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Theme

Desgin, implementation and control of a single phase inverter

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Abstract

Standalone inverters play a vital role in various applications, such as renewable energy systems, backup power systems, and remote off-grid installations. The purpose of this work is to study, simulate,design and control a single-phase inverter to ensure the stability of the output voltage and carry out experimental test bench at the laboratory. The basic structures and explanation of different types of inverters is presented followed by simulating the global control system using MATLAB/ SIMULINK environment. Explanation of Pulse Width Modulation control techniques and their presented proportional resonant voltage controller and low pass filter is discussed to eliminate low order harmonics.

ملخص

تلعب المحولات المستقلة دورًا حيويًا في العديد من التطبيقات، مثل أنظمة الطاقة المتجددة وأنظمة الطاقة الاحتياطية والمنشآت البعيدة خارج الشبكه.

الغرض من هذا العمل هو دراسة ومحاكاة وتصميم والتحكم في عاكس أحادي الطور لضمان استقرار جهد الخرج وإجراء اختبار تجريبي في المختبر

يتم عرض الهياكل الأساسية وشرح الأنواع المختلفة للعاكسات متبوعة بمحاكاة نظام التحكم باستخدام بيئة ماتلاب SIMULINK

شرح تقنيات التحكم في تعديل عرض النبض ووحدة التحكم في الجهد ومرشح التمرير المنخفض للتخلص من التوافقيات ذات الترتيب المنخفض.

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ABOU FARHANA NAEL
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September 2023

Dedication

بعد الحمدلله الذي بنعمته تتم الصالحات فاني اهدي هذا المشروع إلى الذي قال فيهم ربنا عزوجل:

(وَاخْفِضْ لَهُمَا جَنَاحَ الذُّلِّ مِنَ الرَّحْمَةِ وَقُل رَّبِّ ارْحَمْهُمَا كَمَا رَبَّيَانِي صَغِيرًا)

إلي من زرعوا في قلبي بذور حب العلم والسعي نحو النجاح وأسباب توفيقي والدي و والدتي الغاليين

إلي اخوتي الأحباء وعائلتي إلي بلادي فلسطين الارض المباركه

إلي بلدي الثاني الذي لم اشعر فيه بالغربه إلي بلد الشهداء الجزائر الحبيبه

وإلي كافة اساتذتي الذين ساندوني في مساري التعلمي.

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Abbreviation

Abbreviation	**Definition**
THD	Total Harmonic Distortion
PWM	Pulse Width Modulation
Vdc	Input DC Voltage (v)
Fsw	Switching Frequency(HZ)
C	Capacitor(uF)
I0	Output current (A)
V0	Output Voltage (V)
Vref	Reference voltage(V)
Gs	Transfer fuction for signal phase inverter
Ki	Integral gain of PR regulator
Kp	Proportional gain of PR regulator
L	Inductor (mH)
ω_0	natural frequency
ξ	damping ratio
PR	proportional-resonant
R	resistance Load(ohm)

General Introduction

In the past decade solar photovoltaic renewable energy has gained an exponential growth around the globe up to 181 GW installed worldwide as of the end of 2018 .The is because the ease of installation and less maintenance due to no moving part involves in the photovoltaic system, besides that, the cost of the photovoltaic system has been reduced significantly throughout the years are that major factors that favour photovoltaic system as popular choices in the renewable energy industry[1]. power inverter is a static converter providing DC-to-AC conversion, supplied with DC voltage. This voltage can be obtained by means of inverters which eliminate fluctuations in the input DC current[2]. The inverter plays an important role in the renewable energy chain, it is an indispensable parts of solar photovoltaic and battery energy storage system. Inverter has basically divided into three distinct categories, there are grid connected inverter, off-grid inverter and On/Off Grid Tie Inverter. Each inverter has there are own challenges. The off-grid inverter basically uses in standalone system, the main challenges are to step up low DC battery voltage to AC supply voltage level in either single or three phase. It must be capable to maintain the AC output voltage magnitude and frequency under various load conditions within it rated power capacity[1]. In this dissertation, we will attempt to solve the problem of controlling DC-AC converters (single-phase inverters) using a control technique that is well known in the field of linear systems[2]. dissertation will be organized into three chapters, with a general introduction and a general conclusion offering suggestions:

The first chapter: is devoted to a general overview of single-phase full-bridge and half-bridge inverters, and exposes a study of analyzing their operation, characteristics, control and applications, and looking at the origins of harmonics and their solutions.

The second chapter: will be divided into two parts:

- In the first part
  we studied the inverter control techniques pwm (continued to the control techniques in the first chapter) and their characteristics and types, then simulated them in the MATLAB program(open loop)
- In the second part
  we will focus on studying the closed loop control of a system when the input value changes or the linear loads increase and the type of controller is chosen proportional resonant for system stable .

The third chapter , we test experimental implementation of the simulation results. By performing real-world experiments, we validate the performance of the proposed (PR) control strategy

Chapter 1

DC-AC Converters

1.1 Introduction

Power electronics circuits convert electric power from one form to another using electronic devices. Power electronics circuits function by using semiconductor devices as switches, thereby controlling or modifying a voltage or current. Applications of power electronics range from high-power conversion equipment such as dc power transmission to everyday appliances, such as cordless screwdrivers, power supplies for computers, cell phone chargers, and hybrid automobiles. Power electronics includes applications in which circuits process milliwatts or megawatts. Typical applications of power electronics include conversion of ac to dc, conversion of dc to ac, conversion of an unregulated dc voltage to a regulated dc voltage, and conversion of an AC power source from one amplitude and frequency to another amplitude and frequency. The design of power conversion equipment includes many disciplines from electrical engineering. Power electronics includes applications of circuit theory, control theory, electronics, electromagnetics, microprocessors (for control), and heat transfer. Advances in semiconductor switching capability combined with the desire to improve the efficiency and performance of electrical devices have made power electronics an important and fast-growing area in electrical engineering[3].

This chapter introduces the single-phase inverter structure, looks at its different uses, and studies the idea of total harmonic distortion (THD). It shows the significance of single-phase inverters in power conversion systems and the requirement to comprehend their topology, application domains, and the effect of harmonics on system performance.

1.2 DC-AC converter description

An inverter is a DC-AC power electronic converter that transforms direct (DC) voltage or current to alternating (AC) voltage or current with a desired frequency and amplitudes. The symbol of a single-phase DC-AC converter is shown in figure (1.1)[4].

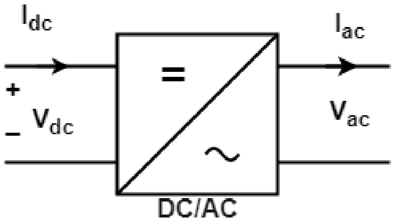

Figure 1.1: DC-AC converter

1.3 Inverter types

The two main types of inverters:

1.3.1 A line commutated inverter

This type of inverters uses a switching device like a commutating thyristor that can control the timing of Turn on but cannot control the timing of turn-off by itself. Turn-off should be performed by reducing circuit current to zero with the help of a supplemental circuit or a source.

1.3.2 A self-commutated inverter

It uses a switching device that can freely control the ON-state and the OFF-state, such as an IGBT or a MOSFET. A self-commutated inverter can freely control the voltage and the current waveform at the AC side, adjust the power factor, and suppress the harmonic current, and is highly resistant to utility system disturbance. Due to advances in switching devices, most inverters for distributed power sources such as photovoltaic power generators now employ self-commutated inverters[5].

1.4 Classification of self-commutated inverters

Inverter can be classified into many types based on the nature of the output power, the input source and the type of the load.

1.4.1 Nature of source

Voltage Source Inverters(VSI)

Voltage Source Inverters is one in which the DC source has small or negligible impedance. In Other words VSI has stiff DC voltage source at its input terminals.

Current Source Inverters(CSI)

A current source inverter is fed with adjustable current from a DC source of high impedance, i.e; from a stiff DC current source. In a CSI fed with stiff current source, output current waves are not affected by the load[6].

1.4.2 Nature of output

Square wave

This is the basic type of inverter. Its output is an alternating square wave. The harmonic content in this wave is very large. This inverter is not efficient and can give serious damage to some of the electronic equipment. But due to low cost, it has some limited number of applications in household appliances.

Modified sine wave

A modified sine wave inverter actually has a waveform more like a square wave, but with an extra step or so. Because the modified sine wave is noisier and rougher than a pure sine wave, clocks and timers may run faster or not work at all. A modified sine wave inverter will work fine with most equipment, although the efficiency or power will be reduced with some. But with most of the household appliances it works well.

Pure sine wave

This type of inverter provides output voltage waveform which is very similar to the voltage waveform that is received from the Grid. The sine wave has very little harmonic distortion, what makes it ideal for running electronic systems such as computers and other sensitive equipment without causing problems or noise[7].

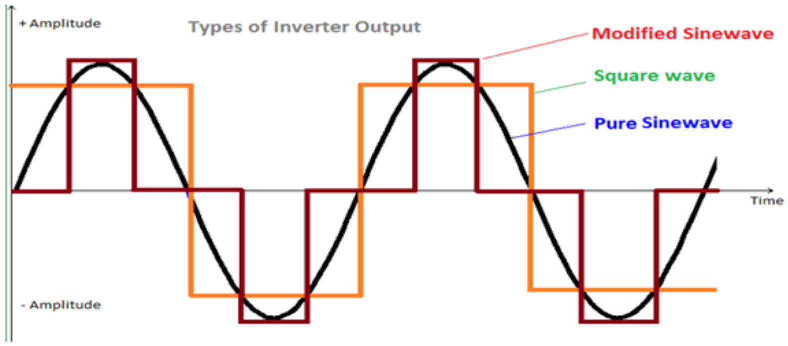

Figure 1.2: Types of inverter output

1.5 Comparison between square wave,modified square wave and pure sine wave

Table 1.1: Types of inverter output [8, 9, 10, 11]

List of Features	Square Wave	Modified Sine wave (quasi-sine)	Pure Sine Wave
Supported Appliances	Square wave inverters are a better choice for supporting only motors.	choice to run appliances and equipment that is less sensitive to power fluctuations, such as lights and some tools	supporting delicate household appliances like laptops, ovens, and refrigerators.
Safety Level	don't work as well and are also dangerous to use with appliances.	safer than square wave	sine wave inverters safely power most devices.
Noise Interference	make a very loud noise.	Make noise less than square wave	make a regular sound
Cost	Less money is spent on Square wave than on sine wave	are often more affordable than their pure sine wave counterparts. (solution for larger projects that require less efficient power)	Square wave cost less than sine wave

1.6 Inverter applications

Among the many areas of use of stand-alone inverters, there are mainly The inverters with forced switching frequency: Most often supplied by a battery, they usually play the role of safety power supply, they constitute as such, the current loop principle of stand-alone inverters. Variable frequency inverters with forced switching : Supplied from the industrial network through a rectifier assembly, they deliver a voltage of high frequency and high value necessary to make an AC motor turn at variable speed[12].

1.6.1 Speed regulation a synchronous motor

The speed of a synchronous motor is determined by the pulsation of the static currents. To change the speed it is necessary to change the frequency of the supply voltages. As the grid voltage frequency is fixed, It is necessary to rectify the voltage of the grid which supplies a standalone inveter that can generate voltages with desired frequencies.

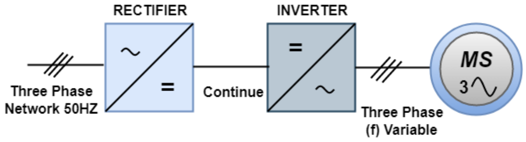

Figure 1.3: regulation the speed of rotation of a synchronous motor

1.6.2 Emergency power supply

During a power failure, an UPS ensures the continuity of power to the machines from batteries. In professional computing, an UPS is essential to avoid the loss of information in case of a power failure[12].

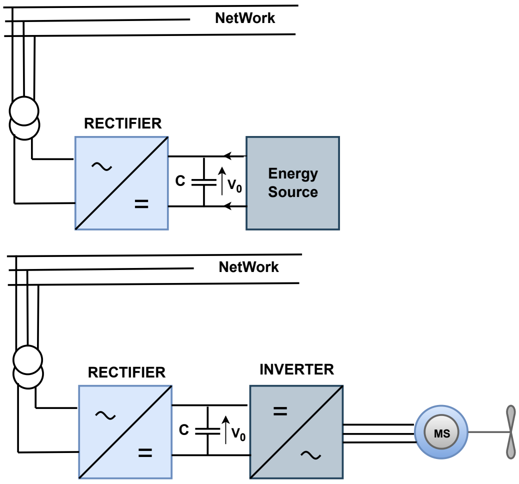

Figure 1.4: Emergency power supply

1.7 Harmonic analysis of the output voltage

1.7.1 Harmonics sources

voltage harmonics are the results of current harmonics which originate because of the presence of non-linear loads like variable speed drives, inverters, UPS, television sets, PCs, semiconductors-based circuits, and welding sets in the system. They act as harmonic current sources. The resulting current waveform can be quite complex depending on the type of load and its interaction with other components of the system.

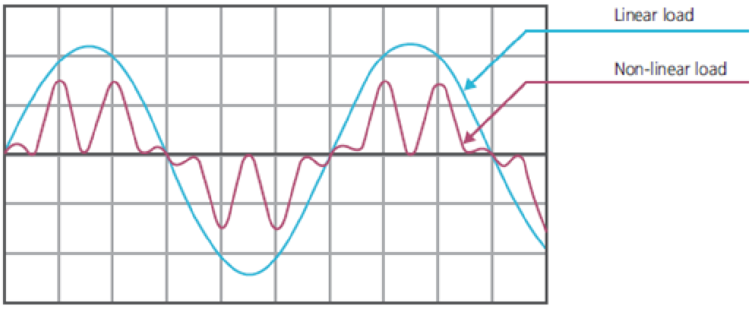

Figure 1.5: linear load and non linear(current)

1.7.2 The effect of current and voltage harmonics on the load

Current harmonics increase the RMS current flowing in the circuit and thereby, increase the power losses. Current harmonics affect the entire distribution all the way down to the loads. They may cause increased eddy current and hysteresis losses in motors and transformers resulting in overheating, overloading in neutral conductors, nuisance tripping of circuit breakers, over-stressing of power factor correction capacitors, interference with communication, etc. They can even lead to overheating and saturation of reactors. Voltage harmonics affect the entire system irrespective of the type of load. They affect sensitive equipment throughout the facility like those that work on the zero-voltage crossing as they introduce voltage distortions[13].

1.7.3 Frequency spectrum

The spectrum is a histogram providing the amplitude of each harmonic according to its rank and its importance[14].

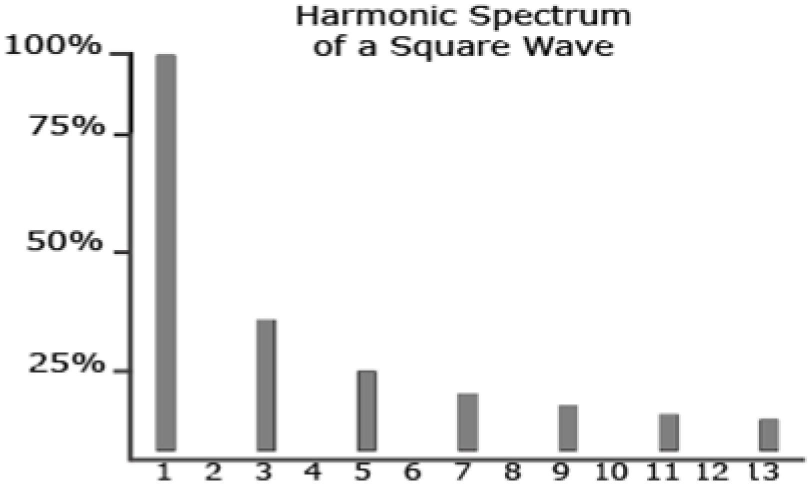

Figure 1.6: Harmonic spectrum of a given electrical signal

1.7.4 Total Harmonic Distortion

Harmonic problems are almost always introduced by the consumers' equipment and installation practices. Harmonic distortion is caused by the high use of non-linear load equipment such as computer power supplies, electronic ballasts, compact fluorescent lamps and variable speed drives etc, which create high current flow with harmonic frequency components. The limiting rating for most electrical circuit elements is determined by the amount of heat that can be dissipated to avoid overheating of busbars, circuit breakers, neutral conductors, transformer windings or generator alternators.[8]

It is given by the following expression:

$$THD(\%) = \frac{\sqrt{\sum_{i=2}^{n} V_i^2}}{V_1} = \frac{\sqrt{V_{rms-}^2 V_{1rms}^2}}{V_{1rms}} \tag{1.1}$$

with V_1 the peak value of the fundamental voltage and V_i the peak values of the different harmonics of the voltage. The frequency range that corresponds to the study of harmonics is generally between 100 and 2000 Hz. That is to say from the harmonic of rank 2 to the harmonic of rank 40. It should also be noted that the amplitude of harmonics generally decreases with the frequency[13].

