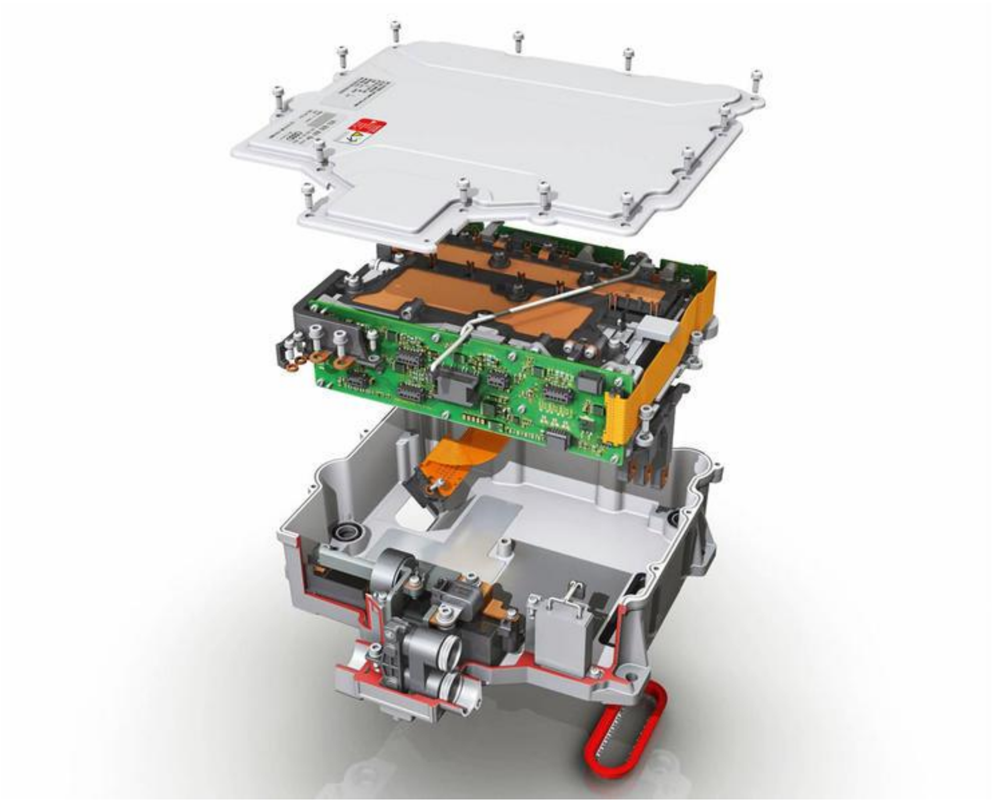
Manufacturing of an inverter



Contents

1 Introduction

1.1 Overview

A converter is usually a power electronic device that converts power between a DC voltage and an AC voltage an consequently current, if the voltages drive currents. The conversion does not have to be between DC and AC, it can also be between DC and DC e.g. different voltage levels) or even AC and AC (e.g. different voltages and different frequencies).

Figure 1-1 shows a schematic overview of a converter that can convert between DC and AC. By utilizing the advantages of state of the art semiconductors, the conversion can be performed at high power levels and high efficiency. The most used semiconductors for inverters in the automotive industry have traditionally been IGBTs, but the trend is shifting towards SiC MOSFETs [1,2]. IGBT is an abbreviation for Insulated Gate Bipolar Transistor, a more technical term describing the way the semiconductor is built up on the chip level. SiC MOSFET means a Silicon Carbide Metal Oxide Semiconductor Field Effect Transistor where SiC states the semiconductor material and MOSFET describes the way the semiconductor is built up on the chip level. The IGBTs have the advantage of being able to have a higher voltage rating than regular Si MOSFETs, with the drawback of higher switching losses. State of the art SiC MOSFET have a voltage rating of 1200V or more with very low switching losses. The main drawback of SiC components is the high cost compared to regular Si devices. See section 1.6 for more details on different semiconductor materials.

Efficiency is an important parameter as the power flow through an inverter can be 10’s or 100’s of kW. At such high power levels even a low percentage of losses will generate a substantial amount of heat, increasing the demand on the cooling system.

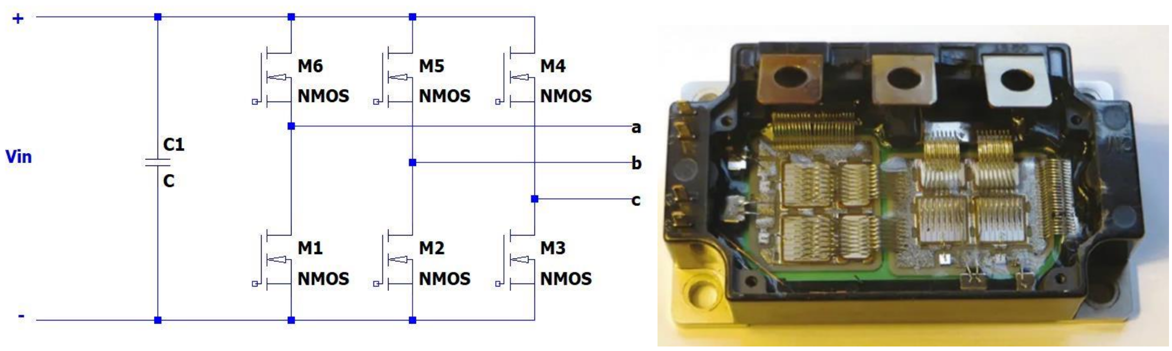


Figure 1-1: Left: Schematic with the main components of an inverter. Right. One phase of the converter partly opened [3].

1.2 Functionality

A power electronic device that can convert DC voltage to AC voltage is an important part of an electric drivetrain. DC voltage from the on board battery is converted into AC voltage, driving the electric traction machine. The energy flow can also go in the opposite direction when the machine is breaking, converting AC to DC. The conversion is made possible by using several switches, that are operated in open or closed mode. The transistor has three terminals, where the connection between the two terminals in the vertical plane in Figure 1 is the main path for current and the third connection (to the left in the same figure) is a control terminal with which it is possible to turn the transistor “on” or “off”. “On” means that it is able to conduct current easily along the main current path, and “off” means that it cannot easily conduct current. It works very much like a light switch in a room, with the difference that it can be turned “on” and “off” at a rate of 10’s of thousands of times per second.

