YILDIRIM BEYAZIT UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

COMPUTER SIMULATION AND EXPERIMENTAL IMPLEMENTATION OF SINGLE PHASE POWER INVERTERS REGARDING OUTPUT WAVEFORMS

M.Sc. Thesis by
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COMPUTER SIMULATION AND EXPERIMENTAL IMPLEMENTATION OF SINGLE PHASE POWER INVERTERS REGARDING OUTPUT WAVEFORMS

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We have read the thesis entitled “COMPUTER SIMULATION AND EXPERIMENTAL IMPLEMENTATION OF SINGLE PHASE POWER INVERTERS REGARDING OUTPUT WAVEFORMS” completed by Mustafa Sacid ENDİZ under supervision of Prof. Dr. Şerafettin EREL and Asst. Prof. Dr. Mustafa YAĞCI and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

Recent rises in electrical energy costs have done alternative energy options more attractive. A device such as solar panel is able to convert photons from the sun into the DC (Direct Current) electric which can be used by the end users. However, there is a problem by using this kind of energy. Our electric grid and most of the house appliances are based on the AC (Alternating Current) electric so the energy achieved by the sun or wind power needs to be converted from DC to AC to be useful. This converting process is done by an electronic device called inverter. Inverters can be found in a wide area of power electronics in the industry. The produced output voltage and frequency at the AC side of an inverter depend on the circuit structure, transformers and applied components. In this thesis, comparative analysis of single phase power inverters regarding their output waveforms was performed. Square wave, modified square wave and true sine wave inverter circuits were designed and analyzed using Proteus Professional package program. This comparison was fulfilled with respect to the circuit configuration, THD (Total Harmonic Distortion) and output efficiency. After simulation results these inverter circuits were realized on PCB (Printed Circuit Board) circuits. Efficiency of the inverters was calculated using Extech true RMS digital multimeter and THD values were measured by means of the Fluke 435 Power Analyzer device. According to the simulation and experimental results, the analyzed square wave inverter circuit has about 55% THD and 45% efficiency due to the circuit structure. The analyzed modified square wave inverter circuit has about 38% THD and 60% efficiency better than square wave inverter. The analyzed true sine wave inverter circuit having with about 10% THD and an efficiency of 75% has the most ideal output signal among the inverter types. Tests on resistive and inductive loads were carried out under laboratory conditions and output signals were observed with the help of Tektronix digital storage oscilloscope. Test results and simulation outcomes were confirmed to each other. It was found out that true sine wave inverter circuit is better and more efficient in many aspects compared to the modified and square wave inverter circuits in spite of their complicated structures and higher costs.

2015, 07 October

Keywords: Power Inverters, Output Waveform, Harmonic Analysis

TEK FAZLI GÜÇ EVİRİCİLERİNİN ÇIKIŞ DALGA FORMLARINA GÖRE BİLGİSAYAR SİMÜLASYONU VE DENEYSEL OLARAK GERÇEKLEŞTİRİLMESİ

ÖZET

Son zamanlarda elektrik enerjisinin maliyetindeki artışlar alternatif enerji seçeneklerini daha cazip hale getirmiştir. Solar paneller, güneşten absorbe ettiği foton enerjisini tüketiciler tarafından kullanılan doğru akım elektrik enerjisine dönüştürebilme özelliğine sahiptir. Bununla beraber bu elde edilen enerjinin kullanılması problem oluşturmaktadır. Şebekeden kullandığımız elektrik enerjisi ile evde kullanılan birçok cihazın doğru şekilde çalışabilmesi alternatif akım enerjisine dayanmaktadır. Bu nedenle solar panellerden veya rüzgâr türbinlerinden elde edilen doğru akım enerjisi faydalı olabilmesi için alternatif akım enerjisine çevrilmelidir. Bu çevrim işlemini evirici (Inverter) adı verilen cihazlar yaparlar. Eviriciler sanayide geniş bir yelpazede kullanım alanı bulan güç elektroniği dönüştürücüleridir. Eviricinin çıkışında üretilen alternatif sinyalin gerilim ve frekans değerleri, devrenin yapısına, transformatörlere ve kullanılan elemanlara bağlı olarak değişiklik gösterir. Bu tezde tek fazlı güç eviricilerinin çıkış dalga formlarına göre karşılaştırmalı olarak analizi yapılmıştır. Kare dalga, modifiye kare ve saf sinüs dalga eviricileri Proteus Professional programı kullanılarak tasarlanıp benzetimi elde edilmiştir. Analiz yapılırken devre yapıları, çıkış voltajındaki harmonik bozulmalar ve verimlilik dikkate alınmıştır. Yapılan simülasyonlardan sonra eviriciler PCB karta basılmıştır. Verimlilik hesabı Extech marka doğru RMS dijital multimetre yardımı ile hesaplanmış, harmonik hesabı ise Fluke 435 marka güç analizörü kullanılarak ölçülmüştür. Yapılan benzetim ve deney sonuçlarına göre kare dalga evirici devresinin %55 civarında harmonik bozulma ve %45 verimliliğe sahip olduğu gözlemlenmiştir. Modifiye kare dalga evirici devresi ise %38 harmonik bozulma ve %60 verimle kare dalga evirici devresinin önünde yer almaktadır. Saf sinüs evirici devresi ise %10 civarında harmonik bozulma ve %75'in üzerinde verimliliğinden dolayı diğer evirici devrelere kıyasla öne çıkmaktadır. Her bir evirici devresi için rezistif ve indüktif yükler altında yapılan testler Tektronix marka dijital osiloskop yardımıyla gözlemlenmiş ve test sonuçları ile simülasyon sonuçlarının birbirleriyle örtüştüğü görülmüştür. Elde edilen sonuçlara göre saf sinüs evirici devresinin daha yüksek maliyet ve daha karmaşık devre yapısı olmasına rağmen kare dalga ve modifiye kare dalga evirici devrelerine göre daha iyi ve verimli olduğu ortaya çıkarılmıştır.

7 Ekim 2015

Anahtar Kelimeler: Güç Eviricileri, Çıkış Dalga Formu, Harmonik Analiz

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Without you, I wouldn’t be here.

2015, 07 October Mustafa Sacid ENDİZ

CONTENTS

ABBREVIATIONS

Symbol	**Description**
R	Resistor
L	Inductor
C	Capacitor
V	Volt
A	Ampere
Hz	Hertz
AC	Alternating Current
DC	Direct Current
RMS	Root Mean Square
UPS	Uninterruptible Power Supply
EMI	Electro Magnetic Interference
PV	Photo Voltaic
IEEE	Institute of Electrical and Electronics Engineers
IC	Integrated Circuit
DG	Distributed Generation
VSI	Voltage Source Inverter
CSI	Current Source Inverter
THD	Total Harmonic Distortion
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
SCR	Silicon Controlled Rectifier
BJT	Bipolar Junction Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
IGBT	Insulated Gate Bipolar Transistor
PCB	Printed Circuit Board

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CHAPTER 1

INTRODUCTION

Energy is an important and indispensable resource that is used in all areas of our daily lives. One of the today’s most important issues is to prevent global warming. Thanks to CO_2 emission reduction policies and increasing prices of fossil fuels, significant improvements in the field of renewable energy sources are being observed during recent years. Today most of the world's energy is supplied from the fossil fuels that are not renewable energy sources in limited supply [1].

Daylight is an unlimited and clean source of energy that can be converted into the electrical power via photovoltaic technology. This kind of energy can be harvested by use of photovoltaic arrays. The photovoltaic generation systems can either be operated as isolated systems or be connected to the grid as a part of an integrated system, with other electrical generation. The efficiency of commercial PV panels is around 15-20% today. Therefore, it is very important that the power produced by these panels is not wasted by using inefficient power electronics systems. The efficiency and reliability of both single-phase and three phase PV inverter systems can be improved using new and better technologies. Simulation of modern devices such as electrical systems using power electronics has been a challenge due to the nonlinear behavior of power switches, their connection to continuous subsystems and the design of the whole system control. The integration of the renewable energy sources to the utility grid requires high efficiency power transformation, maximum power extraction and costs minimization, which can only be achieved with the use of the proper power electronics inverters [2-3].

Power Electronics deals with the converting of electrical energy from one form to another in an efficient, clean, compact, and robust manner for convenient utilization. It is the science associated with efficient conversion, control and conditioning of electric power from its available input into the desired output form. Power inverters that are able to convert direct current (DC) into alternating current (AC) made a head start when the first switching device Silicon Controlled Rectifier (SRC) was proposed by Bell laboratories [4].

Power inverters are devices that can convert electrical energy of DC form into AC form. They are widely used in industrial applications such as variable speed AC motors, induction heating, standby power supplies and uninterruptible power supplies and they could be in different shapes and sizes, from low power devices to high power industrial motors in case of power outage. The purpose of a DC/AC power inverter is generally to get DC power supplied by a renewable energy sources, such as a 12 volt solar panel or car battery, and transform it into a 220 volt AC power source operating at 50 Hz, like the power available at an ordinary household electrical outlet. In the last years power inverters are broadly used for industrial as well as domestic appliances for the control of power flow from DC into AC. The choice of topology for any inverter should be based on for the usage of the inverter. Today a lot of inverter circuit topologies have been searched that are used in many industrial applications. The inverter topologies can be categorized as inverters with transformer isolation and inverters without transformer isolation. There are a lot of publications dealing with these different types of inverters. Single phase inverters can be considered as half-bridge and full-bridge inverters [4-5].

In VSI (Voltage Source Inverters), the output voltage level can be controlled from the input sources using the amplitude and frequency. Switched mode or static power inverters are mainly composed of power switching devices and widely used for uninterruptible power supply (UPS), the alternating current motor drivers in industrial applications. In VSI inverters, due to constant source of input power switching elements are working always in forward-switching region. Therefore switching elements such as BJT (Bipolar Junction Transistor), IGBT (Insulated Gate Bipolar Transistor) and MOSFET (Metal Oxide Semiconductor Field Effect Transistor) are suitable for use in power inverters [6-7].

The main method used to make an inverter is a bridge-type inverter in which the controlled power bridge uses any modulation technique. In case of using a low voltage in this bridge-type inverter, the cost and volume of the inverter can significantly increase. However, being small in size and light weight of the inverter is an important in many applications. Inverter circuits are designed as a single-phase or three-phase according to the power requirements and output voltage. Single-phase inverters are sufficient for applications requiring low power, while the three-phase inverters are used in medium and high power applications. Single-phase inverters, being in low power and voltage level, widely used in UPS (Uninterruptible Power Supply) applications. Unlike single phase, three-phase inverters offer more appropriate solutions for the middle and high power/voltage industrial applications. Consequently both groups of inverters have been developed using various topologies related to the effective controlled of the output voltage, amplitude, phase, and frequency [8].

According to the output generated waveforms inverters can be classified as square wave, modified square wave and true sine wave inverter. Square wave inverters are no more applied in the industry due to their many disadvantages such as low efficiency and higher harmonics. Modified square inverters are popular and used for many devices without trouble but they are also not as efficient as true sine wave inverters. True sine inverter topology is the best one that works fine with all the equipments without making any problems. However their mainly disadvantages are the high price and circuit complexity. The sine wave generation is very important in power electronics because the need of the power rating required to operate electronic appliances should be smoothly. Most of the applied industrial UPSs have actually square wave inverters or modified square wave inverters. Electronic devices, operated by these inverters may be damaged due to the contents of the harmonics. Contrary to this true sine wave inverters are able to drive all the appliances without making any damages because their output is sinusoidal and harmonics at the output is very low [9-10].

In addition to the half bridge and full bridge inverters that are called traditional inverters, there are also multilevel inverters (MLI) with many advantages. The concept of multilevel converters has been used since 1980’s. The term multilevel began with the three-level converter. Subsequently, several multilevel converter topologies have been developed. Most of the research has focused on three types of inverter topologies. In multilevel inverters the first introduced topology was the diode clamped design with series of capacitors initiated by Nabae and his colleagues in 1981. This was followed by the flying capacitor topology without using clamping diodes. Another multilevel design involves series of h-bridges with separated DC sources called cascaded h-bridge inverter topology with minimum number of components. MLIs have created tremendous interest in the field of high power applications since they can perform high voltage and high power output with the increased number of output levels and decreased harmonics at the output voltage and current [11-13].

The main goal of this thesis is to study and compare single phase power inverters with respect to output waveforms, voltage harmonics and efficiency at the output signal. This work could be separated mainly to five chapters as mentioned below:

Chapter one: Introduction to the background of the research and literature for the thesis. The chapter finishes with an outline of the thesis.

Chapter two: This chapter overviews inverter background and applications, different inverter types and their characteristics.

Chapter three: This chapter focuses on the modulation techniques of the power inverters used to control the power switching transistors, concept of pulse width modulation technique and total harmonic distortion.

Chapter four: This chapter deals with the computer simulation and experimental implementation of single phase power inverters regarding output waveforms.

Chapter five: The final conclusion is presented, based on the theoretical and experimental results. Furthermore, guidelines for future work are given.

CHAPTER 2

POWER INVERTERS

2.1 Overview of Power Inverters

With the development of power electronic technology, the inverter has been widely used in many fields around the world today. Inverters change DC current to AC current namely it uses DC power supply and creates AC power supply, usually at a voltage similar to normal mains supply. In other words, it enables to run household appliances from a low voltage DC such as a car battery or a more sophisticated solar power system. An inverter will use different kinds of transistors to continually switch the direction of the voltage or in an oscillator to produce a sine wave. This switching or oscillation will happen 50 or 60 times a second, according the required frequency [14].

Alternating current is easier to transport through cables over long distances than direct current. The electricity itself is still the same concept. It is the method of delivering that electrical current that changes to that it is in a specified frequency and power scale in accordance with individual power related needs. However, the smallest of these can have something as simple as 12V battery attached to it and will generate a safe and reliable form of alternating current as a portable or emergency power supply that can run many smaller types of electronic equipment. DC form of electricity is generally lower in voltage but it has a continuous stream of steady power. Direct current is normally found in batteries both internal and external. Conversely alternating current has negative and positive alternating cycles. This is useful for equipment that requires a surging style of power as well as transferring electrical current across large distances through conductive metal wires [15]. Figure 2.1 shows various kinds of solar inverters in different sizes.

Figure 2.1 Various inverters for solar panels.

2.1.1 Voltage Source Inverter

When the DC voltage remains constant, then it is called voltage source inverter (VSI) or voltage fed inverter. It is the type of inverter in which the independently controlled AC output is voltage waveform. The output voltage waveform is mostly remaining unaffected by the load. Output voltage does not dependent on the load and requires feedback diodes. Due to this property, the VSI have many industrial applications such as adjustable speed drives (ASD) and also in Power system for FACTS (Flexible AC Transmission) [16]. In Figure 2.2 is a voltage source inverter.

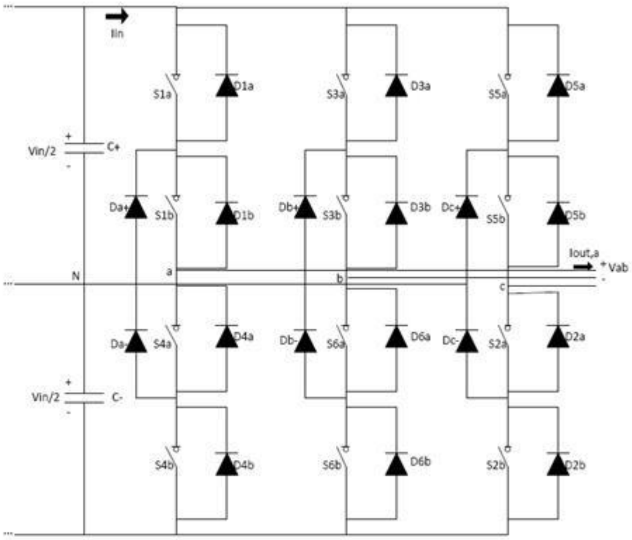

Figure 2.2 Voltage source inverter.

2.1.2 Current Source Inverter

When input current is maintained constant, then it is called current source inverter (CSI) or current fed inverter (CFI). In this type of inverter independently controlled ac output is a current waveform. The output current waveform is mostly remaining unaffected by the load. The amplitude of output current is independent of the load and it does not require any feedback diodes. These are widely used in medium voltage industrial applications, where high quality waveform is required [16]. In Figure 2.3 is a current source inverter.