Since the amplitudes of the harmonics are needed to calculate the THD, Fourier analysis can be used to determine the THD[15].

$$\begin{gathered} s(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + \sum_{n=1}^{\infty} b_n \sin(n\omega t) \\ a_0 = \frac{2}{T}\int_0^T s(t)dt \\ a_n = \frac{2}{T}\int_0^T s(t)\cos(n\omega t)dt = \frac{2}{2\pi}\int_0^{2\pi} s(\theta)\cos(n\theta)d\theta \\ b_n = \frac{2}{T}\int_0^T s(t)\sin(n\omega t)dt = \frac{2}{2\pi}\int_0^{2\pi} s(\theta)\sin(n\theta)d\theta \end{gathered} \tag{1.2}$$

Importance of THD in Systems

THD is important in several types of systems, including power systems, where a low THD means higher power factor, lower peak currents, and higher efficiency; audio systems, where low THD means that the audio signal is a more faithful reproduction of the original recording; and communication systems, where low THD means less interference with other devices and higher transmit power for the signal of interest[15].

1.8 Single-phase inverters with one square pulse per half-cycle

There are several topologies available, in this section we will briefly explain the two most common ones: Half Bridge and Full Bridge.

1.8.1 Single-phase half-bridge inverter

Only two switchers are required in this topology. The DC input is divided in two identical sources and the output is referenced to the middle point[7].

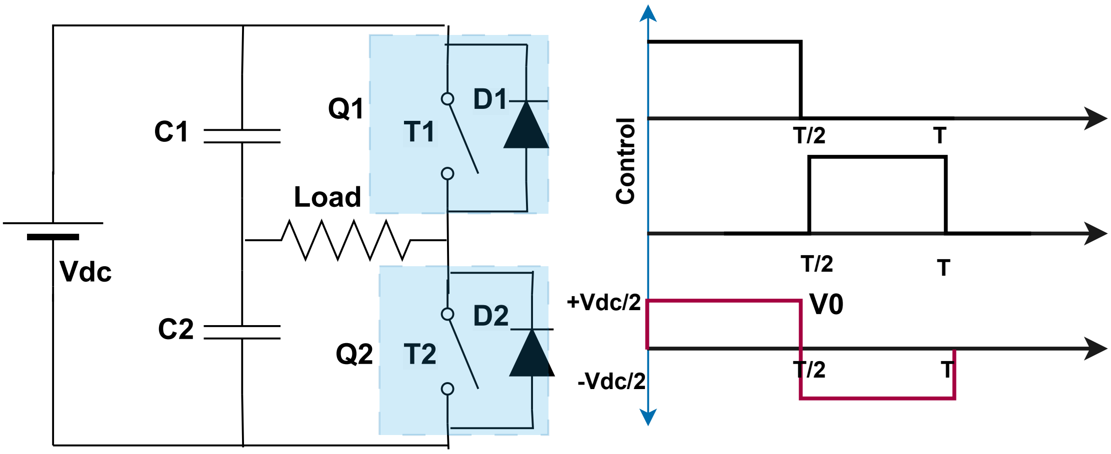

Figure 1.7: Single-phase Half-Bridge voltage inverter

Control strategy

It consists mainly of a single arm with two power switches Q1 and Q2 with complementary control. The control (180o) denies the conduction time of each of the switches is then half a cycle corresponding to the frequency of the output signal required when the switch Q1 is closed, the voltage across the load would therefore be +Vdc/2, and takes the value -Vdc/2 when the second switch, Q2 is closed[14].

The full wave control(plain wave) has the same frequency as the output signal

$$V_{a_0} = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n\theta) + b_n \sin(n\theta) \tag{1.3}$$

V_{a_0} is a symmetrical odd signal with zero mean value which leads to: $a_0 = a_n = 0$

$$\begin{aligned} V_{a_0} &= \sum_{n=1}^{\infty} b_n \sin(n\theta) \\ b_n &= \frac{2}{2\pi}\int_0^{2\pi} V_{a0}\sin(n\theta)d\theta = \frac{4}{2\pi}\int_0^{\pi} V_{a0}\sin(n\theta)d\theta \\ &= \frac{2}{\pi} * \frac{V_{dc}}{2}\int_0^{\pi}\sin(n\theta)d\theta = \frac{2}{\pi} * \frac{V_{dc}}{2}\left[1 - \frac{1}{n}\cos(n\theta)\right] \\ &= \frac{2}{n\pi} * \frac{V_{dc}}{2}[1 - \cos(n\pi)] \end{aligned} \tag{1.4}$$

For $n = 2; 4; 6; 8 \ldots .(.n$ even number) $b_n = 0$

For $n = 1; 3; 5; 7 \ldots\ldots($ n odd number) $b_n = \dfrac{4}{n\pi} * \dfrac{V_{dc}}{2}$

The peak value of the fundamental frequency component in the output waveform of the inverter can be obtained as follows:

$$V_{a_0} = \frac{4}{n\pi} * \frac{V_{dc}}{2} = 1.273 * \frac{V_{dc}}{2} \tag{1.5}$$

For the other harmonics ($n \geq 2$)

$n = 3 \ldots\ldots\ldots\ldots\ldots\ldots b_3 = 0.42 * V_{dc}/2$, $n = 9 \ldots\ldots\ldots\ldots\ldots\ldots\ldots$ $b_9 = 0.14 * V_{dc}/2$

n= 5. . . . . $b_5 = 0.25 * V_{dc}/2$, $n = 11 \ldots\ldots\ldots\ldots\ldots\ldots b_{11} = 0.115 * V_{dc}/2$

$n = 7 \ldots\ldots\ldots\ldots\ldots\ldots$ $b_7 = 0.18 * V_{dc}/2$, $n = 13 \ldots\ldots\ldots\ldots\ldots\ldots b_{13} = 0.097 * V_{dc}/2$

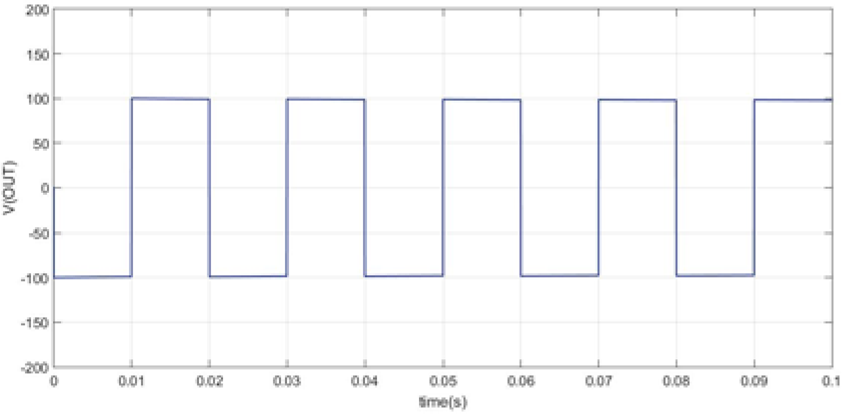

Figure 1.8: square wave half-bridge

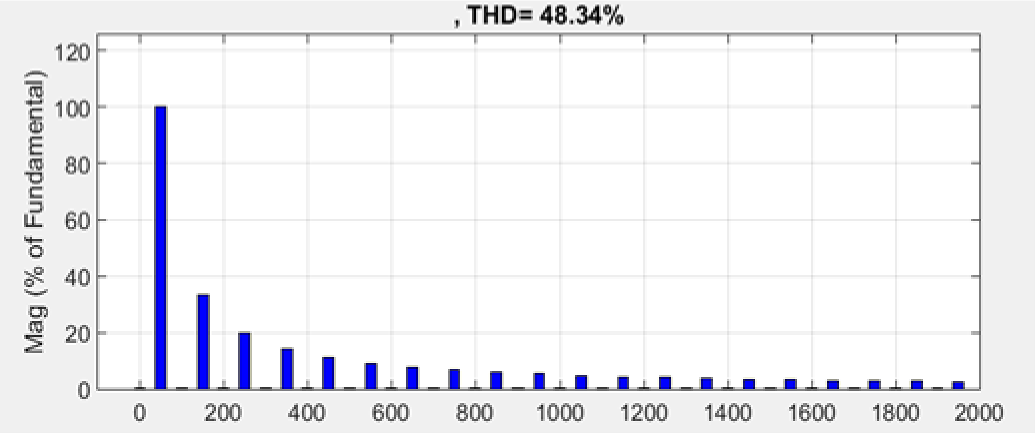

Figure 1.9: THD for inverter control in half-bridge

1.8.2 Single-phase full bridge inverter

To avoid the need for a midpoint source and to double the output voltage, a bridge inverter is used in this case. The transistors Q1, Q2 are controlled on a half period and the transistors Q3, Q4 on the rest of the period[14].

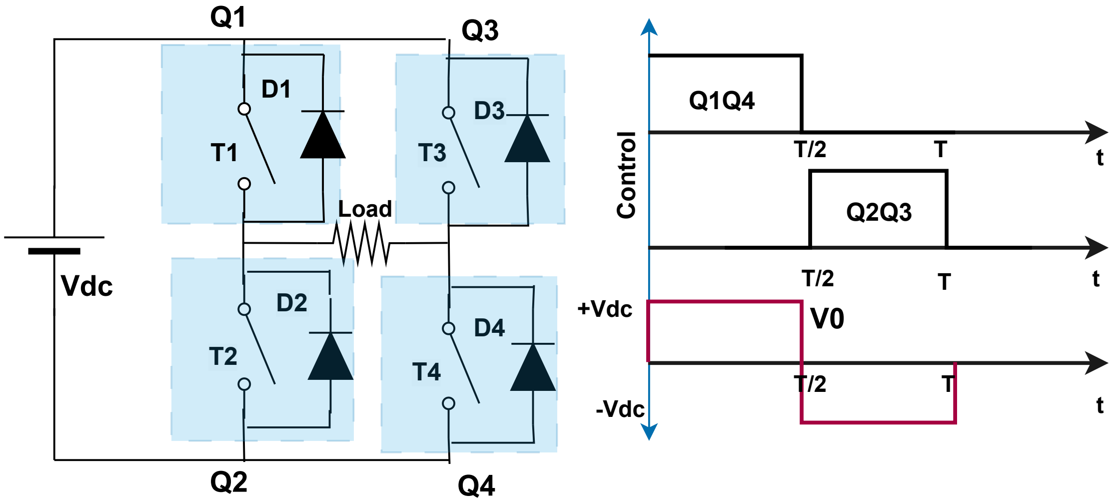

Figure 1.10: Control signals and output voltage for single-phase inverter

$$
\begin{aligned}
V_{a_0} &= \sum_{n=1}^{\infty} b_n \sin(n\theta) \\
b_n &= \frac{2}{2\pi}\int_0^{2\pi} V_{a_0}\sin(n\theta)d\theta = \frac{4}{2\pi}\int_0^{\pi} V_{a_0}\sin(n\theta)d\theta \\
&= \frac{2}{\pi} * V_{dc}\int_0^{\pi}\sin(n\theta)d\theta = \frac{2}{\pi} * \frac{V_{dc}}{2}\left[1-\frac{1}{n}\cos(n\theta)\right] \\
&= \frac{2}{n\pi} * V_{dc}[1-\cos(n\pi)
\end{aligned}
\tag{1.6}
$$

For n = 2, 4,6, 8....(n even number) $b_n = 0$

For n = 1, 3, 5, 7.......(n odd number) $b_n = \frac{4}{n\pi} * V_{dc}$

For the other harmonics ($n \geq 2$)

$n = 3$.....................$b_3 = 0.42 * V_{dc}$, $n = 9$...................... $b_9 = 0.14 * V_{dc}$

$n = 5$..................... $b_5 = 0.25 * V_{dc}$, $n = 11$.....................$b_{11} = 0.115 * V_{dc}$

n= 7..................... $b_7 = 0.18 * V_{dc}$, $n = 13$.....................$b_{13} = 0.097 * V_{dc}$

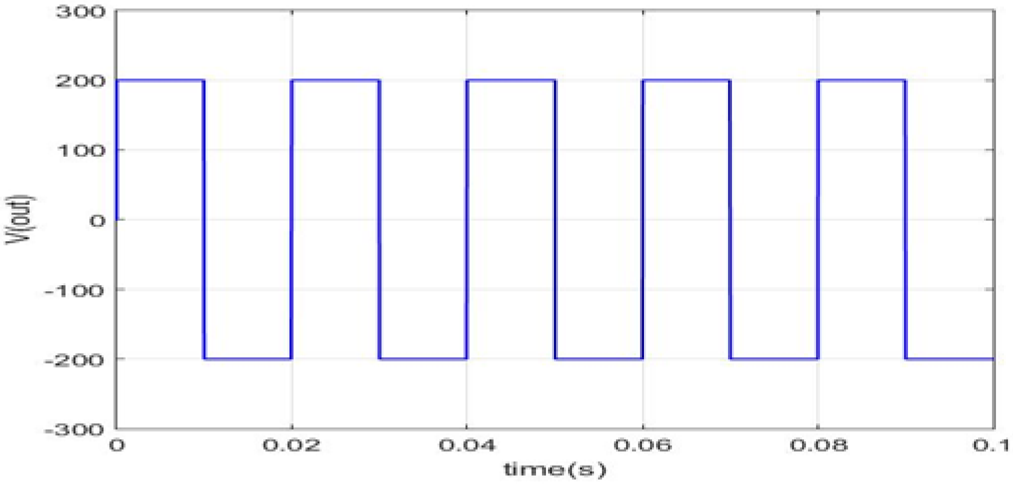

Figure 1.11: Square wave full bridge

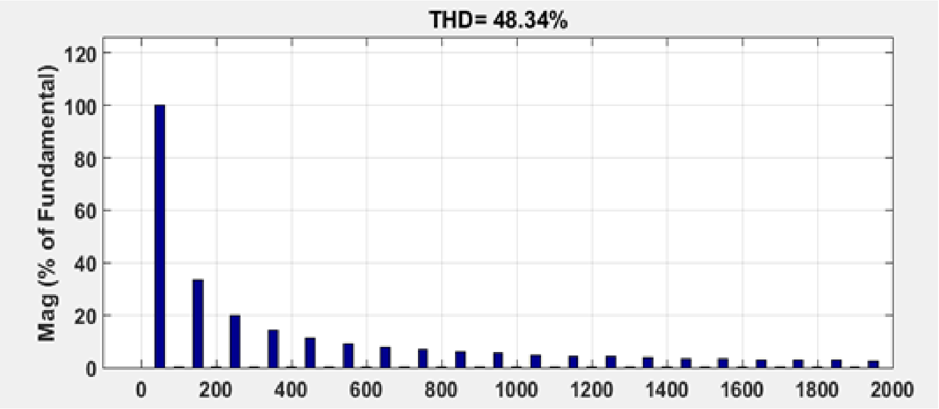

Figure 1.12: THD for Full wave control

1.9 Phase-shifted Single-phase full-bridge inverter

This specific control strategy can be applied only in single-phase full-bridge inverters. The purpose of this command is to close or open the switches (Q1, Q4) and (Q2, Q3), simultaneously but with a certain time delayTd . So it allows to act on the effective value and on the fundamental amplitude of the output voltage[14]. This technique presents important losses because of the existence of filtering circuit.

