DEVELOPMENT OF A MICROCONTROLLER-BASED PURE SINEWAVE INVERTER FOR SOLAR ENERGY HARVESTING APPLICATION

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronics Engineering Technology (Industrial Electronics) with Honours

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DEDICATION

This thesis is dedicated to the people who have assisted me throughout my studies. Thank you for making me see this journey through to the end.

ABSTRACT

The development of a microcontroller-based pure sine wave inverter for solar energy harvesting primarily focuses to meet the demand for efficient and reliable energy conversion in renewable energy systems. This project aims to develop and construct a pure sine wave inverter utilising a microcontroller that transforms DC current from solar panels into AC power suitable for residential use. The inverter is built with two single-phase H-bridge inverter circuit with present-day Pulse Width Modulation (PWM) technologies, namely Sinusoidal PWM (SPWM), to lower harmonic distortion in the waveform and increase the quality of the electricity. Passive filters have been implemented to the circuit design to enhance the output waveform purity. The project met its goal of developing a cost-effective, efficient, and dependable inverter system capable of delivering high-quality AC output. The findings show that this technology has tremendous potential for use in household and commercial solar energy systems, contributing to sustainable energy solutions and lowering reliance on nonrenewable energy sources. Future development will concentrate on increasing the system's scalability, incorporating smart grid capabilities, and investigating commercialization prospects to fulfil the growing need for renewable energy technology.

ABSTRAK

Pembangunan inverter gelombang sinus tulen berasaskan mikropengawal untuk penuaian tenaga suria terutama menumpukan untuk memenuhi permintaan bagi penukaran tenaga yang cekap dan boleh dipercayai dalam sistem tenaga boleh diperbaharui. Projek ini bertujuan untuk membangun dan membina inverter gelombang sinus tulen menggunakan mikropengawal yang mengubah arus DC daripada panel solar kepada kuasa AC yang sesuai untuk kegunaan kediaman. Inverter ini dibina dengan litar inverter jambatan-H fasa tunggal dengan teknologi Modulasi Lebar Denyut (PWM) masa kini, iaitu Sinusoidal PWM (SPWM), untuk mengurangkan distorsi harmonik dalam bentuk gelombang dan meningkatkan kualiti elektrik. Penapis pasif telah diterapkan pada reka bentuk litar untuk meningkatkan ketulenan bentuk gelombang keluaran. Projek ini mencapai matlamatnya untuk membangunkan sistem inverter yang kos efektif, cekap, dan boleh dipercayai yang mampu memberikan output AC berkualiti tinggi. Penemuan menunjukkan bahawa teknologi ini mempunyai potensi besar untuk digunakan dalam sistem tenaga solar domestik dan komersial, menyumbang kepada penyelesaian tenaga yang lestari dan mengurangkan kebergantungan kepada sumber tenaga tidak boleh diperbaharui. Pembangunan masa depan akan menumpukan kepada meningkatkan skalabiliti sistem, menggabungkan keupayaan grid pintar, dan menyelidik prospek pengkomersilan untuk memenuhi permintaan yang semakin meningkat untuk teknologi tenaga boleh diperbaharui.

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LIST OF SYMBOLS

C	-	Capacitance
A	-	Current
fc	-	Cutoff frequency
Hz	-	Hertz
μF	-	Microfarad
Ω	-	Ohm
%	-	Percentage
R	-	Resistance
$Vsine$	-	Sine wave voltage source
$Vtri$	-	Triangular wave voltage source
V	-	Voltage
Vs	-	Voltage source

LIST OF ABBREVIATIONS

AC	-	Alternating current
DC	-	Direct current
$FPGA$	-	Field Programmable Gate Array
$MOSFET$	-	Metal-Oxide-Semiconductor Field-Effect Transistors
$MPWM$	-	Modified Pulse Width Modulation
PV	-	Photovoltaic
Vpp	-	Peak-to-peak Voltage
PWM	-	Pulse Width Modulation
RC	-	Resistor-Capacitor
$SPWM$	-	Sinusoidal Pulse Width Modulation
THD		Total Harmonic Distortion

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CHAPTER 1

INTRODUCTION

1.1 Background

The conversion and control of electrical power in various energy systems is a topic of study in the field of power electronics. Power electronics has been a rapidly expanding industry for many years due to being well-developed, more trustworthy, and affordable components compared to traditional electronic components. The cost of power electronics components (PEC) is decreasing due to increased demand and manufacturing. Additionally, power electronics are generally proven as an efficient technology for harvesting electricity from renewable energy sources. Renewable energy is energy which can be derived from natural sources that are replenished at a higher rate than they are consumed [1]. As post-industrialised nations struggle with rising energy demands and actively look for affordable alternatives, renewable energy is one of the fastest-growing trends in these cultures. One possible source that is favoured over others because of accessibility, simplicity, little maintenance, and reliable functioning is solar energy [2]. Even though naturally harvesting Direct Current (DC), it is not suitable for all domestic, commercial, and industrial applications. Therefore, an inverter must be implemented to convert DC into alternating current (AC). The conversion is done by a single-phase full bridge inverter where four diodes are used in two pairs which are used as a switching device that generates a square wave AC output voltage on the application of direct current input by adjusting the switch turning ON and OFF based on the appropriate switching sequence [3]. The converted AC can be used for any load designed to be used as AC. The Pulse Width Modulation (PWM) is a technique which is characterised by the generation of constant amplitude pulses by modulating the pulse duration by modulating the duty cycle [4]. Analogue circuitry with the help of PWM allows the conversion to digital outputs based on microprocessors [5]. The general act of converting AC to DC is insufficient. The quality of the sine wave generated is essential to determine the functionality of electrical loads. Both are efficient, but SPWM is way more efficacious when it is compared to PWM as the output of SPWM has a lower Total Harmonic Distortion (THD). This elucidates the impression that SPWM maximises the inverter efficiency more than PWM [6].

SPWM serves as a common ground in the field of power electronics for power digitization, that allows the voltage pulse generation through power switching. Pulse width modulation inverters have been used in power electronics for a long time due to their simple circuitry and powerful control. The SPWM switching technique has become prevalent in industrial settings. It uses stable amplitude pulses that have different duty cycles each period to accurately regulate the inverter output voltage and decrease harmonics. SPWM is very popular for motor control and inverter applications because of its efficacy. With the rapid development of advanced power conversion devices, electronic equipment, computers, office automation, air-conditioning systems, and adjustable speed heating ventilation, the operating conditions have changed significantly, which can cause current distortion due to harmonics to increase significantly [7].

According to the Electric Power Research (EPR) in 1995, 35-40% of all electric power flows through electronic converters. This is expected to increase to 85% by the year 2010 [8]. All these devices are known as non-linear loads and become sources of harmonics. Loads can be categorised into linear and non-linear loads. Whether it is linear or non-linear depends on how it uses electricity from the mains power supply waveform. Ohm's law states that, for a linear load, the relationship between the voltage and current waveform is sinusoidal and that the current at any given time is proportional to the voltage. The following are some examples of linear loads: capacitors, motors, and transformers. When a load is non-linear, the impedance changes with applied voltages, and impedance changes mean that the current drawn by the non-linear load will not be sinusoidal even when connected with an alternating signal [9].

1.2 Tackling Global Issue Through Pure Sine Wave Inverter Project

The creation of a pure sine wave inverter powered by a microcontroller tackles important societal and global problems with energy access and sustainability. Worldwide, 759 million people, mostly in rural and developing areas do not have access to electricity [10]. Economic growth, healthcare, and education are all impacted by this absence. Furthermore, using non-renewable energy sources increases the effects of climate change and environmental deterioration. Integrating renewable energy systems, like solar or wind power, into the grid requires a pure sine wave inverter, which effectively transforms DC to AC power. This method provides a more stable power source, allowing modern electrical devices to function simultaneously inspiring further growth in renewable energy sources.

1.3 Problem Statement

Power quality challenges occur not solely in distribution networks, but also in renewable energy generation, especially during the conversion of direct current (DC) to alternating current (AC). The process is critical and is unable to performed without inverters. Microcontroller-based pure sine wave inverters play an important part in this process, turning the DC waveform into a pure sine wave AC output. Microcontroller-based inverters, as opposed to traditional inverters, allows the generation of a pure sine wave without the need for extra filters to smooth it out.

Analogue inverters usually generate a square wave which involves complex circuitry and comparators to almost resemble a sine wave. This leads to higher cost design and time-consuming procedures. Sine wave inverters generate a smooth, grid-like power waveform, making DC to AC conversion more efficient than square wave inverters simultaneously decreasing power waste. However, square wave outputs may generate harmonics and voltage spikes, which might have a detrimental influence on the operation of the AC motor [11]. Changing these structures requires reworking every aspect of the circuit, which results in greater costs and prolonged prototyping times, consequently there is limited flexibility [12]. The drawbacks of the system also include complex closed loop management, increased space requirements, and sophistication. In contrast, digital inverters, controlled by microcontrollers, can be easily reprogrammed for different functionalities, allowing for quick prototyping and adjustments through simple code modifications. This flexibility reduces both the time and cost associated with development and maintenance. Additionally, pure sine wave output from digital inverters ensures compatibility with a wide range of sensitive electronic devices, improving overall system reliability and efficiency.

In the face of climate change and its increasingly severe impacts, reliable access to electricity is critical, particularly during sudden emergencies when the power supply is cut off. For example, natural disasters such as floods often result in prolonged power outages, leaving communities without access to essential services like communication and healthcare. One of the most significant renewable energy sources nowadays is solar energy. Solar energy, which can meet demand for 83 to 94 percent of hours of uninterrupted electricity without energy storage, is overtaking other renewable energy sources like wind and solar, according to research published in "Nature Communications" [13]. In Malaysia, there are two ways for users to use solar energy: on-grid and off-grid. Home appliances can be powered by an on-grid solar system with enough energy, and any additional electricity can be supplied back into the grid using grid-tied inverters [14]-[16]. Solar panels can continue to generate electricity even when traditional power grids are down, providing a crucial lifeline in emergencies. Conventional backup systems, such as burning fossil fuels, are expensive, unreliable, and polluting. When fossil fuels are combusted, they release substantial quantities of carbon dioxide, a greenhouse gas, into the atmosphere. These greenhouse gases trap heat, resulting in global warming [17]. The creation of a microcontroller-based pure sine wave inverter for solar energy harvesting application provides a practical answer by producing dependable and affordable electricity. This technology is low-maintenance, environmentally friendly, and can be used as a temporary power source solution

1.4 Project Objective

This implementation is carried out because it has numerous objectives, including:

a) To develop a microcontroller-based SPWM algorithm to produce pure sinewave AC voltage for households.

b) To design and implement a single-phase inverter circuit for solar-to-AC power conversion.

c) To validate the system's functionality through extensive testing, with emphasis on waveform quality, conversion efficiency, and dependability.

1.5 Scope of Project

The scope of this project are as follows:

a) Development and implementation of sinewave pulse width modulation (SPWM) algorithms for producing a pure sinewave AC output using Arduino Due as microcontroller.

b) Design and simulate a single-phase full bridge inverter circuit.

c) Produce a single-phase inverter circuit prototype.

d) Analyze the inverter's efficiency, stability, and output waveform quality to verify it fulfils criteria for powering home appliances.

e) Evaluate the inverter's compatibility with domestic loads to provide reliable electricity for diverse appliances.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will detail the literature review, including all the research and writing associated with this study. This research incorporates all previously conducted research and related work. A greater level of explanation and understanding is required to complete and assess this field project.

The desire for efficient and dependable power conversion solutions has fueled the development of sine wave inverters, particularly in terms of renewable energy integration. Sine wave inverters play an important role in transforming DC power from sources such as solar panels into high-quality AC power appropriate for domestic use. This literature review examines the evolution, design principles, and performance characteristics of microcontroller-based pure sine wave inverters, highlighting their significance in supporting sustainable energy usage in modern homes.

2.2 Understanding the Global/Current Issue in Literature

The development of successful electricity conversion technology is critical in expanding worldwide energy needs and an evolution towards renewable energy sources. Pure sine wave inverters have become a significant component in this environment, outperforming modified sine wave and square wave inverters by producing cleaner, more reliable alternating current. This counts as an essential step for sensitive electrical devices and appliances, which require stable voltage and frequency to perform effectively and securely.

Microcontroller-based sine wave inverters that employ sine wave pulse width modulation (SPWM) algorithms offer accurate management and flexibility, improving power conversion reliability and efficiency. As more families and businesses employ renewable energy alternatives, such as solar panels, the demand for high-quality inverters increases. By converting absorbed solar energy into pure sine wave AC power, these inverters assist in decreasing energy losses, increase appliance lifetime, and encourage global sustainable energy consumption.

2.3 Design concept of a Full-Bridge Inverter Circuit

Full-bridge inverters are converters that convert direct current (DC) to alternating current (AC). Furthermore, these inverters are popular in DC-AC power conversion field as they can interface with a variety of applications, namely photovoltaic (PV) systems and uninterruptible power supply (UPS). Figure 2.1 depicts the basic circuit for a full-bridge converter that provides a square-wave output voltage to highlight the fundamental principle of inverters producing an alternating current output waveform. These converters include semiconductor switches, diodes, loads, and capacitors.

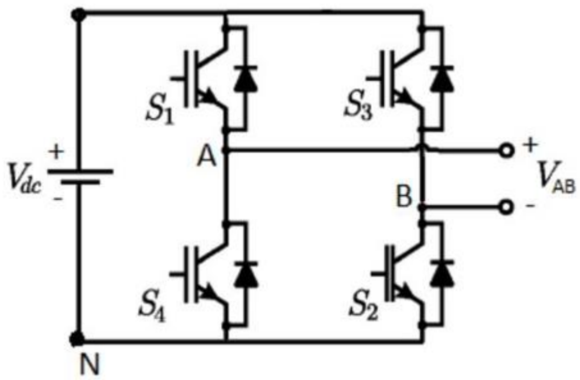


Figure 2.1: Single-Phase Full-Bridge Inverter circuit

The inverter circuit is divided into two phases by a switching system: phase 1, which consists of Switch 1 (S_1) and Switch 2 (S_2), and phase 2, which consists of Switch 3 (S_3) and Switch 4 (S_4). As a result, switches in phase 2 must be switched OFF while those in phase 1 are switched on, and vice versa. The switching processes for this inverter are as follows: S_1 and S_2 will be turned ON simultaneously to provide a positive voltage across the load, while S_3 and S_4 will be turned OFF. Meanwhile, S_3 and S_4 will be turned on concurrently to provide a negative voltage across the load, while S_1 and S_2 will be turned off [18]. Therefore, S_1 and S_4 or S_2 and S_3 should not be operated simultaneously since this will cause an inverter short circuit. Periodic switching between the positive and negative voltage of the load voltage results in a square wave voltage across the resistive load.

2.4 Square Wave, PWM, SPWM and MPWM switching techniques in single-phase Full-bridge inverter

Semiconductor switches can operate a single-phase full-bridge inverter by receiving gate switching signals such as square wave, pulse width modulation (PWM), or sinusoidal pulse width modulation (SPWM) switching techniques. Then, the only distinction between a square wave and a PWM signal is that a square wave has a constant ON and OFF period (50 per cent duty cycle), but a PWM signal has a variable duty cycle as well. Compared to a square wave switching technique, PWM switching can control the output voltage and frequency amplitude with less total harmonic distortion (THD) and a higher quality of the output waveshapes [19]. Especially compared to square wave switching, PWM switching can regulate the amplitude of the output voltage and frequency with less total harmonic distortion (THD) and a higher quality of the output waveshapes.

Sinusoidal PWM is a frequently used type of PWM. First, the sinusoidal AC voltage reference is quick compared to the high-frequency triangle carrier wave to determine the switching states of each pole in the inverter. Then each phase of the switches is turned on and off by a reference signal greater than the carrier voltage (S_1 and S_2 will be on). The carrier signal is greater than the reference voltage (S_3 and S_4 will be on) according to Figure 2.1 and the waveforms depicted below in Figure 2.2 [20].

Modified Pulse Width Modulation (MPWM) is more and less like SPWM, but the dead time or blanking time is being considered. Dead time must be considered because when switch 1 and switch 2 are operating, switch 3 and 4 need to be turned off. Otherwise, a short circuit would occur. Dead time resulted from a switching delay due to the gate driver. Therefore, the dead time should be considered, and the solution for it is to increase or decrease the rising or fall edge time to prevent switch 1 and switch 4 from working simultaneously [21].

Table 2.2: Difference between Square wave, PWM, SPWM and MPWM

Square wave	PWM	SPWM	MPWM
-Produces constant On and Off with a fixed duty cycle of 50%	-Variable duty cycle -Capable of controlling the amplitude of output voltage -The frequency with less THD	-Type of PWM (Sinusoidal Pulse width modulation) -AC sine wave is compared to triangular wave (high frequency) to produce switching frequency	- Similarly to SPWM, but the death time is being considered - Death time caused by gate driver switching delay -Microseconds in rising or falling edge of each switch is being added

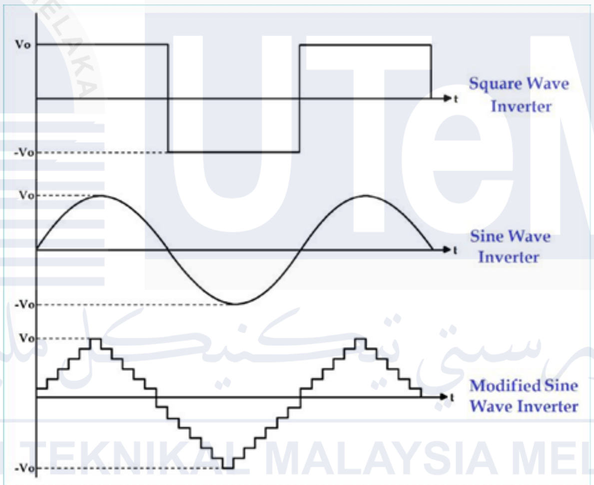


Figure 2.2: The difference between between Square wave, PWM, SPWM and MPWM output voltage waveform

The switches in phase 1 and phase 2, comprised of S_1: S_2 and S_3: S_4 in the same inverter, operate in a complimentary way, with one switch activated and the other switched off. Comparing the sinusoidal modulating wave with the triangular wave delivers two distinct gating signals. The comparison produces a switching frequency for Switch 1 and 2. This switching frequency is then inversed by using a logic gate called not gate to produce switching frequency for Switch 3 and 4. When S_1 and S_2 operate together, it produces a positive signal which is the positive value of the input voltage. In the other hand, S_3 and S_4 produce a negative value of the input voltage. V_{AN} and V_{BN}

represent the terminal voltages of the inverter, and the inverter output voltage is equal to V_{AN} minus V_{BN}, as depicted in Figure 2.3. Since the V_{AB} waveform alternates between positive and negative DC voltages, this method is known as bipolar PWM [22].

