CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Over the years, the world has come to realize that fossil-fuel based energy systems are unsustainable and has huge adverse effects on the earth's ecosystem. This has resulted in an increased investment in renewable energy systems, and a renewed vigor towards perfecting their technologies [1]. Solar power systems are one of the most important and widely used renewable energy systems in the world today. They involve the use of active solar techniques such as the use of photovoltaic systems, to harness and transform solar energy into a useful source of electricity [2]. However, in order to be able to utilize the electrical energy produced from these systems, the technology of DC to AC converters (inverters) play a very fundamental role.

An inverter is a device that is used to change a DC input voltage to a symmetric AC output voltage of desired magnitude and frequency [3]. In a solar power system, inverters are required in converting the DC output of the solar panels to alternating current (AC) on which a majority of residential and commercial appliances run. These inverters can be interfaced directly with the solar panels and connected with the electrical grid (grid-tied systems) or they can take their DC power from batteries that are charged by these solar panels and/or the mains power supply. The input voltage of an inverter may also come from fuel cells and other DC voltage sources [4].

The output voltage of an inverter could be fixed or variable at a fixed or variable frequency. A variable output voltage can be obtained by varying the input DC voltage and keeping the gain of the inverter constant. However, if the DC input voltage is fixed and not controllable, a variable output voltage can be obtained by varying the gain of the inverter. This is normally accomplished through a process known as Pulse Width Modulation (PWM) [3]. The output voltage waveforms of ideal inverters should be sinusoidal. However, the waveforms of practical inverters are non-sinusoidal and contain certain harmonics. For low and medium power applications, square-wave or quasi-square-wave voltages may be acceptable. However, for high power applications, low distorted sinusoidal waveforms are required. With the availability of high-speed power semiconductor devices, the harmonic contents of output voltage can be minimized or reduced significantly by switching techniques [3].

The switching circuitry and control mechanism of an inverter system is regarded as its most critical part as it dictates the properties and operating parameters of the inverter system. Hence, great care is usually taken in designing this section of the system in order to minimize or avoid failure. This switching circuitry normally consists of controlled turn-on and turn-off devices such as Bipolar Junction Transistors (BJTs), Metal Oxide Semiconductor Field-Effect Transistors (MOSFETs), Insulated-Gate Bipolar Transistors (IGBTs), Metal Oxide Semiconductor Controlled Thyristors (MCTs), Static Induction Transistors (SITs), and Gate-Turn-Off Thyristors (GTOs) [3]. However, MOSFETs which are the most commonly used switching devices in inverter systems are used for the purpose of this work.

Power MOSFET semiconductor devices are normally used in power electronic systems due to their high heat transfer capability and high power density [5]. As a result of the critical nature of the switching circuitry and control mechanism of these systems, the reliability and performance of these power MOSFETs are very significant. Power MOSFETs are commonly used under high ambient temperatures and frequent power cycling conditions [5]. This often results in an increase in the junction temperature which is the highest operating temperature of the actual semiconductor material in an electronic device. In operation, this temperature is higher than the case temperature and the temperature of the part's exterior [6]. Many semiconductors and their surrounding optics are small, making it difficult to measure junction temperature with direct methods such as thermocouples. However, junction temperature can be determined through indirect methods by determining the corresponding case temperature and mathematically evaluating the junction temperature [7]. All semiconductors have some specified safe upper limit for junction temperature, usually in the order of 150°C. This maximum junction temperature is a worst case limitation which must not be exceeded as it results in device failure [8]. Hence, for reliability reasons, it is important to ensure that the power MOSFETs, used in the switching circuitry of the inverter system, always operate within their respective thermal limits.

In an inverter system, MOSFETs are normally used in various switching topologies or configurations between voltage rails. Here, a malfunctioning of the control mechanism or a defective switching of the MOSFETs will effectively short-circuit the supply in a condition known as a 'shoot-through' [8]. When this arises, all supply decoupling capacitors discharge rapidly through both MOSFETs during every switching transition, causing short but large current pulses. Overcurrent even for a short duration can cause progressive damage to a MOSFET, often with little noticeable temperature rise before failure [8]. This condition threatens the safe operation of the switching circuitry of inverter systems and should be mitigated.

In this project, a sinusoidal wave inverter system is designed and implemented using a primary and a secondary microcontroller. The primary microcontroller is used solely for the purpose of achieving a seamless Sinusoidal Pulse Width Modulation (SPWM) in the switching mechanism, whereas the secondary microcontroller is incorporated in order to improve the general working of the system by minimizing failure. The secondary microcontroller with the aid of temperature sensors is used to monitor the MOSFET junction temperatures by constantly measuring their case temperatures, and computing their corresponding junction temperatures in real-time. It is also used along with high frequency current sensors; to detect and manage short-circuits in the switching circuitry as well as system overload conditions, in order to timely avert a system breakdown. All these are done in a bid to improve the general working condition of the average inverter system.

1.2 Statement of Problem

Power electronic components in an inverter system are normally used under frequent power cycling conditions. This results in an increase in the junction temperature of these components and results in failure if they eventually surpass their specified safe upper limits. It also results in an increased risk of a short-circuit at the slightest malfunctioning of any of these components, which could result in an extensive damage of the system. Hence, there is a need to incorporate methods that will ensure that these components operate constantly within their respective thermal limits, and also help to check the harmful effects that may result from a short-circuit and other overcurrent conditions. This will help to improve the general working condition of the inverter and hence its reliability.

1.3 Aim and Objectives of the Study

The aim of this project is to improve the working condition of a 500W pure sine wave inverter system.

The objectives of this project are:

i. To design and wind a 500W transformer.

ii. To design and implement a 12V and 5V D.C power supply circuit using capacitors, LM7812 and LM7805 voltage regulators.

iii. To design and implement a primary control circuit (oscillator) using a PIC16F684 microcontroller.

iv. To design and implement a feedback circuit using diodes, capacitors, resistors and opto-coupler.

v. To design and implement a secondary control circuit using a PIC16F887A microcontroller.

vi. To design and implement a temperature sensing circuit using thermistors and resistors.

vii. To design and implement a short-circuit/overload sensing circuit using an ACS712 high bandwidth hall effect-based linear current sensor.

viii. To design and implement a battery level sensing circuit using resistors.

ix. To design and implement a MOSFET driver circuit using opto-couplers, capacitors, resistors and diodes.

x. To design and implement a H-bridge power circuit using MOSFETs and resistors.

1.4 Significance of the Study

This project will be of great benefit to:

i. Companies that deal on inverter systems design and manufacturing, as it will help them to improve the working condition of their products.

ii. Power electronics engineers and students for the purpose of research into D.C to A.C converter design.

1.5 Scope of the Study

The scope of this project is delimited to an inverter with a:

i. Sinusoidal wave output.

ii. 24V D.C input voltage.

iii. 500W maximum load.

iv. Single phase supply.

CHAPTER TWO

LITERATURE REVIEW

In order to develop efficient and more reliable means of converting DC to AC, a lot of research has been done in the area of inverter systems design over the years. This has resulted in the formulation of various techniques for improving the working condition and reliability of inverter systems.

In [9], a 600W, single-phase, pure sine wave inverter was designed using a PIC16F877A microcontroller. In order to protect the bridge circuit and hence improve the working condition of the system, MOSFET gate protection was incorporated by introducing a resistor between the gate and source of the MOSFETs. This was done to prevent the accidental turn on of the MOSFETs by external noise usually at startup when the gate is floating. A MOSFET may sometimes turn on with a floating gate because of the internal drain to gate Miller capacitance. A gate to source resistor acts as a pull-down to ensure that the MOSFETs are turned off. The principle behind this operation is that when the parasitic capacitance of the circuit comes into play, the resistor creates an RC circuit with its time constant. This RC circuit delays the time the circuit switches on just enough to allow the complementary part of the bridge circuit to switch off. Typical values of this resistor are 1 kΩ, 10 kΩ, or 100 kΩ depending on the rail voltage of the H-bridge. This technique helps in preventing any shoot-through condition that might result from the accidental turn on of MOSFETs from external noise; however it has no means of protecting the bridge if the control circuit were to malfunction. It also has no means of protecting the bridge if the inverter became overloaded, or makes any provision to prevent the MOSFETs from exceeding their safe operating thermal limits. These factors serve as setbacks to the technique adopted by [9] to improve the working condition of the inverter system.

In [10], a digital, single-phase, high frequency sine wave inverter was designed and implemented using an STM32F103VCT6 microcontroller. This microcontroller is a high-density performance line ARM-based 32-bit microcontroller. It was used because it has a number of inbuilt modules (e.g. an inbuilt temperature sensing module) that could ease the process of improving the working condition of the inverter. This work aimed to protect the inverter against the harmful effects of some abnormal conditions which may occur in inverter operation such as the short circuiting of the main circuit or overcurrent, overheating of the heat sink and so on. STM32F103VCT6 is internally integrated with 12-bit precision analog to digital conversion module with built-in sample/hold (ADC). According to the technical requirements of the system, the accuracy of the 12-bit ADC could meet the detection and control requirements of the resolution of voltage, current and temperature. Therefore, the internal integrated ADC of the control chip was used directly to meet the control precision. The protection circuit detects the overcurrent signal of the power switch tube and the short circuit signal by means of Holzer current sensors and also detects the overheating signal. Once these signals are received, the protection circuit sends a signal to the DSP power protection pin of the microcontroller, to notify the control system and take corresponding measures in order to limit the damage. However, the method adopted by this work in detecting excessive temperature rise serves as a drawback. This is because measuring the case temperature of the switches from the heat sink is error-prone as it gives an inaccurate interpretation of the actual temperature of the switches (since heat sinks do not have a perfect thermal conductivity). Furthermore, the junction temperatures of the switches, which are the actual temperature values that bear a relevance to the reliability of the switches, are not the values that are being computed by the microcontroller. Hence this work lacks accuracy in its attempt to maintain the switching devices within their permissible thermal limits.

In [11], a real-time system for protecting and monitoring an inverter was designed and constructed for a 300W, single-phase, pure sine wave inverter. The proposed system consists of a hardware protection unit for fast reaction, load protection and inverter fail-safe operation and a microcontroller unit for calculating critical parameters of the inverter operation. The microcontroller used is the Intel 80C196KC with a 16 MHz clock. It has a 16-bit CPU, a 10-bit, 8-channel successive approximation A/D converter, a 4KB internal RAM, a 16KB internal EEPROM and a serial communication port. In this work, an IC temperature sensor was used to measure the ambient temperature while negative temperature coefficient (NTC), low-cost thermistors were used to monitor the temperature of the inverter power MOSFETs. The output signals from these sensors were compared with predefined thresholds and the results were stored in an external register-set consisting of latches in the microcontroller. Also overcurrent protection circuits were developed for the protection of every set of parallel-connected MOSFETs. The output values of the MOSFETs overcurrent protection circuits were also stored in the register-set. During normal operation, all register-set bits are in logic state ‘1’, while in case of inverter specifications violation, the corresponding register set bits are set to logic ‘0’. Then the hardware protection circuit turns-off the inverter and forwards an interrupt to the microcontroller, causing the check of the register-set bits one by one. The microcontroller parses the nature of the problem from the position of logic 0s in the register-set and informs the operator accordingly. However, a flaw in the technique adopted in this work in improving the inverter working condition, can be seen in its temperature monitoring. The temperature values that were measured in this work, and used in maintaining the MOSFETs within their thermal limits were the case temperatures. This approach is a flaw since the case temperature of the MOSFET is an inaccurate representation of the MOSFET junction temperature, which is the actual temperature that determines its reliability and level of operation.

In [12], a design and hardware implementation of an 8051 microcontroller based single-phase inverter was carried out. In order to improve the working condition of the inverter design, a protection technique known as snubber circuit protection was incorporated into the bridge circuit. When the rate of rise of voltage across a switching device is high, the charging current flows through it and the device is turned on without any gate signal. This type of triggering is called false triggering and could result in a short-circuit. Hence, a snubber circuit is needed to help keep the rate of rise of voltage within specified limits. A snubber circuit is a series combination of resistance and capacitance and is connected across the switching device. Connecting only a capacitor across the device could be sufficient in protecting the device from unwanted triggering. This is because when the switch is closed, the supply voltage suddenly appears across the circuit and the capacitor behaves like a short circuit, making the voltage across the switch to be zero. With time, voltage across the capacitor builds up slowly with a rate of rise of voltage that is less than its maximum limit. However, the snubber resistance is needed to limit the discharging current because the resistance of the device during forward conduction is quite low. Discharging current flows when the switch is turned on by gate pulse and snubber capacitance finds a path to discharge through the closed switch. Discharging current should be limited to prevent any damage to switching device due to high rate of rise of current during turn on. The technique adopted in this work goes a long way in protecting and preventing the false triggering of switching devices. However, this technique provides no help in ensuring that the switching devices always operate within their thermal limits, which is a big reliability issue. It also provides no help in ensuring that the switching devices are safe if a shoot-through condition were to occur by any means.

[13] involves the design and construction of single phase pure sine wave inverter for photovoltaic application using PIC18F4431. The system consists of a Switch Mode Power Supply (DC-DC boost converter), a full bridge inverter circuit with a passive filter. High frequency Pulse Width Modulated (PWM) pulses are generated by the microcontroller and provided to the switches in a full bridge connection. The full bridge inverter outputs a PWM sine which is later conditioned to pure sine by an L-C filter. The technique adopted in this design to improve inverter system reliability is known as soft start mechanism. Some electronic devices, such as motors, consume 600-800% of its full load current to start. This initial current is called the inrush current, which can have hazardous effects on the inverter system and appliances connected to it. Soft start is required to prevent this inrush current. To implement soft start, the voltage across the load is notched by gradually increasing the modulation index, instead of letting it jump to the full voltage. This is done by creating a nested loop in the microcontroller program, which increases the modulation index in several stages. An analog port of PIC18F4431 intakes modulation index value and by ADC (Analog-to-Digital Conversion) retrieves the value, then accordingly revises the sine lookup table by multiplying the modulation index with the peak values of sine wave sample. This modulation index is used to implement the soft start mechanism. The technique adopted by [13] above does its own fair share of limiting the chances of failure in inverter operation. However, it still shares similar shortcomings as [9] and [12], as it is found wanting in areas like temperature monitoring and control.

