TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Mechanical Engineering

Design of Invertor and its Packaging

Master Thesis

Study programme: N2301 Mechanical Engineering
Study branch: Machines and Equipment Design

Author: **Abhishek Vittalapura Rajanna**
Thesis Supervisors: Ing. Radek Votrubec, Ph.D.
    Department of Manufacturing Systems and Automation

Liberec 2021

Master Thesis Assignment Form

Design of Invertor and its Packaging

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Identification number:	S19000366
Study programme:	N2301 Mechanical Engineering
Study branch:	Machines and Equipment Design
Assigning department:	Department of Manufacturing Systems and Automation
Academic year:	**2020/2021**

Rules for Elaboration:

1. Inverter modelling and Assembly of components on PCB for required Application.
2. Optimization for compact and Modular size of inverter.
3. Mechanical design of inverter and packaging and thermal management.
4. Manufacturing of the inverter and its cost analysis.

Scope of Graphic Work: as required
Scope of Report: 50
Thesis Form: printed/electronic
Thesis Language: English

List of Specialised Literature:

[1] BEQUETTE, B. Process control: modeling, design, and simulation. Upper Saddle River, N.J.: Prentice Hall PTR, 2003. ISBN 0133536408.
[2] Arduino Learning: Getting Started with Arduino. In: Arduino [online]. 2014 [cit. 2015-01-09]. available from: http://arduino.cc/en/Guide/HomePage.
[3] Palani, R.K., Harjani, R. Inverter-Based Circuit Design Techniques for Low Supply Voltages, Springer, ISBN 978-3-319-46628-6.

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Date of Thesis Assignment: November 19, 2020
Date of Thesis Submission: May 19, 2022

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Liberec   March 5, 2020

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ACKNOLDEGEMENT

It is with immense gratitude; I acknowledge the support of my university for providing me this great opportunity to develop in deepest manner my engineering skills while accomplishing this diploma thesis and help them to further develop the importance in machine construction design.

I am indebted firstly to thank especially **Ing. Radek Votrubec, Ph. D** for his professional guidance, encouragement and good advices all along. This thesis becomes much better because of him. Thanks to his supervision and support.

I would like to thank our head of the department **Ing. Petr Zelený Ph.D.** who has been a great support in every way to pursue our academics. Without his help, I might otherwise have never encountered successfully.

I would like to express my gratitude to The Department of Manufacturing System and process of Automation at the Technical university of Liberec for providing me the support I required, which gave me the opportunity to proceed freely with this work.

Finally, I am grateful to thank my parents and friends, who have been a moral support in all the situations and encouraging my works.

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ABSTRACT

This thesis offers with the design of enclosure for a standard voltage source.
Inverter for high current applications widely used in electric vehicles/ hybrid electric vehicles.
The developed construction will provide flat shape from both top and bottom.
This can be used significantly for double side cooling design for high heat dissipation. Main goal of this thesis to remove heat from the different locations or zones in the Inverter casing block with combined cooling or just with water cooling with aluminum block at the bottom. Another alternative solution can be depending of the heat developed the air fins plate can be bolted onto the casing.
Proper electrical, thermal and fluid mechanics modeling as well as computational testing of the module pack under transient load conditions tender using a multidisciplinary approach of the design process. Different rates of cooling is needed for different range of loads and duty cycle with corresponding head generation in other terms to effectively meet the highly demanding cooling requirements of an electric vehicle inverter. The duty cycle depends on the driving cycles of passenger vehicles and during acceleration tests in several ambient environments. The aluminum cooling plate block is designed as a reference to the solutions available in standard flow, type of fluid used and deposit inside the heat sink.

KEYWORDS

Inverter Cooling, Electric Vehicles, Heat sinks, Combined Cooling, Inverter Casing and Packaging.

ABSTRAKT:

Tato práce se zabývá návrhem krytu pro standardní zdroj napětí, kterým je frekvenční měnič velice často používaný pro vysoce aktuální aplikace široce používaný v elektrických vozidlech / hybridních elektrických vozidlech. Vyvinutá konstrukce spočívá v plochém tvaru shora i zdola, což lze významně využít pro oboustranný design chlazení pro vysoký odvod tepla. Hlavním cílem této práce je odstranit teplo z různých míst nebo zón v bloku frekvenčního měniče s kombinovaným chlazením nebo jen s vodním chlazením s hliníkovým blokem ve spodní části. Dalším alternativním řešením může být v závislosti na vyvíjeném teplu, že k pouzdru může být přišroubována deska se vzduchem chlazenými žebry.
Proces návrhu zahrnuje multidisciplinární modelování elektrické části, tepelné a kapalinové mechaniky. Testovací výpočty jsou prováděny za podmínek různých přechodných zatížení. K efektivnímu splnění vysoce náročných požadavků na chlazení frekvenčního měniče elektrického vozidla jsou pro různé rozsahy zatížení a pracovní cyklus s odpovídající generací tepla v různých podmínkách zapotřebí různé intenzity chlazení. Pracovní cyklus závisí na jízdních cyklech vozidel, například během zrychlení za několika podmínek. Blok hliníkové chladicí desky je navržen s ohledem na průtok, typ použité kapaliny a usazení uvnitř chladiče.

KLÍČOVÁ SLOVA:

frekvenční měnič, elektromobil, chladič, kombinované chlazení, návrh krytí

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LIST OF SYMBOLS

PCB – Printed circuit Board

DC – Direct Current

AC – Alternating Current

CAD – Computer Aided Design

1. INTRODUCTION

Electrification of vehicles is a very prominent change in the engineering world one, which have impacted the traditional automotive industries. The applicability of the electrical impulsion systems for mobile usage may be limited considering many factors such as cost of implementation, drivability and the range of Operation that includes both duty cycle and operational time of the equipment.[1] These technology trends are also equally applicable for hybrid and plug-in hybrid vehicles.
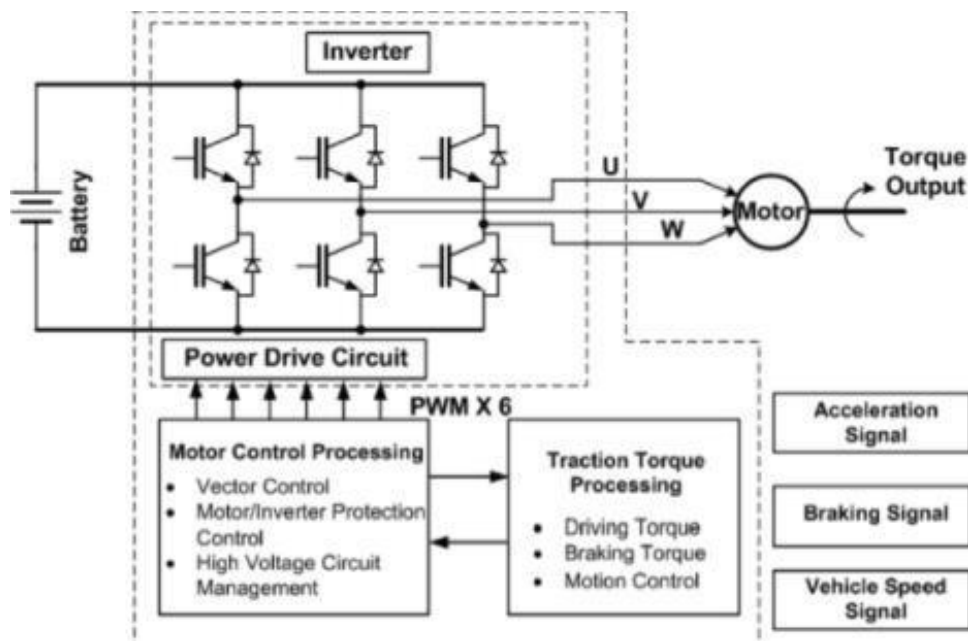
Figure 1 Typical propulsion system components of a EV powertrain[1]

An inverter is a device, which converts DC power into AC power at desired output voltage and frequency[2]. The direct current input of the inverter is obtained from an existing power source or of a rotary alternator via rectifier or a battery, a fuel cell, a photovoltaic or a magneto hydrodynamic generator. For home applications, the inverter converts the DC power for the battery to 240V AC.

In this diploma Thesis, the size of the PCB board is decided based on the electrical components, which has to be placed on the board itself. These components are selected based on the application of the equipment. The board size can be designed with various approaches such stacking the board on top of each other to reduce the length of the PCB board or using a single PCB board and placing all the components on it. However, this approach does not yield us the modularity and compact size for many applications.

An example of PCB board in Stack configuration is shown below

Figure 2 EV Traction inverter [3]

This type of configuration might lead to increase in the height of the inverter.

The trend of densely populated printed circuit boards and high processing power electronics and telecommunications systems has created a challenge in developing sustainable thermal management systems. The problem lies in the research of effective means of controlling the temperature and heat dissipation level chip and rack systems for safe and reliable operation. A large number of researches in thermal management electronics have been carried out.

The cooling of the inverter also depends of the material of the casing used hence there is effective heat transfer and the head can be removed easily also. In this diploma thesis I am going to be using an Aluminum Sheet metal box designed in CAD software and with appropriate holes for mounting purposes with the PCB and this will be designed keeping in mind the cost on manufacturing and DFMA principles of Product design. This packaging should be designed in such a way that it is easy for service and maintainability.

Also, possibility of cooling such as using a heat sink below the PCB board is being used here this can also be improved by combined cooling so that in cooling rate is enhanced and the cooling of the inverter can be achieved for higher temperatures as well.

2. INTRODUCTION TO DIFFERENT TYPES OF INVERTERS[4]

The alternating current supply is operated for almost all residential, commercial and industrial purposes. However, the biggest problem with AC is that it cannot be stored for future use.
 The alternating current is therefore converted into direct current; the direct current is stored in batteries and ultra-capacitors. Now, whenever AC power is DC current is again converted to current to operate AC devices. Therefore, the device, which converts direct current into current, is called Inverter. The inverter is used for converting direct current to variable alternating. This variety can be within the magnitude of voltage, number of stages, recurrence or phase contrast.

2.1 CLASSIFICATION OF INVERTER

Inverter can be categorized in to the following types

1. Based on Output Characteristic
    - ➢ Square wave inverter
    - ➢ Sine wave inverter
    - ➢ Modified Sine wave inverter

2.1.1 SQUARE WAVE INVERTER

The waveform of output voltage for inverter is square wave. This kind of inverter is the least used amongst all different sorts of inverters due to the fact all devices are designed sine wave power supply. If we offer a square to sine wave device, it is able to be broken or the losses are high. The price of this inverter could be very low however could be very rare. It may be utilized in easy equipment with familiar motor.

2.1.2 SINE WAVE INVERTER

The output waveform of the voltage is sine wave and it gives us great output at the mains power. This is the major advantage of this inverter because all the we use are designed for sine wave. Therefore, that is the appropriate end result and offers the assurance the
system will work properly. This type of inverter is more expensive but widely used in residential and commercial applications.

2.1.3 MODIFIED SINE WAVE

The construction of this sort of electrical converter is complicated than square wave electrical converter however easier compared to pure wave inverter. The output of this electrical converter is neither pure wave nor square wave. The output of such electrical converter is one among 2 squares. The output wave isn't exactly a sin wave, however it's sort of a waveform.
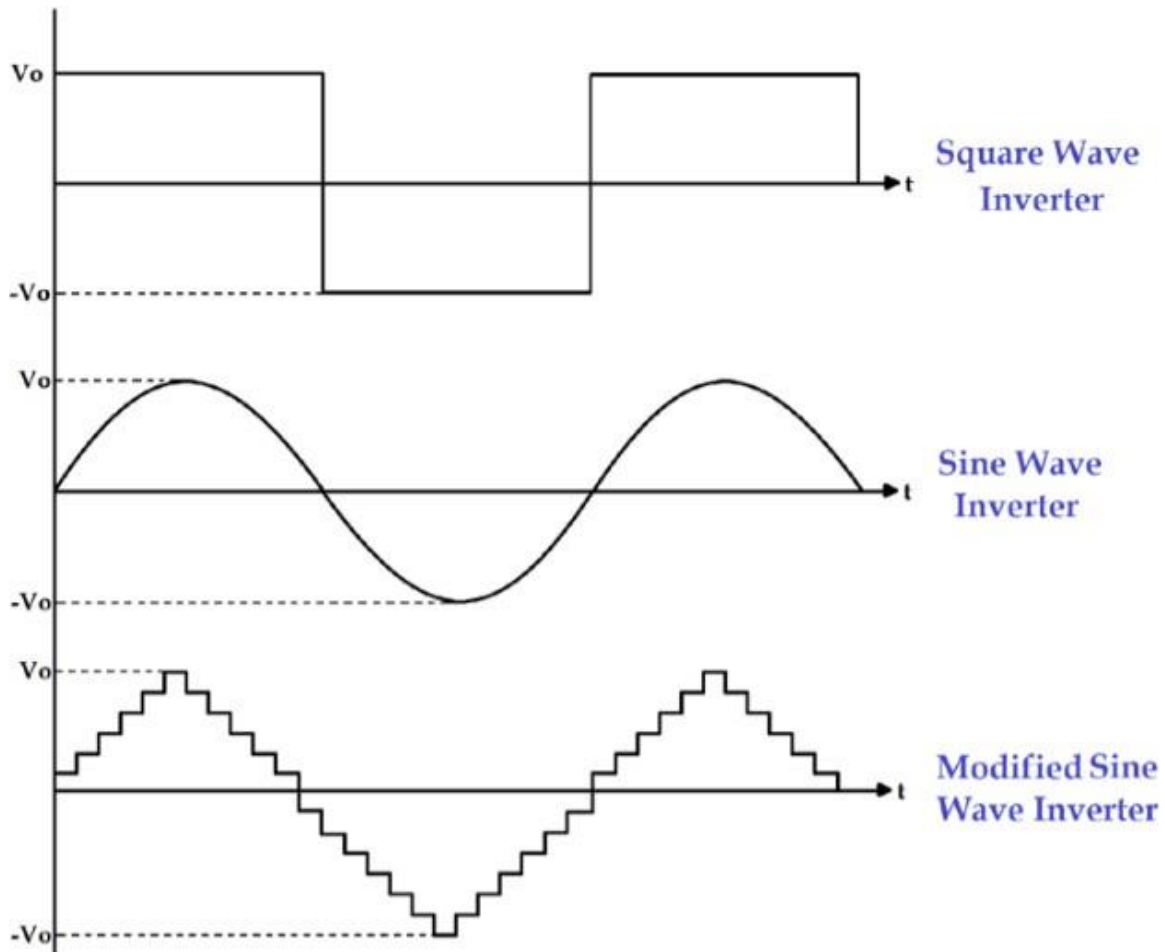
Figure 3 Classification based on output Characteristic [4]

2.2 BASED ON SOURCE OF INVERTER

  ➢ Current source Inverter

2.2.1 CURRENT SOURCE INVERTER

The input is a current source. This type of inverters is used in medium industrial application where high quality current waveforms required.

➢ Voltage source Inverter

2.2.2 VOLTAGE SOURCE INVERTER

The input is a voltage source. This type of inverter is used in all application it Is more efficient and provides greater and faster dynamics response.