In power electronics these switches are often considered to be ideal, with the states fully open or fully closed. This is often a good approximation as the voltage drop across the main current path through the transistor is small compared to the DC-link voltage. For thermal design and loss estimation it is very important to not use this approximation and instead use actual component parameters. The control circuitry of the inverter is in direct control of these switches and can therefore control these switches such that the output voltage is controlled, both in terms of amplitude and frequency. The control method is called modulation. To stay with the comparison to a light switch, imagine reducing the light in a room to e.g., half by turning it “on” and “off” equal amounts of time 10 000 times per second. The light would indeed be lowered but the mechanical switch on the wall would be worn out, but a power electronic switch is not worn out. It can do this for years and years.

There are different inverter topologies where the simplest form is shown in Figure 1-1, a 2-level inverter. 2-level inverter means that the output phase (a, b or c in Figure 1) can be connected to either of the sides of C1, i.e. the output phase can be connected to one out of two different voltage levels. The function of a “switch” is accomplished by two transistors on top of each other, a so called “phase leg” the converter in Figure 1-1 has three such phase legs. The two transistors in a phase leg are operated in opposite modes, such that if the upper transistor is “on”, the lower is “off” and vice versa. Thus, they together operate like a switch between the upper and lower side of C1.

Multilevel inverters have more than 2 levels for the output voltage, therefore they require more switches compared to the 2-level inverter. The complexity of the power electronics and the control is therefore increased as the number of levels is increased. Even though the complexity is increased it can be beneficial to increase the number of levels. By having more switches, the voltage rating of each switch can be reduced. This can also have a positive effect on losses in the switches. By reducing the losses, the cooling system can also be reduced while keeping the components cool enough. Another benefit from having more levels in the converter is that the voltage steps are smaller and therefore the dV/dt is smaller, which results in reduced EMI. With dV/dt we mean the rate at how fast an output voltage change between two levels. If the change is 600 V and it takes place in 100 nanoseconds, then dV/dt is 6000 MegaVolt per second. This fast change of the output voltage is a severe source of disturbances to the surroundings and actually wear insulation material in the traction machine windings as well.

1.3 Modulation

To achieve high energy efficiency, the output voltage is modulated with a Pulse Width Modulation (PWM). In a PWM controlled voltage the output switches between high and low at some rate in the kHz range. The average output voltage is therefore depending on the ratio between the time spent at the high and low output voltage levels.

The modulation for a 2-level inverter is based on a comparison between a carrier wave and a reference level for each leg in the inverter. When the reference is above the carrier wave the upper transistor in a leg conducts and when the reference is below the carrier wave the lower transistor conducts. The result of this is a PWM modulated output voltage. The modulation with a 1 kHz carrier wave is shown in Figure 1-2.

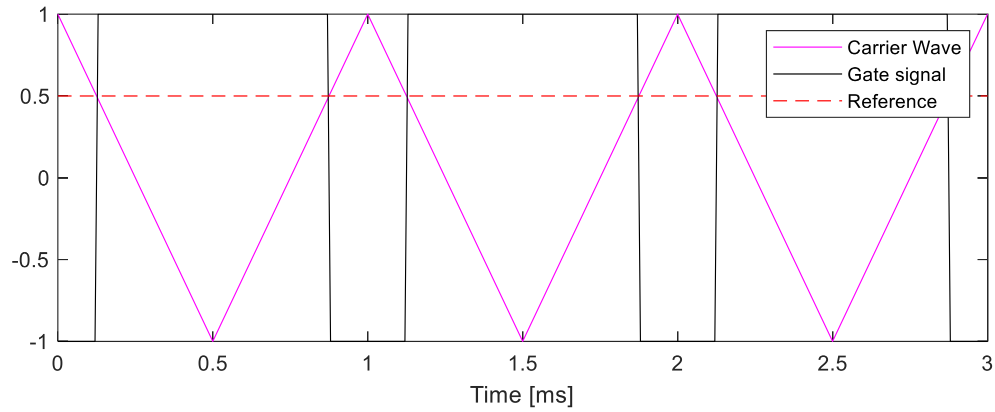


Figure 1-2: Shows modulation with a 1 kHz carrier wave.

1.4 Losses

The main losses in an inverter is often from losses in the switching transistors are from conduction and switching losses.

1.4.1 Conduction losses

Conduction losses are generated when the transistor is turned “on” and a current is flowing through the transistor. This loss is from the voltage drop over the main current path through the transistor times the current through that path.

1.4.2 Switching losses

When switching between two levels of the output voltage, the transistors involved change the voltage drop across them from either isolating to almost perfectly conducting or the other way. In the same time, the current through the transistor is either increasing (when turning the transistor “on”) or decreasing (when turning the transistor “off”). This means that during the switching itself, there is a high level of losses in the transistor = the voltage across the transistor times the current through it. Since both the voltage and the current can be high the power can be very high, in the order of 100’s of kW or even MW. Luckily, the switching time is really short (around a microsecond) so the energy dissipated in one switching is still relatively low, but it is repeated at every switching and thus the switching losses are proportional to switching frequency.

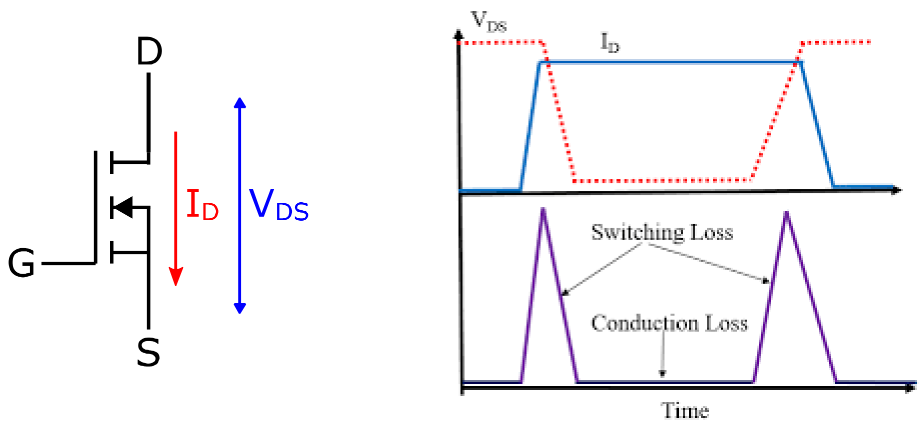


Figure 1-3 Voltage across a transistor and current thorough while switching results in switching losses, and in between the switching there are conduction losses [4].