The output signal is an odd signal (or makes a translation of the axis of abscissa B) V_{a_0} is

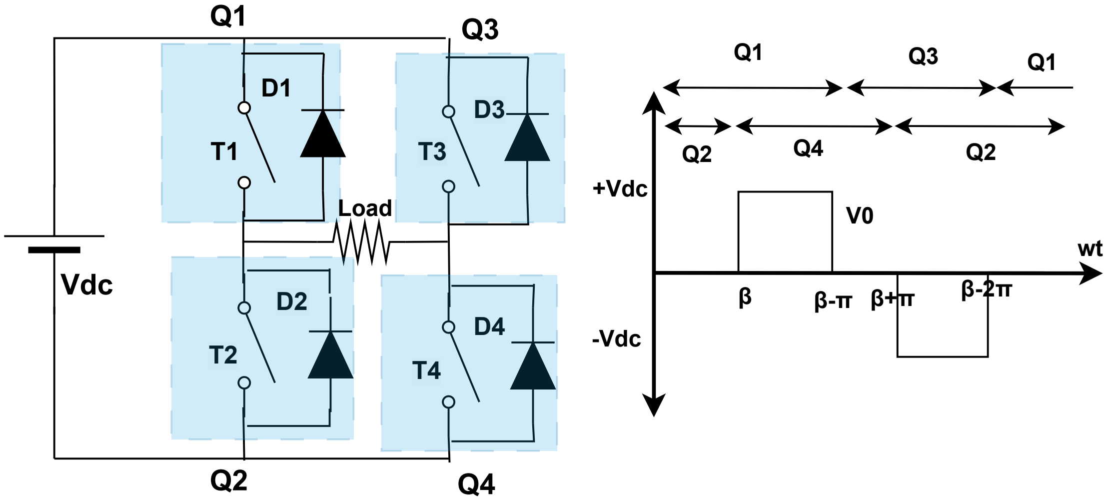

Figure 1.13: Shifted duty cycle control

an odd symmetrical signal with zero mean value. $a_0 = a_n = 0$

$$V_{a_0} = \sum_{n=1}^{\infty} b_n \sin(n\theta)$$

$$\begin{aligned} b_n &= \frac{2}{2\pi}\int_0^{2\pi} V_{a_0}\sin(n\theta)d\theta = \frac{4}{2\pi}\int_0^{\pi} V_{a_0}\sin(n\theta)d\theta \\ &= \frac{4}{2\pi} * V_{dc}\int_{\beta}^{\pi-\beta} V_{dc}\sin(n\theta)d\theta = \frac{2}{n\pi} * V_{dc}[\cos(n\beta) - \cos(n\pi - n\beta)] \\ &= \frac{2}{n\pi} * V_{dc}\cos(n\beta)[1 - \cos(n\pi)] \end{aligned} \tag{1.7}$$

For n = 2, 4,6, 8. . . .(n even number) $b_n = 0$

For n = 1, 3, 5, 7. . . . . . .(n odd number)

$$b_n = \frac{4}{n\pi} * \cos(n\beta) \tag{1.8}$$

For n = 1 the fundamental has an amplitude of :

suppose $\beta = \frac{\pi}{6}$

$$b_1 = V_{a_0} = \frac{4}{\pi}V_{dc}\cos(\beta) = 1.1 * V_{dc} \tag{1.9}$$

For the other harmonics ($n \geq 2$)

$n = 3$. $b_3 = 0$, n= 9. $b_9 = 0$

$n = 5$.................... b_5= -0.22 *V_{dc} , n= 11.................... b_{11}=0.1 * V_{dc}

$n = 7$.................... b_7 = -0.1575 * V_{dc} , n= 13.............. b_{13}= 0.08 * V_{dc}

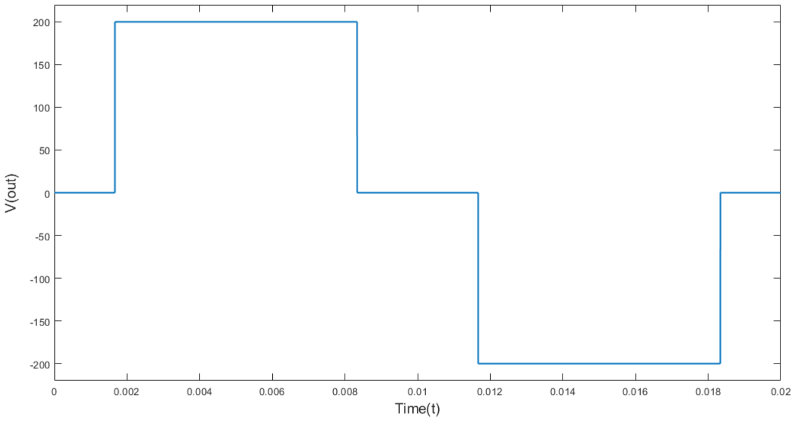

Figure 1.14: Shifted duty cycle

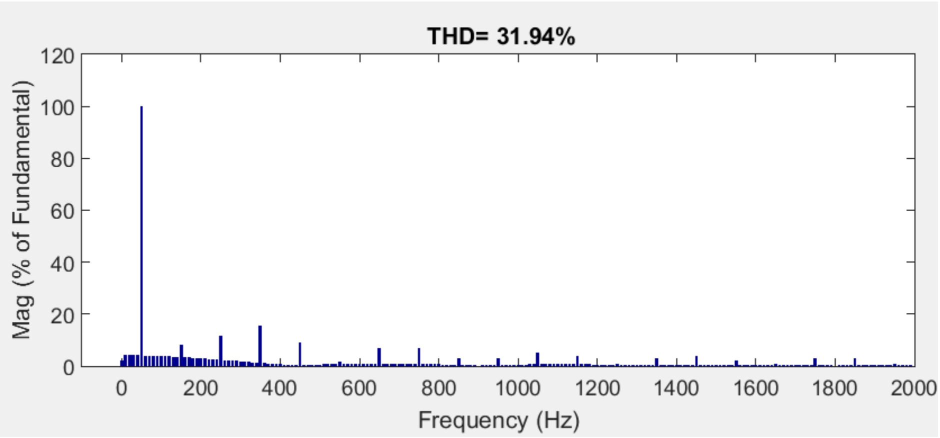

Figure 1.15: THD Shifted duty cycle

1.10 Pulse Width Modulation (PWM)

Pulse Width Modulation refers to a method of carrying information on a train of pulses, the information being encoded in the width of the pulses. The pulses have constant amplitude but their duration varies in direct proportion to the amplitude of analog signal[16].

1.11 Pulse Width Modulation Principles

Pulse Width Modulation (PWM) is a powerful method for generating an analog signal using a digital source. A PWM signal consists of two main components that define its behavior: a duty cycle and a frequency. The duty cycle describes the amount of time the signal is in a high (on) state as a percentage of the total time of it takes to complete one cycle. The frequency determines how fast the PWM completes a cycle (i.e. 1000 Hz would be 1000 cycles per second), and therefore how fast it switches between high and low states. By cycling a digital signal off and on at a fast enough rate, and with a certain duty cycle, the output will appear to behave like a constant voltage analog signal when providing power to devices. Output signal alternates between on and off within specified period, yields Controls power received by a device. The voltage seen by the load is directly proportional to the source voltage. The on-off behavior changes the average power of signal .A PWM signal is not constant, the main parameter is a duty cycle that is a part of PWM period and describes the proportion of on time to regular interval[17].

$$\text{Duty Cycle } = \frac{\text{on time}}{\text{periode}} * 100\% \tag{1.10}$$

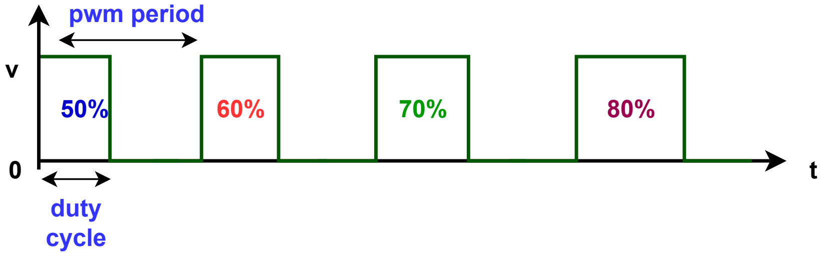

Figure 1.16: Caption

1.12 PWM Generation

Several methods were used to Generate PWM signals. one of them Analogue method. Analogue PWM signals (comparator output) can be made by combining a saw- tooth waveform and a sinusoid, the higher the DC level is, the wider the PWM pulses are. The DC level is the demand signal[17].

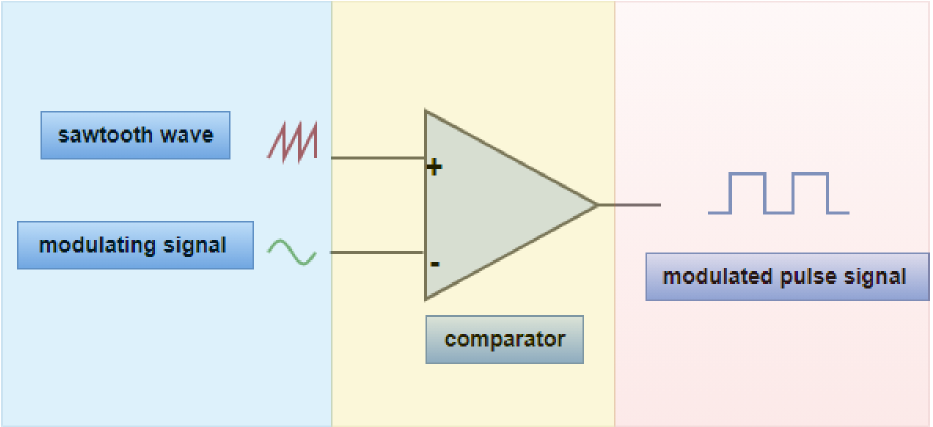

Figure 1.17: PWM Generation

1.12.1 ADVANTAGES OF PWM

- The output voltage control is easier with PWM than other schemes and can be achieved without any additional components.

- The lower order harmonics are either minimized or eliminated altogether.

- The filtering requirements are minimized as lower order harmonics are eliminated and higher order harmonics are filtered easily.

- It has very low power consumption[16].

1.13 SINGLE PHASE PWM INVERTERS

In many industrial applications, to control the output voltage of the inverters is necessary for the following reasons

- To adjust with variations of dc input voltage

- To regulate voltage of inverters

-To satisfy the contain volts and frequency control requirement[16].

1.13.1 Different PWM techniques

MODIFIED SINUSOIDAL PULSE-WIDTH MODULATION

In SPWM the widths of pulses that are nearer the peak of the sine wave do not change significantly with the variation of modulation index. This is due to the characteristics of sine wave. In modified sinusoidal pulse-width modulation technique the SPWM technique is modified so that the carrier wave is applied during the first and last 60° intervals per half-cycle.

The fundamental component is increased and its harmonic characteristics are improved. This technique reduces number of switching of power devices and therefore reduces the switching loss.

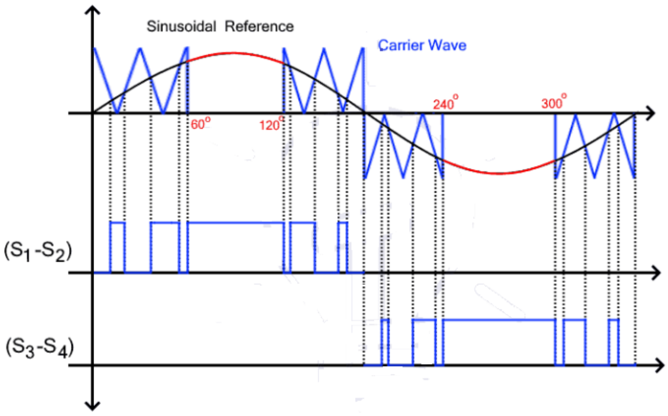

Figure 1.18: MODIFIED SINUSOIDAL PWM

SINGLE PULSE-WIDTH MODULATION

In single pulse-width modulation control, there is only one pulse per half cycle. The width of the pulse is varied to control the inverter output voltage. The gating signals are generated by comparing a rectangular reference signal with a triangular carrier wave. The frequency change is achieved by varying the frequency of reference signal . In single pulse-width modulation the dominant harmonic is the third harmonic and the distortion factor increases significantly at a low output voltage.

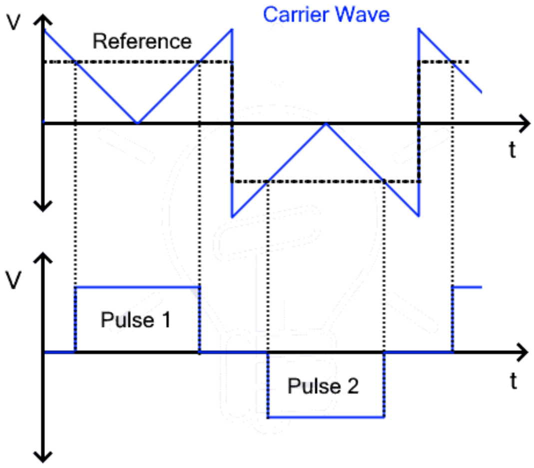

Figure 1.19: SINGLE PWM

SINUSOIDAL PULSE-WIDTH MODULATION

In sinusoidal pulse-width modulation (SPWM) the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the center of the same pulse instead of maintaining the width of all pulses the same in the case of multiple pulse-width modulation. This technique significantly reduces the distortion factor and lower-order harmonics and therefore this technique is the most commonly used technique in industrial application. The number of pulses per half-cycle depends on the carrier frequency. The frequency of reference signal determines the inverter output frequency and its peak amplitude controls the modulation index then in turn the R.M.S. output voltage[18]. Bipolar and Unipolar switching are the two available methods of switching (SPWM). Both methods compare the reference signal and the carrier signal and cause switching conditions that correspond to the two signals[17].

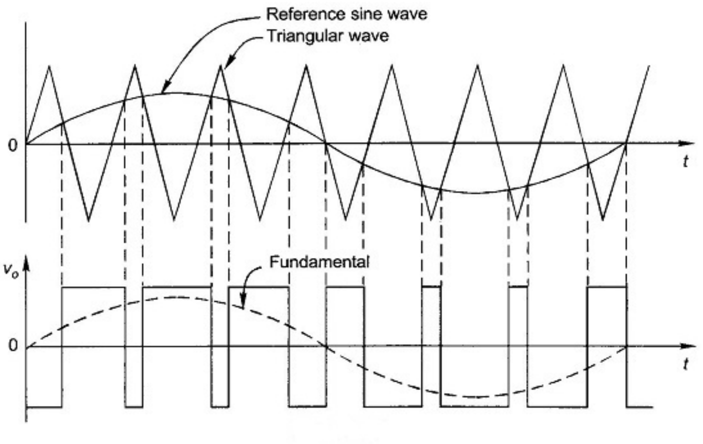

Figure 1.20: Bipolar SPWM

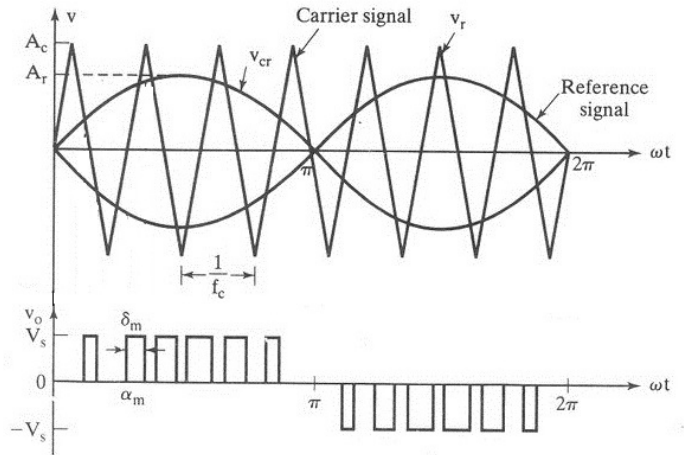

Figure 1.21: Unipolar SPWM

1.13.2 Characteristic of the Pulse Width Modulation (PWM)

The essential parameters of the pwm are:

- The index of modulation is:

$$m = \frac{f_c}{f_r} \tag{1.11}$$

The frequlency $f_c = \frac{1}{T_P}$

Where:

f_r : is the frequency of the reference.

f_c : is the frequency of the carrying wave.

The control factor in voltage is:

$$\boldsymbol{r} = \frac{A_r}{A_c} \tag{1.12}$$

Where:

A_r : Amplitude of the reference.

A_C : Amplitude of the carrying wave[19].

$$V_{ref} = A_r * \sin(\omega t + \theta) \tag{1.13}$$

1.14 Filters

Because the output voltage waveform is squared, a filter is required in order to obtain a sine wave form, as well as helping in reducing harmonics, which may disturb the correct operation of the output load connected. A filter is, in its most basic sense, a device that enhances and/or rejects certain components of a signal. It can be analogic or digital and depending on its behavior, there are mainly four types.

Type of filter	***Feateures***
Low pass	They let pass low frequencies and attenuate the ones over a cut point
High pass	They attenuate frequencies below a cut point
Band pass	They let pass frequencies between a range
Band rejection	The block frequencies between a range

Once the type of circuit is selected, the cut point and the ranges of frequencies can be chosen by modifying the components. As in this case the objective is to attenuate harmonics, a low pass filter will be selected. For a low pass filter, there are two options regarding circuitry: RC (resistor - capacitance) or LC (inductance - capacitance). For all H-bridge inverters, a low-pass output filter is needed to obtain the fundamental frequency output. Generally, there are four different types of H-bridge inverter filters. They are L filter, LC filter, LCL filter[7].

1.14.1 L Filter

The L type filter, shown in Fig.1 consists of an inductor only. Over the entire frequency range, L type filters have an attenuation of -20 dB/dec. In order to suppress the output Current harmonics, a high value inductor is needed. A large inductance leads to a larger filter size and higher cost. The high voltage drop over the big inductor worsens the system dynamics.

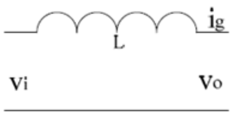

Figure 1.22: L filter

1.14.2 LC Filter

The LC filter, shown in Fig. , is a second-order filter with an attenuation of -40 dB/dec. The LC filter design process is fairly easy. The trade-off of the design is that a higher capacitance may help reduce the cost of the inductor. However, the system may encounter inrush current and high reactive current flow into the capacitor at the fundamental frequency . If an inverter is tied to the grid through an LC filter, the resonance frequency of the filter becomes dependent upon the grid impedance . However, the LC filter is good fit for stand-alone inverters due to its compact size and good attenuation performance.