Single phase inverter

Regularly private and commercial stack utilize a control supply. The single-phase inverter is utilized for this sort of application. The single-phase inverter is divided into two parts;

     i.   Single Phase Half Bridge Inverter

    ii.   Single Phase Full Bridge Inverter

2.2.3 SINGLE PHASE HALF BRIDGE INVERTER

This type of inverter consists of two thermistors and two diodes and the connection is like shown in figure below.
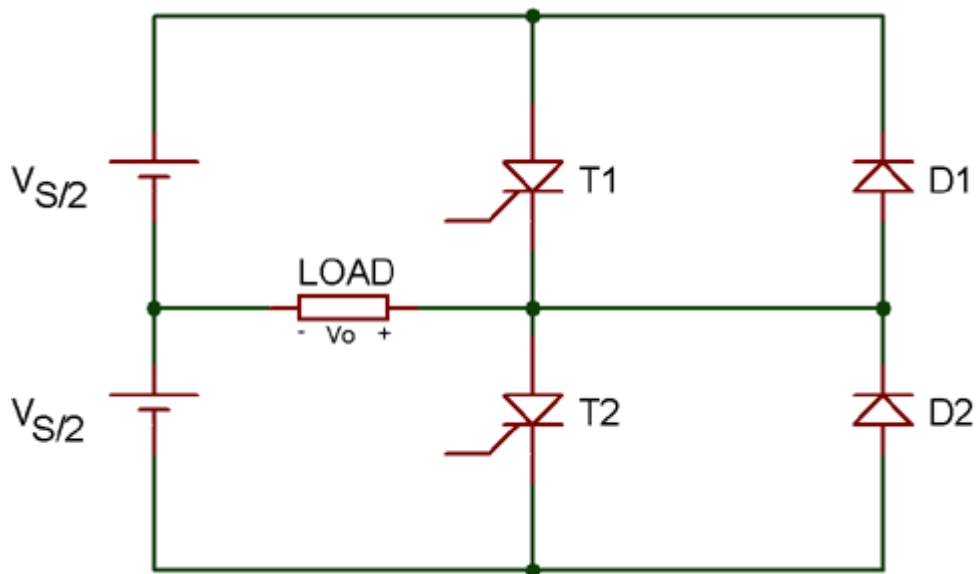
Figure 4 Half Bridge Inverter [4]

In this case, the total DC voltage is Vs divided into two equal parts Vs / 2. The duration of a cycle is T sec. For half cycle of 0 <t <T/2, thyristor T1 conducts. The load voltage is Vs/2 due to the upper voltage source Vs/2. For the second half cycle of T/2 <t <T, thermistor T1 is commutated and T2 conducts. During this period, the load voltage is -Vs/2 due to the lower source Vs/2.
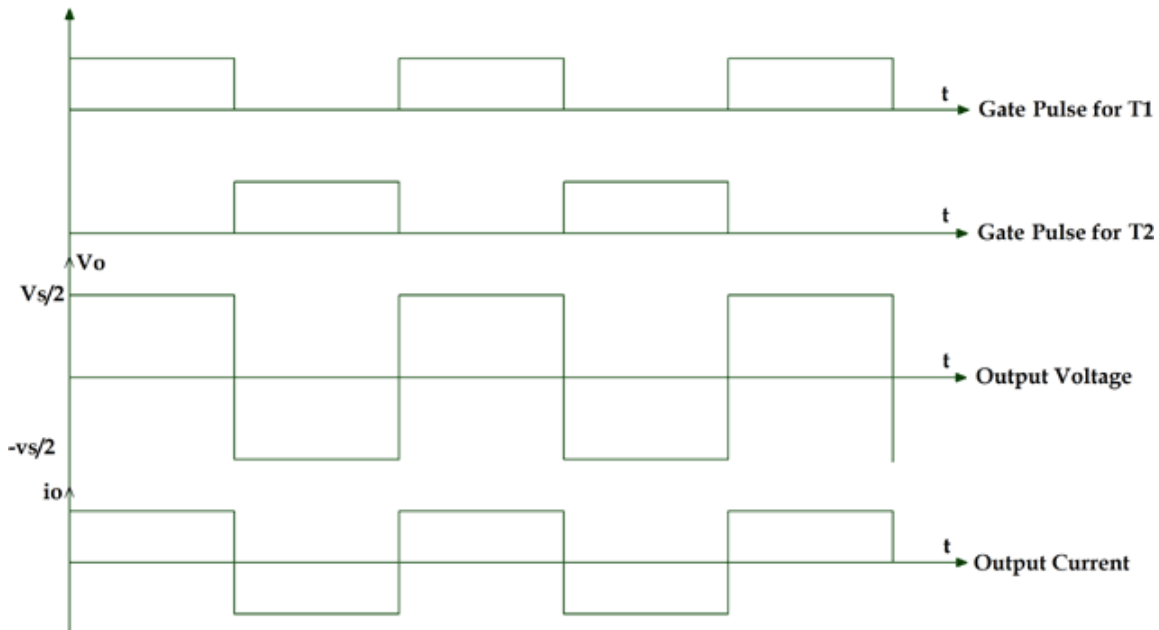
By this operation, we can get an alternating voltage waveform with a frequency of 1 / T and a peak amplitude Vs / 2. The output waveform is a square wave. It will pass through the filter and remove the unwanted that gives us a pure sine waveform. The frequency of the waveform can be controlled both ON time and OFF time of thermistor.

The amplitude of the output voltage is half the supply voltage and the period of use of the is 50%. This is a downside of half bridge inverter and solution is full bridge inverter.

2.2.4 SINGLE PHASE FULL BRIDGE INVERTER

In this type of inverter, four thermistors and four diodes used. The circuit diagram of single-phase full bridge is in the figure below.
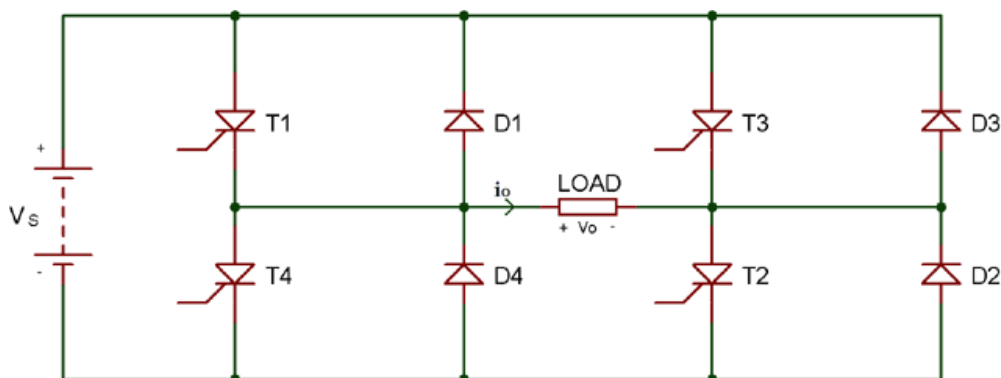
Figure 5 Full bridge Inverter [4]

At a time two thermistors T1 and T2 conduct for first half cycle 0 < t < T/2 During this period, the load voltage is Vs, that is comparable to the DC supply voltage. For second half cycle T/2 < t < T, two thermistors T3 and T4 conducts. The load voltage during this period is -Vs.
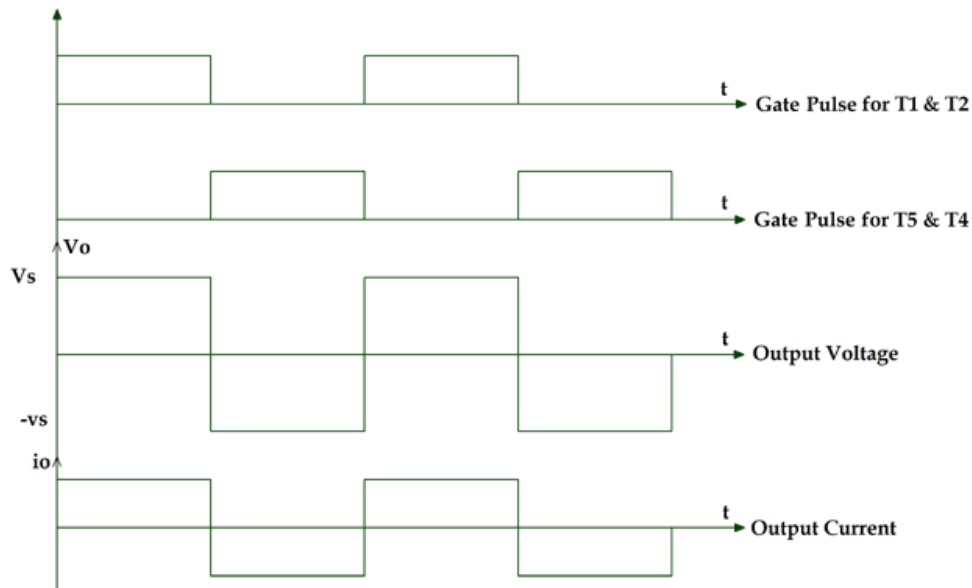
Figure 6 Output Waveform [4]

Here we can get the same output voltage as DC supply voltage and source duty cycle is 100%. The output voltage waveform is a square wave and filters are used for it to a sine wave. If all thermistors conduct at the same time or pair or then the source will be short-circuited. The diodes are connected in the circuit as a feedback diode as they are used for the power to the DC source.

If we compare full bridge inverter with half bridge inverter, for given supply voltage load, the output voltage is twice the output power is four times in at full bridge.

2.2.5 THREE PHASE BRIDGE INVERTERS

In case of industrial load, a three-phase power supply is and for this, we have to use a three-phase inverter. In this type of inverter, six thermistors and six diodes used and they are connected as shown in the below.
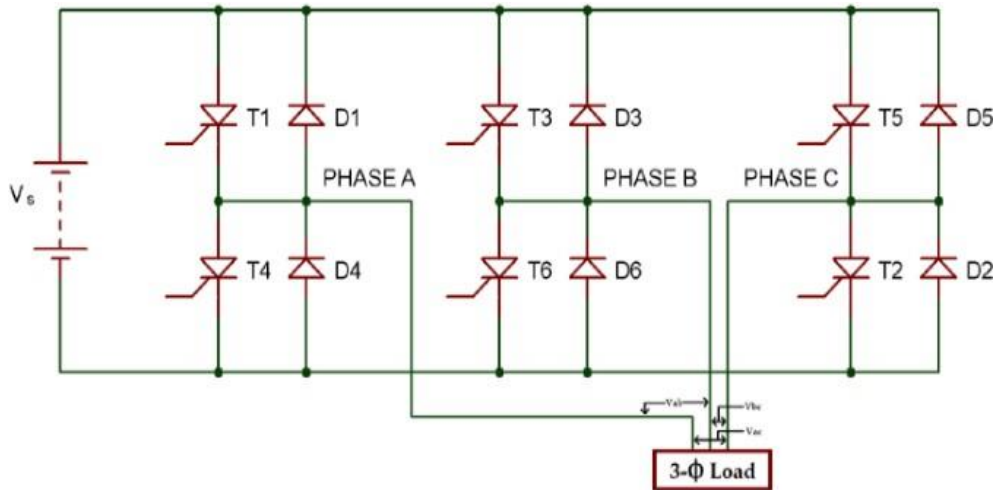
Figure 7 3-phase bridge inverter [4]

2.3 BASED ON DIFFERENT PWM TECHNIQUES

➢ Simple Pulse Width Modulation (SPWM)

➢ Multiple Pulse Width Modulation (MPWM)

➢ Sinusoidal Pulse Width Modulation (SPWM)

➢ Modified sinusoidal Pulse Width Modulation (MSPWM)

Inverter output is square wave and signal is not used for load. The pulse width modulation technique is used to control the AC output voltage. This control is obtained by controlling the periods and off the switches. In the PWM technique, two signals are used; one is the reference signal and the second is the triangular carrier signal. The gate pulse for switches is generated in these two signals.

There are different types of PWM techniques

2.3.1 SINGLE PULSE WIDTH MODULATION (SINGLE PWM)

For each half cycle, the single pulse is available in control technique. The reference signal is a square wave signal the carrier signal is a triangle wave signal. The pulse from gate for the switches is generated as the reference signal and the carrier signal. The frequency of the output voltage is controlled the frequency of the reference signal. The amplitude of the reference signal is Ar and the carrier signal amplitude is Ac, then the modulation index can be set as Ar / Ac. The main disadvantage of this technique is high harmonic content.
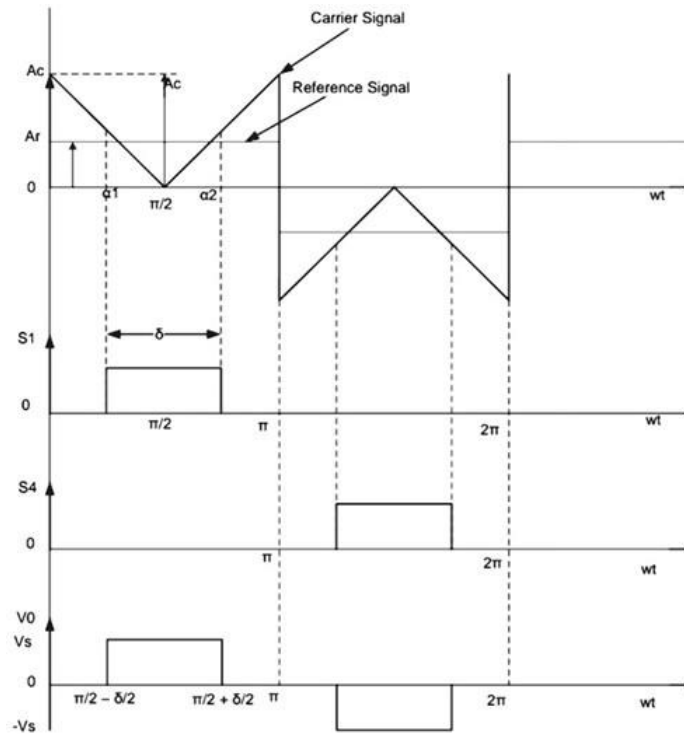
Figure 8 Single Pulse Width Modulation [4]

2. Based on Number of output Level

2.3.2 REGULAR TWO LEVEL INVERTER

These inverters have only voltage levels, which are a positive peak voltage and a negative peak voltage. Sometimes having zero voltage level is also referred to as two level inverters.

2.3.3 MULTI-LEVEL INVERTER

These inverters may have a couple of voltage stages on the output. The multi-level inverter is divided into four parts.

- Flying capacitor Inverter

- Diode-clamped Inverter

- Hybrid Inverter

- Cascade H-type Inverter

Each inverter has its own design of operation. Here we have briefly explained these inverters to get a basic idea about them.

3. MECHANICAL PACKAGING DESIGN

Electronic bundling configuration is the development and production of electronic gadgets going from computer chips to broad electronic frameworks. Since electronic manifestations are viewed as delicate, the plan of the encasing of the electronic item should consider the against outrageous temperatures, mechanical harm, cooling, radio recurrence clamor outflows, electrostatic release and high recurrence commotion emanations [5].

Product safety standards may dictate the essentials of a product utilization, for instance, the exterior case temperature or the grounding of unprotected or uncovered metals [6]. The external case temperature or the grounding of exposed metals. Prototypes and industrial apparatus made in small numbers may use normalized commercially available enclosures such as card cages or prefabricated boxes [6].

Technological developments also exert a lot of pressure on electronic packaging companies, as the functions of electronic packaging design are evolving rapidly in accordance with modern technology. Functions do not remain constant as as technology improves, requirements for electronic packaging as well and change accordingly.

Figure 9 Example for Electronic Enclosure [7]

3.1 ELECTRONIC PACKAGING CAN BE CATEGORIZED BY LEVELS:

Electronics packaging design is structured in multiple levels viz. Level 0 up to Level 5.

➢ Level 0 - This level of electronic conditioning protects chips and semiconductors which are the simple and most basic parts of an electronic system.

➢ Level 1 – This electronic enclosing level shields electronic components.

➢ Level 2 – This electronic packaging level safeguards the PCB.

➢ Level 3 - This electronic packaging level assembly, one or more wiring boards and recounted components.

➢ Level 4 – This electronic packaging level shields modules or assortment of assemblies.

➢ Level 5 - This electronic packaging level the system, a set of modules combined for some function.

➢ Level 6 – IP Resistance Ratings [8]

IP stands for Worldwide Assurance Stamping, or moreover commonly alluded to as Entrance Assurance Checking. This classification rates the degree and reasonability of security against entrance of farther matter (dust, solid objects, and moisture) into a walled in region or item lodging.

Figure 10 IP rating abbreviation

3.1.1 STRONG OBJECTS/DUST SECURITY LEVELS (1ST DIGIT AFTER IP) [8]

- Level zero – No Protection
- Level one – Effective against >50mm – Any huge surface of the body, adore the rear of a hand, however no assurance against consider contact with a body portion.
- Level two – Effective against >12.5mm – Fingers or connected objects
- Level three – Effective against >2.5mm – Tools, thick wires, etc.
- Level four – Effective against >1mm – Most wires, slender screws, giant ants etc.
- Level five – dirt Protected Entrance of dust not utterly avoided; however, it should not enter in Associate in Nursing adequate quantity to meddled with the appetizing operation of the instrumentation
- Level six – dirt Tight – No access of dust; complete protection against contact ("dust tight"). A vacuum should be connected. Test term of up to eight hours supported discuss stream.

3.1.2 LIQUID/MOISTURE ENTRANCE SECURITY LEVELS (2ND DIGIT AFTER IP)

- Level 0 – No Protection
- Level 1 – Useful against vertically falling water drops
- Level 2 – Useful against dripping water when tilted at 15 degrees
- Level 3 – Useful against spraying water at any angle up to 60 degrees from vertical
- Level 4 – Useful against splashing of water at any direction
- Level 5 – Useful against water jets from any direction
- Level 6 – Useful against powerful water jets from any direction
- Level 6K – Useful against water jets with increased pressure from any direction
- Level 7 – Useful against immersion in freshwater up to 1m (3ft) depth
- Level 8 – Useful against immersion in freshwater 1m (3ft) or more depth
- Level 9K – Useful against powerful high temperature water jets from varying angles

3.2 OTHER PROTECTIONS/LETTER INFO (3RD DIGIT AFTER IP)

- f – Oil Resistant
- H – High voltage device
- M – Device moving during water test
- S – Device stationary during water test
- W – Weather conditions

These stages are fundamental for help hardware organizations to effortlessly survey the electronic bundling materials expected to develop an electronic bundling. This makes tasks more skillful and smoother they can without much of a stretch find what they need by depicting the degree of electronic molding they are as of now chipping away at. A similar electronic framework might be wrapped as an advantageous gadget or modified for fixed mounting in an instrument rack or consistent durable establishment. Bundling for aviation, marine, or military frameworks forces various kinds of plan measures.

A designer must balance many purposes and practical factors when selecting packaging methods:

- ➢ Threats to be guarded against mechanical damage, exposure to weather and dirt, electromagnetic interference[9].
- ➢ Heat dissipation conditions
- ➢ Compromises between tooling capital cost and per-unit cost
- ➢ Compromises between time to first delivery and production rate
- ➢ Accessibility and competence of suppliers
- ➢ UI (User interface) design and convenience
- ➢ Ease of accessible to internal parts of the components when required for maintenance
- ➢ Product safety, and compliance with regulatory standards
- ➢ Aesthetics, and other marketing considerations
- ➢ Service life and reliability

Electronic packaging depends on mechanical engineering theories such as dynamics, stress analysis, heat transfer and fluid mechanics. High- dependability apparatus often must survive Drop tests, loose cargo vibration, secured cargo vibration, extreme temperatures, humidity,

water immersion or spray, rain, sunlight (UV, IR and visible light), salt spray, explosive shock, and many more.[10]

Many electrical commodities require the manufacturing of high-volume, low-cost parts such as enclosures or covers by techniques such as injection molding; die casting, investment casting, and so on. The plan of these products depends on the generation strategy and require cautious consideration of measurements and tolerances and tooling design.