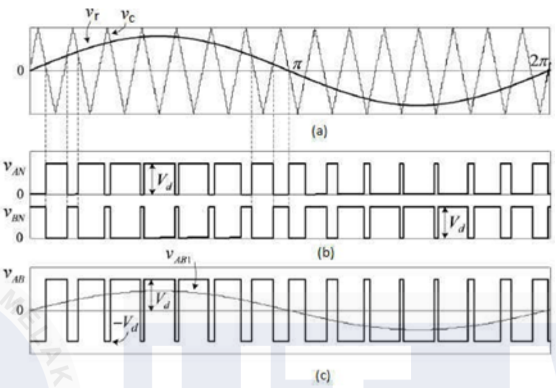


Figure 2.3: Bipolar SPWM switching technique

2.4.1 Unipolar SPWM Technique

The unipolar SPWM modulation, also known as three-level modulation, is utilized instead of bipolar SPWM to reduce THD. Besides that, THD voltage level should be less than 5% for ordinary devices, 5% to 8% for significant harmonic distortion and greater than 8% is considered as high harmonic distortion. Unipolar modulation typically requires two sinusoidal modulating waves, reference sinewave 1 and reference sinewave 2, which are identical in size and frequency. Still, the second reference sinewave is 180 degrees out of phase. The two modulating waves are compared to a triangular carrier wave to produce two gating signals (VS_1 and VS_3) for the upper two switches. In contrast to bipolar PWM, in which all four devices are switched simultaneously, unipolar PWM does not switch the upper two devices [23]. Meanwhile, the output frequency of the input is equal to these reference sine waveforms. Therefore, the magnitude of the output can be varied by controlling the modulation index of the sine wave reference waveforms. While (S_1: S_4) operated by referring to the first positive sine wave reference waveform and (S_2: S_3) operated by referring to the second negative sine wave reference waveform. In addition, the unipolar SPWM reference, triangle, switching, and output waveforms are shown in Figure 2.4 and Table 2.2.

Table 3.2: Operating of switches in the inverter

Switches	State	Operation
S_1	On	$V_{sine} > V_{triangle}$
S_2	On	$-V_{sine} < V_{triangle}$
S_3	On	$-V_{sine} > V_{triangle}$
S_4	On	$V_{sine} < V_{triangle}$

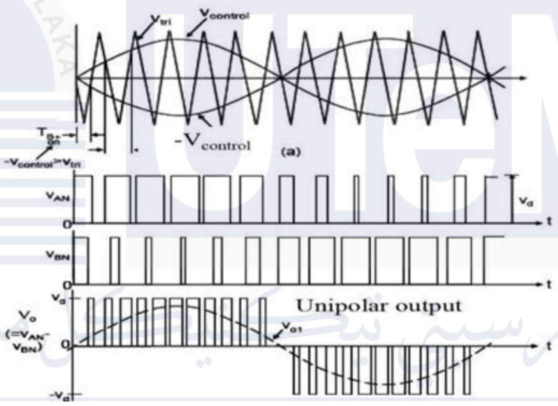


Figure 2.4: Unipolar SPWM switching technique

Table 2.3: Summary of bipolar and unipolar

Aspects	Unipolar PWM	Bipolar PWM

Voltage range	0 to positive	Positive to negative
Typical applications	Systems requiring a voltage range between zero and a positive voltage level	Systems requiring a voltage range between positive and negative voltage levels
Type of wave used to	Two sine waves are used but one has 180° with the same frequency and magnitude. One triangular wave is used for higher frequency	One sine wave and one high-frequency triangular wave (carrier wave)
Switching frequency for S_1 and S_2	1st Sine wave and carrier wave are compared to generate switching frequency	Sine wave is compared to carrier wave (triangular wave) to produce switching frequency
Switching frequency for S_3 and S_4	2nd sine wave and carrier wave are compared to generate switching frequency.	The switching frequency of S_1 and S_2 is inversed using a not-gate to produce frequency for S_3 and S_4

2.5 Total Harmonic Distortion (THD)

Total Harmonic Distortion (THD) is a key indicator for determining signal quality, especially in the context of inverters. THD quantifies the departure of a waveform, typically a sine wave, from its ideal shape caused by the presence of harmonics. When represented as a percentage, it is the ratio of the sum of all harmonic frequencies to the power of the primary frequency [24]. Higher THD values indicate more distortion. This may interfere with the operation of associated electrical equipment. THD has a vast range of effects on sine waves. For example, increased heat production, poorer efficiency, and increased electromagnetic interference, that might cause potential harmful effects on the reliability and safety of inverter-powered items [25]. THD can be possibly be lowered down as there are plenty of solutions to this problem, including the usage of filtering components, namely capacitors and inductor. Additionally, pulse-width modulation (PWM) techniques for waveform quality control and well-planned system design reduce the total harmonics produced [26]. Notably, it is important to have an accurate component selection and to conduct frequent services to ensure the industry standards are being adhered. Hence, this is also a critical step to ensure the overall performance of the inverter are functioning as desired.

2.6 Passive filters in circuits

A filter is a critical electronic circuit or component that selectively passes desired frequencies of an electrical signal while attenuating or blocking undesirable frequencies [27]. The primary function of a filter is to adjust the frequency response of a signal facilitating duties like noise reduction, signal conditioning, and frequency separation within a circuit. Passive filters offer various advantages, including functionality, low cost, and durability. It employs the usage passive components like as resistors, capacitors, and inductors. [28]. They are used in a variety of applications, such as audio processing, power supply filtering, and RF communication [29]. Passive filters have properties such as cutoff frequency, bandwidth, and roll-off rate that influence their filtering efficacy. Their effects on a circuit include impedance matching, signal attenuation, and phase shifting.

2.6.1 Cutoff frequency in RC filters

The cutoff frequency of RC filters, a crucial threshold in signal processing algorithms, indicates when the filter changes from passing to attenuating frequencies[30]. The frequency, indicated by fc, indicates exact calibration of resistive and capacitive components inside the circuit. At , commonly described as the frequency where the output signal strength decreases to half its highest value, the interaction between resistance (R) and capacitance (C) is visible in the elegant equation $fc = \frac{1}{2\pi RC}$. This critical parameter not only determines the filter's bandwidth and capacity to distinguish between desirable and unwelcome signals, but it also acts as a primary design factor for designing filters for specific applications [31].

2.7 Comparisons with related works

This section provides a comprehensive analysis of our study with comparable publications in the area, highlighting both similarities and differences. By examining these similarities, a full knowledge of the unique contributions and prospective areas of additional exploration are presented.

2.7.1 Design and Real-Time Implementation of SPWM based Inverter [32]

This study looks at the design and execution of a 1kW SPWM (Sinusoidal Pulse Width Modulation) inverter that converts DC from a photovoltaic array to 220V, 50Hz AC.

The inverter uses a low-cost 16-bit PIC microcontroller to generate high-frequency SPWM, which allows for the use of smaller capacitors and inductors for smooth sine wave output. The SPWM code was written in MPLAB and simulated with Proteus software, and the real-time implementation was tested on a resistive load with results shown on an LCD. High-frequency SPWM is noted for its increased efficiency, lower harmonic distortion, and smaller passive components, which results in a more compact and reasonably priced design. The precision of modern microcontrollers improves performance and dependability. However, problems include sophisticated microcontroller programming and probable electromagnetic interference (EMI), which necessitate thoughtful design. Although models and testing can provide useful data on performance, they may not adequately address long-term stability and environmental implications. This study shows the benefits and challenges of modern photovoltaic inverters.

2.7.2 Design of a single-phase SPWM inverter application with PIC micro controller [33]

In recent research, a single-phase full-bridge inverter was created to look into the harmonic content of unipolar and bipolar voltage switching methods using Pulse Width Modulation (PWM). The system relied on a PIC16F877 microcontroller to create sinusoidal control signals and maintain inverter parameters. The study used a PIC-based control strategy to reduce total harmonic distortion while also developing a small, economical, and extremely reliable inverter system. The control interface was created with an LCD display coded in PIC Basic Pro. The working principles and circuit designs of the intended system were thoroughly investigated, demonstrating that including software algorithms for scalar control, ramp function, and parameter regulation significantly improved the inverter's operation.

2.7.3 FPGA-Based Electronic Pulse Generator for Single-Phase DC/AC Inverter [34]

The main objective of this project is to develop a sinusoidal pulse width modulation (SPWM) signal generator that can be utilised to control a full-wave power switch in a single-phase inverter using a Field Programmable Gate Array. The FPGA, which is known for its superior parallel processing capabilities, was employed to improve computing efficiency. FPGAs also provide advantages including more rapid processing, better flexibility, reduced power consumption, and smaller circuit footprints [35][36]. Quartus Prime 18.0 Lite Edition and ModelSim were used to describe and model SPWM generation units. The SPWM signal generator created sine and triangle waveforms using the Look-Up Table (LUT) method, which were saved in the FPGA's internal storage area. In a full-bridge configuration, the single-phase inverter utilised a MOSFET IRFP460 semiconductor switch. Before conducting practical testing on the inverter device, simulations were run using PSpice A/D Lite. It can be deduced that the system produced great results, with the FPGA control module operating at a high frequency of 100 kHz and an output voltage amplitude of 20V.

2.7.4 Design of SPWM control unit based on microcontroller for photovoltaic inverters [37]

The paper "Design of SPWM Control Unit Based on Microcontroller for Photovoltaic Inverters" describes a novel way for creating a digital Sinusoidal Pulse Width Modulation (SPWM) using a PIC16F876 microcontroller. This technique is particularly effective for controlling the DC/AC inverter output voltage in applications like solar pumping systems and motor drives. It greatly minimises frequencies and distortions. The method comprises turning a collected dc-biased sine wave signal into a sequence of pulses with sinusoidally varying widths. Because of the low hardware requirements, this strategy is simple, cost-effective, and dependable. However, it is restricted by the microcontroller's memory and processing capabilities. The researchers employed and evaluated several amplitude modulation indices ranging from 0.5 to 1.3 at a switching frequency of 1 kHz. Experimental findings confirmed the SPWM method's ability to maintain a constant output voltage amplitude, proving its suitability for dependable solar inverter operation under a range of environmental conditions. This study demonstrates a balanced technique for achieving excellent performance in solar energy applications.

2.7.5 Design and implementation of a Single-phase Bipolar SPWM Inverter Power Supply Based on STM32 [38]

This paper presents a digitally controlled single-phase bipolar SPWM inverter power supply was developed using an STM32 microcontroller. The STM32 served as the main controller, generating SPWM pulses for DC-AC conversion via a full-bridge inverter circuit. The final output waveform was obtained through a filter circuit. An A/D detection circuit provided real-time monitoring of output current and voltage, with the sampling circuit electrically isolated from the inverter output for enhanced safety. STM32 software programming facilitated input undervoltage protection and output overcurrent protection. Moreover, this system includes a display module and a keyboard module for improved user interaction. Under a 10Ω load, the system consistently produced a stable sine wave with a 1% error margin and achieved an efficiency of 94.40%. This system is characterized by its digital control, user-friendly interface, and high efficiency.

2.7.6 Design and Real-Time Implementation of Transformer-less Pure Sine-Wave Inverter [39]

This study discusses the constraints of standard photovoltaic inverters that use transformers, which are bulky, complicated, inefficient, and have been linked to the rise in total harmonic distortion (THD). To tackle these difficulties, the paper describes the design and immediate implementation of a 1kW transformer-less pure sine wave inverter. The inverter transforms a monitored 12V DC input from a solar panel to a standard grid output of 220V at 50Hz. The proposed two-stage system includes a DC/DC converter that transforms 12V DC to 320V DC, accompanied by a DC/AC inverter powered by a high-frequency Sinusoidal Pulse Width Modulation signal. The passive components in the circuit design then filters out the AC output voltage to produce a cleaner sine wave.

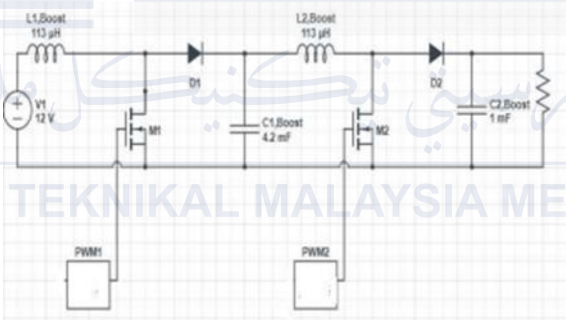


Figure 2.5 Circuit of a DC-DC Converter

2.7.7 DC-AC Inverter 220-230 VAC for Home Scale Photovoltaic Systems [40]

This research addresses the creation of a DC-AC inverter built for home-scale solar-powered electrical systems with an output of 220-230 VAC. The design follows standardised This study focuses on the development of a DC-AC converter designed for home-scale solar-powered electrical systems having an output of 220-230 VAC. The concept adheres to conventional Total Harmonic Distortion (THD) values, yielding high-quality power output.

Two pulse waveforms for switching power MOSFETs were studied: square wave pulse (SWP) and sinusoidal pulse width modulation (SPWM). The inverter generates the necessary pulse signals using a 36V DC supply and a microcontroller. To eliminate voltage harmonics induced by the switching process and provide a pure sine wave output, the design incorporates low passive filters and dampers. On the contrary, studies of SWP and SPWM using both simulation and experimental data demonstrate that the SPWM switching approach produces significantly lower THD percentages, highlighting its benefit in producing cleaner, more efficient AC power. This study emphasises the importance of complicated switching mechanisms and harmonic reduction measures in enhancing inverter performance for residential solar applications.

2.7.8 Microcontroller Based Pure Sine Wave Inverter [41]

The microcontroller-based pure sine wave inverter project aims to deliver a dependable 220V, 50Hz output using the sinusoidal pulse width modulation (SPWM) technique, with an emphasis on low power applications. This inverter offers various advantages, particularly low harmonic distortion, which enhances the quality of the output waveform and extends the life of connected loads. SPWM shifts harmonics to higher frequencies, making them easier to filter out while resulting in a more sinusoidal output than traditional square wave inverters. The project also emphasises the design's simplicity and cost-effectiveness, with a 12V battery input and IoT capabilities for remote monitoring and control that do not require expensive gear.

2.7.9 Design and Implementation of a Sine-Wave Inverter using Microcontroller with Modified Pulse Width Modulation Technique [42]

The paper concerns the key challenges of load shedding and rising power generation costs in Bangladesh by providing a low-cost modified sine wave inverter for photovoltaic systems. The proposed inverter type outperforms conventional push-pull inverters in terms of harmonic performance. It has a variety of protection features, such as high and low voltage protection, overload protection, and low battery protection, to ensure stable and dependable operation. The design has a feedback system that improves low voltage recovery at the output. With the addition of a small LCL filter, the simulation results reveal a total harmonic distortion (THD) of 56.11%, which is dramatically reduced to 0.08%. This significant improvement illustrates the efficacy of the proposed harmonic reduction strategy. To allow the confirmation of the simulation results, a single-phase laboratory prototype was built to show the practical usability and efficacy of the proposed inverter topology. This study stresses the viability of combining low-cost and highly reliable inverters into household solar energy systems, particularly in locations with inadequate electricity supply.

2.7.10 Highly efficient Pure Sine Wave Inverter Using Microcontroller for Photovoltaic Applications [43]

This work describes the design and evaluation of a high-efficiency single-phase sine wave inverter for photovoltaic (PV) applications. The PIC 18F4550 microcontroller emits pulse width modulation (PWM) pulses, which are subsequently channelled through a high-speed CMOS logic quad 2-input multiplexer to the H-Bridge load. This circuit design employs closed-loop system that allows the lowewring of waveform distortion, making it suitable for inductive and capacitive loads. The recommended inverter differs from conventional inverters as this inverter focuses on reducing harmonic distortion through a simple and practical design. Practical trials demonstrate its capacity to sustain sensitive AC loads, with a focus on applications requiring pure sine wave outputs. While the benefits, such as higher efficiency and decreased harmonic distortion, potential drawbacks include the complexity of integrating MPPT with the inverter and the requirement for precise control methods. Nonetheless, this novel technique enhances PV energy conversion and uninterruptible power supply (UPS) applications, leading to cleaner and more dependable power delivery. If the main electrical source does not work, the UPS unit offers a backup emergency energy source for any attached loads units. While many UPS systems produce uninterruptable power, they may not deliver a pure sine wave signal [44][45].

