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Electrical safety and isolation in high voltage discrete component applications and design hints

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1 Introduction

Knowledge on safety and related topics for electronic systems is essential for people dealing with power semiconductors. Since electronic equipment has to meet the requirements of certain safety standards, engineers need a solid understanding on these topics. This document gives an easy to read overview and describes also practical design examples[1].

2 Safety standards

Discrete power semiconductors like MOSFETs or IGBTs are operated with high voltages. These products as well as the applications/equipments in which they are used need to comply with safety and isolation requirements, which are defined in safety standards. Given the large assortment of regulating organizations and the associated standards and specifications, regulatory compliance for semiconductor manufacturers and equipment suppliers can be confusing.

The starting point of standards compliance is to know the appropriate regulatory organization and its responsibility. Various regions of the world determine their individual standards and an organization in that country issues approvals or certificates for equipment and products. Since standards bodies have often begun as national organizations, many countries have their own regulatory environment. Nowadays continental or international standards are applied. Table 2.1 shows a list of some important standards bodies. UL, CSA and DKE have similar charters as national organizations. In general each body will have its own standards and overlap and harmonization is visible.

Table 2.1: List of standard bodies

Organization name	acronym	charter
European Committee for Electrotechnical Standardization	CENELEC	Harmonizing of European Standards
Underwriters Laboratories Inc.	UL	U.S. Standards
International Electrotechnical Commission	IEC	International electrical standards
Canadian Standards Association	CSA	Canadian standards
German Electrotechnical Commission (Deutsche Elektrotechnische Kommission)	DKE	German standards

Table 2.2 is a cross reference of various specifications by the respective regulatory organizations. These specifications are written at the equipment level. Each equipment specification is a master document, but many subordinate specifications are referenced to complete the total requirements. Subordinate specifications are critical to certification.

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[1] *Please note that the purpose of this application note is just related to electrical safety and isolation. For correct mounting and assembly methods and thermal management aspects, please refer to respective application notes*

While UL60950 is most widely applied standard for power supplies today, it is intended for use with information technology, business and telecom equipment. Other standards exist for other industries, such as IEC60065 for audio and video, IEC6061 for medical, IEC61010 for laboratory supplies and others.

Table 2.2: cross reference of various specifications (equipment level)

	Organization				
	International	Europe	U.S.	Canada	Germany
Application	IEC	CENELEC (EN)	UL	CSA	DIN/VDE
Industrial	204 604	50178	508	14-M91	160
IT Equipment	950	60950	60950	950	60950
Medical Equipment	601	60601	2601-1	601	750
Household	65	60065	8730-1		860
Measurement and Control	1010-1	61010-1	1262	1010	0410 0411
Telecom	950	60950	1459	225	804

The equipment level specifications are usually referencing to general standards on insulation like:

- IEC60664 Insulation coordination for equipment within low-voltage systems
- UL840 Insulation coordination including clearances and creepage distance for electrical equipment

Besides equipment level specifications there are component level standards. Table 2.3 shows the important specifications on component level. The equipment level specification can reference the component level specification as a subordinate document.

Table 2.3: component level standards

	Organization				
	International	Europe	U.S.	Canada	Germany
Components	IEC	CENELEC (EN)	UL	CSA	DIN/VDE
Electronic devices	60747 60748	60747	1577	-	60747

General standards address safety and regulatory specifications of wide classes of applications of an industrial segment. There might be hundreds of equipment types in each application and some of these have safety standards not captured in general standards. An example is shown in Table 2.4, which lists some particular specific standards.

Table 2.4: examples of specific standards in an application field

Organization	International Standard	Description
IEC	601-2-6	Particular requirements for the safety of micro-wave ovens
IPC	9592	Performance parameters for power conversion devices
VDE	700	General requirement for the safety of households
VDE	0700-T24	Particular requirements for refrigerators, food freezers and ice makers

3 Creepage, clearance and isolation

The spacing distance between components that is required to withstand a given voltage is specified in terms of clearance and creepage. A visual representation of the distinction between these terms and their applicability to board-mounted components is shown in Fig. 3.1.

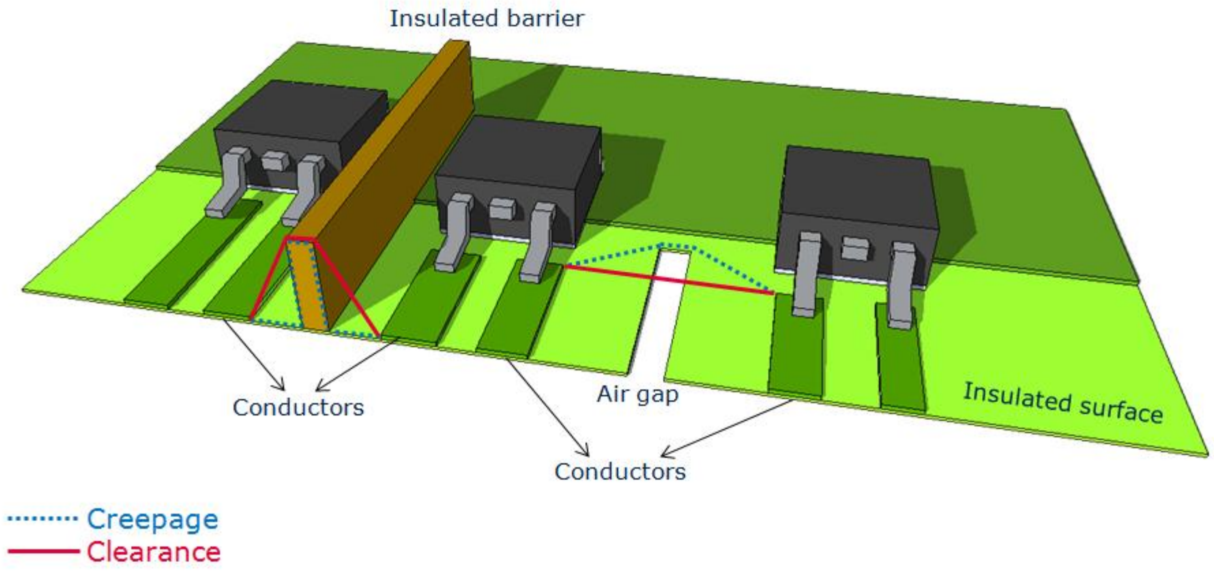

Fig. 3.1: Definition of creepage and clearance

3.1 Creepage

Creepage distance is defined as the shortest path between two conductive materials measured along the surface of an isolator which is in between. Maintaining a certain creepage distance addresses the risk of tracking failures over lifetime. The generation of a conductive path along the isolator surface due to the high voltage applied over long time is more related to the RMS value and depends on environmental conditions, which are described by a pollution degree and the material characteristics of the isolator (see CTI Comparative Tracking Index).

To determine the creepage distance the following parameters have to be considered:

- Working voltage
- Pollution degree
- Type of isolation
- Tracking resistance of isolation materials (CTI value)
- Circuit type (primary circuit, etc.)

It has to be noted that breakdown of the creepage distance is a slow phenomenon determined by dc or rms voltage rather than peak events or transients. Inadequate creepage spacings may last for days, weeks or even months before they fail.

3.2 Clearance

Clearance distance describes the shortest distance between two conductive materials measured through air. Sufficient clearance distance prevents an ionisation of the air gap and a subsequent flashover. Similar to creepage distance the pollution degree, temperature and relative humidity influence the tendency for a breakdown. Breakdown along a clearance path is a fast phenomenon where damage can be caused by a very short duration impulse. Therefore, it is the maximum peak voltage, including transients, that is to be used to determine the required clearance spacing

To determine the clearance distance the following parameters have to be considered:

- Working voltage
- Supply voltage
- Overvoltage category and allowable transients
- Pollution degree
- Type of isolation
- Installation altitude[2]
- Periodical transients in primary circuits

Clearances shall be dimensioned that overvoltage transients which may enter the equipment and peak voltages which may be generated within the equipment do not break down the clearance.

3.3 Comparative tracking Index CTI

The Comparative Tracking Index or CTI is used to measure the electrical breakdown (tracking) properties of an insulating material. Comparative tracking index is expressed as that voltage which causes tracking after 50 drops of 0.1 percent ammonium chloride solution have fallen on the material. The results of testing the nominal 3 mm thickness are considered representative of the materials performance in any thickness (according to IEC60112).

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[2] Standards use 2000 m as max. installation altitude. If installations are higher than 2000 m a correction factor depending on altitude has to be considered.

Material Group I	600 ≤ CTI
Material Group II	400 ≤ CTI < 600
Material Group IIIa	175 ≤ CTI < 400
Material Group IIIb	100 ≤ CTI < 175

Typically, mold compounds for discrete semiconductor packages belong to material group II (400-600V). For specific products or packages please contact local Infineon sales, marketing or application engineering.