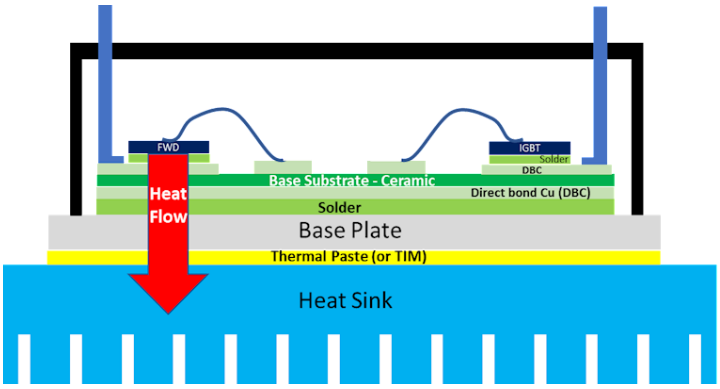
1.5 Semiconductor cooling

An inverter can generate a large amount of heat during operation. Even at an efficiency of 97% the losses are 3 kW for a 100 kW inverter at full load. These losses are mostly generated in the main semiconductors, which can be e.g. IGBTs or MOSFETs. The heat needs to be transferred away from the semiconductors and out from the inverter case to prevent the inverter from overheat.

Different components have different temperature ratings. The main switches usually have a maximum junction temperature of 150 or 175 °C, which must not be exceeded. The junction means the part of the chip where the main current flows. This junction temperature is located inside the semiconductor package, making it difficult to measure directly. There are ways to estimate the junction temperature by e.g. measure the forward voltage drop at a very low current. Another way to estimate the junction temperature is by measuring the case temperature, accessible from the outside of the package, and then combine the results with a thermal model for the package. This thermal model is normally given in the semiconductor datasheet. The model given in the datasheet is for a new component and the model parameters can change throughout the lifetime of the component.

The junction temperature is important to consider, at least in the design stage of the inverter as ageing of the semiconductors is related to the junction temperature swing. A larger temperature swing results in more stresses inside the component and eventually wear out the component and it fails.

Different semiconductor packages require different ways of mounting to the heat sink. A normal power module has a backplate, see Figure 1-4, that is electrically insulated from the terminals of the module. This makes it possible to attach the module directly to a heatsink without having to insulate the heatsink from other conductive parts. It also makes it possible to use several power modules on the same heatsink.



Layer	Contribution To Thermal Resistance
Baseplate to Terminal Material (Thermal Paste)	50%
Device	3%
Solder	6%
Base Substrate - Ceramic	33%
Base Substrate - DBC	3%
Base Plate	5%

Figure 1-4 Internal structure of an IGBT module, with the baseplate in the bottom [5].

For a component without an electrically insulated backplate, such as the standard TO-247, more care is needed to not cause an electrical short circuit or to energize conductive parts that should not be energized. A thermal pad that is an electrical insulator can be used between the semiconductor package and the heatsink to prevent an electric connection between component and heatsink. This allows heat to easily flow from the semiconductor to the heatsink while keeping the electric insulation. It should be noted that a thermal pad is often a larger thermal barrier than a thin layer of thermal paste.

1.6 Si, SiC and GaN

In the search for higher efficiencies and better performance of the inverter, the choice of semiconductor material becomes important. In traditional designs components based on Si are dominating. SiC and GaN devices are considered wide bandgap semiconductors with a bandgap of 3.3 eV and 3.4 eV compared to 1.1 eV for Si. The wider bandgap allows for an increased breakdown voltage, reaching up to 1200-1700 V. Other advantages over Si semiconductors are the low on state resistance and fast switching times. This allows for higher power densities and lower losses in designs utilizing wide bandgap semiconductors. The most prominent drawbacks are the high price and the extra care needed to perform efficient switching.

Poor gate driving designs can result in unwanted ringing and voltage overshoots. For every new inverter design, it is important to weigh the benefit of improved performance and efficiency to the increased cost. To reach high efficiency the switching event should be performed quickly to reduce switching losses that occur during the switching event. This increases the requirements of the gate driver, which needs to be able to output a current to charge the gate capacitor of the semiconductor. Since these wide bandgap semiconductors can switch faster, they allow for higher switching frequencies. Faster switching times means fast transitions between on/off states and high dV/dt. This may cause increased EMI and unwanted wear on electric insulation. Electric insulation degrades over time as it is exposed to high voltages and dV/dt. The reason for this is the presence of partial discharge, which is a localized breakdown in the insulation. The partial discharge normally starts in impurities of the insulation material, such as gas voids trapped in the solid medium. At a certain point the electric field reaches the corona inception voltage and there is arcing withing the impurity.

2 Main components of an inverter

Figure 2-1 shows the inside of an inverter from a Tesla model S and is an example of what can be found inside an inverter. Different manufacturers have different designs, but the main components are the same.

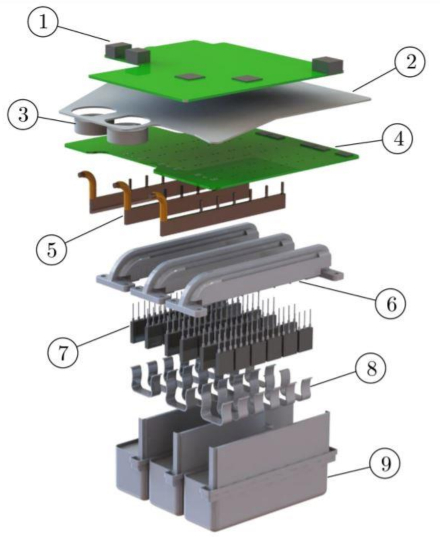


Figure 2-1: Figure and caption taken from [1]. Tesla model S inverter. 1) Control board. 2) Aluminum shield. 3) Phase current sensor ferrite ring. 4) Gate driver board. 5) Phase busbars. 6) Heat sink. 7) IGBTs. 8) IGBT clips. 9) DC-link capacitors.

2.1 PCB

The Printed Circuit Board (PCB) holds the discrete components in place and routes the different signal and power paths to the correct component. Depending on the complexity of the PCB, the number of layers can differ. By increasing the number of layers there is more flexibility to route signals between components on the PCB. It also allows for more power planes, which are important to keep voltages stable across the entire PCB and to increase EMC performance [6].