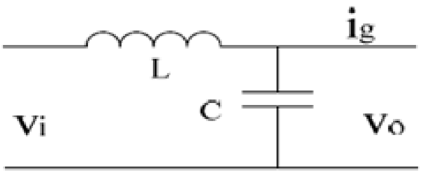

Figure 1.23: LC filter

$$fc = \frac{1}{2\pi * \sqrt{LC}} \tag{1.14}$$

1.14.3 LCL Filter

The third-order LCL filter, displayed in Fig()., is widely used with grid-connected inverters due to its high attenuation beyond resonance frequency. Compared to the LC filter, the LCL filter gives a better decoupling capability between the filter and the grid impedance. The design process of the LCL filter has to consider the resonance of the filter and the current ripple flowing through the inductors [20].

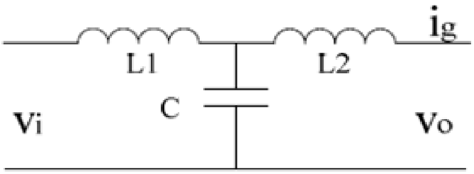

Figure 1.24: LCL Filter

1.15 Conclusion

In this chapter, different structures of single-phase inverters are presented. The techniques used for controlling the inverters have the same frequency as the output signal (voltage). The Frequency analysis has shown that output signal of such control techniques contains harmonics with important magnitude compared to the fundamental, which may affect and harm some types of loads. For this reason, filters are needed to extract the fundamental signal and eliminate the harmonics. Different filters are available. The choice of one of them depends on the system in which the inverter is used. The next chapter will present the PWM control technique used as an alternative to the aforementioned techniques.

Chapter 2

Modeling and Control of Single Phase Inverter

2.1 Introduction

The combination of PWM method with closed-loop PR control in a single-phase inverter system is the main topic of this chapter. It illustrates how the control scheme's PWM signals are fed into the inverter's switching components to control the output waveform. Based on the feedback data, the closed-loop PR controller constantly modifies the control signals, improving the system's capability for stability, response, and harmonic mitigation.

2.2 System Description

The scheme of single-phase voltage-source fullbridge inverter which is used in this investigation is shown in Figure 2.1. In this analysis, inverter configuration has four main parts:

The DC source voltage: Vdc is ripple free and constant.

Inverter switching devices :here is the important bloc that is converting a DC to alternative voltage which is H-bridge converter composed of four electrical IGBT transistor.

The LC filter:In the output of the single phase inverter system, low pass filter is designed to convert the square voltage waveform saturated into a pure sinusoidal waveform

Load:Load type is linear.[21][22][23].

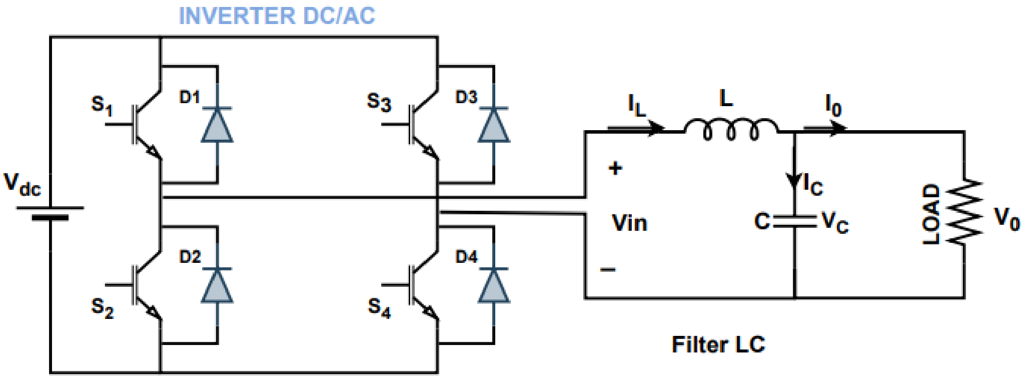

Figure 2.1: single phase inverter with lc filter

2.2.1 mode operation of switch

To generate an AC waveform in single-phase inverter, the switches S1, S4 ON and S3, S2 off for period t1 and t2 as shown in figure 2.2. For that period, the output is a positive voltage.

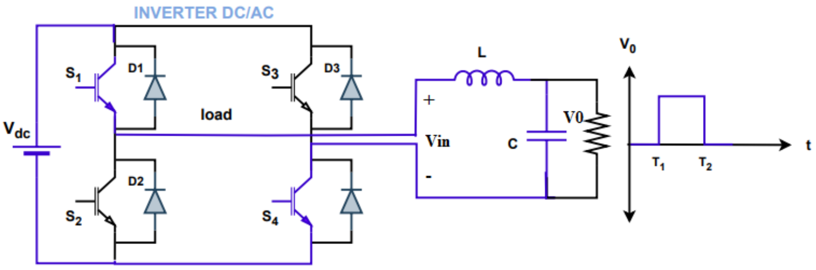

Figure 2.2: Output voltage for S1, S4 ON; S3, S2 OFF

For period t3 to t4 in figure 2.3, the switches S3, S2 are on and S1 and S4 are off to obtain negative voltage.

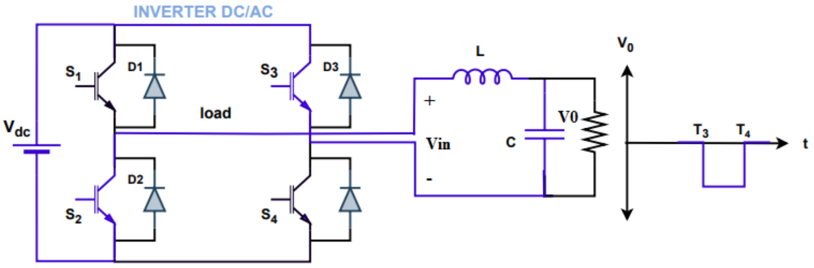

Figure 2.3: Output voltage for S2, S3 ON; S4, S1 OFF

For period t2 to t3 in figure 2.4, the switches S2, S4 are on and S1 and S3 are off to obtain zero voltage.

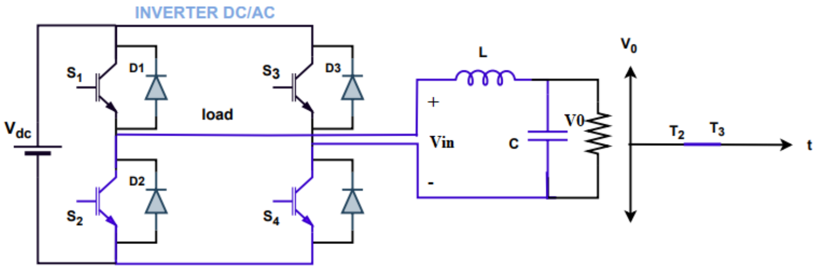

Figure 2.4: Output voltage for S2, S4 ON; S1, S3 OFF

Switches S1 and S2 should not be closed simultaneously, the same for switches S3 and S4. Otherwise short circuit of the DC bus will occur[24].

2.3 mathematical model for signal phase inverter

2.3.1 State space model

State-space modelling is a very well known approach to describe dynamical systems by a set of differential equations, which relates the input variables to the output. variables. A linear state-space model is written as:

$$\begin{aligned} \dot{X} &= Ax(t) + Bu(t) \\ Y &= Cx(t) + Du(t) \end{aligned} \tag{2.1}$$

with x(t) states, u(t) inputs and y(t) outputs. A is called the state matrix, B the input matrix, C the output matrix, and D the direct transmission matrix[25].

In the case of a single phase inverter and according to Kirchhoff's laws, the differential equations describing the dynamics of a single-phase inverter can be written as:

$$\begin{gathered} V_{in} - V_L - V_C = 0 \\ V_L = L\frac{dI_l(t)}{dt} \end{gathered} \tag{2.2}$$

The inductor current, output capacitor current, and load current are related as

$$\begin{gathered} I_L = I_C + I_0 \\ I_C = I_L - \frac{V_C}{R} \end{gathered} \tag{2.3}$$

I_0 is the output current through the load R, given by

$$I_0 = \tfrac{V_C}{R} \tag{2.4}$$

I_C is the Capacitor current , given by

$$I_C = C\frac{dv_C}{dt} \tag{2.5}$$

From equation 2.3, substitute

$$\tfrac{dV_C(t)}{dt} = \tfrac{I_L}{C} - \tfrac{V_C}{RC} \tag{2.6}$$

Therefore the state-space equations by differential equation can be written as follows

$$\begin{gathered}
\dot{X} = AX + BU \\
Y = CX + DU \\
X_1 = I_L(t) \\
X_2 = V_C \\
\dot{X}_1 = \frac{dI_l(t)}{dt} = \frac{V_L}{L}
\end{gathered} \tag{2.7}$$

$$\begin{gathered}
\dot{X}_2 = \frac{dV_C}{dt} = \frac{I_L}{C} - \frac{V_C}{RC} = \frac{X_1}{C} - \frac{X_2}{RC} \\
V_{in} = LX_1 + X_2
\end{gathered}$$

Then the state equation becomes

$$\rightarrow \dot{X}_1 = (V_{in} - X_2) * \frac{1}{L} \tag{2.8}$$

$$\rightarrow \dot{X}_2 = \frac{X_1}{C} - \frac{X_2}{RC} \tag{2.9}$$

The output equation

$$\rightarrow Y = X_2 \tag{2.10}$$

The dynamic model can be represented by the following equations.

$$\begin{aligned}\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\end{bmatrix} &= \begin{bmatrix}0 & -\frac{1}{\mathrm{L}}\\ \frac{1}{\mathrm{C}} & -\frac{1}{\mathrm{RC}}\end{bmatrix}\begin{bmatrix}X_1\\ X_2\end{bmatrix} + \begin{bmatrix}\frac{1}{\mathrm{L}}\\ \mathbf{0}\end{bmatrix}\mathbf{Vin}\\ Y &= \begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}X_1\\ X_2\end{bmatrix}\end{aligned} \tag{2.11}$$

2.3.2 Transfer Fuction

transfer fuction for signal phase inverter from state space matrice

$$G_S(S) = \frac{\mathrm{Y(S)}}{U(S)} = \mathrm{C} * \varphi(\mathrm{S}) * \ \mathrm{B} + \mathrm{D} \tag{2.12}$$

Applying Laplace transform to above equation

$$\varphi(\mathrm{S}) = [SI - A]^{-1} \tag{2.13}$$

The transfer function of the inverter with LC filter and resistive load can be expressed by the following equation

$$G_S(S) = \frac{V_{in}}{LCS^2 + \frac{L}{R}S + 1} \tag{2.14}$$

by matching with fonction transfer of Second order system

$$G_S(S) = \frac{k_0\omega_0^2}{S^2 + 2\xi\omega_0 S + \omega_0^2} \tag{2.15}$$

calculate natural frequency from 2.16

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{2.16}$$

calculate damping ratio from eq 2.17

$$\xi = \frac{1}{2RC\omega} = \frac{\sqrt{LC}}{2RC} \tag{2.17}$$

2.3.3 Design of LC filter

In order to deliver, clean power to the load, a proper design of L-C filter is required. The magnitude of the ripple content in the inductor depends upon its size and operating frequency. The value of the filter inductance can be calculated as:

$$L_f = \frac{V_{dc}}{4 f_s \Delta i} \tag{2.18}$$

Where Vdc is the input DC voltage, Δi is the amount of ripple present in the inductor current and f_s is the switching frequency.
For the allowable output voltage ripple ΔV_0, The filter capacitor can be calculated as [26]

$$C = \frac{\Delta i}{8 f_s \Delta V_o} \tag{2.19}$$

The following figure2.5 shows the bode plot for low pass filter lc

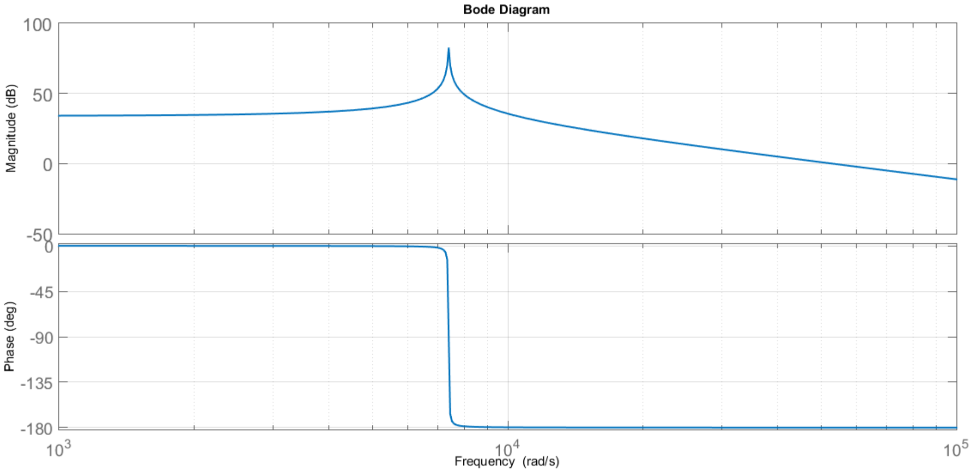

Figure 2.5: bode diagram for the transfer function

2.4 Closed Loop Control For Single Phase Inverter

The DC/AC inverter, either single-phase design, can be considered as the core of the whole system characteristics and its inherent over-current limitation capabilities. One of the most important issues in inverter control is the load voltage regulation. proportional-integral (PI) controller has been used in controlled of voltage source inverter (VSI) in various applications such as gridconnected and stand-alone systems. The PI control of a single-phase inverter has well-known drawbacks which are steady-state magnitude error, phase error and also it has a very limited disturbance rejection capability.

Stationary Proportional Integral (PI) controller is conventionally regarded as unsatisfactory for ac system because of the supposedly unavoidable steady-state amplitude and phase errors. But synchronous PI controller acts on DC signals and can achieve the zero steady-state error with the integral part. In order to achieve zero steady-state error, Proportional resonant (PR) controller has been introduced to overcome these problems. As compared with the conventional PI controller, the PR controller can introduce an infinite gain at the fundamental frequency hence, it can achieve zero steadystate error without requiring a complex transformation and a dc-coupling technique. [27] [28].

2.5 The PR controller

The proportional-resonant controllers are commonly used in AC voltage and/or AC current control applications such as grid controllers, a resonant pole is added at fundamental frequency to obtain high gain and to remove the steady state error. The PR controllers are proposed to AC voltage and/or AC current control. The PR controller has high infinite gain at certain frequency (resonant frequency) and has no gain at other frequency values. Thus the steady state error is removed. With this feature, the PR filters are used in active power filter applications to track the harmonic reference signal precisely and to eliminate selected harmonics. The PR controllers are also commonly used in grid interactive inverters to control the inverter output current with fast transient response and no steady state error .The ideal PR controller is represented by Eq (2.11)[29].

$$G_{PR}(s) = \frac{Y(s)}{U(s)} = K_p + \frac{K_i s}{s^2 + \omega_{11}^2} \tag{2.20}$$

where KP is the proportional gain, Ki is the integral gain term andω is the resonant frequency. The PR-controller provides very large gain at the resonant frequency; therefore, steady state error is eliminated at this frequency. The proportional controller gain, Kp is chosen such that good transient response and stability margins are achieved. Kp also determines the bandwidth of the outer feedback voltage loop of the system. Kr is chosen

such that the magnitude and phase steady-state error are eliminated[30].
The Bode plot of the PR controller at Kp=0.15, Ki=100 and $\omega 11 = 2 * \pi * 50$ rad/sec is shown in Figure2.6.