3.4 Pollution degree

Pollution degree is divided into four categories:

- Pollution degree 1: No pollution or only dry. The pollution has no influence (example: sealed or potted products)
- Pollution degree 2: Normally only nonconductive pollution occurs. Occasionally a temporary conductivity caused by condensation must be expected (example: product used in typical office environment); Typical usage: office and household environment
- Pollution degree 3: Conductive pollution occurs, or dry, nonconductive pollution occurs that becomes conductive due to expected condensation (example: products used in heavy industrial environments that are typically exposed to pollution such as dust). Typical usage: industrial environment.
- Pollution degree 4: Pollution generates persistent conductivity caused, for instance, by conductive dust or by rain or snow

Steps can be taken to control the pollution degree by design features or the consideration of the operating characteristics of the product.

- Pollution degree 1 can be achieved by encapsulation or hermetic sealing of the product.
- Pollution degree 2 can be achieved by reducing possibilities of condensation or high humidity through the provision of ventilation or the continuous application of heat (use of heaters or continuous energizing). Continuous energizing is considered to exist when the equipment is operated without interruption or when interrupted do not allow cooling to the point where condensation to occur.
- Pollution degree 3 can be achieved by the use of appropriate enclosures which act to exclude or reduce environmental influences, particularly moisture in the form of water droplets.

3.5 Protection with isolation

The general requirements are that a single level of insulation is acceptable if the circuit is not accessible, but wherever there are accessible components, they must be insulated from hazardous voltages by a double-level system, and each level must meet the insulation specifications appropriate to the application.

Five categories of insulation can be defined

- **Functional insulation (F)** is that which is only necessary for circuit operation. It is assumed to provide no safety protection.
- **Basic insulation (B)** provides basic protection against electric shock with a single level; however this category does not have a minimum thickness specification for solid insulation and is assumed to

be subject to pinholes. Safety is provided by a second level of protection such as supplementary insulation or protective earthing.

- **Supplementary insulation (S)** is normally used in conjunction with basic insulation to provide a second level of protection in the event that the basic level fails. A single layer of insulating material must have a minimum thickness of 0.4 mm to be considered as supplementary insulation.
- **Double insulation (D)** is a two-level system, usually consisting of basic insulation plus supplementary insulation.
- **Reinforced insulation (R)** is a single-insulation system equivalent to double insulation. It also requires a minimum thickness of 0.4 mm for use in a single layer (according to UL60950/EN60950).

Solid insulation material in sheet form must conform to the following thickness requirements:

- If a single layer of insulation is provided, the min. thickness is 0.4 mm
- With two sheets together, there is no thickness requirement but each sheet must meet the required electrical strength value
- With three or more sheets there is also no minimal thickness but every combination of two sheets must have adequate electric strength
- There is no thickness requirement for functional or basic isolation

3.6 PCB spacing requirements

A proper clearance and creepage distance between PCB traces is critical to avoid flashover or tracking between electrical conductors. As listed in chapter 2 there is a variety of safety standards that prescribe different spacing requirements depending on the voltage, application and other factors. When a product has to be recognized by a certain safety agency, specific insulation requirements have to be met. For example, for mains-powered or battery-powered information technology equipment, the minimum allowed PCB spacing should be determined from EN/UL 60950-1. This standard specifies creepage and clearance distance for various grades of insulation depending on working voltage, pollution degree, PCB material group and coating. The required grade of insulation depends on the location of the circuits. The standard specifies functional, basic, supplementary, double and reinforced insulations. For example, when a breakdown of insulation can create a hazardous voltage on user accessible conductive parts (such as in case of insulation between mains circuits and low-voltage secondary circuits), a double or reinforced insulation is required.

The distances provided in EN/UL 60950-1 exceed the spacing necessary for proper operation of circuits (functional isolation). This was done in order to provide increased protection against electric shock. For the circuits whose locations do not require electric shock protection, spacing between printed circuit tracks can be made smaller. For the so called functional insulation, EN/UL 60950-1 permits to use distances which are smaller. They just have to withstand the electric strength test (HiPot). The test voltage varies depending on the working voltage and generally is several times greater than actual working voltage between separated traces.

Besides safety standards also IPC standards can be used as a guideline (Association Connecting Electronics Industries, organization whose aim is to standardize the assembly and production requirements of electronic equipment and assemblies). Note that generally all IPC documents are voluntarily rather than mandatory.

The following standards can be applied:

- IPC- 2221 Generic Standard on Printed Board Design
- IPC 9592 Performance Parameters for Power Conversion Devices

If there is no legal requirement to meet UL/EN standards, IPC-2221A or IPC-9592 distance recommendations can be used as a guideline. E.g.: the new IPC-9592 standard for power conversion circuits provides linear functional spacing requirements: creepage (mm) = 0.6+Vpeak×0.005. However, where shortage of space on a PCB is an issue, a smaller spacing may be chosen, provided it still withstands the test voltage.

3.7 Class categories

The process of defining insulation starts with identifying each circuit block with the system according to SELV (safety extra low voltage, nonhazardous circuits are classified as SELV), ELV, hazardous, etc. With this knowledge the appropriate insulation type and number of levels can be defined for use between blocks and between internal components and the user.

According to IEC60064, categories are used to define different classes of circuits and the type of insulation needed for each, as:

- **Class 0 equipment:** These appliances have no protective-earth connection and feature only a single level of insulation and were intended for use in dry areas. A single fault could cause an electric shock or other dangerous occurrence. Sale of these items has been banned in most EU countries.
- **Class 01 equipment**: Similar to Class 0, but appliance has an earth terminal which is unused since two core cable is used
- **Class I equipment:** Systems which use protective earthing (e.g.: grounded metal enclosure) as one level of insulation and thus require only basic insulation between the enclosure and any part of hazardous voltage
- **Class II equipment:** Use of double or reinforced insulation to eliminate the need for a grounded metal enclosure as well as a grounded power plug
- **Class III equipment:** Powered from SELV source and with no potential for generation of hazardous voltages internally, and therefore only requiring functional insulation.

4 Good design practices to achieve high electrical safety

4.1 Regulatory safety standards in design environments at system level

Before to read this chapter, please be aware, that this does not imply, neither claims in any way and form that INFINEON Technologies components are approved for these standards. Equipment and systems manufacturers must have their equipments/systems approved by the respective general and/or specific safety regulatory standards. Infineon’s intention is simply to interpret the standards to show possible compliance and to show good design practices to improve systems in respects to safety and to regulatory standards. This does not mean that INFINEON technologies, in any shape or form, takes any warranty, responsibility or liability for equipment level standards or approvals related to the mentioned Infineon Technology devices.

4.1.1 Spacings

Spacings through air (clearance distances), over surfaces (creepage distances) and through insulator (isolation distances) between an electrically isolated semiconductor device and its surroundings are important definitions (and requirements) in the matter of electrical safety and voltage isolation. Any international standard has its own definitions to specify the terms “spacings”, but in general these definitions can be divided into two simple categories:

a) between uninsulated live parts of opposite polarity

This includes spacing between terminals, adjacent components, connectors, bare wires, etc…

b) between uninsulated live parts and any other uninsulated metal parts

This includes spacing between terminals and heatsink, chassis, metal boxes, cabinet, etc…

The main intention of this chapter is to describe how to improve creepage and clearance isolation distances in real applications at system level, using practical examples of assembled electrical equipments.

4.1.2 Example of increased spacings between uninsulated live parts of opposite polarity (and adjacent components)

The most common example to start with is on how to increase the spacings between uninsulated live parts of opposite polarity. This could be a typical case of a TO-263 (D2PAK) soldered on PCB or IMS board. A TO-263 is soldered on a Printed Circuit Board (PCB) and two external components (i.e. MELF resistors in this case, as shown in Fig. 4.1) are placed nearby the power device. In case of presence of high voltage and harsh environment such distances (red arrows shown in Fig.4.1) are not enough to fulfil most of the relevant standard for the electrical equipment. Therefore, a simple way to overcome this problem is to protect the TO-263 providing a high temperature silicone potting directly on the device terminations in order to cover it completely. Automatically, this measure will improve the electrical safety increasing the “spacings” of the TO-263 terminations offering a higher pollution degree level at the same time and the clearances between termination and adjacent component.