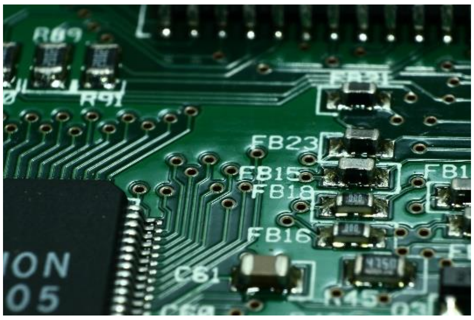


Figure 2-2: PCB

2.2 Busbar

Busbars are used to distribute power within a device. A busbar is often uninsulated, this makes it possible to connect components directly to the busbar and increase the cooling of the busbar. The busbar needs to have a low inductance and that is accomplished by placing the busbar conductors close, like in Figure 2-3.

The choice of material and geometry depend on requirements for the specific application. Aluminum and copper are two common materials due to their good electric conductivity. Busbars main task is to allow a flow of current which results in resistive losses and heat. Depending on the amount of current the cross-section area needs to be large enough for the available cooling. By making the busbar flat a larger surface area is obtained, which results in better cooling compared to a smaller area. The skin effect should also be considered when deciding on busbar geometry.

Figure 2-3 Example of bus-bar, with two layers of aluminum, separated and isolated from each other and connection points for power electronic components [7]

2.3 Full-bridge

Figure 2-4: Half bridge. Picture from [9].

For a 3-phase inverter at least six switches are needed. These switches must have a high enough voltage rating to withstand the DC-link voltage and any additional voltage that arises during switching events. A common practice is to apply a safety margin of e.g. 20% to increase reliability of the switches [8]. To increase a full-bridges current capability multiple switches can be connected in parallel, as can be seen in Figure 2-1. This results in lower current per switch for a fixed amount of total current, thus also less losses per switch. Losses in the switches needs to be transferred away from the switches and dissipated through the cooling system, which can be a liquid or an air cooled cooling system. The cooling is crucial to consider as when the temperature of the switches increase the current capability must be derated.

The choice between discrete components, such as TO-247, or modules depends on the design parameters for the specific inverter.

2.4 DC-link capacitor

Figure 2-5: DC-link capacitor. Picture from [12].

DC-link capacitors store energy and are needed to stabilize the input voltage to the full-bridge as well as to filter the pulsed current drawn by the full-bridge. If the DC-link capacitors act as a perfect filter, only the average current would be drawn from the energy supply, not a pulsed current. In any real application the capacitors are never perfect. There are current and voltage ripple when the full-bridge switches between different states, that results in losses and leakage currents.

There are many different types of capacitors, which are useful in different applications. For an inverter a fast capacitor is needed to be able to provide energy in bursts. Film capacitors provide good performance with low series resistance and inductance [10,11].

2.5 Gate driver

The gate driver is important as it controls the switching events. Most gate drivers used in inverter designs are isolated, meaning that the low voltage control side is isolated from the high voltage side. This isolation is achieved by galvanically separate the low and high voltage side. Gate driver signals are still required to pass by the isolation gap, which is possible through an optical or inductive coupling [13]. By using an isolated gate driver potential ground loops can be avoided, thus increasing performance. The low voltage side is also protected from voltage spikes on the high voltage side, which can damage the components on the low voltage side.

Figure 2-6: *Left*: Gate driver schematic [14]. Middle: Example of gate driver card [15]. Right: Example of gate driver s Picture from [16].

2.6 Cooling

Heat generated inside the inverter affects the temperature of the inverter. A well-designed cooling system is needed to dissipate the heat, keeping the temperature from reaching too high levels. This cooling system could be anything from a simple heatsink for the semiconductors to a liquid cooled system, cooling most of the components in the inverter and transporting the heat to a radiator outside of the inverter. A cost-efficient design needs to consider the design criteria regarding performance, estimated lifetime and the environment the inverter is used in.

The cooling circuit is often shared between the power electronic converter and the traction machine. Figure 2-7 shows this on an EV drive where the power electronic converter is mounted on top of the traction machine and receives the cooling water first, since it needs the lowest cooling media temperature.

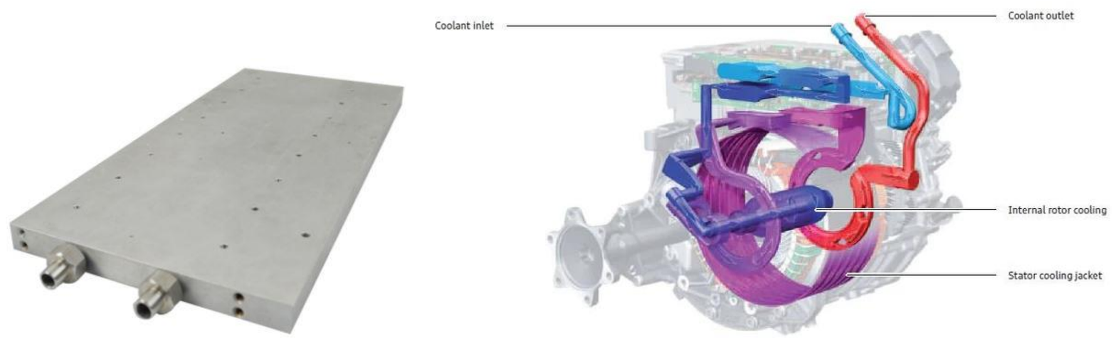


Figure 2-7: Left: Water cooling block. Picture from [17], Right. Audi E-Tron front drive colling circuit [18].

3 Manufacturing & Assembling

3.1 PCBA

A PCBA or a PCB assembly is a PCB with all its components mounted and attached to it.

3.1.1 PCB

Manufacturing of a PCB requires multiple steps where the first step is to do the PCB design. Once the design is finished and quality approved by the involved engineers the design can be printed. The usual printer for printing PCB designs is a plotter printer, which uses a tool such as e.g., a pencil to make accurate straight lines [19,20]. In case of a multilayer PCB each layer needs its own prints. Each individual layer is then etched to remove copper from the laminates to perfectly match the prints. X-ray alignment and optical inspection is used to correctly align the layers before bonding the laminates together [20]. The last steps of the PCB manufacturing process include adding the solder mask and the silkscreen to the PCB.

3.1.2 Pick and place

A pick and place machine is used to position the Surface Mount Devices (SMD) on the PCB. At first a solder mask is added to the PCB where the components are to be placed. This solder mask is sticky and holds the components in place until the soldering process is complete. The pick and place machine takes a component or multiple components and place them on the PCB at a high rate. Through hole components can also be placed on the PCB by a machine, but the process is more complicated and slower compared to for SMD components. After all the components are placed on the PCB it is ready for the soldering process.