The design and implementation carried out in this work, aims to rectify a number of flaws in the techniques analyzed above for improving the working condition of the inverter system. The method adopted in this work is focused on protecting the inverter against two common sources of failure which are overheating of switches and overcurrent conditions. This overcurrent could be as a result of a short-circuit in the load terminals, a short-circuit in the inverter bridge (shoot-through condition) or an overload. Hence in this work, temperature sensors are interfaced with a microcontroller and used in computing the real-time junction temperatures of the inverter switches. These values are used to ensure that the inverter switches never exceed their respective thermal limits in order to avoid failure. Furthermore, high frequency current sensors are interfaced with the microcontroller and used to ensure that the inverter bridge is adequately protected from the harmful effects that might result from the occurrence of any overcurrent condition.

CHAPTER THREE

METHODOLOGY

3.1 Block Diagram of the Design

The block diagram below shows in schematic form, the interconnections between the various units of the inverter system designed in this work.

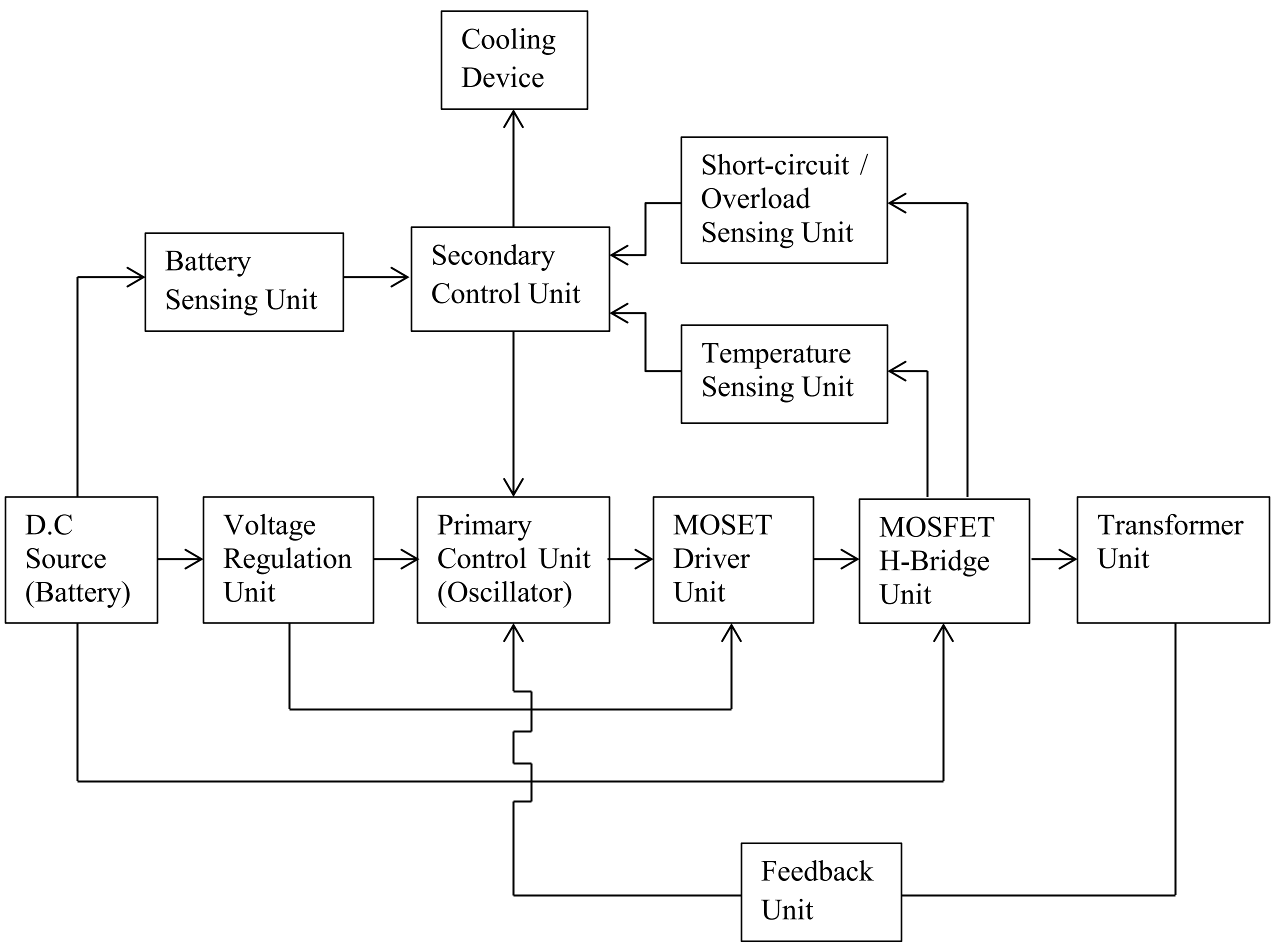

Fig. 3.1: Block Diagram of the Inverter System.

As shown in the diagram above, the inverter system designed in this work consists of two distinct control units which are the primary and secondary control units. The primary control unit serves as the oscillator of the inverter while the secondary control unit on the other hand, serves to improve the working condition of the system. The secondary control unit receives data signals of various operating parameters of the inverter system from the short-circuit/overload sensing unit, battery sensing unit, and temperature sensing unit. These data signals are processed and interpreted by the secondary control unit, and used to ensure that the inverter system always operates at optimal conditions.

3.2 Voltage Regulation Unit

The voltage regulation unit performs the function of regulating the D.C source voltage to the required levels needed to power the various sections of the inverter system. In this unit, the 24V from the battery is first regulated to 12V and then subsequently to 5V. The 12V is needed to power sections like the MOSFET driver unit and the change-over unit while the 5V is needed to power the control units, short-circuit/overload sensing unit and the temperature sensing unit. The electronic components used in designing this unit are as follows:

Table 3.1: Electronic Components Used in the Design of the Voltage Regulation Unit

S/N	Component Name	Value/Rating/Type
1.	Fixed Voltage Regulator	LM7812, LM7805
2.	Capacitors	100uF (16V)

The LM7812 and LM7805 are linear voltage regulators used in maintaining steady output voltages of 12V and 5V respectively. These regulators are capable of supplying up to 1A of output current at their respective fixed voltages, which is sufficient to power all the electronic components used in the design. Filtering capacitors of 100uF (16V) were also connected at the outputs of these regulators for further smoothing as a result of the sensitive nature of some of the electronic components (like the microcontroller) to ripples. The circuit diagram of the voltage regulation unit is shown below:

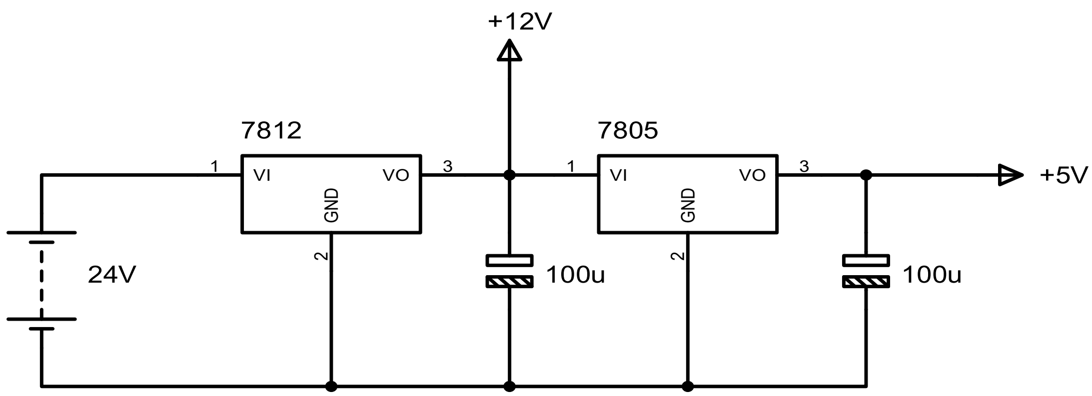

Fig. 3.2: Circuit Diagram of the Voltage Regulation Unit.

3.3 Primary Control Unit

The primary control unit serves as the oscillator of the inverter system. It is regarded as the heart of the inverter system as it dictates the nature of the output voltage that is obtained from the system. This unit generates the sinusoidal pulse-width modulated signals which are required to switch the MOSFETs of the bridge circuit accordingly. It also receives input signals from the feedback unit which it uses to adjust the pulse-width and maintain the output voltage of the inverter at a constant voltage. The electronic components used in designing this unit are as follows:

Table 3.2: Electronic Components Used in the Design of the Primary Control Unit

S/N	Component Name	Value/Rating/Type
1.	Microcontroller	PIC16F684
2.	Crystal Oscillator	16MHz
3.	Capacitors	22pF
4.	Fixed Resistors	4.7kΩ, 10kΩ

The primary control unit in this work is a digital kind of oscillator. Hence, a microcontroller was programmed and used in performing this function. Microcontrollers are small computers on a single integrated circuit. They contain one or more CPUs (processor cores) along with memory and programmable input/output peripherals. A PIC16F684 microcontroller is used in designing the primary control unit in this work. PIC16F684 is a 14-pin, flash-based, 8-bit CMOS microcontroller. This microcontroller was chosen because it contains an Enhanced Capture, Compare, PWM module (ECCP) which makes it possible to produce a variable pulse width signal based on a pulse width and period value set in the applications code along with auto-shutdown, auto-restart, dead-band delay and PWM steering modes [14]. These features greatly reduce the length of code required to achieve an efficient sinusoidal pulse-width modulation (SPWM). In addition, the ECCP module makes it possible to directly obtain multiple output PWM signals, for various PWM arrangements, without having to incorporate any other hardware components like logic gates. This microcontroller is also of a sufficiently low cost when compared to other microcontrollers and is readily available. The PIC16F684 has the following main features [14]:

i. Enhanced Capture, Compare, PWM module: 16-bit Capture/Compare, 10-bit PWM with 1, 2 or 4 output channels, programmable "dead time" and max frequency of 20 kHz.

ii. 10-bit, up to 8-channel Analog-to-Digital Converter (A/D)

iii. Maximum Crystal Speed of 20MHz

iv. Wide operating voltage range of 2.0V to 5.5V

v. Flash Program Memory of 2048 words

vi. Data Memory (RAM) of 368 bytes

vii. EEPROM Data Memory of 256 bytes

viii. Analog Comparator module with two analog comparators

The pin diagram of the PIC16F684 microcontroller is as follows:

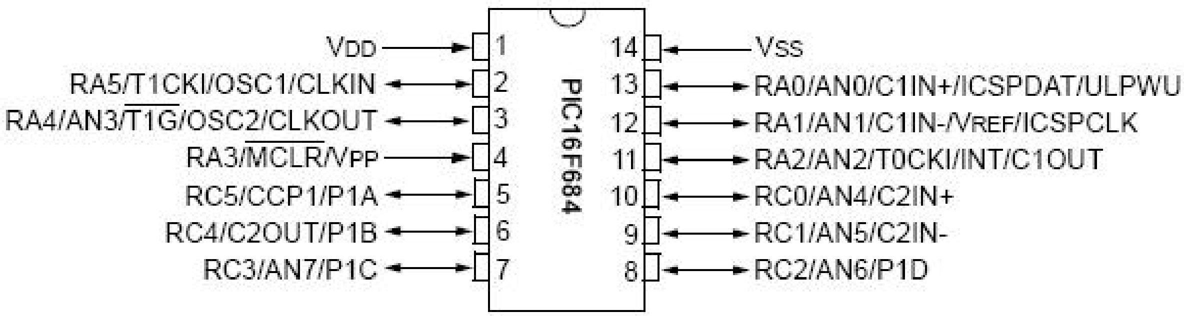

Fig. 3.3: Pin Diagram of the PIC16F684 Microcontroller [14].

Table 3.3: Pin Descriptions for the PIC16F876A Microcontroller [14].

S/N	Pin Name	Pin No.	Description
1.	V_{DD}	1	Positive supply for logic and I/O pins.
2.	RA5/OSC1	2.	PORTA digital I/O or Oscillator crystal input
3.	RA4/AN3/OSC2	3.	PORTA digital I/O or A/D channel 3 input or Oscillator crystal output
4.	RA3/MCLR/V_{PP}	4	PORTA digital I/O or Master clear reset or Programming voltage input.
5.	RC5/CCP1/P1A	5	PORTC digital I/O or Capture input/Compare output or PWM output
6.	RC4/ /C2OUT/P1B	6	PORTC digital I/O or Comparator 2 output PWM output
7.	RC3/AN7/P1C	7	PORTC digital I/O or A/D channel 7 input or PWM output
8.	RC2/AN6/P1D	8	PORTC digital I/O or A/D channel 7 input or PWM output

9.	RC1/AN5/ C2IN-	9	PORTC digital I/O or A/D channel 5 input or Comparator 2 input
10.	RC0/AN4/ C2IN+	10	PORTC digital I/O or A/D channel 4 input or Comparator 2 input
11.	RA2/AN2//INT/ C1OUT	11	PORTA digital I/O or A/D channel 2 input or External Interrupt or Comparator 1 output
12.	RA1/AN1/ C1IN-	12	PORTA digital I/O or A/D channel 1 input or Comparator 1 input
13.	RA0/AN0/ C1IN+	13	PORTA digital I/O or A/D channel 0 input or Comparator 1 input
14.	V_{SS}	14	Ground reference for logic and I/O pins

In this design, ports RC5, RC4, RC3 and RC2 (P1A – P1D) were configured as PWM outputs and used in generating two SPWM signals and two square wave signals for the four sides of the H-bridge. Port AN0 was also used in receiving analog voltage signals from the feedback unit, which the microcontroller uses to adjust the pulse-width of the gating signals. The external interrupt pin at port RA2 of the microcontroller was configured as an auto-shutdown pin for the ECCP module in the microcontroller program. This auto-shutdown is activated only when logic zero (ground) is sent to this external interrupt pin. Hence, this pin was pulled up to V_{DD} using a 4.7kΩ resistor to ensure that logic zero never appears at the interrupt pin by error in order to avoid code malfunction.