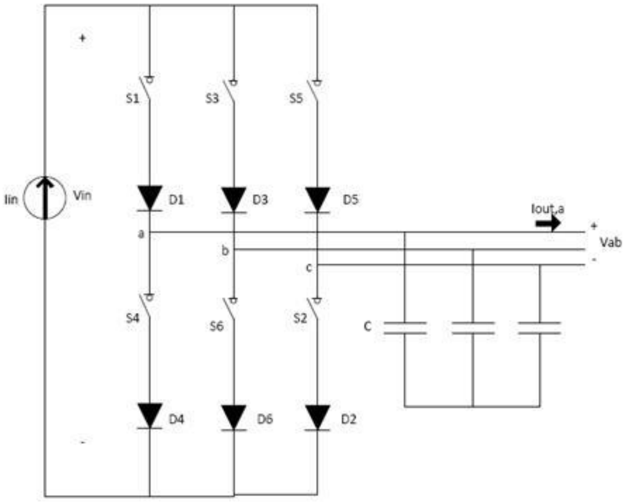

Figure 2.3 Current source inverter.

2.1.3 H-Bridge Configuration

H-bridge inverter is a switching configuration composed of four switches (mostly power transistors) in an arrangement that resembles a letter H. By controlling different switches in the bridge, a positive, negative, or zero potential voltage can be achieved across a load. There are four possible switch positions that can be used to get different voltages across the load. These positions are presented in Table 2.1. It should be avoided from other possibilities, as they would short circuit power to ground, potentially causing damage to the device or rapidly depleting the power supply. The H-bridge circuit consists of four switches corresponding to high side left, high side right, low side left, and low side right. The switches that are used to implement an H-bridge configuration can be mechanical or done from solid state transistors [17]. The use of an H-bridge configuration to drive a load is shown in Figure 2.4.

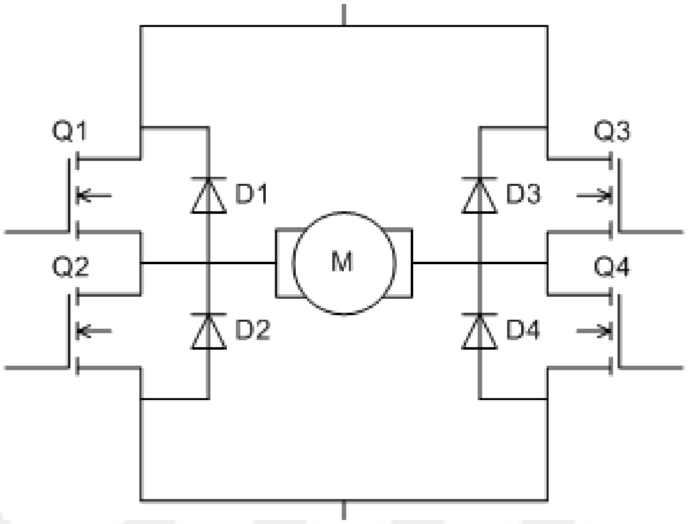

Figure 2.4 H-bridge configuration circuit.

Table 2.1 Switch positions of h-bridge circuit configuration.

High Side Left	**High Side Right**	**Low Side Left**	**Low Side Right**	**Voltage Across Load**
On	Off	Off	On	Positive
Off	On	On	Off	Negative
On	On	Off	Off	Zero Voltage
Off	Off	On	On	Zero Voltage

2.2 Inverters Input and Output Voltage

A characteristic power inverter device or circuit demands a relatively stable DC power source capable of supplying sufficient current for the intended power demands of the system. The input voltage of a power inverter depends on the design and purpose of the related circuit. The AC output voltage of a power inverter device is often the same as the standard power line voltage, such as household 240V AC. This makes possible the inverter to power numerous types of electrical devices in case of power outage [17].

2.3 Inverters Output Frequency

The AC output frequency of a power inverter circuit or device is generally the same as standard power line frequency, about 50 Hz or 60Hz. The output frequency of an inverter can be adjusted using different oscillator circuits changing resistor and capacitor values. If the output of an inverter circuit is stepped up such as 220V, then the frequency should be much higher for transformer efficiency [17].

2.4 Inverters Output Power

A power inverter will in many cases have a general power rating described in watts or kilowatts. This explains the power that will be available to the load the inverter is driving and the power that will be required from the DC source. Smaller popular consumer and home appliances are designed to operate low powers typically range from 150 to 3000 watts. But for industrial applications the inverter output should be in kilowatts. It should be considered that when a load is being driven the inverter should be able to supply more power than operating power which is called peak power [17].

2.5 Inverters Output Waveforms

Generally there are three types of the output waveforms for the power inverters. According to the output waveforms inverters can be classified into three groups that are square waveform, modified waveform and true sine waveform. Today the two dominant commercialized waveform types of power inverters are modified square wave and true sine wave.

2.5.1 Square Waveform

This is the basic type of inverter waveform. 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 [18]. Figure 2.5 is a basic inverter type called square output waveform.

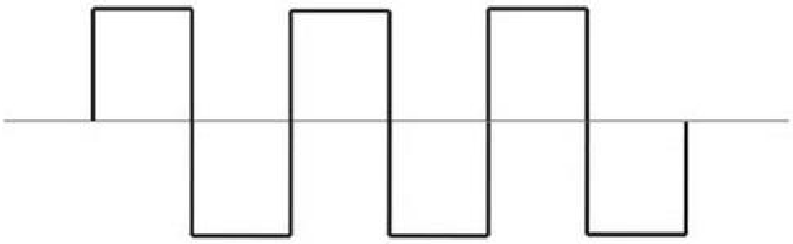

Figure 2.5 Square waveform.

2.5.3 Modified Square Waveform

A modified square wave inverter actually has a waveform more like a square wave, but with an extra step or so. Because the modified square wave is noisier and rougher than a pure sine wave, clocks and timers may run faster or not work at all. A modified square 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 [18]. Figure 2.6 is modified square inverter output form.

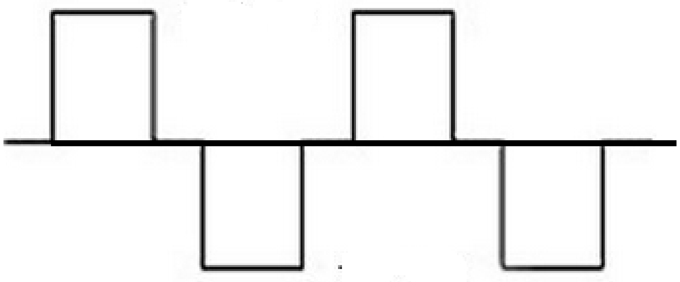

Figure 2.6 Modified square waveform.

2.5.3 True Sine Waveform

This type of inverter provides output voltage waveform which is very similar to the voltage waveform that is received from the utility grid. The sine wave has very little harmonic distortion resulting in a very clean supply and makes it ideal for running electronic systems such as computers, digital racks and other sensitive equipment without causing problems or noise. Things like mains battery chargers also run better on pure sine wave converters [18]. Figure 2.7 is a true sine wave inverter output signal.

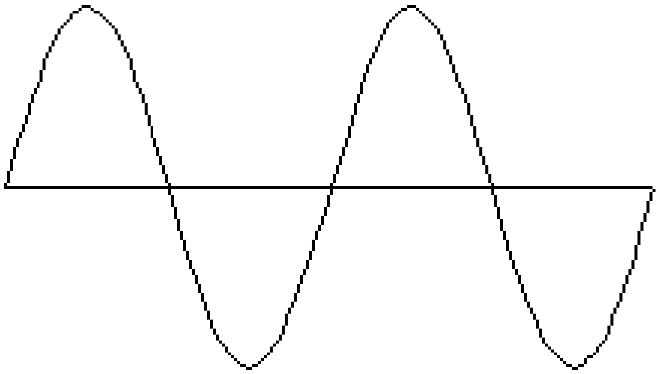

Figure 2.7 True sine waveform.

2.6 Single Phase Inverters

These inverters supply single phase AC power. Single phase inverters output are connected only to one phase line. Single phase AC power is what we get from the outlets at homes. They are mainly used for low power applications such as home appliances and come at lower prices compared to the three phase inverters. Single phase inverters consist mainly of half bridge and full bridge circuits.

2.6.1 Half Bridge Inverter

Single Phase Half Bridge Inverter consists of two semiconductor switches T1 and T2. These switches may be BJT, mosfets or IGBT with a commutation circuit. In Figure 2.8 is shown a single phase half bridge inverter. D1 and D2 are called freewheeling diode also known as the feedback diodes as they feedback when the load is reactive power.

Half bridge inverters are for lower voltage applications and commonly used in power supplies. These inverters have the basic topology in power electronic and they need two switching elements, three-wire dc source and two identical capacitors for the operation. For the regular operation of this inverter, only one transistor should be closed at any time [19].

The rms value of the output voltage for half bridge inverter is;

$$\mathrm{Vo} = \sqrt{\frac{2}{\mathrm{T0}}\int_0^{\mathrm{To}/2}\frac{(\mathrm{Vdc})^2}{4}\,\mathrm{d}(\mathrm{t})} \qquad \textbf{(2.1)}$$

The rms value of the fundamental component for half bridge inverter is;

$$\mathrm{Vo} = \sum_{\mathrm{n}=1,3,5\ldots}^{\infty}\frac{2\mathrm{Vdc}}{\mathrm{n}\pi}\sin \mathrm{wt} \qquad \textbf{(2.2)}$$

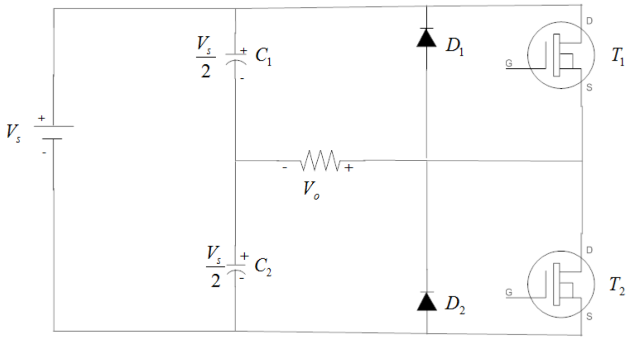

Figure 2.8 Single phase half bridge inverter.

In Table 2.2 T1 is ON during the positive half cycle of the output voltage, which makes Vo=+Vdc/2 and when T2 is ON during the negative half cycle making Vo= -Vdc/2.

Table 2.2 Switching states for single phase half bridge inverter.

T1	T2	V_O
ON	OFF	$+\frac{Vdc}{2}$

2.6.2 Full Bridge Inverter

It consists of two arms with a two semiconductor switches on both arms with antiparallel freewheeling diodes for discharging the reverse current. The full bridge inverter accomplishes its task in much the same manner as half bridge circuit. The circuit is operated by switching T1, T2, T3, and T4. When transistors T1 and T2 are connected, the input voltage +Vdc appear across the load. But if the transistors T3 and T4 are connected, the voltage across the load is –Vdc.

Full bridge inverters have evolved with the improvement in transistor characteristics. In case of resistive-inductive load, the reverse load current flow through these diodes. These diodes provide an alternate path to inductive current which flows during the off condition [19]. In Figure 2.9 can be seen single phase full bridge inverter.

The rms value of the output voltage for full bridge inverter is;

$$\mathrm{Vo} = \sqrt{\frac{2}{\mathrm{T0}}\int_{0}^{\mathrm{To}/2}(\mathrm{Vdc})^{2}\mathrm{d}(\mathrm{t})} \qquad \textbf{(4.17)}$$

The rms value of the fundamental component for full bridge inverter **is**;

$$\mathrm{Vo} = \sum_{\mathrm{n}=1,3,5\ldots}^{\infty}\frac{4\mathrm{Vdc}}{\mathrm{n}\pi}\sin \mathrm{wt} \qquad \textbf{(4.18)}$$

In Table 2.3 the switching states are named for the switching transistors T1, T2, T3 and T4. In Table 2.4 component comparison of the single phase inverters have been presented.

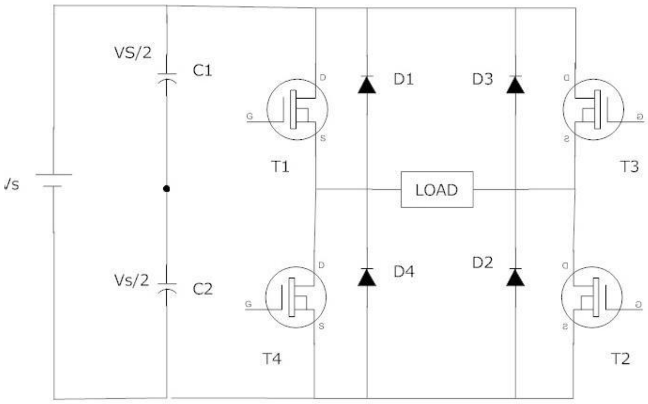

Figure 2.9 Single phase full bridge inverter.

Table 2.3 Switching states for single phase full wave bridge inverter.

T1	**T2**	**T3**	**T4**	**V_O**
OFF	ON	ON	OFF	V_{DC}
ON	OFF	OFF	ON	$-V_{DC}$
ON	OFF	ON	OFF	0
OFF	ON	OFF	ON	0

Table 2.4 Component comparison of the single phase inverters

Single Phase Inverters				
Parameters	**Switches**	**Diodes**	**Capacitors**	**Power Rating**
Half Bridge	2	0	2	< 2kV
Full Bridge	4	0	2	< 2kV

2.7 Inverter Applications

An inverter is basically a device that converts electrical energy of DC form into that of AC. The purpose of DC-AC inverter is to take DC power from a battery source and converts it to AC. For example the household inverter receives DC supply from 12V or 24V battery and then inverter converts it to 220V AC with a desirable frequency of 50Hz or 60Hz. These DC-AC inverters have been widely used for industrial applications such as uninterruptible power supply (UPS), AC motor drives. Recently, the inverters are also playing an important role in various renewable energy applications such as photovoltaic systems [20]. In Figure 2.10 and 2.11 we can recognize inverter applications and interface with utility grid, remote energy sources and external loads.

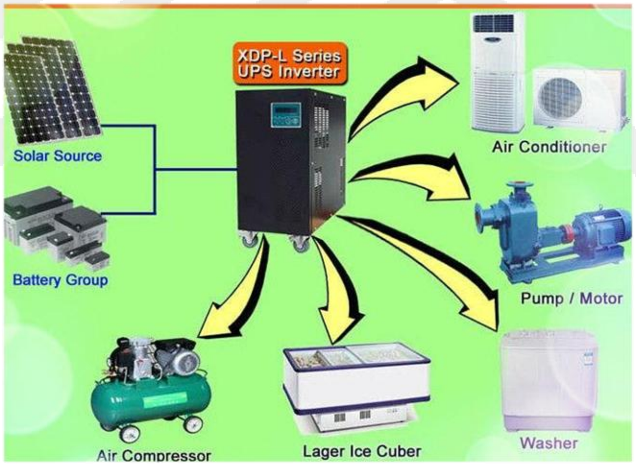

Figure 2.10 Inverter applications.

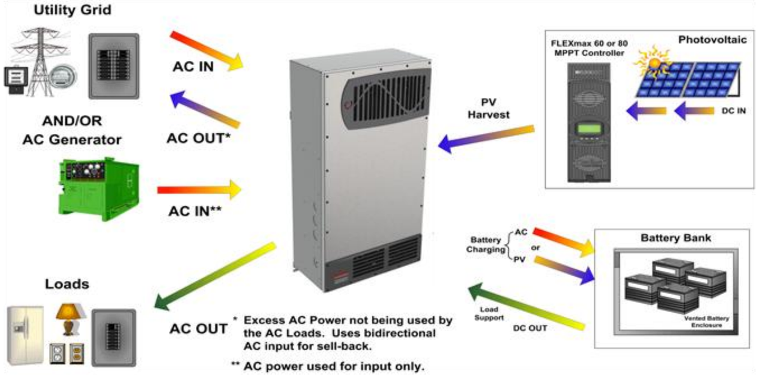

Figure 2.11 Inverter interface with other systems.

CHAPTER 3

INVERTER MODULATION TECHNIQUES

3.1 Inverter Control Techniques

Power inverters are widely used for industrial and domestic applications such as renewable energy sources, AC motors, induction heating, and uninterruptible power supplies. Inverters are mainly classified into two types that are single phase and three phase. Each inverter type has controlled turn on and turn off switching devices. They generally use PWM (pulse width modulation) control signals to get an AC output signal. The main function of the inverter is to convert DC input voltage to a AC output voltage of the desired magnitude. The output voltage waveforms of the ideal inverters should be sinusoidal, however the waveform of the practical inverters are non sinusoidal and contains different harmonics. Square wave or quasi-square-wave voltages are acceptable only for low and medium power applications, but for high power applications low distorted sinusoidal waveforms are required. By using high speed power semi conductor devices and by using different switching techniques we can reduce the harmonic content in output voltage [21].