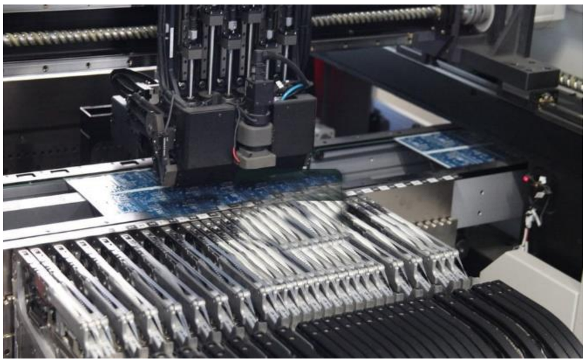


Figure 3-1: SMT pick and place machine. Picture from [21].

3.1.3 Soldering

Soldering involves the PCB and all the components mounted on the PCB, such as gate drivers and control circuitry. The soldering process requires an increase in temperature of the solder joint to melt the solder [22]. Solder can be based on several different metals, including lead, tin, silver, copper, and so on [22]. The choice of solder material depends on the application as solder made from different metals have different properties.

There are different types of solder processes. Reflow soldering is the preferred soldering process for SMD components and wave soldering for through hole components. Boards which contain both SMD and through hole components should go through reflow soldering first to attach the SMD components before using wave soldering to attach the through hole components. The reason for this is that the temperature is higher for reflow soldering compared to wave soldering and if performed the other way around components may be unsoldered [23].

3.1.3.1 Reflow soldering

First the PCB is preheated to reach a predefined temperature. After the preheating phase the temperature is increased and the flux is activated. The activation of the flux cleans the surface of the solder pads and removes oxide. At a certain temperature the solder paste melts and starts to reflow. It is important that the proper temperature is reached in order not to damage components from a too high temperature or fail to solder by having too low temperature. After the solder is melted the temperature should be reduced to let the solder solidify [23]. Reflow soldering is performed in a reflow oven.

Figure 3-2: Reflow oven: Picture from [24].

3.1.3.2 Wave soldering

Flux is sprayed on the board to make sure the board is free from oxide and dirt during the soldering process. The PCB is preheated before reaching the wave solder stage of the soldering line. After the PCB is preheated the PCB is run through a wave of melted solder. This wave is like a bath of solder that attach to exposed metal parts but will not stick to the solder mask. Once the wave soldering is complete the PCB is allowed to cool down to let the solder solidify [23].

Figure 3-3: Wave soldering. Picture from [25].

3.1.3.3 Manual soldering

Manual soldering is most common when the number of PCBs and components are low and the additional cost of automating the soldering process is too high. Manual soldering is performed by manually placing a component on the PCB and then using a soldering iron to make the solder joints.

3.1.4 Inspection

After the soldering process the PCBAs can undergo different types of inspection. This can be optical imaging in which an image of the PCB is compared to an image of a known working PCBA. Manual optical inspection is also an alternative when production volumes are lower. X-ray is used for components which have the soldering interface hidden, e.g. a Ball Grid Array (BGA) component. The X-ray can then see through the component and detect bad solder interfaces.

3.2 Busbar

Manufacturing of the busbar itself is relatively simple as it is a metal bar, solid or hollow. In addition to manufacture the metal bar a coating may also be desired to improve the performance or durability of the busbar. A coating can be used to prevent corrosion, insulate, or for visual reasons.

3.3 Full-bridge

Manufacturing of the semiconductor modules used in the full bridge is not considered in this document, as those are usually sourced. Therefore, the manufacturing of the full bridge is simple and require either soldering the discrete semiconductors onto a PCB or connecting modules together with e.g. busbars.

It is important to minimize parasitic elements to limit voltage overshoots and improve switching performance. To do this the switches in the full-bridge should be placed close to each other and loop areas should be kept small.

3.4 DC-link capacitor

As for the semiconductors, the manufacturing of the DC-link capacitor is not within the scope of this document. Just like the power semiconductors it is usually sourced. The DC-link capacitor should be placed as close to the H-bridge as possible to minimize stray inductances. By placing the capacitor close to the H-bridge, the stray inductance causing overshoots during switching events is reduced. The capacitor is likely a through hole component or connected by screw terminals, depending on the power rating of the inverter.

3.5 Gate driver

The gate driver is a SMT component and is placed on the PCB together with other components required for the gate driver, such as resistors and capacitors. The placement of the gate driver on the PCB should be as close to the gate of the transistor as possible. Shorter traces on the PCB generally results in better switching performance. Manufacturing of the gate driver and any additional components are not considered.

3.6 Cooling & Case

3.6.1 Stamping

A metal sheet is pressed in a press to obtain the intended shape [26]. During the stamping process the tool can punch holes in the workpiece, make bends, or other shapes [27]. This technique is suitable for high volume production [26].

3.6.2 Cold forging

A piece of metal is squeezed between two dies, usually at room temperature. This forces the metal to obtain the desired shape. Cold forging is a relatively fast process, which leaves the finished product with a good surface finish [28]. Low cost at high volumes [28].

3.6.3 Die casting

Die casting uses a reusable mold in which molten metal is pressed at high pressures. Because of the mold being reusable, this process efficient for high volume production [29, 30]. The mold itself is expensive and die casting is therefore preferred only if the volume is high [26].

3.6.4 Extrusion

The material is pushed through a die, which forms the extruded product to the correct shape. For extrusion, the cross section is the same throughout the whole workpiece [31]. Only a small amount of material is wasted in the extrusion process, and together with a high production rate this is a low cost production process [32].

3.6.5 Machining from full block

A CNC machine processes a full block of metal to achieve the desired geometry. The CNC machine can produce complex geometries, but at a high cost [26].

3.7 Materials

Different materials with different properties can be utilized in a product. However, it is important to consider how the material combinations work together. A mismatch in thermal expansion can induce stresses in the materials during manufacturing or at different operating points. Corrosion can also occur when different metals are in contact with each other.

Materials used during production can be categorized into different types [33]:

- Polymers are cheap and easy to use, but with the disadvantage of low durability.
- Metals are durable but more expensive that polymers. Metals are usually used in high durability products or when heat is a concern.
- Ceramics are cheap and lightweight. They are fragile and can be difficult to process.
- Composites can be customized and have different properties depending on the combined materials.

Materials with good thermal conductivity while being an electric insulator are used to mount semiconductor packages without an insulated backplate. A common component is the TO-247 which have the backside of the component electrically connected to one of the leads, see Figure 3-4

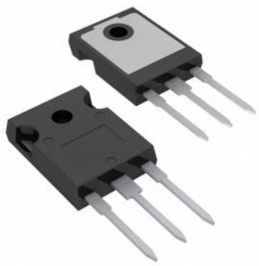


Figure 3-4 TO 247 Capsule [34].