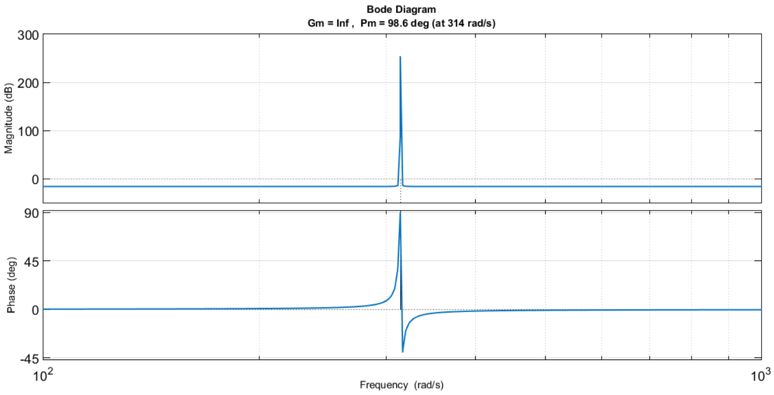

Figure 2.6: Magnitude and phase responses of the PR controller

2.5.1 calculate the transfer function for closed loop

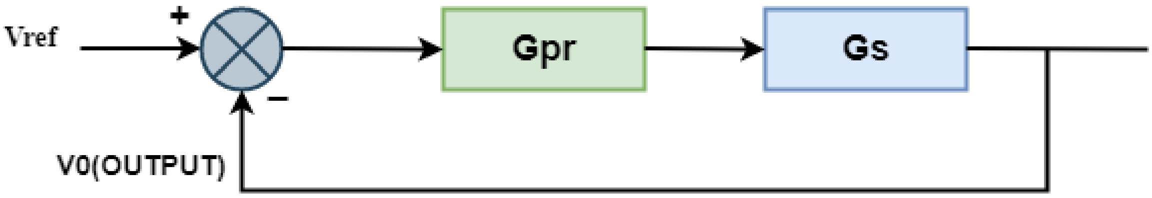

Figure 2.7: closed loop transfer function block diagram

The block diagram of a closed-loop PR controller is shown in Figure2.7. The closed-loop transfer function of the voltage can be defined as:

$$G_C = \frac{Gpr(S) * G_S(S)}{1 + Gpr(S) * G_S(S)} \tag{2.21}$$

The characteristic equation is

$$\begin{aligned} &S^4 + 2\xi_0\omega_0 S^3 + \left(\omega_0^2 + \omega_{11}^2 + k_P k_0 \omega_0^2\right) S^2 \\ &\qquad + \left(2\omega_0\xi_0\omega_{11}^2 + 2k_i k_0 \omega_0^2\right) S + \left(\omega_{11}^2\omega_0^2 + k_P \omega_{11}^2 k_0 \omega_0^2\right) \\ &\qquad = \left(S + p_0\right)\left(S + p_1\right)\left(S^2 + 2\varepsilon\omega_0 S + \omega_0^2\right) \end{aligned} \tag{2.22}$$

$$\left(S + p_0\right)\left(S + p_1\right)\left(S^2 + 2\varepsilon\omega_0 S + \omega_0^2\right) \tag{2.23}$$

$$\begin{gathered} S^4+\left(2\xi_1\omega_1+\left(p_0+p_1\right)\right)S^3+\left(\left(p_0+p_1\right)\left(2\xi_1\omega_1\right)+\omega_1^2+p_0p_1\right)S^2 \\ +\left(\left(p_0+p_1\right)\omega_1^2+2\xi_1\omega_1p_0p_1\right)S+p_0p_1\omega_1^2=0 \end{gathered} \tag{2.24}$$

By matching equation 2.22 with equation 2.24 , I get the following equations

$$2\varepsilon_1\omega_1+\left(p_0+p_1\right)=2\xi_0\omega_0 \tag{2.25}$$

$$\left(p_0+p_1\right)\omega_1^2+2\xi_1\omega_1p_0p_1=2\omega_0\xi_0\omega_{11}^2+2k_ik_0\omega_0^2 \tag{2.26}$$

$$\left(p_0+p_1\right)\left(2\xi_1\omega_1\right)+\omega_1^2+p_0p_1=\omega_0^2+\omega_{11}^2+k_Pk_0\omega_0^2 \tag{2.27}$$

$$p_0p_1\omega_1^2=\omega_{11}^2\omega_0^2+k_P\omega_{11}^2k_0\omega_0^2 \tag{2.28}$$

Remark 3.1:

By setting ξ_1 and ω_1 ,one can solve the above equation to find kp and ki using the algorithme presented in appendix and for the parameters (ξ , ω)

Figure2.7 below shows the PR voltage control strategy of single phase inverter . V0 is the inverter output voltage which is used as feedback and Vref is the inverter voltage reference[31].

2.6 Simulation matlab of Sinusoidal pulse width Modulation technique

The proposed inverter for both schemes are simulated in Matlab/Simulink and the results for both schemes are observed. Simulation is executed with discrete power and fixed at 0.1 sec sample time. The simulation models of both SPWM unipolar and bipolar switching scheme are demonstrated in the Figures 2.8 and 2.14[32].

Signal phsae inverter Bipolar switching

The process of implementing the bipolar sinusoidal PWM pulses generation for a single phase full bridge inverter is explained in Figure 2.82.9. A sinusoidal signal of reference fundamental frequency is compared with a triangular signal of carrier frequency. The value and the sign of the output voltage depend on the instantaneous values of reference and carrier waveforms. The output voltage will be +Vdc or –Vdc depending on the instantaneous values of the comparison levels of the reference and carrier signals as shown [33]:

$$\begin{aligned} v_o &= +V_{dc} \text{ when } v_{\text{sine}} > v_{\text{tri}} \\ v_o &= -V_{dc} \text{ when } v_{\text{sine}} < v_{\text{tri}} \end{aligned} \tag{2.29}$$

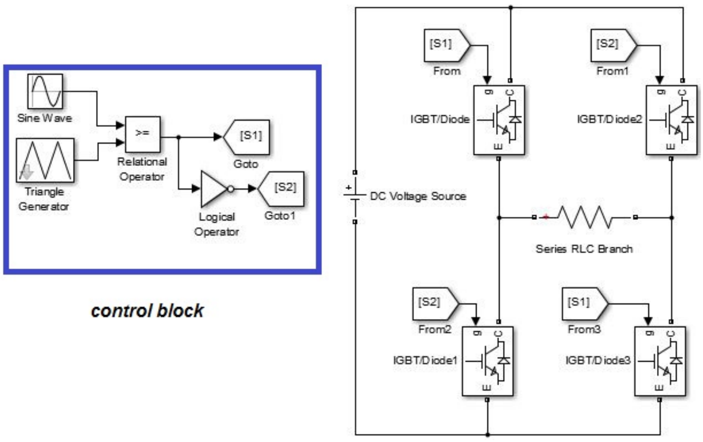

Figure 2.8: CONTROL BLOCK Bipolar SPWM

figure2.9 show comparing one sinusoidal modulating wave Vref and triangular carrier wave vcr to produce switching pulses to the IGBT.

Table 2.1: Bipolar PWM switching states and outputs

S1(Q1)	**S2(Q2)**	**S1'(Q3)**	**S2'(Q4)**	**output**
on	off	on	off	Vdc
off	on	off	on	-Vdc

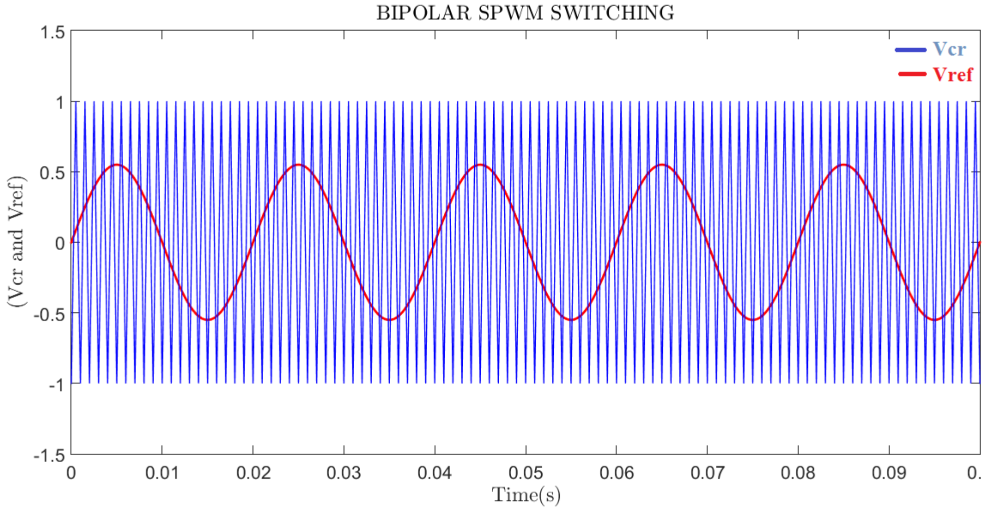

Figure 2.9: Bipolar Switching

figure 2.10show the form of output voltage before filtering

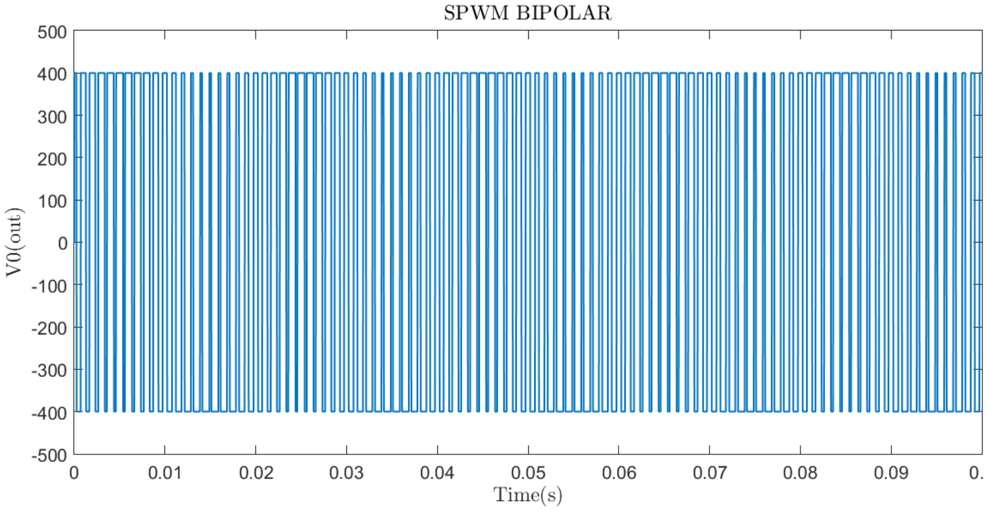

Figure 2.10: output voltage before filtering

THD before and after LC filter

THD of the output voltage before and after filtering Figures 2.122.13 show the signal magnitude and the frequency spectrum of output voltage for bipolar scheme in FFT analysis

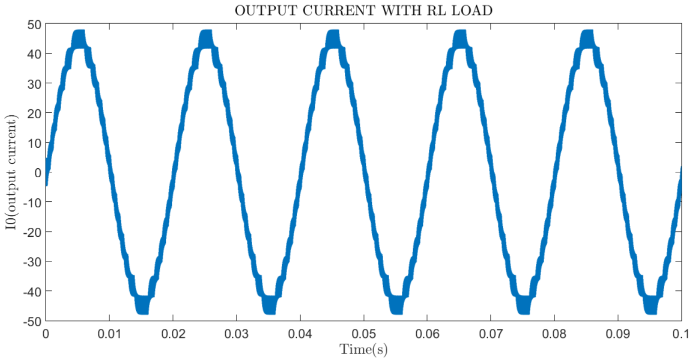

Figure 2.11: Output current with R-L load

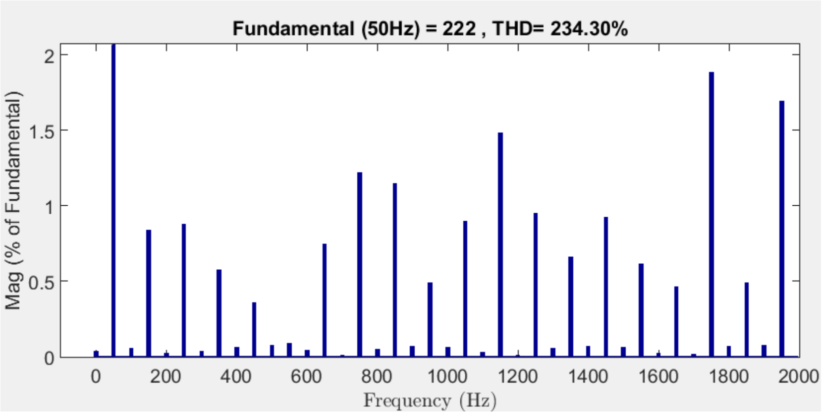

Figure 2.12: THD BEFORE LC FILTER

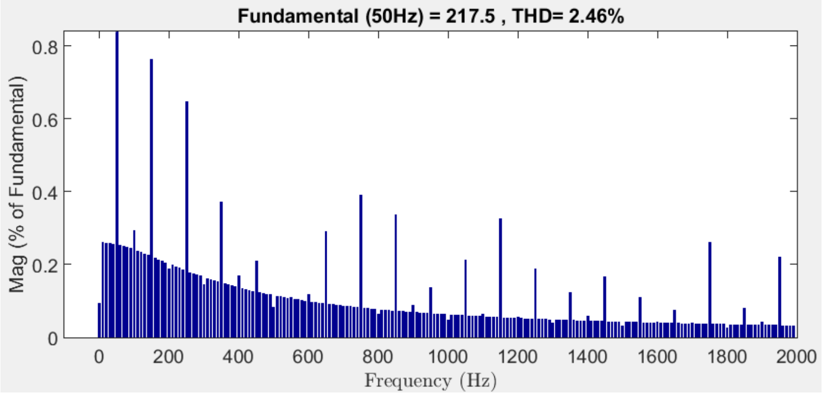

Figure 2.13: THD AFTER LC FILTER

2.6.1 Signal phsae inverter Unipolar switching

Figure 2.142.15 shows the process of implementing the unipolar sinusoidal PWM scheme for a full bridge single phase inverter. To have a unipolar sinusoidal PWM scheme, the output is switched among three levels: +Vdc, zero voltage, or -Vdc. In unipolar scheme, the output voltage also depending on the instantaneous values of the the reference and carrier signals,the switch controls are as[33]:

Q_1 is on when $v_{\text{sine}} > v_{tri}$

Q_2 is on when $-v_{\text{sine}} < v_{tri}$

Q_3 is on when $-v_{\text{sine}} > v_{tri}$

Q_4 is on when $v_{\text{sine}} < v_{tri}$

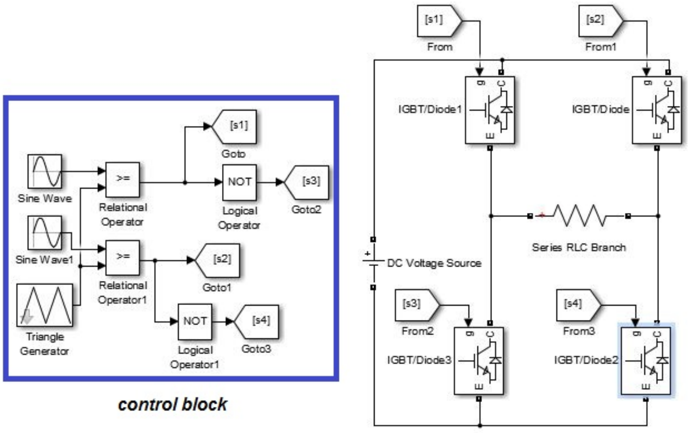

Figure 2.14: CONTROL BLOCK unipolar SPWM

Figure2.15 show two sine wave signal (reference signal) has 180 phase opposite to each other compared with triangular wave and produce switching pulses to the IGBT .

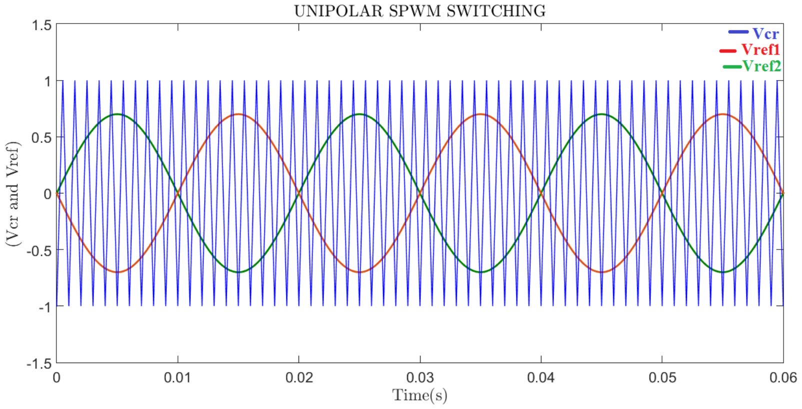

Figure 2.15: Unipolar Switching

Table 2.2: Unipolar PWM switching states and outputs[34]

S1(Q1)	**S2(Q2)**	**S1'(Q3)**	**S2'(Q4)**	**output**
on	off	on	off	Vdc
on	on	off	off	0
off	off	on	on	
off	on	off	on	-Vdc

figure 2.16 show the form of output voltage before filtering figure 2.17show the form of output voltage after filtering

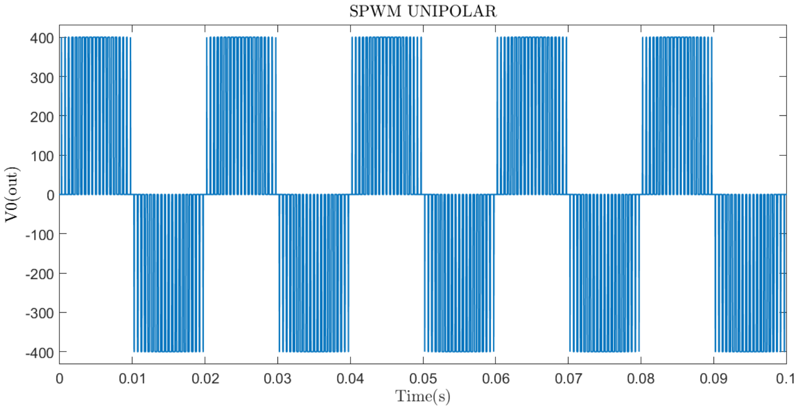

Figure 2.16: output voltage before filtering

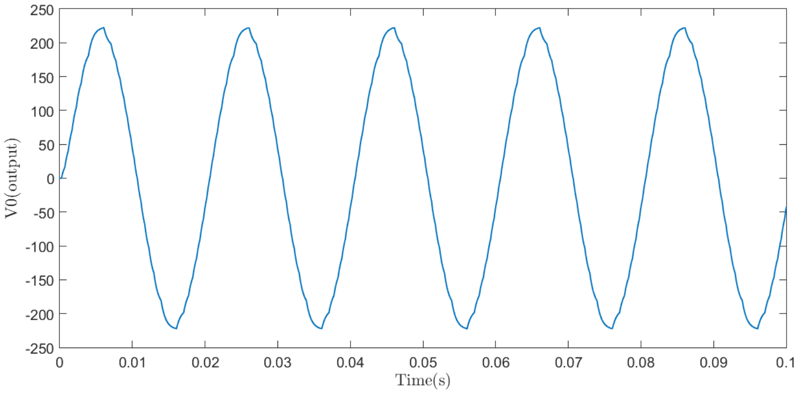

Figure 2.17: output voltage after filtering

THD before and after LC filter

THD of the output voltage before and after filtering Figures 2.182.19 show the signal magnitude and the frequency spectrum of output voltage for unipolar switching scheme in FFT analysis.

