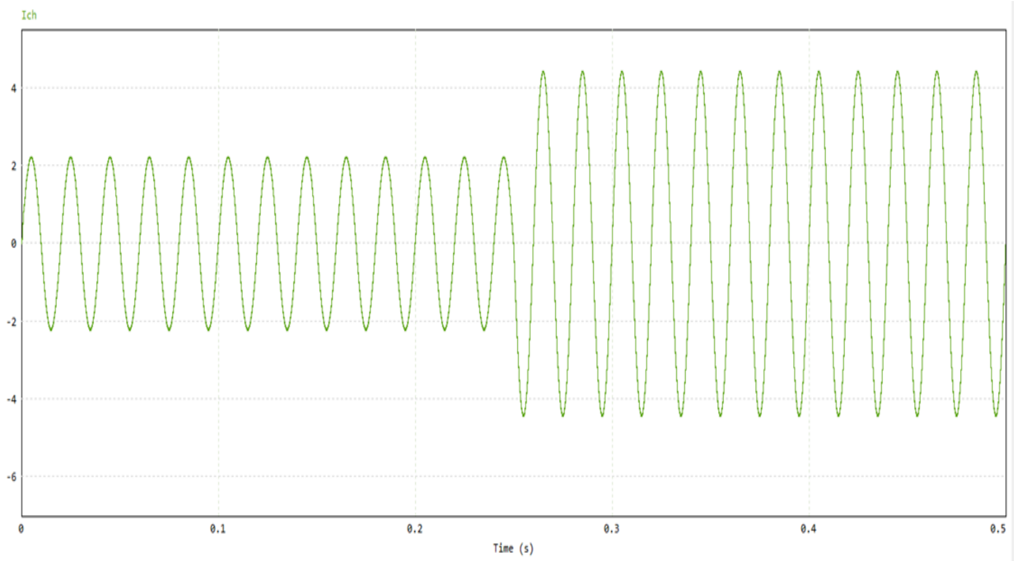

Figure (III.8): current ich

Where there was a close match between the Ich and IL curves.

As indicated in the following document.

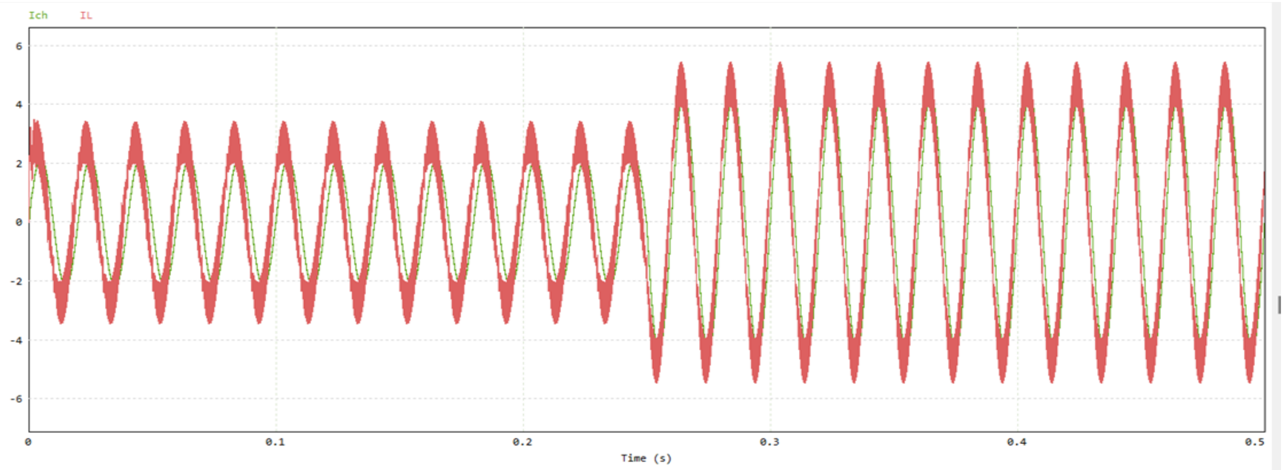

Figure (III.9): current ich il

Also, the voltage between the two inverter terminals, Vab, was as follows.