Table 2.4: Comparision with related works

No.	Author	Title	Description	Inverter	Microcontroller	Switching Technique
1.	Sundas Hannan Sohaib Aslam, Muhammad Ghayur (2018)	Design and Real-Time Implementation of SPWM based Inverter	This study investigates the design and execution of a 1kW SPWM (Sinusoidal Pulse Width Modulation) inverter that converts DC from a photovoltaic array to 220V, 50Hz AC. It uses 16-bit PIC microprocessor for high-frequency SPWM. Advantages: 1. Smaller passive components 2. Improved performance and dependability due to precise microcontrollers. Disadvantages: 1. Sophisticated microcontroller programming. 2. Potential electromagnetic interference (EMI), requiring careful design. 3. Models and testing may not fully address long-term stability and environmental impacts	Single-Phase Full-Bridge Inverter	PIC24FJ128GA010	SPWM Technique
2.	Yaşar Birbir, Kaner Yurtbasi, Volkan Kanburoglu (2019)	Design of a single-phase SPWM inverter application with PIC micro controller	This system configures PWM approaches studied harmonic content, enhancing functionality with software algorithms. Advantages:	Single-Phase Full-Bridge Inverter	PIC16F877	SPWM Technique

			1. Minimizes total harmonic content. 2. Smaller size for better portability Disadvantages: 1. Learning curve for PIC Basic Pro			
3.	Muhamad Rusdi Faizal Arya Samman Rhiza S. Sadjad (2019)	FPGA-Based Electronic Pulse Generator for Single-Phase DC/AC Inverter	This research intended to develop an SPWM signal generator utilizing an FPGA to control a single-phase inverter via a MOSFET IRFP460 switch. Modelling was done using Quartus Prime and ModelSim, and PSpice simulations yielded outstanding results at 100 kHz. Advantages: 1. Operates at high frequency allowing smoother output generation. 2. Excellent processing because it utilizes FPGA’s parallel processing. Disadvantages: 1. Sophisticated design due to FGPA involvement. 2. High cost.	Single-Phase Full-Bridge Inverter	Utilizes FGPA instead of microcontroller	SPWM Technique
4.	Abdennabi Brahmi et al. (2020)	Design of SPWM control unit based on microcontroller for photovoltaic inverters	The paper outlines how a PIC16F876 microcontroller generates digital SPWM to control DC/AC inverter output voltage, reducing harmonics and distortion in photovoltaic systems and motor drives. **Advantages** 1. Simple design. 2. Cost-effective.	Single phase full bridge	PIC16F876	SPWM Technique

			Disadvantages 1. Limited by microcontroller memory. 2. Limited by processing performance.			
5.	Jieling Lei Jiming Sa (2020)	Design and implementation of a Single-phase Bipolar SPWM Inverter Power Supply Based on STM32	An STM32-controlled single-phase bipolar SPWM inverter accomplished 94.40% efficiency and 1% error at a 10Ω load, integrating real-time monitoring, protection isolation, and an easy-to-use interface. Advantages: 1. High efficiency 2. It has protection features for input undervoltage and output overcurrent. Disadvantages: 1. Complex programming requires STM32 software expertise. 2. Specific load dependency due to the performance measured with a 10Ω load	Single-Phase Full-Bridge Inverter	STM32	SPWM Technique
6.	Sajid Sarwar et al. (2020)	Design and Real-Time Implementation of Transformer-less Pure Sine-Wave Inverter	This paper presents a 1kW transformer-less pure sine wave inverter converting 12V DC from a photovoltaic panel to 220V, 50Hz AC using a two-stage topology with SPWM control. Advantages: 1. Reduced weight as there is no transformer. 2. Easier installation.	Single-Phase Full-Bridge Inverter	PIC24FJ128GA010	SPWM Technique

			Disadvantages: 1. Potential electromagnetic interference (EMI).			
7.	Faizal Arya Samman Muhammad Aswan Andi Ejah Umraeni Salam (2021)	DC-AC Inverter 220-230 VAC for Home Scale Photovoltaic Systems	The research develops a DC-AC inverter for home solar systems, providing 220-230 VAC with low THD. Comparing SWP and SPWM techniques, it finds SPWM superior in reducing THD and producing cleaner AC power, using a 36V DC source, microcontroller, and passive filters. Advantages 1. Effective harmonic reduction with filters and dampers. 2. Clean and efficient AC power. 3. Suitable for home-scale solar systems. Disadvantages 1. Requires complex switching mechanisms. 2. Involves advanced harmonic reduction strategies.	Single-Phase Full-Bridge Inverter	Arduino Uno R3	SPWM Technique
8.	Nasim Ahmed Md. Ziaur Rahman Khan (2021)	Microcontroller Based Pure Sine Wave Inverter	The paper introduces a microcontroller-based pure sine wave inverter for a reliable 220V, 50Hz output using SPWM, focusing on minimal harmonic distortion and simplicity, with IoT integration for remote control. Advantages 1. Minimal harmonic distortion enhances output waveform quality. 2. Prolongs the lifespan of connected	H-bridge inverter	PIC16F72	SPWM Technique

			loads. 3. Emphasize simplicity and cost-effectiveness. Disadvantages 1. May have limited power capacity due to focus on low-power applications. 2. Complexity may increase with additional features like IoT integration.			
9.	Razibul Awal et al. (2022)	Design and Implementation of a Sine-Wave Inverter using Microcontroller with Modified Pulse Width Modulation Technique	The paper proposes a low-cost modified sine wave inverter for photovoltaic systems to address load shedding and rising power costs. It offers superior harmonic performance and protection features. Simulations show THD reduction from 56.11% to 0.08% with an LCL filter. Advantages 1. Low-cost solution. 2. High and low voltage protection. 3. Low battery protection. Disadvantages 1. Initial THD is high before filtering. 2. Requires an LCL filter for optimal performance.	H-bridge inverter	Atmega328	Bipolar-SPWM Technique
10.	Ahmed Badawi et al. (2023)	Highly efficient Pure Sine Wave Inverter Using Microcontroller for Photovoltaic Applications	The paper details the design and testing of a highly efficient single-phase sine wave inverter for photovoltaic (PV) applications, using a PIC 18F4550 microcontroller to generate PWM	H-bridge inverter	PIC18F4550	PWM Technique

			pulses and employing closed-loop control. It is suitable for both inductive and capacitive loads, focusing on reducing harmonic distortion with a simple design. Advantages 1. High efficiency. 2. Minimal harmonic distortion. Disadvantages 1. Complexity in integrating MPPT with the inverter. 2. Requires precise control methods.			

2.8 Gap of Study

The research component devoted to a gap analysis describes in depth the comparison between the proposed project and prior work described in other studies. The study gap is defined based on the system's performance and the application system used in prior research.

Table 2.6 shows the research gap between the planned study and existing studies conducted by other researchers. There is a comparison of switching techniques, inverter design, and microcontroller used. Based on Table 2.6, SPWM is the most used switching strategy due to its THD mitigation. Inverter improvements in technology are centered on enhancing reliability, effectiveness, and affordability. Microcontroller-based SPWM inverters continue to be popular because of their simplicity and low cost, as demonstrated in research by Brahmi et al. (2020) using the PIC16F876 and Ahmed et al. (2021) with the PIC16F72. These systems, however, have constraints in memory, processing capacity, and complexity when added capabilities such as IoT integration. Because of their parallel processing capabilities, FPGA-based inverters, as those developed by Rusdi et al. (2019), provide cleaner AC power with less harmonic distortion. Despite their benefits, FPGA designs are complicated and expensive. To address these problems, this study will optimize inverter control approaches for high-frequency, real-time applications utilizing FPGA technology, therefore improving performance and adaptability. Nonetheless, microcontrollers continue to be popular due to their low cost and simplicity, making them ideal for a wide range of practical applications.

CHAPTER 3

METHODOLOGY

3.1 Overview

The research approaches used for this project's procedure will be covered in this chapter. This chapter's main goal is to summarize the project's progress for each subcomponent. The following section will detail each project component, including how it was studied, examined, and compared with the PSIM simulation findings. This subtopic also describes how to ensure this project's efficient and successful completion.

This part explains the steps used to build a microcontroller-based pure sinewave inverter for solar energy harvesting. The project starts by selecting a microcontroller that is capable of handling sinewave pulse width modulation (SPWM), by focusing on processing power, the simplicity of programming used, and compatibility with SPWM algorithms. SPWM algorithms were then designed and implemented into the selected microcontroller to accurately regulate the inverter output. Additionally, a single-phase H-bridge inverter circuit was constructed employing MOSFET as the power electronic component. The inverter's performance was carefully verified, and the output waveforms were compared to the PSIM simulation results to confirm the design. A solar panel was added to the system, and its output was controlled to maintain a constant DC input for the inverter. Continuous testing and modification were used throughout the project to increase efficiency and performance. This thorough strategy, which included both hardware implementation and software development, resulted in the successful construction of a pure sinewave inverter prototype capable of effectively converting gathered solar energy into AC power suited for domestic usage.

3.2 Sustainability of the Microcontroller-based Pure Sine Wave Inverter Project

The creation of a microcontroller-based pure sine wave inverter for solar energy collecting applications has greatly increased the sustainability of residential energy use. The consumption of solar energy has helped to reduce reliance on fossil fuels, lowering carbon emissions while also contributing to a better future. Pure sine wave inverters allow household equipment to perform more efficiently, enhance their longevity, and eliminate electrical waste. Furthermore, the SPWM algorithm allows for significant improvements in energy conversion efficiency, resulting in less power loss from acquired solar energy. This innovation encourages the use of renewable energy, promotes energy independence, and offers a dependable and sustainable answer to domestic energy requirements.

3.3 Operating principle for Microcontroller Based Pure Sinewave Inverter Project

In this project, a microcontroller-based sinewave pulse width modulation (SPWM) algorithm is generated and fed to a prototype inverter is built to provide pure sinewave AC power for home usage. The solar panel converts sunlight into direct current (DC), which is then regulated and provided to a microcontroller. If a solar panel is not available, a DC power supply will be utilised instead. The microcontroller is programmed to generate SPWM signals that precisely govern the switching of a single-phase H-Bridge inverter circuit composed of four MOSFETs. These switches convert regulated DC electricity into an SPWM-modulated AC signal. This modulated signal containing high-frequency components is then passed through a low pass passive RC filter, which smoothes the waveform by removing high-frequency noise, resulting in a clean sinewave AC output. The voltage obtained from the pure AC sine wave is used to act as a substitute for powering up household appliances. Analysis of the system's performance helps guarantee maximum productivity in residential settings.

3.4 Project flowchart

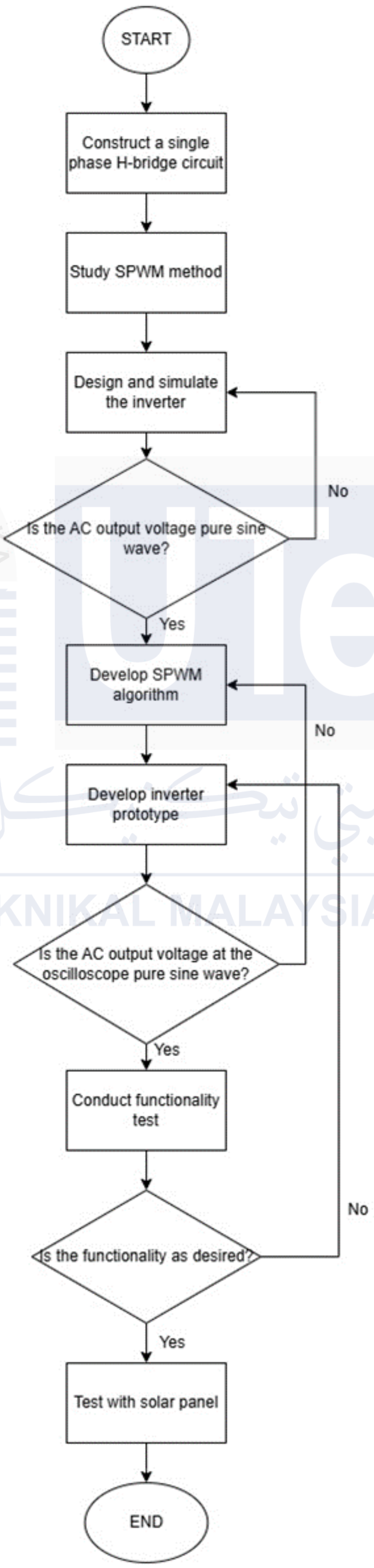


Figure 3.1: Project Flowchart

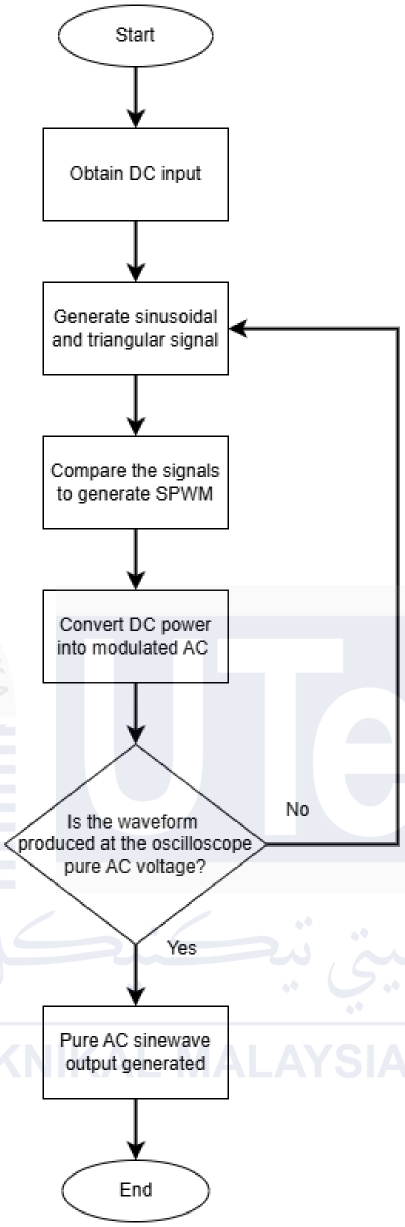


Figure 3.2: Flowchart to develop a microcontroller-based SPWM algorithm to produce pure sinewave AC voltage for households.

Creating a microcontroller-driven Sinusoidal Pulse Width Modulation (SPWM) algorithm requires crafting accurate control signals to produce a clean sinewave AC output. The SPWM technique modulates switching signals for the H-bridge inverter, minimizing harmonic distortion. This guarantees high-quality waveform generation appropriate for home appliances, aiding in the effective and dependable transformation of DC into AC power.

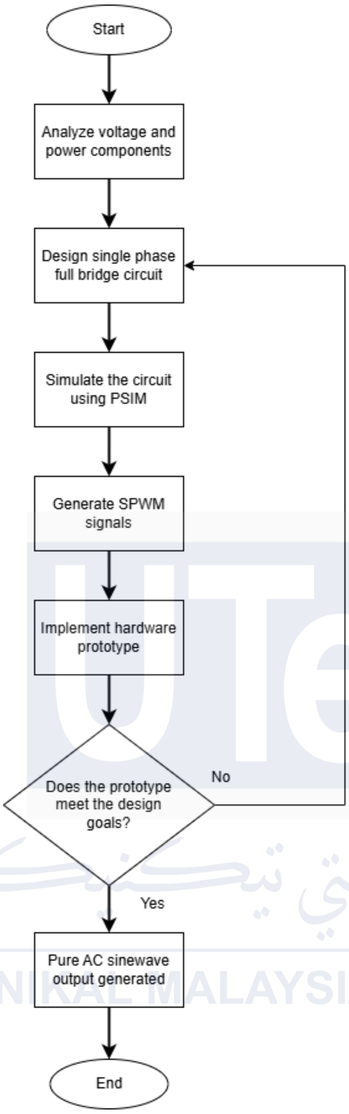


Figure 3.3: Flowchart to design and implement a single-phase inverter circuit for solar-to-AC power conversion.

The creation and execution of the single-phase H-bridge inverter include the combination of power elements such as MOSFETs and RC filters to transform DC power from solar sources into AC. Circuit simulation confirms performance, whereas hardware assembly guarantees functionality. This phase guarantees compatibility with household loads, enhancing energy efficiency and stability for solar-to-AC power uses.

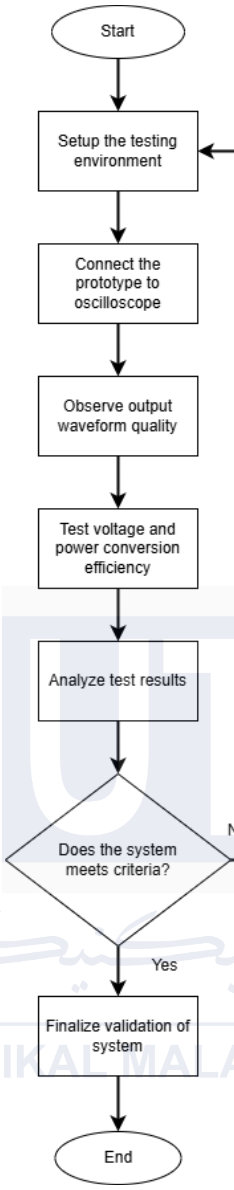


Figure 3.4: Flowchart to validate the system's functionality through extensive testing, with emphasis on waveform quality, conversion efficiency, and dependability.

The system's performance was confirmed through thorough testing, focusing on waveform quality, conversion efficiency, and reliability. By employing instruments like oscilloscopes and power meters, essential parameters including Total Harmonic Distortion (THD) and long-term reliability were examined. Testing verifies that the system satisfies design specifications, delivering reliable, efficient, and high-quality AC output for practical applications.

3.5 Block diagram

The block diagram depicts the architecture of a microcontroller-based pure sinewave inverter for solar energy collecting applications. This project seeks to create a prototype inverter capable of converting the DC electricity provided by solar panels into a steady, pure sinewave AC voltage appropriate for home usage.