Due to this the backside cannot be directly connected to a metal heatsink without putting the heatsink on a possibly high electric potential. Normally giving the heatsink a high voltage is undesired as it needs to be insulated from other electrically conductive parts and only components connected to the same potential can be attached to the same heatsink. A particular case then the backside of the uninsulated components should be directly attached to a heatsink is when the heatsink is used as a conductor.

Thermal paste is commonly used as an interface material to increase the thermal conductivity of an interface between two surfaces. Even if a surface seems smooth to the naked eye there are small surface imperfections. These imperfections reduce the effective contact area, thus increasing the thermal resistance of the interface. The thermal paste fills the voids in the interface and since the paste is a better thermal conductor than air, the result is a reduced thermal resistance. When choosing a thermal paste, it is important to consider the effect of all of its properties and not only choose based on thermal conductivity. One important parameter is how thin the paste can be spread out, as a thin layer results in a lower thermal resistance compared to a thicker layer.

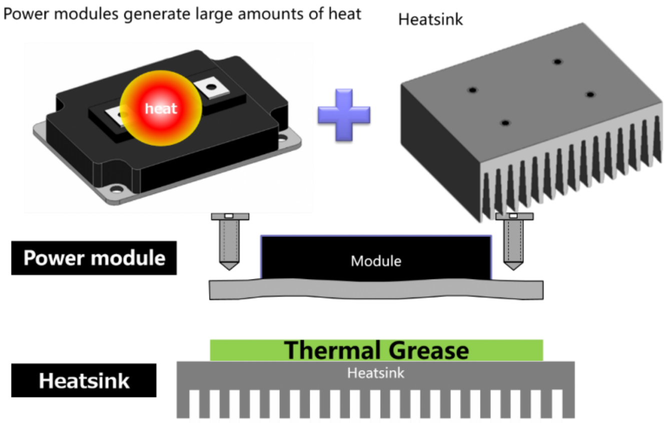


Figure 3-5 Application of thermal paste when mounting a power semiconductor package, to increase thermal conductivity from the transistor module to the heatsink [35].

The requirement of insulation materials increases as the voltage increase and with the use of wide bandgap semiconductors, such as SiC MOSFETs. As explained in Section 1.6 electric insulation degrades faster the higher the voltage and dV/dt it is exposed to. Partial discharge, which is a localized breakdown in the insulation material, can over time wear out the insulation and cause an insulation fault. Another parameter that affects the amount of partial discharge is air pressure. At lower pressures the partial discharge is increased, and this is important to consider for high altitude applications [36].

4 Testing

Testing of the different parts in a product is important to ensure high quality. This testing can be performed both at a system level and at a subsystem level. By ensuring functionality of the sub systems before the full assembly, faulty components or manufacturing issues are easier to locate.

Testing requires time and equipment, increasing the cost of the product for each test that is performed. Due to this there is a trade-off between testing and cost, where the trade-off depends on the product that is being manufactured.

4.1 Standards

To ensure high quality of the inverter and to fulfil safety regulations, the inverter should be tested according to certain standards. SS-EN 61800-5-1 is one example of a standard that describes in detail which tests are needed for a regular inverter and under what circumstances the inverter should be tested. To certify a product an external third-party checks that the product is tested according to any relevant standards. During the certification process it is important to consider replacement components, such as transistors from different manufacturers. Only the specific components present during the certification process are certified, and if a replacement is needed for some reason and it was not in the original certification the inverter needs to be recertified.

4.2 Number of samples to test

Often every single unit goes through some sort of testing throughout the manufacturing process. By testing a unit in stages starting with the PCB, many early defects can be found. This reduces the total cost of the defect units as less components are wasted. Note that if the process has been proven reliable, after enough testing, it may be more profitable to not test every unit. The standards do not explicitly state that every unit must be tested, but a customers may demand it.

4.3 PCBA

The first tests often include optical and X-ray inspection of the PCBAs. These tests can reveal structural faults, such as a bad solder or incorrect positioning of a component [37].

In-Circuit-Testing (ICT) is a useful testing method for PCBAs to ensure the functionality of the board. The PCBA is placed in a bed of nail fixture, which have several needle-like probes that physically connect to the PCB. Depending on the tests that are being performed the probes can either measure or supply power or signals to the board to activate certain functions. This kind of testing require the designer of the PCB to have made test points on the PCB where the testing should take place [37].

4.4 Finished product

The finished product is tested according to the standards. These tests include e.g. faulty components, EMC, cooling, and more. Note that many of these tests may not be needed for the production phase. For many tests the power should flow through the inverter for an extended period of time, requiring the cooling system to be fully installed. Testing can take up more time than the development of the product, it is therefore important to have an efficient test procedure and consider what fraction of the total units that need to be fully tested for high volume production. To make this decision, manufacturing quality, customer requirements and testing cost need to be considered.

4.5 Production

After the product passed the certification tests according to the different standards, it is important to reduce the number of tests per unit. The full list of tests from the standards can be used as a starting point and from which tests should be removed depending on the product. In high volume production, every test that can be avoided is a reduction of manufacturing costs. Exactly which tests that can be removed depends on the product and reliability of the manufacturing process.

4.6 Examples of test equipment

- X-ray: Used to inspect PCBAs and solder joints.
- Optical inspection: Used to inspect PCBAs, where images of the PCBA are compared to pictures of known working samples.
- Bed of nails: Test pins connect to different test points on the PCB to test the functionality of the PCBA. The test pins can provide set voltage levels to test both hardware and software of the installed components.
- Insulation tester: Test the insulation between parts in the inverter.
- Motor test bench: The inverter is connected to a motor, which is connected to a generator to create a breaking torque. This setup can be used to load the inverter.
- Power analyzer: Map the inverters efficiency under different load conditions.
- EMC chamber: A chamber in which radiated emissions can be measured.
- Vibration table: Test how vibrations affect the inverter.
- Climate chamber: Vary the temperature and humidity to test the inverter in different conditions.
- Static discharge tester: Test that the inverter can handle a static discharge on parts that are exposed.
- Kelvin measurement: Measure the contact resistance of important joints.

5 Design considerations

When designing a product there are always trade-offs as cost, performance, and manufacturability need to be considered. This section explains some of the important parameters that must be considered when designing an inverter.