3.2 Pulse Width Modulation

Pulse Width Modulation, or PWM, is a technique for requiring analog results with digital means. Digital control is used to make a square wave, a signal changed between on and off. This on-off condition can simulate voltages in between 5 Volts and 0 Volts by adjusting the ratio of the time the signal is on versus the time that the signal is off. The time period of “on” is called the pulse width. To get changing analog values, it should be modulated the pulse width. Analog PWM control requires the generation of both reference and carrier signals that are feed into the comparator and based on some logical output, the final output is generated. The reference signal is the desired signal output maybe sinusoidal or square wave, while the carrier signal is either a saw tooth or triangular wave at a frequency significantly greater than the reference [22]. Figure 3.1 shows us a PWM signal duty cycles.

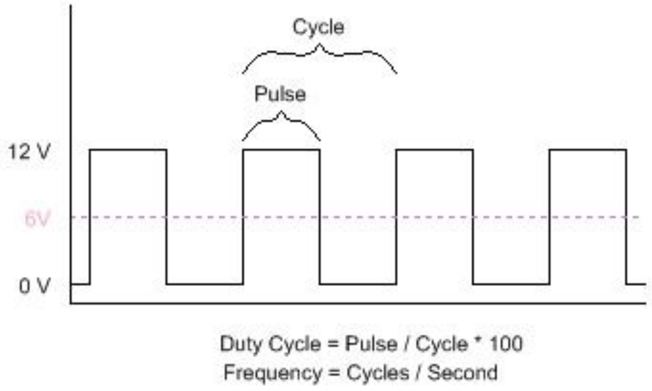

Figure 3.1 PWM signal duty cycles.

There are various types of PWM techniques and so we get different output and the choice of the inverter depends on cost, noise and efficiency.

There are three basic PWM techniques:

1. Single Pulse Width Modulation
2. Multiple Pulse Width Modulation
3. Sinusoidal Pulse Width Modulation

3.2.1 Single Pulse Width Modulation

In this modulation there is an only one output pulse per half cycle. The output is changed by varying the width of the pulses. The gating signals are generated by comparing a rectangular reference with a triangular reference. The frequency of the two signals is nearly equal to each other [23]. In Figure 3.2 there is a single phase width modulation with low frequency reference and high frequency carrier signals.

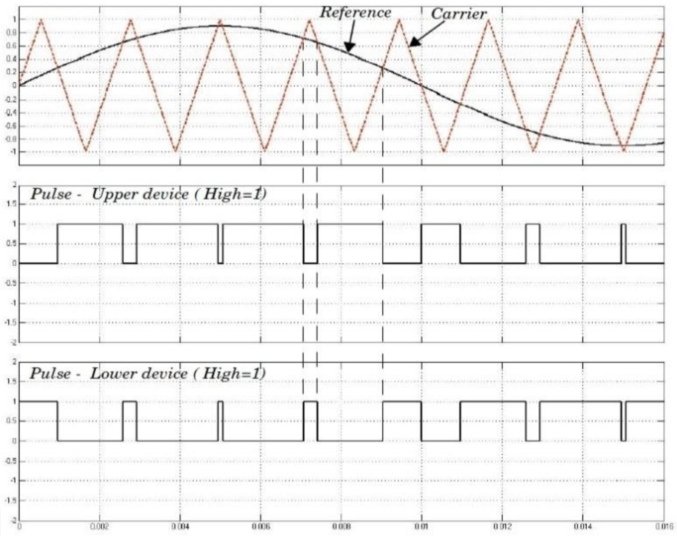

Figure 3.2 Single phase width modulation.

3.2.2 Multiple Pulse Width Modulation

In this modulation there are multiple numbers of output pulses per half cycle and all pulses are of equal width. The gating signals are generated by comparing a rectangular reference with a triangular reference. The frequency of the reference signal sets the output frequency (f_o) and carrier frequency (f_c) [23]. The rate between output frequency and carrier frequency is modulation index shown in equation 3.1. The number of pulses per half cycle is determined by p shown in equation 3.2. In Figure 3.3 is multiple pulse width modulation.

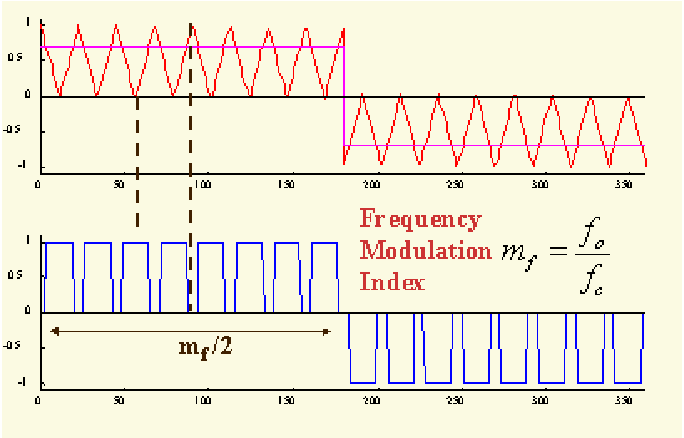

Figure 3.3 Multiple pulse width modulation.

$$m = \frac{fo}{fc} \tag{3.1}$$

$$p = \frac{fc}{2f0} \tag{3.2}$$

3.2.3 Sinusoidal Pulse Width Modulation

This modulation technique has multiple numbers of output pulses per half cycle and pulses are of different width. The width of each pulse is varying in proportion to the amplitude of a sine wave evaluated at the center of the same pulse. The gating signals are generated by comparing a sinusoidal reference with a high frequency triangular signal [23]. Figure 3.4 is sinusoidal pulse width modulation.

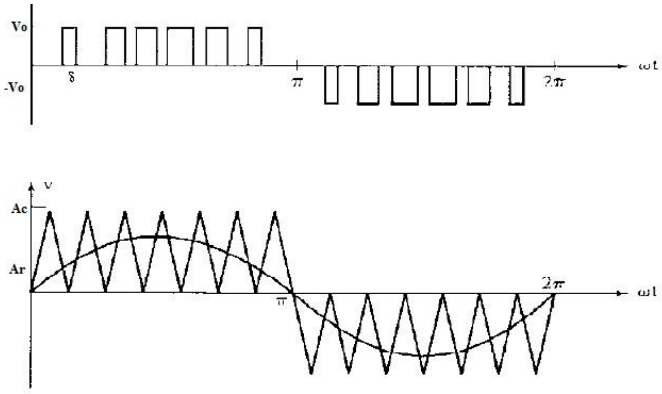

Figure 3.4 Sinusoidal pulse width modulation.

3.3 Sine Wave Generation

The most common and popular technique for generating true sine wave is PWM. SPWM is the best technique within these techniques. This PWM technique involves generation of a digital waveform, for which the duty cycle can be modulated in such a way so that the average voltage waveform corresponds to a pure sine wave. The simplest way of producing the SPWM signal is through comparing a low power sine wave reference with a high frequency triangular wave. This SPWM signal can be used to control switches.

Through an LC or RC filters, the output of Full Wave Bridge Inverter with SPWM signal will generate a wave approximately equal to a sine wave. This technique produces a much more similar AC waveform than that of others [24]. In figures 3.5, 3.6 and 3.7 are shown SPWM comparison signals, unfiltered and filtered SPWM outputs respectively.

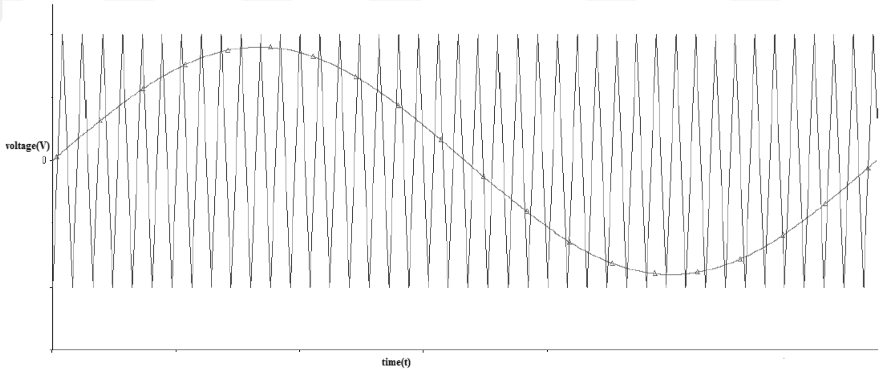

Figure 3.5 SPWM comparison signals.

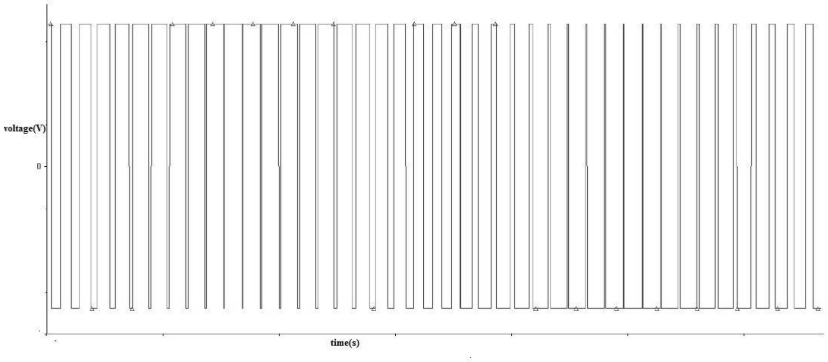

Figure 3.6 Unfiltered SPWM output.

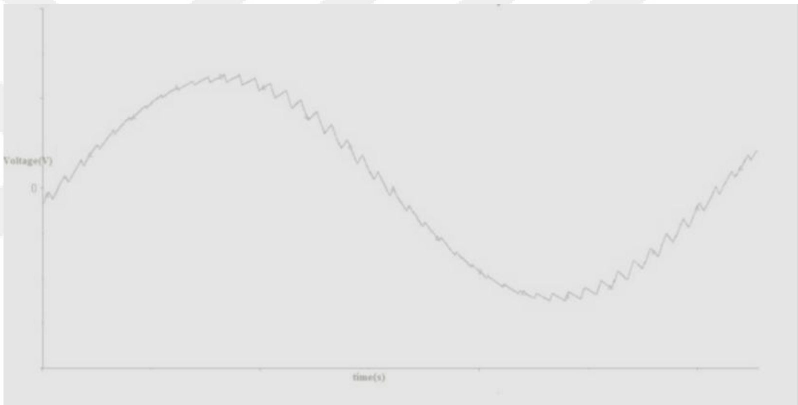

Figure 3.7 Filtered SPWM output.

3.4 Inverter Output Power Quality

Most of the power inverters draw harmonic current and reactive power from AC source and causes the power quality problems. When the applied load is resistive, the output voltage and current are in phase but when an inductive load is applied; voltage and current signals at the output are not in phase. Square and modified square wave inverters have more THD (Total Harmonic Distortion) at the outputs and that causes poor power quality because beside fundamental frequency there are some undesired higher frequencies. But true sine wave inverters have exactly the same signal as of the utility power and as a result they have very low THD and desired power quality. The power quality of an inverter plays an important role for operating sensitive devices. With lower

THD an inverter can be used for any devices either for industrial both for domestic appliances [25].

3.4.1 Total Harmonic Distortion

A load is considered non-linear if its impedance becomes different with the applied voltage. This difference means that the current drawn by a non-linear load will not be sinusoidal even when it is connected to a sinusoidal voltage. These non-sinusoidal currents contain harmonic currents that interact with the impedance of the power distribution system to create voltage distortion that can affect both the distribution system equipment and the loads connected to it. The term of harmonics referred to power quality that means how pure the output voltage and output current waveform is. In accordance with the ideal, the electrical supply should have a fine sinusoidal waveform without any kind of distortion. If the output current or voltage waveforms are distorted from its perfect form it will be called as harmonic distortion. This harmonic distortion could occur from many reasons such as arc furnaces, personal computers, large variable frequency drives, and heavy rectifiers [26-27].

The quality of the inverter output wave form is expressed using Fourier analysis data to calculate. The following equation is known as the Fourier series used to calculate the harmonics.

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos\frac{n\pi x}{L} + b_n \sin\frac{n\pi x}{L} \right) \qquad \textbf{(3.3)}$$

The coefficients of the Fourier series are;

$$\mathrm{A} = \frac{1}{2\pi}\int_0^{2\pi} f(x)dx \qquad \textbf{(3.4)}$$

$$\mathrm{an} = \frac{1}{\pi}\int_0^{2\pi} f(x)sin\ nxdx \qquad \textbf{(3.5)}$$

$$\mathrm{bn} = \frac{1}{\pi}\int_0^{2\pi} f(x)cos\ nxdx \qquad \textbf{(3.6)}$$

Any periodic waveform can be shown to be composed of the superposition of a direct component with a fundamental pure sine wave component, together with pure sine waves known as harmonics of frequencies which are multiplies of the fundamental frequency. THD value can be calculated in the following equations shown below.

A0 is dc mean value, A1 is maximum value of fundamental component, A2 is maximum value of second harmonic and $\emptyset$ defines the relative angular reference.

$$\mathrm{f(x) = A0 + A1\sin(x + \emptyset 1) + A2\sin(2x + \emptyset 2) + \ldots + Ansin(nx + \emptyset n)} \tag{3.7}$$

Therefore the voltage can be written;

$$\mathrm{V = V0 + V1\sin(x + \emptyset 1) + V2\sin(2x + \emptyset 2) + \ldots + Vnsin(nx + \emptyset n)} \tag{3.8}$$

The current can be written in similar way;

$$\mathrm{I = I0 + I1\sin(x + \emptyset 1) + I2\sin(2x + \emptyset 2) + \ldots + Insin(nx + \emptyset n)} \tag{3.9}$$

THD, which is the ratio of the rms value of the harmonics (Hn) to the rms value of the fundamental frequency (H1), can be calculated as;

$$\mathrm{\%THD} = \frac{\sqrt{\mathrm{H2^2+H3^2+H4^2+\ldots+Hn^2}}}{\mathrm{H1}} \times 100 \tag{3.10}$$

The ratio of the rms value of the “n” harmonic to the rms value of the fundamental is;

$$\mathrm{HDn\ \%} = \frac{\mathrm{Hn}}{\mathrm{H1}} \times 100 \tag{3.11}$$

THD value of the voltage form is;

$$\mathrm{\%THD} = \frac{\sqrt{\mathrm{V2^2+V3^2+V4^2+\ldots+Vn^2}}}{\mathrm{V1}} \times 100 \tag{3.12}$$

THD value of the current form is;

$$\mathrm{\%THD} = \frac{\sqrt{\mathrm{I2^2+I3^2+I4^2+\ldots+In^2}}}{\mathrm{I1}} \times 100 \tag{3.13}$$

3.4.2 Inverter Harmonics Mitigation

Filter circuits are applied when it is necessary to reduce the harmonic distortion rate at the output of the power inverters. These filter circuits are tuned to the frequency of the undesired current harmonic to be eliminated. Basically, the filter is installed for dominant harmonics to be limited and it presents low impedance at the cut-off frequency and absorbs nearly all the harmonics. Mainly passive filters are used that consist of passive elements such as inductance, capacitance, and resistance configured and tuned to control harmonics. They are commonly used and relatively cheap for many applications compared with other solutions for eliminating harmonic distortion. Below in Figure 3.8 is a common passive filter configuration which is responsible for eliminating of harmonics. LC low pass filter only allows low frequency signals from 0Hz to its cut-off frequency to pass while blocking any higher frequencies [28-30].

Principally passive filters are made up of LC branch with a cut-off frequency as shown in the following equation;

$$\mathrm{fr} = 1/(2 * \pi * \sqrt{(\mathrm{L} * \mathrm{C})}) \tag{3.14}$$

Where L is inductance and C is capacitance of the filter circuit.

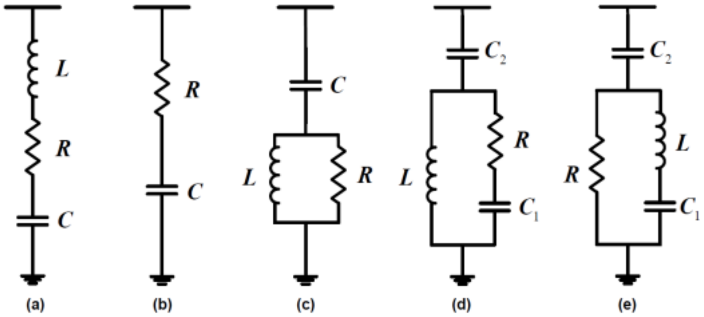

Figure 3.8 Common passive filter configurations.

CHAPTER 4

COMPARATIVE ANALYSIS OF INVERTERS

With the increasing popularity of alternate power sources, the need for static inverters to convert DC energy to conventional AC energy has increased substantially in recent years. Inverter circuits are designed as a single-phase or three-phase according to the power requirements. Single-phase inverters are sufficient for applications requiring low power, while the three-phase inverters are used in medium and high power applications. Each type can use controlled turn on and turn off devices. These inverters generally use pulse width modulation control signals to provide an AC output signal. As an applied source, inverters can be based on voltage source inverters (VSI) and current source inverters (CSI). The VSI are broadly used in many industrial applications and as a result, novel topologies are improved for more efficient inverter circuits [31-35]. In this chapter, comparative study and experimental implementations of single phase inverters related to their output waveforms were performed with the help of Proteus Professional package program.