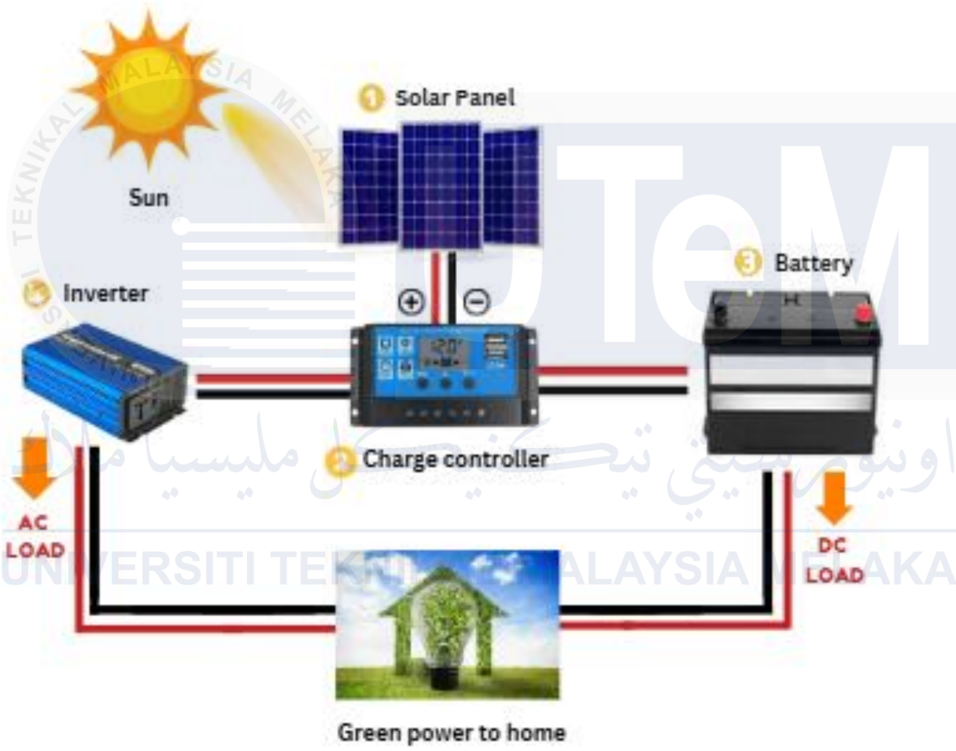


Figure 3.5: Overall block diagram for a solar inverter

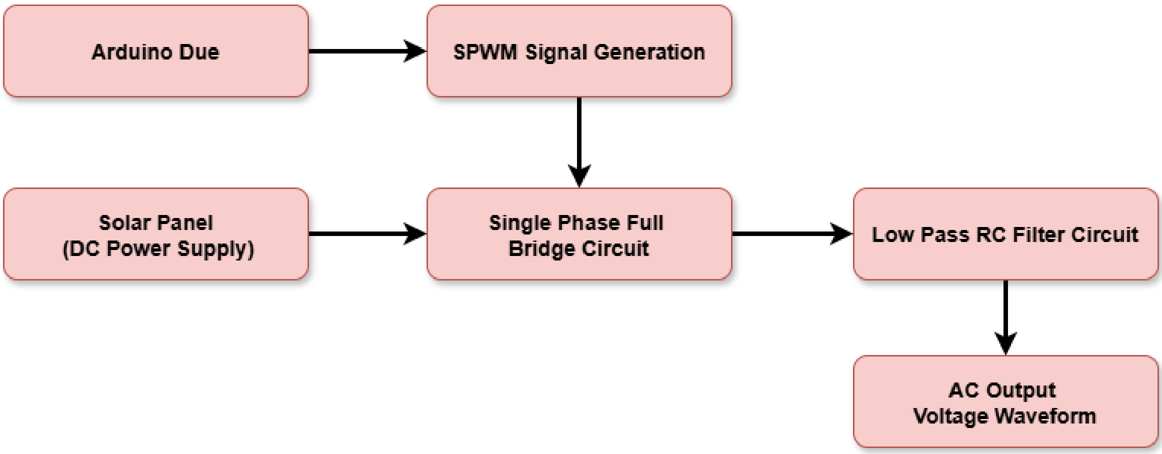


Figure 3.6: Overall block diagram of project

3.6 Filter parameters

The use of overrated components can be avoided if proper calculations are made. Hence, when proper calculations are performed, an ideal design can be made, and a lot of costs can be reduced or avoided. Implementing a filter is an essential step to ensure that it smoothens output waveforms by lowering harmonics and suppressing high-frequency noise. This noise might interfere with sensitive electronic devices linked to the inverter, triggering problems or poor performance. Employing a filter guarantees a clean and steady AC output signal, which is required for the correct operation of electrical gadgets and appliances.

3.6.1 Components parameter selection for circuit design

Table 3.1 shows the components and system parameters that were identified for the parameter performance analysis in PSIM, which was utilized to simulate the system and get the digital unipolar SPWM.

Table 3.1: Simulation parameters used for performance analysis in PSIM

Parameters	Values
Vs (DC)	240V
Vtri (Frequency)	5000Hz
Vsine	50 Hz
Switching device	MOSFET
Designed filter	Low pass passive RC filter

3.6.2 Design and calculation for RC filter

The advantages of using a low-pass RC filter in an inverter project are its accessibility, the effectiveness of costs, and usefulness in reducing high-frequency noise. For instance, RC filters are simple to manufacture and operate, employing only fundamental components such as resistors and capacitors. This adaptability translates into price, making RC filters a popular choice for a wide range of applications, including inverters. Second, RC filters can efficiently reduce noise by attenuating high-frequency components and allowing low-frequency AC signals to pass. This helps to provide a cleaner and more dependable AC output signal, which is required for the proper operation of electrical equipment connected to the inverter. Furthermore, RC filters may be set to certain cutoff frequencies, allowing for customization according to the demands of the inverter circuit. In conclusion, the low-pass RC filter is a valuable and efficient approach for removing undesired distortion from inverter circuits, resulting in more consistent operation and performance. For the layout of the filter, connect the resistor in series with the source signal and the capacitor in parallel with the output load. This configuration enables frequencies below fc to pass but attenuates higher frequencies.

Formula of cutoff frequency, fc:

$$fc = \frac{1}{2\pi RC} \tag{3.1}$$

Assume cutoff frequency, fc = 350 Hz and value of resistor, R = 1 Ω

By substituting values,

$$350 = \frac{1}{2\pi(1)C} \tag{3.2}$$

Hence,

C = 454.73 µF

When determining a capacitor for a hardware application, the closest standard value accessible is often used. Capacitors are made in specified standard values, and while 454.73 microfarads (µF) are not a standard number, comparable quantities may be found. The nearest standard capacitor is 470 µF. It can be deduced that a 470 µF is used for this project simulation and in hardware application

Table 3.2: Value for capacitor and resistor in RC filter

Component	Selected value
Capacitor	470 μF
Resistor	1 Ω

The selected values are based on the datasheet provided by industries which need to be considered as available in the market.

3.7 Software Implementation

3.7.1 PSIM Software

Figure 3.7: PSIM Software

PSIM is a simulation programme known for its range of uses and effectiveness in the power electronics and motor drive sectors. PSIM, with its user-friendly interface and broad component library, allowing users to easily construct, analyse, and optimise complex power systems. One fo the highlights of this software include, exact circuit modellling. In PSIM, there is also powerful simulation techniques and real-time functionality assesment. PSIM applications namely the creation of inverters, converters, motor drives, and also renewable energy systems. Its extensive features accelerate the prototyping process, enabling engineers to swiftly review and enhance distinctive concepts for a wide range of uses.

3.7.2 Arduino IDE

Figure 3.8: Arduino IDE Software

Arduino IDE is a developement platform for Arduino microcontrollers and is mostly used in major programming and development tools. This software comes with pre-written code library and has a user-friendly interfacing mode. Arduino IDE is compatible with various Arduino boards because it is easy to link to third-party libraries and hardware components. This advantage has boosted the platform's versatility and adaptability. The Arduino IDE was used to code the Arduino microcontrollers, which allowed for the creation of custom functionalities and the execution of research project duties. Vast features of this software has ensured smooth and reliable operation throughout the process.

3.8 Hardware Implementation

3.8.1 Arduino Due

Figure 3.9: Arduino Due

Arduino Due is specifically chose as the microcontroller that is uses for this project. Arduino Due has a very rapid switching switching speed which plays a major role in assisting for precise control over power components such as MOSFETs or the IGBTs in an inverter circuit. This is because it is a powerful microcontroller with high-performance ARM Cortex-M3 architecture and posses high processing power and also the memory capacity to handle complex algorithma and tasks. Furthermore, its integration with the Arduino development environment allowed for simple programming and rapid prototyping, making it an ideal option for carrying out the experimental methodologies described in this study methodology.

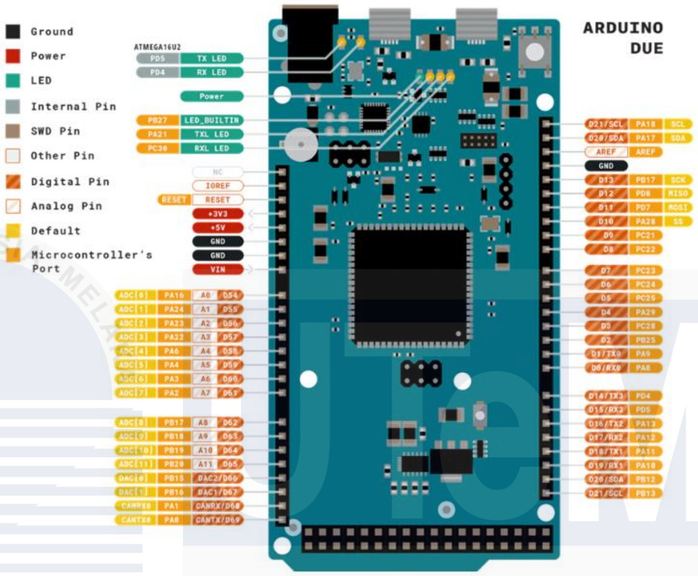


Figure 3.10: Arduino Due pin arrangement

3.8.2 MOSFET

Figure 3.11: MOSFET

MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) are a vital element for power switching and control in the experimental setup. MOSFETs, also has high switching speed, is important in controlling the current flow in circuits. Their capability to withstand high voltages and currents while dissipating low power while makes them ideal for power electronics applications. Moreover, MOSFETs offer exquisite management of switching operations, allowing for precise manipulation of electrical signals. MOSFET IRF740 has been chosen as the transistor in this project. This is because the MOSFET's 400V drain-source voltage rating and 10A current handling capabilities is suitable for a microcontroller-based pure sine wave inverter, assuring dependability in medium-power applications.

3.8.3 Capacitor

Figure 3.12: Capacitor

The main function of a capacitor is to store and release elctrical signals. Hence, this function allows them to smoothen out voltage swings and filter out distortion in the circuit. It is crucial to select a suitable capacitance value and voltage ratings in order to meet the system requirements. Capacitors also plays a significant role in timing circuits, signal coupling, filters and decoupling.

3.8.4 Resistor

Figure 3.13: Resistor

A resistor mostly controls current and handles voltage division. Besides, they also function in a variety of tasks including circuit biassing because they have the ability to provide steady operating points for transistors and amplifiers, guaranteeing optimal transistor behaviour and signal amplification. Timing circuit also employs the use of resistor to have control over the frequency of oscillators or the length of pulses in digital systems.

3.8.5 Solar panel

Figure 3.14: Solar panel

Solar panels are essential in engaging photovoltaic phenomenon for transforming sunlight to electricity. These solar cells, which are usually made with silicon, convert solar energy into direct current (DC) electricity. Solar panels are adaptable, scalable, and environmentally friendly, giving them a cost-effective alternative to traditional energy sources. They are mostly placed on rootftops or in solar farms. This allows sustainable energy generation while reducing the dependability on fossil fuels and cutting carbon dioxide emissions.

3.8.6 MOSFET Driver

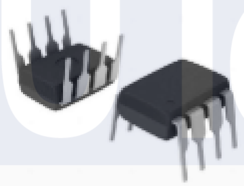


Figure 3.15: MOSFET Driver

MOSFET drivers amplify and control the gate signals of MOSFETs, ensuring proper switching for efficient circuit operation. They act as intermediaries between low-power controllers, like microcontrollers, and high-power MOSFETs, providing the necessary voltage and current to drive the MOSFETs quickly and reliably. Key functions include reducing switching losses, ensuring synchronized operation in dual-side configurations, and providing protection features like dead-time control to prevent shoot-through currents. MOSFET drivers enhance efficiency and performance in applications like inverters, motor drives, and power converters.

3.8.7 Diode

Figure 3.16: Diode

A diode permits current to pass in a single direction while obstructing reverse current, which is crucial for rectification, safeguarding, and signal modulation within circuits. In this project, diodes facilitate a steady current flow and safeguard components against voltage surges. They are small, dependable, and effective at managing high-speed switching. Diodes minimize energy losses with their low forward voltage drop, improving overall efficiency. Their durability and capacity to function in elevated temperature settings make them perfect for power electronics, guaranteeing dependable inverter operation.

3.8.8 Oscilloscope

Figure 3.17: Digital Storage Oscilloscope

An oscilloscope gauges and presents voltage signals over time, enabling the visualization of waveforms for examination. It is essential for diagnosing and evaluating circuits, guaranteeing correct functionality and waveform precision. The main role of the oscilloscope is to display the AC waveform that is generated at the output. Based on the waveform produce, only the problem is able to be identified. The oscilloscope comes with many parameters meausrement allowing it to be multi-purpose, hence offering comprehensice analysios of circuit analysis.

3.9 Circuit design for generating SPWM signals

Generally, to create a sinusoidal PWM (SPWM) signal from a sine wave and a triangle wave, a comparator plays an essential role. First, a sinusoidal reference signal (V_sine) is created to represent the intended AC output waveform, which is usually at a standard frequency like 50 Hz or 60 Hz. Meanwhile, a high-frequency triangular carrier signal (V_tri) is generated, with a frequency significantly higher than V_sine, often in the range of several kHz. In this circuit, a 5kHz frequency is employed. The comparator's function is to continuously compare between these two signals. When the amplitude of V_sine is higher that of V_tri, the comparator will generate producea a high signal (logic 1), whereas when V_sine is less than V_tri, it produces a low signal (logic 0). The same concept is applied here to generate the SPWM signals.

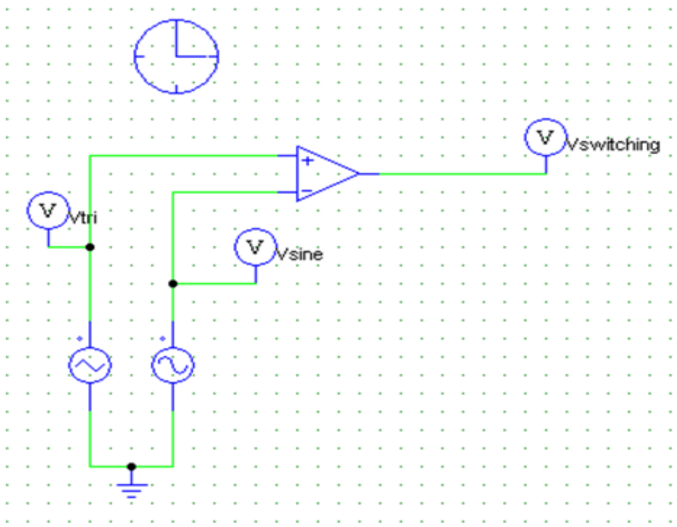


Figure 3.18: Circuit design for generating SPWM signal

3.9.1 Parameters for Circuit Design for generating SPWM signal

These are the settings for the circuit simulation design. Displaying these attributes has significance because it presents exact simulation control, which facilitates precise adjustments and optimisations. Optimal parameter values can help with design authenticity, function forecasting, and discovering possible circuit faults.

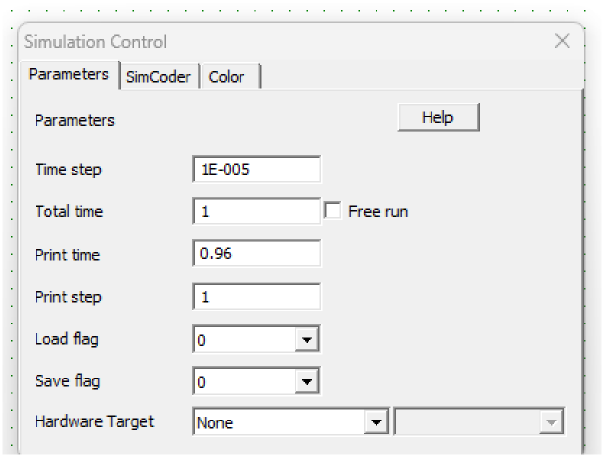


Figure 3.19: Parameter for Simulation Control

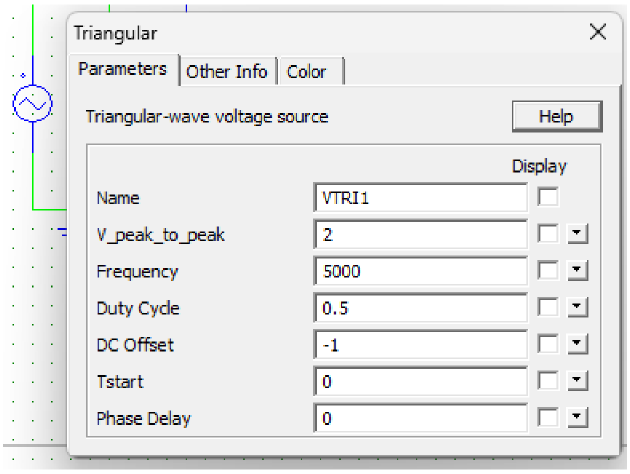


Figure 3.20: Parameter for Triangular-wave voltage source

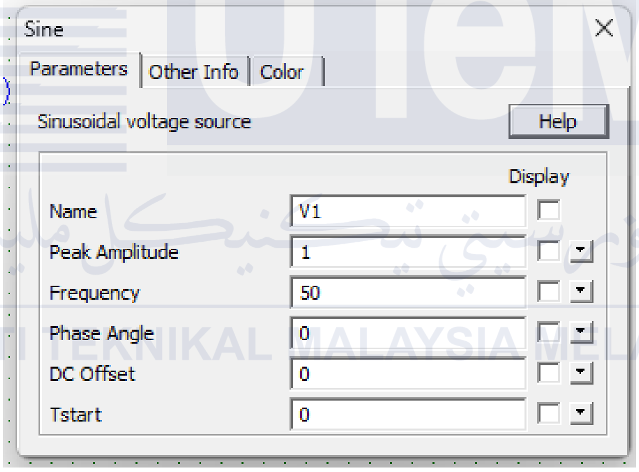


Figure 3.21: Parameters for Sinusoidal voltage source

3.9.2 SPWM Voltage Sources: Sinusoidal, Triangular and Switching

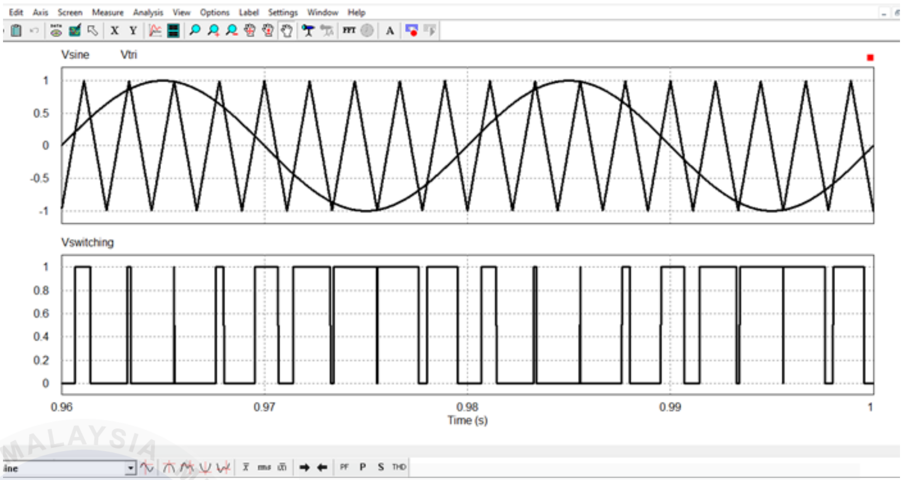


Figure 3.22: Output voltage waveform for SPWM voltage sources

Theoretical evaluation and simulation are key elements in assessing SPWM signal generation performance. The process involves contrasting the produced waveforms to theoretical expectations to determine the correctness and functioning of the SPWM technology. This verification assures that the SPWM approach is stable and performs well in practical situations, enhancing its usefulness in a wide range of technical domains.