3.3 Creating custom electronics, packaging designs are directed on achieving intentions by covering these following qualifications:

I.   **Understanding of Specifications or Requirements**

In addition to the electrical circuits, the electronic packaging engineer must be able to interpret the non-electrical concerns compulsory for the design of the electronic packaging. These non-electrical disquiets are functionality, reliability, durability and cost of production. Even though the electrical circuits are all in place as the design failed to any of these concerns, the packaging design of the electronic product can be considered a non-compliance.

II.   **Implementing the Design Approach**

Despite the fact that the electronic bundling engineer is furnished with and information to make customized electronic bundling, should consistently have a plan approach set up to take care of business. The right item configuration approach is important to meet the necessities set on the bundling plan

III.   **Cost-Efficiency**

On the off chance that you are in the realm of assembling, you ought to comprehend the significance of the connection among cost and worth. Having an excessively costly electronic bundling configuration would compensate for it is regardless of whether it is completely useful. The electronic plan architect ought to investigate all choices in regards to electronic bundling froth and electronic bundling materials until the outcome is a sane expense for esteem.

Being beneficial is a critical part of assembling just in gadgets. Item improvement with models' organizations help.

IV.   Mechanical Knowledge

Most electronics design companies seek mechanical help and do not rely solely on electrical experts when it comes to custom electronics packaging. Their knowledge and expertise could compensate areas related to the project circuits to ensure that all aspects are covered.

Reliability evaluation of electrical enclosure a typical dependability prerequisite includes the following types of environmental highlights: -

➢ Burn-in

Burn-in is the process by which components of a system are used prior to being placed in service. This testing process will force some failures to occur under supervised conditions so that an understanding of the product load can be established.[11]
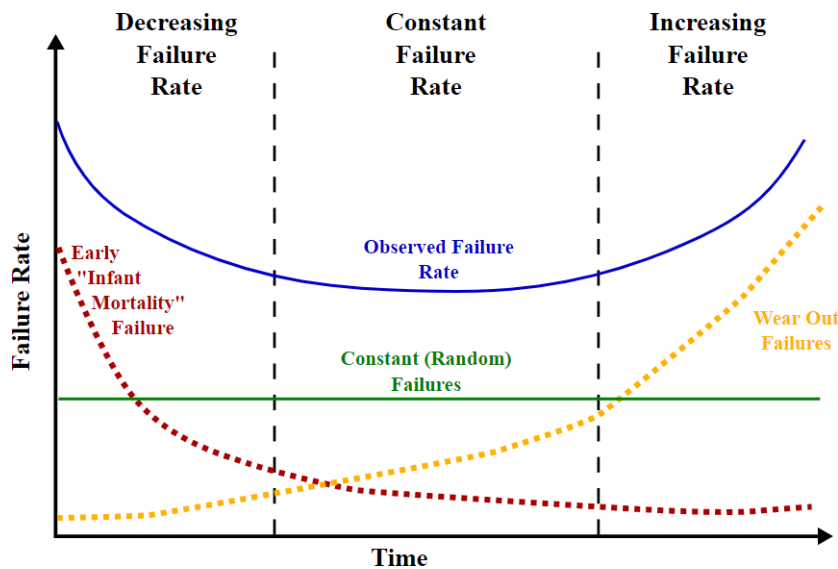
Figure 11 Burn in Graph for usage of components[11]

➢ Temperature cycling

Temperature cycling is the process of two extremes of temperature, usually at comparatively high proportions. This is an environmental stress test, which is usually exercised in the reliability of the product as well as in the detection of early latent defects by inducing thermal fatigue. [12]

➢ Thermal Shock

➢ Solderability

➢ Autoclave

An autoclave is a machine used to produce industrialists and scientists requiring a temperature and a pressure in relation to the pressure / ambient temperature.[13]
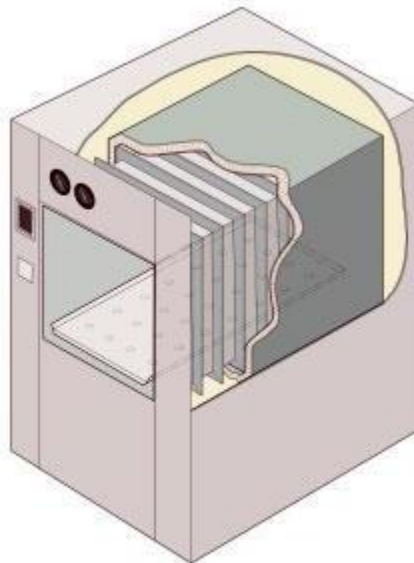
Figure 12 Example of Rectangular Autoclave[14]

➢ Visual inspection

➢ Hygrothermal/moisture resistance

Hygrothermal test is executed in chambers with temperature and humidity. It is an natural stress test utilized in assessing product reliability. The typical Hygrothermal test is 85°C temperature and 85% relative humidity. During the test, the sample is periodically taken out to test its mechanical or electrical properties.[15]

3.4 PACKAGING MATERIALS USED: -

Semiconductors	Si, SiGe, GaAs
Metals	Solders for interconnects (Sn-Pb, Sn-Ag, Sn-Ag-Cu, Sn-Au, Sn-Sb) Au or Cu wirebonds Cu leadframes (Kovar, CuBe, Alloy 42) Cu traces in substrates W, Mo traces in cofired ceramics Ag, Au, Pd for thin/thick films on ceramics Ni diffusion barrier metalizations Al heat sinks
Ceramics	Al_2O_3 substrates modified with BaO, SiO_2, CuO, etc. LTCC substrates Al_2O_3 modified with low-temperature glass (e.g., PbO) SiN dielectrics Diamond heat sinks
Polymers	Epoxies (overmold) Filled epoxies (overmold) Silica-filled anhydride resin (underfills) Conductive adhesives (die bonding, interconnects) Laminated epoxy/glass substrates Polyimide dielectric Benzoyclobutene Silicones Photosensitive polymers for photomasks (acrylates, monomers, etc.)
Glasses	SiO_2 fibers for optoelectronics Silicate glasses for sealing Borosilicate glass substrates Glass fibers for epoxy/glass substrates (FR-4)

Figure 13 Examples of materials used in electronic packaging [16]

These materials and how they are utilized in an electronic bundle could be utilized. The attention is on the accompanying classes of materials:

Metals are utilized as conveyors in the envelope, transcendently electrical yet in addition warm for power gadgets. This contains meager metal interconnects on the coordinated circuit made of Al, Cu or Au and the interconnects between the incorporated circuit and the bundle that are either wire security interconnects or weld joints. Metals are additionally used to go about as warmth sinks for power gadgets and as shields for RF applications.

Ceramics production and glasses are utilized as dielectrics or encasings. Pottery are utilized in gadgets as dielectrics to shape capacitors and inductors. In the actual bundle, the ceramics are utilized as protecting materials and as substrates that give an underlying base that electrically segregates lines and cushions.

Polymers are utilized as covers and, in a composite structure, as conductors. As an encasing, polymers are encapsulating, under fills and substrates (note: in these applications, polymers are utilized as composites with silica or glass fillers). Polymers are likewise utilized as protecting cements to stick parts to a substrate or board to give mechanical strength. The expansion of metal particles to the polymer can make it a conductive material utilized as a conductive glue interconnect.

Composite materials are a blend of materials that can be custom-made for either mechanical conduct upgrades, warm improvement or as an electrical transmitter. A considerable lot of the composite materials utilized in bundles depend on a polymer network as indicated in the polymer segment above.

Few more materials used -

- Sheet metal
- Cast metal
- Molded plastic
- Potting
- Porosity sealing or impregnation
- Liquid filling
- Conformal coating
- Printed circuit assemblies
- Hermetic metal/glass cases

➢ Hermetic ceramic packages

Figure 14 Example of Enclosures [17]

3.5 PCB THERMAL MANAGEMENT TECHNIQUES

Most electronic parts disseminate heat at whatever point a current course through them. The measure of warmth relies upon the force, gadget qualities, and circuit plan. Other than the parts, the obstruction of the electrical associations, copper follows, and vias add to some warmth, and force misfortunes.

To dodge disappointments or circuit glitches, creators should target delivering PCBs that work and stay inside safe temperature limits. While a few circuits will work without extra cooling, there are circumstances where adding heat sinks, cooling fans, or a blend of a few instruments is unavoidable.

This article will examine configuration rehearses that guarantee better warm administration, including some regular strategies for eliminating abundance heat from a PCB.
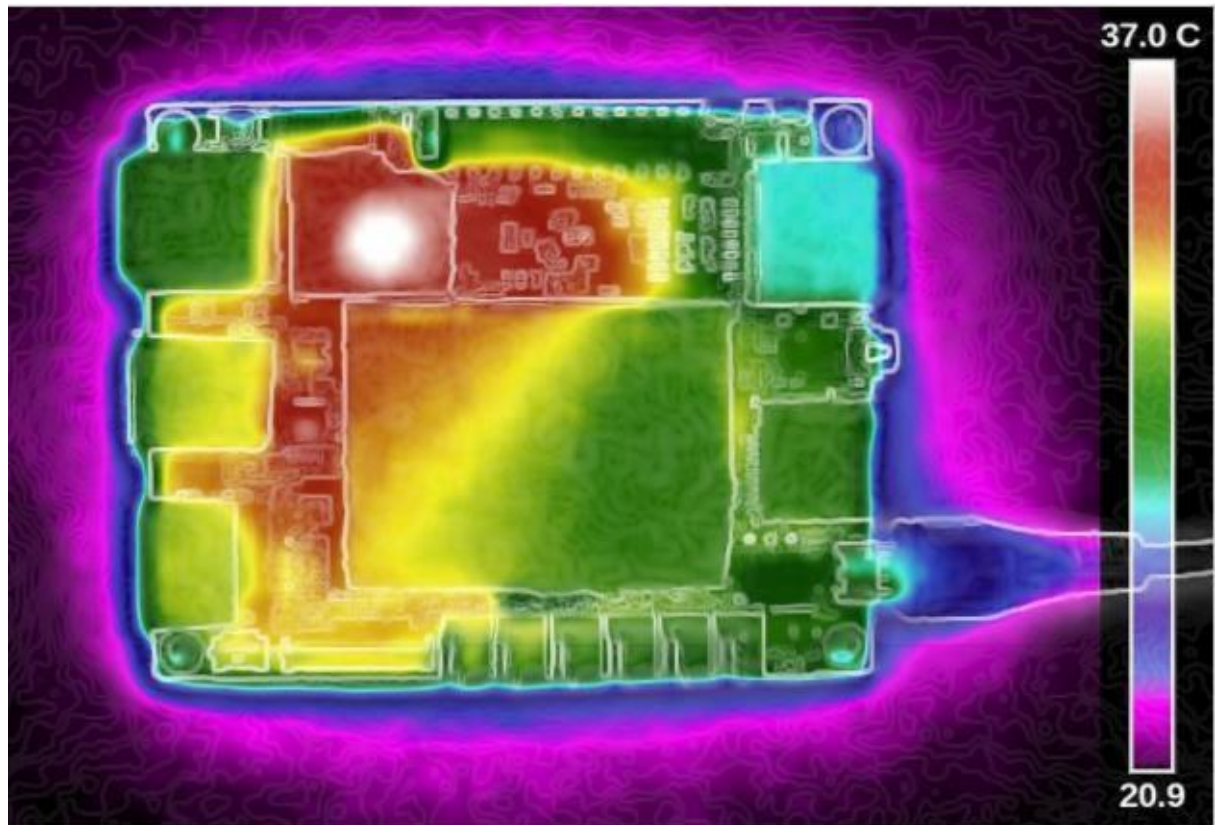
Figure 15 Thermal image of single board computer [18]

3.6 GOOD PCB DESIGN PRACTICES

Significant issues to consider during configuration are:

- Performance data and dimensions of the components

- Major heat-dissipating components

- Size of the PCB

- PCB material, layout, and component placement

- Mounting peripherals

- Temperature of the application environment

- Amount of heat dissipated

- Appropriate cooling methods, i.e., cooling fans, heat sink, etc. [18]

A best practice is to deal with the temperature at the segment and framework level while thinking about the working climate. Variables to consider when settling on a cooling system incorporate the bundle properties of the semiconductor, heat dispersal properties; and so on, this data is typically accessible from the maker's datasheet.

Common convection cooling is sufficient for PCBs with modest quantities of warmth dispersal. In any case, PCBs with overabundance heat require heat sinks, heat pipes, fans, thick copper or a mix of a few cooling strategies.

3.7 REDUCE THERMAL RESISTANCE

A low thermal opposition guarantees that the heat is moved through the material a lot quicker. This obstruction is straightforwardly corresponding to the length of the thermal way and conversely relative to the cross-sectional region and thermal conductivity of the heat path.

Thermal resistance

$$Q = \frac{t}{A \, X \, K}$$

Where

t is the thickness of the material

K is thermal conductivity factor

A is the cross-section area

Designers often reduce thermal resistance by [18]

Employing a slenderer PCB to decrease the thermal path

Adding thermal vias for vertical heat conduction

Copper foil and thick tracks for even heat conduction
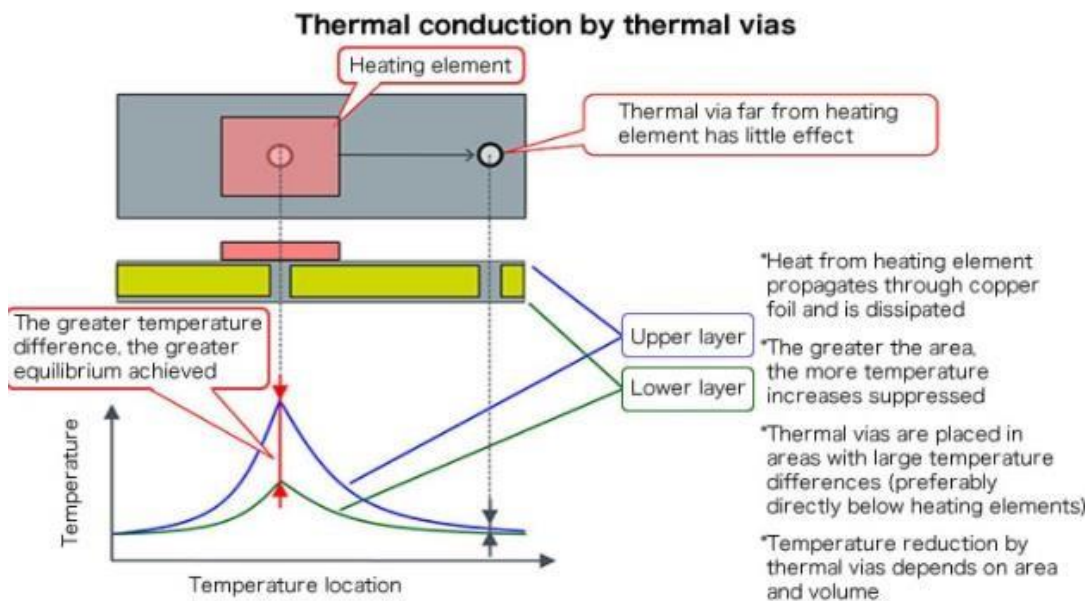
Figure 16 thermal conduction by thermal vias[18]

3.7.1 IDENTIFY COMPONENTS WITH THE POTENTIAL TO DISSIPATE MORE HEAT

It is essential to comprehend what segments produce the most heat and settle on the best evacuation component. Utilizing the producer's datasheet, an originator should discover the heat appraising and qualities of the gadget. Frequently, the designers will give rules on the most proficient method to eliminate abundance heat.

3.7.2 CONSIDER COMPONENT PLACEMENT, ORIENTATION, AND ORGANIZATION

Segments that disseminate more force ought to be situated in zones giving the best heat evacuation. This ought not be at the corners or edges of the PCB except if there is a heat sink. Setting parts some place close to the center guarantees heat scattering around the gadget, nonetheless, there ought to be sufficient space for satisfactory air circulation.

Despite the fact that it could be hard to guarantee an even temperature distribution, it is critical to try not to think the high-power components together. Circulating them equitably forestalls problem areas.

Another great practice is to put touchy segments like little ICs, semiconductors, and electrolytic capacitors in low-temperature territories. In circuits that depend on convection cooling, orchestrating parts, for example, ICs in a flat or vertical long way helps in thermal management.

3.7.3 CONDUCT THERMAL ANALYSIS

Performing a thermal analysis sets up how the parts and PCB will carry on at various temperatures and conditions. The analysis furnishes architects with a thought of the heat generation and move inside the circuit.