4.1 Analysis of the Inverters Regarding Output Waveforms

A power inverter can be useful anywhere where the utility power is not available. It can operate mains appliances like radios, tape recorders, DVD players, televisions, electric shavers, fluorescent lamps or cell phone charger. The maximum load depends on the transformer, transistors, and the size of the mounted heat sink.

According to the output waveforms power inverters can be categorized into square, modified square and true sine inverters. AC electricity reverses in direction 50 times per second and does so with a constantly varying force, surging forwards, slowing to a stop, surging in reverse, slowing to a stop. This steady increase and decrease in force as the current changes from forwards to reverse and to forward again is referred to as sine waveform. Renewable energy sources such as photovoltaic modules use DC. Therefore it is needed an inverter to change the DC to AC in order to make useful the power being generated standby power sources. For the maximizing of the energy output, it is critical to select an inverter with the following characteristics like high efficiency, low standby losses, high surge capacity and low harmonic distortion [36-39].

Older style power inverters generate square wave, modified square wave or stepped wave electricity. Some sine wave inverters have sharp edge sine waves, while others have very smooth sine waves, by using hundreds of steps and more complex AC output filtering. The AC output wave form is affected by the load being driven and the DC input voltage level. Many square wave inverters cannot regulate the AC output voltage when driving more difficult loads such as sensitive devices, which can damage sensitive appliances while true sine wave inverters can drive any loads without failure [40-45].

4.1.1 Single Phase Square Wave Inverter Circuit

The simplest AC output wave form to generate is a square wave, in which the voltage alternates from positive 220 volts to negative 220 volts, keeping back and forth. This wave form has a lot of THD and results in poor operation of almost any loads. Square wave inverters produce 220V AC when the battery is at 12V DC.

Below in Figure 4.1 is a power inverter schematic which can generate square wave at the output for 500W. The source of 50 Hz frequency is a 555 timer circuit. The frequency can be set by the resistance values of R_2 and capacitor values of C_2. As switches two N-type power mosfets are applied. One is driven directly from the 555 circuit, the other through a logic inverter with BC547 NPN transistor. Transformer is a mains one with two secondary windings 12V and must be designed for the maximum load required. The heat sink of the two power transistors should be in the right size according to the load. They are mounted on isolation pads. It can be used separate heat sinks for each transistor and no isolation pads, but then the heat sinks must not touch each other and not be grounded. The 12V power supply should be sufficiently hard, in the range of about 10 - 15V. In products that are not dependent on the frequency of 50Hz, it is possible to use a higher frequency, about 100 - 300Hz. This reduces the standby power. The frequency can be set by changing the values of R_2 and C_2 in the circuit.

MOSFETs can be IRFZ44 for loads up to 500W or IRF3205 above 600W. For output above 600W multiple transistors should be combined in parallel. This DC/AC power inverter has an output voltage in square waveform and as a result it has poor THD at the output voltage.

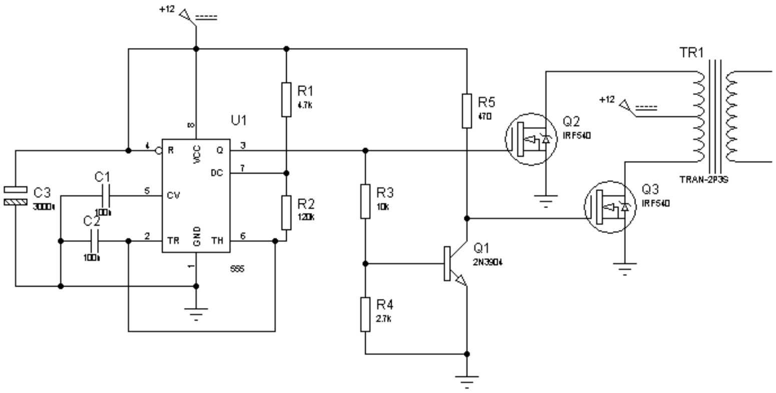

Figure 4.1 Square wave inverter schematic.

4.1.2 Single Phase Modified Square Wave Inverter Circuit

Modified Square wave is the term used when the electric current has a constant force, like it has with DC but switches direction more or less, immediately at the same kind of frequency as the normal utility supply. In Figure 4.2 is a single phase modified square wave inverter schematic for 500W. The operating of the circuit is pretty much unique and different from the normal inverters which include oscillator stage for powering the transistors.

The two arms of the inverter circuit operate in a regenerative manner. The two halves of the circuit no matter how much they are matched will show a slight inequality in the parameters surrounding them like the resistors. Due to this, both halves are not able to conduct together at one time. When the upper transistor conducts first, it will be getting their biasing voltage through the lower half winding of the transformer via R_7. However when it saturates and conducts fully, the entire battery voltage is pulled through their collectors to the ground. This gets any voltage through R_7 to their base and they immediately stop conducting. This gives an opportunity for the lower transistors to conduct and this cycle repeats. The whole circuit thus starts to oscillate and at the output of the circuit is a modified square wave. The base emitter resistors are used to fix a particular threshold for their conduction and they help fixing a base biasing reference level.

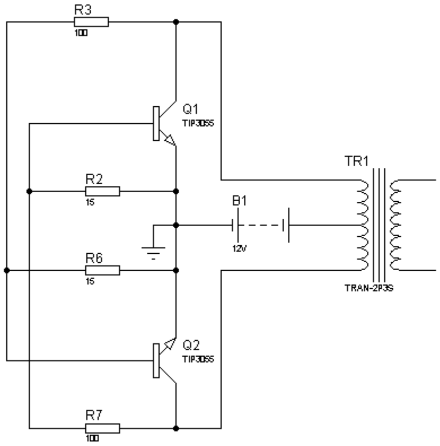

Figure 4.2 Modified square wave inverter schematic.

4.1.3 Single Phase True Sine Wave Inverter Circuit

True sine wave inverters can operate nearly any load without making problems and have better power quality than the utility grid with low THD, since the utility distribution system can be affected negatively by non-linear AC loads resulting in power-quality issues. Below in Figure 4.3 is a powerful, stable and efficient schematic for 500W true sine wave inverter circuit. A simple PIC micro controller with its internal clock would produce a stable 50Hz frequency AC output. The PIC16F628A is programmed to produce a logic 5V signal for 5ms at pin 17 then 15ms off. Then the same process occurs at pin 18, 5ms on then 15ms off. That is one cycle which is then looped. It can be seen from the related Figures below, two 5V pulses from pins 17 and 18 oscillates. These two pins are then sent to the gates of the power MOSFET's. These are N-type power MOSFET's that require only 5V to switch on fully. They have a very low 0.014Ω source to drain resistance when they are on which means they can switch high currents without wasting power as heating. This keeps the whole system efficient.

The MOSFET's could be in parallel pairs for even more power requirements. This circuit can get 220V AC from the 12-0-12 transformer with a 12V standby power sources like a car battery but as this circuit is so efficient a 10-0-10 transformer is able to give at least 220V AC at 12V. It has been used the low voltage side as the primary, and the high voltage side as the secondary. To get a sinusoidal wave form at the output it has been used passive filter stage consisted of LC components. LC low pass filter only allows low frequency signals from 0Hz to its cut-off frequency (fundamental frequency) to pass while blocking any higher frequencies. After filter stage implemented it has been achieved a resembled sine wave in the following simulations below.

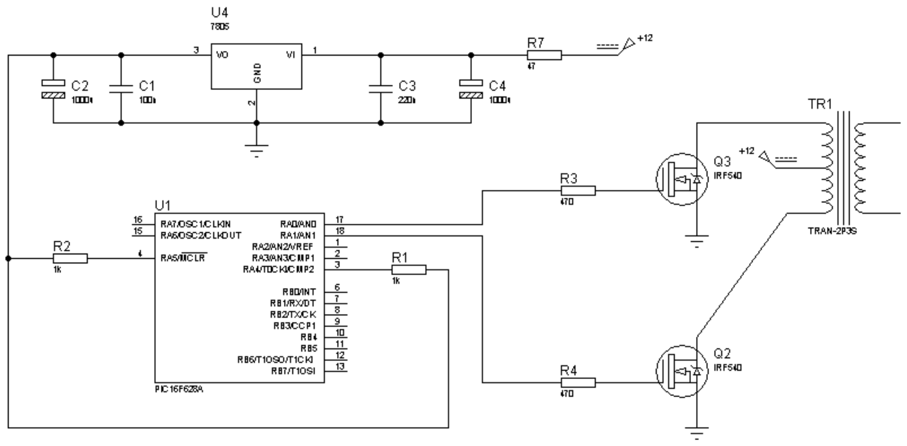

Figure 4.3 True sine wave inverter schematic.

The related equation for resonance frequency is given below;

$$fc = 1/(\sqrt{(L * C)}) \tag{4.1}$$

$$fc = 1/(\sqrt{(9 * 10^{-6} * 4000 * 10^{-6})}) = 500\text{Hz}$$

The filter performance with respect to the output voltage is determined by its resonance frequency. In order to achieve an almost sinusoidal output voltage, the resonance frequency of the filter has to be below the lowest harmonic frequency of the inverter voltage. To avoid additional resonance suppressing control, the resonance frequency has to be above the fundamental frequency of the inverter voltage. The resonance frequency (fc) is calculated as about 500Hz which is greater than the fundamental frequency (50Hz) according to the capacitor (4000µ Farad) and inductor (900µ Henry) values used in the filter stage. While higher harmonics have been eliminated with the help of the low-pass filter circuit, fundamental frequency has not been eliminated due to its lower frequency value [46].

4.2 Simulations and Experimental Results of the Analyzed Inverters

The simulations have been performed by using Proteus Professional which is wholly unique in offering the ability to simulate both high and low-level microcontroller code in the context of a mixed-mode SPICE circuit simulation. Proteus PCB design combines the schematic capture and ARES PCB layout programs to provide a powerful, integrated and easy to use suite of tools for professional PCB Design.

After implementations of the inverter circuit’s efficiency analysis were done using Extech true RMS (Root Mean Square) digital multimeter which is shown in Figure 4.4, THD analysis for each inverter was measured by means of the Fluke 435 Power Analyzer device which is shown in Figure 4.5. The Fluke 435 Power Quality and Energy Analyzer is the Power Quality analyzer that can monetize the cost of energy waste due to poor power quality. The wide range of measurement functions and measurement methods in the device make it the ideal tool for both power quality troubleshooting and discovering energy savings.

Figure 4.4 Extech true RMS digital multimeter.

Figure 4.5 FLUKE 435 Power Analyzer.

4.2.1 Analyze Results of the Square Wave Inverter

The comparative analysis is demonstrated via simulations for each inverter circuit using Proteus Professional package program. After performing of the comparative analysis for the inverters according to the output waveforms, circuit implementations based on the simulation results have been realized.

Below in the following Figures 4.6, 4.7, and 4.8 we can see voltage waveform simulations using Proteus Professional package program without load, with resistive load and inductive load for square wave inverter circuit respectively.

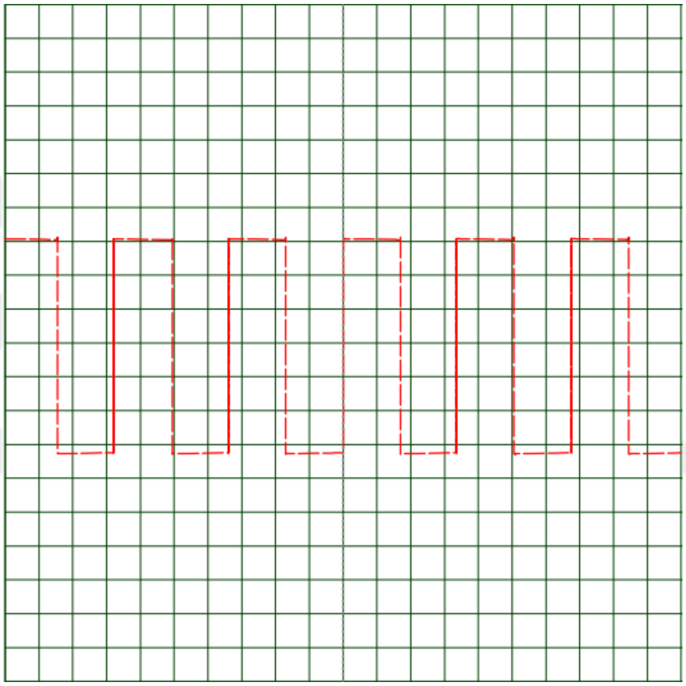

Figure 4.6 Voltage waveform without load.

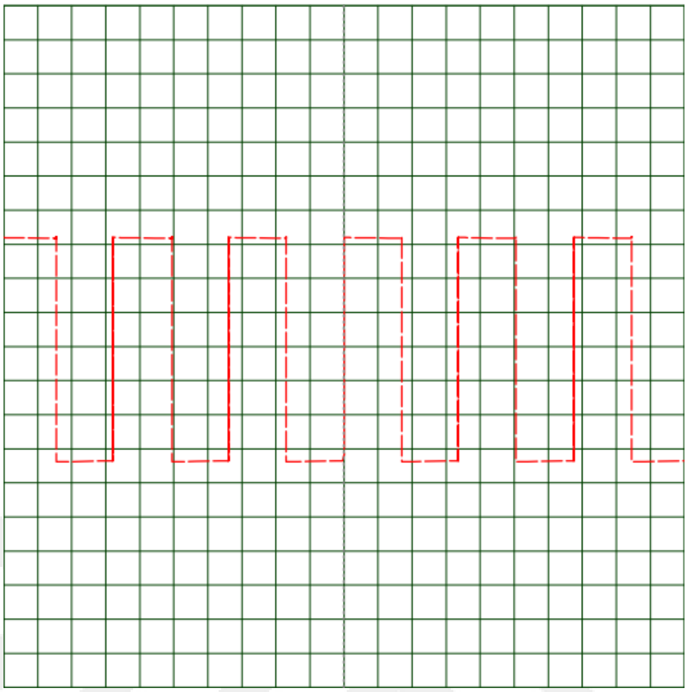

Figure 4.7 Voltage waveform for resistive load.

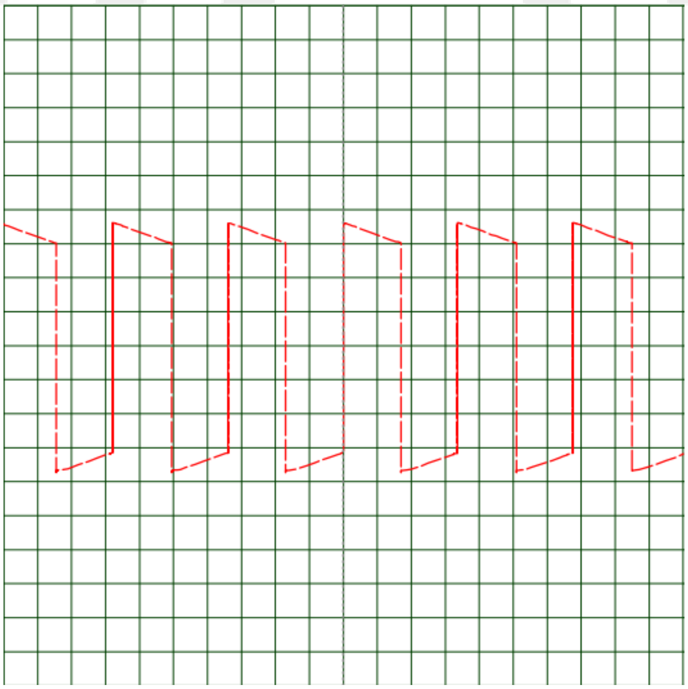

Figure 4.8 Voltage waveform for inductive load.

In the following Figures we can see the experimental results of the implemented inverter circuits. After performing of the comparative analysis for the inverters according to the output waveforms, circuit implementations based on the simulation results were done. Tests on different loads were carried out under laboratory conditions and output signals were observed with the help of a digital oscilloscope. Test results compared with the circuit simulations confirmed to each other. In Figure 4.9, 4.10, and 4.11 are shown voltage waveforms of the square wave inverter on the oscilloscope without load, with resistive and inductive loads respectively. We can observe from the related Figures that the simulation and experiment results confirmed to each other for the square wave inverter circuit.