An external oscillator circuit made up of a 16 MHz crystal oscillator and two 22pF capacitors was connected between pins 2 and 3 of the microcontroller. Crystal oscillators are used to generate clock pulses required for the synchronization of all the internal operations of the microcontroller. A 16MHz crystal oscillator was used because its value is below the maximum crystal speed of the microcontroller which is 20MHz.

Ports RC5 – RC2 of the microcontroller, which were configured as PWM outputs, were pulled down to ground using 10kΩ resistors. This was done in order to ensure that these output pins are kept low (0) until the microcontroller gives out a high (1) through them. A 10kΩ resistor was used for the pull-down because of the 330Ω limiting resistors connected in series with the output pins to protect the opto-couplers. A sufficiently higher resistance of 10kΩ ensures that nearly all the current from the output pin of the microcontroller flows through the 330Ω resistors when the output pins give out a high. This is because current always tends to flow through the path of least resistance.

The Master Clear Reset input pin (MCLR) was also pulled up to the +5V supply using a 4.7kΩ resistor. This pin is an active low reset pin for the microcontroller. Hence, it was pulled up to ensure that the MCLR pin never receives a low by error to avoid any interruption of the microcontroller program.

In the microcontroller program, the carrier frequency of the SPWM signal was set at 16 kHz. This is because 16 kHz is found towards the end of the audio frequency spectrum; hence the noise generated will not be excessive. Also, this frequency is less than 20 kHz which is the maximum frequency of the ECCP module of the microcontroller.

In order to calculate the number of pulses that will be required in the SPWM signal for this carrier frequency, the following calculations were done:

$$Total\,number\,of\,pulses\,required = \frac{Time\,period\,of\,reference\,signal}{Time\,period\,of\,carrier\,signal} \tag{3.1}$$

Frequency of reference signal = 50 Hz, hence;

$$Time\,period\,of\,reference\,signal = {}^{1}/_{50} = 0.02\,s$$

Frequency of carrier signal = 16 kHz, hence;

$$Time\ period\ of\ carrier\ signal = {}^{1}/_{16000} = 6.25\ \times 10^{-5}\ s$$

Therefore,

$$Total\ number\ of\ pulses\ required = \frac{0.02}{6.25\ \times 10^{-5}} = 320$$

However, pulses are generated for only half a cycle and then inverted and used for the other half of the cycle. Hence,

$$Number\ of\ pulses = \frac{320}{2} = \mathbf{160}$$

However, for the purpose of conserving ROM space on the microcontroller, 32 pulses were generated and each pulse was called a total of 5 times to obtain the required total of 160 pulses.

The program of the microcontroller in this unit was written using MikroC Compiler. The circuit diagram of the primary control unit is shown below:

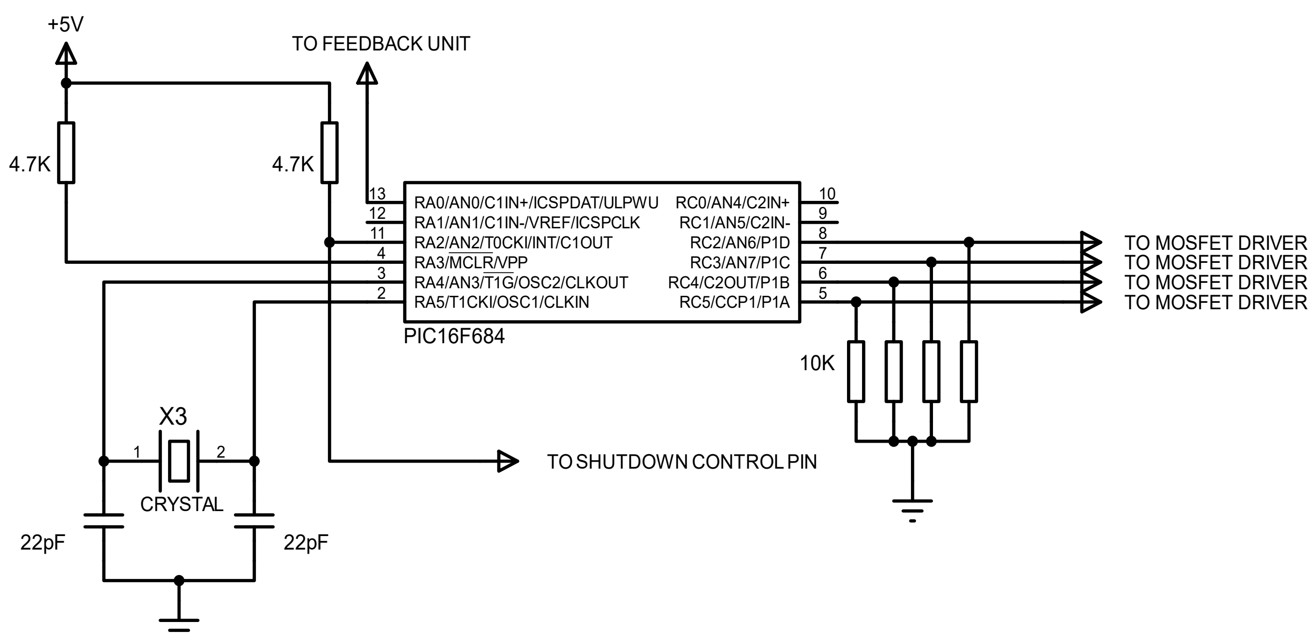

Fig. 3.4: Circuit Diagram of the Primary Control Unit.

3.4 MOSFET Driver Unit

The MOSFET driver unit serves the purpose of amplifying the power of the control signals, from the primary control unit, before feeding them to the gate of the MOSFET switches. For operating a MOSFET as a switch, a voltage sufficiently larger than the threshold voltage of the gate needs to be applied between the gate and source terminals. However, the output signals from logic devices like microcontrollers, which lie within 0 – 5V, is usually not high enough to fully turn on these MOSFETs. Hence, MOSFET drivers need to be connected between the logic device and the MOSFET for signal amplification. These drivers also provide isolation between the high power side and low power side of the inverter as a means of protecting the logic circuit (low power side) during faults. The electronic components used in designing this unit are as follows:

Table 3.4: Electronic Components Used in the Design of the MOSFET Driver Unit.

S/N	Component Name	Value/Rating/Type
1.	Isolated MOSFET Driver	TLP250
2.	Capacitors	100uF, 0.1uF
3.	Fixed Resistors	330Ω

TLP250 is an isolated gate driver which consists of a GaAlAs light emitting diode and an integrated photo-detector. It is suitable for gate driving circuits of IGBTs or power MOSFETs. This device was selected because it has a supply voltage range of 10 – 35V and output current of ±1.5mA (max) which is suitable for driving the MOSFETs that were used [15]. The pin diagram of the IC is shown in Fig. 3.5:

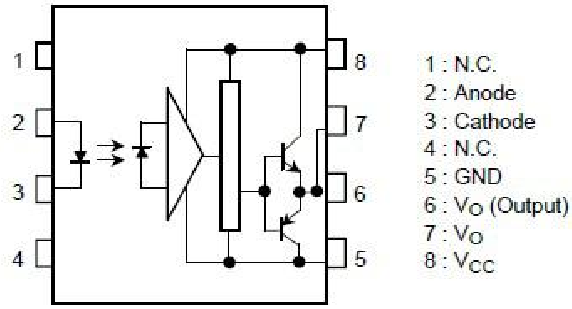

Fig. 3.5: Pin Diagram of TLP250 Gate Driver IC [15].

In order to protect the LED connected between pins 2 and 3 of the TLP250, a limiting resistor had to be connected at the input. The value of this resistor was calculated as shown below:

Forward current of LED = 10mA

Amplitude of microcontroller signal = 5V

Forward voltage of LED = 1.8V

$$R = \frac{V}{I} \tag{3.2}$$

Therefore,

$$R = \frac{(5 - 1.8)}{10 \times 10^{-3}} = \mathbf{320\Omega}$$

Hence, a 330Ω resistor which was the closest to the obtained value was used in the design. A bypass capacitor of 0.1uF was also connected between V_{CC} (pin 8) and ground (pin 5). This capacitor stabilizes the operation of the high gain linear amplifier in the TLP250 and failing to provide it may impair the switching property.

In this work, four N-channel MOSFETs were used in the bridge circuit. In this setup, turning on the high-side MOSFETs become a little bit complex. This is because when the device is already conducting, the source is roughly at the same potential as the drain (which is connected to the positive terminal of the supply). This becomes an issue since an N-channel MOSFET is turned on only when the gate is more positive than the source. Hence, an additional voltage has to be generated and fed to the gate since the source is already at the potential of the highest power available in the system (battery voltage). Therefore, a bootstrap capacitor of 100uF, which serves as a charge pump, was connected between the V_{CC} and ground of the high-side drivers to provide this additional voltage. The circuit diagram of the MOSFET driver unit is shown below:

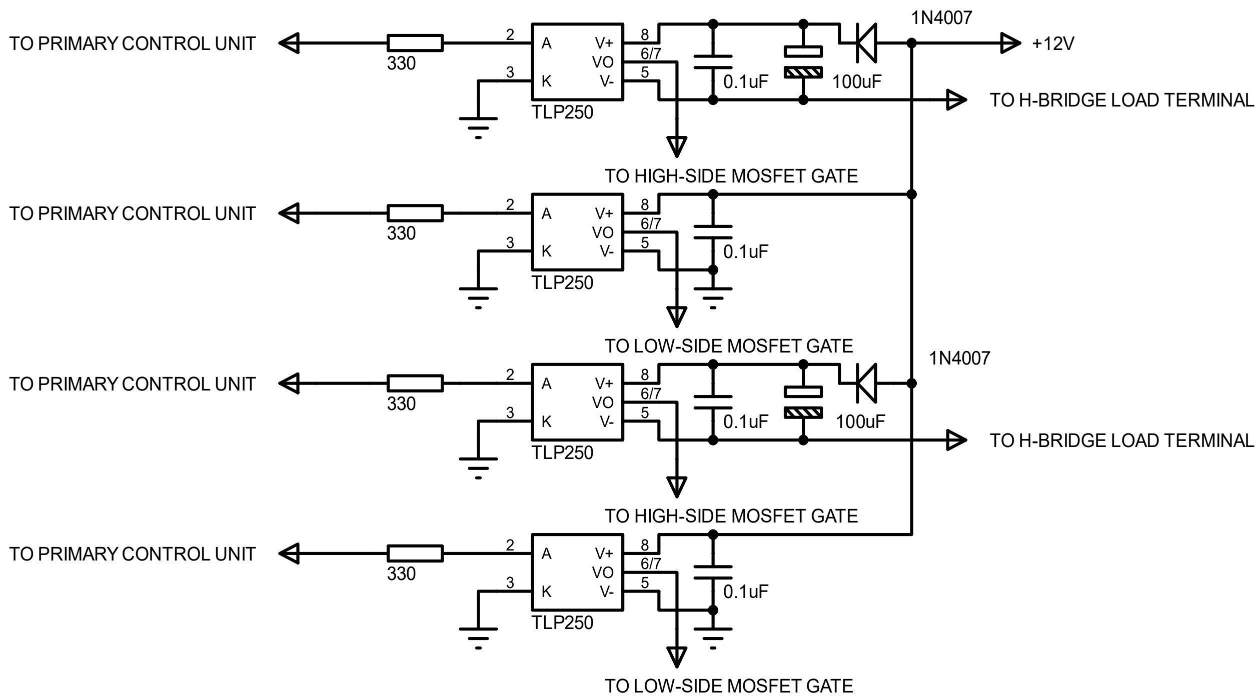

Fig. 3.6: Circuit Diagram of the MOSFET Driver Unit.

3.5 MOSFET H-Bridge Unit

The MOSFET H-Bridge is the unit where the actual transformation from D.C power to A.C power takes place. It consists of four MOSFET switches with the load terminals at the center, in an H-like configuration, connected between the positive and negative terminals of the battery.

The control signals from the primary control unit dictates the switching sequence of the four MOSFET switches, which results in an alternating current across the load terminals of the H-bridge. The electronic components used in designing this unit are as follows:

Table 3.5: Electronic Components Used in the Design of the MOSFET H-Bridge Unit.

S/N	Component Name	Value/Rating/Type
1.	MOSFETs	IRF3205
2.	Fixed Resistors	10Ω, 10kΩ

In this design, IRF3205 was selected because it has the voltage and current ratings which are suitable for the proposed ratings of the inverter system. The inverter system designed in this work has a voltage rating of 24V. That is to say that at full charge, the D.C input voltage should be about 26V. Assuming a 100% tolerance, as a result of transient over-voltages which might result from body diode recovery, the selected MOSFET should have a drain to source voltage (V_{DSS}) rating of 52V or more.

To determine the current rating of the MOSFET, we considered the maximum current flow through the switches. This maximum current to be determined would occur at the maximum power rating of the inverter and at the lowest battery voltage while factoring in the converter efficiency. Hence, assuming that each of the batteries are allowed to discharge down to 11V, and considering an inverter power rating of 500W at 0.85 converter efficiency:

$$Estimated\ maximum\ current\ flow\ through\ the\ MOSFET = {}^{500}/_{0.85 \times 22} = 26.7A$$

Again, assuming a 100% tolerance, the selected MOSFET should have a continuous drain current rating (I_{DMAX}) of 53.4A or more. The IRF3205 has a continuous drain current of 80A at

100˚C and a drain to source voltage of 55V [16]. Hence, a single IRF3205 was used for the four sides of the H-bridge circuit. A small resistor of 10Ω was used as a limiting resistor for the gate of each MOSFET, to ensure that enough current is supplied for the rapid charging of the gate capacitors. The gates of the MOSFETs were also pulled up to the source using 10kΩ resistors. This was done to ease the turning off of the high-side N-channel MOSFETs by keeping the gate-source voltage at below or equal to 0.