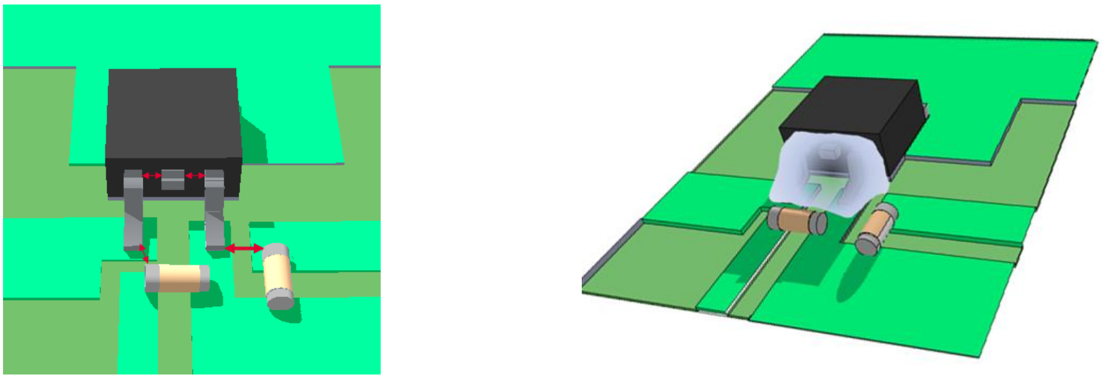
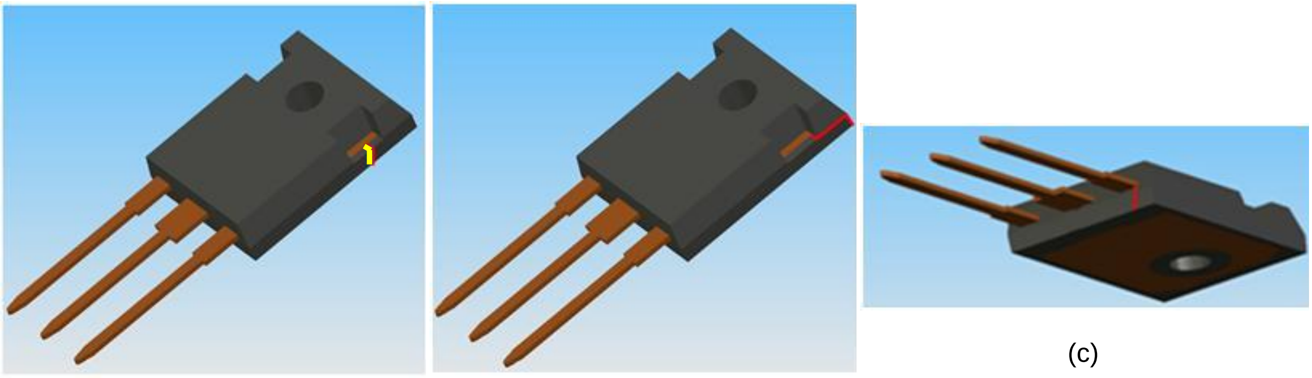


Fig. 4.1: Example of a TO-263 soldered on PCB and very close to other two components (MELF resistors). left side: spacing between terminations and between terminations and adjacent component. right side: solution to increase spacings, using high temperature silicone potting over TO-263 terminations.

4.1.3 Example of increased spacing isolation between uninsulated live parts and other uninsulated metal parts (e.g. heatsink)

The other most common example that can be found in practical applications is the isolation coordination of discrete THD (through-hole-devices) components (for example, in this case a TO-247-3) toward a heatsink or metal enclosures. This example (shown in Fig. 4.2 and Fig. 4.3) shows how to increase isolation distances when using a TO-247-3 soldered on a PCB and screwed on a heatsink.

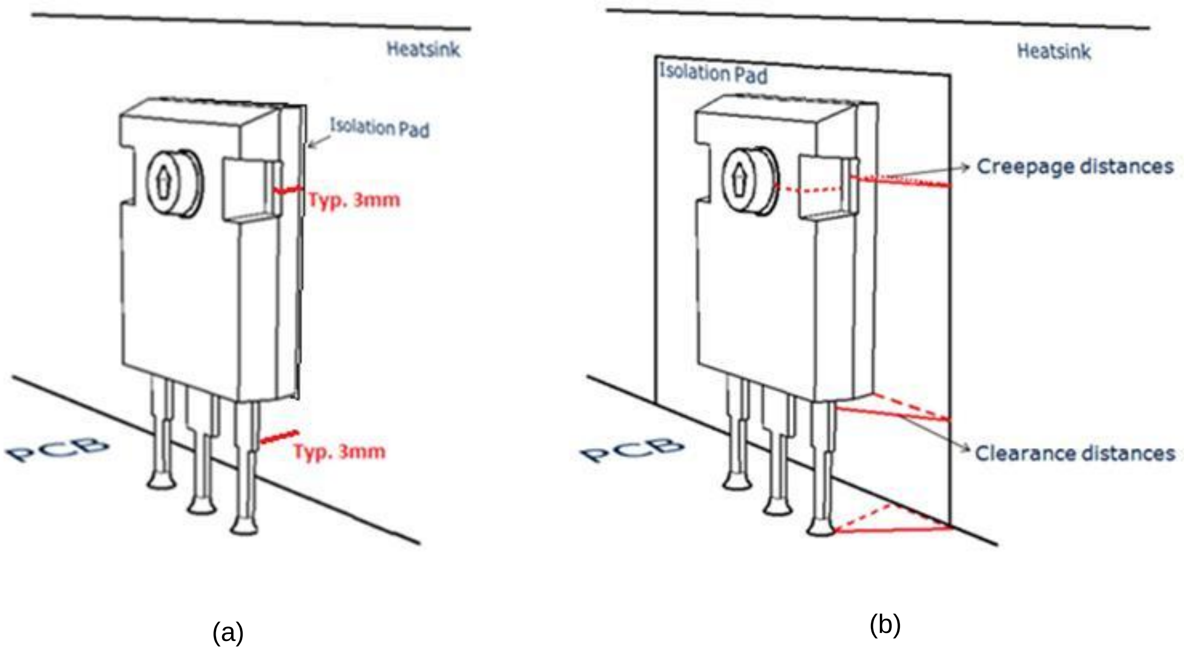
Fig. 4.2 shows the minimum isolation distances for a TO-247-3 package to be taken under consideration during the electrical safety design and isolation coordination. The distance between top side leadframe exposed tab (Fig. 4.2 a) and heatsink is about 3 mm in the lateral direction and about 6 mm (Fig. 4.2 b) in the upper direction. The minimum distance between terminations and heatsink (Fig. 4.2 c) is about 3 mm. Increasing this spacing is mandatory in several cases in order to comply with specific international standards which require high safety isolation level.



(a) (b) (c)

Fig. 4.2: Minimum creepage (and clearance) paths toward heatsink on a standard TO-247-3. (a) minimum creepage distance from top side exposed leadframe and heatsink: ~3 mm in the lower direction. (b) minimum creepage distance from top side exposed leadframe and heatsink: ~ 6 mm in the upper direction. (c) minimum creepage and clearance distance from terminations and heatsink: ~3 mm in the lower direction

In the following Fig. 4.3 a typical assembly configuration for a TO-247-3 is shown with isolation foil ensuring electrical isolation between collector/cathode/drain and heatsink. As shown in Fig. 4.3.b, by extending the isolation foil size both clearance (red continuous lines) and creepage distances (red dashed lines) can be increased to achieve the minimum value in compliance with the related standard. It should also be considered that due to the presence of the metal screw the heatsink potential can be present also on top of the device creating a possible further creepage path between the screw and the exposed leadframe. This high potential on the top side of the device is also present when using a clip to connect the heatsink to the component top surface.



(a) (b)

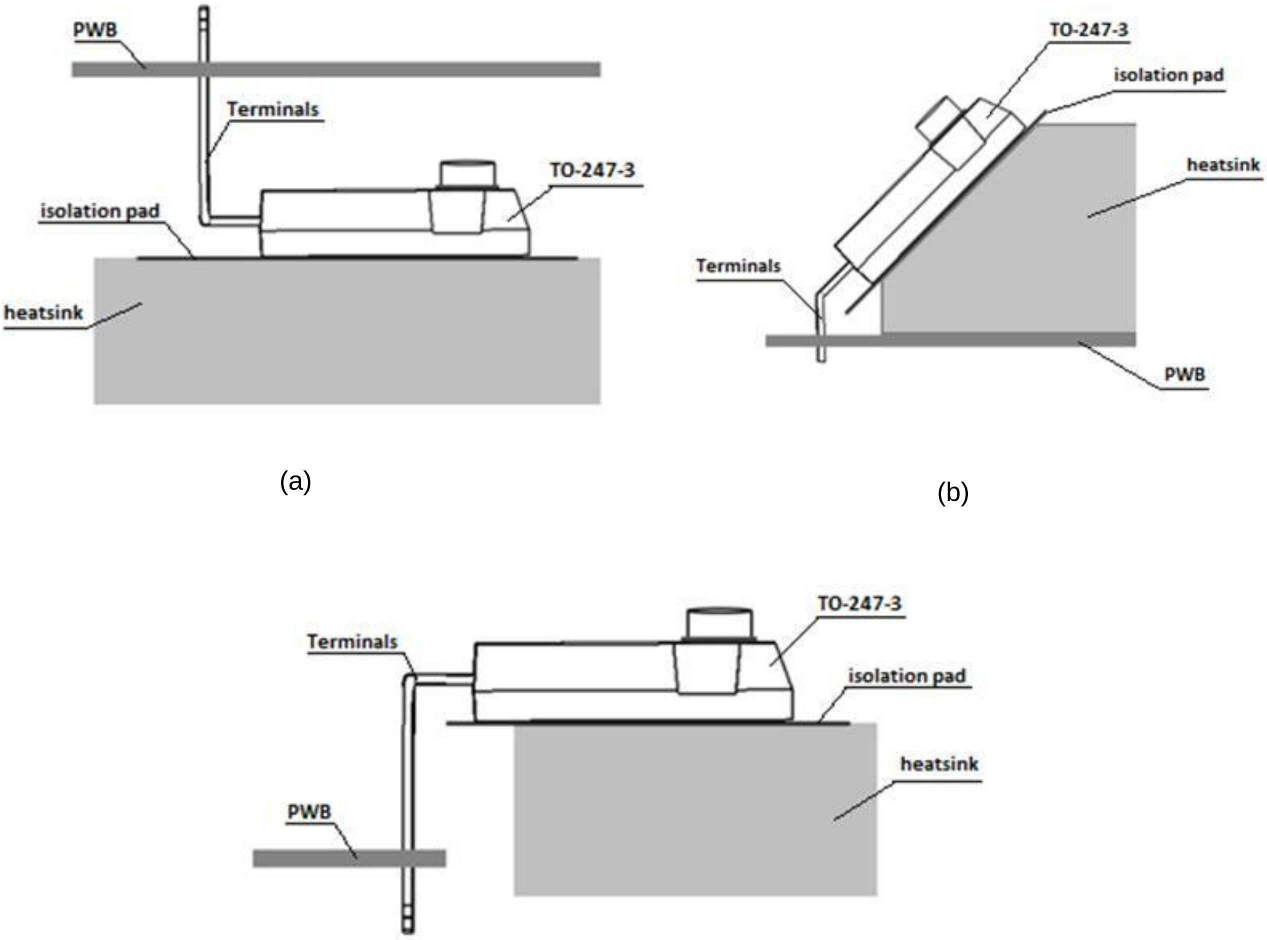
Fig. 4.3: How to increase the clearance and creepage distance between discrete components and heatsink. (a) typical isolation distance of ~ 3 mm, when using an isofoil having same dimensions of TO247-3 backside. (b) extending the isolation pad size the same isolation distances can be increased to comply with the required standard