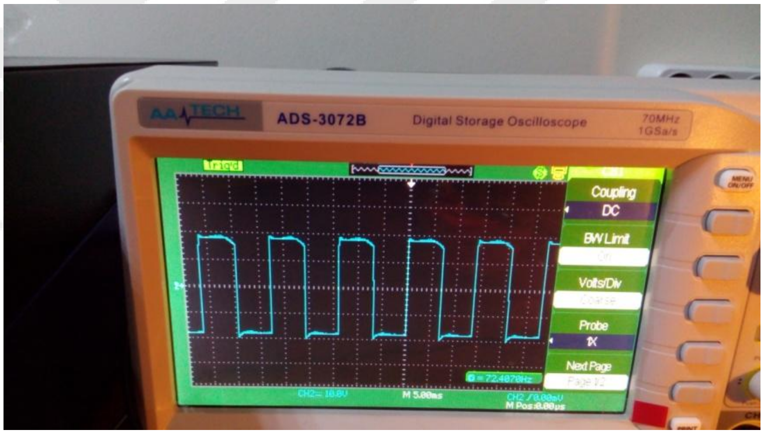

Figure 4.9 Voltage waveform on the oscilloscope without load.

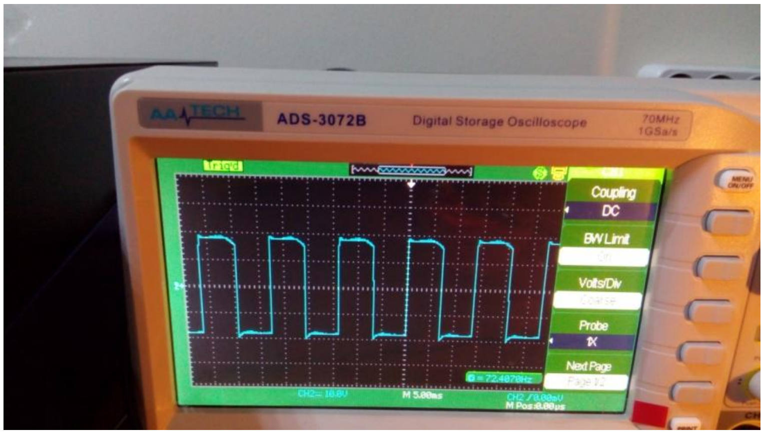

Figure 4.10 Voltage waveform on the oscilloscope for resistive load.

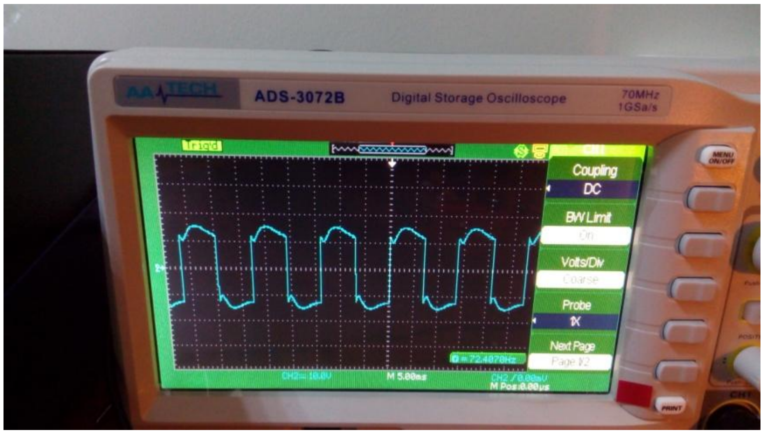

Figure 4.11 Voltage waveform on the oscilloscope for inductive load.

Similarly THD values of the output voltage affected by resistive and inductive loads were analyzed for showing the harmonics using Proteus Professional package program. In Figure 4.12, 4.13, and 4.14 are shown simulation results. In Figure 4.15 is shown experimental result of the harmonic measurement under laboratory conditions using FLUKE 435 Power Analyzer.

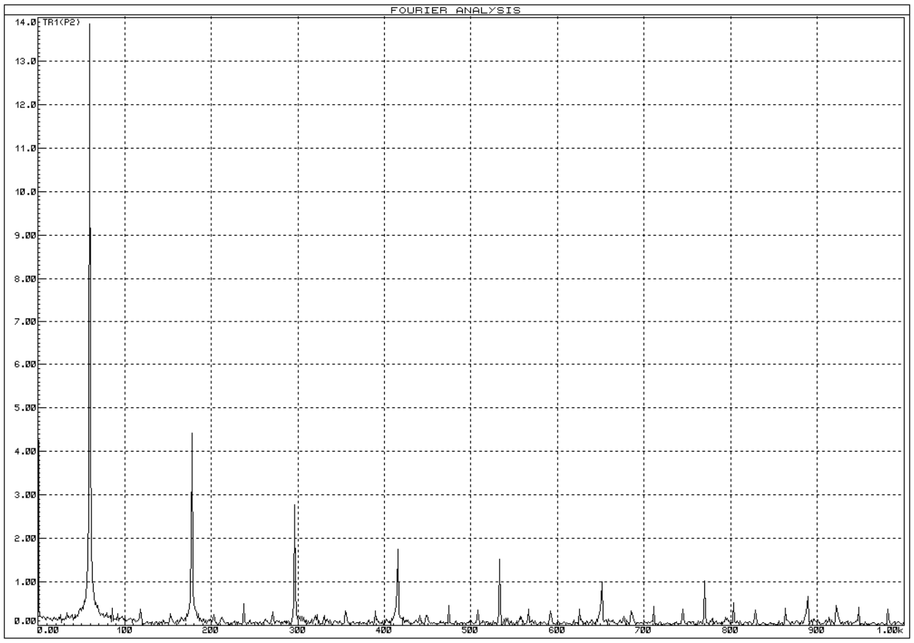

Figure 4.12 THD voltage analysis without load.

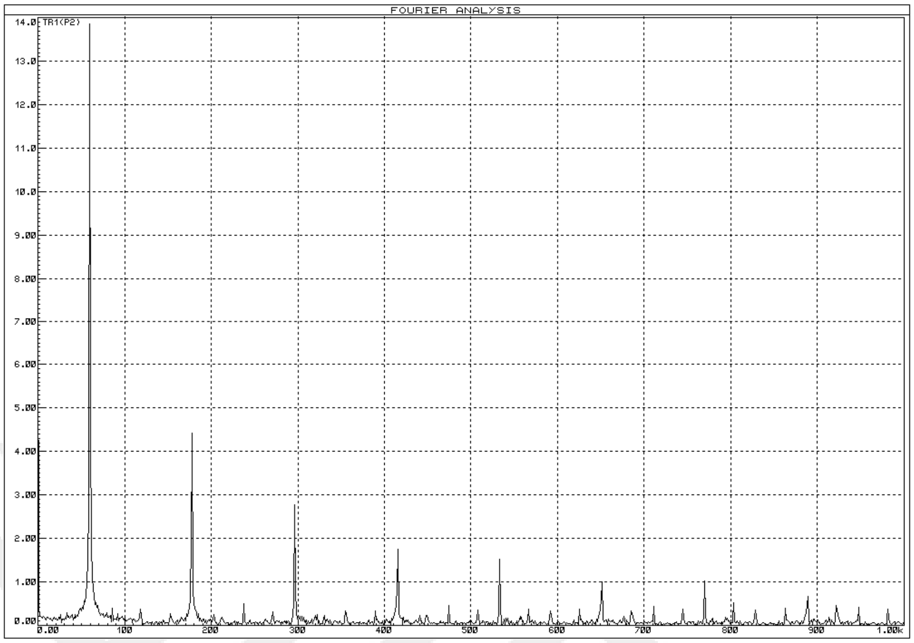

Figure 4.13 THD voltage analysis for resistive load.

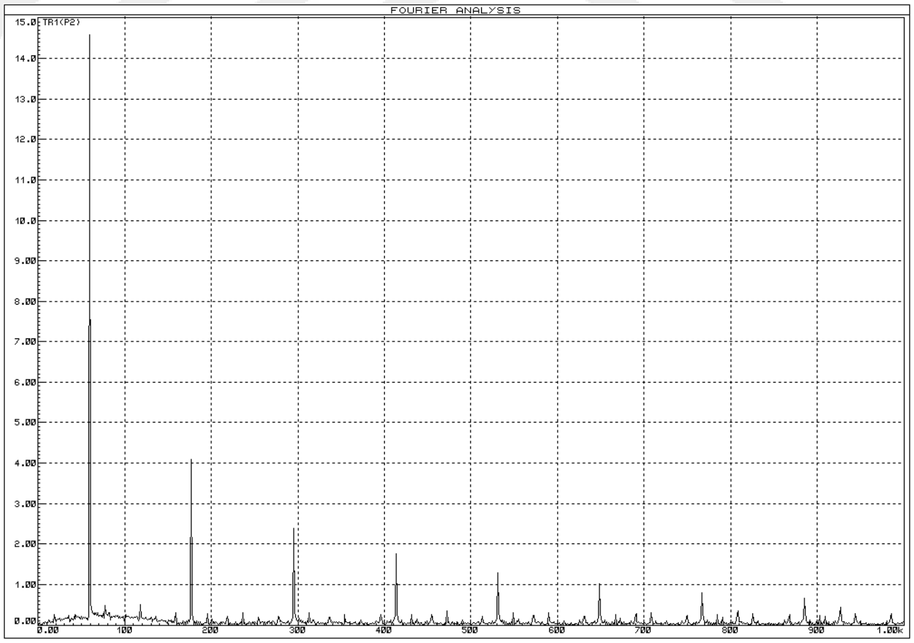

Figure 4.14 THD voltage analysis for inductive load.

Figure 4.15 THD voltage measurement using FLUKE 435 Power Analyzer.

4.2.2 Analyze Results of the Modified Square Wave Inverter

Below in the following Figures 4.16, 4.17 we can see voltage waveform simulations using Proteus Professional package program without load, with resistive and inductive load for modified square wave inverter circuit respectively.

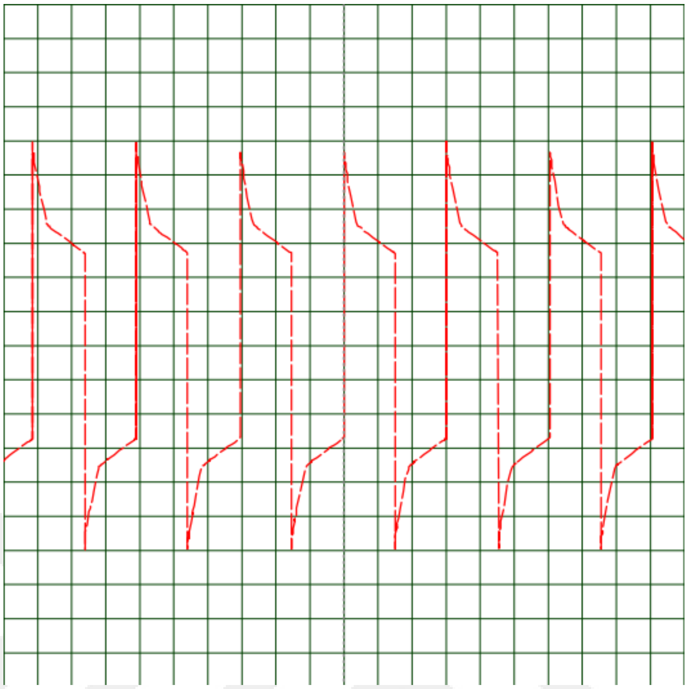

Figure 4.16 Voltage waveform without load.

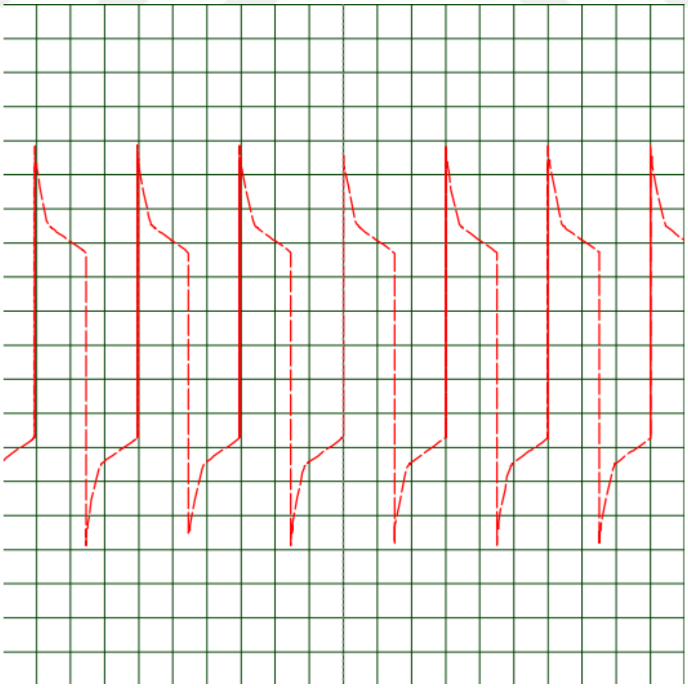

Figure 4.17 Voltage waveform for resistive load.

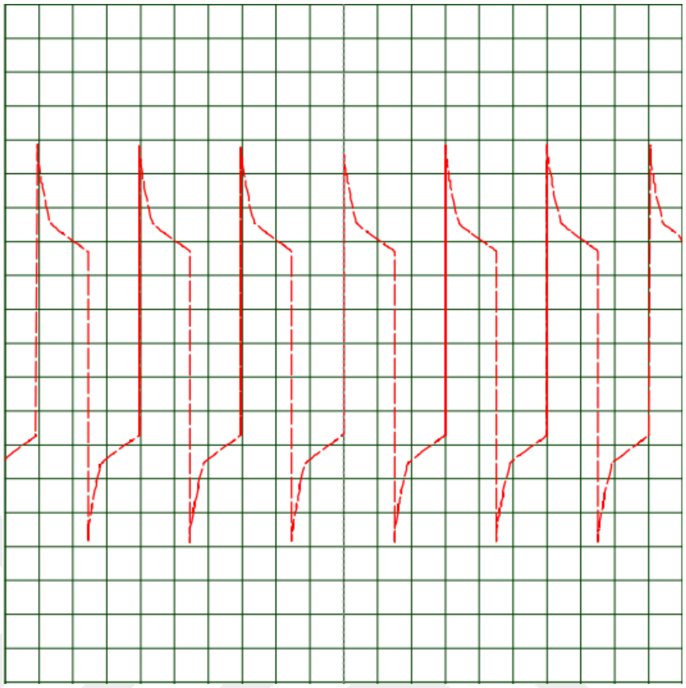

Figure 4.18 Voltage waveform for inductive load.

In Figure 4.19, 4.20, and 4.21 are shown voltage waveforms of the modified square wave inverter on the oscilloscope without load, with resistive and inductive loads respectively. We can see from the related Figures that the simulation and experiment results confirmed to each other for the modified square wave inverter circuit.

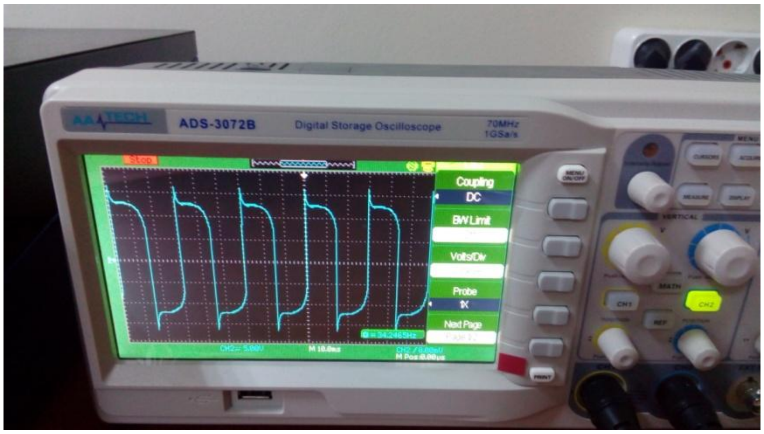

Figure 4.19 Voltage waveform on the oscilloscope without load.

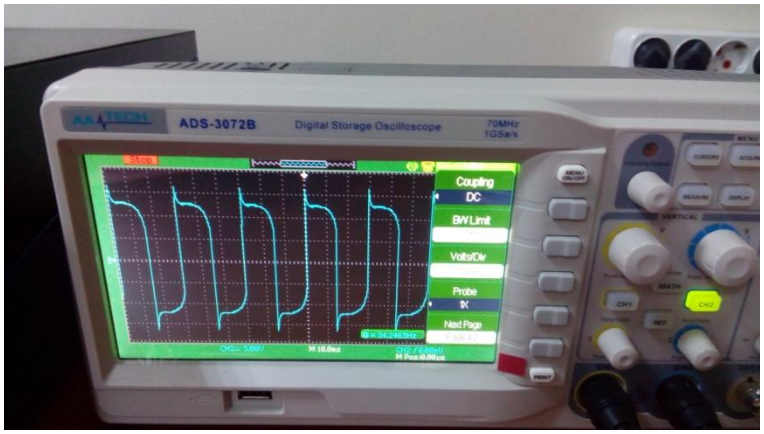

Figure 4.20 Voltage waveform on the oscilloscope for resistive load.