MOSFETs in this circuit are used under frequent power cycling conditions which greatly increases their temperature. Hence, for the purpose of increasing the component lifetime of the MOSFETs, it is vital to ensure adequate removal of heat from the device. This can be achieved by attaching passive heat exchangers known as heat sinks onto the body of the MOSFETs. To ensure proper heat dissipation, heat sinks must be correctly sized for the required power dissipation. This is done by determining the minimum sink-ambient thermal resistance (R_{SA}) value of the heat sink using the formula:

$$T_J = P_D\left(R_{JC} + R_{CS} + R_{SA}\right) + T_A \tag{3.3}$$

where,

T_J = *Junction temperature of the MOSFET*

P_D = *Power dissipation of the MOSFET*

R_{JC} = *Junction to case thermal resistance of the MOSFET*

R_{CS} = *Case to sink thermal resistance of the MOSFET*

R_{SA} = *Sink to ambient thermal resistance of the heat sink*

T_A = *Ambient temperature*

In the above equation, every parameter except P_D is either assumed or given in the datasheet of the MOSFET. P_D is a sum of the MOSFET on power dissipation (P_{Don}) and the MOSFET switching power dissipation (P_{Dsw}). MOSFETs dissipate power due to I^2R when they are on. From the MOSFET datasheet [16], the on resistance of the MOSFET is given as 8m**Ω**. Hence,

$$P_{Don} = I^2 R_{DS(on)} \tag{3.4}$$

$$P_{Don} = 26.7^2 \times 8 \times 10^{-3} = 5.7W$$

MOSFETs also dissipate some power each time they are switched on or off. To determine the approximate value of this power P_{Dsw} (it is an approximate since the actual value depends on a lot of factors), we use the formula:

$$P_{Dsw} = {(C_{RSS} \times V_{IN}{}^2 \times F_{SW} \times I_{LOAD})}/{I_{GATE}} \tag{3.5}$$

where,

C_{RSS} = Reverse transfer capacitance of the MOSFET

V_{IN} = Input voltage of the converter

F_{SW} = Switching frequency

I_{LOAD} = Estimated maximum load current through the MOSFET

I_{GATE} = MOSFET gate driver's sink/source current at the MOSFET turn-on threshold

From the datasheets [15], [16], C_{RSS} = 211pF and I_{GATE} = 0.5A.

From the design parameters, V_{IN} = 24V, F_{SW} = 16000Hz and I_{LOAD} = 26.7A.

Therefore,

$$P_{Dsw} = \frac{(211 \times 10^{-12} \times 24^2 \times 16000 \times 26.7)}{0.5} = 0.104W$$

Hence, $P_D = 5.7 + 0.104 = 5.804W$

Therefore, to determine R_{SA} of the heat sink,

$T_J = 100^\circ C$, $T_A = 25^\circ C$, $R_{JC} = 0.75^\circ C/W$, $R_{CS} = 0.5^\circ C/W$

From $100 = 5.804(0.75 + 0.5 + R_{SA}) + 25$

$\therefore$ R_{SA} = **11.67˚C/W**

The circuit diagram of the MOSFET H-bridge unit is shown below:

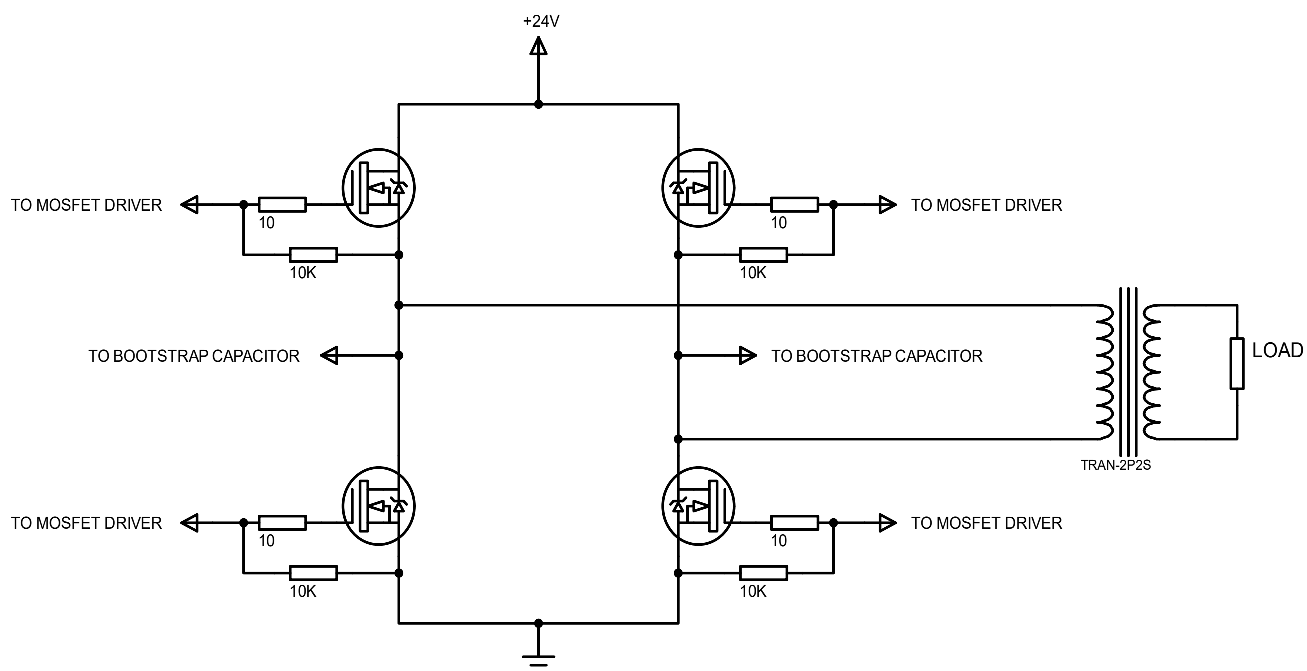

Fig. 3.7: Circuit Diagram of the MOSFET H-Bridge Unit.

3.6 Short-Circuit/Overload Sensing Unit

The short-circuit/overload sensing unit is one of the major contributors to the improvement in the inverter working condition carried out in this work. This is because it aims to protect the inverter system against one of its major sources of failure which are over-currents. This unit serves the purpose of instantly detecting any short-circuit or overload condition in the bridge circuit, and sending out a signal to the secondary control unit to that effect, for necessary action. Short-circuits in inverters occur in two common forms which are; as shoot-though conditions and as short-circuits in the load. Shoot-through conditions occur when MOSFETS on the same side of the H-bridge are turned on at the same time, thereby creating a low-resistance path between power and ground which effectively short-circuits the supply. This condition could be caused by a malfunctioning of the control unit which might result in an overlapping of MOSFET gating signals. It could also be caused by a malfunctioning of the MOSFETs themselves, as voltage spikes at the gates of MOSFETs could easily damage them and cause them to close permanently. Short-circuiting of the live and neutral terminals of the inverter output (load), or overloading the inverter system beyond its designed power rating will also cause the MOSFETs to draw a current that is beyond the maximum current which they were designed to carry. All these overcurrent conditions can destroy the bridge circuit of the inverter and overheat the battery.

MOSFETs often carry a high peak-current rating, but these typically assume peak currents only lasting for about 300 microseconds. Hence, the short-circuit / overload sensing unit is aimed at sensing these overcurrent conditions and notifying the secondary control unit to shut-down the system in a time well below the MOSFETs peak-current time limit, in order to protect the inverter system. The electronic components used in designing this unit are as follows:

Table 3.6: Electronic Components Used in the Design of the Short-Circuit/Overload Sensing Unit.

S/N	Component Name	Value/Rating/Type
1.	High Bandwidth Hall Effect-Based Linear Current Sensor	ACS712ELCTR-30A-T
2.	Capacitors	1nF, 0.1uF

ACS712 is a high bandwidth hall effect-based linear current sensor which provides precise solutions for A.C or D.C current sensing. Hall Effect is the production of a voltage difference across an electrical conductor, transverse to an electric current in the conductor and to an applied magnetic field perpendicular to the current. The ACS712 consists of a precise, low-offset, linear Hall sensor circuit with a copper conduction path located near the surface of the die. Applied current flowing through this copper conduction path generates a magnetic field which is sensed by the integrated Hall IC and converted into a proportional voltage. The device was selected because it has a high bandwidth of 80 kHz which is very much suitable for reading current at the high switching frequency (16 kHz) of the inverter. The device has the following main features [17]:

i. Low-noise analog signal path
ii. 5 µs output rise time in response to step input current
iii. 80 kHz bandwidth
iv. Total output error 1.5% at $T_A = 25°C$
v. 1.2 mΩ internal conductor resistance
vi. 2.1 kVrms minimum isolation voltage from pins 1-4 to pins 5-8
vii. 5.0 V, single supply operation

viii. 66 to 185 mV/A output sensitivity

ix. Output voltage proportional to AC or DC currents

x. Factory-trimmed for accuracy

xi. Extremely stable output offset voltage

xii. Nearly zero magnetic hysteresis

The model of ACS712 used in this design is the ACS712ELCTR-30A-T. This model was chosen because it has a wide current sensing range of ±30A which covers the estimated maximum current for the bridge circuit (26.7A). It also has a sensitivity of 66 mV/A [17]. This sensor is connected in series at the high side of the bridge circuit. The main advantage of connecting it this way is that any current that leaves the battery through the bridge is measured. This means that even if it goes through the load or through the chassis towards ground due to a loose wire or through the MOSFETs due to internal damage, it is caught by the sensor. The pin diagram of the sensor is shown below:

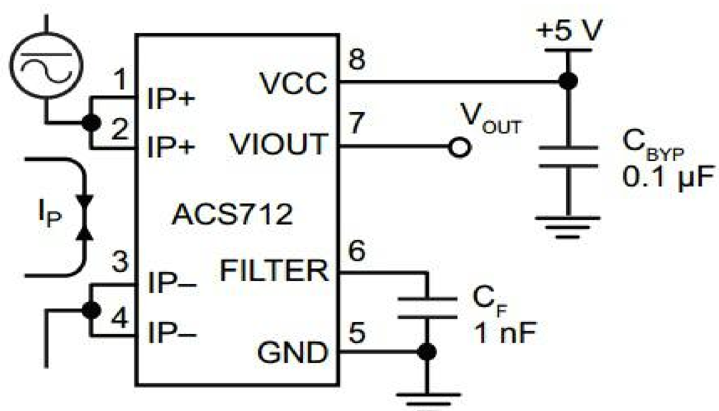

Fig. 3.8: Pin Diagram of the ACS712 Current Sensor IC [17].

A 1nF filtering capacitor is normally connected between the filter and ground pins of the IC for noise management with values that depend on the application. A bypass capacitor of 0.1uF is also connected between the V_{CC} and ground pins in order to stabilize the operation of the high gain linear amplifier in the IC. The circuit diagram of the short-circuit / overload sensing unit is shown in Fig. 3.9:

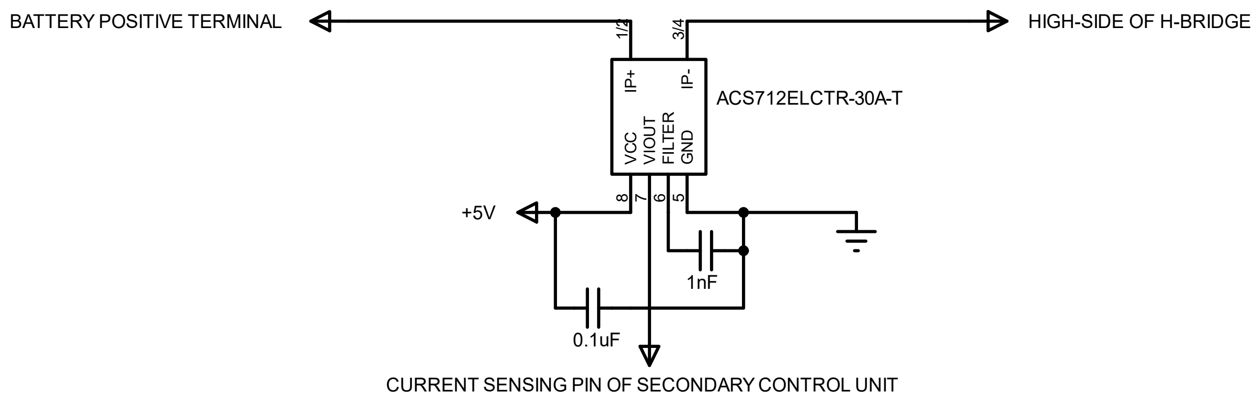

Fig. 3.9: Circuit Diagram of the Short-Circuit/Overload Sensing Unit.

3.7 Temperature Sensing Unit

The temperature sensing unit is another major contributor to the improvement in the inverter working condition carried out in this work. The purpose of the temperature sensing unit is to measure the ambient temperature and the case temperatures of the MOSFETs in the bridge circuit, in the form of analog voltage signals, and send these values to the secondary control unit for the computation of the junction temperatures of these MOSFETs in real-time. The temperature monitoring process carried out in this work is a unique one. This is because instead of just measuring the case temperature and using its value for temperature monitoring (which is very common in many works), the case temperature is measured and used in computing the respective junction temperatures of the MOSFETs. Junction temperature is the highest operating temperature of the actual semiconductor material in an electronic device. Hence, it is the temperature which bears an actual relevance to the level of operation of the MOSFETs. In operation, this temperature is higher than the case temperature and the temperature of the part's exterior. Many semiconductors and their surrounding optics are small, making it difficult to measure junction temperature with direct methods such as thermocouples. However, junction temperature can be determined through indirect methods by determining the corresponding case temperature and ambient temperature, and mathematically evaluating the junction temperature using the formula:

$$T_J = T_C + (T_C - T_A) \times {}^{R_{JC}}/_{R_{CS}+R_{SA}} \tag{3.6}$$

where,

T_J = *Junction temperature of the MOSFET*

T_C = *Case temperature of the MOSFET*

T_A = *Ambient temperature*

R_{JC} = *Junction to case thermal resistance of the MOSFET*

R_{CS} = *Case to sink thermal resistance of the MOSFET*

R_{SA} = *Sink to ambient thermal resistance of the heat sink.*

All semiconductors have some specified safe upper limit for junction temperature, usually in the order of 150°C. This maximum junction temperature is a worst case limitation which must not be exceeded as it results in device failure. Hence, for reliability reasons, it is important to ensure that the power MOSFETs, used in the bridge circuit of the inverter system, always operate within their respective thermal limits. The electronic components used in designing this unit are as follows:

Table 3.7: Electronic Components Used in the Design of the Temperature Sensing Unit.