Designers would then be able to utilize analysis results and recreations to think of strategies that will help them had better deal with the heat.
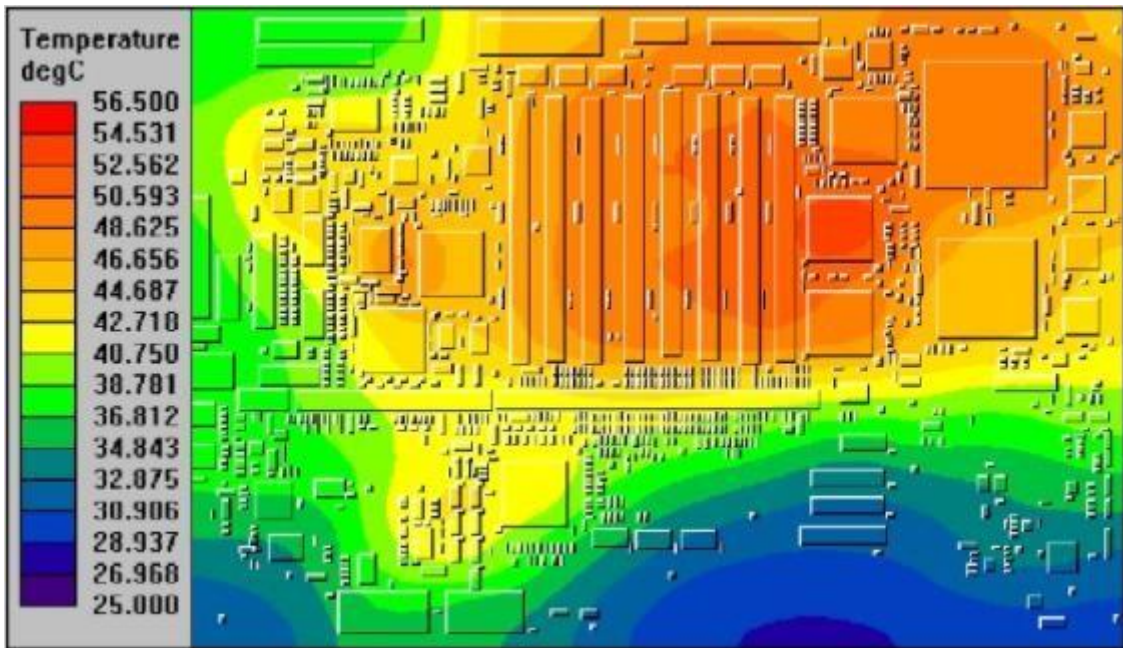
Figure 17 Typical thermal analysis of PCB board [18]

3.8 METHODS TO REMOVE HEAT FROM CIRCUIT BOARDS

There are a few methods that designers can use to eliminate heat from segments and PCBs. The regular instruments incorporate warmth sinks, cooling fans, heat lines, and thick copper. Frequently, circuits producing more heat require more than one innovation. For instance, cooling a PC processor and show chips requires a warmth sink, heat pipe, and a fan.

- **Heat Sinks and Cooling Fans**

  A heat sink is a thermally conductive metallic part with an enormous surface territory, typically appended to segments, for example, power semiconductors and exchanging gadgets. A heat sink permits the segment to disseminate its heat over a bigger zone and move that heat to the environmental factors. Now and again, for example, high current force supplies, adding a cooling fan helps in quicker and better heat removal.

- **Heat Pipes**

  Heat pipes are reasonable for minimal gadgets with restricted space. The lines give a solid and financially savvy aloof warmth move. Advantages incorporate with no vibration activity, great thermal conductivity, low upkeep, and calm activity since they have no moving parts.

  A common line contains limited quantities of nitrogen, water, or Ammonia. These liquids help to assimilate the heat, whereupon they discharge a fume that movements

along the line. The line has a condenser where, as the fume goes through, it gathers back to its fluid structure and the cycle starts once more.

- **Thermal Via Arrays**

Thermal vias increment the mass and territory of the copper, diminishing the warm obstruction and improving warmth dissemination from the basic segments through conduction. Accordingly, better execution is accomplished when the vias are set nearer to the heat source.

In certain applications, heat from a gadget, like a thermally enhanced IC, is led away through the mix of a warm by means of exhibit and cushion. This disposes of the requirement for a heat sink while improving the heat scattering through the PCB.
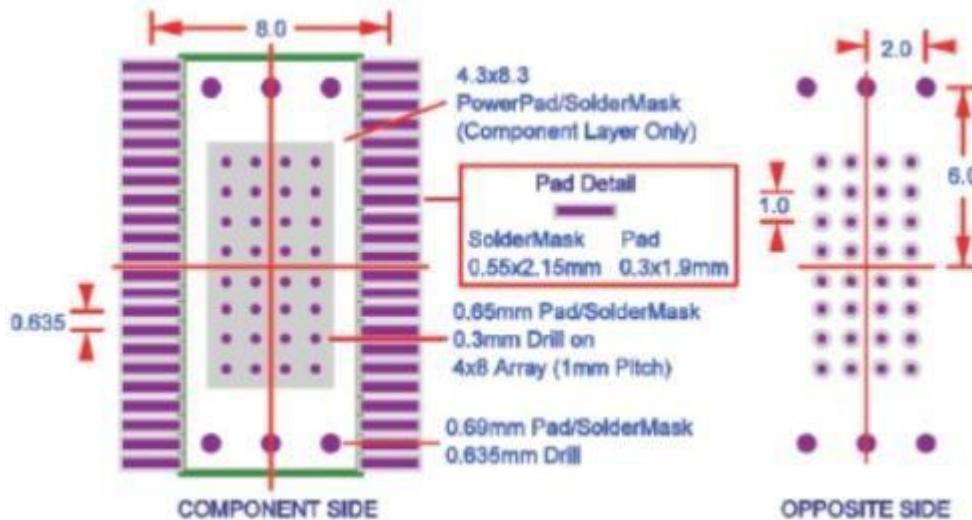
Figure 18 Thermal via array

PCB thermal management methods rely upon various elements including the measure of heat the parts and circuit disseminate, the climate, the general plan, and the walled in area. In the event that heat age is low, the circuit can work without extra cooling. Nonetheless, if the circuit produces higher measures of heat, there ought to be a cooling instrument to remove the heat.

To give thermally streamlined PCBs, designers ought to consider all that impacts temperature directly from the idea stage and all through the plan and assembling stages.

4. COMPONENTS USED FOR INVERTER

4.1 TRANSISTOR

A transistor could be a semiconductor gadget utilized to intensify or switch electronic signals and electrical control. Transistors are one of the fundamental building squares of present-day hardware. It is composed of semiconductor fabric as a rule with at slightest three terminals for association to an outside circuit. A voltage or current connected to one match of the transistor's terminals controls the current through another match of terminals. Since the controlled (yield) control can be higher than the controlling (input) control, a transistor can open up a flag. Nowadays, a few transistors are bundled separately, but numerous more are found inserted in coordinates circuits.[19]
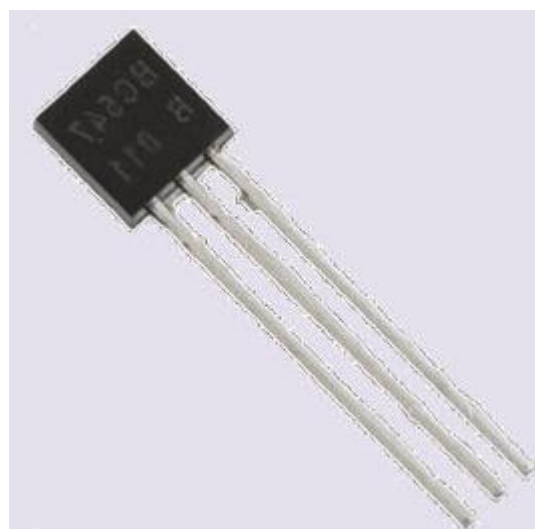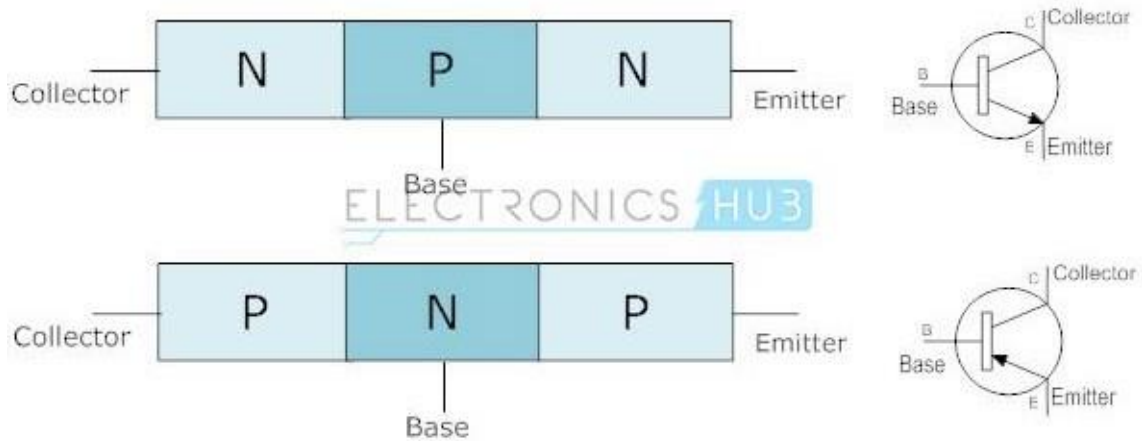
Figure 19 Transistor Examples [20]

4.1.1 TRANSISTOR MECHANICAL PACKAGING AND ARRANGEMENT [21]
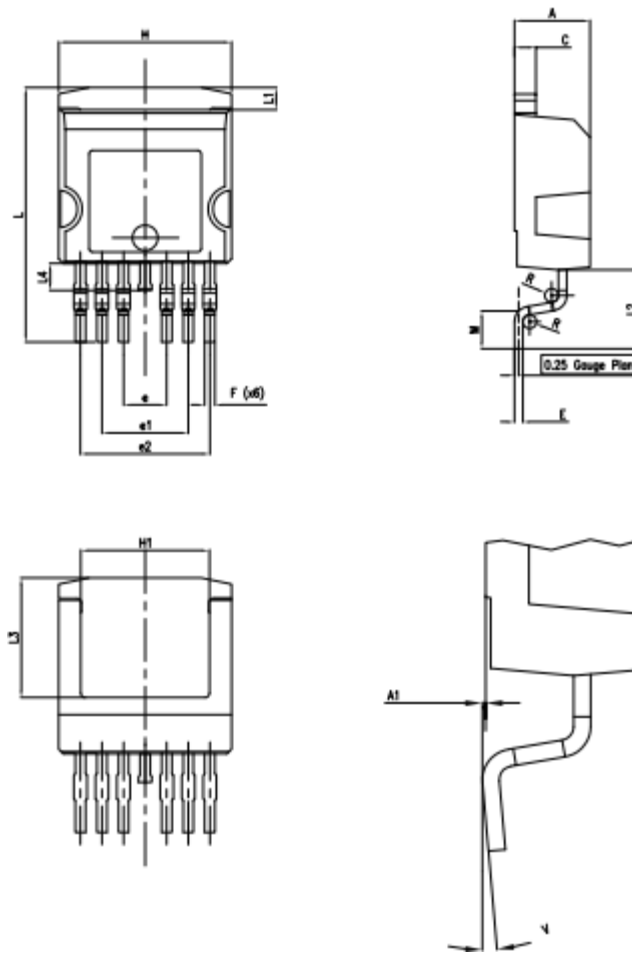
Figure 20 Transistor Candidate [21]
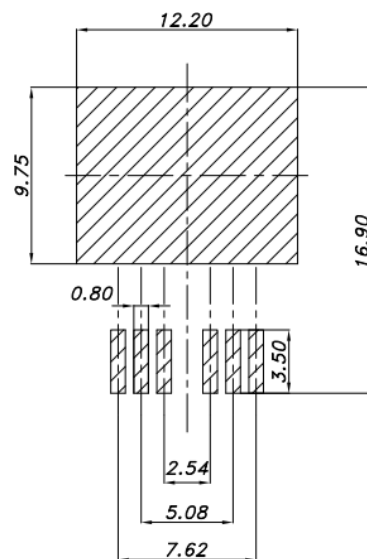
Figure 21 Transistor Foot Print [21]
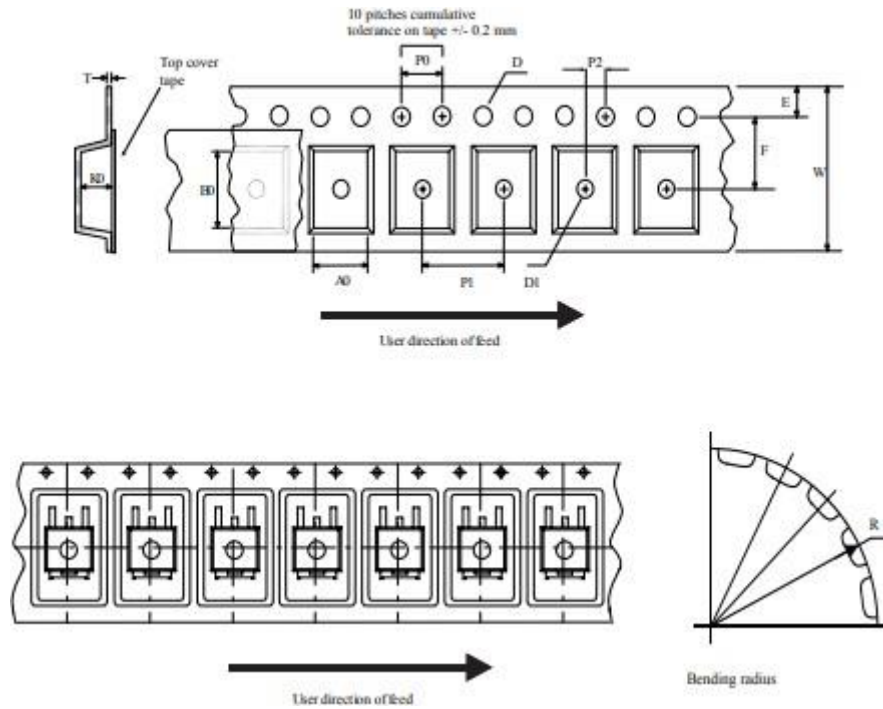
Figure 22 Transistor Arrangements [21]

4.2 CAPACITORS: -

A capacitor could be a two-terminal, electrical component. Alongside resistors and inductors, they are one of the foremost crucial detached components we utilize. You'd need to see exceptionally difficult to discover a circuit which didn't have a capacitor in it. What makes capacitors extraordinary is their capacity to store vitality; they're like a completely charged electric battery. Caps, as we ordinarily allude to them, have all sorts of basic applications in circuits. Common applications incorporate nearby vitality capacity, voltage spike concealment, and complex flag sifting. [22]

Figure 23 Sizes of Capacitors [22]
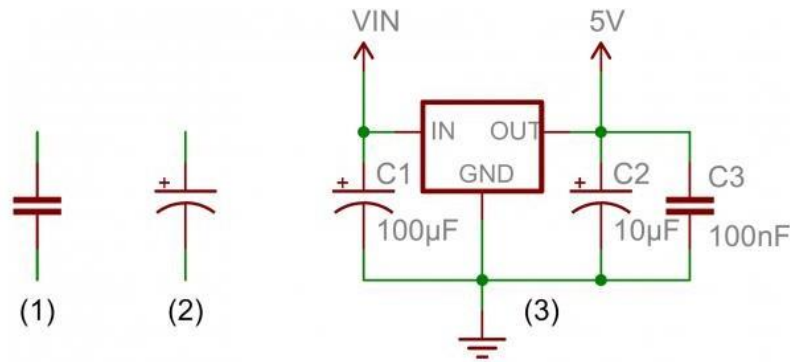
Figure 24 Examples of Capacitors used in PCB[22]

4.3 SHUNT FOR CURRENT MEASUREMENT

A shunt resistor is utilized to measure electric current, alternating or direct. This is completed by measuring the dip across the resistor. [23]

A gadget to measure electric current is called an ammeter. Most advanced ammeters degree the voltage drop over a accuracy resistor with a known resistance.

Be that as it may, when the current is as well tall for the ammeter, a diverse setup is required. The arrangement is to put the ammeter in parallel with an exact shunt resistor. Another term that's some of the time utilized for this sort of resistor is ammeter shunt. Usually this is often a tall exactness manganin resistor with a low resistance esteem.

The current is separated over the shunt and the ammeter, such that as it were a little (known) rate streams through the ammeter. In this way, huge streams can still be measured. By accurately scaling the ammeter, the real amperage can be straightforwardly measured.

Utilizing this setup, in hypothesis the most extreme amperage that can be measured is unending. Be that as it may, the voltage rating of the estimation gadget must not be surpassed. This implies that the greatest current duplicated by the resistance esteem, cannot be higher than the voltage rating.
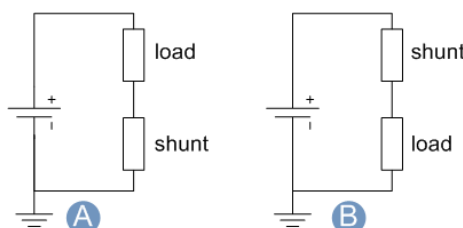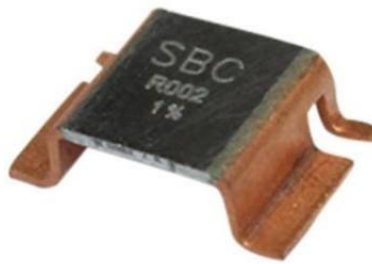
Figure 25 Uses of Shunts [24]

4.4 GATE DRIVERS

A gate driver could also be a control enhancer that acknowledges a low-power input from a controller IC and produces a high-current drive input for the entryway of a high-powered semiconductor equivalent to an IGBT or control MOSFET. Gate drivers is given either on-chip or as a separate module. In pith, a door driver includes of A level shifter together with an speaker.