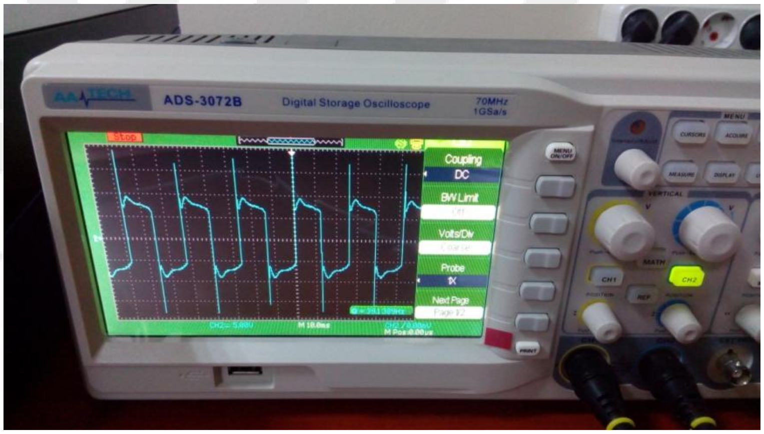

Figure 4.21 Voltage waveform on the oscilloscope for inductive load.

Similarly THD values of the output voltage affected by resistive and inductive loads were analyzed for showing the harmonics using Proteus Professional package program. In Figure 4.22, 4.23, and 4.24 are shown simulation results. In Figure 4.25 is shown experimental result of the harmonic measurement under laboratory conditions using FLUKE 435 Power Analyzer.

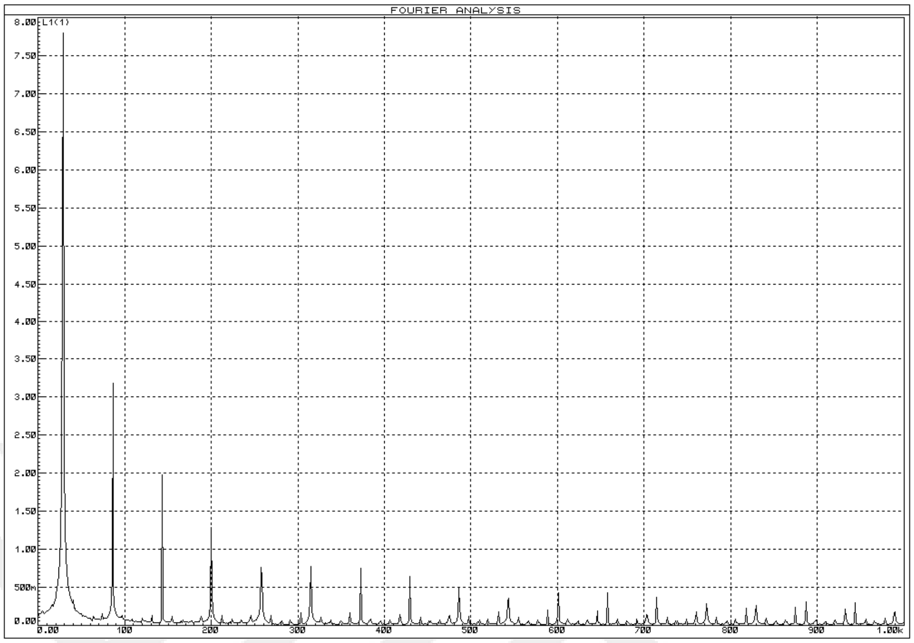

Figure 4.22 THD voltage analysis without load.

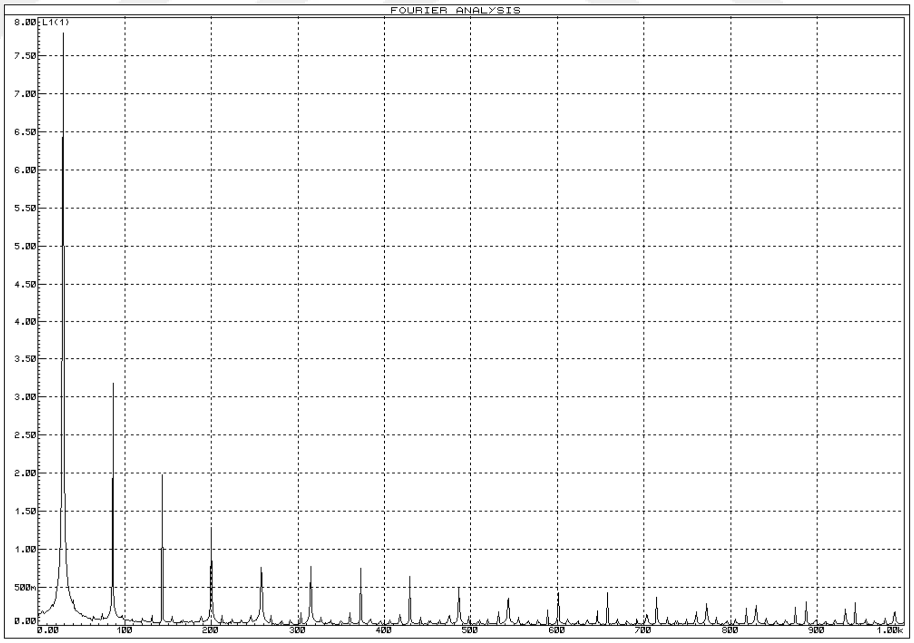

Figure 4.23 THD voltage analysis for resistive load.

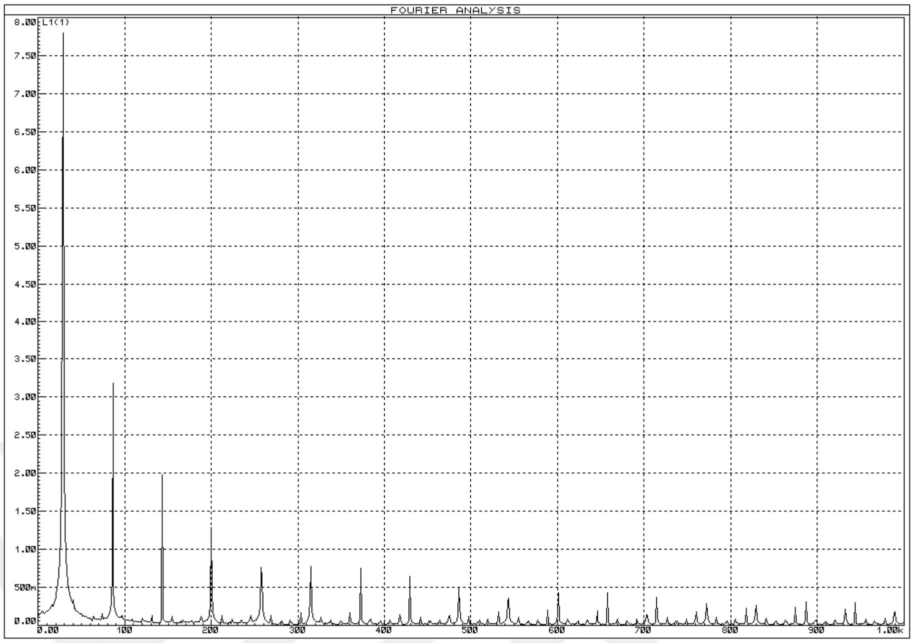

Figure 4.24 THD voltage analysis for inductive load.

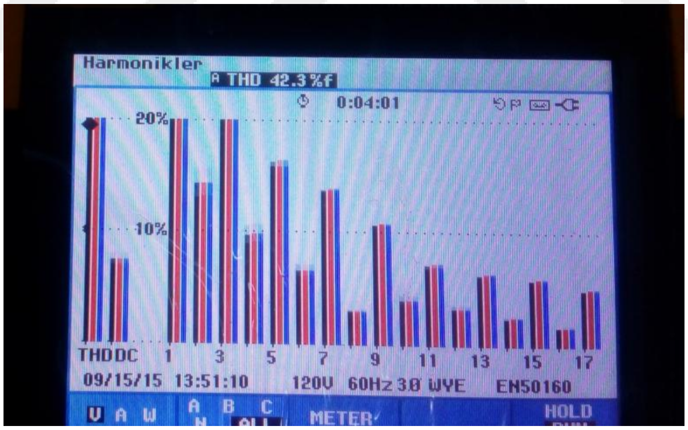

Figure 4.25 THD voltage measurement using FLUKE 435 Power Analyzer.

4.2.3 Analyze Results of the True Sine Wave Inverter Circuit

In Figures 4.26, 4.27, and 4.28 we can see voltage waveform simulations using Proteus Professional package program without load, with resistive load and inductive load for true sine wave inverter circuit respectively.

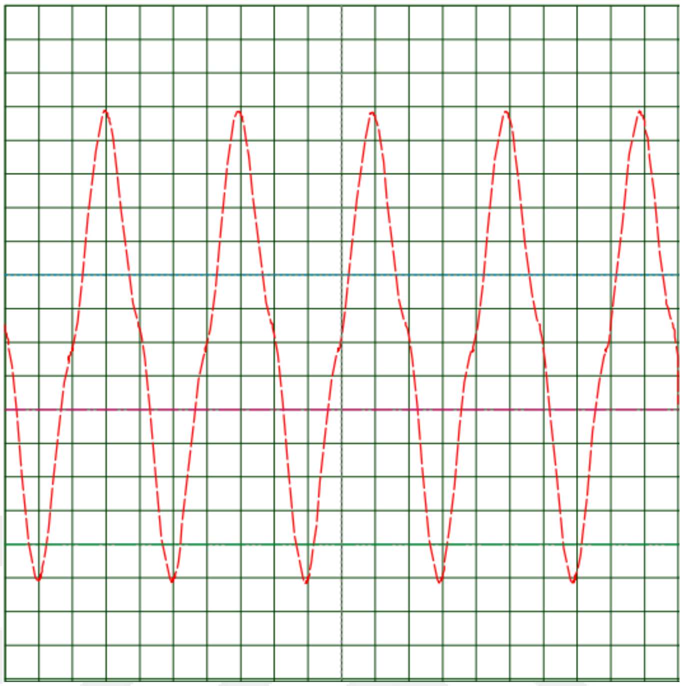

Figure 4.26 Voltage waveform without load.

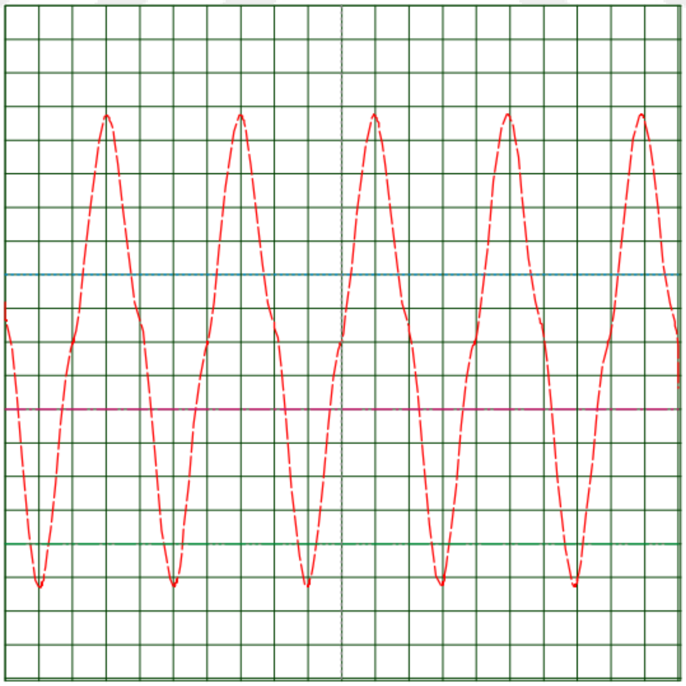

Figure 4.27 Voltage waveform for resistive load.

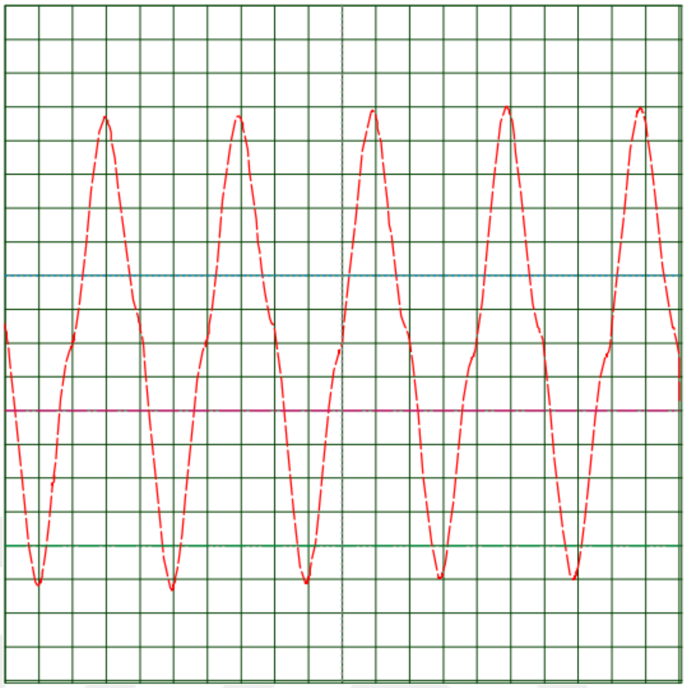

Figure 4.28 Voltage waveform for inductive load.

In Figure 4.29, 4.30, and 4.31 are shown voltage waveforms on the oscilloscope of the true sine wave inverter without load, with resistive and inductive loads. We can notice from the related Figures that the simulation and experiment results confirmed to each other for the true sine wave inverter circuit.

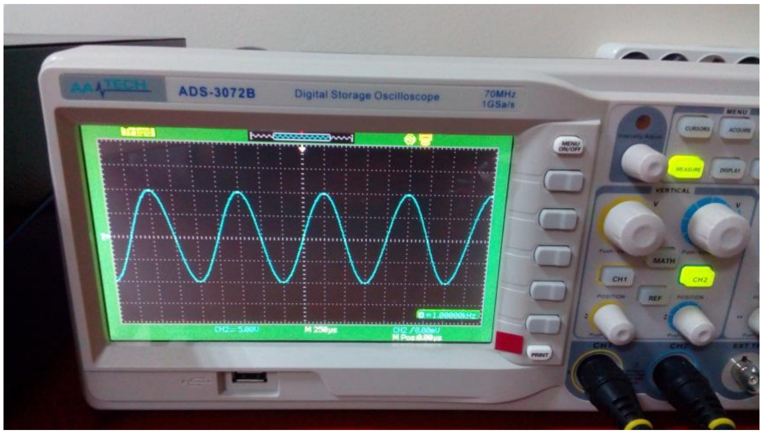

Figure 4.29 Voltage waveform on the oscilloscope without load.

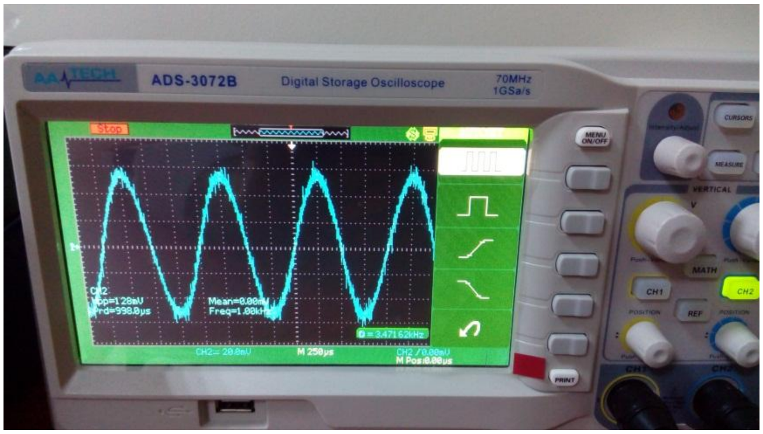

Figure 4.30 Voltage waveform on the oscilloscope for resistive load.

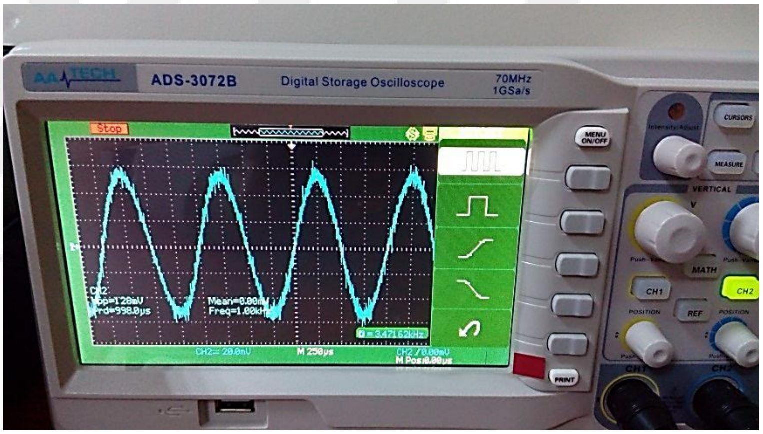

Figure 4.31 Voltage waveform on the oscilloscope for inductive load.