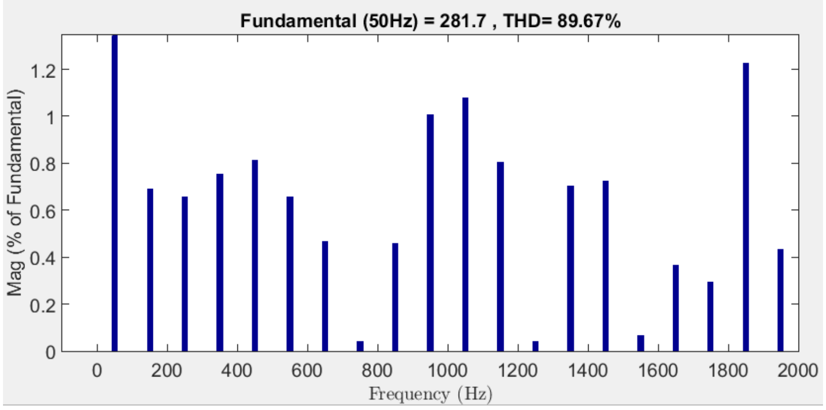

Figure 2.18: THD before LC filter

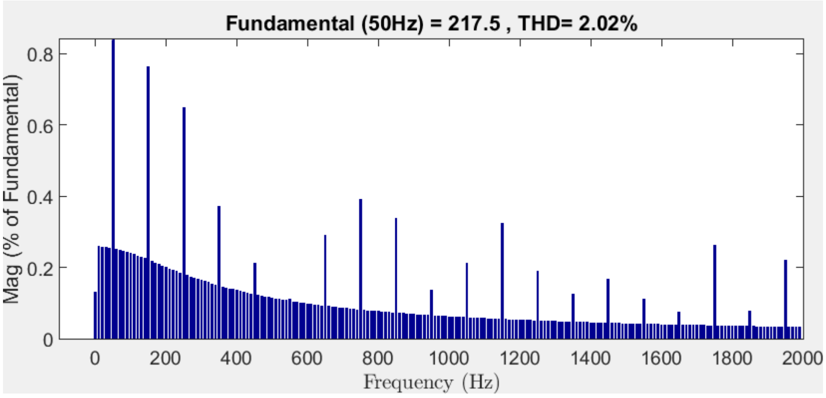

Figure 2.19: THD after LC filter

Based on the results obtained from both scheme, it can be observed that the bipolar switching scheme produced more harmonic distortion compared to the unipolar switching scheme. It can be concluded that the unipolar switching scheme offered better performance in term of efficiency and lower THD as compared to bipolar switching scheme [32].

2.7 Simulation matlab of closed loop

The single-phase inverter with PR controller is modeled and simulated as per the design calculation. The inverter power switches are triggered by unipolar PWM pulses generated by the PR controller block. The system is demonstrated in MATLAB Simulink as per the proposed design shown in figure 2.20[35].

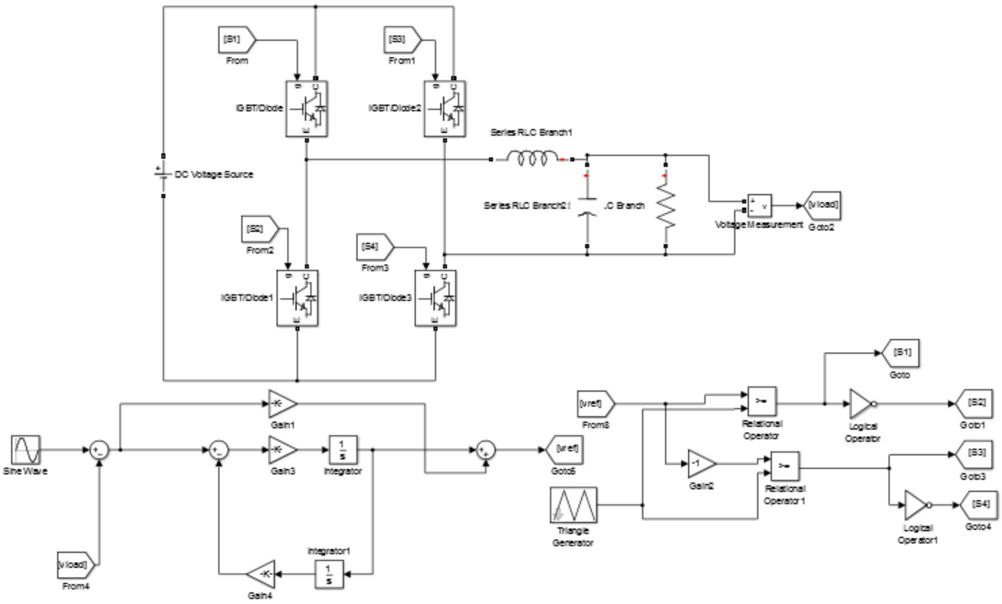

Figure 2.20: schema matlab of signal phase control

Table 2.3: PARAMETERS OF SIMULATED INVERTER

Parameter	Value
switching frequency(Fsw)	20kHZ
Input DC Voltage(Vdc)	50 V
Load resistance(R)	1400 ohm
Output Fundamental frequency(F0)	50HZ
capacitor (C)	26.18uF
inductance (L)	0.7mH

In the figure 2.21 below show the voltage load follows the voltage reference without any error with the use of a PR-controller

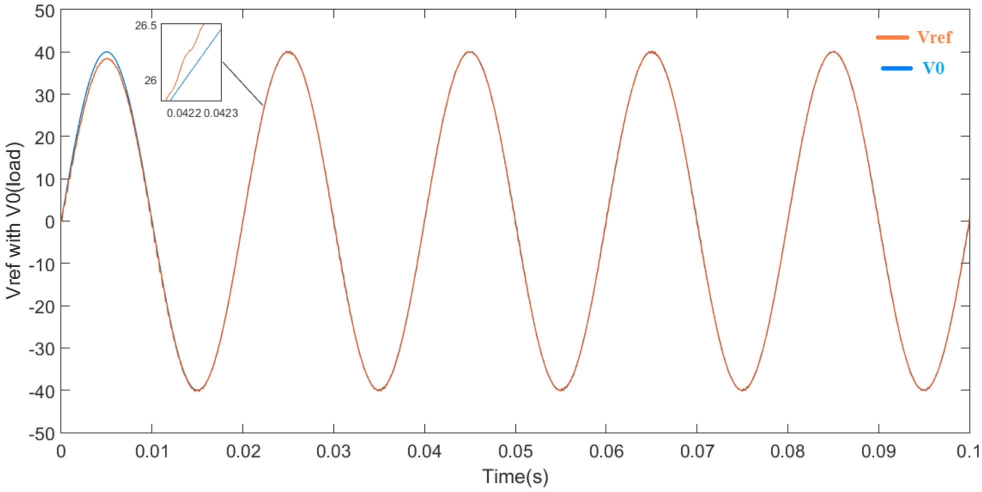

Figure 2.21: voltage reference with output voltage load (V0)

In the figures 2.22 and 2.23 below show fast response to variations of the load when the resistive load increases or decreases to fixed the value of output voltage and frequency [36][37].

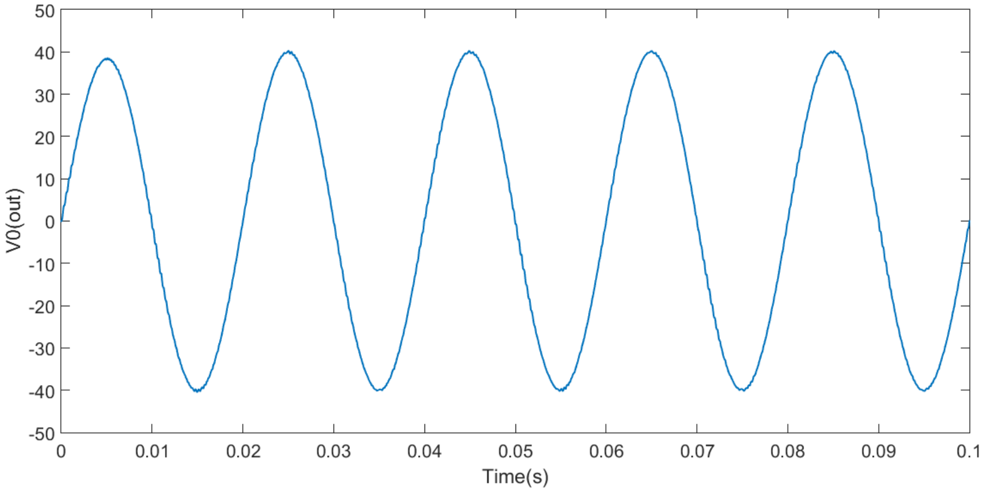

Figure 2.22: output voltage load (V0) for 1400 ohm

Voltage form when the load value changes

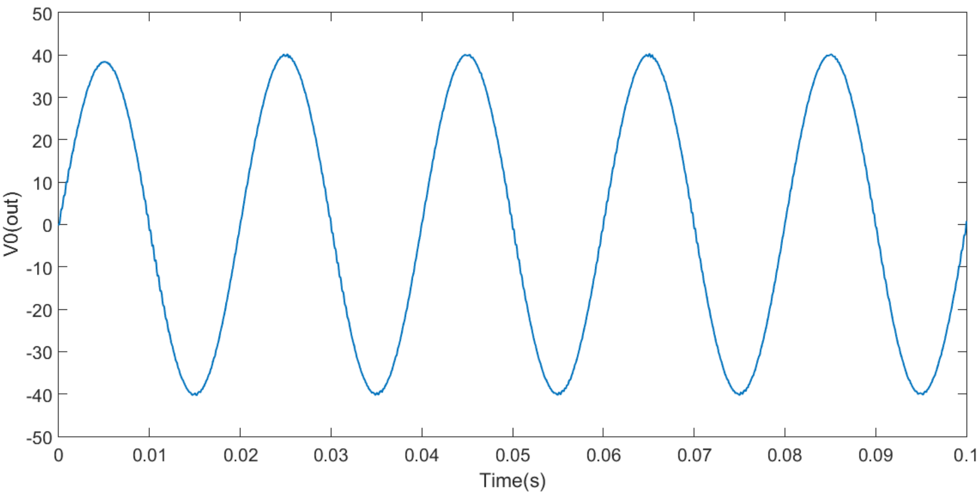

Figure 2.23: output voltage load (V0) for 2000 ohm

In the figure 2.24 below show the output current I0 fast response variation when the resistive load decreases from 2000 ohm to 400 ohm . At the same time, the balance of the neutral point is kept under the proposed voltage balancing controller.

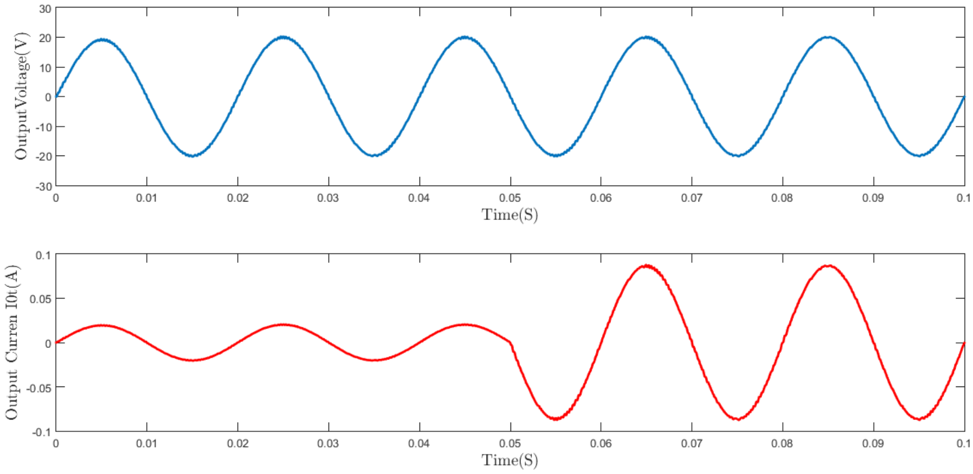

Figure 2.24: Output current I0 response variation when the resistive load decreases

In order to test the robustness of the proposed method of controller PR, thevoltage reference is changed as shown in Figure 2.25. the reference signal Vref is changed to 35 V peak to peak from 20 V peak to peak in the 0.06s, then at 0.12s Vref is changed from 35 V to 45V peak to peak. Under the proposed control scheme, the output voltage followed the change of the reference signal with fast dynamic responses[38].

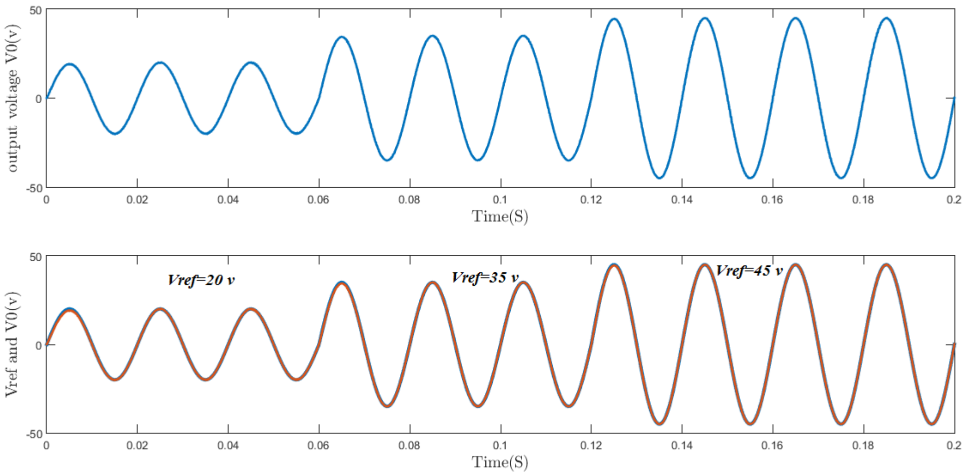

Figure 2.25: Reference variation

From Figure2.26 obtaining the fundamental about 40 V at frequency of 50 Hz and the THD is considered lowest and its value is 0.91.

From Figure 2.26 can arrive at a judgment that the inverter studied with the proposed PR control in the standalone mode has noticeable features including lowest distortion harmonic, selective lower order harmonic compensation, high conversion efficiency, strong control performance and high quality of sinusoidal wave form[39][40].

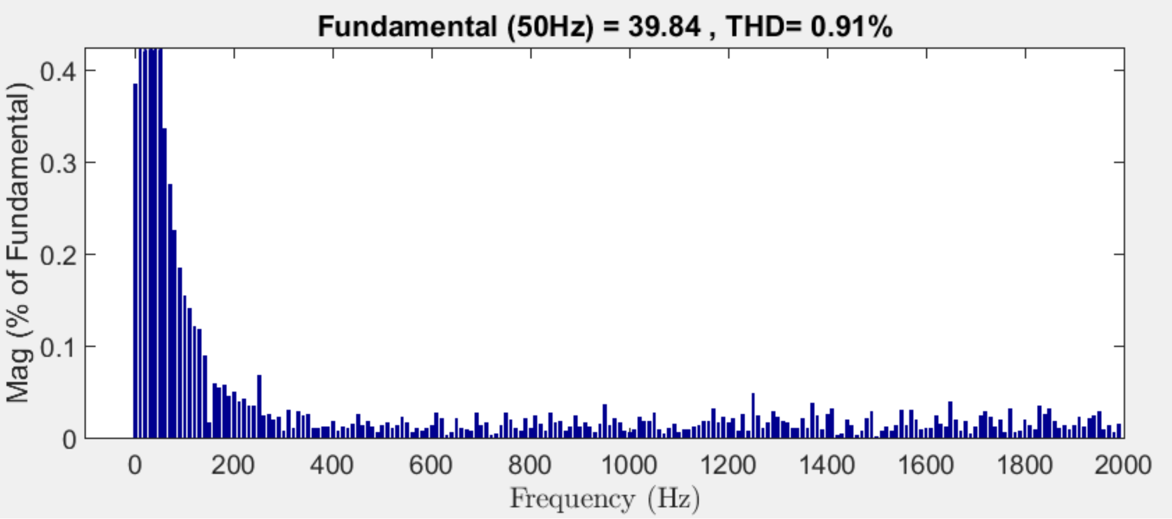

Figure 2.26: THD of the load voltage by using PR controller

2.8 Conclusion

In this chapter, we talked about pwm and effect of THD decreasing through the displacement of harmonics the pulse width modulation is proven to be the technique most adapted for the controlled inverter while having a good neutralization of the output wave. Also, we talked about closed loop control and the effect of the PR controller that I came up with Proportional resonant controller is function to eliminate the harmonic existed in power system. It has infinite gain at resonant frequency which ensures zero steady-state error thus resulting in minimization of the load voltage distortion and harmonic content in the inverter

Chapter 3

Experimental Results

3.1 Introduction

This chapter presents the experimental workbench used for the verification and correctness of the control technique developed in the previous chapter. The Power converter design, construction, control and all experimental tests are conducted in LACoSERE laboratory at Laghouat University.