5.1 Semiconductor

The first parameter that needs to be considered when deciding on a semiconductor is the operating voltage. The semiconductor needs to be able to handle the operating voltage and have a margin to withstand overvoltage during switching events. IGBTs generally have higher voltage ratings than MOSFETs and are used for applications with high voltage levels. MOSFETs have faster switching characteristics and lower switching losses, which makes them well suited in an application where switching frequency is important. With wide bandgap semiconductors the voltage rating of MOSFETs have been increased to over 1200 V and can therefore handle a DC-link voltage of at least 800V depending on the inverter design.

When the voltage rating of a device increases the conduction losses also increase. Due to this, it is important to choose an appropriate voltage rating for the component to keep the losses as low as possible.

5.2 Switching frequency

A higher switching frequency results in more switching losses, but with the benefit of less ripple in the output current for a fixed output filter or load. For a fixed current ripple, the output filter or load can be reduced in size if the switching frequency increases. Therefore, it is a trade-off between multiple parameters when deciding on a switching frequency. The choice of semiconductor becomes more important the higher the switching frequency.

In switched converters where the switching frequency is in the audible range, noise can often be heard and can give a negative experience for the user. By selecting the switching frequency above 20 kHz the audible noise can be reduced.

5.3 Stray inductance

Stray inductance is usually an unwanted inductance in an inverter that cause voltage overshoots and increased losses. Stray inductance is due to stored energy in the magnetic field around e.g. a conductor. When the current path is broken the energy is transferred from the stray inductance to other elements in the circuit, since energy cannot disappear. These elements are usually capacitive elements, which means the voltage rises when the energy increases. It is important to consider the amount of energy stored in the stray inductance and where this energy is transferred and dissipated during a switch or fault event. If the parasitic capacitive elements are not enough a snubber may be needed. The combination of an inductive and capacitive element can also cause unwanted ringing in the circuit, which may require a snubber to dampen the ringing.

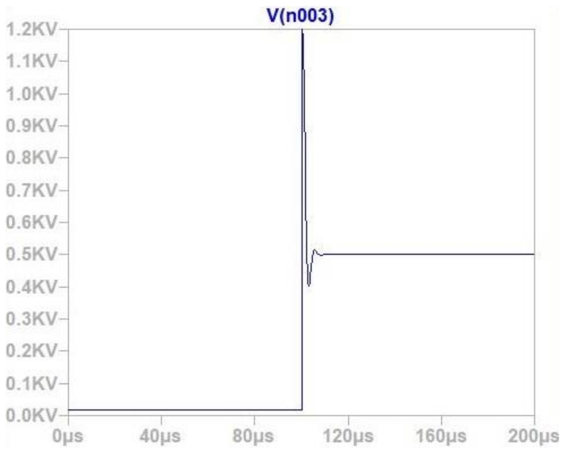


Figure 5-1: Overshoot of the voltage across a switch transistor when opening the switch carrying a current that flows in a conductor with a certain(stray) inductance.

The design and placement of the components inside the inverter directly affects the stray inductance. One example of a design rule is to keep loop areas as small as possible. It is also good practice to place the DC-link capacitors close to the full bridge to further reduce the stray inductance that affects the semiconductor switches.

In rare cases the stray inductance can be used in a design instead of installing a dedicated inductor. This can be the case when working with e.g. high frequencies.

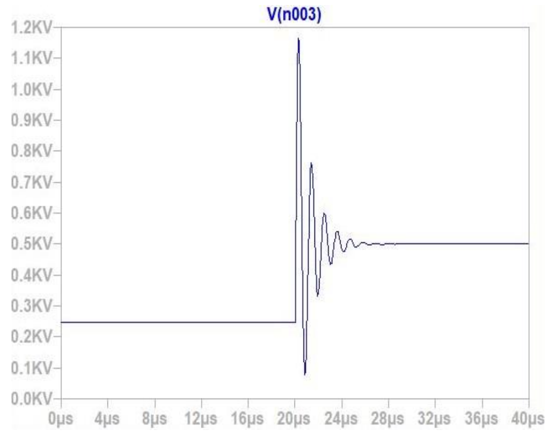


Figure 5-2: Ringing caused by capacitive and inductive elements.

5.4 Cooling

Most of the heat is generated in the semiconductors. Cooling of these components is important and with the low thermal mass of semiconductors the thermal coupling between the semiconductor and heatsink must be good enough to handle peak losses. This is as the temperature in the semiconductor package can increase rapidly if the thermal coupling is poor. The heatsink is a larger mass compared to the semiconductors and acts as a filter, making the temperature more stable during variations in losses.

Liquid cooling is most suitable to cool high power inverters as the generated losses are large and are focused to a small area. Liquid cooling is also of high interest if volume of the inverter is important. A liquid cooling system with electrically insulated heatsinks can share the cooling loop with other components.

5.5 Integration of electric machine and inverter

Integration of the electric machine and inverter can be a cost-efficient solution as the case can be shared by both components. This also makes a more compact design possible. As a result of the integration the cables between the inverter and electric machine can be shortened, reducing cost. With shorter cables the filtering effect is reduced since the stray inductance is reduced. This can increase the stresses on the insulation of the electric machine, causing increased wear. The reason for the increased wear is that the insulation experiences a larger dV/dt as the switching events are not filtered the same amount as with longer cables. A lower filtering effect may also cause increased EMI between the inverter and electric machine.

6 References

[1] J. Reimers, L. Dorn-Gomba, C. Mak and A. Emadi, "Automotive Traction Inverters: Current Status and Future Trends," in IEEE Transactions on Vehicular Technology, vol. 68, no. 4, pp. 3337-3350, April 2019.

[2] B. Şarlioğlu, "Automotive Power Electronics: Current Status and Future Trends," 2019 International Aegean Conference on Electrical Machines and Power Electronics (ACEMP) & 2019 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), 2019, pp. 1-2.

[3] B. Jayant Baliga, "The IGBT Device: Physics, Design and Applications of the Insulated Gate Bipolar Transistor", 18 March 2015.

[4] M. S. Haque, M. Mohammad, J. L. Pries and S. Choi, "Comparison of 22 kHz and 85 kHz 50 kW Wireless Charging System Using Si and SiC Switches for Electric Vehicle," 2018 IEEE 6th Workshop on Wide Bandgap Power Devices and Applications (WiPDA), 2018, pp. 192-198.

[5] ABB, "LoPak1 module lifetime and performance improved using new Thermal Interface Material (TIM)", https://new.abb.com/news/detail/57729/lopak1-module-lifetime-and-performance-improved-using-new-thermal-interface-material-tim, accessed on 2020-03-02.