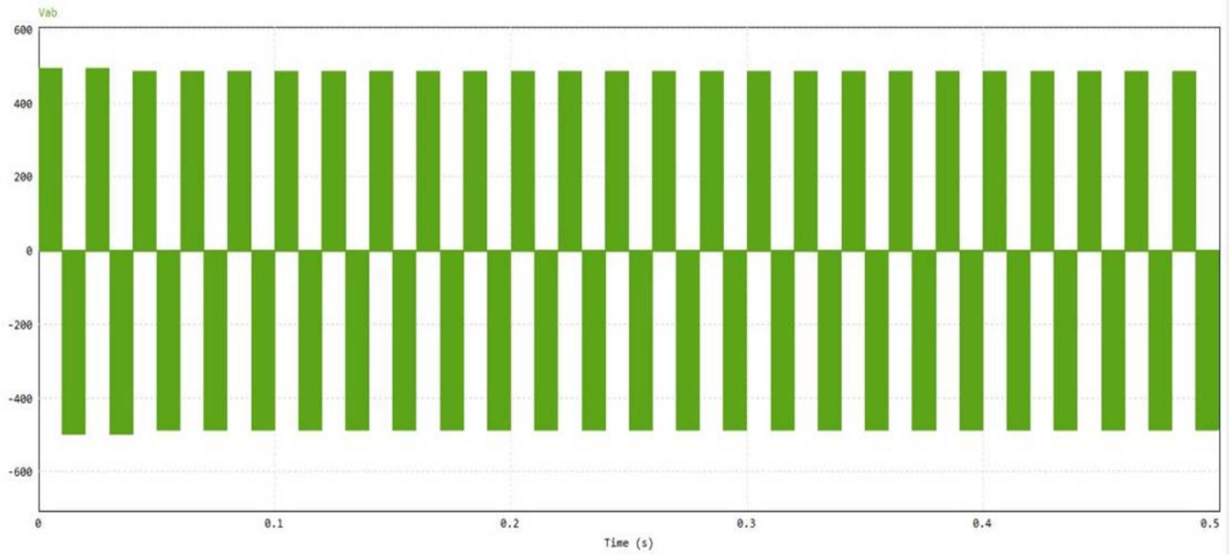

Figure (III.10): voltage Vab

Table III.1: Parameters of the simulation study[28]

Parameter	Symbol	Unit	Value
Nominal voltage	En	V	220
Nominal frequency	Fn	Hz	50
Switching frequency	Fs	KHz	20
DC voltage	Udc	V	495
Output filter capacitor	C	μF	23
Output filter inductor	L.r	$mH\Omega,$	2,1

5. Total Harmonic Distortion :

Improving Total Harmonic Distortion (THD) values is crucial for devices consuming conver- ted power, as lower THD levels result in enhanced efficiency and reduced stress on electrical components. By minimizing harmonic distortion, the quality of the power supply improves, lea- ding to increased reliability and lifespan of equipment. Moreover, lower THD levels contribute to meeting regulatory standards and requirements, ensuring compliance with industry norms and enhancing overall system performance. Therefore, optimizing THD values is essential for maintaining the integrity and efficiencyof power conversion systems, ultimately benefitingboth consumers and the broader electrical infrastructure. The obtained THD result was 0,004%