4.1.4 Impact of bending terminals on isolation toward heatsink

In case of horizontal mounting (or with a different angle) of THD devices with respect to the PCB the terminals have to be bent (Fig. 4.4). Normally, terminals are bent in the upper direction (Fig. 4.4 a), because the heatsink is often of large dimensions and it is mechanically fixed to the chassis. This happens quite often in solar and UPS applications, where there is the need of very efficient and large heatsinks. In this case, there are no special restrictions if the assembly is performed following the indications of Fig. 4.4 a, extending the isolation pad size over the knee of the terminals.

Sometimes (i.e. in case that the heatsink is made of casting aluminium or because of different shapes of the chassis), the terminals have to be bent with an angle of about 45°- 60° (as shown in Fig. 4.4 b). In this case, it is suggested to shape the heatsink and the isolation foil as indicated in Fig. 4.4 b, which increases spacings (sometimes the isolation foil can be also further extended up to the solder joint).

Fig. 4.4 shows the “worst case” situation when the terminals have to be bent in the lower direction, (offering a shorter clearance and creepage distance toward the heatsink/chassis). It is suggested here to cut the heatsink as shown in Fig. 4.4 c, just after few millimetres after the edge of the copper leadframe on the device backside. This assures a good thermal dissipation and at the same time it will increase the distance between terminals and heatsink.



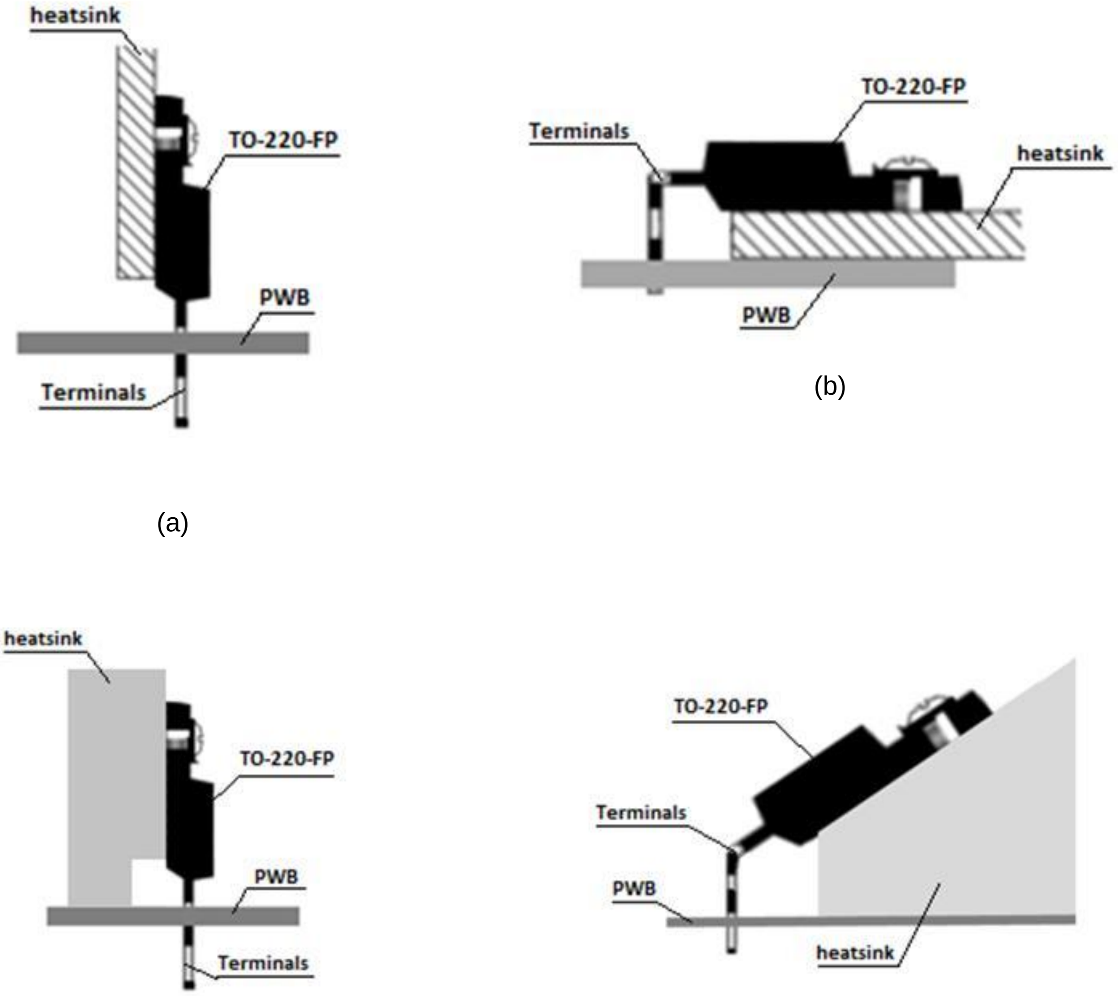
(a)

(b)

(c)

Fig. 4.4: Example of mounting a TO-247-3 with different bending of terminals and different heatsinks. (a) terminals bent in upper direction (normal mounting for high power equipments and large heatsinks). (b) terminals bent with 45° angle. (c) terminals bent in lower direction

Similar situation can happen with fully isolated devices (e.g.: TO-220 FullPAK, TO-220FP). In this case more attention should be paid on the assembly, since there is no isolation pad anymore, which could increase the “spacings”. In this case the heatsink itself, which should be pulled back from edge of the TO-220FP as shown in Fig. 4.5 a and Fig. 4.5 b. In Fig. 4.5 c and Fig. 4.5 d different embodiments, where the heatsink is shaped in a proper way to increase as much as possible the distances between terminals and heatsink are shown.



(a)

(b)

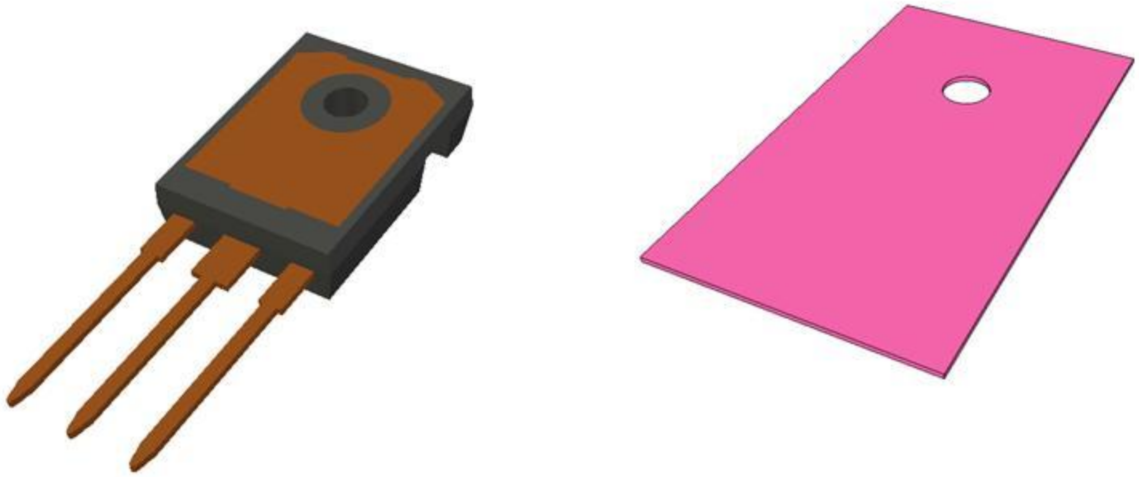
(c)

(d)

Fig. 4.5: Example of mounting a TO-220 FullPAK with different bending of terminals and different heatsinks. (a) Straight Terminal, with Heatsink raised from PCB. (b) Terminals bent in lower direction. (c) Straight terminals with step shaped heatsink to increase the spacings (d) Terminals with 45° angle bending

4.1.5 Thermal interface materials and isolation foils

In electrical topologies, where isolation to the heatsink is needed (e.g.: DC/DC converters, two and three level inverters, active rectifiers, PFC…), normally isolation foils are used. This isolation material (Fig. 4.6 b) must also provide good thermal behaviour in order to allow adequate power dissipation. As shown in previous sections the assembly methods play an essential role concerning electrical safety and isolation coordination. Indeed, heatsinks are generically connected to the ground earth (PE) for safety reasons and for EM interference.