[6] CADENCE PCB SOLUTIONS, "Power Plane PCB: Best Practices for Power Planes in Multi-board Design", https://resources.pcb.cadence.com/blog/2019-best-practices-for-power-planes-in-multi-board-pcb-design, accessed on 2021-10-19.

[7] Amphenol AUXEL, "Low inductive busbars", https://www.auxel.com/products-services/auxel-laminated-busbars/standard/, accessed on 2021-12-11.

[8] Sanjay Havanur, "Power MOSFET Basics - Understanding Voltage Ratings", https://www.mouser.com/pdfdocs/Vishay_AN861.pdf, application note.

[9] C. Hammerschmidt, " 1200V half-bridge SiC module targets electric powertrains", https://www.eenewsautomotive.com/news/1200v-half-bridge-sic-module-targets-electric-powertrains, accessed on 2021-10-19.

[10] Tom Colella, "How to Select a DC Link Capacitor", https://cdn.shopify.com/s/files/1/0085/1863/1479/files/electrocube-how-to-select-dc-link-capacitor-tech-bulletin.pdf

[11] WIMA, "WIMA DC-LINK Capacitors", https://gr.mouser.com/pdfDocs/WIMA_DC_Link_Capacitors.pdf, accessed on 2021-10-19.

[12] CRE, "High current DC link film capacitor for electric drivetrain inverters", https://www.cre-elec.com/high-current-dc-link-film-capacitor-for-hybrid-electric-vehicles-and-electric-drivetrain-inverters-product/, accessed on 2021-10-19.

[13] D. Varajao Carmen & M. Matrisciano, "Isolated gate driving solutions, Increasing power density and robustness with isolated gate driver ICs", https://www.infineon.com/dgdl/Infineon-GateDriverIC_EiceDRIVER_isolated_gate_driving_solutions-ApplicationNotes-v01_01-EN.pdf?fileId=5546d462700c0ae60170a0c4af851028, application note.

[14] Analog Devices, https://www.analog.com/en/products/monitor-control-protection/isolated-gate-drivers.html, accessed on 2021-12-11.

[15] Mouser, “Power Integrations SCALE-2 IGBT Gate Drivers”, https://www.mouser.co.uk/new/power-integrations/power-integrations-scale-2-igbt/, accessed on 2021-12-11.

[16] Digi-Key, “Gate Drivers”, https://www.digikey.se/sv/product-highlight/f/fairchild-semi/gate-drivers, accessed on 2021-10-19.

[17] Dr Forge, “Water cooler heatsink”, https://drforge.com/custom-heat-sinks/water-cooler-heat-sink/, accessed on 2021-10-19.

[18] Audi MediaCenter, https://www.audi-mediacenter.com/en/audimediatv/video/audi-e-tron-cooling-concept-e-motor-animation-4847, accessed on 2021-12-11.

[19] Perfect Colours, What is a plotter printer?”, https://www.perfectcolours.com/blog/2017/10/31/what-is-a-plotter-printer/, accessed on 2021-10-19.

[20] MCL, “WHAT IS THE PCB MANUFACTURING PROCESS?“, https://www.mclpcb.com/blog/pcb-manufacturing-process/, accessed on 2021-10-19.

[21] S. Das, ”SMT Pick and Place Machine”, http://www.electronicsandyou.com/blog/smt-pick-and-place-machine.html, accessed on 2021-10-19.

[22] TWI, “WHAT IS SOLDERING? A FULL GUIDE (MEANING, DEFINITION AND TYPES)“, https://www.twi-global.com/technical-knowledge/faqs/what-is-soldering#WhatMetalsareUsed, accessed on 2021-10-19.

[23] Tech Briefs, “Comparison Between Wave Soldering and Reflow Soldering“, https://www.techbriefs.com/component/content/article/tb/pub/features/articles/28337, accessed on 2021-10-19.

[24] Wikipedia, https://en.wikipedia.org/wiki/Reflow_oven, accessed on 2021-10-19.

[25] ZFP, “Key Points of Wave Soldering in PCBA Assembly Process“, https://uetpcb.com/key-points-of-wave-soldering-in-pcba-assembly-process/, accessed on 2021-10-19.

[26] Priatherm, “Technologies for heat sink manufacturing“, https://priatherm.com/en/technologies-for-heat-sink-manufacturing/, accessed on 2021-10-19.

[27] Thomas, “Understanding Metal Stamping”, https://www.thomasnet.com/articles/custom-manufacturing-fabricating/understanding-metal-stamping/, accessed on 2021-10-19.

[28] Industrial Quick Search, “Cold Forging”, https://www.iqsdirectory.com/articles/forging/cold-forging.html, accessed on 2021-10-19.

[29] A. Stark, ” What is Die Casting? Development, Processes and Materials in Die Casting”, https://www.spotlightmetal.com/what-is-die-casting-development-processes-and-materials-in-die-casting-a-818604/, accessed on 2021-10-19.

[30] CUSTOMERPART.NET, “Die Casting”, https://www.custompartnet.com/wu/die-casting, accessed on 2021-10-19.

[31] Paul Murphy Plastics Company, “Extrusion Process : Working, Types, Application, Advantages and Disadvantages”, https://paulmurphyplastics.com/2019/09/25/extrusion-process-working-types-application-advantages-and-disadvantages/, accessed on 2021-10-19.

[32] Engineering Product Design, “Metal Extrusion”, https://engineeringproductdesign.com/knowledge-base/metal-extrusion/, accessed on 2021-10-19.

[33] Pacific Research Laboratories, INC, “What Types of Materials Are Used in Manufacturing?“, https://www.pacific-research.com/what-types-of-materials-are-used-in-manufacturing-prl/, accessed on 2021-10-19.

[34] Digi-Key, “IKW40N120CS6XKSA1”, https://www.digikey.se/sv/products/detail/infineon-technologies/IKW40N120CS6XKSA1/9477947, accessed on 2021-12-11.

[35] Panasonic Industry, “Solving Thermal Grease Issues by Using Graphite TIM”, https://industrial.panasonic.com/ww/ss/technical/p4, accessed on 2021-12-11.

[36] L. Wishart, “Partial Discharge at Altitude”, https://www.lectromec.com/partial-discharge-at-altitude/, accessed on 2021-10-19.

[37] JTAG Technologies, “Testing of Electronics”, https://www.jtag.com/testing-of-electronics/, accessed on 2021-10-19.