A door driver IC serves as the interface between control signals (computerized or analog controllers) and control switches (IGBTs, MOSFETs, SiC MOSFETs, and GaN HEMTs). An coordinates gate-driver arrangement diminishes plan complexity, advancement time, charge of materials (BOM), and board space whereas moving forward unwavering quality over discretely-implemented gate-drive arrangements. [25]

Figure 26 Gate Driver Examples [26]

4.4.1 MECHANICAL PACKAGING OF GATE DRIVERS
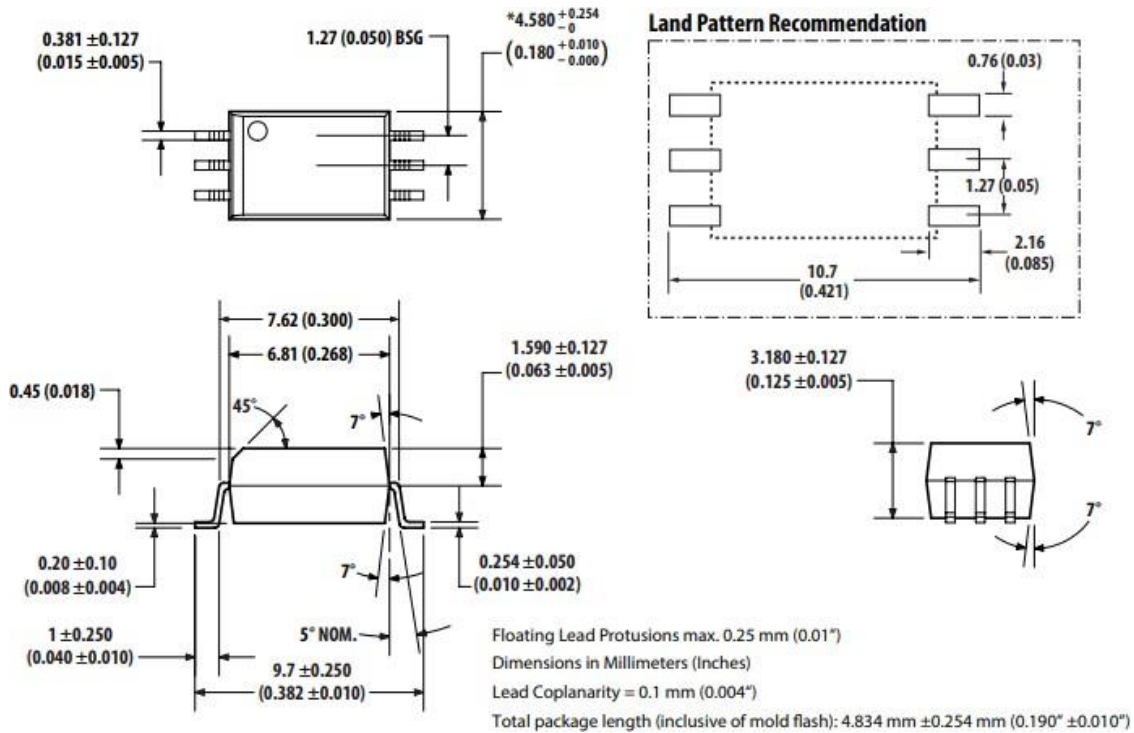
Figure 27 Gate Driver Candidate [27]

4.5 HEAT SINK

A heat sink may well be an inactive heat exchanger that trades the heat made by an electronic or a mechanical contraption to a fluid medium, habitually examine or a liquid coolant, where it is dispersed absent from the gadget, hence allowing control of the device's temperature. In computers, heat sinks are utilized to cool CPUs, GPUs, and a few chipsets and Ram modules. A heat sink is planned to maximize its surface region in contact with the cooling medium encompassing it, such as the discuss. Air speed, choice of fabric, bulge plan and surface treatment are variables that influence the performance of a warm sink. Heat sink connection strategies and thermal interface materials to influence the pass on temperature of the coordinates circuit. Thermal cement or thermal glue progress the heat sink's execution by filling discuss holes between the heat sink and the heat spreader on the device. A heat sink is ordinarily made out of aluminum or copper. [28]

A heat sink as a rule comprises of a metal structure with one or more level surfaces to guarantee good thermal contact with the components to be cooled, and a cluster of comb or blade like bulges to extend the surface contact with the discus, and in this way the rate of

warm dissipation. A warm sink is in some cases utilized in conjunction with a fan to extend the rate of wind current over the warm sink. This keeps up a bigger temperature angle by replacing warmed discuss quicker than convection would. Usually known as a forced air system. [29]

Overseeing heat is additionally a critical portion of printed circuit board plan and fabricating. A board that isn't outlined to scatter the heat it produces may conclusion up with operational issues or indeed total failure. During fabricating it is additionally important that the heat be overseen in arrange to resist the tall temperatures connected amid the patching handle. Making beyond any doubt to utilize satisfactory PCB warm scattering procedures for plan is exceptionally imperative, and here are a few suggestions that will be supportive to you on your following extend. [30]

TYPES OF HEAT SINKS

AIR COOLED BY USING OF FINS

Design Factors for fins

- **Thermal resistance**

  Semiconductor devices used in an assortment of client and mechanical devices; the thought of thermal resistance disentangles the determination of heat sinks. The heat stream between the semiconductor passes on and surrounding discuss is modeled as an arrangement of resistances to heat stream; there's a resistance from the pass on to the device case, from the case to the heat sink, and from

  the heat sink to the encircling air. The entirety of these resistances is the full thermal resistance from the pass on to the surrounding air. Thermal resistance is characterized as temperature rise per unit of control, closely resembling to electrical resistance, and is communicated in units of degrees Celsius per watt (°C/W). If the gadget scattering in watts is known, and the full thermal resistance is calculated, the temperature rises of the pass on over the ambient discuss can be calculated.

- **Material**

The foremost common heat sink materials are aluminum alloys. Aluminum alloy 1050 has one of the higher thermal conductivity values at 229 W/m•K but is mechanically delicate. Aluminum alloys 6060 (low stress), 6061, and 6063 are commonly utilized, with thermal conductivity values of 166 and 201 W/m•K, individually. The values depend on the mood of the alloy. One-piece aluminum heat sinks can be made by expulsion, casting, skiving or processing. [31]

Copper has fabulous heat sink properties in terms of its thermal conductivity, erosion resistance, biofouling resistance, and antimicrobial resistance (See moreover Copper in warm exchangers).

Copper has around twice the thermal conductivity of aluminum, around 400 W/m•K [32] for immaculate copper. Its primary applications are in mechanical offices, control plants, solar thermal water systems, HVAC systems, gas water radiators, constrained air heating and cooling systems, geothermal heating and cooling, and electronic systems.

Copper is three times as dense and costlier than aluminum. One-piece copper heat sinks can be made by skiving or processing. Sheet-metal blades can be fastened onto a rectangular copper body. Copper is less pliable than aluminum, so it cannot be expelled into heat sinks.

- **Fin efficiency**

Fin effectiveness is one of the parameters which makes the next thermal conductivity material imperative. A blade of a heat sink may be considered to be a level plate with heat flowing in one conclusion and being dissipated into the encompassing liquid because it voyages to the other.

As heat flows through the fin, the combination of the thermal resistance of the heat sink blocking the flow and the heat lost due to convection, the temperature of the fin and, so, the heat exchange to the liquid, will diminish from the base to the conclusion of the fin. [33]

Fin effectiveness is characterized as the genuine warm exchanged by the fin, isolated by the heat exchange were the fin to be isothermal (theoretically the blade having boundless thermal conductivity).

Below Equation used for Fin efficiency

$$\eta_{fin} = \frac{\tanh(mLc)}{(mLc)} \text{[34]}$$

$$mLc = \sqrt{\frac{2h_f}{kt_f}}\, L_f \text{ [34]}$$

where

- h_f is the convection coefficient of the fin
- Air: 10 to 100 W/(m2K)
- Water: 500 to 10,000 W/(m2K)
- k is the thermal conductivity of the fin material
- Aluminum: 120 to 240 W/(m·K)
- L_f is the fin height (m)
- t_f is the fin thickness (m)

Fin proficiency is expanded by diminishing the fin aspect ratio (making them thicker or shorter), or by utilizing more conductive material

- **Fin Arrangement**

A pin fin heat sink may be a heat sink that has pins that expand from its base. The pins can be round and hollow, curved or square. A stick is one of the more common heat sink sorts accessible on the market. These straight fins run the whole length of the heat sink. A variety on the straight fin heat sink may be a cross cut heat sink.

A straight fin heat sink is cut at standard intervals. In common, the more surface zone a heat sink has, the better it works. In any case, this is often not continuously genuine. The concept of a pin fin heat sink is to undertake to pack as much surface zone into a given volume as conceivable.

In spite of the actual fact that the pin fin has 194 cm2 surface zone whereas the straight fin has 58 cm2, the temperature distinction between the heat sink base and therefore the encompassing discuss for the pin fin is 50 °C. For the straight fin it absolutely was 44 °C or 6 °C superior than the pin fin. Pin fin heat sink execution is actually method better than straight fins once used in their aiming application wherever the liquid streams pivotally on the pins rather than because it were digressively over the pins. [35]

Comparison of a pin fin and straight fin heat sink of comparable measurements.

Heat sink fin type	Width [cm]	Length [cm]	Height [cm]	Surface area [cm²]	Volume [cm³]	Temperature difference, $T_{case} - T_{air}$ [°C]
Straight	2.5	2.5	3.2	58	20	44
Pin	3.8	3.8	1.7	194	24	51

Figure 28 Gathered Data for heat removal [35]

Figure 29 Types of Fins Arrangement [36]

4.5.2 WATER BLOCK

A water block is the water-cooling identical of a heatsink. It could be a sort of plate heat exchanger and can be utilized on numerous distinctive computer components, counting the central preparing unit (CPU), GPU, PPU, and Northbridge chipset on the motherboard. It comprises of at slightest two main parts; the "base", which is the range that produces contact with the gadget being cooled and is ordinarily made from metals with tall thermal conductivity such as aluminum or copper.

The moment portion, the "beat" guarantees the water is contained safely interior the water square and has associations that permit hosing to associate it with the water-cooling circle. The best can be made of the same metal as the base, straightforward Perspex, Delrin, Nylon, or HDPE. Most more current high-end water squares too contain mid-plates which serve to include jet tubes, nozzles, and other flow modifying devices. [37]

The base, best, and mid-plate(s) are fixed together to make a "piece" with a few sort of way for water to flow through. The ends of the way have inlet/outlet connectors for the tubing that connects it to the rest of the water-cooling system. Early plans included spiral, zig-zag design or heatsink like fins to permit the biggest conceivable surface range for heat to exchange from the device being cooled to the water. These plans by and large were utilized since the guess was that most extreme flow was required for tall execution.

Trial and blunder and the advancement of water block plan has appeared that exchanging flow for turbulence can regularly progress execution. The Storm arrangement of water blocks is a case of this. Its jet tube mid plate and measured base plan makes it more prohibitive to the stream of water than early labyrinth plans but the expanded turbulence comes about in a huge increment in execution.

A water block is superior at disseminating heat than an air-cooled heatsink due to water's higher particular heat capacity and thermal conductivity. The water is usually pumped through to a radiator which permits a fan pushing discuss through it to require the heat made from the device and remove it into the air.

A radiator is more productive than a standard CPU or GPU heatsink/air cooler at removing heat since it features a much larger surface area. Installation of a water piece is additionally comparative to that of a heatsink, with a warm cushion or warm oil set between it and the device being cooled to help in heat conduction.

Figure 30 Water Block (Water cooling) [38]

4.6 PCB Design Techniques to Dissipate Heat

To handle the more prominent thermal issues of tall speed and tall control sheets, here are a few plan procedures that can offer assistance

- Huge metal cushions beneath hot parts to act as a "thermal" cushion.

- Heat sinks associated to thermal cushions of hot parts.

- Utilizing board materials with superior thermal properties such as polyimides or metal center sheets.

- Cooling fans as well as key component situation to put hot components into the circulating way of the fan.
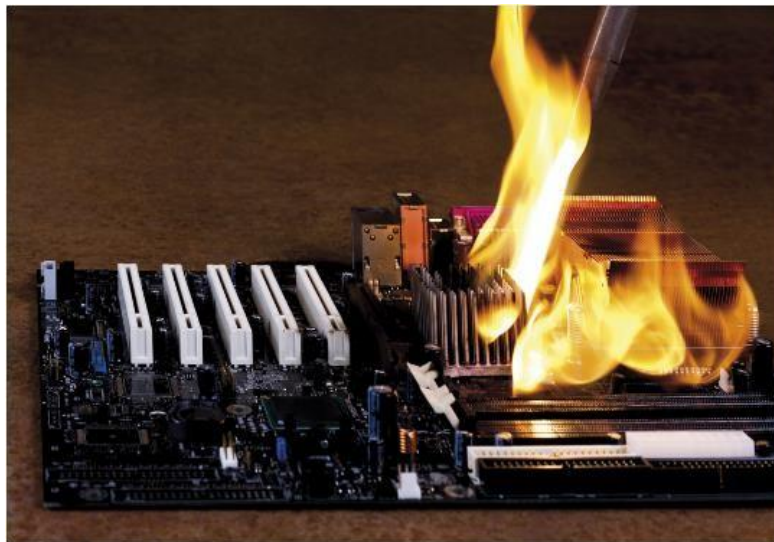
Figure 31 Results of improper Cooling [30]

5. 3D MODEL CREATION

Due to compactness and Modularity of the inverter packaging all the components will be moved to different levels hence the final component will be optimally compact as possible. Given below are the different levels of components

- 1st level - Transistors and shunts resistors
- 2nd level - Control board
- 3rd level - Gate Drivers board
- 4th level - Capacitors Assembly

5.1 POSSIBLE VERSIONS OF ASSEMBLY
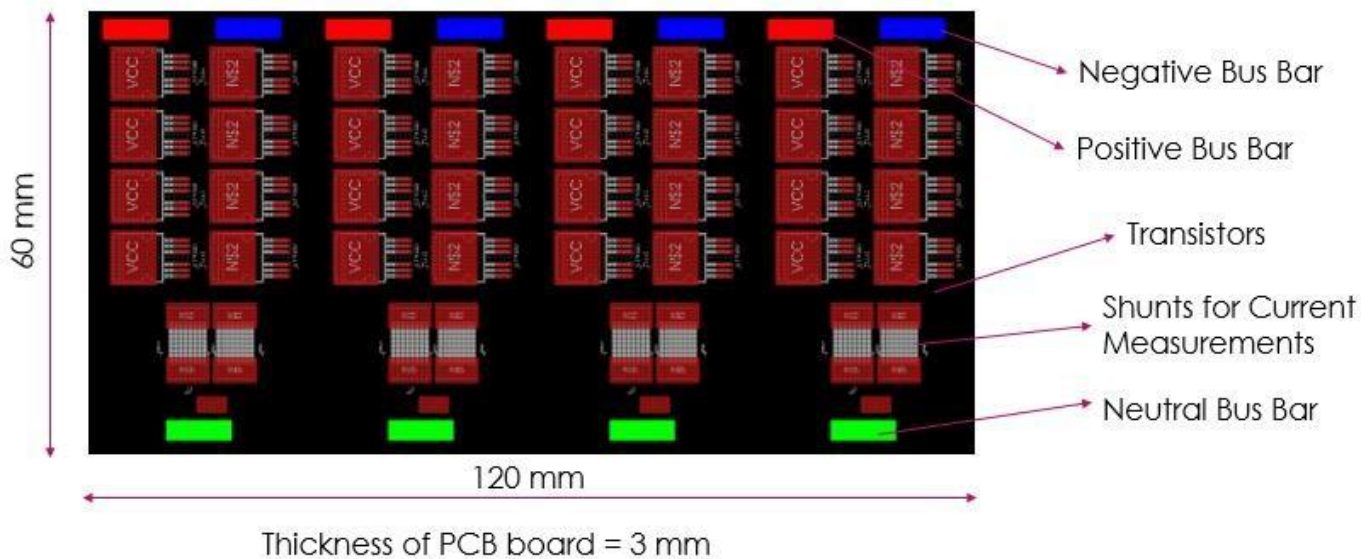
Figure 32 1st configuration

In this configuration the bus bars are stationed on top and the neutral bus bar is stationed near to the shunt resistors. The transistors are into 4 sections with 8 transistors in each section. Each section current measurement is done using Shunt resistors. The overall size of the PCB Board is 60mm x 120mm.Each section has one set one Positive, negative and Neutral points. This type of configuration is general practice to connect all the section in series.
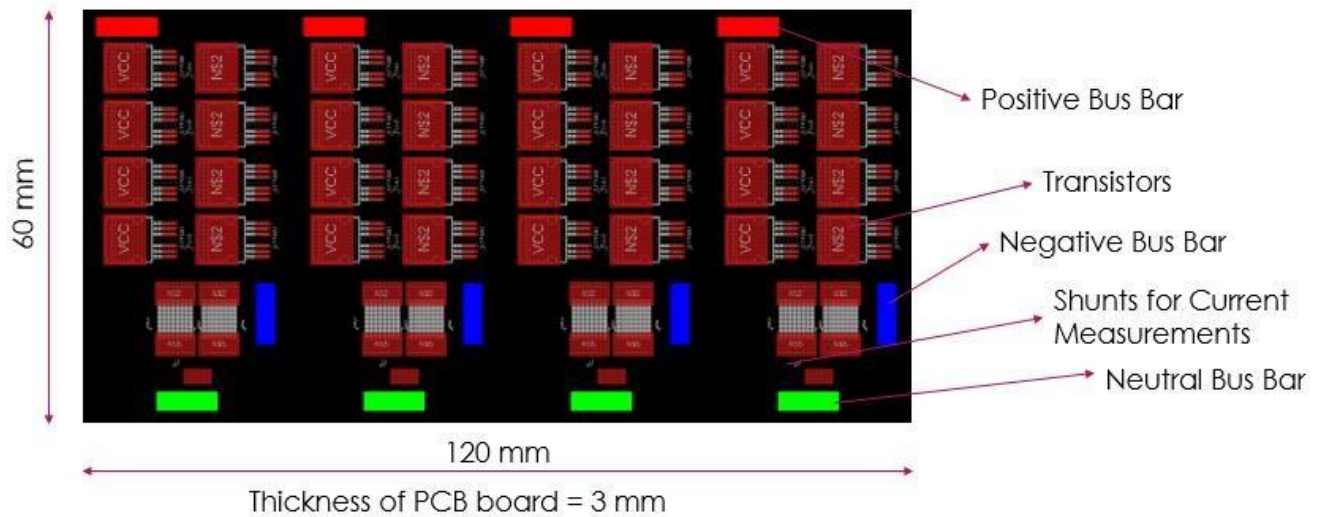
Figure 33 2nd configuration

In this configuration the bus bars are stationed near the top is the positive and the neutral bus bar and negative bus bar is stationed near to the shunt resistors. The transistors are into 4 sections with 8 transistors in each section. Each section current measurement is done using Shunt devices. The overall size of the PCB Board is 60mm x 120mm. Each section has one set one Positive, negative and Neutral points.