S/N	Component Name	Value/Rating/Type
1.	NTC Thermistors	10kΩ
2.	Trimpot Variable Resistors	10kΩ
3.	Fixed Resistors	1kΩ

A Thermistor is a special type of variable resistive element that changes its physical resistance when exposed to changes in temperature. For an NTC thermistor, an inverse relationship exists between resistance and temperature while for a PTC thermistor a direct relationship exists. In this design, the NTC thermistors were used to implement voltage dividers in order to be able to convert the change in resistance parameters of the thermistors into a change in output voltage. In the voltage dividers, the 10kΩ thermistors were connected on the high side while the 1kΩ fixed resistors were connected on the low side. This was done in order to achieve a direct relationship between temperature and the output voltage of the voltage divider.

Trimpot variable resistors of 10kΩ were also connected across the thermistors and the 1kΩ fixed resistors for the purpose of calibrating the temperature value with the microcontroller in the secondary control unit. A total of five voltage dividers were designed in this work; for sensing the case temperature of the MOSFETs on the four sides of the H-bridge, and for sensing the ambient temperature. The circuit diagram of the temperature sensing unit is shown in Fig. 3.10:

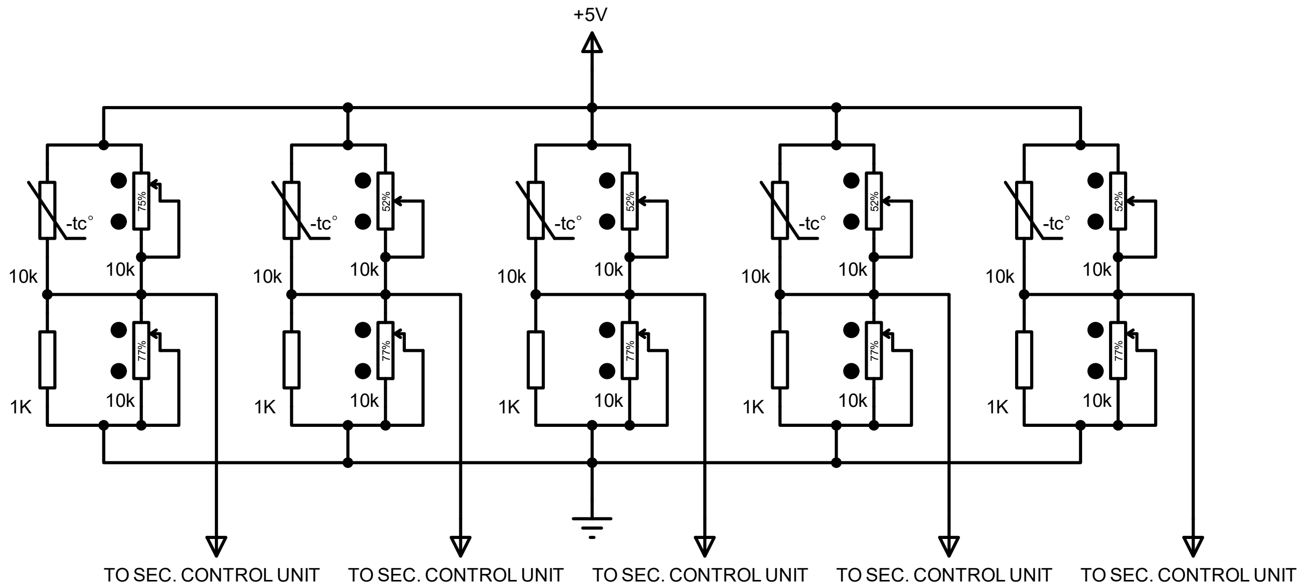

Fig. 3.10: Circuit Diagram of the Temperature Sensing Unit.

3.8 Battery Sensing Unit

The battery sensing unit serves the purpose of constantly monitoring the battery voltage to ensure that the inverter always operates within its permissible input voltage limits. Operating the inverter at a voltage higher than its designed input voltage could damage the bridge circuit, while operating it at a voltage lower than its designed input voltage results in an output voltage that is below the designed value. Also, constantly discharging an inverter battery below its recommended value could potentially shorten the battery life. Hence, battery voltage monitoring is important for the sake of maintaining the reliability of the inverter. The electronic components used in designing this unit are as follows:

Table 3.8: Electronic Components Used in the Design of the Battery Sensing Unit.

S/N	Component Name	Value/Rating/Type
1.	Trimpot Variable Resistors	10kΩ
2.	Fixed Resistors	220kΩ, 1kΩ

The battery sensing unit is a voltage divider which consists of the aforementioned resistors. The voltage divider was used in order to step down the battery input voltage to a range of 0 – 5V, which is the acceptable voltage range by the microcontroller of the secondary control unit. The resistors of the voltage divider were selected such that even at the maximum input voltage of the battery (about 26V), the voltage divider will still give an output voltage that is below 5V. The low-side resistor was selected and then the high-side resistor was calculated for using the formula:

$$V_{OUT} = \frac{R_{LS}}{R_{HS} + R_{LS}} \times V_{IN} \tag{3.7}$$

The circuit diagram of the battery sensing unit is shown below:

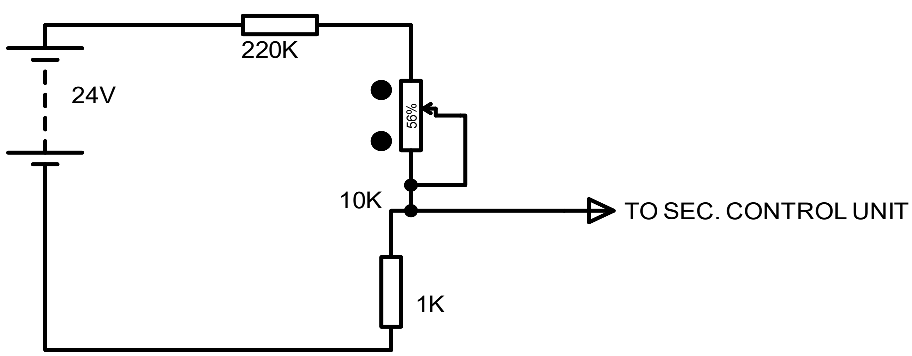

Fig. 3.11: Circuit Diagram of the Battery Sensing Unit.

3.9 Secondary Control Unit

The secondary control unit serves as the brain that makes sense out of all the units put in place to improve the working condition of the inverter. This unit performs the following functions:

i. It receives analog input signals from the short-circuit/overload sensing unit, processes these signals to evaluate the current in the bridge, and then determines whether or not to shut down the primary control unit.

ii. It also receives analog input signals from the temperature sensing unit, processes these signals to determine the junction temperature of the MOSFETs of the bridge, and then determines whether or not to turn on the fan or to shut down the primary control unit entirely.

iii. It receives analog input signals from the battery sensing unit, processes these signals to evaluate the battery voltage, and then determines whether or not it is safe to keep the system running. If it is not, it shuts down the primary control unit.

The electronic components used in designing this unit are as follows:

Table 3.9: Electronic Components Used in the Design of the Secondary Control Unit.

S/N	Component Name	Value/Rating/Type
1.	Microcontroller	PIC16F887
2.	Crystal Oscillator	20MHz
3.	Transistor	BD135
4.	Capacitors	22pF
5.	Fixed Resistors	1kΩ, 4.7kΩ, 10kΩ

A PIC16F887 microcontroller was used in designing the secondary control unit. A PIC16F887 microcontroller is a 40 - Pin 8-Bit CMOS microcontroller with nanowatt technology. This microcontroller was chosen because it has a large number of analog channels (14 channels) which were required for the numerous sensing circuits in the system. This microcontroller was also readily available in the market. The PIC16F887 has the following main features [18]:

i. 10-bit, up to 14-channel Analog-to-Digital Converter (A/D)

ii. Maximum Crystal Speed of 20MHz

iii. Wide operating voltage range of 2.0V to 5.5V

iv. I/O Ports: Ports A, B, C, D, E

v. Flash Program Memory of up to 8192 words

vi. Data Memory (RAM) of up to 368 bytes

vii. EEPROM Data Memory of up to 256 bytes

viii. Analog Comparator module with two analog comparators

The pin diagram of the PIC16F887 microcontroller is as follows:

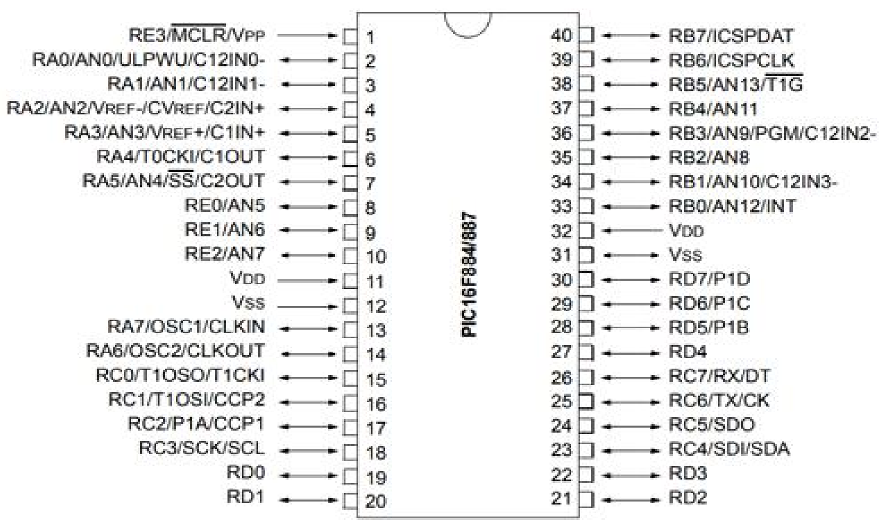

Fig. 3.12: Pin Diagram of the PIC16F887 Microcontroller [18].

Table 3.10: Pin Descriptions for the PIC16F887 Microcontroller [18].

S/N	Pin Name	Pin Number	Description
1.	RE3/MCLR/V_{PP}:	1	PORTE Digital I/O or Master Clear Reset or programming voltage
2.	RA0/AN0 – RA3/AN3:	2 - 5	PORTA bidirectional I/O port:

	RA0 – RA3 AN0 – AN3		PORTA Digital I/O PORTA Analog input 0 – 3
3.	RA4/T0CKI	6	PORTA Digital I/O or Timer T0 clock input
4.	RA5/AN4	7	PORTA Digital I/O or PORTA Analog input 4
5.	RE0/AN5 – RE2/AN7 RE0 – RE2 AN5 - AN7	8-10	PORTE bidirectional I/O port PORTE Digital I/O PORTA Analog input 5 – 7
6.	V_{DD}	11, 32	Positive Supply
7.	V_{SS}	12, 31	Ground
8.	RA7/OSC1	13	PORTA Digital I/O or Oscillator crystal input
5.	RA6/OSC2	14	PORTC Digital I/O or Oscillator crystal output
6.	RC0 – RC3	15 - 18	PORTC Digital I/O port.
7.	RD0 – RD3	19 - 22	PORTD Digital I/O port.
8.	RC4 – RC7	23 - 26	PORTC Digital I/O port.
9.	RD4 – RD7	27 - 30	PORTD Digital I/O port.
10.	RB0 – RB7	33 - 40	PORTB Digital I/O port.
11.	AN8 – AN13	33 - 38	PORTA Analog input 8 – 13

In this design, ports AN0 to AN4 were used in receiving analog voltage signals from the five voltage dividers in the temperature sensing unit. The microcontroller processes these signals to determine the case temperatures of the MOSFETs and the ambient temperature. Then it uses these parameters to compute the junction temperatures of the MOSFETs all in real-time. Ports AN5 and AN6 were also used in receiving analog voltage signals from the battery sensing unit and the short-circuit / overload sensing unit respectively. The microcontroller processes these signals to determine the battery voltage and detect over-currents in the system. Port RD5 was used as the shutdown control pin. This pin is used in switching a transistor that sends a negative (logic zero) to the shutdown pin of the primary control unit, which triggers the auto shutdown of its ECCP module, whenever the reliability of the inverter is threatened. Port RC7 was used as a digital output pin which triggers the cooling device. This pin is used in switching a transistor which sends a negative to complete the circuit of the 12V DC fan. Ports RD2, RD3 and RC4 were also used to trigger the indicator LEDs for shutdown due to high temperature, low battery and overcurrent respectively. Hence, a total of 12 input/output (I/O) ports of the microcontroller were used in this design.

An external oscillator circuit made up of a 20 MHz crystal oscillator and two 22pF capacitors were connected between pins 13 and 14 of the microcontroller. It is used to generate clock pulses required for the synchronization of all the internal operations of the microcontroller. A 20MHz crystal oscillator was used because it was equal to the maximum crystal speed of the microcontroller. The highest possible frequency of crystal oscillator was chosen because the secondary control unit is required to operate at the highest possible speed in order to be able to improve the working condition of the inverter. For a PIC microcontroller, the instruction cycle is four times the clock cycle. Hence, the instruction cycle achieved for this microcontroller program is 0.2 microseconds.

Ports RD2, RD3, RD5, RC4 and RC7 of the microcontroller, which are used as digital output pins, were pulled down to ground using resistors. This was done in order to ensure that these output pins are kept low (0) until the microcontroller gives out a high (1) through them. A 10kΩ resistor was used for the pull-down because of the 1kΩ transistor base resistors connected in series with the output pins. A sufficiently higher resistance of 10kΩ ensures that nearly all the current from the output pin of the microcontroller flows through the 1kΩ base resistors when the output pins give out a high. This is because current always tends to flow through the path of least resistance.

The Master Clear Reset input pin (MCLR) was also pulled up to the +5V supply using a 4.7kΩ resistor. This pin is an active low reset pin for the microcontroller. Hence, it was pulled up to ensure that the MCLR pin never receives a low by error to avoid any interruption of the microcontroller program.

Finally, BD135 NPN transistors are connected to the ends of Ports RC5 and RD7 which are used in switching negative to the cooling unit and the shutdown pin of the primary control unit. This was done for the sake of current amplification.