3.10 Circuit design for pure sine wave generation

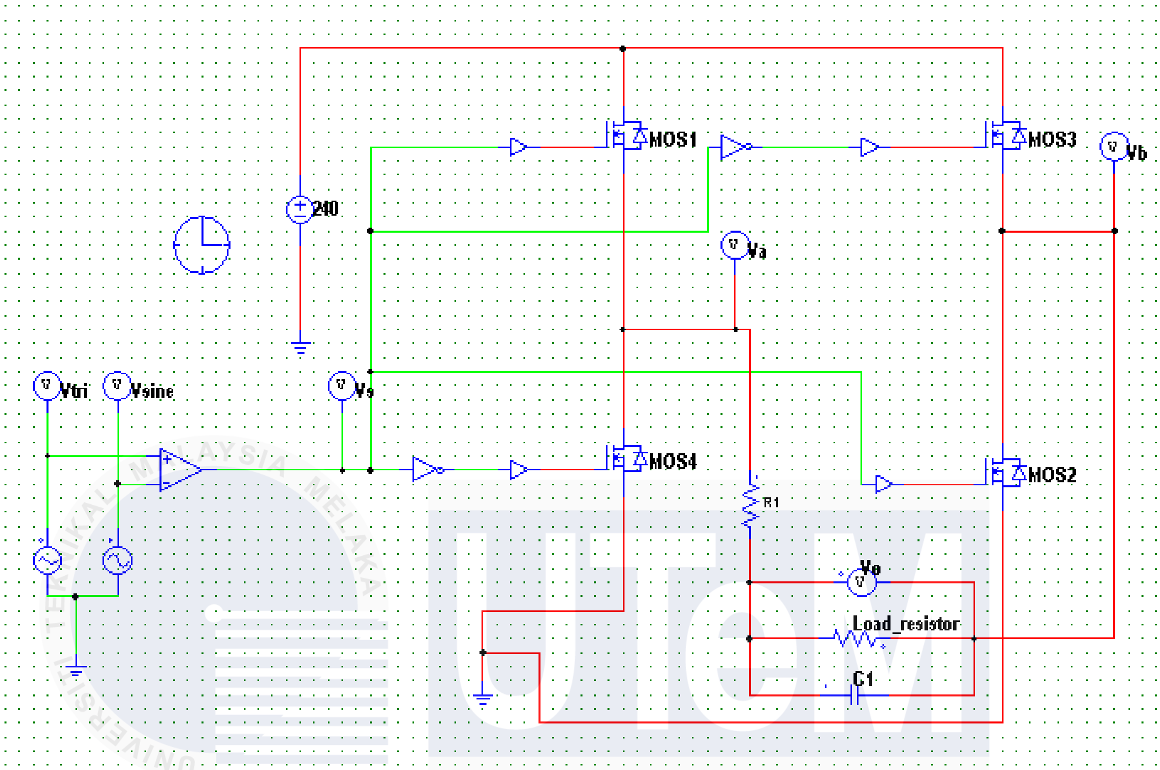


Figure 3.23: Complete circuit design for single-phase full-bridge inverter circuit

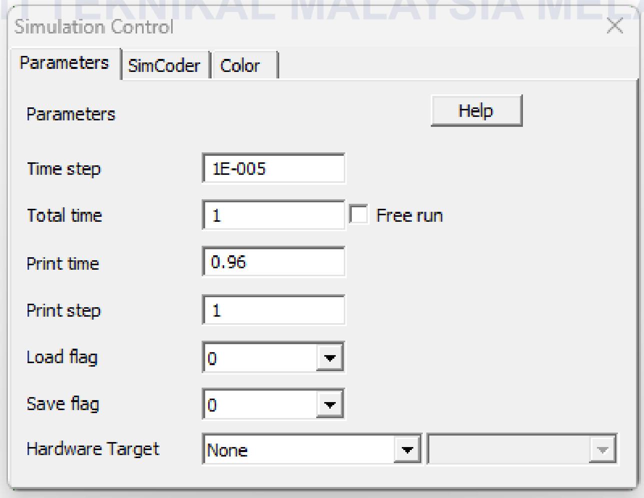


Figure 3.24: Parameter for Simulation Control

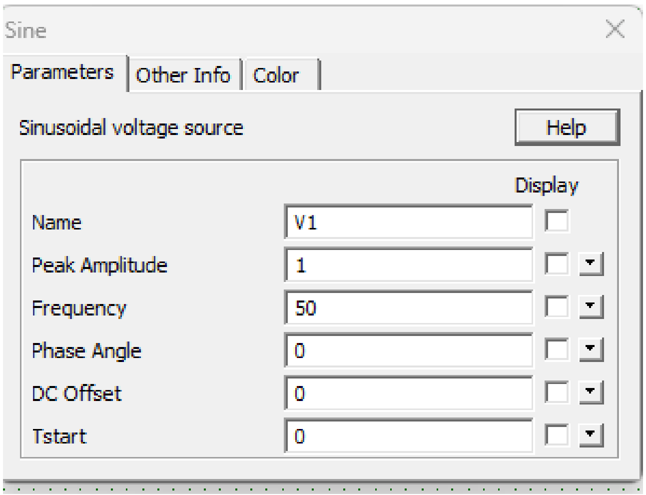


Figure 3.25: Parameter for Sinusoidal voltage source

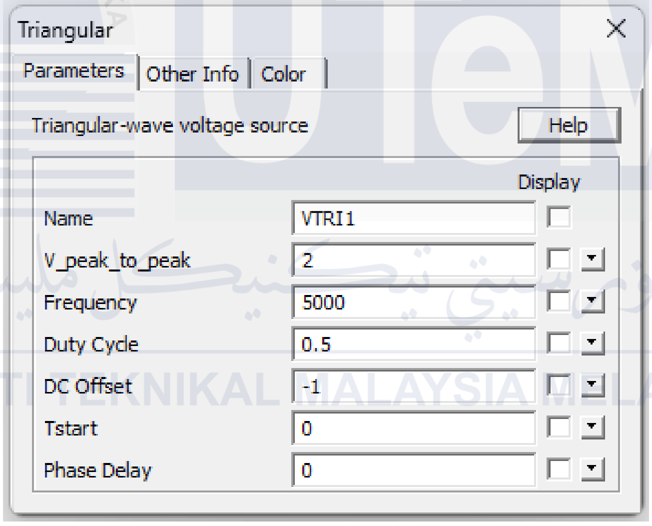


Figure 3.26: Parameter for Triangular-wave voltage source

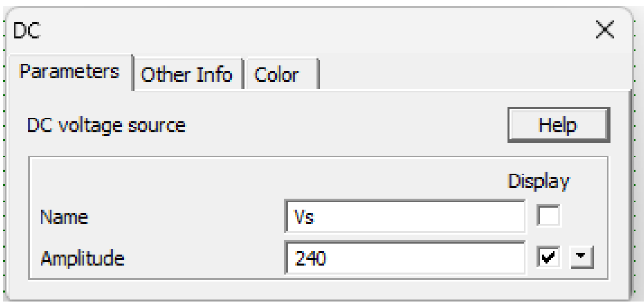


Figure 3.27: Parameter for DC voltage source

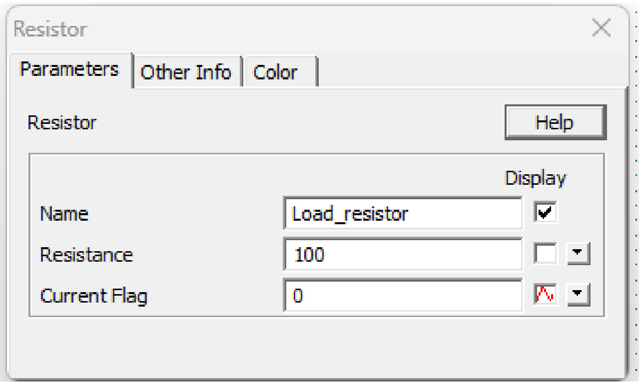


Figure 3.28: Parameter for load resistor

The single-phase full-bridge converter is made up of four MOSFETs in a bridge configuration that is linked to a DC power supply. This layout facilitates reversible current flow, leading to an improvement in AC output production. Peak performance depends on accurate parameter settings. Effective layout ensures efficient power transformation, minimum losses, and reliable performance.

3.11 Circuit Implementation for SPWM Signal Generation

3.11.1 Connection of Microcontroller and Oscilloscope for SPWM signal generation

Pins 38 and 34 on the Arduino Due are utilized to create high and low inputs, correspondingly, for MOSFET drivers because of their PWM features and capacity to generate complementary signals. Pin 38 serves as the high-side input, whereas pin 34 functions as the low-side input, with both managed by the microcontroller's sophisticated timers. These timers enable accurate pulse-width modulation with integrated dead-time management, avoiding shoot-through currents during functioning. When only utilized to produce SPWM signals, the high input (pin 38) connects to channel 1 of the oscilloscope, whereas the low input (pin 34) links to channel 2. Their strategic positioning and simple setup render them perfect for synchronized signal creation and waveform assessment in uses such as pure sine wave inverters.

Figure 3.29: Connection of microcontroller and oscilloscope for SPWM signal generation

3.11.2 Code Development and Algorithm Design

The coding design and developed in this section is to manipulate and control the Arduino Due output pins. The software creates a sequence of timed output signals by changing the states of pins 38 and 34. By using suitable time intervals, the code will produce signals sequentially known as either HIGH or LOW. The aim of this program is to demonstrate how to manipulate the pin states based on temporal control simultanenously exploring the microcontroller’s capabilities to generate particular signal patterns.

The data displayed in the below table are taken from sine wave at an interval time of 1ms using the PSIM software.

Table 4.3: Data of SPWM Interval

	SWITCHING	COUNT	DURATION (MICROSECONDS)	SET
1	ON	4	80	A
2	OFF	1	20	
3	ON	9	180	B - 14 SET
4	OFF	1	20	
5	ON	9	180	
6	OFF	1	20	
7	ON	9	180	
8	OFF	1	20	
9	ON	9	180	
10	OFF	1	20	
11	ON	9	180	
12	OFF	1	20	
13	ON	9	180	
14	OFF	1	20	
15	ON	9	180	
16	OFF	1	20	
17	ON	9	180	
18	OFF	1	20	
19	ON	9	180	
20	OFF	1	20	
21	ON	9	180	
22	OFF	1	20	
23	ON	9	180	
24	OFF	1	20	
25	ON	9	180	
26	OFF	1	20	
27	ON	9	180	
28	OFF	1	20	
29	ON	9	180	
30	OFF	1	20	
31	ON	8	160	C
32	OFF	3	60	
33	ON	7	140	D - 6 SET
34	OFF	3	60	
35	ON	7	140	
36	OFF	3	60	
37	ON	7	140	
38	OFF	3	60	
39	ON	7	140	

40	OFF	3	60	
41	ON	7	140	
42	OFF	3	60	
43	ON	7	140	
44	OFF	3	60	
45	ON	6	120	E
46	OFF	5	100	F - 6 SET
47	ON	5	100	
48	OFF	5	100	
49	ON	5	100	
50	OFF	5	100	
51	ON	5	100	
52	OFF	5	100	
53	ON	5	100	
54	OFF	5	100	
55	ON	5	100	
56	OFF	5	100	
57	ON	5	100	
58	OFF	6	120	G
59	ON	3	60	H - 6 SET
60	OFF	7	140	
61	ON	3	60	
62	OFF	7	140	
63	ON	3	60	
64	OFF	7	140	
65	ON	3	60	
66	OFF	7	140	
67	ON	3	60	
68	OFF	7	140	
69	ON	3	60	
70	OFF	7	140	
71	ON	3	60	I
72	OFF	8	160	
73	ON	1	20	J - 13 SET
74	OFF	9	180	
75	ON	1	20	
76	OFF	9	180	
77	ON	1	20	
78	OFF	9	180	
79	ON	1	20	
80	OFF	9	180	
81	ON	1	20	
82	OFF	9	180	
83	ON	1	20	

84	OFF	9	180	
85	ON	1	20	
86	OFF	9	180	
87	ON	1	20	
88	OFF	9	180	
89	ON	1	20	
90	OFF	9	180	
91	ON	1	20	
92	OFF	9	180	
93	ON	1	20	
94	OFF	9	180	
95	ON	1	20	
96	OFF	9	180	
97	ON	1	20	
98	OFF	9	180	
99	ON	1	20	K
100	OFF	19	380	
101	ON	1	20	L - 13 SET
102	OFF	9	180	
103	ON	1	20	
104	OFF	9	180	
105	ON	1	20	
106	OFF	9	180	
107	ON	1	20	
108	OFF	9	180	
109	ON	1	20	
110	OFF	9	180	
111	ON	1	20	
112	OFF	9	180	
113	ON	1	20	
114	OFF	9	180	
115	ON	1	20	
116	OFF	9	180	
117	ON	1	20	
118	OFF	9	180	
119	ON	1	20	
120	OFF	9	180	
121	ON	1	20	
122	OFF	9	180	
123	ON	1	20	
124	OFF	9	180	
125	ON	1	20	
126	OFF	9	180	
127	ON	1	20	M

128	OFF	8	160	
129	ON	3	60	N - 6 SET
130	OFF	7	140	
131	ON	3	60	
132	OFF	7	140	
133	ON	3	60	
134	OFF	7	140	
135	ON	3	60	
136	OFF	7	140	
137	ON	3	60	
138	OFF	7	140	
139	ON	3	60	
140	OFF	7	140	
141	ON	3	60	O
142	OFF	6	120	
143	ON	4	80	
144	OFF	5	100	P - 11 ITEM
145	ON	5	100	
146	OFF	5	100	
147	ON	5	100	
148	OFF	5	100	
149	ON	5	100	
150	OFF	5	100	
151	ON	5	100	
152	OFF	5	100	
153	ON	5	100	
154	OFF	5	100	
155	ON	6	120	Q
156	OFF	3	60	
157	ON	7	140	R - 6 SET
158	OFF	3	60	
159	ON	7	140	
160	OFF	3	60	
161	ON	7	140	
162	OFF	3	60	
163	ON	7	140	
164	OFF	3	60	
165	ON	7	140	
166	OFF	3	60	
167	ON	7	140	
168	OFF	3	60	
169	ON	8	160	S
170	OFF	1	20	
171	ON	9	180	T - 14 SET

172	OFF	1	20	
173	ON	9	180	
174	OFF	1	20	
175	ON	9	180	
176	OFF	1	20	
177	ON	9	180	
178	OFF	1	20	
179	ON	9	180	
180	OFF	1	20	
181	ON	9	180	
182	OFF	1	20	
183	ON	9	180	
184	OFF	1	20	
185	ON	9	180	
186	OFF	1	20	
187	ON	9	180	
188	OFF	1	20	
189	ON	9	180	
190	OFF	1	20	
191	ON	9	180	
192	OFF	1	20	
193	ON	9	180	
194	OFF	1	20	
195	ON	9	180	
196	OFF	1	20	
197	ON	9	180	
198	OFF	1	20	
199	ON	5	100	U
200	OFF	1	20	

<u>Understanding coding for SPWM Signal Generation</u>

Based on the coding, it can be observed that the program starts off by initializing two pins, which are pin 38 and pin 34, as output pins using the pinMode() function. This allows the pins to transmit digital signals namely HIGH or LOW. Pin 38 serves as the main output, whereas pin 34 acts as its inverted version. This dual-pin configuration enables complementary signal creation, a typical necessity in digital control systems. The code also employs the Parallel Input/Output Controller (PIO) registers of the Arduino Due to manage the conditions of the output pins. In particular, the PIO_SODR (Set Output Data Register) serves to set a pin HIGH, while the PIO_CODR (Clear Output Data Register) functions to set a pin LOW. For example, the command PIOC->PIO_SODR = 0x40; activates pin 38 to HIGH, while PIOC->PIO_CODR = 0x4; deactivates pin 34 to LOW. This method allows for accurate control of pin states right at the hardware level, essential for obtaining the necessary timing precision. For example, SET A will generate a cycle with 80 microseconds HIGH and 20 microseconds LOW, whereas SET B replicates a comparable cycle 14 times with a 180-microsecond HIGH period. These collections are executed through direct manipulation of registers and are frequently reiterated with for loops to ensure timing consistency.