(a)

(b)

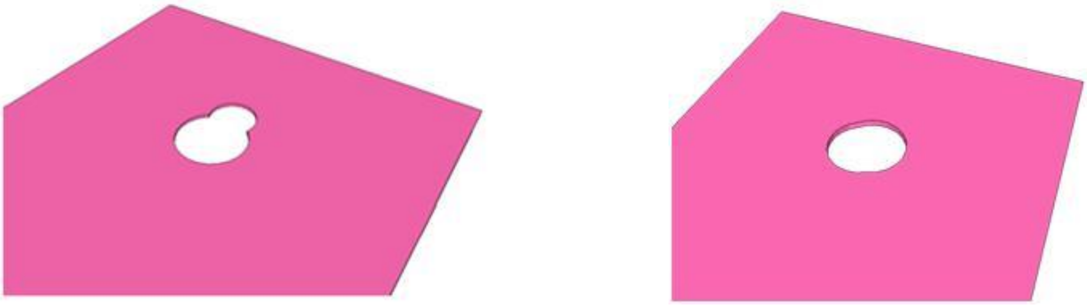
Fig. 4.6: (a) TO-247-3 seen from the rear side and, (b) related isolation foil already preformed and provided with hole for mechanical fixing.

Most commonly used isolation materials are listed in the Table 4.1. The intention of the table is not to give the complete list of possible materials, but rather to offer a general overview with emphasis on the isolation levels. Normally, silicone based sheets reinforced with fiber glass or polyimide composites are preferred, especially in standard household and industrial applications. In special cases, when a higher isolation level is demanded for the application, or a higher reliability level is required, or even a special EMI compatibility is needed, an inorganic insulator can be used. From electrical safety point of view, these materials could offer higher dielectric strength capability, good thermal performance and very low hygroscopic level, but as a drawback they can be cracked, if not correctly applied and usually they have a higher cost. Lately, especially where thermal performances are challenging, some special phase change material with embedded isofoil can be also found.

Table 4.1 Overview of interface materials

Isolation materials and assembly methods	Material examples	Features	THD	SMD
Electrically insulating organic based reinforced materials	Silicon based fiber glass reinforced materials Silicon based polyimide reinforced materials	Most commonly used Average thermal performance Easy to mount Relatively low BV	✓	
Electrically insulating phase change materials		Rarely used High thermal performance Complex mounting Relatively low BV	✓	
Inorganic insulator sheets	AIN, Al2O3, BeO, Si3N4 foils, Mica sheets	Rarely used High thermal performance Critical mounting High BV	✓	
PCB, high performance PCB and substrates	MLFR4, IMS boards, TF, UTTF, LTTC, DCB, DAB, AMB substrates	Rarely used High thermal performance Complex mounting High BV		✓
Gap filler materials	Thermally conductive foams or liquid fillers	Commonly used Low thermal performance Complex mounting Low BV	✓	✓

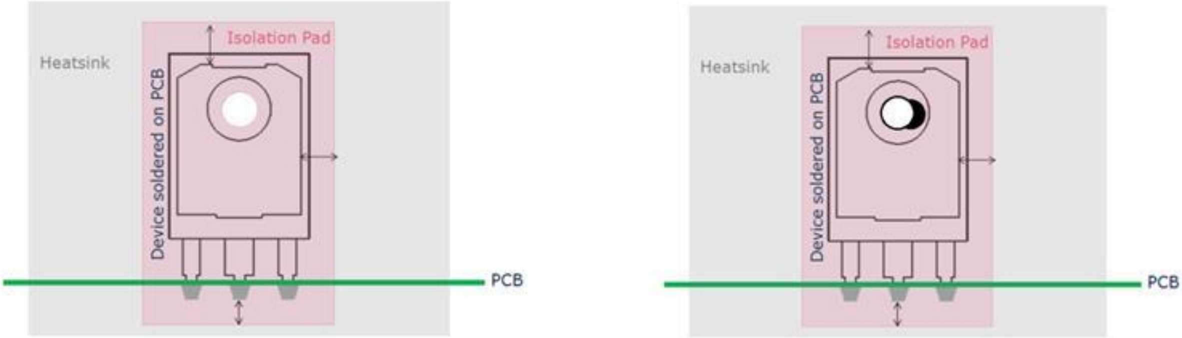
In terms of electrical safety and isolation, it is extremely important to take care about correct pre-shaping and mounting of the isolation foil. Indeed, during pre-shaping (sometime also during assembly), the fixing hole of the isolation pad can be deformed (e.g. it can show a double circle caused by incorrect screwing, or a bad pre-shaping (Fig. 4.7a) or an oval deformation (Fig. 4.7b). Unfortunately, in both cases the isolation between backside tab and heatsink is affected, causing possible short circuit or lateral flashovers. It is suggested to use high quality material (materials listed in Table 4.1), which does not break or crack easily, since this would immediately lead to equipment failure.



(a) (b)

Fig. 4.7: (a) Isolation foil with wrong pre-forming, and (b) isolation foil with deformation of fixing hole

As shown in the Fig. 4.8 the hole in the isolation foil should have the same external diameter of the isolation bushing (or the same measure of the screw, when using plastic, teflon or in general isolated screws), even better if few hundred µm smaller. As shown in Fig. 4.8b a deformation or a simple de-centering of the two holes may lead to uncovered areas and to a reduced creepage distance with increased possibility of arching and flashover.



(a) (b)

Fig. 4.8: Transparency view from the heatsink side of a TO-247-3 assembly (without screw). (a) example of good pre-forming of an isolation foil for a TO-247-3. (b) wrong pre-forming of isolation foil (de-centering of the hole of the isolation in respect to the TO-247 hole, which left uncovered area and leads to reduced creeepage distances.

Other important thermal interface materials, which could impact the electrical safety are gap fillers, which allow heat removal also from the top side of the devices. Here, the same rule applies as described in the previous chapters. Especially, in case of a heatsink or metal enclosures connected to ground earth, these new creepage paths via gap fillers material must be carefully considered.

A special category of materials, which allow SMD isolation from heatsinks and enclosures, are the substrate materials. Typical substrates are: DBC (Direct Bonding Copper), DAB (Direct Aluminium Bonding), TF (Thin Thick Film), IMS (Inter Metallic Substrate) or AMB (Active Metal Brazing) substrates. In general these materials offer a superior reliability, especially if based on inorganic materials (such as ceramics, minerals and glasses). Adequate care should be taken during assembly to avoid cracks. Recently, also IMS, especially the most recent solution for high voltage application, achieved important reliability level, even comparable with ceramic for isolation voltages below 2kV rms per 1min.

4.2 Impact of assembly methods on electrical safety and isolation

In this section, different methods with which discrete devices are assembled into the equipment and the ways how these assembly methods impact the electrical safety and the isolation of the equipment will be shown.

In order to be more consistent and to exemplify the description of these methods, the assembly solutions will be divided and rearranged into three major categories:

1. Screw mounting assembly methods.
2. Clip mounting solutions. (Single/Common clip mounting, self-clip heatsink mounting).
3. Solderable devices (SMD devices soldered on IMS, PCB or other substrates).

4.2.1 Screw mounting

The most common way to fix a THD discrete device on a heatsink is to use a screw. In general, there are two different ways of assembly of the discrete components:

1. assembly on “common/grounded” heatsinks
2. assembly on “floating” heatsinks

4.2.1.1 Assembly of discrete devices on “floating” heatsink

This is the case of un-insulated heatsink applications. Typically, this happens in all single ended transistor applications. Here, it is demanded to the external equipment enclosures to provide a double or reinforced isolation level: defined as Class II. In this case, the device is usually mounted simply using a thermal interface material having good thermal properties, but not intended as insulation barrier.

This is usually performed using a very thin layer of silicon, oil based thermal grease (commonly filled with Al_2O_3, ZnO, AlN… and the like), a very thin high thermal conductivity foil, or a phase change material. It should be considered that even if these materials usually offer a high ohmic resistance, the resistance values and the extremely thin layers adopted, do not assure any sufficient isolation level, neither any physical protection against electrocution in case of touching the heatsink. In this case, it is always recommended to emphasize the potential presence of hazardous high voltages on the heatsink, as recommended by international standards.

In any case, even if not required from the specific regulatory requirements, since human life is involved, it is strongly recommended as a good electrical design safety practice to adequately isolate the heatsink from the external chassis/cabinets through external isolation spacers and to make it inaccessible through external isolation barriers, even if the equipment could be labelled as Class 0. Furthermore, consider that in this case, the spacing between heatsink and Gate/Emitter terminals should be considered not only because of the specific requirements, but also to avoid electric arching and flashovers, which may happen especially in case the equipment operates in harsh environments.