5.2 SOLIDWORKS 3D MODEL
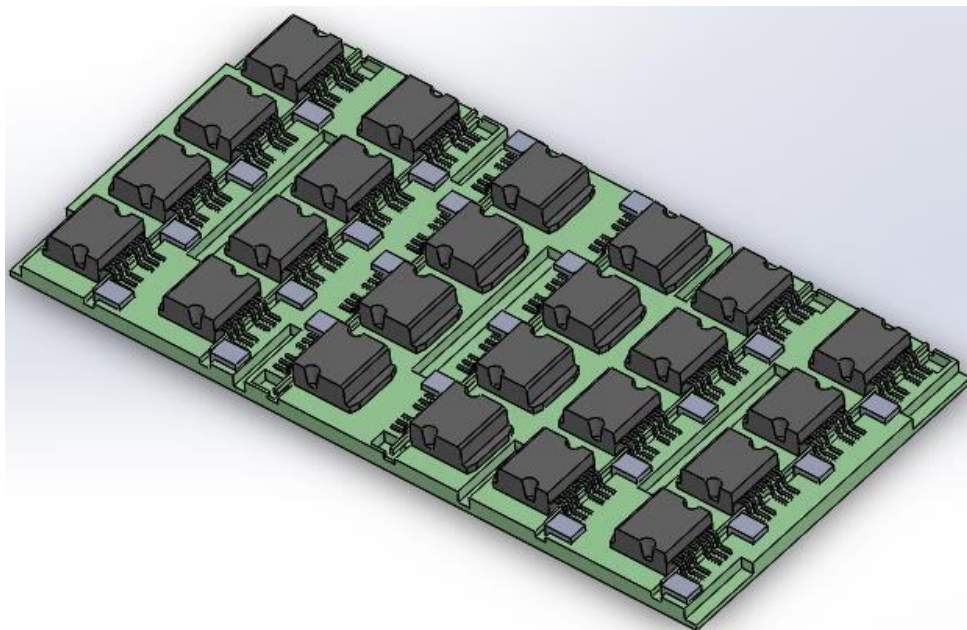
Figure 34 Transistors and shunts resistors

ITEM NO.	PART NUMBER	QTY.
1	PCB BOARD	1
2	CANDIDATE 01	25
3	SHUNT	24
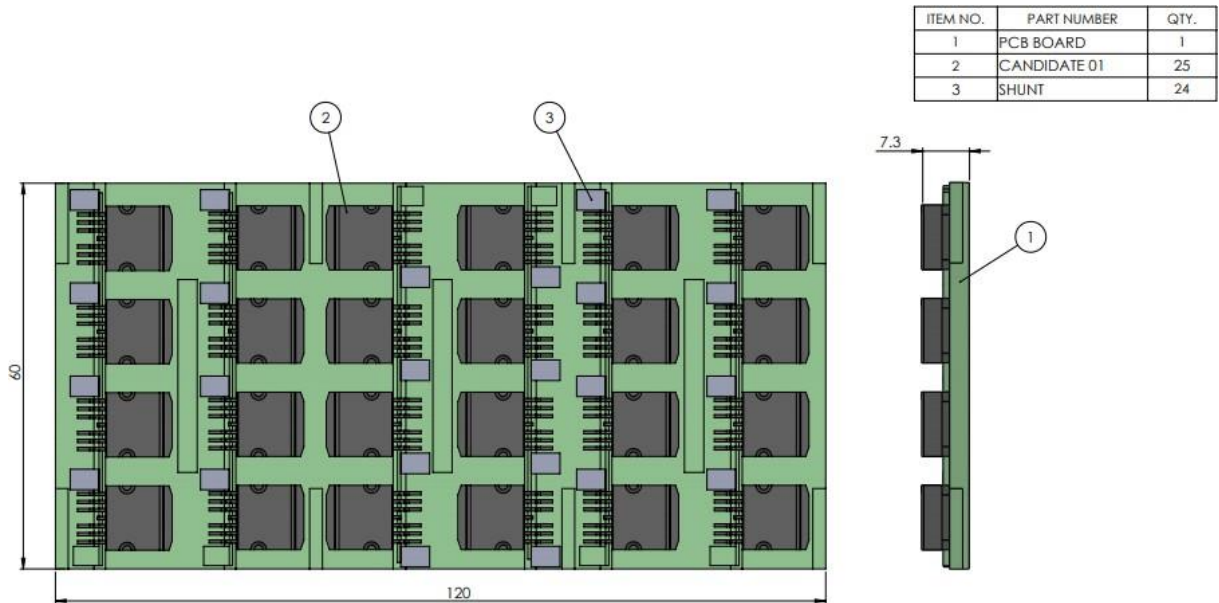
Figure 35 PCB Layout Drawing

The above picture shows the final version of the arrangement of the transiters with corresponding shunts. The over all thickness of the PCB board is around 1.5 mm. In total 24 transistors are being used. Overall Inverter has 4 floors and the Board is structurally stabilized by using spacers.
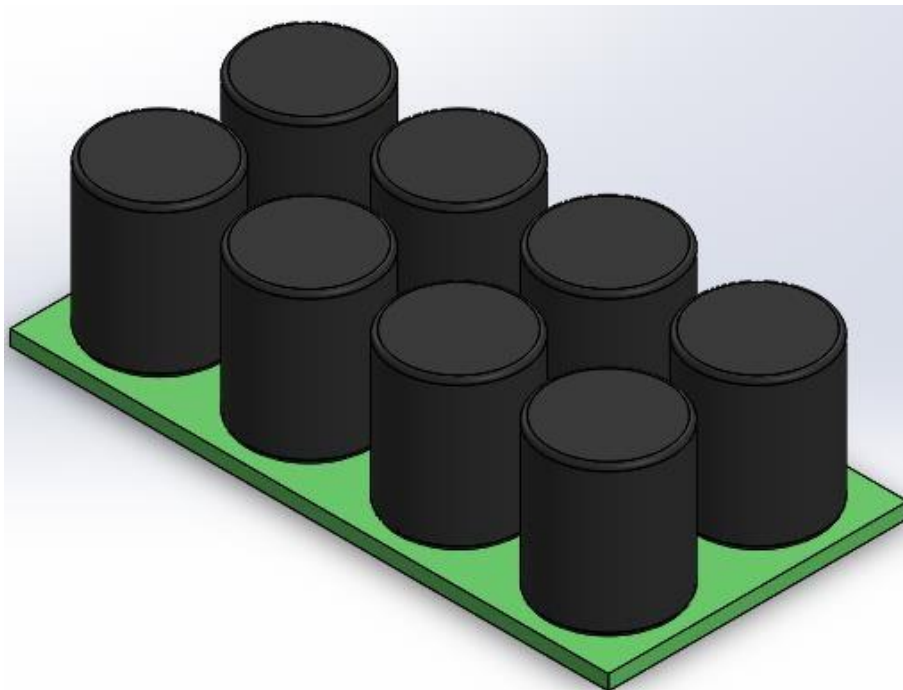
Figure 36 Capacitor Board

The capacitors are being arranged in series as show in the above picture. The have diameter of around 25mm and 8 capacitors have been placed with a spacing of around 35mm from each other.

ITEM NO.	PART NUMBER	QTY.
1	Capacitor board	1
2	Capacitors	8
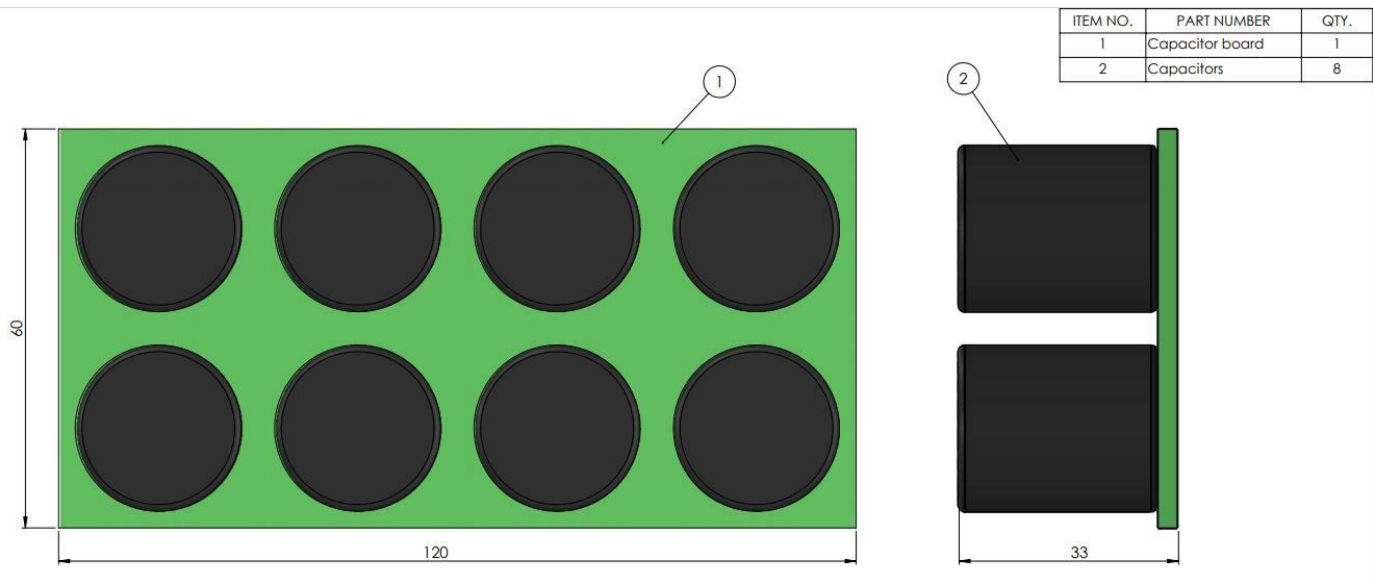
Figure 37 Capacitor Board Drawing

5.3 ALUMINUM WATER BLOCK FOR LIQUID COOLING
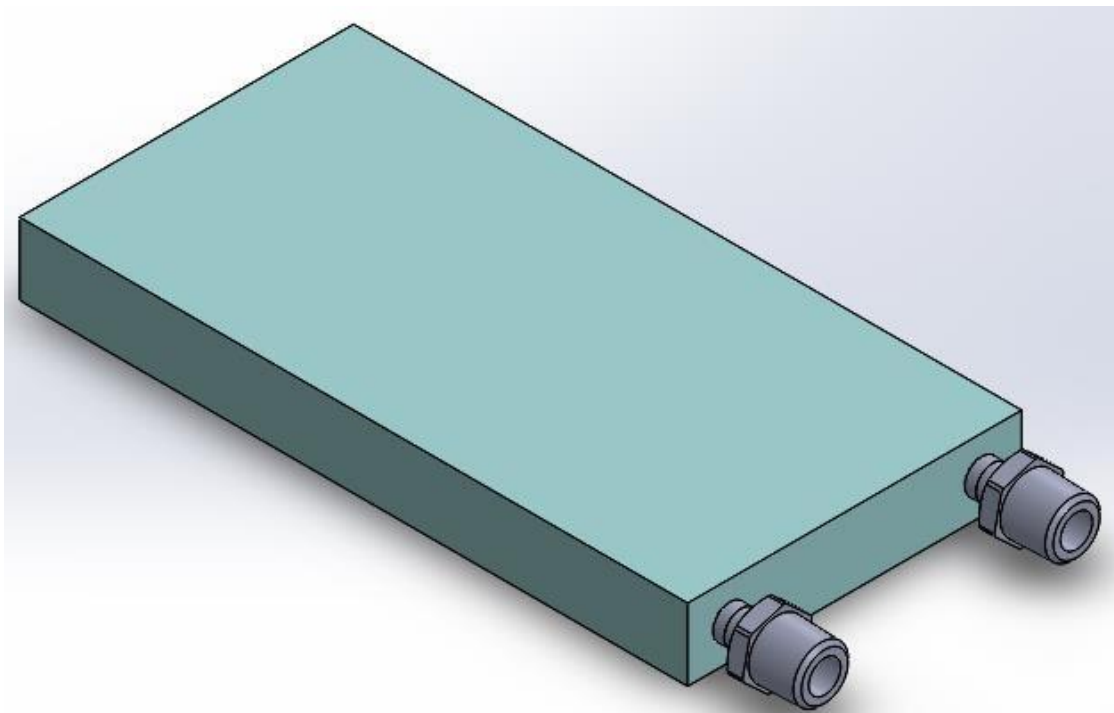
Figure 38 Aluminum Water Block [39]

ITEM NO.	PART NUMBER	QTY.
1	cooling_block	1
2	cooling_pipes	1
3	connector	2
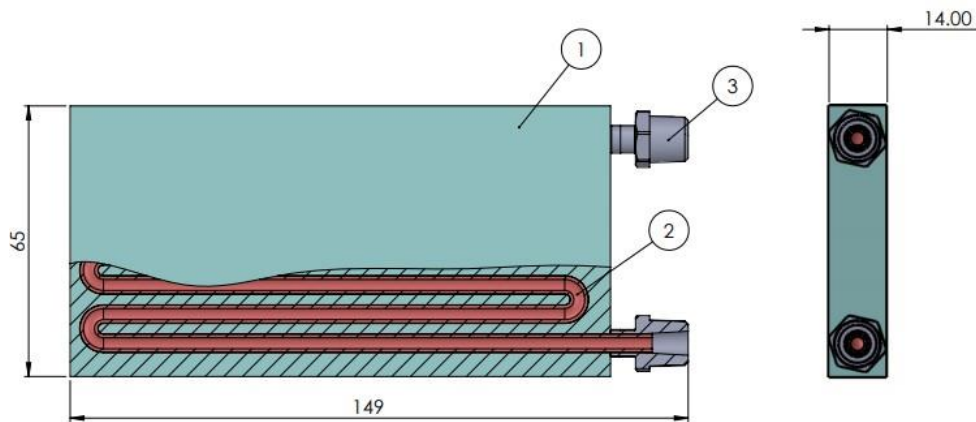
Figure 39 Aluminum Water Block Drawings

The outer surface of the coolant block is made out of aluminum and the pipes are copper.

One side of the pipes are connected to the input and other is connected to the output.

The coolant has several holes on top of the surface of that dowel pins are used to connect the cooling plate and the aluminum block. The input coolant is free from external debris.
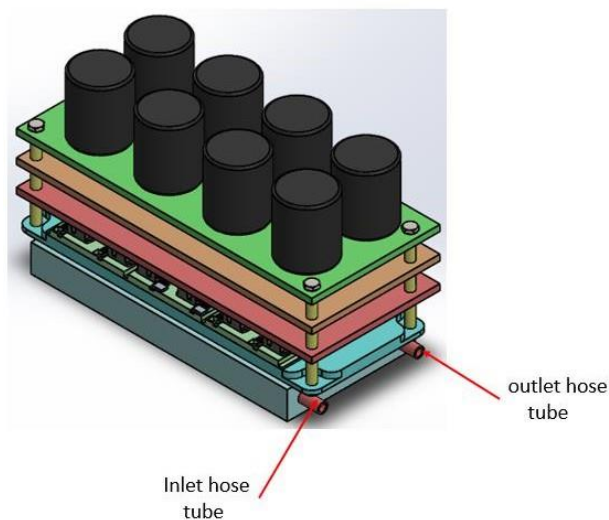
Figure 40 Inlet and outlet ports

Specification of Heat Sink [39]

- Cold plates made in aluminum and copper (5mm pipe) with 4 coils.
- Extruded or core hole drilled cooling channels
- Project-specific dimensioning
- ½ inch BSP adapter
- Total weight of the Water Block 3 Kgs.