The program of the microcontroller in this unit was written using Great Cow Basic Compiler and is shown in Appendix I. The circuit diagram for the secondary control unit is shown below:

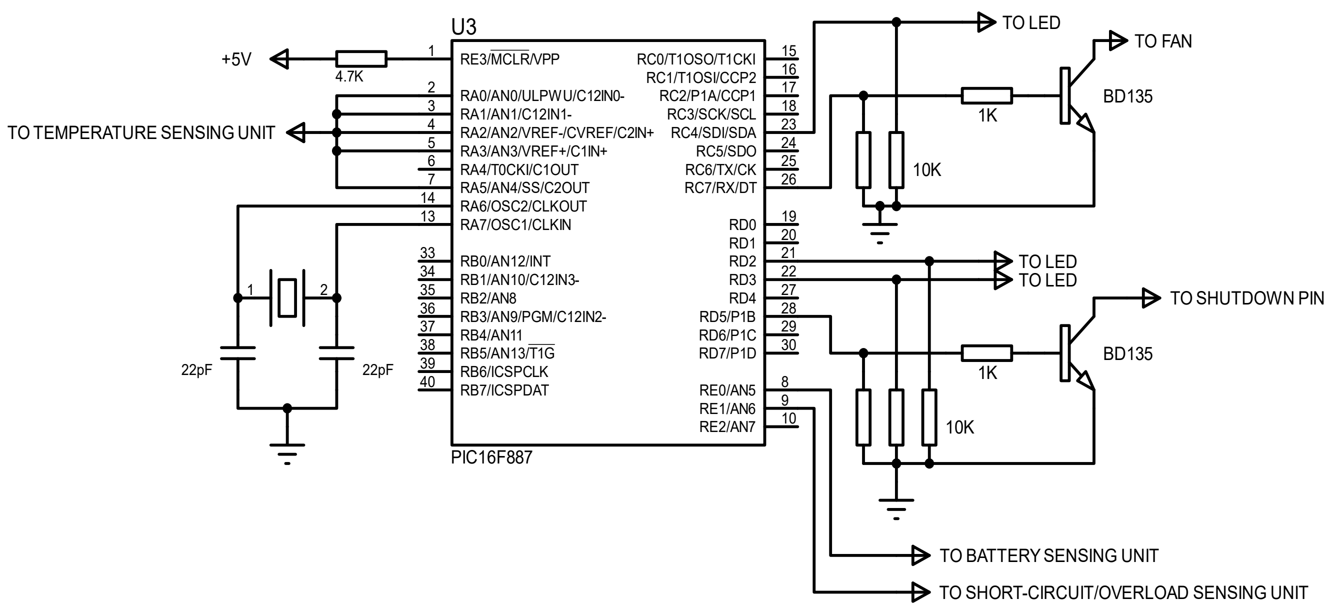

Fig. 3.13: Circuit Diagram of the Secondary Control Unit.

3.10 Transformer Unit

The transformer unit serves the purpose of stepping up the voltage from the MOSFET H-bridge unit to the conventional supply voltage level of 220V. The transformer should be designed such that its rated power is equal to the desired maximum load that the inverter system is expected to carry. In this design, the inverter system is rated at 500W. Hence, the following calculations were done in the transformer design:

3.10.1 Design Calculations for the Transformer

Predetermined parameters for the design are as follows:

- Rating of the inverter = 500W
- Minimum voltage to the system = 22V

Using the dimensions from the core area (centre – limb) of the lamination, ply-wood and glue were used in constructing the coil former of the transformer. In order to determine the iron area A_i for the winding calculations, the length and width of the constructed coil former were measured as:

- Length of core former = 6.1cm
- Width of coil former = 5.0cm

$$Iron\ area,\ A_i = Length\ of\ core\ former \times Width\ of\ coil\ former \quad (3.8)$$

$$\therefore A_i = 6.1 \times 5.0 = 30.5cm^2 = 0.00305m^2$$

In order to determine the size of copper wire to be used for the primary and secondary windings, the maximum allowable current for these windings were determined as follows:

$$Maximum\ allowable\ current\ for\ primary\ (I_P) = \frac{Power\ rating}{Minimum\ input\ voltage} \quad (3.9)$$

Assuming converter efficiency of 85%,

$$I_P = \frac{500}{0.85 \times 22} = 26.7A$$

$$Maximum\ allowable\ current\ for\ secondary\ (I_S) = \frac{Power\ rating}{Minimum\ output\ voltage} \tag{3.10}$$

$$I_S = \frac{500}{220} = 2.3A$$

From the American Wire Gauge (AWG) table, the suitable wire gauge for the primary winding is gauge 15 with a maximum allowable current of 28A. This wire gauge has a corresponding copper diameter of 1.45034mm, and an area of 1.65mm^2. For the secondary winding, the suitable wire gauge is gauge 25 with a maximum allowable current of 2.7A. . This wire gauge has a corresponding copper diameter of 0.45466mm, and an area of 0.162mm^2.

With the wire gauge for winding the transformer determined, the next step was to calculate the number of turns for each winding.

From the transformer E.M.F equation,

$$V_P = 4.44fN_PB_{max}A_i \tag{3.11}$$

$$where; f = 50Hz, B_{max} = 0.9,\ A_i = \ 0.00305m^2$$

$$18.7 = 4.44 \times 50 \times N_P \times 0.9 \times 0.00305$$

$$N_P = 30.7 \approx 31\ turns$$

Using the relationship; $\frac{N_P}{N_S} = \frac{V_P}{V_S}$ (3.12)

$$N_S = \frac{30.7 \times 260}{18.7}$$

$$N_S = 426.8 \approx 427\ turns$$

3.11 Feedback Unit

The feedback unit serves the purpose of relaying the output voltage information of the inverter to the primary control unit which it uses to adjust the duty cycle of the MOSFET gate pulses in order to maintain the output voltage at the required level. As an inverter is being used, the output voltage decreases as a result of a decrease in the input voltage (discharging of the battery). This decrease in output voltage is undesirable as loads connected to the inverter are designed to operate at a given output voltage range. In order to maintain the output voltage at the required level, the on-time (duty cycle) of the MOSFETs of the bridge have to be increased to allow more current flow. Hence, the feedback unit enables the primary control unit to know the voltage level of the inverter output and by what degree it should increase or decrease the duty cycle to maintain a fixed output voltage. The electronic components used in designing this unit are as follows:

Table 3.11: Electronic Components Used in the Design of the Feedback Unit.

S/N	Component Name	Value/Rating/Type
1.	Opto-coupler	PC817
2.	Diodes	1N4007
3.	Capacitors	4.7uF
4.	Variable Resistor	20kΩ
5.	Fixed Resistors	220kΩ, 100kΩ, 1kΩ

This unit takes its input from the secondary of the transformer. Since the output is A.C voltage and needs to be fed to the microcontroller, it is first rectified using a bridge rectifier consisting of four 1N4007 diodes. This diode was selected because it has a peak inverse voltage of 1000V, which was suitable for handling the output voltage of the inverter. After rectification, this voltage is fed to the input of a PC817 opto-coupler. This was done in order to provide isolation between the high power side and low power side of the inverter as a means of protecting the microcontroller. The collector of the PC817 was biased with +5V such that the maximum output to be opened from the emitter does not exceed 5V since it is being fed to the microcontroller. The output from the emitter is passed through a 20kΩ variable resistor connected in parallel for the purpose of setting the reference voltage of the inverter output. It is also passed through a 100kΩ limiting resistor connected in series and finally through a 4.7uF capacitor for filtering.

The circuit diagram for the feedback unit is shown below:

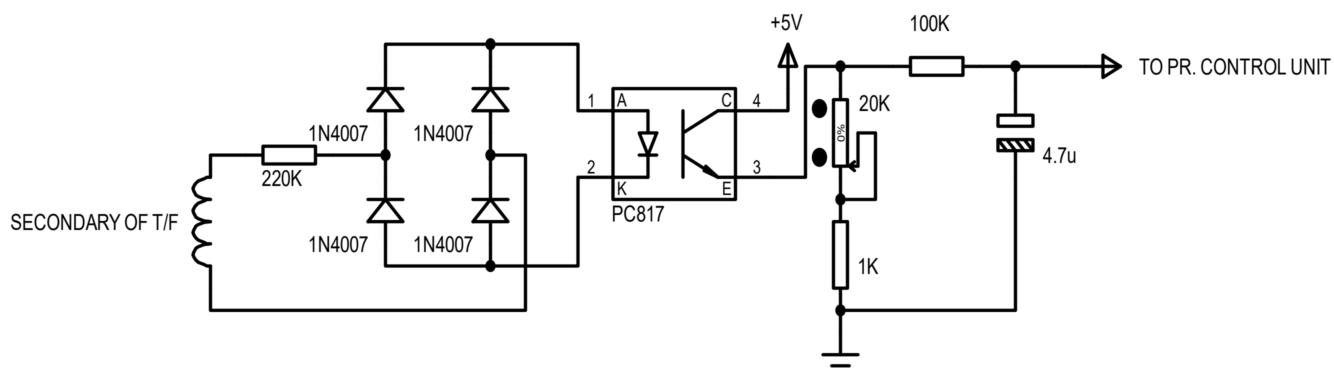

Fig. 3.14: Circuit Diagram of the Feedback Unit.

CHAPTER FOUR

TESTS, RESULTS AND ANALYSIS

4.1 Tests and Results from the Voltage Regulation Unit

After the implementation of this unit, the voltages at major points in the circuit were tested using a multimeter to verify that these points were at the desired voltages. The following results were obtained from the test:

i. Voltage at the output of LM7812 = **12.01V**

ii. Voltage at the output of LM7805 = **4.99V**

The voltages obtained above were in line with the design voltages. Hence, the unit was found to be working in good condition.

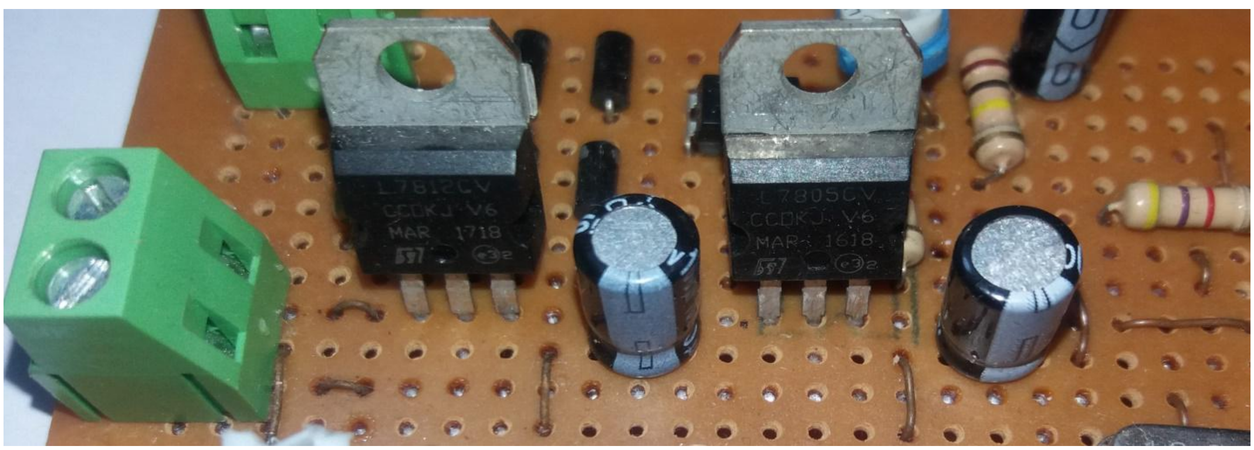

Fig. 4.1: Implemented Voltage Regulation Unit.

4.2 Tests and Results from the Primary Control Unit

After the microcontroller program for the primary control unit was written using MikroC Compiler, it was successfully compiled indicating that there were no bugs or errors in the code.

The program was tested using a Proteus 8 Professional simulator application. The pulse-width modulation output signals obtained for the four sides of the H-bridge are shown in Fig. 4.1:

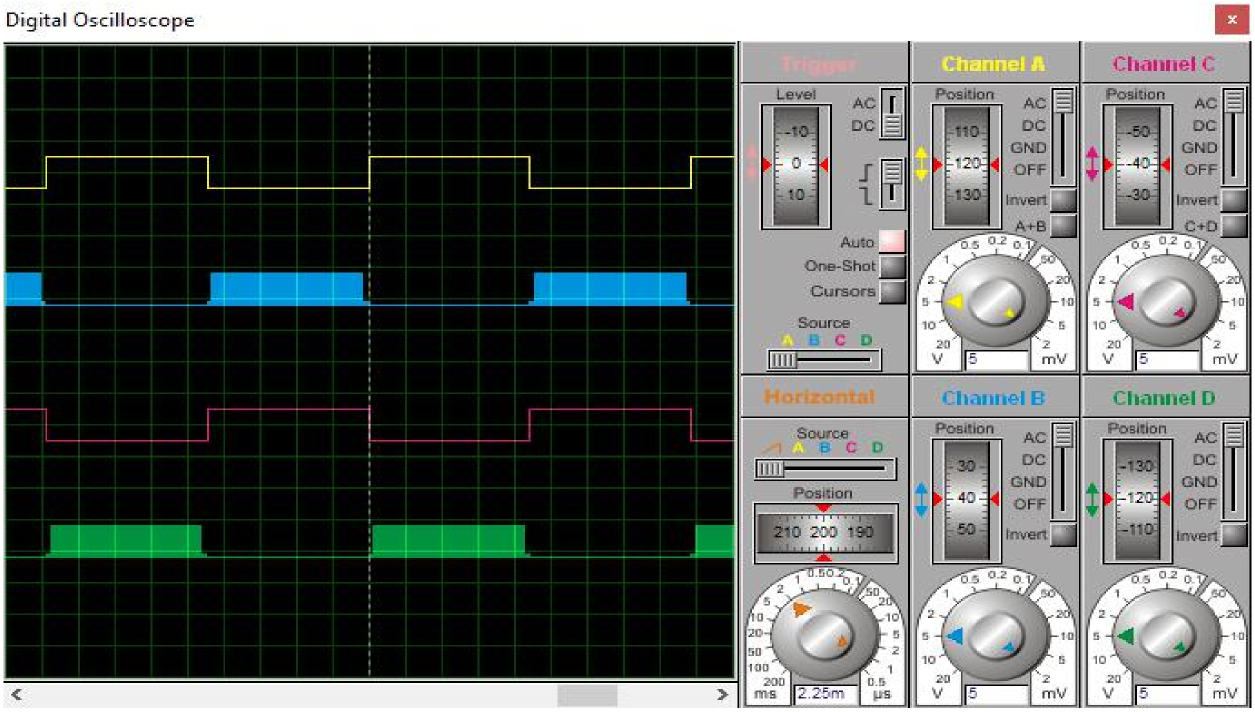

Fig. 4.2: Pulse-Width Modulation Output Signals Obtained from the Microcontroller.