4.2.1.2 Common/grounded heatsink

This is the case of an isolated heatsink. Here, special emphasis is placed on the isolation between the discrete component and the heatsink. An exploded cross section of a correct TO-220 assembly on a horizontal heatsink is shown in Fig. 4.9.

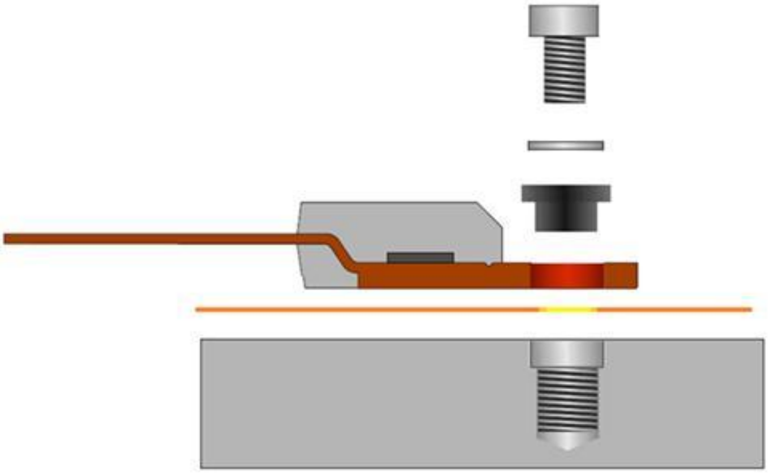


Fig. 4.9: Example of correct assembly of a TO-220 screwed on a heatsink via threatened blind hole

In this case the heatsink is usually safely connected to the ground earth as a good design practice. The electrical safety is demanded both: to the isolation foil and to the ground Fault Circuit Interrupter (GFCI) with which the equipment must be provided according to the General IEC 61140 safety regulatory standards. Furthermore, in some few special cases (not allowed in the EU), simple Class 0 or Class 01 applies. Also here, even if not required by the specific regulations, it is always strongly recommended as a good electrical safety design practice to adequately isolate the heatsink from the external chassis/cabinets through external isolation spacers and to make it inaccessible through external isolation barriers. Here, the whole electrical safety is then demanded to the chosen isolation foil/pad. Therefore, this is one of the most critical assemblies in regards to the electrical safety and therefore particular care must be taken to preserve a good safety margin.

In some special cases it is warmly recommended to use thick and reliable inorganic material isolation sheets (such as Al2O3, AlN or Mica derivatives) or thick silicone based imide reinforced thermally conductive isolation foils. At the same time, it is suggested to use correct bushing elements, which have good isolation and mechanical properties to work as washer at same time. (Indeed, please consider that adding large external metal steel, zinc-Iron or brass washers would reduce the clearance distances as for example already illustrated by Fig. 4.3b).

These measures may be suggested in general cases (also for Class I and Class II equipments), where there is presence of voltage levels above 1 kV, very harsh environments, high ambient temperatures, polluted and hygroscopic environment. Indeed, water absorption at temperature above 80°C in combination with pollution particles (especially conductive ions) could reduce the maximum breakdown voltage and lead to possible flashovers.

In the particular case when using thin heatsinks having fixing through holes, a solution as shown in Fig. 4.10. could be suggested. In this closed-up cross section a TO-247-3 is screwed on a heatsink and in order to increase the internal creepage path (red arrow in Fig. 4.10) it is suggested to use from top side an isolated by-passing element and from the bottom side a further isolation pipe. Such isolation pipes should be made by special reinforced glass fiber plastics with limited coefficient of thermal expansion to prevent ageing (caused by wear and tear during temperature variation). Furthermore, special anti-screwing washers can be used to prevent the thermal ageing and avoid unwanted unscrewing, which leads to possible reduction of the mechanical pressure. In this case, the creepage can be further extended (up to several mm).

In case of blind holes, the embodiment shown in Fig. 4.9, which uses special isolated bushing elements, should be enough to prevent arching or flashover. In some special cases the length of this bushing elements can be further increased (it is easy to find these bushing elements available on the market with different sizes) to ensure higher electrical safety.

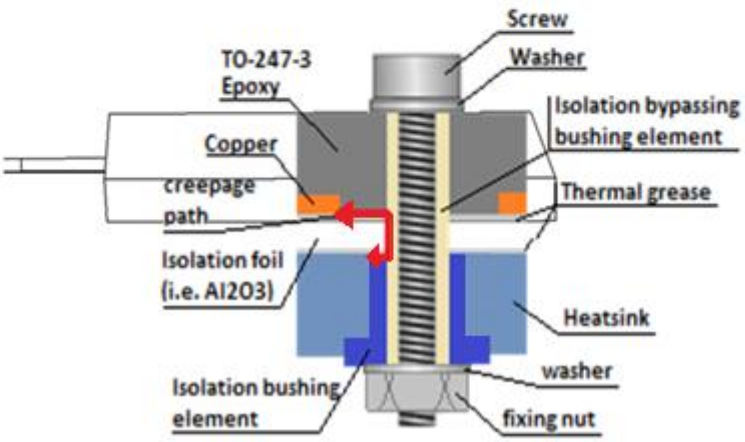


Fig. 4.10: Cross section of a special embodiment for a TO-247 assembly, typically used in presence of high voltage

Same design practices used for un-insulated devices apply to FullPAK solutions. Obviously, in this case the isolation foil is not needed any longer since the internal isolation is already offered by the plastic body. But, because of this reason, special attention is required to maintain an adequate electrical safety level. In this case the recommendations already illustrated in Fig. 4.5 are still valid. Further details can be observed in the Fig. 4.11c for the horizontal mounting.

It should also be considered that the whole isolation would be totally demanded to the TO-220 plastic body (no need to use isolation foil and, as already explained, the resistance offered by the necessary thin layer of thermal grease would not offer any safety isolation). Therefore, in this case, and especially when simply Class 0 or 01 isolation levels are required, it is warmly recommended to use redundant safety protection systems!

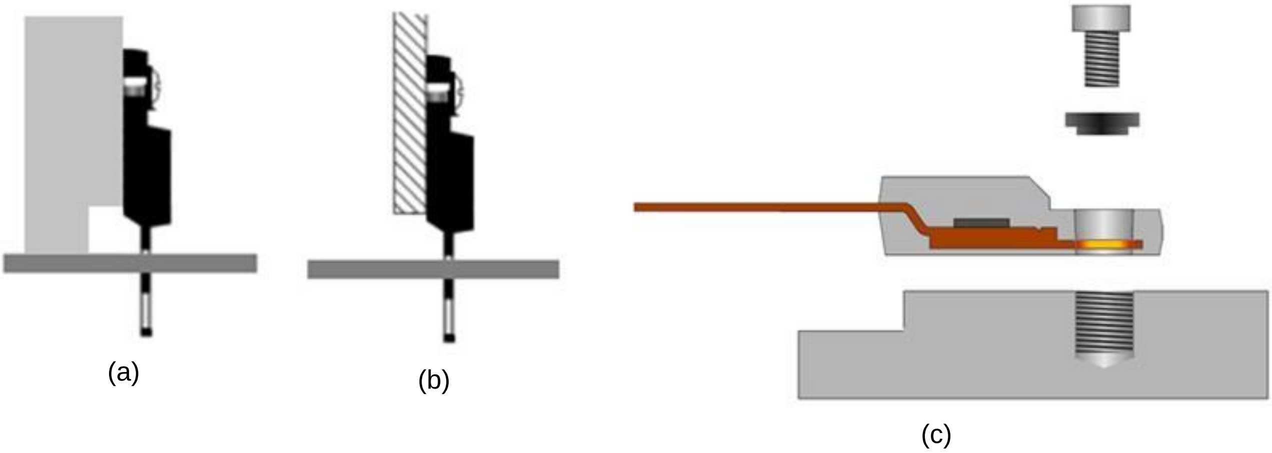


Fig. 4.11: Correct examples of assembly embodiments for a TO220 FullPAK (a) and (b) in vertical position and (c) in horizontal position

4.2.2 Clip mounting

The alternative method to assemble THD devices is to use clips. In general, clips can be screwed, engaged in the heatsink without screw, shared with other components (commonly known as bar clip) or could be simply integrated into the heatsink itself (self-clip heatsinks). All these solutions work similar in terms of isolation, creepage and clearance distances. Indeed, it should be considered that these clips may offer an electrical continuity with the heatsink and bring the same heatsink potential on top of the discrete device. Potential creepage and clearance path reductions must be taken into consideration to verify the compliance with respective demanded international standards. Fig. 4.12 shows a practical example of a clip assembly with possible creepage paths.