Fig. 3.1 shows the main parts of the test bench. The description of each element will be presented in detail in the following subsections.

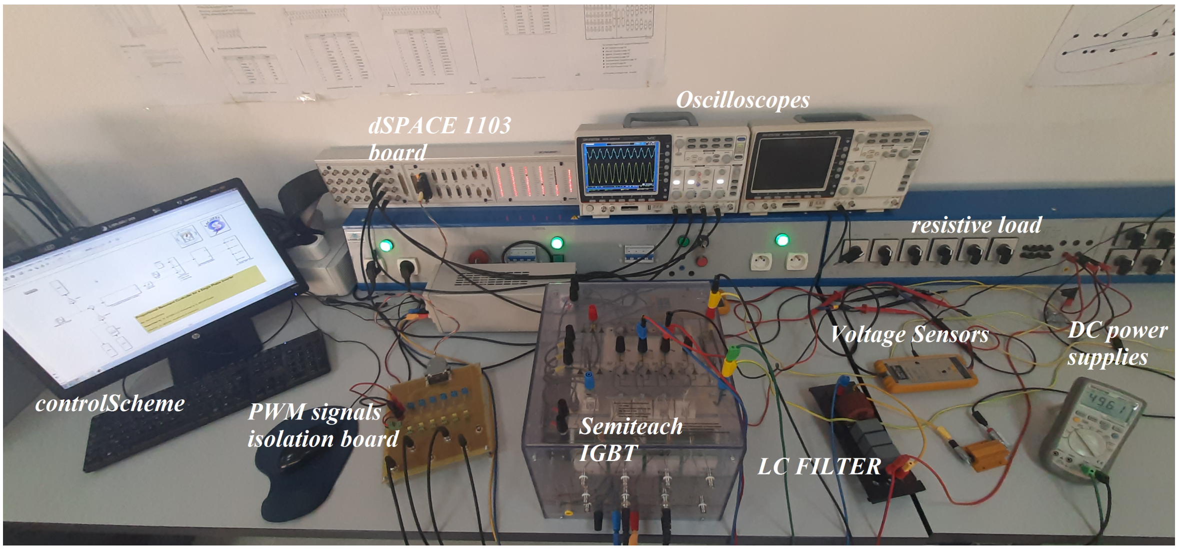

Figure 3.1: Experimental setup ofsingle phase inverter

3.2 Description of the Test Bench

In this section, we will present the test bench and the main hardware used in the validation process. As illustrated in Figure 3.1. this test bench consists of:

- single phase inverter(Semiteach IGBT converter) ,
- dSPACE 1103 board,
- PWM signals isolation board,
- current and voltage sensors,
- Oscilloscopes,
- Isolated DC power supplies,
- resistive load.
- LC filter

In the next , we will present each part with more details.

3.3 dSPACE Board

The DS1103 is an all-rounder in rapid control prototyping. Its processing power and fast I/O are vital for applications that involve numerous actuators and sensors. Used with Real-Time Interface (RTI), the controller board is fully programmable from the Simulink® block diagram environment. You can configure all I/O graphically by dragging RTI blocks. This is a quick and easy way to implement your control functions on the board.

The controller board is designed to meet the requirements of modern rapid control prototyping and is highly suitable for applications such as induction motor control, robotics, positioning systems and stepper motors, active vibration control, and rapid control prototyping for automotive controllers. With its versatile software environment and seamless integration with the comprehensive dSPACE toolkit, the Dspace 1103 provides engineers and researchers with a reliable and efficient platform for developing and validating control algorithms in real-time environments[41].

In our experimental tests, the DS 1103 shown in Fig. 3.2 is used for:

Figure 3.2: dSPACE board.

- Measuring all the required signals, the output voltage of the single phase inverter , the voltages of the input source, which is achieved using parallel channels of the D/A converter.
- Displaying and storing, when needed, in real time the measured signals by means of the Control Desk software interface.
- Performing the control law by generating FOUR PWM signals, in real time, via the DACs connectors.

3.4 PWM-signals isolation Board

the board in question is shown in Figure3.3 which is used for safety reasons. Firstly, PWM signals are isolated and amplified by this circuits in order to meet the inputs requirement of the igbt inverter. PWM signals are generated with +15/-15 volt levels, which enhance the switch-off time of the IGBTs.The voltage output from the dSpace system is only 5V So we use PWM-signals isolation board. Figure 3.4 shows the pwm signal for control the IGBT.

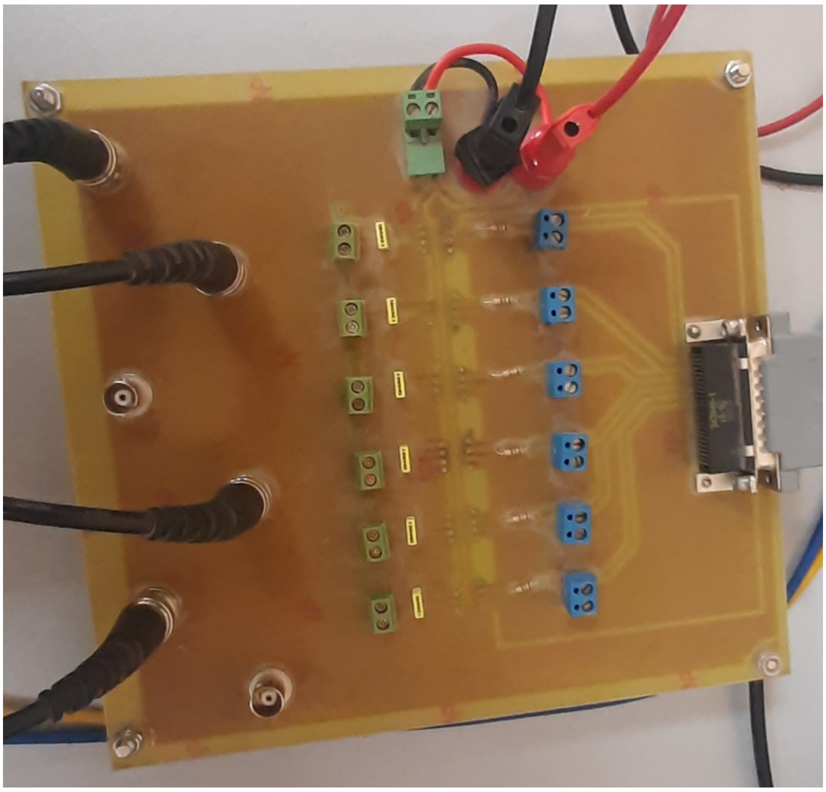

Figure 3.3: PWM-signals isolation Board.

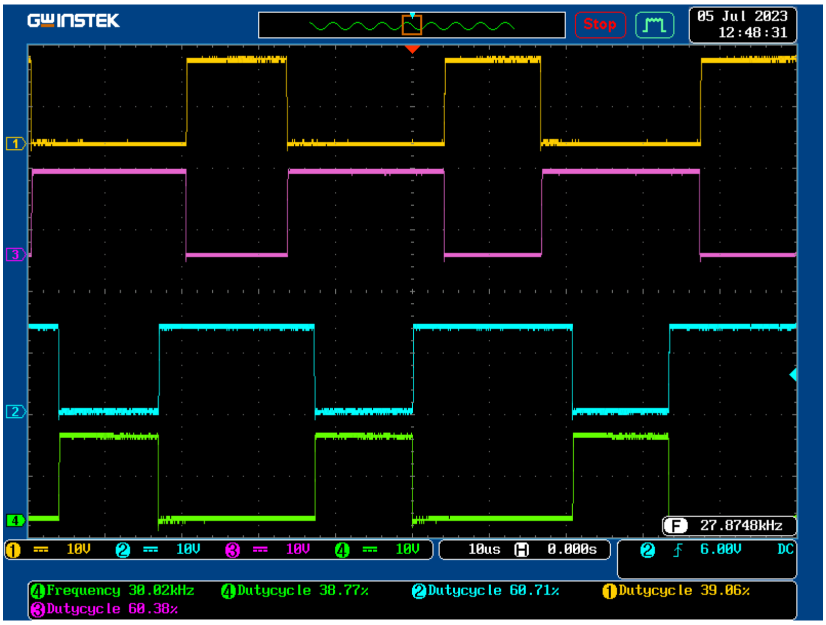

Figure 3.4: PWM-signals

3.5 Semiteach IGBT converter

For usage in eduction , the SemiTeach inverter was created with minimal power. The project will only require four IGBTs out of the seven that are contained in the three-phase rectifier and inverter with brake chopper. By putting a rheostat between two bridges and setting it to 10 ohms, the SemiTeach inverter's single phase output was first tested. 20V of power was provided to the inverter's input terminal, and its power drivers received 15Vdc. Logic ports (s1 and s4, etc.) are connected to a rectangular wave produced as PWM signals by a signal generator. These PWM signals have been used to turn on and off every two IGBTs simultaneously[42].

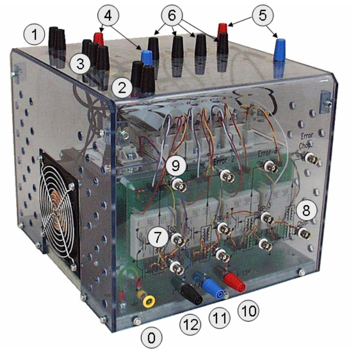

Figure 3.5: Semiteach IGBT converter

N°	Type	Function	Voltage level	Max current
0	Grounding panel socket	Earth connection	0V	30 A
1	Banana connector 4mm	Fan power supply	230V/50Hz	1 A
2	Banana connector 4mm	Thermal trip	15V	5 A
3	Banana connector 4mm	Rectifier input	230 / 400V	30 A
4	Banana connector 4mm	DC rectifier outputs	600 VDC	30 A
5	Banana connector 4mm	DC IGBT inverter inputs	600 VDC	30 A
6	Banana connector 4mm	AC IGBT inverter + chopper outputs	400 VAC / 600 VDC	30 A
7	BNC coaxial insulated 50 Ω	PWM input of inverter	C-MOS logic 0/15 V	1 A
8	BNC coaxial insulated 50 Ω	PWM input of brake chopper	C-MOS logic 0/15V	1 A
9	BNC coaxial insulated 50 Ω	Error output	C-MOS logic 0/15V	1 A
10	Banana connector 4mm	15V driver power supply	15V	5 A
11	Banana connector 4mm	0V driver power supply	15V	5 A
12	Banana connector 4mm	Temperature sensor	0-5V	1 A

3.6 Voltage and current Sensors

In order to ensure an isolation between the power stage and the control unit, we used for the measurement isolated voltage sensor that use optically isolated amplifiers designed specifically for voltage sensing, and Hall-effect based current sensor, which is galvanically-isolated sensor. Fig. 3.6 shows the sensors used in the experimental tests.

Figure 3.6: Current and voltage measurement sensors.

At this level, we presented an overview about the developed experimental setup and the next section will be devoted to testing the inverter operation under the proposed control law.

3.7 Experimental Results

The experimental setup has been set as shown in Figure 3.7 . The PWM input to the inverter is based on a sinusoidal reference voltage . With a DC voltage of 50 V to the inverter, the desired output voltage of the system should be a sinusoidal waveform of 40 or 30 V peak to peak. The output voltage has been measured after the LC filter under no load and load conditions[43]. Resistive loads of 1400 ohm were used in the closed-loop test. In the closed-loop system, the output voltage is measured using the voltage sensor and feedback to the controller(PR) for control actions to be taken . The parameters of (PR)controller from table 3.1

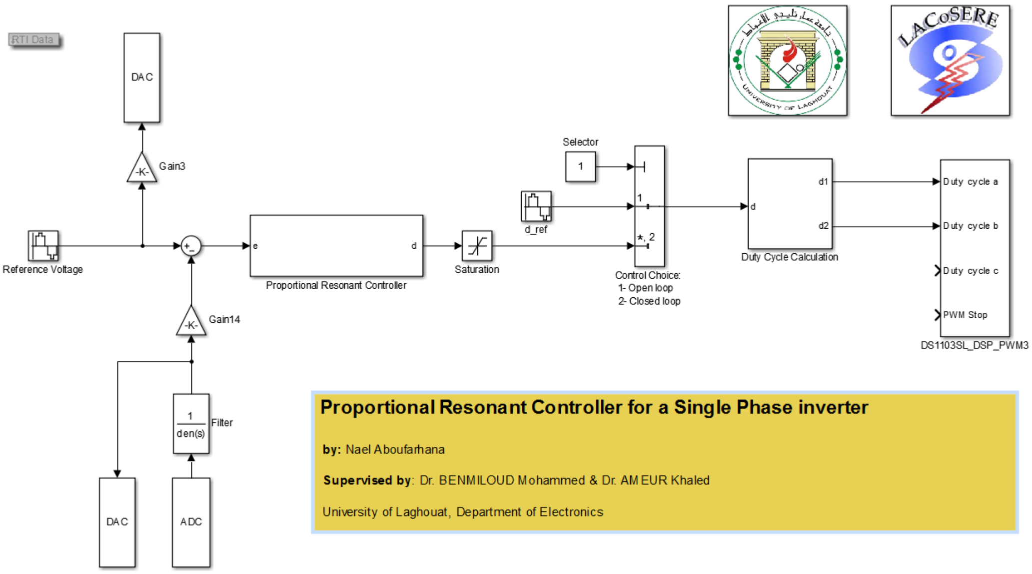

Figure 3.7: controlScheme

Parameter	Value
switching frequency(Fsw)	20KHZ
Input DC Voltage(Vdc)	50 V
resistance Load(R)	1400 ohm
Output Fundamental frequency(F0)	50HZ
capacitor (C)	26.18 uF
inductance (L)	0.7mH
Output voltage	40 V
Ki	0.3
Kp	0.15

Table 3.1: Parameters of Experimental work

3.7.1 Open Loop Results

Figure 3.8 shows the experimental result to the inverter output voltage for resistive load without LC filter

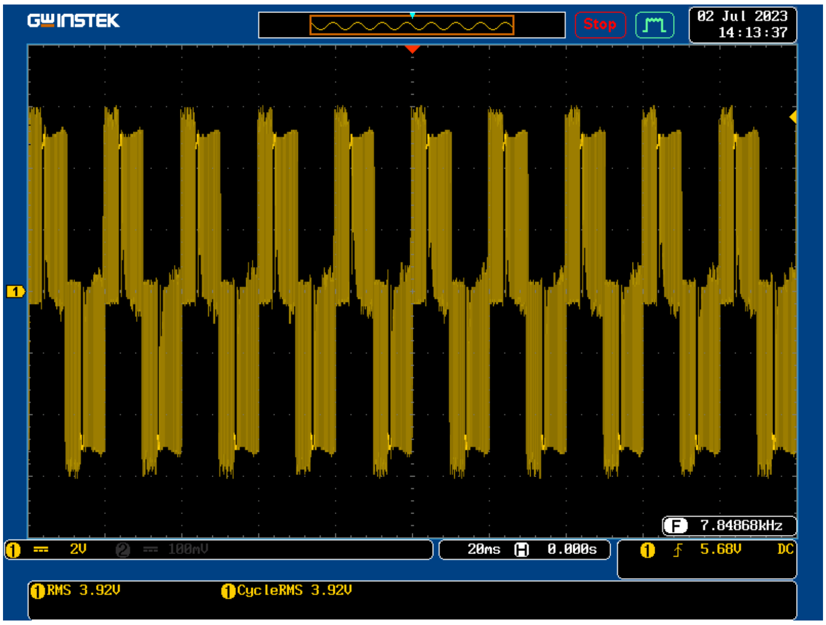

Figure 3.8: output voltage without LC filter

figure 3.9 shows the experimental result to the inverter output voltage for resistive load 1200 ohm with LC filter that give good sinusoidal wave form.