5.4 INVERTER OVERALL INPUT
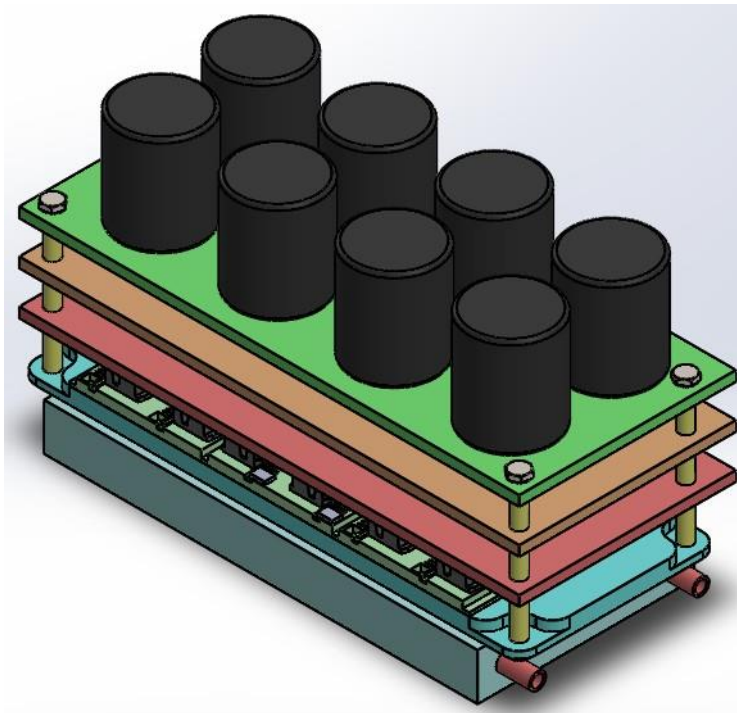
Figure 41 Inverter Board with cooling plate
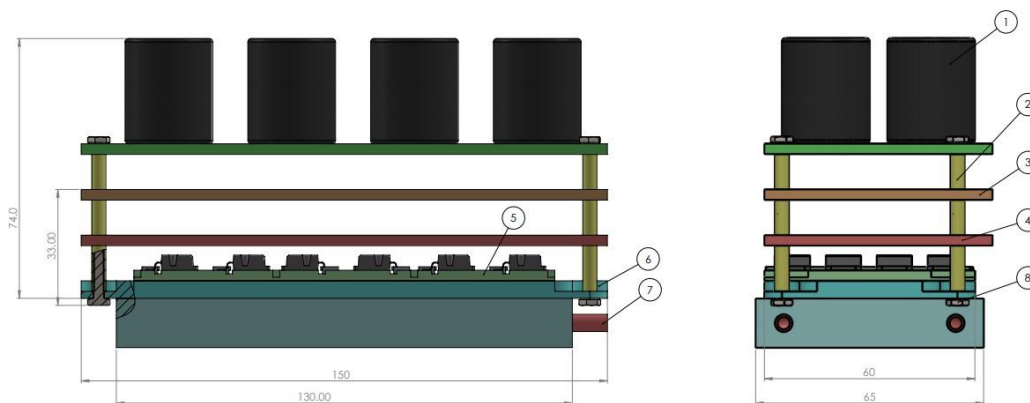
ITEM NO.	PART NUMBER	QTY.
1	Capacitor board assembly	1
2	spacer	4
3	Gate Driver Board	1
4	Control Board	1
5	Transitor Board	1
6	Cold_plate	1
7	cooling_assembly	1
8	ISO 4014 - M3 x 20 x 12-N	8

Figure 42 Inverter Board with cooling plate Drawing

The final structure of the PCB board that has 4 floors which are held together with long bolts from both from top and bottom. The Final inverter has an overall size of around 74mm * 150mm* 60 mm. This is the total envelope the enclose has be designed with easy assembly and dissembled also with minimal effort and without damaging the PCB board.

6. ENCLOSURE DESIGN

- Material: - Sheet metal Aluminum

- Gauge : - Gauge 15 thickness from table 1.4 mm [40]

- Total weight of Enclosure = 2 kgs

- Cost of per Kg of sheet metal = 200 Kc

Sheet Metal Gauge Guide				
Gauge	Steel (mm)	Galvanized (mm)	Stainless (mm)	Aluminum (mm)
3	0.2391 (6.07)	--	--	--
4	0.2242 (5.69)	--	--	--
5	0.2092 (5.31)	--	--	--
6	0.1943 (4.94)	--	--	0.162 (4.1)
7	0.1793 (4.55)	--	0.1875 (4.76)	0.1443 (3.67)
8	0.1644 (4.18)	0.1681 (4.27)	0.1719 (4.37)	0.1285 (3.26)
9	0.1495 (3.80)	0.1532 (3.89)	0.1563 (3.97)	0.1144 (2.91)
10	0.1345 (3.42)	0.1382 (3.51)	0.1406 (3.57)	0.1019 (2.59)
11	0.1196 (3.04)	0.1233 (3.13)	0.1250 (3.18)	0.0907 (2.30)
12	0.1046 (2.66)	0.1084 (2.75)	0.1094 (2.78)	0.0808 (2.05)
13	0.0897 (2.28)	0.0934 (2.37)	0.0940 (2.40)	0.0720 (1.80)
14	0.0747 (1.90)	0.0785 (1.99)	0.0781 (1.98)	0.0641 (1.63)
15	0.0673 (1.71)	0.0710 (1.80)	0.0700 (1.80)	0.0570 (1.40)
16	0.0598 (1.52)	0.0635 (1.61)	0.0625 (1.59)	0.0508 (1.29)
17	0.0538 (1.37)	0.0575 (1.46)	0.0560 (1.40)	0.0450 (1.10)
18	0.0478 (1.21)	0.0516 (1.31)	0.0500 (1.27)	0.0403 (1.02)
19	0.0418 (1.06)	0.0456 (1.16)	0.0440 (1.10)	0.0360 (0.91)
20	0.0359 (0.91)	0.0396 (1.01)	0.0375 (0.95)	0.0320 (0.81)
21	0.0329 (0.84)	0.0366 (0.93)	0.0340 (0.86)	0.0280 (0.71)
22	0.0299 (0.76)	0.0336 (0.85)	0.0310 (0.79)	0.0250 (0.64)
23	0.0269 (0.68)	0.0306 (0.78)	0.0280 (0.71)	0.0230 (0.58)
24	0.0239 (0.61)	0.0276 (0.70)	0.0250 (0.64)	0.0200 (0.51)
25	0.0209 (0.53)	0.0247 (0.63)	0.0220 (0.56)	0.0180 (0.46)
26	0.0179 (0.45)	0.0217 (0.55)	0.0190 (0.48)	0.0170 (0.43)
28	0.0149 (0.38)	0.0187 (0.47)	0.0160 (0.41)	0.0126 (0.32)

Figure 43 Gauge sheet [40]

Using the above Sheetmetal gauge sheet and depending of the total weight of the entire structure. The thickness of around 1.4 mm should be strong enough.

6.1 COMPLETE ENCLOSURE
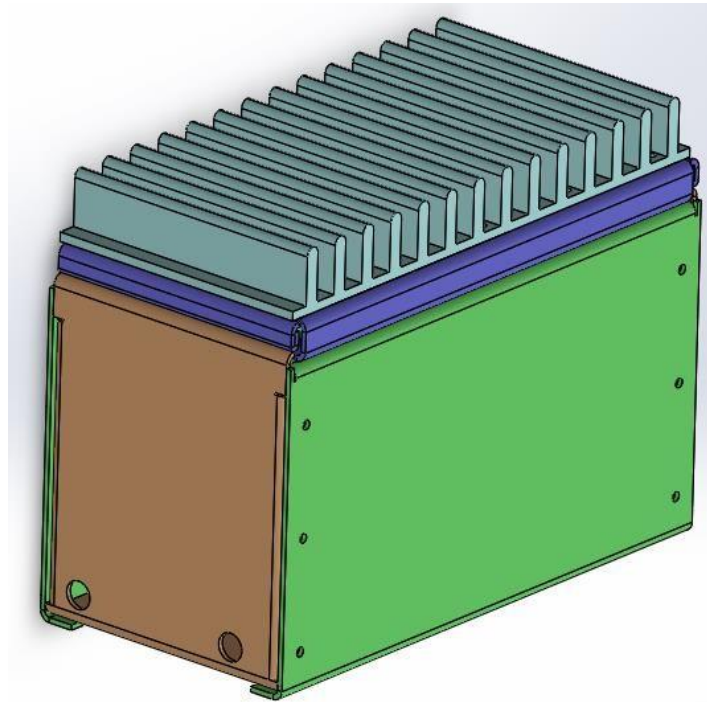
Figure 44 Sheetmetal Enclosure

ITEM NO.	PART NUMBER	MATERIAL	QTY.
1	enclosure_bottom	AL6061	1
2	Side enclosure	AL6061	2
3	top cover	AL6061	1
4	fins	AL6061	1
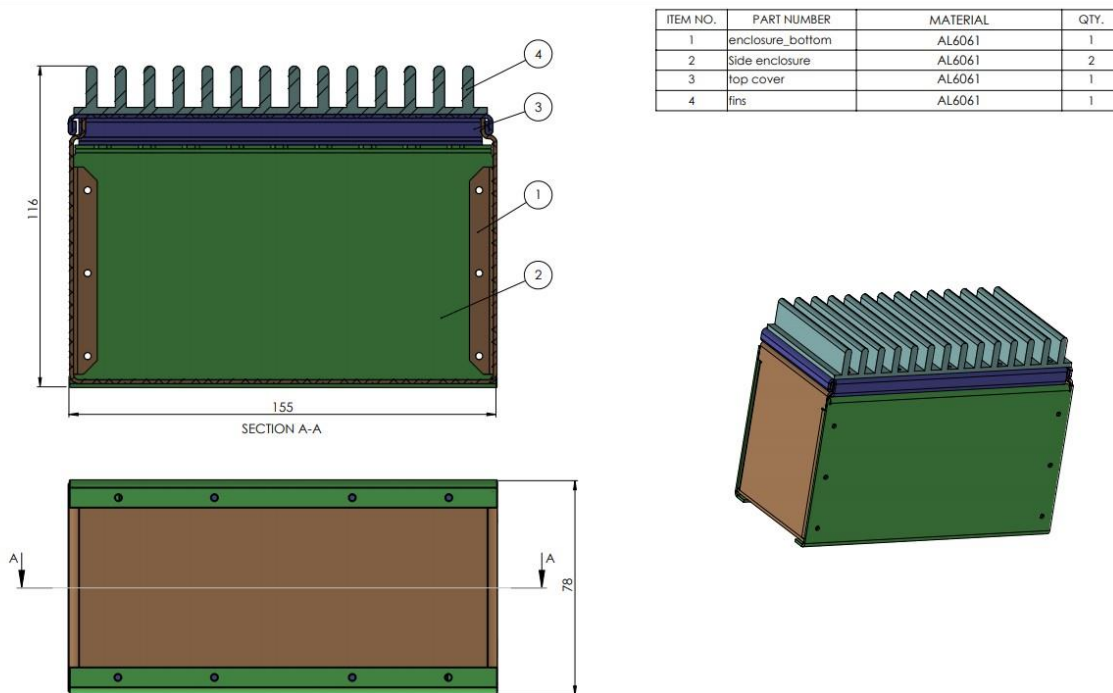
Figure 45 Enclosure Assembly Drawing

The final enclosure has 4 components and the fins are assembled together with the help of screw of M3 size. This type of enclosure might have various vents on the sides incase there is no condition for the enclosure to be air tight or water proof.

6.2 FINAL ENCLOSURE WITH PCB BOARD

SECTION A-A

ITEM NO.	PART NUMBER	QTY.
1	cooling_assembly	1
2	Transitor Board	1
3	Gate Driver Board	1
4	spacer	4
5	Control Board	1
6	Cold_plate	1
7	Capacitor board assembly	1
8	ISO 4014 - M3 x 20 x 12-N	8
11	cover	1
10	ISO 7380 - M3 x 10 - 10N	30
11	Fins	1
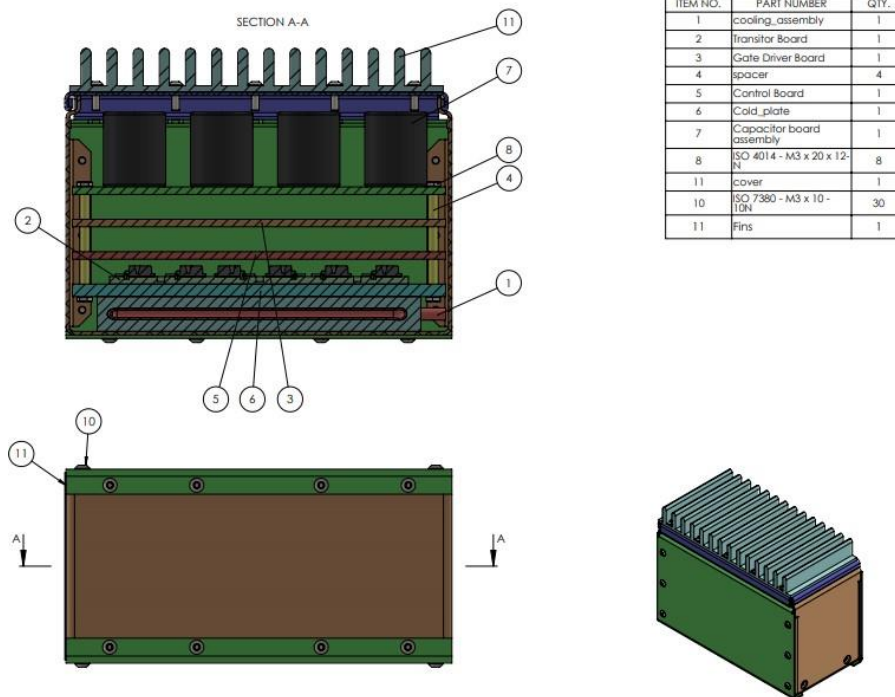
Figure 46 Packaging Assembly

ITEM NO.	PART NUMBER	QTY.
1	cooling_assembly	1
2	Transitor Board	1
3	Gate Driver Board	1
4	spacer	4
5	Control Board	1
6	Cold_plate	1
7	Capacitor board assembly	1
8	ISO 4014 - M3 x 20 x 12-N	8
9	cover	1
10	ISO 7380 - M3 x 10 - 10N	30
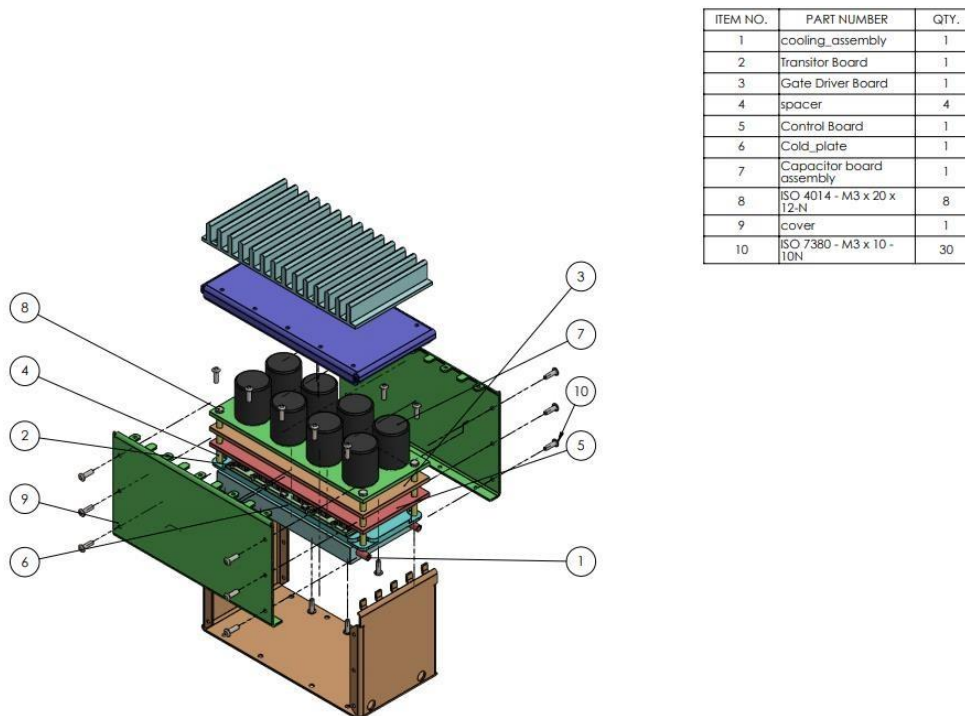
Figure 47 Exploded view of the assembly

The Complete assembly and disassembly of the Enclosure with process of assembly is shown in the image above. The main base is the one is the orange which is placed 1st and the all the components are mounted into this part and fixed together using M3 size bolts.

7. THERMAL MANAGEMENT

7.1 APPROACH OF THE PROBLEM

Heat generation of the PCB board

We can assume that the heat generation in the board is equal to 10% to total power generation. Total current is around 200 A and Voltage of around 220V.

Total power is equal to

Q = V * A

   =220 * 150 = **33000 W or 33 kW**

Total heat loss of 10 % = **3300W or 3.3 kW**

Q = -K* A* (T1-T2)/L

Where,	Enclosure Parameters
Q = Heat in W	Q = 3300 W (100% capacity)
K= Thermal conductivity in W/mK	Aluminum material = 175 W/mK
A= Cross section Area in m^2	(Width . Length) = (0.078 x 0.155) = 0.01209 m^2
T1= Surface Temperature in K	T1 =?
T2= Ambient Temperature in K	T2 = 25°C = 298 K
L = Length of source in m	L = 0.155 m

   Q = -K* A*(T1-T2)/L

3300 = -175 *0.01209*(T1-298)/0.155

   T1 = **268°C or 540 K** (Maximum Temperature)
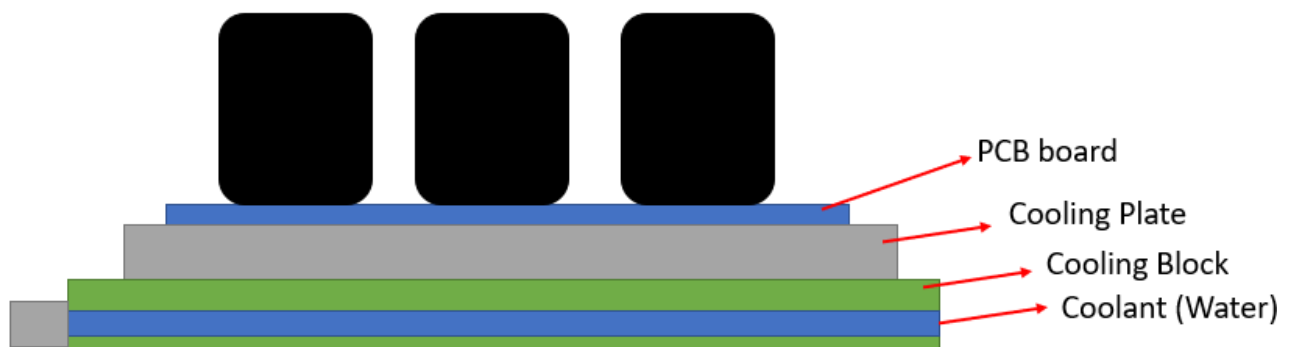
Figure 48 Layout of PCB board

The heat dissipation is around 3.3 kW and this heat is transferred into the cooling plate by the method of heat conduction. Later this Heat is removed from the cooling plate via the cooling block by the method if heat convection.