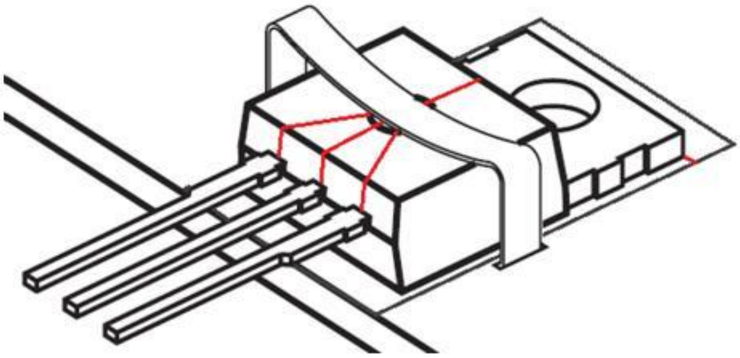


Fig. 4.12: Creepage paths (red lines) for a TO-220 using a simple clip mounting and a small isolation foil

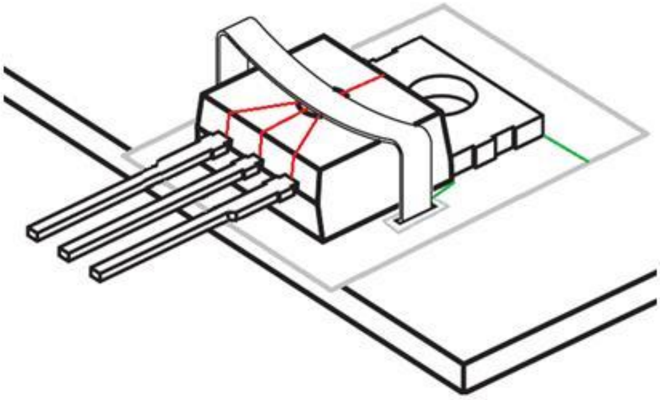


Fig. 4.13: Creepage paths (red lines) for a TO-220 using a simple clip mounting and a larger isolation foil. Green lines show increased creepage paths respect the ones in the previous Fig. 4.12

4.2.2.1 Single clip, multi-clip and common bar mounting solutions

Single clip mounting and even worse, common clip mounting could offer additional creepage paths for the high voltages. This must be considered especially in the designs which use "shared and common clips". For this reason some new solutions, using clips having isolated plastic body which goes in direct contact with the discrete device, are now available on the market Fig. 4.14b.

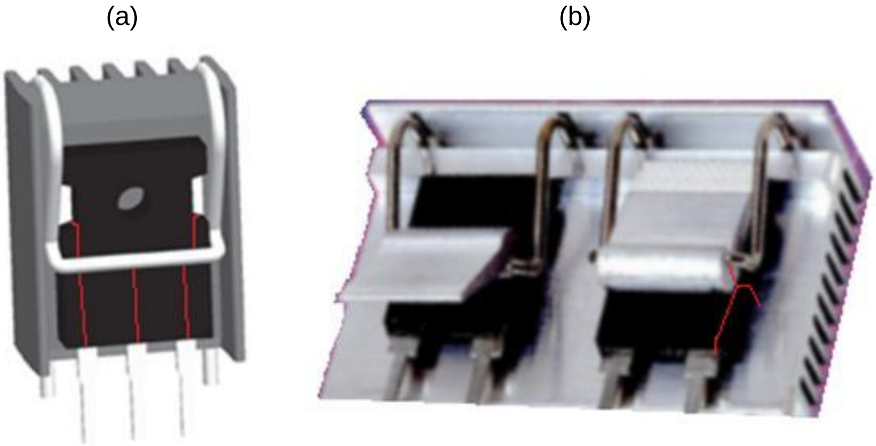


Fig. 4.14: Creepage paths for (a) single clip mounting, (b) isolated clip.

4.2.2.2 Self-clip heatsink mounting solutions

Even if not recommended, in some cases, for light load applications or for low power dissipation levels, self clipping heatsinks can also be used. In most cases, these heatsinks are kept at the same voltage level of the transistors drain/collector since no isofoil is necessary (Typically floating heatsink solutions). Therefore, in this case, it is warmly recommended to keep the creepage distances as specified in the previous sections; and if necessary, to provide a correct bending of the terminals. The clip brings the collector voltage on top of the discrete device and the epoxy of the package case itself works properly as an insulator. As previously specified, even if under the exception of three terminals discrete devices (which allow to reduce the isolation thicknesses if it is proven by the dielectric strength reliability vs. temperature as i.e. per UL746C), the isolation distance between top side of the package case and maximum height of the bonding loop (at emitter voltage level) is kept always higher than 0.4 mm, since some equipment standard requires a minimum of 0.4 mm through isolation per reinforced isolation. However, once mounted on a PCB, minimum external creepage and clearances must be met as per each specified individual equipment standard.

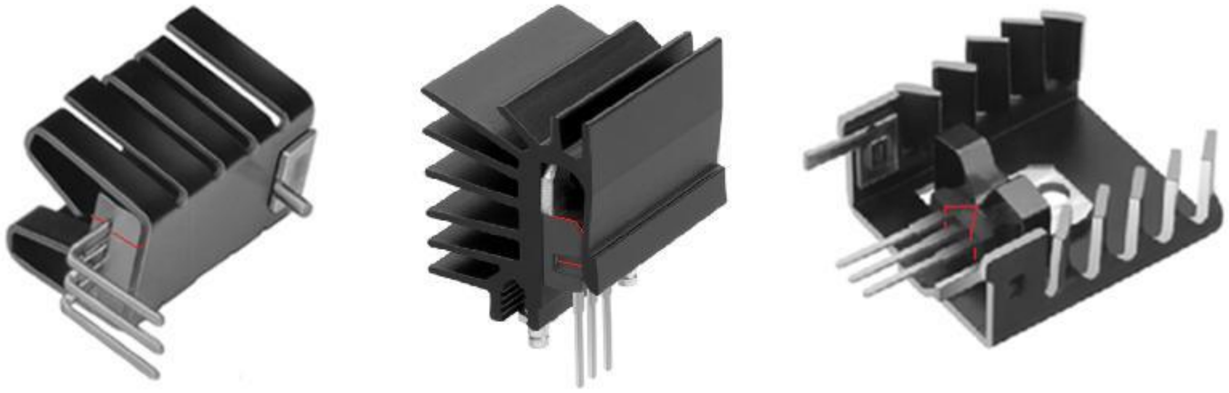


Fig. 4.15: Creepage paths for three different self-clip Heatsinks used in general for low power dissipation levels

4.3. Measures to extend creepage spacings: design “tips and tricks”

Further actions can be taken in order to increase/improve the electrical safety and isolation levels extending the creepage distances between the solder fillets at different voltage levels. This must be considered especially in harsh environments, which usually have to face with very conservative specific standards (examples: outdoor applications, applications having low external protection degree, dirty and polluted environments, high humidity or submarine applications…). ternational Standards.

Table **4.2** examples and recommendations are listed on how to increase the creepage spacings in order to achieve the required level demanded by International Standards.

Table 4.2: Examples on how to increase creepage spacings

Measures taken for creepage/clearance extension	Protection level	THD	SMD
External silicon potting on terminals	Component/system level	✓	✓
Silicon coating (“tropicalization”)	Component/system level		✓
External isolation with plastic covers or plastic ribs	Component level	✓	
External isolation with plastic sleeves on terminals	Component level	✓	
Special interleaved terminations soldering pads	System (PCB) level	✓	
External isolation foil from top side for clip mounting	Component level	✓	✓
Interleaved terminals and terminals pre-bending	Component level	✓	
Special grooves and holes in the PCB between terminals	System (PCB) level	✓	✓
Design examples for 2-layer PCB	System (PCB) level	✓	✓
Design example for 4-layer PCB	System (PCB) level	✓	✓

In the following sections measures to extend creepage and clearance spacings are explained.

4.2.3 External silicone potting on terminals

Adding external silicon potting on terminals is a common practice to provide an extension of the creepage distances and to improve the pollution degree. This solution could also work as external chemical protection and also as a possible mechanical containment and protection (especially for certain types of SMD components), in case of device explosions. High temperature silicon based compounds and epoxy, urethane and polyurethane derivatives are commonly used. Here it is also recommended to avoid any formation of cavities and voids during the deposition process, in order to prevent isolation problems.

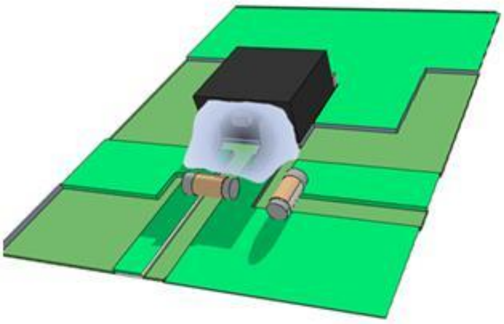


Fig. 4.16: Silicon potting to extend spacings and to improve the pollution degree

4.2.4 Silicone coatings (Tropicalization)

A thin layer of sprayable silicon coating is another typical countermeasure, which could be taken especially for SMD boards. In this case, the primary function is the chemical isolation against external polluted moisture or aggressive atmospheres (high content in salt, chlorides or sulphides) to avoid oxidations/corrosions and to extend component and system lifetime.

Here it should be considered that, because of the very thin layers of silicone used in this methods (typically between 100µm and 300µm), this measure in general is not sufficient to offer adequate safety isolation for voltage levels above a few hundred volts and for applications above 10 kW.