Similarly THD values of the output voltage affected by resistive and inductive loads were analyzed for showing the harmonics using Proteus Professional package program. In Figure 4.32, 4.33, and 4.34 are shown simulation results. In Figure 4.35 is shown experimental result of the harmonic measurement under laboratory conditions using FLUKE 435 Power Analyzer.

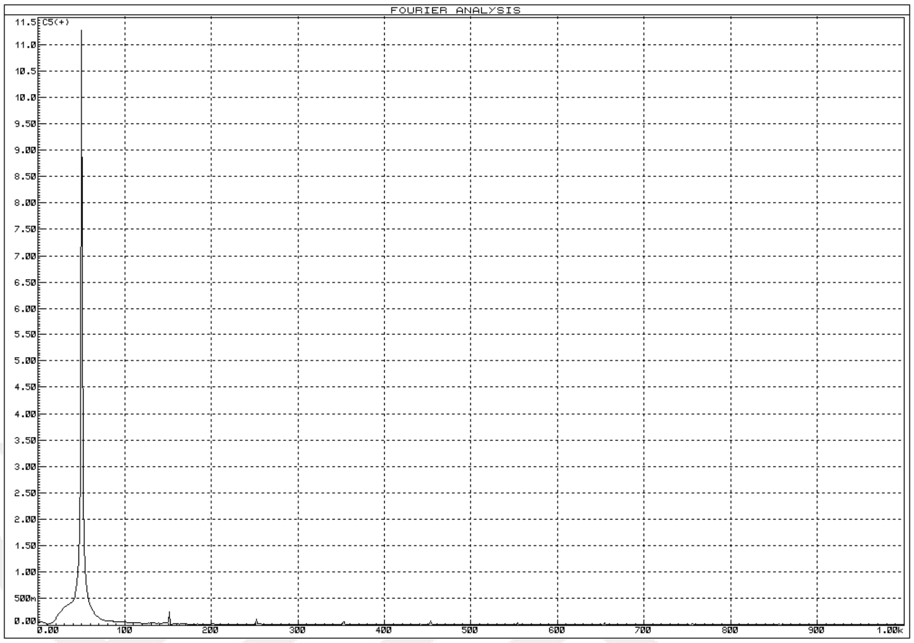

Figure 4.32 THD voltage analysis without load.

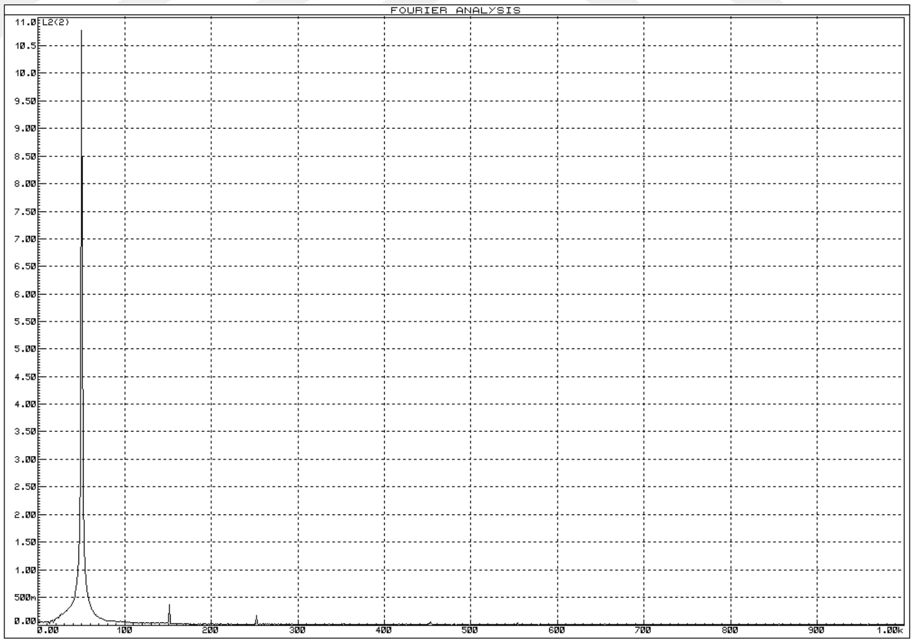

Figure 4.33 THD voltage analysis for resistive load.

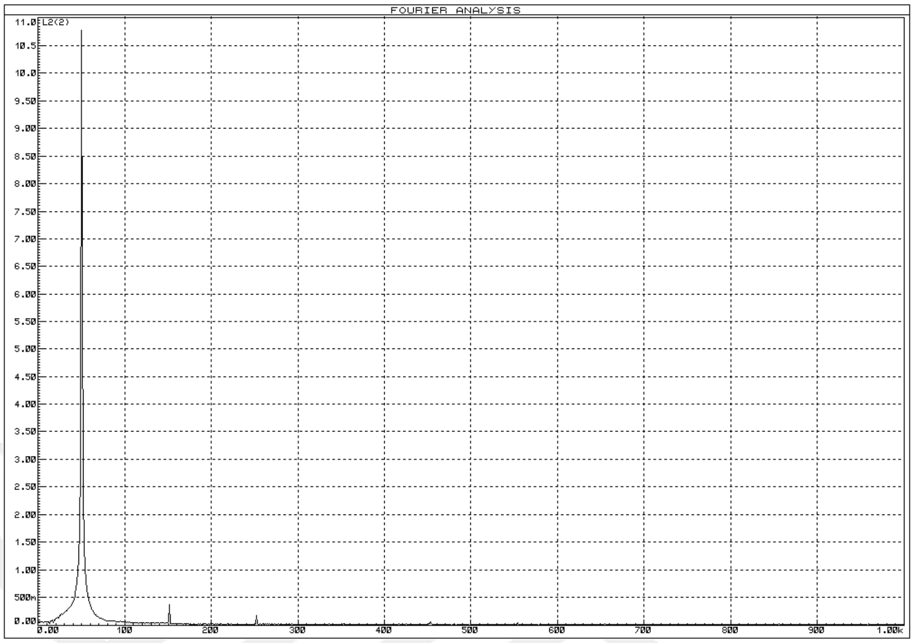

Figure 4.34 THD voltage analysis for inductive load.

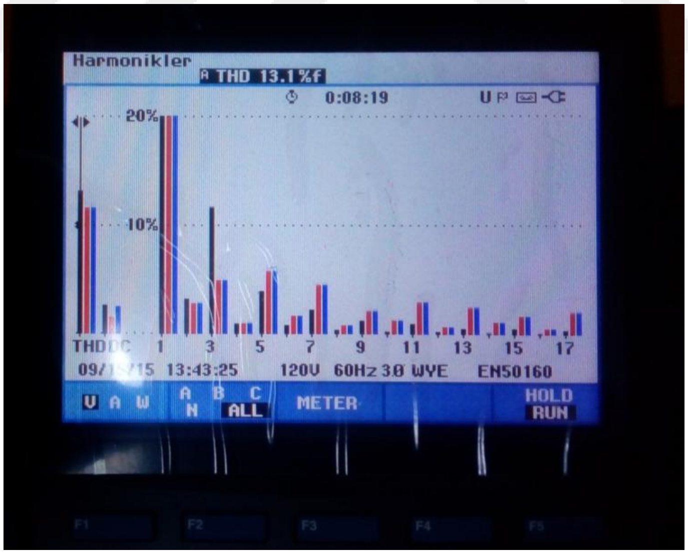

Figure 4.35 THD voltage measurement using FLUKE 435 Power Analyzer.

4.3 Hardware Implementations

Below in the following Figures are shown the implemented PCB (Printed Circuit Board) circuits for square wave, modified square and true sine wave inverters respectively. In

Figure 4.36 is the hardware implementation of the square wave inverter circuit. In Figure 4.37 is shown a lighted lamp as a driven load and in Figure 4.38 is the finished and covered inverter.

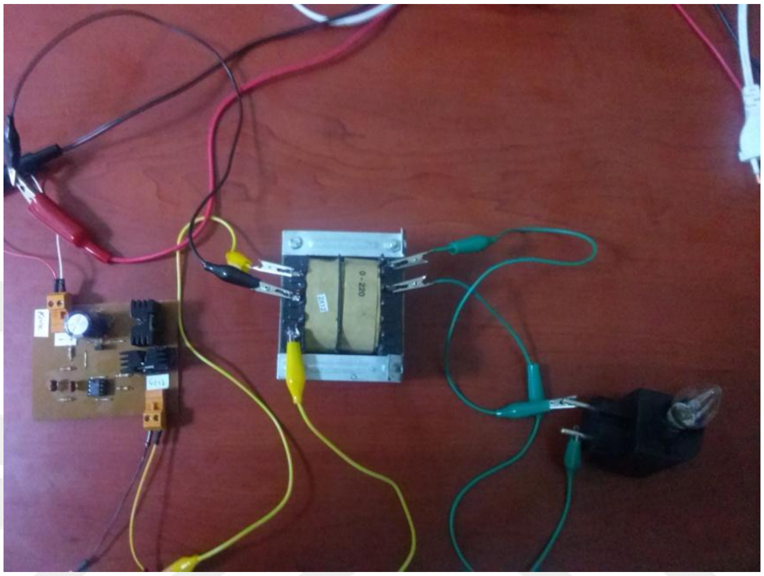

Figure 4.36 Hardware implementation of the square wave inverter circuit.

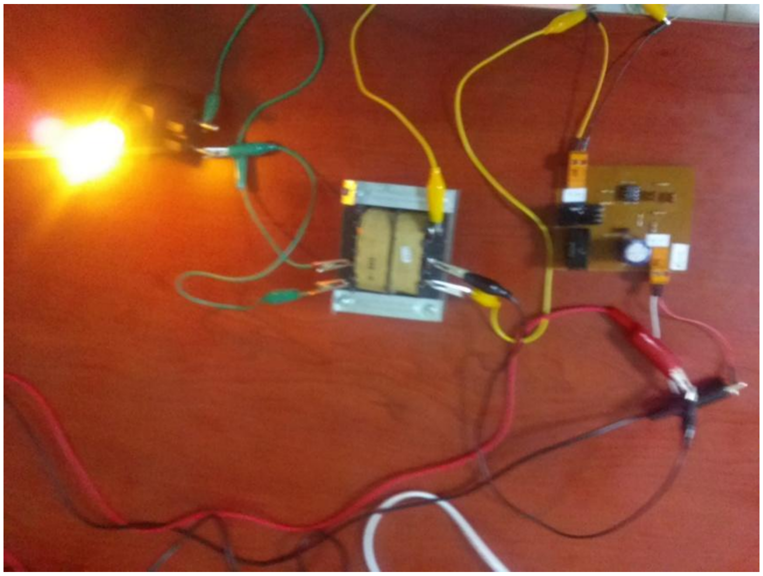

Figure 4.37 Lighted lamp as a driven load.

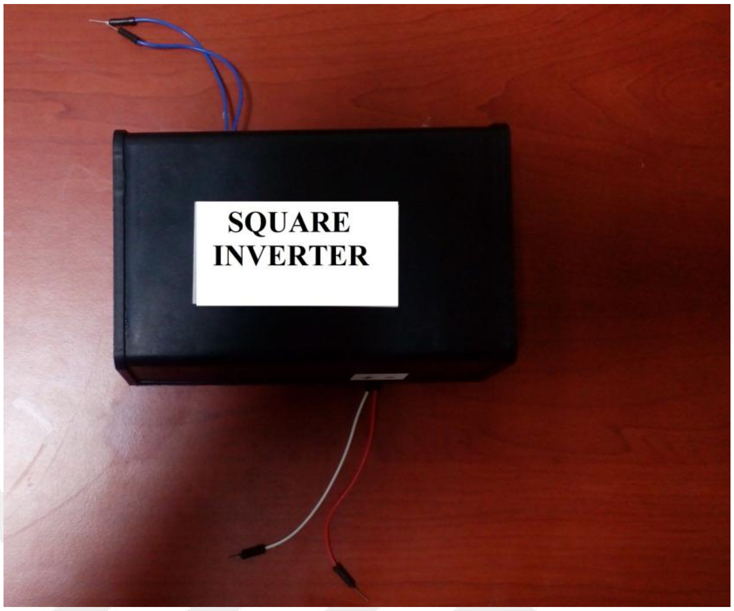

Figure 4.38 Finished and covered square wave inverter.

In Figure 4.39 is given the hardware implementation of the modified square wave inverter circuit. In Figure 4.40 can be seen a lighted lamp as a driven load and 4.41 is the finished and covered inverter.

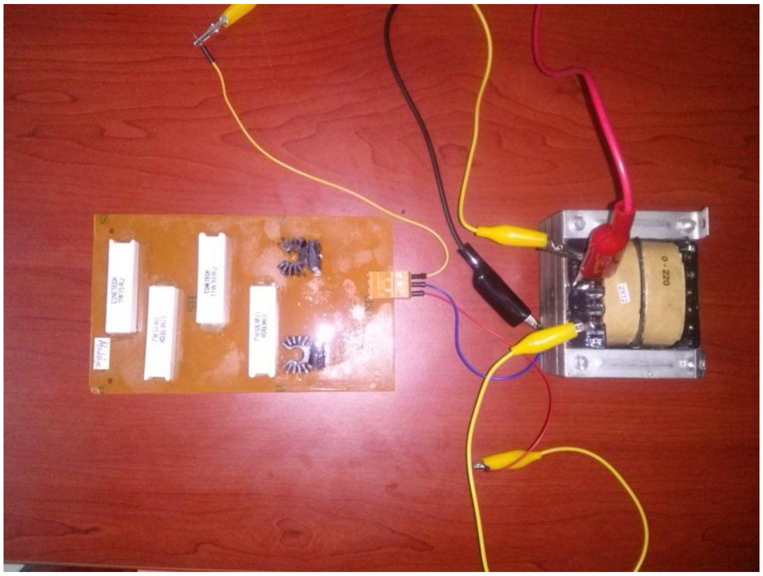

Figure 4.39 Hardware implementation of the modified square wave inverter circuit.

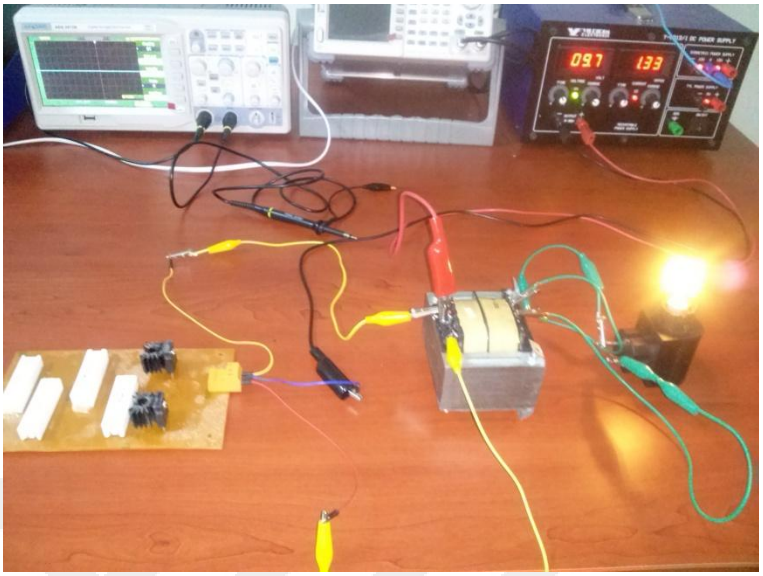

Figure 4.40 Lighted lamp as a driven load.

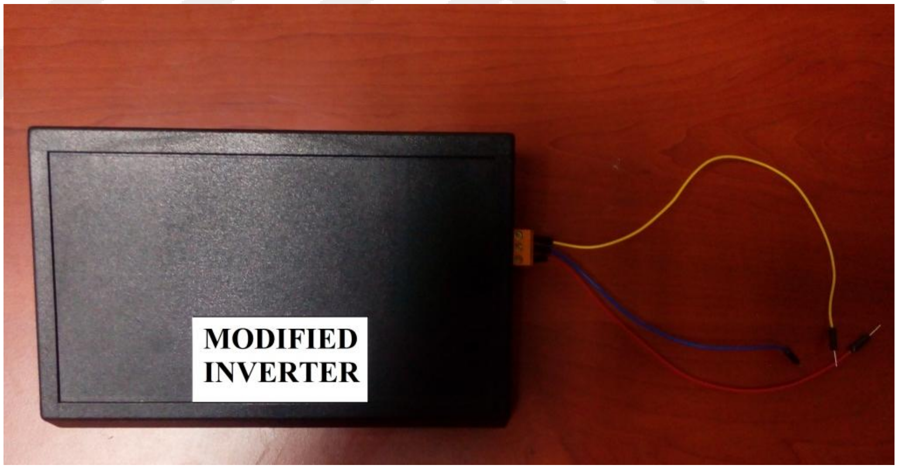

Figure 4.41 Finished and covered modified square wave inverter.