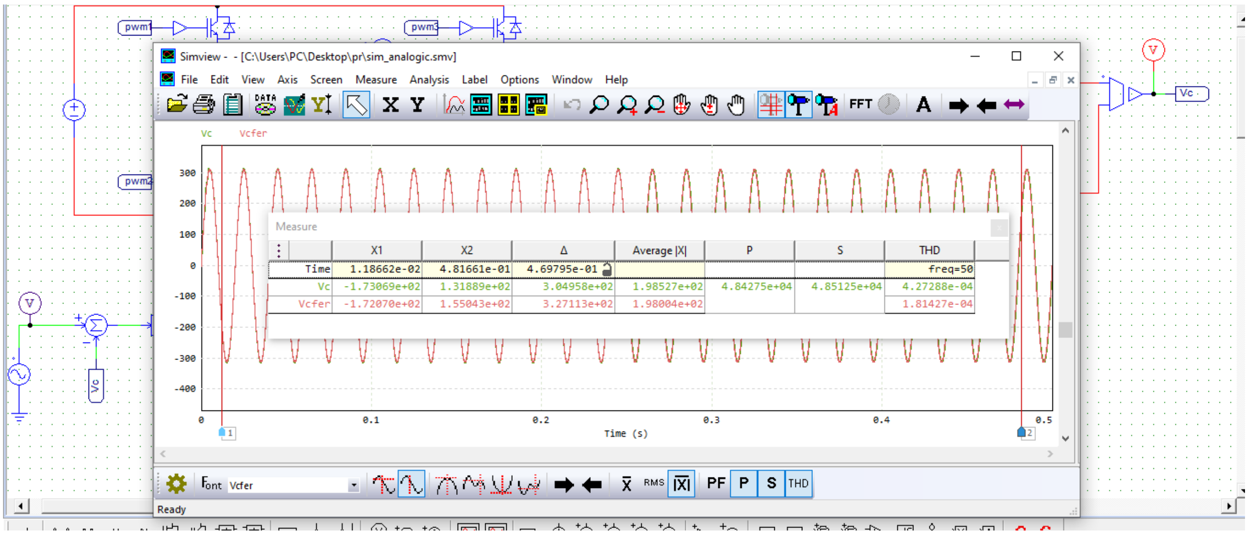

Figure (III.11): THD voltage

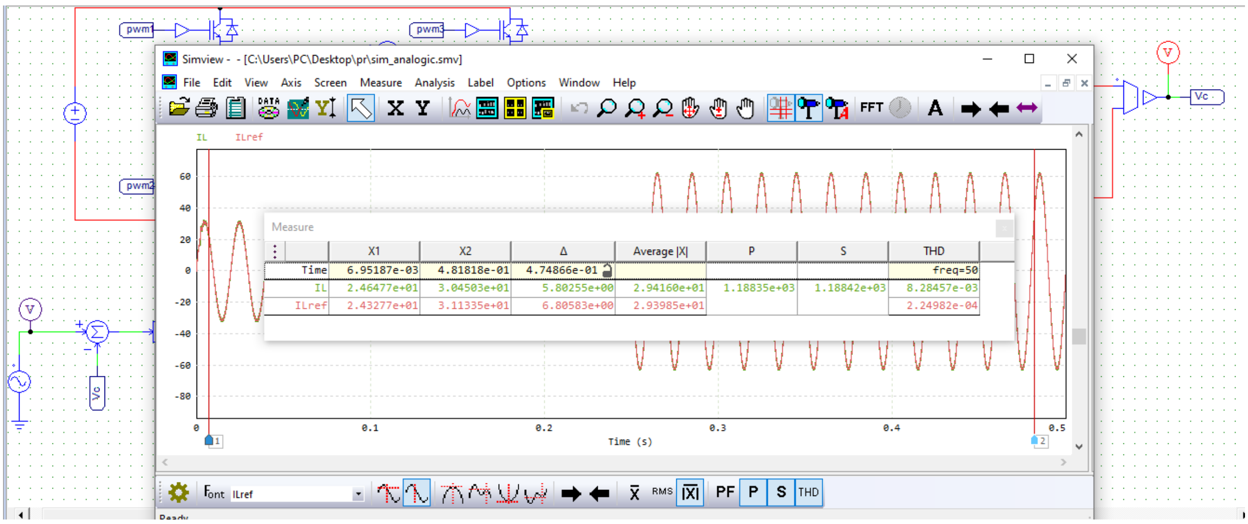

Figure (III.12): THD current

Conclusion:

this chapter has delved into the digital simulation modeling of the single-phase inverter transformer, involving code extraction, modification, and injection into the DSP F28335 card. This process also included the removal of control systems and their replacement with PIL, culminating in precise experimental results aligned with the objectives.

General Conclusion

General Conclusion

In conclusion, this thesis has explored the realm of power electronics with a focus on the implementation of a single-phase inverter for standalone applications using Processor-In-the- Loop (PIL) simulation. The journey began with an overview of the evolution of electronics, particularly in power electronics, highlighting the transition from basic control techniques to advanced strategies like Pulse Width Modulation (PWM).

The thesis then delved into the fundamental principles of single-phase inverters, elucidating their operation mechanisms, control methods, and applications across various sectors. Special emphasis was placed on PWM technology for voltage control, discussing its advantages in terms of efficiency and harmonic reduction.

Moving forward, the study progressed to the synthesis and analysis of inverters, including multi-level voltage inverters, underscoring their significance in medium to high-power applica- tions. Various control strategies were explored, with a particular focus on the Proportional- Integral (PI) control method known for its robustness and effectiveness.

Furthermore, the thesis detailed the implementation of PIL simulation, a powerful technique for testing and validating control algorithms and hardware designs. By integrating real-time processor hardware with simulation software, PIL simulation bridged the gap between software development and hardware implementation, offering a cost-effective and efficient approach to system verification.

The incorporation of a DSP card, specifically the F28335, provided a practical platform for digital simulation modeling of the single-phase inverter. Through code extraction, modification, and injection, the study demonstrated precise experimental results aligned with the defined objectives.

In essence, this thesis not only contributes to the understanding of single-phase inverters and their control strategies but also showcases the efficacyof PIL simulation in accelerating the development and testing of embedded control systems. With its comprehensive exploration and practical insights, this work lays a foundation for further advancements in the field of power electronics and processor-based control systems.

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