The PWM signals above consist of two SPWM signals and two square wave signals. The SPWM signals obtained had a total number of 160 pulses which was in conformation with the microcontroller code.

After the hardware implementation of this unit, the hex file created from the compilation of the program was burnt into the microcontroller using a PICkit3 programmer. The frequency of the PWM output pins of the microcontroller were tested using a frequency meter to verify that they were at the desired frequencies. The frequencies of the SPWM signals and square wave signals were measured as **15.97 kHz** and **50.03 Hz** which were in-line with the design specifications. The automatic shutdown pin (port RA2) for the ECCP module of the microcontroller was also tested by applying logic zero (ground) to it. The microcontroller responded accordingly by instantly setting all PWM outputs to zero.

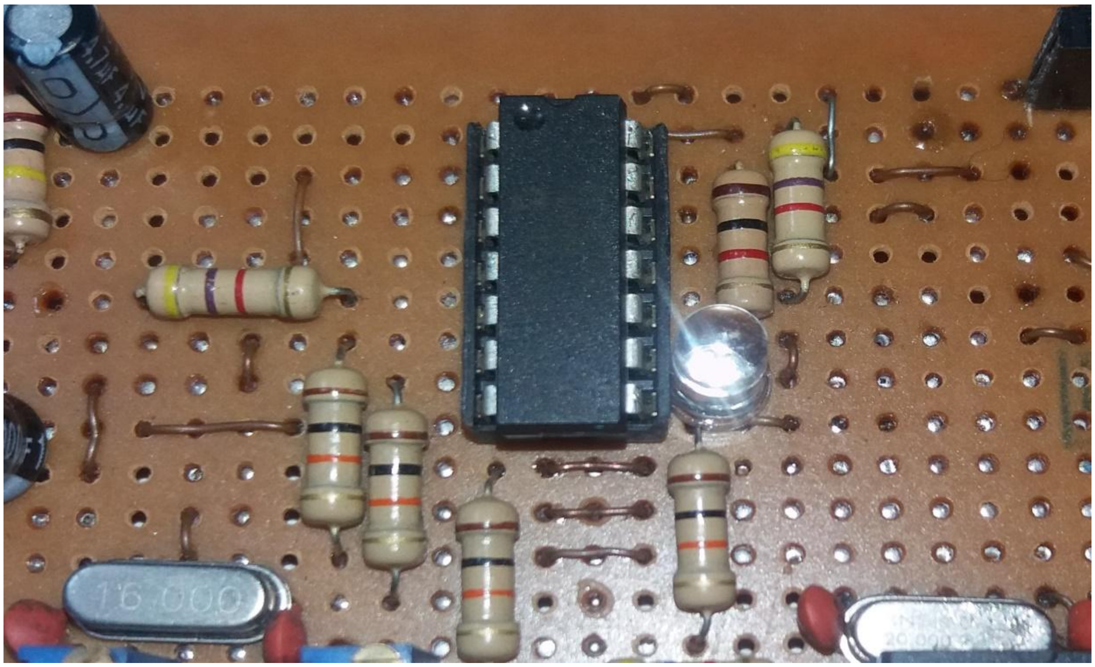

Fig. 4.3: Implemented Primary Control Unit.

4.3 Tests and Results from the MOSFET Driver and H-Bridge Unit

After the implementation of these units, the MOSFET driver unit was effectively connected to the primary control unit on the input side and the H-bridge unit on the output side. An oscilloscope was connected across the load terminals of the H-bridge in order to obtain the output voltage waveform of the inverter. The waveform obtained from the oscilloscope is shown in Fig. 4.4:

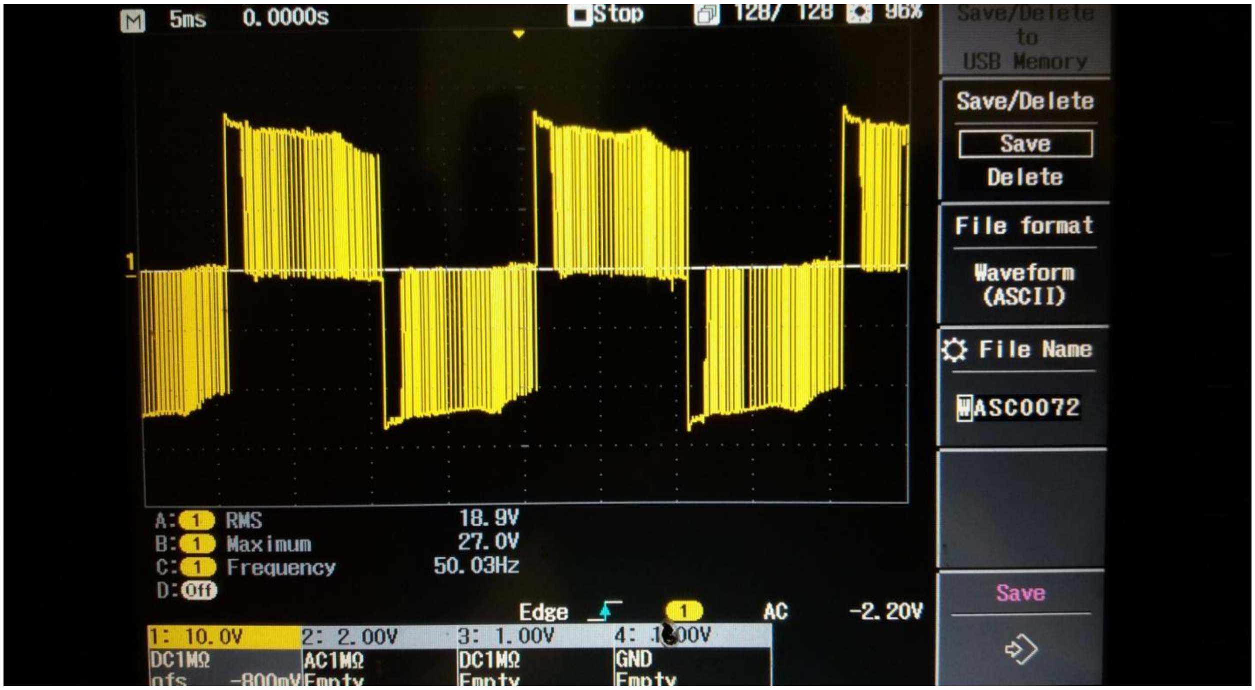

Fig. 4.4: Output Voltage Waveform of the Inverter When Viewed from an Oscilloscope.

The output voltage waveform obtained above assumed the shape of the output of a sinusoidal wave inverter. The output voltage had an RMS value of **18.9V** and a frequency of **50.03 Hz.** hence the MOSFET driver unit and H-bridge unit were found to be working in good condition.

Fig. 4.5: Implemented MOSFET H-Bridge Unit.

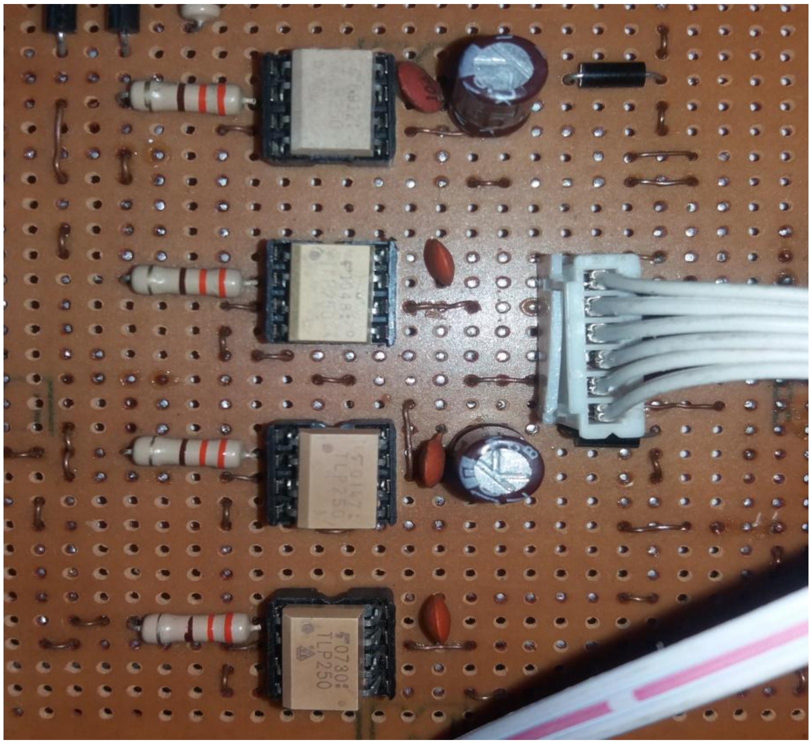

Fig. 4.6: Implemented MOSFET Driver Unit.

4.4 Tests and Results from the Secondary Control Unit

After the microcontroller program for this unit was written using Great Cow Basic Compiler, it was successfully compiled indicating that there were no bugs or errors in the code. The effect of the secondary control unit on the output voltage of the inverter at the occurrence of any overcurrent or overheating was simulated using Proteus 8 Professional application. The nature of the waveform obtained is shown in Fig. 4.7:

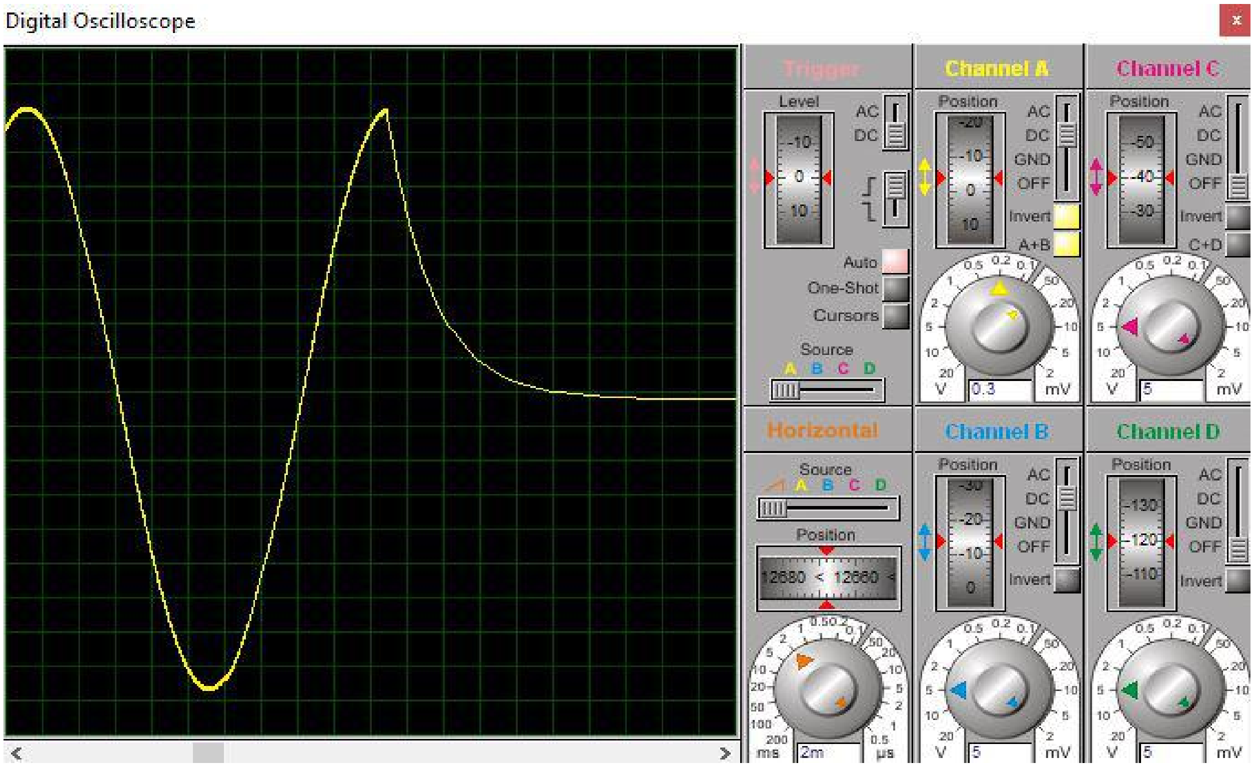

Fig. 4.7: Simulation of the Output Voltage of the Inverter at the Instant Where the Secondary Control Unit Shuts Down the Primary Control Unit.

The waveform above depicts how the output voltage of the inverter falls to zero at the instant of occurrence of any threat to the inverter systems reliability. Hence, the microcontroller program for the secondary control unit was found to be working in good condition. The secondary control unit was then implemented and the hex code of the microcontroller program was burnt into the microcontroller using a PICkit 3 programmer.

Fig. 4.8: Implemented Secondary Control Unit.

4.5 Tests and Results from the Short-Circuit/Overload Sensing Unit

After the successful implementation of this unit, it was tested to ascertain its effectiveness in protecting the inverter bridge from damage as a result of an overcurrent. This was done by inducing a short-circuit between the positive and negative terminals of the bridge circuit using a wire. At the instant of application of the short-circuit, the secondary control unit was seen to effectively shut down the primary control unit as indicated by an LED, whose negative terminal was connected to the shutdown pin of the primary control unit. Considering that the output rise time of the ACS712 is 5 µs and the instruction cycle of the microcontroller is 0.2 µs, the primary control unit was shut down in well under 100 µs, hence ensuring the safety of the MOSFETs in the bridge circuit.