In Figure 4.42 is shown the hardware implementation of the true sine wave inverter circuit. In Figure 4.43 can be seen a lighted lamp as a driven load and in 4.44 is the finished and covered inverter.

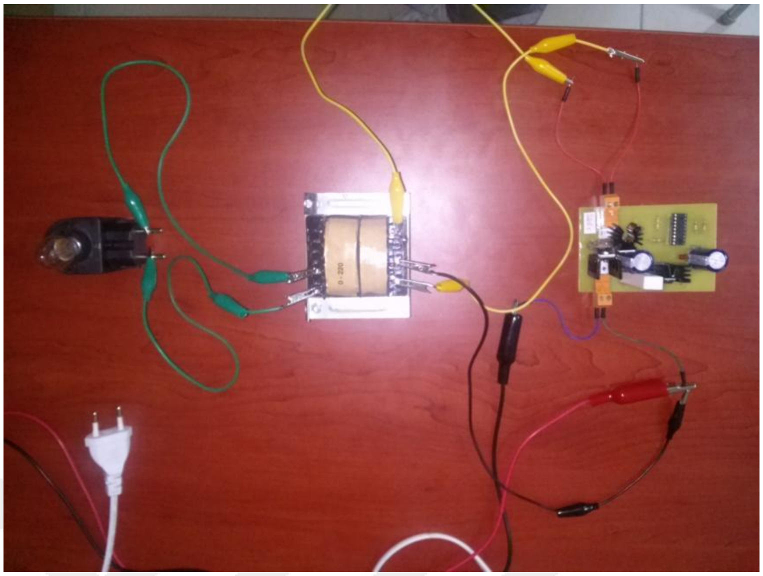

Figure 4.42 Hardware implementation of the true sine wave inverter circuit.

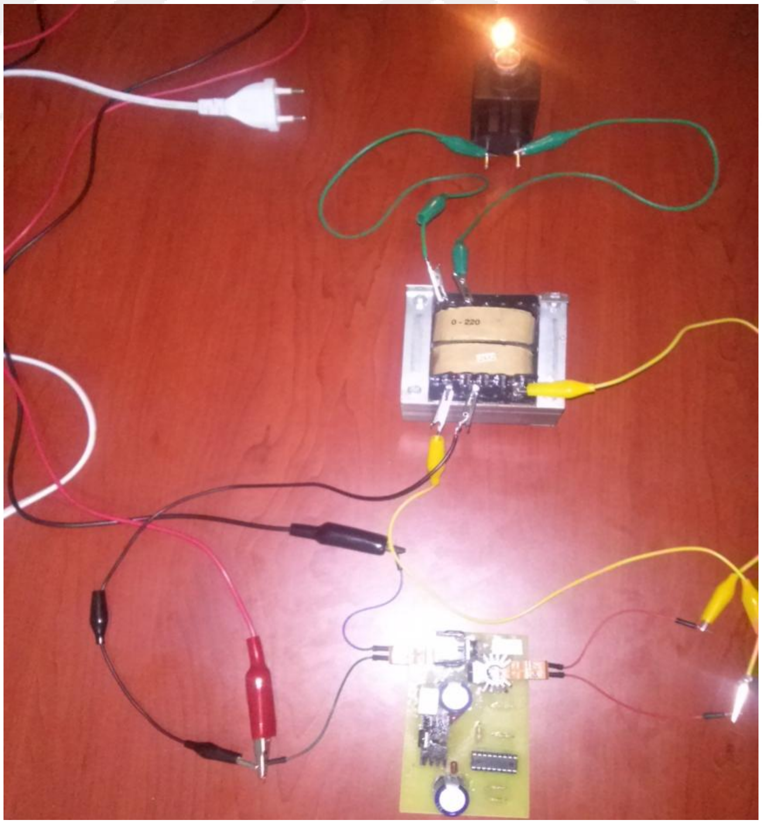

Figure 4.43 Lighted lamp as a driven load.

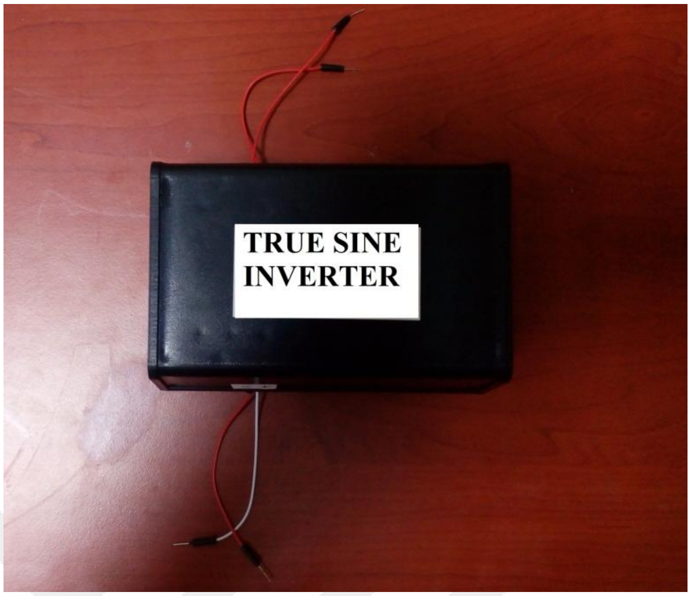

Figure 4.44 Finished and covered true sine wave inverter.

4.4 Efficiency and Harmonic Analysis

Related to the efficiency the analyzed inverters have been compared for the performance on a resistive load. As a resistive load 5W lamp used and input and output voltage-current values have been measured with the help of the Extech true RMS (Root Mean Square) digital multimeter. Input and output powers have been calculated using the following formula below.

$$P = V \times I \tag{4.2}$$

Where P is the output power, V is output voltage on the applied load and I is the current through the applied load. Using this formula the efficiency of the every implemented inverter circuit was determined.

After calculating of the measured values with the help of a digital multimeter, true sine wave inverter circuit has about 75% efficiency, modified square inverter circuit has more than 60% and square inverter circuit has about 45% efficiency. As a result true sine wave inverter circuit has the best efficiency among the inverter circuits. The related calculations were given below for a 5W resistive bulb load.

For the square wave inverter circuit the input voltage and current were measured 10.3V and 1A respectively. The observed output voltage and current under 5W resistive load are about 200V and 24mA. According to the power formula given in the equation 4.2, the input and output powers are calculated.

$\mathrm{Pin} = 10.3\mathrm{V} \times 1\mathrm{A}$ = 10.3W

$\mathrm{Pout} = 200\mathrm{V} \times 24\mathrm{mA}$ = 4.8W

The efficiency of the square wave inverter circuit is the ratio of the output power to the input power which is calculated as follows;

$\mathrm{Efficiency} = {}^{4.8\mathrm{W}}/_{10.3\mathrm{W}} \times 100$ = 46.5%

For the modified square wave inverter circuit the input voltage and current were measured 7V and 0.8A respectively. The observed output voltage and current under 5W resistive load are circa 200V and 17mA. The input and output powers are calculated as follows.

$\mathrm{Pin} = 7\mathrm{V} \times 0.8\mathrm{A}$ = 5.6W

$\mathrm{Pout} = 200\mathrm{V} \times 17\mathrm{mA}$ = 3.4W

The efficiency of the modified square wave inverter circuit is calculated as follows;

$\mathrm{Efficiency} = {}^{3.4\mathrm{W}}/_{5.6\mathrm{W}} \times 100$ = 60.7%

For the true sine wave inverter circuit the input voltage and current were measured 10.3V and 0.5A respectively. The observed output voltage and current under 5W resistive load are circa 200V and 19mA. The input and output powers are calculated as follows.

$\mathrm{Pin} = 10.3\mathrm{V} \times 0.5\mathrm{A} = 5.15\mathrm{W}$

$\mathrm{Pout} = 200\mathrm{V} \times 19\mathrm{mA} = 3.8\mathrm{W}$

$\mathrm{Efficiency} = {}^{3.8\mathrm{W}}/_{5.15\mathrm{W}} \times 100 = 73.7\%$

Besides efficiency comparison of the analyzed inverters, $\mathrm{THD_V}$ values at the output voltage were calculated by means of the FLUKE 435 Power Analyzer device for the square wave, modified square wave and true sine wave inverter circuits respectively with the help of the equation shown below. Between the simulation and experimental results there are only 2% or 3% differences in connection with the used devices and simulation program.

As mentioned before $\mathrm{THD_V}$, which is the ratio of the rms value of the harmonics (Hn) to the rms value of the fundamental frequency (H_1), can be calculated as follows;

$$\%\mathrm{THD} = \frac{\sqrt{\mathrm{H2}^2+\mathrm{H3}^2+\mathrm{H4}^2+\ldots+\mathrm{Hn}^2}}{\mathrm{H1}} \times 100 \quad \mathbf{(3.10)}$$

$\mathrm{THD_V}$ value of the output voltage form is calculated as shown in the previous chapter;

$$\%\mathrm{THD} = \frac{\sqrt{\mathrm{V2}^2+\mathrm{V3}^2+\mathrm{V4}^2+\ldots+\mathrm{Vn}^2}}{\mathrm{V1}} \times 100 \quad \mathbf{(3.12)}$$

$\mathrm{THD_V}$ voltage values for the analyzed square wave inverter with resistive and inductive loads are calculated respectively;

$$\%\mathrm{THD} = \frac{\sqrt{5^2+3^2+2.5^2+2.5^2+1^2+0.5^2+0.3^2}}{12} \times 100 = 55\%$$

$$\%\mathrm{THD} = \frac{\sqrt{5^2+3^2+2.5^2+2.5^2+1^2+0.5^2+0.3^2}}{12} \times 100 = 55\%$$

$\mathrm{THD_V}$ voltage values for the analyzed modified square wave inverter with resistive and inductive loads are calculated respectively;

$$\%\mathrm{THD} = \frac{\sqrt{3^2+2^2+1.5^2+1.5^2+1^2+0.5^2+0.2^2}}{12} \times 100 = 38\%$$

$$\%\mathrm{THD} = \frac{\sqrt{5^2+1.75^2+1.75^2+1^2+1^2+0.5^2+0.2^2}}{12} \times 100 = 39\%$$

THD_V voltage values for the analyzed true sine wave inverter with resistive and inductive loads are calculated respectively;

$$\%\mathrm{THD} = \frac{\sqrt{1^2+0.5^2+0.5^2+0.5^2+0.5^2+0.45^2+0.4^2}}{12} \times 100 = 9\%$$

$$\%\mathrm{THD} = \frac{\sqrt{1^2+0.5^2+0.5^2+0.5^2+0.5^2+0.5^2+0.45^2}}{12} \times 100 = 12\%$$

As it can be seen clearly from the circuit analyses including both simulations and labor experiments, THD_V at the output voltages with resistive and inductive loads for the analyzed true sine wave inverter circuit are considerable low while they have higher THD_V with resistive and inductive loads that can cause many devices to fail or working not well. True sine wave inverter circuit has at the same time higher efficiency related to the output power in compare to the other inverter circuits. This is another advantage of the true sine wave inverters on the square and modified square inverters.

4.5 Comparison of the Analyzed Inverters

An inverter takes DC power from standby sources such as solar panel and converts it into alternating current (AC) power for operating electronic devices. The easiest AC output wave form is a square wave in which the voltage changes from positive to negative, back and forth. This wave form has a lot of THD_V and results in poor operation of almost any AC loads.

As it can be seen in the previous Figures of the simulation results, square wave inverters have the highest THD_V (about 55%) which is not suitable for operating of many sensitive devices. The idle power draw which is the consumption of the inverter during its operation is relatively high because of two-level form. Likewise switching losses in square wave inverters are the most one compared to the modified square wave and true sine wave circuits because of this properties.

Square wave inverters are the cheapest to make, but the hardest to use. They flip the voltage from plus to minus generating a square waveform. They are not very efficient because the square wave has a lot of THD_V at the output signal, it cannot be used by many appliances. Synchronous motors, for example, need the 50Hz fundamental frequency and turn the rest of the frequencies into heat. These higher frequencies at the output voltage, called harmonics, can cause buzzing or other problems with some devices. Modern appliances such as sensitive medical devices will not run on square wave inverters. The main advantage of these inverters is the simplicity and low cost. Because of these drawbacks, no square wave inverters are being manufactured today.

Modified square wave inverters are better than square wave inverters in many aspects. The addition of an off time between the positive and negative pulses of the square wave greatly reduces the THD_V (about 38%). And the shape of the wave form also can be controlled to allow regulation of the AC output voltage level as the battery's voltage changes. Modified square pulses are tall and narrow when the battery voltage is high, but become short and wide when the battery voltage is low. This brings about a stabile average voltage given to the AC loads, and increases load compatibility and performance. However, more sensitive loads, such as variable speed motors on some hand tools and appliances may still operate incorrectly, overheat, and can be damaged from this type of wave form.

All of the inexpensive inverters and some of the affordable off-grid and mobile inverters generate this type of AC wave form. This wave form cannot be used for grid-tied inverters as the THD_V does not meet the utility grid requirements.

True sine wave inverters generate a wave form that closely matches that is supplied by a utility grid. Some of them are able to provide AC power that is better controlled and has lower THD_V (about 10%) than utility power. To make this wave form, a true sine wave inverter generates hundreds of positive and negative pulses for each AC cycle. These pulses are then filtered into a smooth sine wave shape.

Most true sine wave inverters are able to adjust the duration and timing of each pulse by using very fast digital electronic circuits and/or microprocessor control. This allows the voltage and frequency to be well regulated, ensuring that any AC load within the inverter’s power limits will operate properly.

A sine wave is what we achieve from the local utility grid. This is because it is produced by rotating AC machinery and sine waves are a natural product of rotating AC machinery. This is the most desired waveform, as it has the shape of an ideal AC electrical signal from the grid. The major advantage of a sine wave inverter is that all of the equipment which is offered on the market is designed for a sine wave. This makes sure that the equipment will work to its full limitations.

Some appliances, such as motors and microwave ovens will only provide full output with sine wave power. True sine wave inverters are applied mostly to drive sensitive electronic devices that need high quality waveform with little harmonic distortion. In addition, they have high surge potential which means they are able to passes over the rated wattage for a limited time. This makes power motors to start easily which can draw up to five times their rated wattage during startup.

Essentially any electronic device is able to being operated with the output from a true sine wave inverter. A few appliances, such as bread makers, light dimmers, and some battery chargers need only a true sine wave to operate fully. True sine wave inverters are always the most expensive type of inverters compared to the other type of inverters.

Related to the costs of the single phase power inverters, square wave inverters are the cheapest due to the simple circuit structures and lowest component requirements. Modified inverters are cost-effective type of inverters and but more expensive than square wave inverters. True sine wave inverters are the most expensive due to the complex circuit structure. In our thesis analyzed inverters prices are not different from each other because of the low power ratings compared to the commercial inverters.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

In this thesis, comparative analysis of single phase power inverters regarding their output waveforms was performed. Square wave, modified square wave and true sine wave inverter circuit’s simulations were done by Proteus Professional package program. This comparison was fulfilled with respect to the circuit configuration, voltage harmonics and output efficiency. After simulation results these inverter circuits were realized on PCB and experiments were carried out under laboratory conditions for resistive and inductive loads.

According to the simulation and experimental results, square wave inverter circuit has the more than 55% THD_V and circa 45% efficiency. They are used only for some industrial applications, since it is not acceptable to have an output voltage with high THD_V. Square wave inverter circuit is the simplest and the least expensive type of inverters, but it produces the lowest quality of power.

Modified square wave inverter circuit has better THD_V with about 38% than square wave inverter and better efficiency value of about 60%. For many electronic devices that do not require sensitive power, modified square wave inverters are more cost-effective option. Due to their many advantages they are widely used in most applications today.

True sine wave inverter circuit has the best THD_V circa 10% and highest efficiency about 75%. True sine wave inverters provide clean and stable power like the utility grid and are able to drive all the applications that are sensitive to AC voltage. Their only drawbacks are the high-cost and circuit complexity.

The main objective of this thesis is to provide a general notion to readers who are interested in comparative analysis of the single phase power inverters regarding their output waveforms. The future work includes improving the stability of the system and to study various topologies for achieving higher efficiency.

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