3.12 Constructing a driver circuit

A driver circuit is an electrical circuit that generates the control signals required to run power devices like MOSFETs or IGBTs in high-power applications such as inverters, motor controllers, and LED drivers. It provides correct switching by giving the necessary voltage and current and frequently includes features like as isolation, protection, and signal amplification. In this project, the half-bridge driver, IR2304PbF, is used. The IR2304(S) are a high voltage, high speed power MOSFET and IGBT driver with independent high and low side referenced output channels.

3.12.1 Key Parameters to activate a MOSFET Driver

The figure below shows the complete connection to switch on the driver [46].

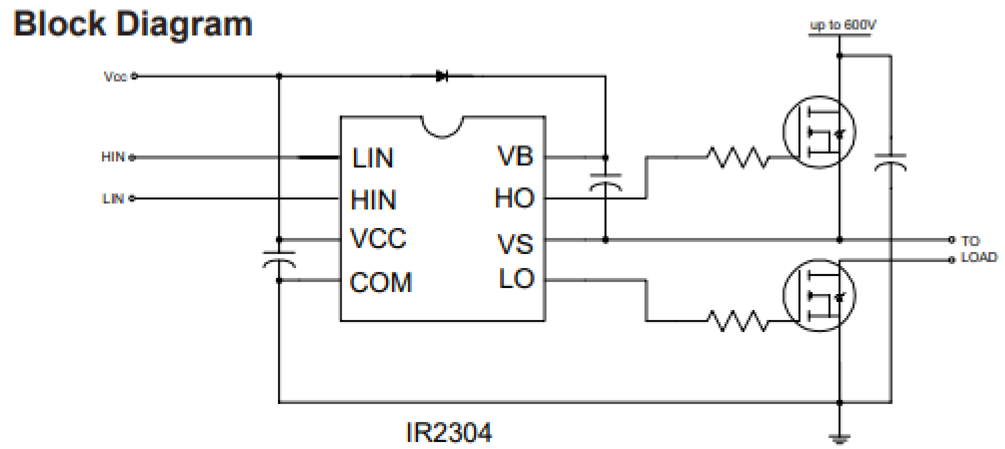


Figure 3.30: Block diagram of IR2304PbF

Symbol	Definition	Min.	Max.	Units
V_B	High side floating supply voltage	V_S + 10	V_S + 20	V
V_S	High side floating supply offset voltage	Note 1	600	
V_{HO}	High side (HO) output voltage	V_S	V_B	
V_{LO}	Low side (LO) output voltage	COM	V_{CC}	
V_{IN}	Logic input voltage (HIN, LIN)	COM	V_{CC}	
V_{CC}	Low side supply voltage	10	20	
T_A	Ambient temperature	-40	125	°C

Figure 3.31: Recommended Operating Conditions for IR2304PbF

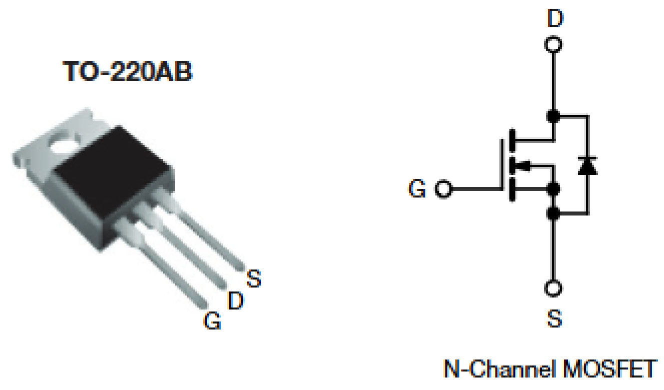


Figure 3.32: Terminal Configuration for IRF740

Based on the datasheet, the recommended operating conditions require a supply voltage (Vcc) ranging from 10V to 20V to operate properly. For this project, a 15V DC power supply is chosen to guarantee dependable operation while remaining comfortably within the designated limits. Additionally, the drain terminal of the transistor is supplied with power source of 5V. The IRF740 features a maximum Vds rating of 400V, which makes it very adaptable for high-voltage uses. The 15V gate drive guarantees that the MOSFET is fully enhanced, reducing losses and promoting efficient switching performance.

3.12.2 Verifying the Driver circuit functionality

It is crucial to ensure that the driver circuit is correctly activated for reliable circuit performance. A effectively working driver generates the gate voltage required to fully switch the MOSFET, minimising power losses, preventing overheating. Once connected, measure the output waveform at the transistor's gate terminal. The intended output waveform should be more than 10V peak-to-peak (Vpp). This measurement must be carried out on both the high- and low-side transistors. Additionally, the high-side output is expected to be higher compared to the low-side output, assuring correct operation of the driving circuit.

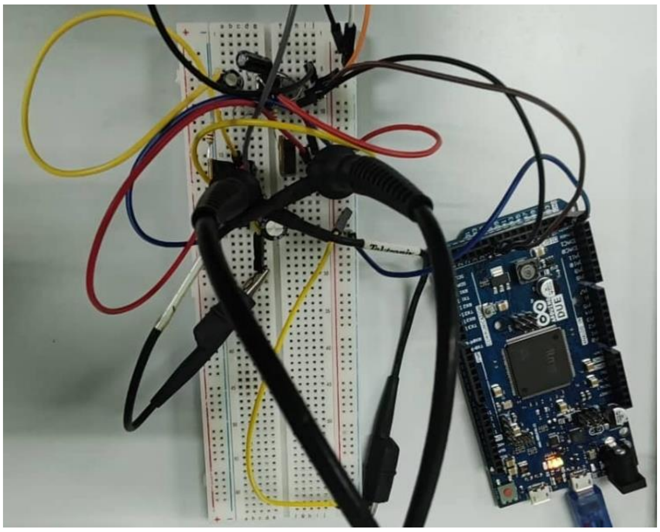


Figure 3.33: Ciruit connection for MOSFET Driver

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Overview

This chapter is purely based on presenting the output of the project. Besides that, this chapter will discuss the analysis and results in detail that were obtained from the PSIM and experimental analysis. Other than that, the output obtained in the prototype was compared with the simulated output as a reference for the project.

4.2 Simulation analysis via PSIM

As a reference for hardware implementation, each parameter was tested, and the output was analyzed. Most importantly, SPWM output, MOSFET switching output, DC voltage output and inverter output are analyzed via PSIM simulations.

4.2.1 SPWM generation output

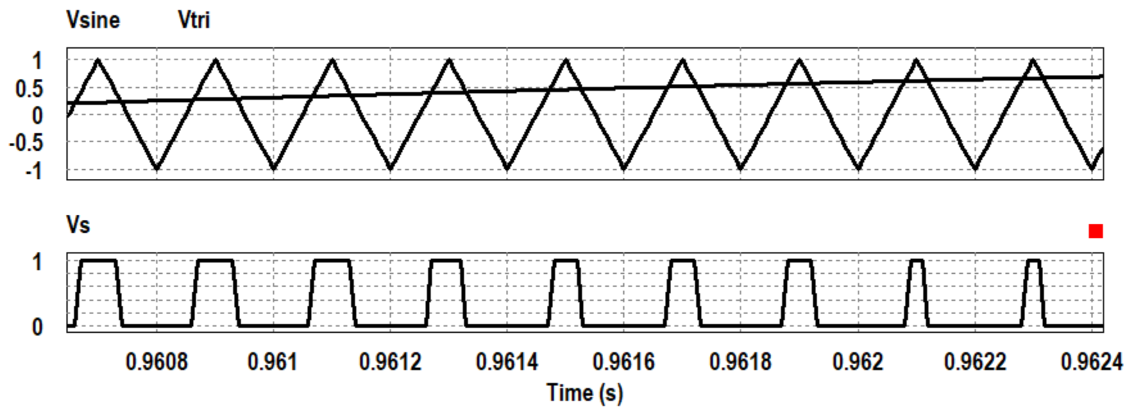


Figure 4.1: Waveform of SPWM generation output

In PSIM, the unipolar SPWM switching signal waveform at 5000Hz displays precise power modulation. At this frequency, the switching happens quickly, with short pauses between pulses. This quick switching motion provides exact regulation of power output, which is critical for maintaining stability and efficiency in the inverter system. The short length of each pulse and the rapid transitions between high and low states help to reduce distortion in the output waveform, which nearly resembles a pure sinusoidal waveform.

4.2.2 MOSFET switching output

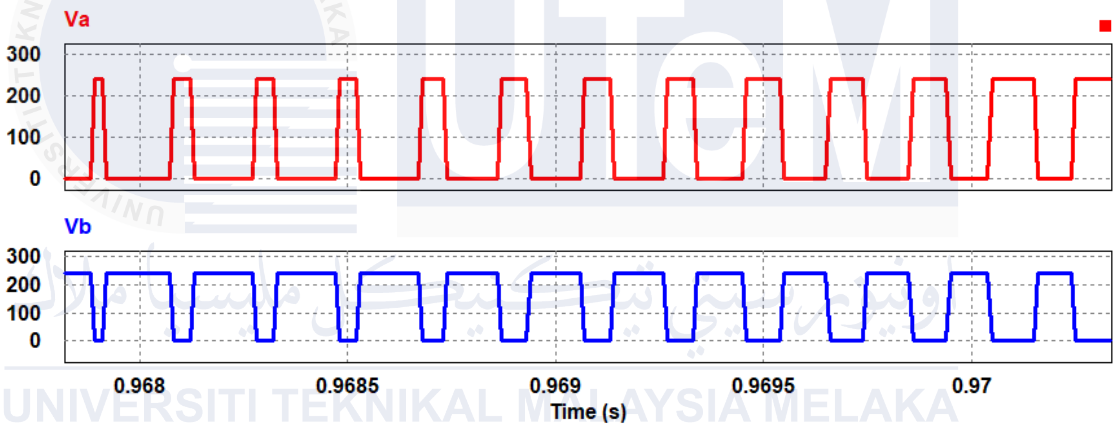


Figure 4.2: Waveform of MOSFET switching output

In the context of MOSFET switching in an H-bridge circuit, the "on" and "off" states denote the MOSFETs' conduction and nonconduction states, respectively. In the "on" state, the MOSFET permits current to flow between its source and drain terminals, effectively conducting electricity. This condition is required for power transmission over the H-bridge circuit, which allows the conversion of DC input power into AC output power or vice versa.

In contrast, in the "off" state, the MOSFET pauses the flow of current between its source and drain terminals, essentially halting the flow of power. This non-conducting condition is critical for managing the flow of power inside the circuit, preventing current from flowing in undesirable directions, and ensuring that the H-bridge design functions properly.

4.2.3 Voltage output waveform of inverter

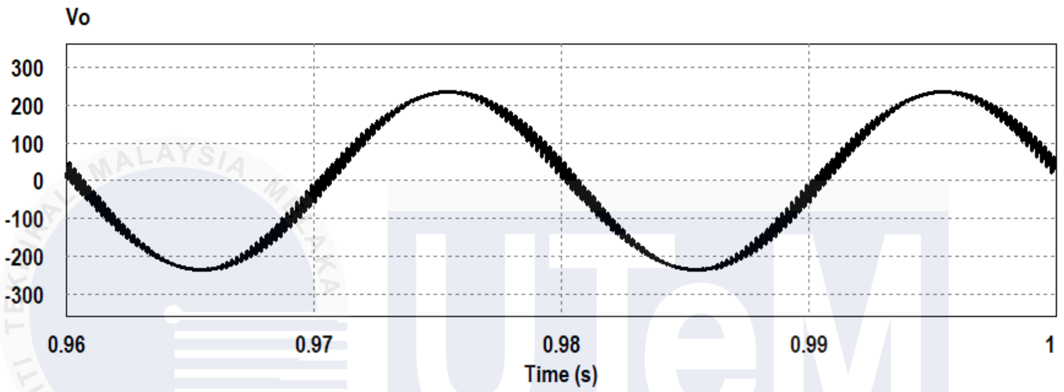


Figure 4.3: Waveform of inverter's output

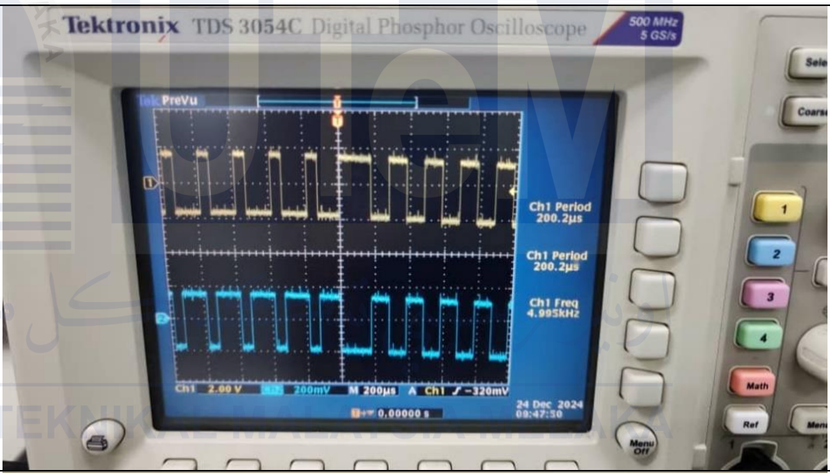
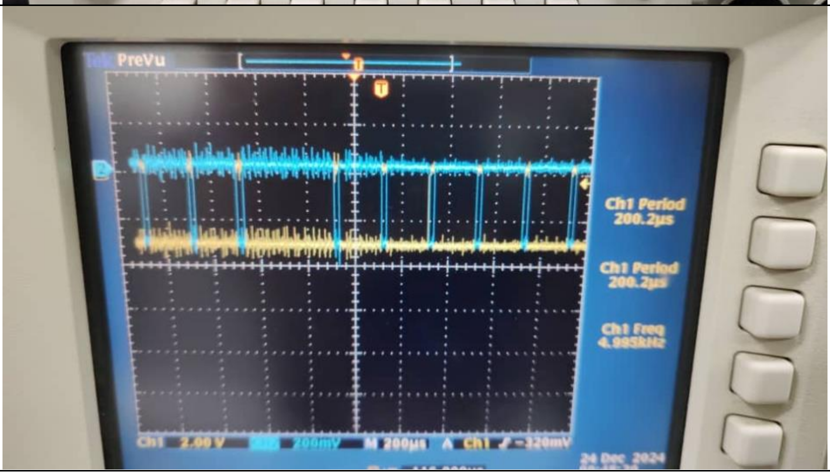
Inverter circuits convert DC electricity to AC, resulting in a sine wave at the output voltage. The RC filter employed in the circuit helps to minimize the distortion and noise that is produced in the waveform. Higher frequencies are attenuated, yielding a smoother sine wave. A 5000Hz frequency helps to ensure efficient filtering. The result is a refined sine wave, which is critical for precision power distribution in a variety of applications, including renewable energy systems and uninterruptible power supply, while also assuring dependability and minimizing electromagnetic interference.

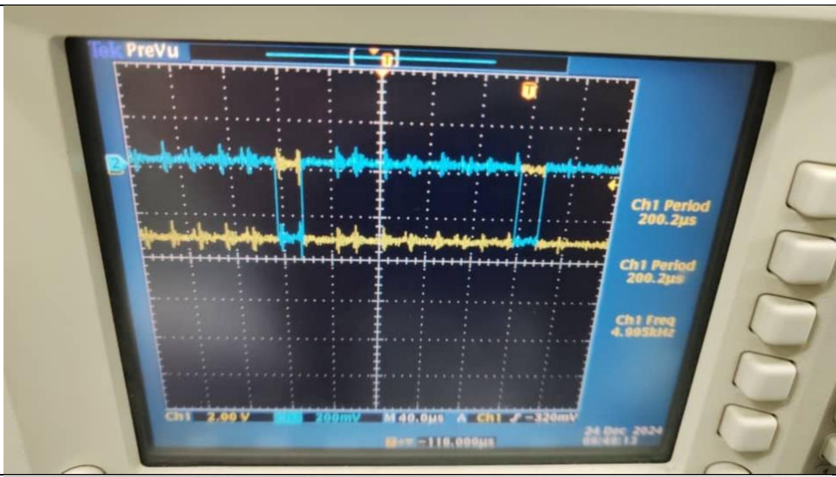
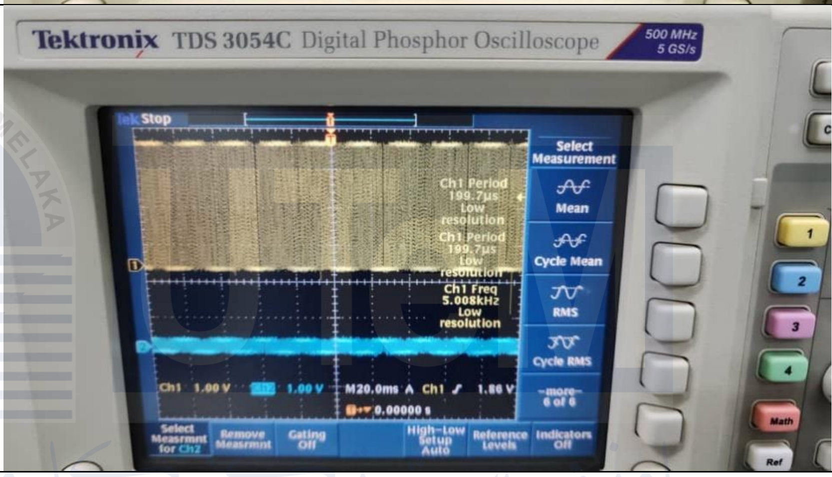
4.3 Hardware Results Analysis

4.3.1 Oscilloscope-Based SPWM Signal Generation

Pin 38 of the Arduino Due is represented by Channel 1 (yellow waveform) in the oscilloscope while Pin 34 is represented by Channel 2 (blue waveform). The simultaneous monitoring of both pins allows a clear comparison between the two waveforms.

Table 5.1: Output result for SPWM Signal

STATE	OUTPUT RESULT
When Pin 38 is high, Pin 34 is low	
When the both waveforms are superimposed	

<table>
<tr><td>The both waveforms are clearly complementary to each other</td><td>
</td></tr>
<tr><td>Both waveforms at timescale 20ms</td><td>
</td></tr>
</table>

The produced SPWM waveforms, illustrated in the figures, validates the coding utilized for SPWM generation is suitable. The two waveforms are complementary and synchronized, providing optimal efficiency for managing inverter switches. This exact synchronization is vital to attain effective power conversion and minimizing harmonic distortion.