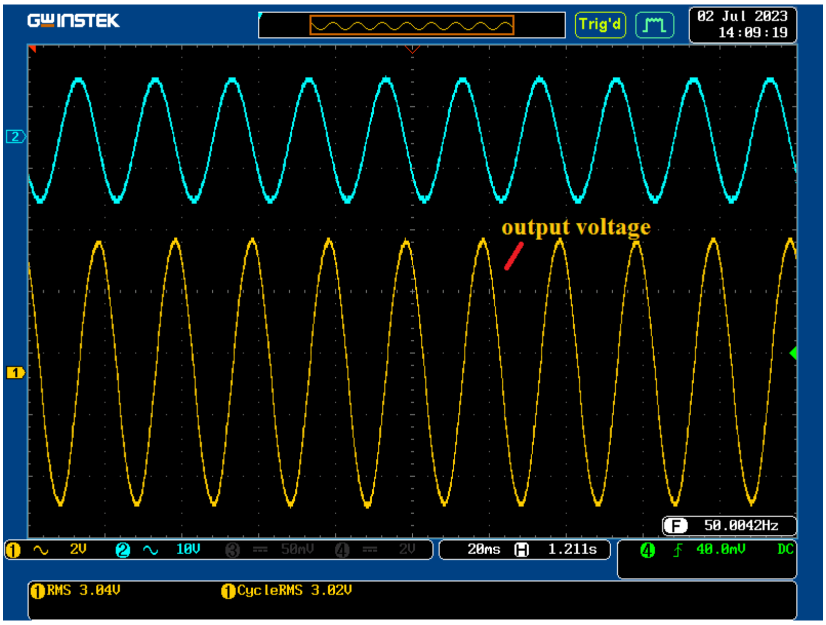

Figure 3.9: output voltage with LC filter

figure 3.10shows the experimental result to the inverter output voltage for resistive load 2000 ohm with LC filter that give good sinusoidal wave form but the value of the output voltage not fixed that change when tha value of resistive load change too.

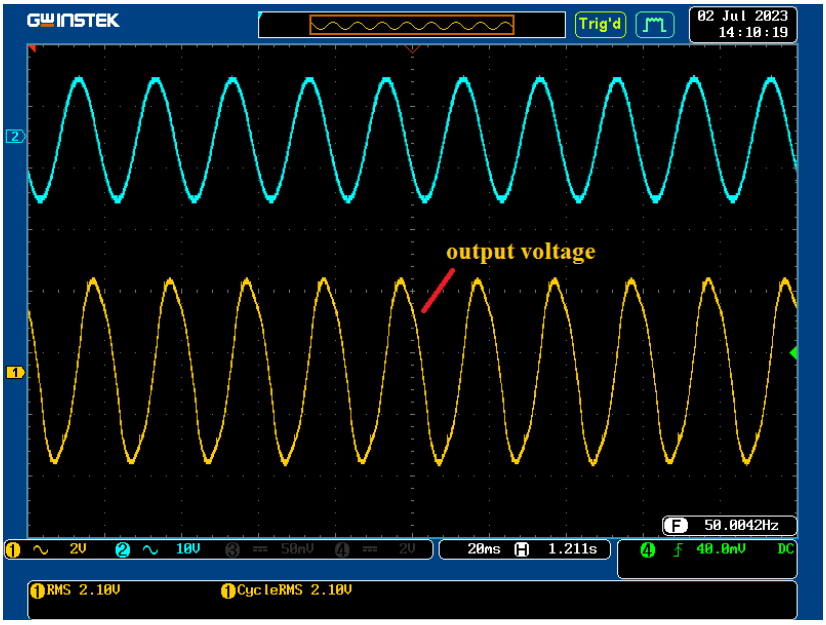

Figure 3.10: output voltage with LC filter

3.7.2 Close Loop Results

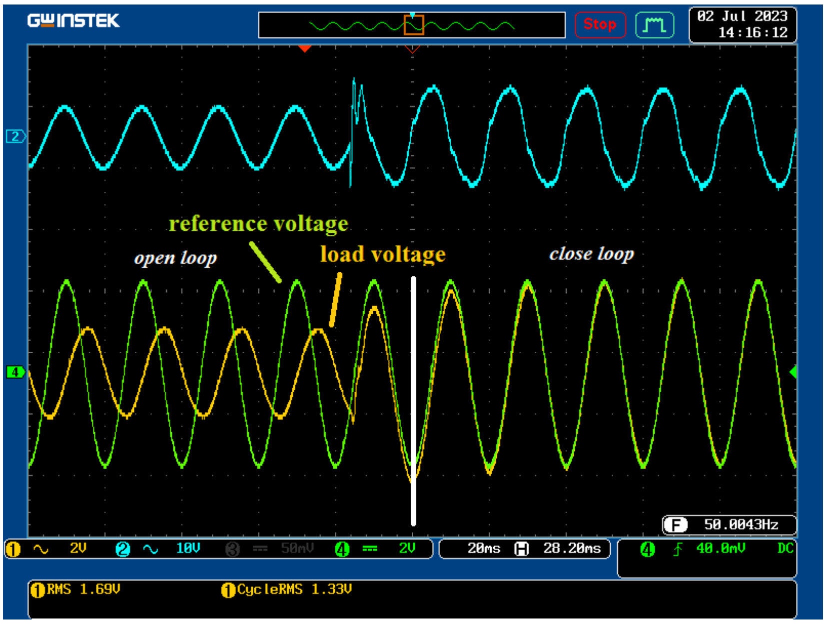

Figure 3.11: Reference voltage with load voltage

figure 3.11 show the moment of change from an open loop to a closed loop, note the effect PR controller in the step response speed. we will find that the load voltage follows the reference voltage.

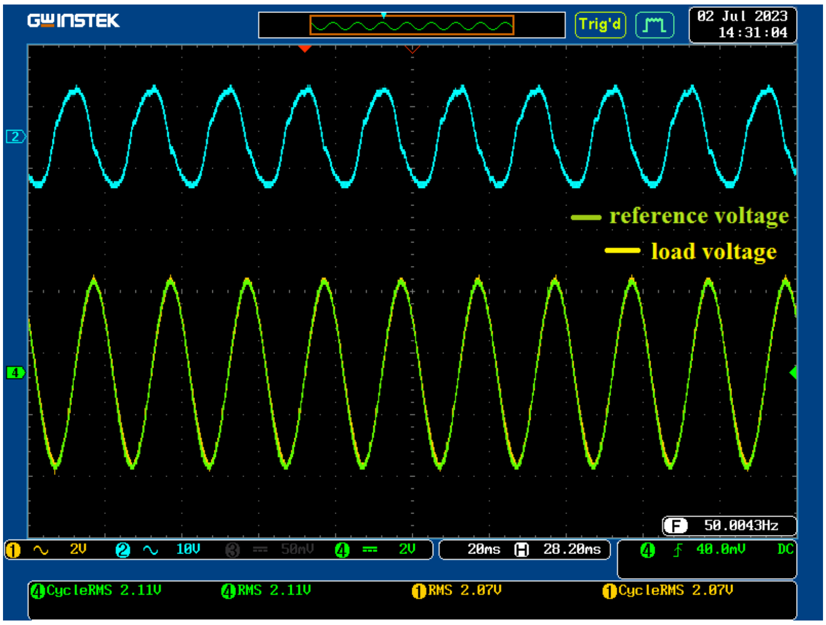

Figure 3.12: Reference voltage with load voltage

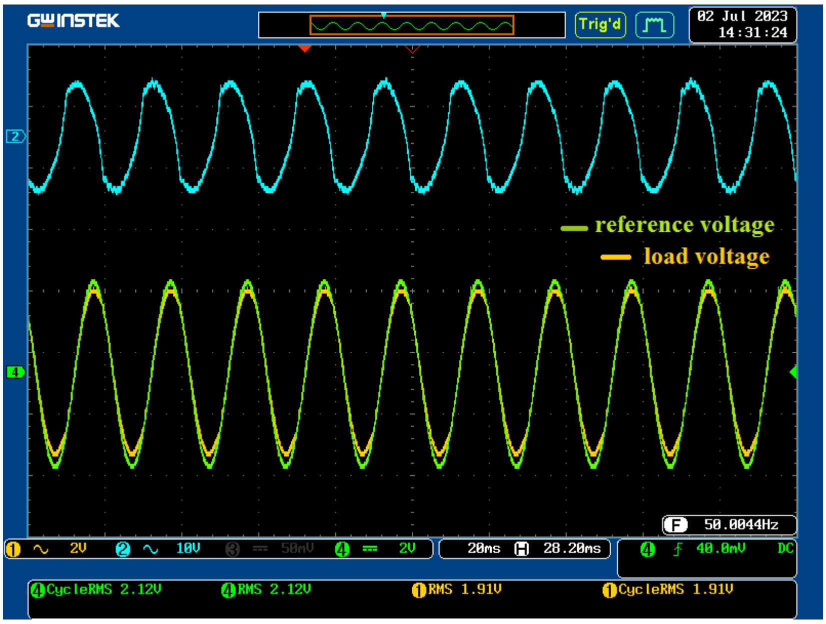

Figure 3.13: Reference voltage with load voltage when change resistive load value

figures 3.12 and 3.13 show when the value of resistive load change from 1200 ohm to 2000 ohm ,when the value of load is changed the load voltage remains same as reference voltage with zero staty state error.

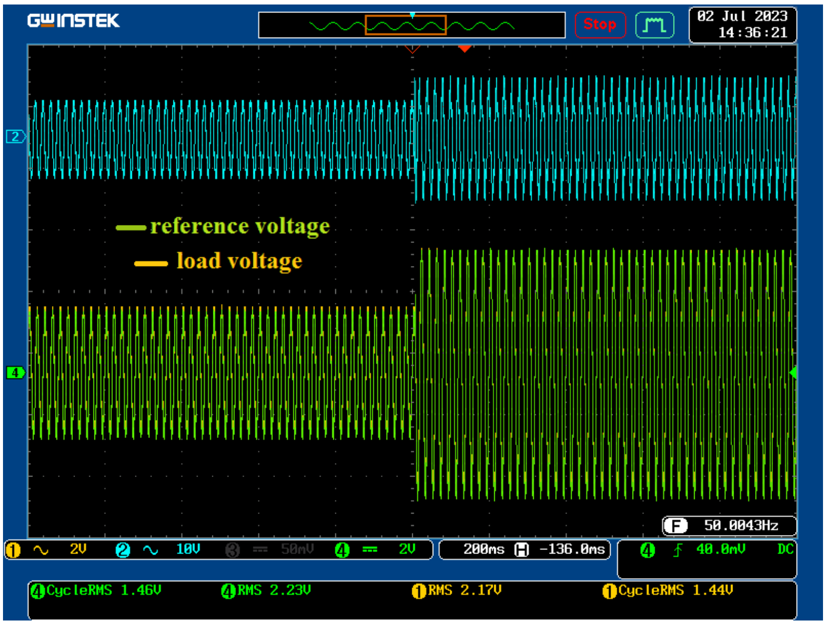

Figure 3.14: change reference voltage value

Remark 3.1:

The moment of switching voltage reference value, note the effect PR on the response speed. You will find that the load follows the reference with no steady state error

3.8 Conclusion

In this chapter, we discussed different parts of the experimental And it's the following the inverter, PWM signals isolation, the dSPACE boards and measurement devices. The control scheme developed in the second chapter implemented in the dSPACE board using Matlab/Simulink results have attested the good performance of the suggested controller, when the value of load change

General Conclusion

This project is part of the work carried out within the instrumentation Team of the LACoSERE laboratory on the subject of static converters control used for photovoltaic systems. One of the objectives is to investigate new power conversion structures with control strategies. The work presented in this master thesis is devoted to the implementation and control of of a single phase inverter, mainly used in solar inverters in the DC-to-AC stage. The project objectives have been successfully attained and comprehensively outlined within the three chapters:

In Chapter One, we introduced DC/AC power converters, We studied the composition and structure of the inverter and the control techniques used in the switches, where we found that the best method is the PWM compared to the control techniques(full wave control and shifted duty cycle) .

In Chapter Two, we got up modeled the system, and then demonstrated an proportional resonant(PR) control which used to minimize the Steady-state error.

In last chapter , we have explored various components of the experimental setup, encompassing the converter and its auxiliary boards, the dSPACE and DSP control boards, and measurement devices,Additionally we showcases the primary outcomes derived from simulations and experimental trials involving the single phase inverter.

Generally DC-to-AC converters are called inverters. The function of an inverter is to convert a DC input voltage into a symmetrical AC output voltage of desired amplitude and frequency. The output voltage waveform of an ideal inverter should be sinusoidal. However, this waveform is not sinusoidal in practice and contains some harmonics. This means that there are voltage harmonics. The aim is to obtain a signal with the lowest possible harmonic distortion at the output. One of the techniques used to improve inverter output voltage quality is the proportional resonant(PR) method.

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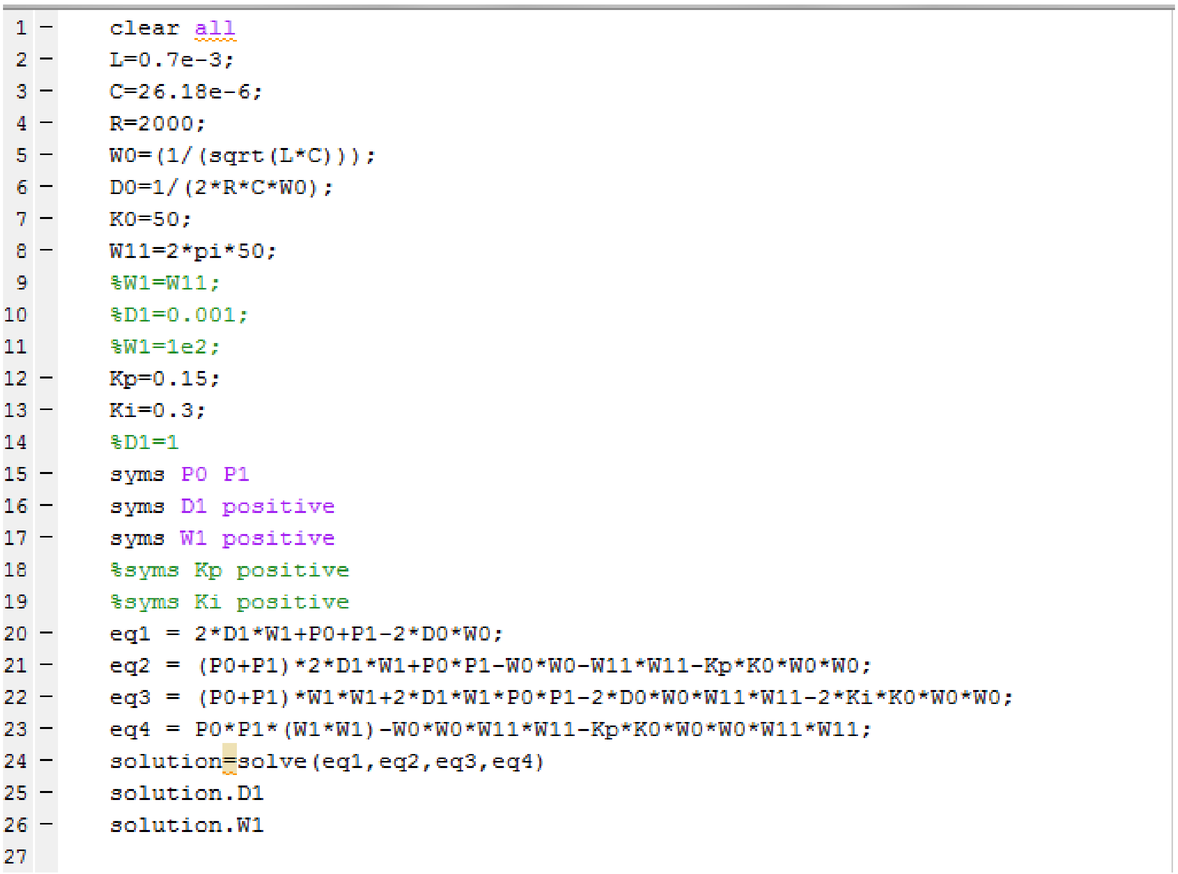
Appendix A

appendix



```
clear all
L=0.7e-3;
C=26.18e-6;
R=2000;
W0=(1/(sqrt(L*C)));
D0=1/(2*R*C*W0);
K0=50;
W11=2*pi*50;
%W1=W11;
%D1=0.001;
%W1=1e2;
Kp=0.15;
Ki=0.3;
%D1=1
syms P0 P1
syms D1 positive
syms W1 positive
%syms Kp positive
%syms Ki positive
eq1 = 2*D1*W1+P0+P1-2*D0*W0;
eq2 = (P0+P1)*2*D1*W1+P0*P1-W0*W0-W11*W11-Kp*K0*W0*W0;
eq3 = (P0+P1)*W1*W1+2*D1*W1*P0*P1-2*D0*W0*W11*W11-2*Ki*K0*W0*W0;
eq4 = P0*P1*(W1*W1)-W0*W0*W11*W11-Kp*K0*W0*W0*W11*W11;
solution=solve(eq1,eq2,eq3,eq4)
solution.D1
solution.W1
```

Figure A.1: code matlab