Cooling of the PCB board is done by both air and water cooling. Onboard the Control board are thermal sensors. The Inverter is cooled with air in the initial stages and once the duty cycle increases or the load increased steadily. The flow of water is controlled by the control board on the PCB. This is programmed so the flow is controlled depending on the temperature inside the envelope. Below table shows the surface temperature at different usage levels ranging from 10 %~ 100 %.

Table 1 Heat distribution

Usage In %	Heat in W	Thermal conductivity in W/mK	Cross section Area in m2	Length of source in m	Ambient Temperature in K	Surface Temperature in C
100	3300	175	0.01209	0.155	298	266.76
90	2970	175	0.01209	0.155	298	242.58
80	2400	175	0.01209	0.155	298	200.82
70	2100	175	0.01209	0.155	298	178.85
60	1800	175	0.01209	0.155	298	156.87
50	1500	175	0.01209	0.155	298	134.89
40	1200	175	0.01209	0.155	298	112.91
30	900	175	0.01209	0.155	298	90.93
20	600	175	0.01209	0.155	298	68.96
10	300	175	0.01209	0.155	298	46.98

7.2 TOTAL HEAT LOST DUE TO THE FINS USED: -

Parameters considered: -

- Ambient temperature of air (T2) = 25°C = 298 K

- Wall temperature (T1) = 266 ^{o}C (100% usage) = 539 K (Max temp)

- Thermal Conductivity of fin (K)= 175 W/mK

- Heat transfer Co-efficient for air (h) = 20 W/m^{2}K

- Length of fin (w) = 0.015 m

- Fin thickness (t) = 0.004 m

- Number of fins (N) = 20
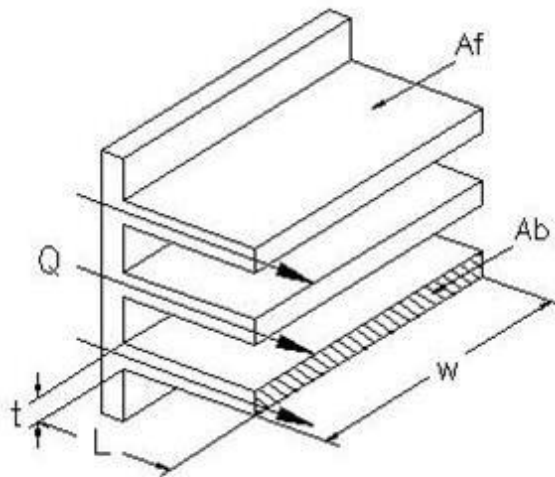
RECTANGULAR FINS

Heat flow rate for rectangular fin is given by

Q = N (K . A . B . n . ΔT) X1 / X2… [41]

Where,

X1 = [(sinh(n . L) + (h / n . K). cosh (n .L)]

X2 = [(cosh(n . L) + (h / n . K).sinh(n .L)]

n for thin fin = $(2*h/K*t)^{0.5}$

Temperature difference, ΔT = T1 - T2 = 25

Fin base area (A) = w x t

           = 0.078 x 0.004

           = 0.000312 m^2

n for thin fin = $(2*h/K*t)^{0.5}$

           = $((2*20)/ (175*0.04))^{0.5}$

           = 7.56

X1 = [(sinh(n *L) + (h / n*K)* cosh (n *L)]

     = 0.167

X2 =   [(cosh(n*L) + (h / n*K)*sinh(n*L)]

      = 1.0137

Q =   N*(K*A*n*ΔT) *(X1 / X2))

    =   20 * (175*000312*7.56*539) *(0.167*1.0137)

    =   **320 W**

Below table shows various heat losses through fins at different temperatures

Table 2 Fins Heat distribution

Usage In %	Heat in W	Thermal conductivity in W/mK	Cross section Area in m2	Length of fins in m	Ambient Temperature in K	Surface Temperature in C	Heat Flow though fins in W
100	3300	175	0.000312	0.02	298	266.76	320
90	2970	175	0.000312	0.02	298	242.58	290
80	2400	175	0.000312	0.02	298	200.82	232
70	2100	175	0.000312	0.02	298	178.85	202
60	1800	175	0.000312	0.02	298	156.87	173
50	1500	175	0.000312	0.02	298	134.89	145
40	1200	175	0.000312	0.02	298	112.91	116
30	900	175	0.000312	0.02	298	90.93	88
20	600	175	0.000312	0.02	298	68.96	57
10	300	175	0.000312	0.02	298	46.98	30

From the table it shows 10 % of heat generation is removed by the fins used. Maintaning the constant parameters then

- Number of fins
- Fin thickness
- Heat transfer Co-efficient for air
- Length of fin

Since the inverter is placed inside the excavator. The ambient temperature is not constant as environmental temperature inside the excavator engine cabin. Although we have a radiator to maintain the steady temperature. Assuming the temperature could be in range of +10°C. I.e., the Temperature could be around 25 °C ~40 °C. Since the heat gases moves towards the upwards and also considered the heat generated by the capacitors. The air fins are used to cool the enclosure. The use of air fins is reducing the power required to run the motor for circulating the water.

The graph below shows the temperature rise with ambient temperature increases from 25 °C to 40°C with 100 % usage of the inverter.
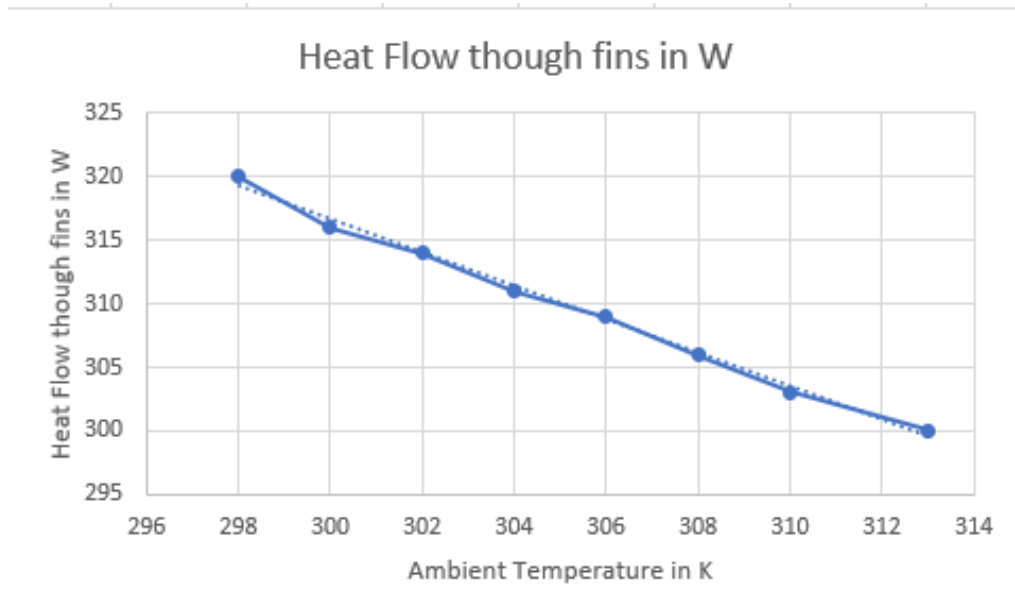
Figure 49 Heat loss due to increase in ambient temperature (100% use)

As we see from the above graph, we can see that even with the increase in the ambient temperature has not much effect on the heat removal so much.

7.3 TOTAL HEAT LOST DUE TO THE COOLING BLOCK USED

Heat is transferred to the water through convection principle. The flow is controlled electronically by achieving the different flow rates. The water or coolant is pumped through from the reservoir which placed on a higher elevation so no air bubbles are present in the system. The hoses are connected to a pump and motor. The reservoir also has a filter system so that no dirt or external objects enters into the system. This calibrating is done on the control board linked to the Data acquisition module.

P = Cp * M * dT

Where,

P = Energy rate of removal measured in kilowatt

Cp = specific heat capacity of water (4200 J/kg/K)

M = the volume of coolant water in L/sec

dT = the temperature rises in the water

Water inlet temperature = 25ºC = 298K

Maximum temperature of the surface = 266ºC = 539 K

P = 3300 W

M =?

 Temperature difference = (539 – 298) = 241

Apply this in the equation we get

3300 = 4200 * M * 241

M = 0.00326 L/sec = 3.26 e -6 m^3/sec

M = A * V

A = area of Cross section of the pipe

V = Velocity of Flow

Diameter of the pipe = 3.5 mm = 0.0035 m

Area = 9.621 e-6 m^2

3.26 e -6 = 9.621 e-6 X V

V = 0.338 m/sec.

7.3.1 Temperature of water leaving the water block: -

Using newtons Law of cooling

Q = h*A* dT

Q = Heat removed in W

A = Surface Area in m^2

T1 = Initial Temperature in K

T2= Final Temperature in K

Heat transfer Co-efficient for water h = 2000 W/m^{2}K (forced convention)

3300 = 2000 * 0.0845 m^2 * (T2-T1)

T2 = 318 K or 45°C

The table below shows respective values for various duty cycles ranging from 10%~100% capacity.

 The constant parameters are given by

- specific heat capacity of water
- Water inlet temperature
- Heat transfer Co-efficient for water

Table 3 Cooling block Heat distribution

Usage In %	Heat in W	Specific heat capacity of water	Surface Temperature in K	Water inlet temperature in K	Temperature difference	Flow rate in L/sec	Water Temperature leaving the Block in K
100	3300	4200	539.76	298	241.76	0.003249976	292.5266272
90	2970	4200	515.58	298	217.58	0.003250036	290.5739645
80	2400	4200	473.82	298	175.82	0.003250077	287.2011834
70	2100	4200	451.85	298	153.85	0.003249919	285.4260355
60	1800	4200	429.87	298	131.87	0.003249954	283.6508876
50	1500	4200	407.89	298	109.89	0.003250003	281.8757396
40	1200	4200	385.91	298	87.91	0.003250077	280.1005917
30	900	4200	363.93	298	65.93	0.0032502	278.3254438
20	600	4200	341.96	298	43.96	0.003249708	276.5502959
10	300	4200	319.98	298	21.98	0.003249708	274.7751479

As we can see from the tables it is concluded that the heat generation in the PCB board is efficiently removed and the max water temperature leaving the cooling block is around 45°C.

The Fins used can used when the heat removal once the machine is either in OFF and this saves the power required to run the pump to circulate the water inside the pump.

Cooling of the PCB board is finished by each air and water cooling. Onboard the control panel are thermal sensors. The electrical converter is cooled with air in the initial stages and once the duty cycle will increase or the load exaggerated steadily. The flow of water is controlled by the control board on the PCB. This is programmed therefore the flow is controlled reckoning on the temperature within the envelope.

7.4 Other liquids used Glycol

Glycol could be a water-miscible coolant that's habitually utilized in warm exchange and cooling applications. It gives way better warm transfer parameters than water, and can be blended with water to supply an assortment of warm exchange characteristics.

The table below shows respective values for various duty cycles ranging from 10%~100% capacity using Glycol as the cooling medium. Unadulterated ethylene glycol contains a particular warm capacity almost one half that of water. So, whereas giving solidify security and an expanded bubbling point, ethylene glycol brings down the particular warm capacity of

water blends relative to pure water. A 1:1 blend by mass includes a particular warm capacity of almost 3140 J/(kg.

At a normal fluid temperature of 200° F, the heat-transfer coefficients gotten utilizing water, ostensible (by volume) 30-70 and 70-30, glycol-water blends are around 3.6, 2.8, and 1.4 times higher, individually, than the heat-transfer coefficients gotten utilizing AN-E-2 ethylene glycol. In this case I am using 70-30 mixture.

Usage In %	Heat in W	Specific heat capacity of Glycol	Surface Temperature in K	Water inlet temperature in K	Temperature difference	Flow rate in L/sec	Water Temperature leaving the Block in K
100	3300	3140	539.76	298	241.76	0.004347102	298.5266272
90	2970	3140	515.58	298	217.58	0.004347182	295.5739645
80	2400	3140	473.82	298	175.82	0.004347237	292.2011834
70	2100	3140	451.85	298	153.85	0.004347025	289.4260355
60	1800	3140	429.87	298	131.87	0.004347072	287.6508876
50	1500	3140	407.89	298	109.89	0.004347138	284.8757396
40	1200	3140	385.91	298	87.91	0.004347237	282.1005917
30	900	3140	363.93	298	65.93	0.004347402	280.3254438
20	600	3140	341.96	298	43.96	0.004346743	278.5502959
10	300	3140	319.98	298	21.98	0.004346743	276.7751479

Using newtons Law of cooling

Q = h*A* dT

Q = Heat removed in W

A = Surface Area in m^2

T1 = Initial Temperature in K

T2= Final Temperature in K

Heat transfer Co-efficient for water and glycol mixture h = 2800 W/m²K (forced convention)

(Assuming a 70-30 mixture)

3300 = 2800 * 0.0845 m^2 * (T2-T1)
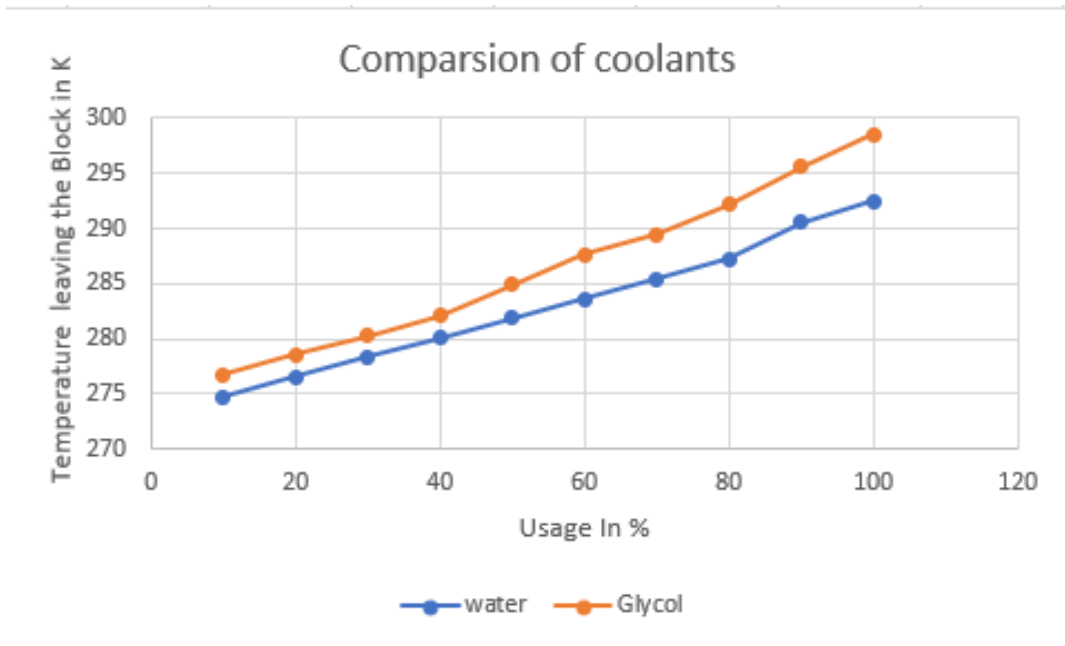
T2 = 312 K or 39° C.

Figure 50 Comparison of Coolants

As we can see from the graph above its is clear that pure water has more heat removal properties. But the only drawback being it can cause corrosion on the copper tubes. So, the Water with Glycol being the better option. Since the heat removal is minimum compared. With a long-term perspective, the water + glycol could be best option.

8. CONCLUSION

The design of inverter and its enclosure study is completed. The main aim of the thesis was to create and enclosure which is compact in size that has a modular design as well.

The arrangement on the PCB was considered as the heart of the problem since we had to have lots of transiters increasing the length of the PCB is not something that is acceptable. Hence the approach to go for vertical direction and place all the components on different floors while keeping the total length to a minimum but the height of the inverter is also increased.

The right box build design will ensure the long-term success of the electronics project. The enclosure was designed with five strategies is mind.

- Fit (the perfect fit that combines safety, functionality, and cost effectiveness)
- Material (outdoors underwater or underground, extreme temperatures, high moisture)
- Transmission (Metallic enclosures can hinder transmission of wireless signals.)
- Layout (Study the aesthetic practices of industry competitors before making decisions that affect the appearance and usability of the product.)
- Compatibility (Before moving into production, compare your CAD to the BOM (bill of materials) to ensure package compatibility**.**)

The enclosure has been designed with aluminum sheet metal. Aluminum was chosen as it has good heat removal capabilities and also due to the fact that it is very light weight. The idea was to create an enclosure which was compact in design so it can assemble easily and takes less place also.

The cooling is done with using both air and water cooling. As we already from the calculation we are able get 10 % of the total heat generated by the use of fins.

The coolant used for the heat removal is a combination of water and Glycol mixed in the 70-30 mixture. The flow is controlled by control board which is coupled thermal sensors as the

temperature increase the flow gradually increases. The temperature is completed dependent of the duty cycle or working cycle.

 The entire cooling circuit is free from debris by using filters at the end of the reservoir. The coolant from the reservoir is pumped using a pump and motor coupled together.

The applications of this type of inverter could be for automotive purposes such as electrical vehicles i.e., cars or locomotives in our case it's an excavator for construction purposes.

SCOPE OF THESIS:

The thesis can be further improved by functions and actions as the requirements

- New material can be used such as plastics which could be used as an alternative.
- The manufacturing could be achieved traditional manufacturing or new technologies such as 3d printing.
- New arrangements inside the PCB to optimize the size of the inverter
- CFD analysis could be done to understand the flow of the fluid to have clearer picture of the heat exchange and using different types of coolant for various cooling characteristics.

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