4.3.2 Analyzing MOSFET Drive Output Signals

The MOSFET Driver's VCC pin is set to receive 15V from DC power supply while the transistor's drain terminal will receive 5V.

Figure 4.4: DC Supply for circuit

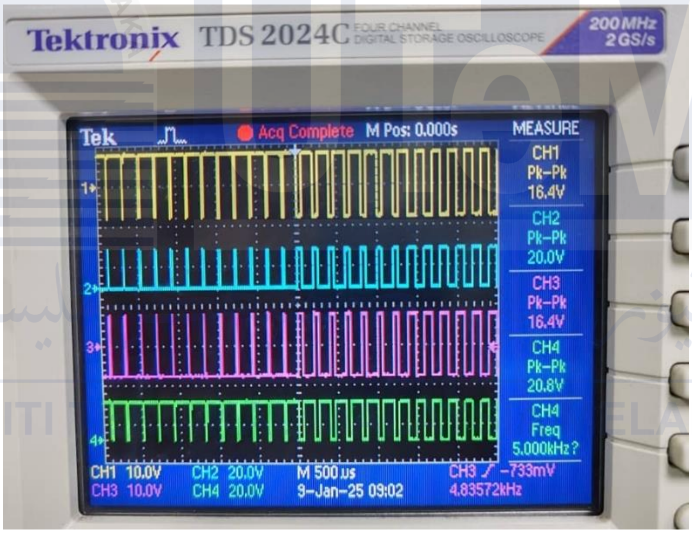


Figure 4.5: Output at each gate of transistor terminal

It is important to measure the output at each gate terminal of the transistor to ensure the MOSFET Driver is functioning correctly. Hence, from the oscilloscope it can be observed that all the transistor is producing 10 Vpp and above. Channel 1 and Channel 3 are both low-side transistors whereas Channel 2 and Channel 4 are high-side transistors. As expected, the output at high-side is greater than the low-side.

4.3.3 Investigating MOSFET Driver Signals Based on DC Supply

Table 4.2: DC Supply vs MOSFET Amplitude Values

DC SUPPLY (V)	OUTPUT SIGNAL (V_{PP})	
	Low-side Transistor	High-side transistor
5	16.4V	20.0V
10	16.4V	25.2V
15	16.4V	30.4V
20	16.4V	38.8V

When tested with different amounts of DC supply, it can be observed that the peak-to-peak voltage of the low-side remains the same while the high-side transistor shows a steady increase. This could be due to gate voltage typically referenced to ground and does not require a higher voltage than the supply.

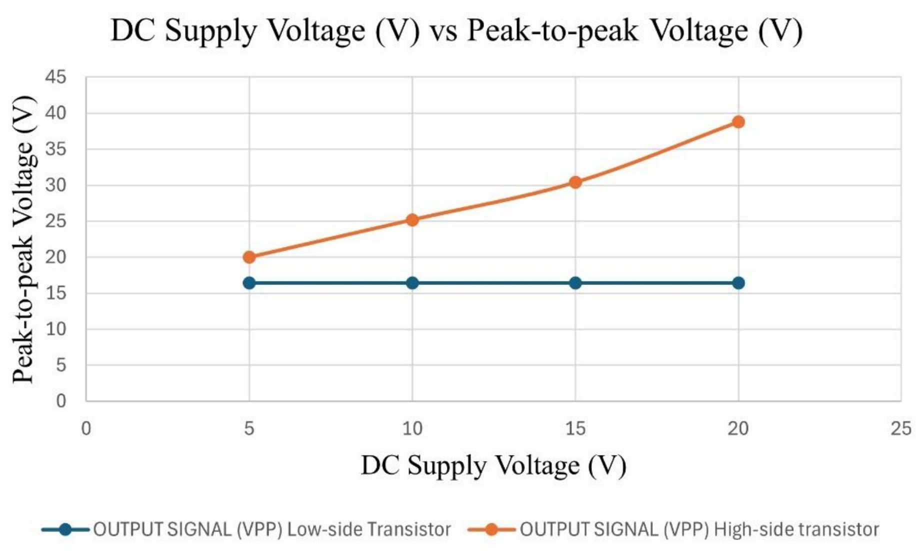


Figure 4.6: DC Supply Voltage (V) vs Peak-to-peak Voltage (V)

4.3.4 Observation of RC Filter Performance

As per methodology, it has been deduced that the cutoff-frequency will be used is 350Hz, along with resistor and capacitor having values of 1Ω and 470 µF respectively. To test the filter, a function generator is used to act as an input voltage supply. The waveform produce is expected to be a clean sine wave with the same frequency used at the input voltage.

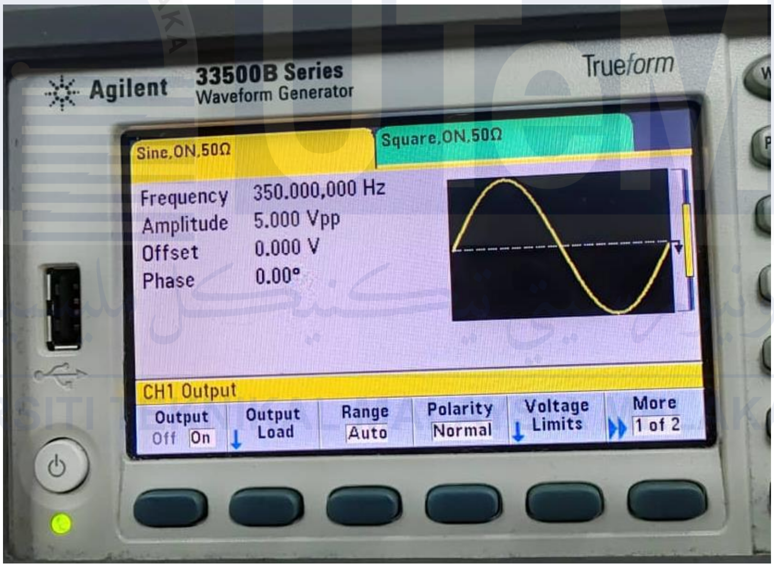


Figure 4.7: Setting for function generator

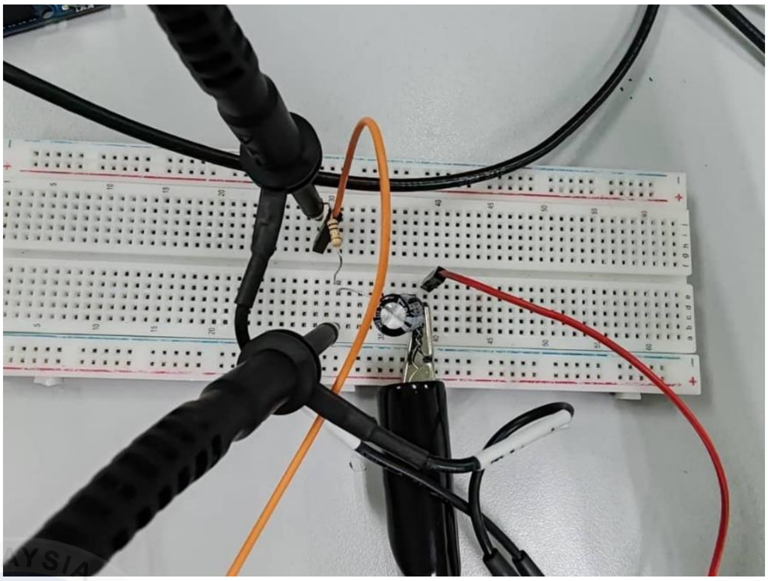


Figure 4.8: Circuit connection for RC Filter

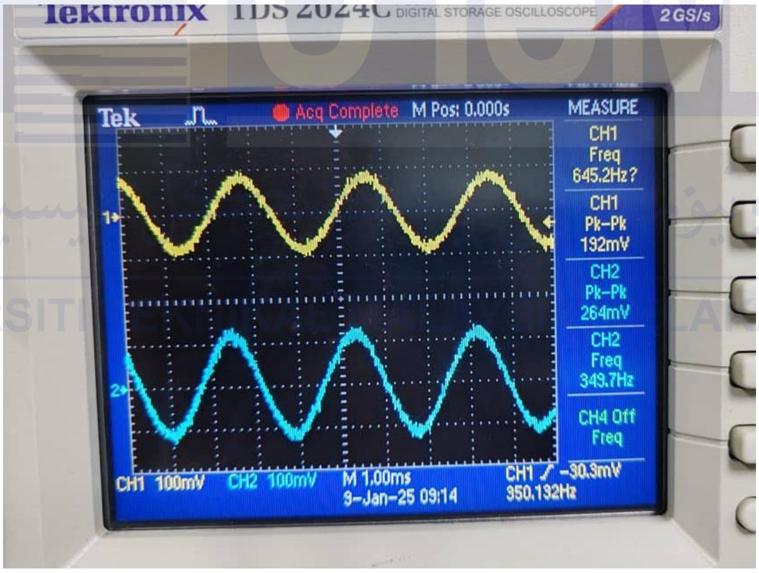


Figure 4.9: Output waveform for RC Filter

From the oscilloscope, it is clearly evident that the RC filter circuit is functioning as desired. The output signal will still have the same frequency (350 Hz), as the RC filter does not affect the frequency of the input signal. The attenuation is so significant that the output voltage is almost negligible.

4.3.5 Oscilloscope Monitoring of the MOSFET Switching

Based on Figure 4.2, the simulation's connections were reproduced in hardware and examined using an oscilloscope. The output is identical, indicating that the two switching complement one another. In an inverter circuit, two transistors are switched on at the same time while the other two remain off. This complimentary switching ensures appropriate functioning, since one set of transistors conducts while the other is off, allowing for the correct phase inversion. Channel 3 represents the first set of transistors while Channel 4 represents the second set of transistors. The peak-to-peak voltage appears to have almost similar values to the input voltage and input frequency. This comparison proves that the switching of the transistor is functioning as desired.

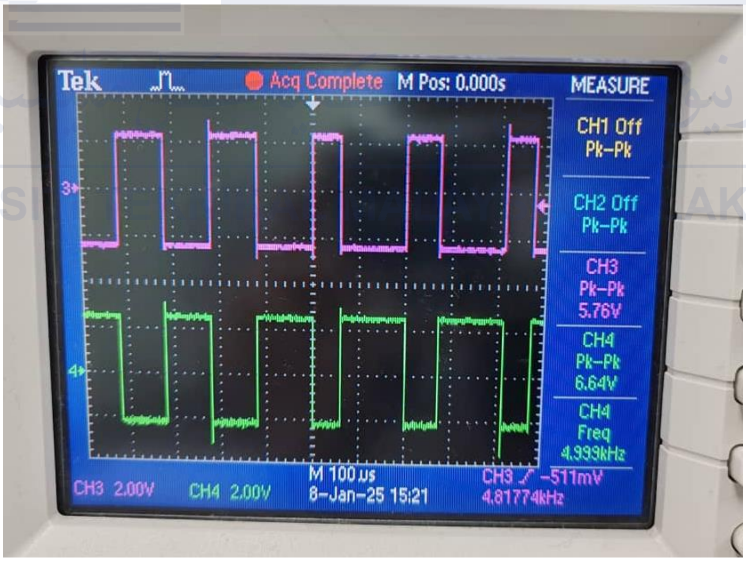


Figure 4.10: MOSFET Switching Output

Figure 4.11: The same output at 10ms

4.3.6 Analysis of Various Capacitor Values for Inverter's Output

The project tested the filter capacitor with three values: 100μF, 220μF, and 470μF, to examine the variations in the purity of the sine wave output generated by the inverter circuit. By examining the impacts of various capacitor values, the effectiveness of the filter in refining the output can be more thoroughly grasped. This procedure aids in refining the filter design, guaranteeing effective functioning of the inverter and enhancing waveform clarity, signal reliability, and the system's overall efficiency.

Table 4.3: Capacitor Values and Peak-to-peak Voltage

Capacitor Values (μF)	Peak-to-peak Voltage (V)
100	7.84
220	6.96
470	6.72

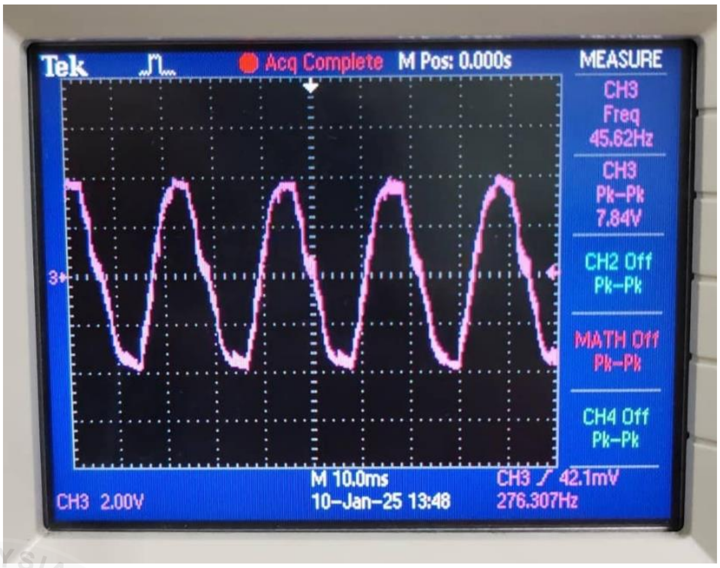


Figure 4.12: Output peak-to-peak voltage for 100µF capacitance

Figure 4.13: Output peak-to-peak voltage for 220µF capacitance

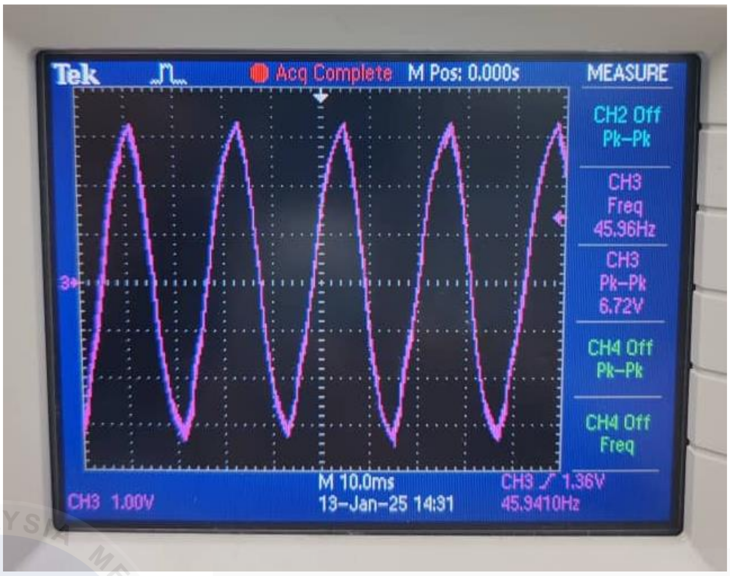


Figure 4.14: Output peak-to-peak voltage for 470µF capacitance

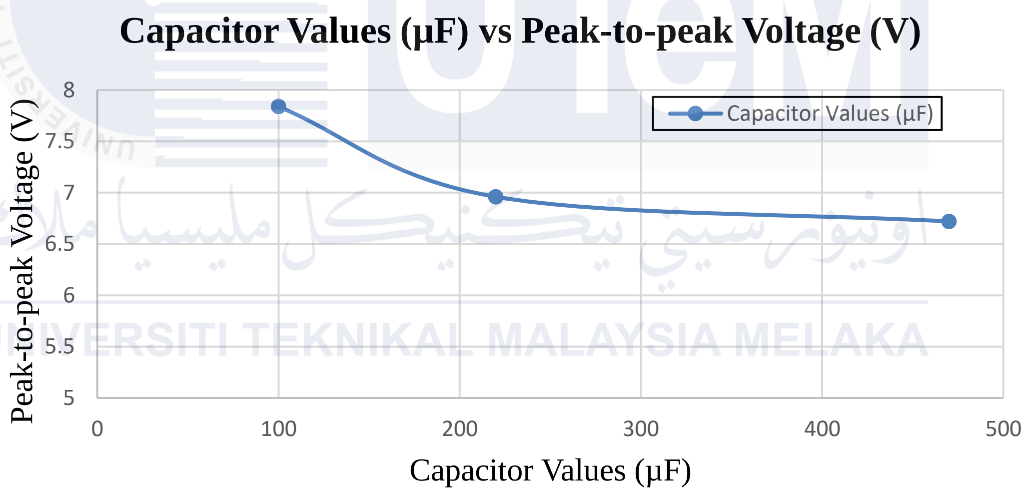


Figure 4.15: Graph of Capacitor Values vs Peak-to-peak Voltage

Based on the above table, a low peak-to-peak voltage indicates that the filter capacitor has reduced ripples in the output voltage. The cleanliness of the signal corresponds to how similar near the output is to the ideal sine wave, with smaller peak-to-peak variations suggesting less ripple and a more consistent signal. Hence, the most suitable capacitance to use is 470µF for this circuit.