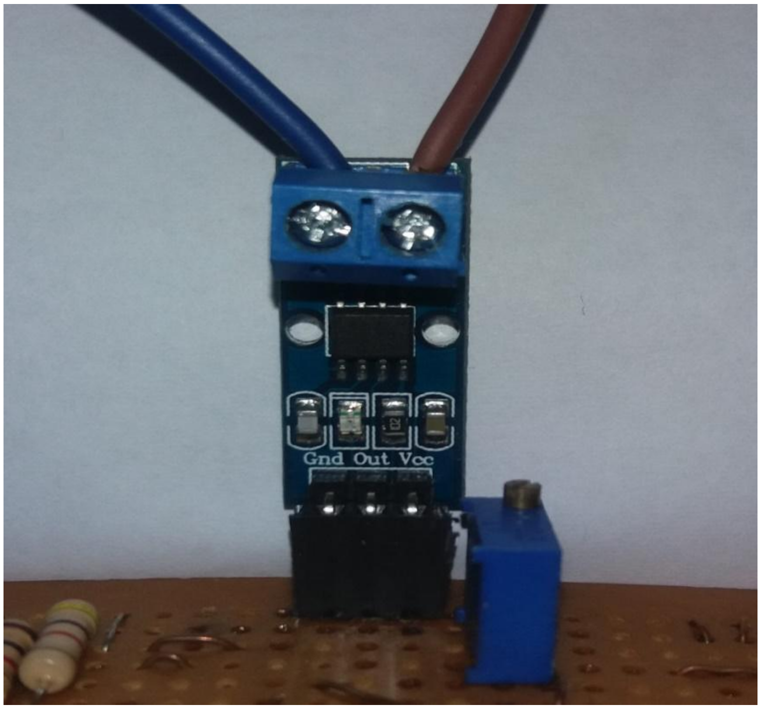

Fig. 4.9: Implemented Short-Circuit/Overload Sensing Unit.

4.6 Tests and Results from the Temperature Sensing Unit

At the end of the implementation of this unit, it was tested to ascertain its effectiveness in protecting the inverter bridge from damage as a result of overheating. This was done by gradually varying the variable resistors connected across the NTC thermistors and low-side fixed resistors of the voltage dividers, in order to achieve an output voltage proportional to that produced by the divider at case temperatures proportional to junction temperatures of 50˚C and 150˚C. As this was being done, the cooling fan was seen to automatically turn on indicating that the junction temperature of one or more of the MOSFETs had exceeded 50˚C as was specified in the microcontroller program. As the varying continued, the secondary control unit was also seen to shut down the primary control unit indicating that the junction temperature of one or more of the MOSFETs had exceeded 150˚C. Hence, affirming the effective response of the system to the specifications made in the microcontroller program.

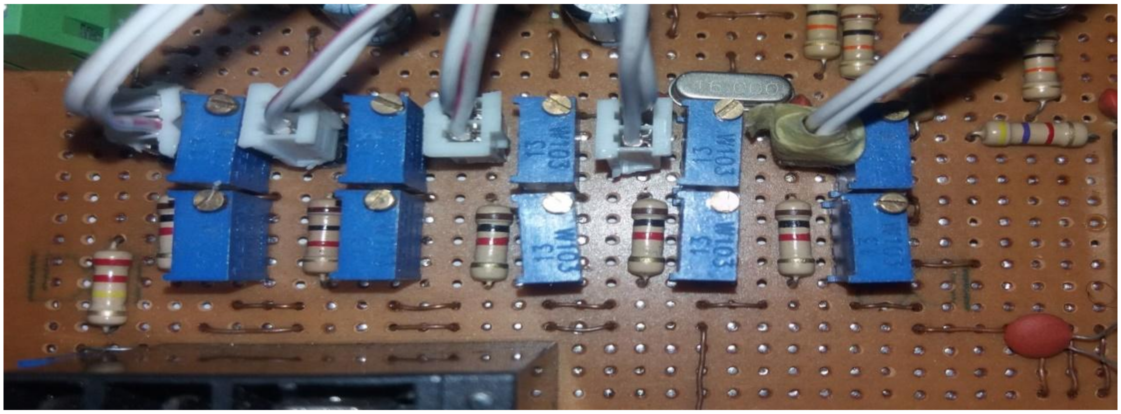

Fig. 4.10: Implemented Temperature Sensing Unit.

4.7 Tests and Results from the Battery Sensing Unit

After the implementation of this unit, it was tested to verify its effectiveness in monitoring the battery voltage. This was done by operating the inverter for a period of time in order to run down the battery voltage below its set threshold of 22V. At the instant where the battery voltage went below 22V, the secondary control unit was seen to effectively shut down the primary control unit. Hence, affirming that the battery sensing unit was working in good condition.

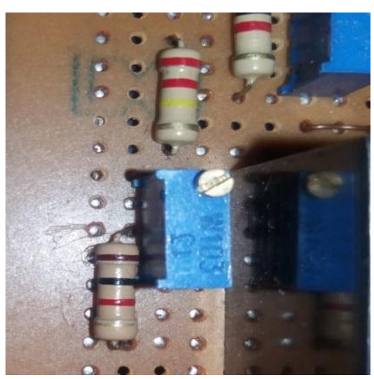

Fig. 4.11: Implemented Battery Sensing Unit.

4.8 Tests and Results from the Transformer Unit

After successfully winding the 500W transformer of the system, the transformer was tested in order to affirm the accuracy of the windings and calculations. This was done by applying a rated voltage of 218 V, which was being supplied from the A.C mains, to the secondary of the transformer rated 260 V. When the primary winding of the transformer was tested using a multimeter, 15.2 V was obtained. This voltage reading was found to be in-line with the voltage rating of the primary winding (18.7 V), hence affirming the fact that no surplus turns were made while winding the transformer.

4.9 Tests and Results from the Feedback Unit

After the implementation of this unit, it was tested to verify its effectiveness in maintaining the output of the inverter at a constant voltage. At no-load, the variable resistor at the output of this unit was used to fix the reference voltage of the inverter at 220 V, by varying the output voltage which was being sent to the primary control unit from the feedback unit. After the output voltage was fixed at 220V, the inverter was then loaded to observe if any variation will occur at the output voltage. The primary control unit was seen to maintain the output voltage at 222 V which was in-line with the reference voltage set. Hence, the feedback unit was found to be working in very good condition.

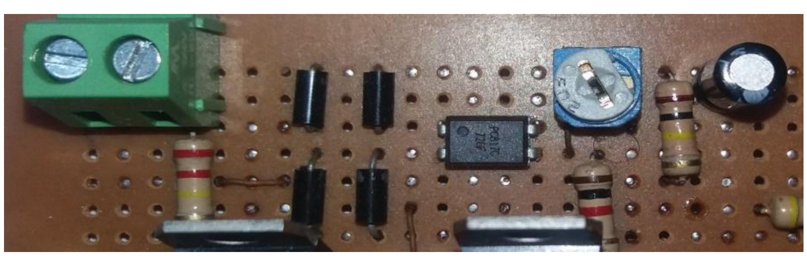

Fig. 4.12: Implemented Feedback Unit.

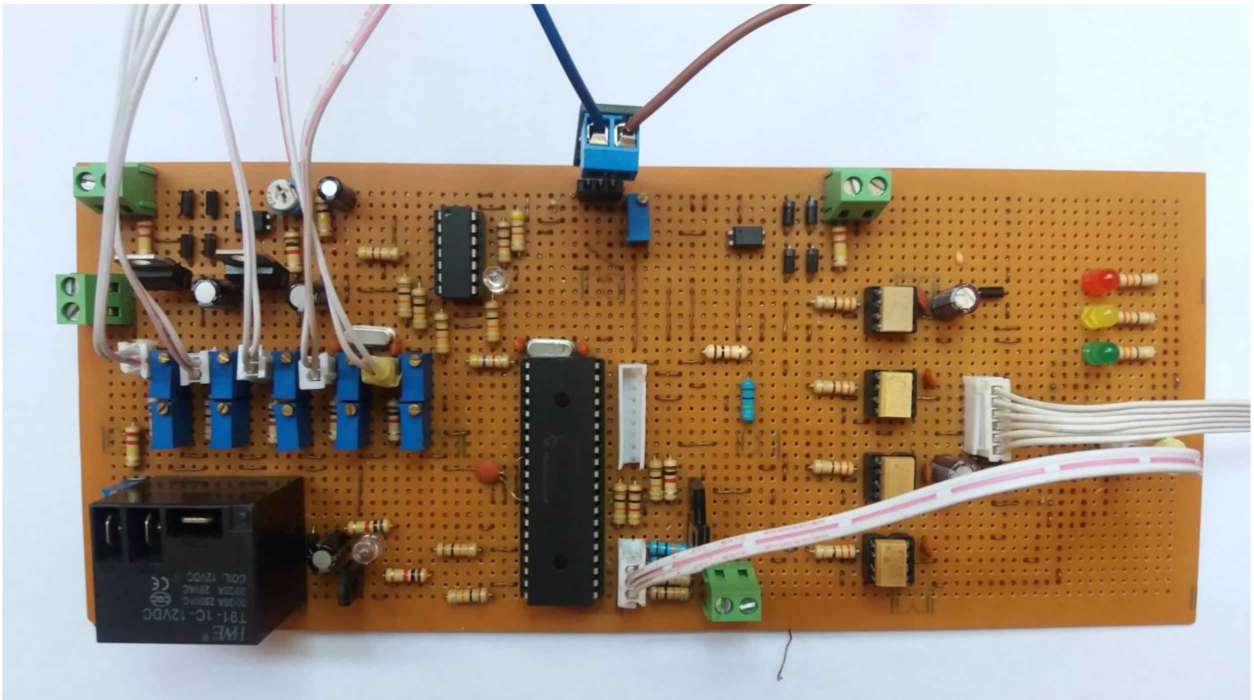

Fig. 4.13: Implemented Inverter Circuit.

4.10 Bill of Engineering Measurement and Evaluation (BEME)

The details of the electrical components and materials used in the implementation of this work are as follows:

Table 4.1: Bill of Engineering Measurement and Evaluation

S/N	MATERIAL	DESCRIPTION	QUANTITY	UNIT PRICE (N)	TOTAL (N)
1.	**Microcontrollers:**				
	PIC16F887	40-Pin, 8-Bit CMOS Microcontroller	1	1500	2400
	PIC16F684	14-Pin, 8-Bit CMOS Microcontroller	1	900	
2.	**MOSFET Driver:**				
	TLP250	Isolated Gate Driver	4	250	1000
3.	**Transistors:**				
	IRF3205	Power MOSFET	150	4	700
	BD135	NPN BJT	50	2	

4.	**Current Sensor:** ACS712	High Bandwidth Hall Effect-Based Linear Current Sensor	1	800	800
5.	**Thermistor:** 10kΩ	NTC	5	250	1250
6.	**Resistors:** 10Ω 330Ω 1kΩ 4.7kΩ 10kΩ 100kΩ 220kΩ 20kΩ 10kΩ	Fixed Resistor " " " " " " Variable Resistor Trimpot Variable	4 7 10 3 16 1 2 1 12	10 10 10 10 10 10 10 20 50	1050
7.	**Capacitors:** 22pF 0.1uF 4.7uF (16V) 100uF (25V)	Non-polarised " Polarised "	4 4 1 4	20 20 50 80	530
8.	**Diode:** 1N4007	Silicon Diode	6	10	60
9.	**Voltage Regulators:** 7805 7812	Linear Voltage Regulator "	1 1	50 50	100
10.	**Opto-coupler:** PC817	Isolator	1	50	50
11.	**Crystal Oscillator:** 16MHz 20MHz	Oscillator "	1 1	100 100	200
12.	**LED:** Transparent Coloured	-	1 3	20 10	50
13.	**DC Fan:** 12V	Large	1	1000	1000
14.	**IC Socket:** 4×4 **7×7** 20×20	-	1 1 1	50 100 200	350
15.	**Connectors:** 40 pin connector	-	1	300	1200

	12 wire connector 16 wire connector 2 port connector		1 1 5	300 350 50	
16.	**Vero board**	Big Vero board	2	200	400
17.	**Heat Sink**	-	-	2000	2000
18.	**Copper wire:** Gauge 25 Gauge 15	-	2 pound 1 pound	2500 2000	4500
19.	**Lamination**	-	-	3500	3500
20.	**Connecting wire**	-	-	700	700
21.	**Soldering Lead**	-	1 roll	2500	2500
22.	**Ply-wood**		-	500	500
	GRAND TOTAL				**24840**

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The inverter system implemented in this work is designed to overcome two common sources of failure in inverters which are overheating of the switches of the bridge circuit and overcurrent conditions. These overcurrent could be as a result of a short-circuit in the load terminals, a short-circuit in the inverter bridge (shoot-through condition) or an overload.

Hence, the 500W pure sine wave inverter system designed in this work incorporates a secondary control unit that is aimed at protecting the inverter against the aforementioned sources of failure. This secondary control unit receives input signals from a short-circuit/overload sensing unit which it uses to constantly monitor the current in the bridge circuit of the inverter, and instantly shuts down the system at the occurrence of any form of overcurrent. The secondary control unit also receives input signals from a temperature sensing unit, which it processes to determine the junction temperatures of the MOSFETs in the bridge circuit, and instantly shuts down the system at the slightest deviation of the MOSFETs from their respective thermal limits.

From the tests conducted on the various units of the inverter system and the results obtained, it is evident that the role played by this secondary control unit ensures that the inverter operates within its specified designed limits at all times, and hence improves its overall working condition.

5.2 Recommendations

In order to further enhance the working condition of inverter systems, the following recommendations are proposed:

i. High frequency current sensors with a shorter output rise time in response to step input current should be used in the short-circuit/overload sensing unit. This will help to improve the effectiveness of the overcurrent detection process and shorten the overall response time of the system to overcurrent.

ii. More efficient methods of determining junction temperature of semiconductors, such as the use of infrared cameras should be used in temperature monitoring. This will improve the accuracy of the junction temperatures of the switching devices obtained and enhance the response of the system to overheating.

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