4.3.7 Observation of Pure Sine Wave Output on Oscilloscope

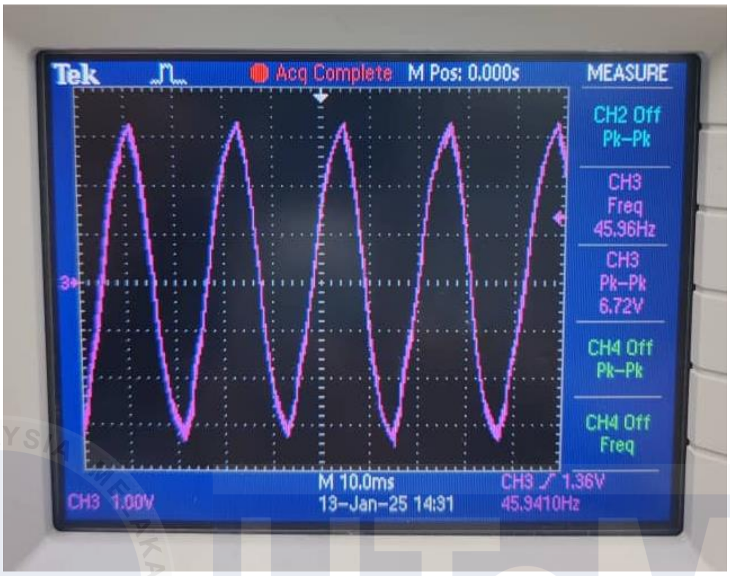


Figure 4.16: Final output of pure sine wave

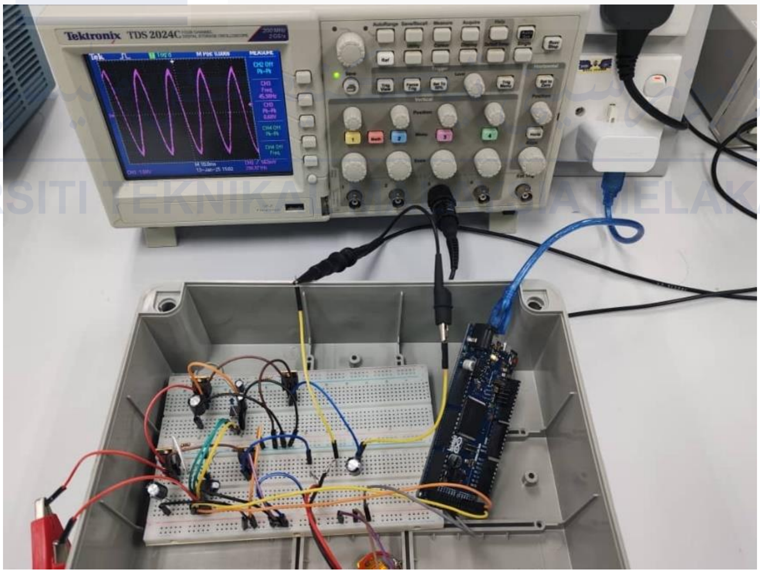


Figure 4.17: Complete hardware setup for circuit connection

4.3.8 Effect of DC Supply Voltage on Peak-to-Peak Sine Wave Output

In this section, various DC supply voltages will be tested to evaluate their impact on the peak-to-peak voltage of the sine wave output, as observed on the oscilloscope. This analysis aims to understand how different supply voltages influence the signal's quality and stability. The results will aid in optimizing the inverter's performance, ensuring consistent and reliable output across varying input conditions. The DC supply voltages tested ranges from 5V to 12V. This range is selected as a part of the sample to observe the impact on the sine wave produced.

Table 4.4: DC Supply Voltage and Peak-to-peak Voltage

DC Supply Voltage (V)	Peak-to-peak Voltage (V)
5	6.72
6	7.00
7	7.12
8	8.3
9	9.6
10	10.6
11	12.2
12	13.4

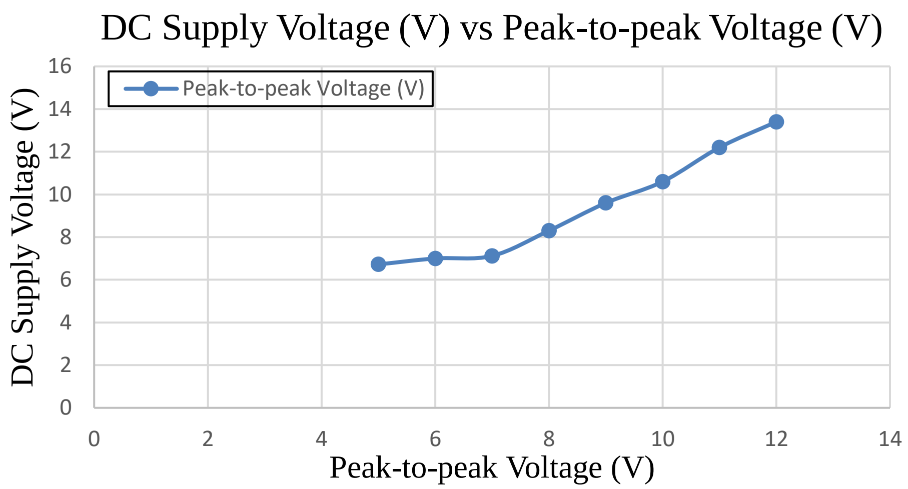


Figure 4.18: Graph of DC Supply Voltage (V) vs Peak-to-peak Voltage (V)

Because the inverter generates the AC waveform using the DC voltage as a reference, the peak-to-peak voltage of the output sine wave rises in tandem with it. The inverter is designed to transform the DC input into an alternating signal, with the output sine wave's amplitude closely corresponding to the input voltage. A greater DC supply gives more "headroom," allowing the inverter to create a bigger voltage swing, which increases the peak-to-peak voltage of the output waveform. As a result, when the DC supply increases, the inverter may produce an AC signal with a larger peak-to-peak voltage.

4.3.9 Calculating Voltage Efficiency

Formula to calculate Voltage Efficiency is,

$$Voltage\ efficiency = \frac{\text{Output Voltage}}{\text{Input Voltage}} \times 100\%$$

The peak-to-peak voltage as observed from the oscilloscope is 6.72 Vpp. Hence when its is divided by 2 to obtain peak voltage, which is the equivalent to the amplitude of the waveform.

$$Peak\ Voltage = \frac{6.72}{2}$$

$$Peak\ Voltage = 3.36\ V$$

Substituting values into voltage efficiency formula,

$$Voltage\ efficiency = \frac{3.36\text{V}}{5\text{V}} \times 100\%$$

$$Voltage\ efficiency = 67.2\%$$

The 67.2% efficiency of the inverter is probably due to various losses. Switching losses in MOSFETs during transitions, particularly at elevated frequencies, converts energy into heat. Conduction losses due to the on-resistance of the MOSFETs and the resistive elements in the circuit additionally diminish efficiency. The RC filter can also aid in energy loss while smoothing the output. Moreover, inadequate thermal management raises component resistance because of elevated temperatures. Load discrepancies or a low power factor may worsen inefficiencies. Enhancing efficiency requires optimizing switching rates, utilizing low-resistance parts, improving cooling systems, and ensuring appropriate load matching to reduce energy losses and boost overall performance.

4.4 Results Discussion

4.4.1 Feature and Performance Comparision Table of Project vs Previous Projects

A comparision table helps to analyse the difference between two categories , providing clear observation and making interpretion of ideas easier.

Table 4.5: Comparision Table of this Project vs Previous Projects

Feature/Performance	This Project	Previous Projects
Microcontroller	Arduino Due	PIC16F877, PIC18F4550, STM32
Switching Technique	Unipolar SPWM	Bipolar SPWM, Modified PWM
Output Voltage	Pure sine wave (220V, 50Hz)	Pure or modified sine wave
Filter	Low-pass RC filter for waveform smoothing	LC or LCL filters
Flexibility	Modular and easily upgradable design	Limited scalability and adaptability
Applications	Household and small-scale solar energy systems	Industrial and larger-scale applications
Cost-Effectiveness	Affordable modular components	High costs due to specialized designs

It can be deduced from the table that this project demonstrates superior waveform quality and affordability, emphasizing its suitability for household applications compared to previous designs. However, there are also some limitations in his design that can be further improved in future designs.

1. **Practical Applications**

The capability of a solar-based pure sine wave inverter to convert DC into AC electricity makes it an efficient way to operate household devices. With minimal harmonic distortion in the waveform, it is suitable for even fragile devices like laptops, LED lighting systems and medical apparatus. This also benefits users as it lengthens the lifespan of the devices.

Moreover, the compact and affordable design of the inverter renders it suitable for use in off-grid regions, where energy availability is restricted. The solar inverter is also suitable to be used in rural areas by providing dependable energy sources. Additionally, the inverter's modular architecture enables scalability, making upgrades or adjustments to higher energy needs straightforward. Its capability for smart grid integration also makes it a significant resource for enhanced energy distribution and storage in upcoming renewable energy systems.

2. Effectiveness of the Inverter

The application of unipolar SPWM boosts energy efficiency by lowering switching losses and enhancing waveform accuracy. The RC filter employed in the circuit helps to enhance the AC output voltage waveform, producing a more stable.

Selecting the Arduino Due microcontroller enhances the system’s performance, providing quick processing capabilities and accurate management of the SPWM signals. These characteristics highlight its feasibility as a dependable and effective energy transformation system, especially for small-scale solar uses.

3. Limitations and Challenges

Despite its benefits, this inverter also has a few limitations. The consistency input of the DC voltage effects the performance of the system. This may affect the uniformity of the output waveform. The low-pass RC filter is efficient but might cause minor delays in response time, hence causing a restriction in its effectiveness during quickly varying load situations.

Another drawback is scalability. Even though the design may be appropriate for residential purposes, making it appropriate for industrial use could cause substantial alterations. For example, increasing power capacity or integrating it with a more advanced cooling system. The Arduino Due might have some restrictions for the system's ability to incorporate more complex functions, like IoT-based tracking, without major improvements.

4. Environmental and Economical Challenges

The employment of solar panels encourages the use of renewable energy, hence reducing dependability on non-renewable sources and minimizing electronic waste. With minimal harmonic distortion, energy loss is reduced, and optimal power are provided to attached devices.

From an economic perspective, the project's focus on affordability allows it to reach a broader audience. This makes it even affordable for low-income families living in off-grid locations. Utilizing easily accessible parts lowers manufacturing costs, and its modular structure decreases upkeep expenses.

4.5 Summary

Throughout Chapter 4, each result obtained using PSIM and hardware output will be presented and discussed thoroughly. Sinusoidal Pulse Width Modulation (SPWM) and MOSFET switching are critical elements in inverter circuits that generate pure sine wave output. SPWM alters the width of pulses in a square wave to resemble a sine wave and decrease harmonic distortion. MOSFETs, due to their high switching speeds and low on-resistance, makes it possible to effectively regulate current flow, allowing accurate voltage regulation and frequency control. It is also crucial to note that selecting the parameters for the filter circuit plays a major role in determining the pureness of a sine wave. Furthermore, inverters play a vital role in a range of sectors, notably clean energy systems and uninterruptible power supplies, by turning DC power into high-quality AC for hypersensitive devices. Testing and validating different values of parameters allow a better understanding of why certain behaviors behave the way they do. In a nutshell, all the results obtained in this chapter prove that this system can function in real-world applications with a few more small improvements, which are detailed in Chapter 5.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Overview

This chapter summarizes the entire project and ensures if the proposed objectives are achieved and recommends a few ideas that could be enhanced in the foreseeable future.

5.2 Conclusion

The successful completion of this project accomplishes the stated objectives, representing a substantial improvement in solar energy harvesting technology. A microcontroller-based Sinusoidal Pulse Width Modulation (SPWM) method was created to provide pure sine wave AC voltage suited for home usage. The embedded system successfully controls the voltage to assure high-quality AC electricity with very little harmonic distortion. This was made possible by the design and construction of a single-phase inverter circuit using a full-bridge configuration. Simulation clearly shows that the output voltage sinusoidal waveform is created as required.

5.3 Potential for Commercialization

The microcontroller-based pure sinewave inverter developed in this study has high commercial potential, answering a growing market need for efficient and trustworthy renewable energy solutions. Given an increasing global emphasis on sustainable living and solar energy systems, this inverter offers an upper hand due to its superior reliability and value for money. The inverter's ability to generate pure sinewave AC power with low harmonic distortion ensures compatibility with an extensive variety of household equipment, making it a viable option for domestic solar energy systems.

To properly market this technology, strategic collaborations with solar panel manufacturers and energy solution providers must be developed. These partnerships can assist incorporate the inverter into extensive solar energy bundles, improving its market appeal. Furthermore, advertising campaigns need to concentrate on the inverter's key benefits, such as greater energy efficiency, reliability, and ecological responsibility. Versatility in production and an established supply network will be necessary to meet anticipated market demand, while guaranteeing the goods are readily available to a wide variety of customers.

5.4 Future Works

To make the inverter current design more efficient with higher performance, a few alterations in certain aspects can be studied. This will allow the system to be more flexible in terms of durability and dependability in an ever-changing environment.

1. Intelligent Grid Implementation for Enhanced Energy Distribution

The inverter will feature sophisticated communication modules for smooth interaction with smart grids. This integration will enhance energy distribution, allowing for immediate load adjustments and effective storage management. Methods for efficient load balancing will be created, guaranteeing a consistent and renewable energy supply while reducing waste,

2. Sophisticated Flaw Identification and Autonomous Repairing Systems

By utilizing advanced algorithms, the inverter system incorporates ongoing surveillance for detecting and analyzing errors. Hence, the system's down-time could be integrated with self-repairing features. This not only prolongs the lifespan of the inverter but also increases its reliability in critical situations.

3. Intelligent Energy Control Through Predictive Analytics

By using historical data and computational methods, a system can predict a future event. Consequently, this allows for more smart energy planning and resource distribution. Cloud-based analytics helps to provide continual optimization by evaluating real-time data to maintain a stable performance.

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APPENDICES

Appendix A GANTT CHART BDP I

No.	Task	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1	• Project proposal • Project approval														
2	• Discuss and improve project idea • Writing project report chapter 1														
3	• Chapter 1 project report correction-scope and problem statement • Make draft for project report chapter 2 • Research on methods of project														
4	• Writing Project report chapter 2 • Presentation of work progress														
5	• Research on hardware and software to be used														
6	• Chapter 2 project report correction														
7	• Writing Project report chapter 3														

8	• PSM 1 report writing														
9	• PSM 1 draft report submission to supervisor														
10	• Presentation / Submission														

Appendix B GANTT CHART BDP II

No.	Task	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1	• BDP 2 Briefing														
2	• Plan and procure hardware components														
3	• Hardware Procurement completed														
4	• Research about sine wave hardware design														
5	• Modify the code to fit project requirements														
6	• Hardware design														
7	• Edit Report														
8	• Finalize Prototype • Update Report														
9	• Presentation BDP 2														
10	• Final Report Submission														

Appendix C ARDUINO DUE CODING

```
void setup()
{
  pinMode(38, OUTPUT); // Set pin 38 as output
  pinMode(34, OUTPUT); // Set pin 34 as output (Inversion of pin 38)
}


void loop()
{
  // SET A - 1 SET (80-20)
  PIOC->PIO_SODR = 0x40;    // Set pin 38 HIGH
  PIOC->PIO_CODR = 0x4;     // Set pin 34 LOW
  delayMicroseconds(80);
  PIOC->PIO_CODR = 0x40;    // Set pin 38 LOW
  PIOC->PIO_SODR = 0x4;     // Set pin 34 HIGH
  delayMicroseconds(20);

  // SET B - 14 SET (180-20)
  for (int i = 0; i < 14; i++)
  {
    PIOC->PIO_SODR = 0x40;
    PIOC->PIO_CODR = 0x4;
    delayMicroseconds(180);
    PIOC->PIO_CODR = 0x40;
    PIOC->PIO_SODR = 0x4;
```

```
  delayMicroseconds(20);
}

  // SET C - 1 SET (160-60)
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(160);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(60);

// SET D - 6 SET (140-60)
for (int i = 0; i < 6; i++)
{
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(140);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(60);
}

// SET E - 0.5 SET (120)
PIOC->PIO_SODR = 0x40; PIOC->PIO_CODR = 0x4; delayMicroseconds(120);
```

```
// SET F - 6 SET (100-100)
PIOC->PIO_CODR = 0x40; PIOC->PIO_SODR = 0x4; delayMicroseconds(100);
for (int i = 0; i < 5; i++)
{
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(100);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(100);
}
PIOC->PIO_SODR = 0x40; PIOC->PIO_CODR = 0x4; delayMicroseconds(100);


// SET G - 0.5 SET (120)
PIOC->PIO_CODR = 0x40; PIOC->PIO_SODR = 0x4; delayMicroseconds(120);


// SET H - 6 SET (60-140)
for (int i = 0; i < 6; i++)
{
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(60);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(140);
```

```
}


  // SET I - 1 SET (60-160)
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(60);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(160);

// SET J - 13 SET (20-180)
for (int i = 0; i < 13; i++)
{
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(20);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(180);
}


  // SET K - 1 SET (20-380)
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(20);
```

```
  PIOC->PIO_CODR = 0x40;

  PIOC->PIO_SODR = 0x4;

  delayMicroseconds(380);


// SET L - 13 SET (20-180)

for (int i = 0; i < 13; i++)

{

  PIOC->PIO_SODR = 0x40;

  PIOC->PIO_CODR = 0x4;

  delayMicroseconds(20);

  PIOC->PIO_CODR = 0x40;

  PIOC->PIO_SODR = 0x4;

  delayMicroseconds(180);

}


  // SET M - 1 SET (20-160)

  PIOC->PIO_SODR = 0x40;

  PIOC->PIO_CODR = 0x4;

  delayMicroseconds(20);

  PIOC->PIO_CODR = 0x40;

  PIOC->PIO_SODR = 0x4;

  delayMicroseconds(160);


// SET N - 6 SET (60-140)

for (int i = 0; i < 6; i++)
```

```
{
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(60);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(140);
}


  // SET O - 1.5 SET (60-120-80)
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(60);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(120);
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(80);


// SET P - 11 SET (100-100)
for (int i = 0; i < 11; i++)
{
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
```

```
  delayMicroseconds(100);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(100);
}


  // SET Q - 1 SET (120-60)
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(120);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(60);


// SET R - 6 SET (140-60)
for (int i = 0; i < 6; i++)
{
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(140);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(60);
}
```

```
  // SET S - 1 SET (160-20)
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(160);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(20);

// SET T - 14 SET (180-20)
for (int i = 0; i < 14; i++)
{
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(180);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
  delayMicroseconds(20);
}

  // SET U - 1 SET (100-20)
  PIOC->PIO_SODR = 0x40;
  PIOC->PIO_CODR = 0x4;
  delayMicroseconds(100);
  PIOC->PIO_CODR = 0x40;
  PIOC->PIO_SODR = 0x4;
```

```
    delayMicroseconds(20);



}
```