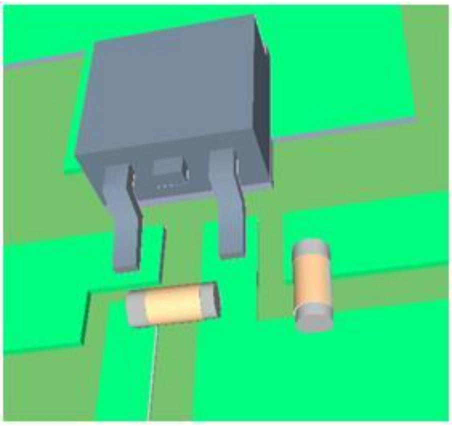


Fig. 4.17: Silicone coatings on TO-263.

4.2.5 External isolation with plastic covers

In case of very harsh and/or polluted environments (i.e. outdoor installations, equipment with low degree of protection, or in special environments like: welders, water pumps or solar converters) the creepage and clearances distances offered by discrete devices are usually insufficient.

Here also applying an external potting could be an insufficient or, at least, inadequate solution. Therefore, special plastic covers could be used in order to achieve the adequate degree of protection and to get a high electrical safety level, even under the worst environmental possible conditions. Furthermore, to protect adequately the terminals, such plastic covers can be also sealed using epoxy or silicone based glues applied on the plastic cover edges.

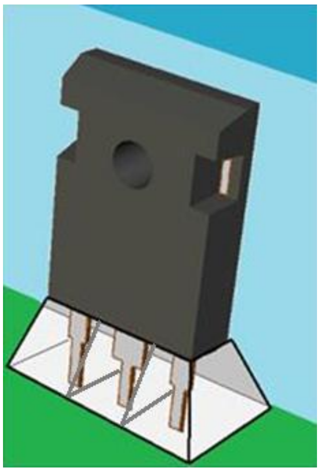


Fig. 4.18: TO-247-3 with plastic cover

4.2.6 External isolation with plastic sleeves on terminals

A cheap alternative to the above mentioned plastic covers are plastic sleeves and/or silicon pipes mounted on the device terminals. This solution is especially used in single ended low power applications in order to protect the two terminals (Gate/Base/Cathode and Emitter/Source/Anode) from the heatsink, which is usually exposed to the Collector/Drain voltage, but is less effective than the countermeasure described in the previous section.

Special care should be paid on avoiding exposed or uncovered areas over the terminals. Also here external glue can be applied to seal the terminals.

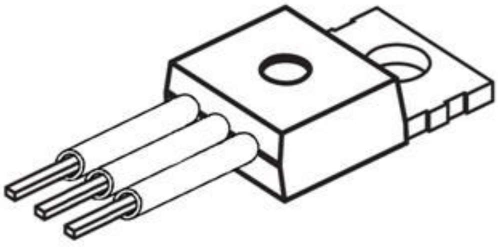


Fig. 4.19: TO-220 with plastic sleeves on terminals.

4.3.4. External isolation foil on top side for clip mounting solutions

Especially in industrial solutions international standards may require a further double (triple) isolation from top side of the discrete component to meet the isolation requirement between heatsink (or in certain cases clips electrically connected with the heatsink) and internal bonding wires of a discrete component (e.g. a TO-220 in Fig. 4.20).

Indeed, in industrial applications the height of the bonding loop into the epoxy insulator, (because of production tolerances) may exceed the minimum values accepted by international standards. Therefore, in order to comply with such standards the solution shown in Fig. 4.20 is recommended.

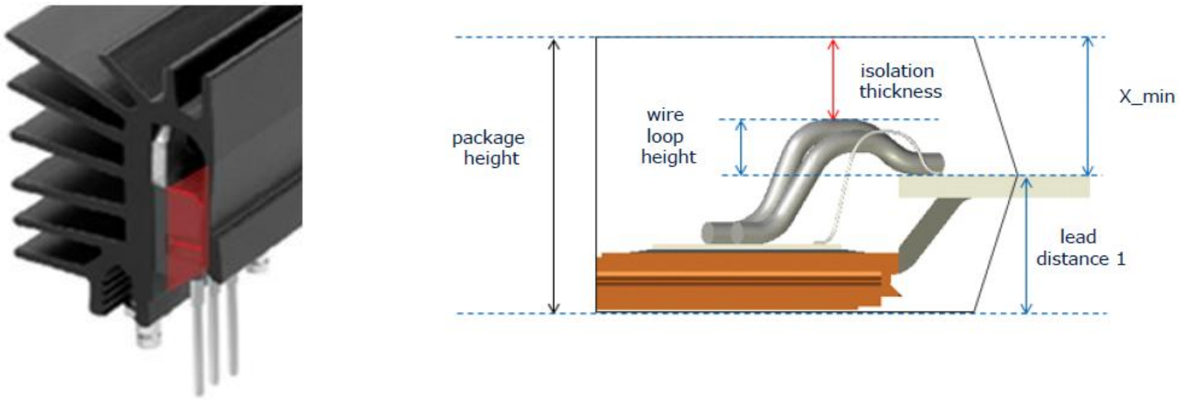


Fig. 4.20: TO-220 mounting with isolation foil on top

4.2.7 Special soldering termination pads

In order to increase creepage and clearance distances on soldering pad terminations special pad shapes can be used. Typical solution used for this purpose, especially for TO-220 devices, is to design pads with an elliptical shape instead of the standard circular shape.

Indeed, rectangular shapes should be avoided because of the electrical field edge effect on the pad corners, even if the creepage distance is higher than for circular or elliptical shapes (blue and yellow lines shown in Fig. 4.21 in comparison with red lines, which measure the distance of the circular shape). Another situation to avoid, when trying to increase the creepage distances, is to reduce the pad area too much, leaving part of the metallization pad uncovered (solution Q4 in Fig. 4.21).

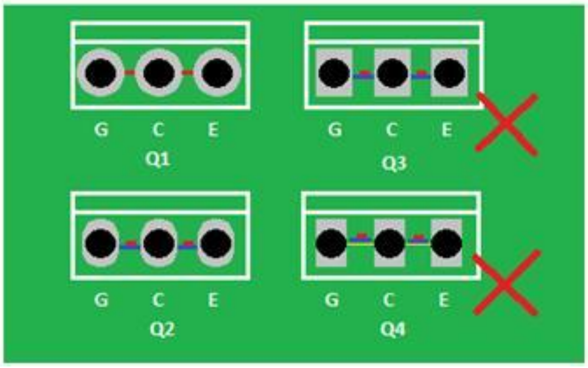


Fig. 4.21: Different geometries of soldering pads

4.2.8 Interleaved terminals and terminals pre-bending

If shaping soldering pad terminals is not sufficient, pre-bending terminations and interleaved spacing between terminations can be realized.

As an example Fig. 4.22 shows a TO-220-5 five lead package, which properly emphasizes this measure. Also here the suggested pad layouts should have a circular or ellipticall shape.

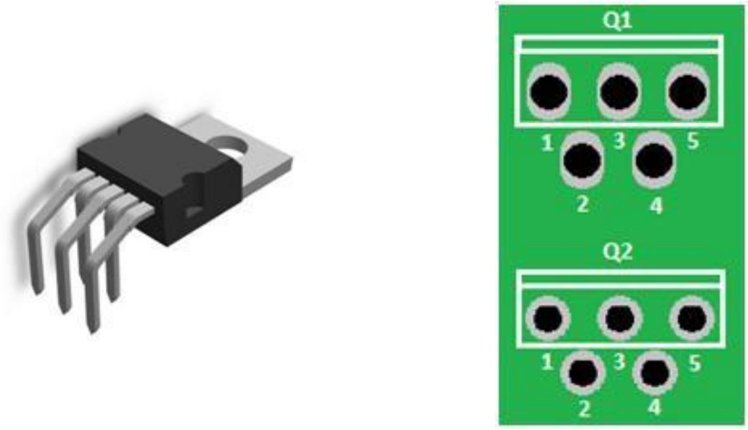


Fig. 4.22: TO-220-5 5 leads and suggested pad layouts

4.2.9 Special cuts/holes in the PCB between pins or terminations

A common practice to increase creepage paths is to introduce special cuts between terminals of different potential levels. When the device is placed on the PCB edge, lateral edge (easier to be realized and also cheaper) can be performed (example Q1 in Fig. 4.23). Alternatively, simple cuts with different geometries can also be provided (example Q3 and Q4 in Fig. 4.23).

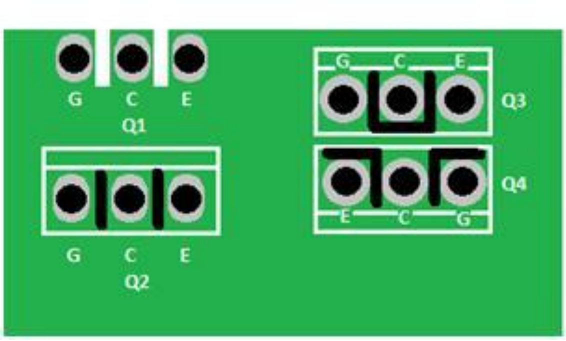


Fig. 4.23: Different cut geometries to increase creepages

4.2.10 Electrical safety designing a two layer PCB

Particular care in terms of electrical safety should be placed when designing a PCB. Besides all the suggestions in terms of PCB spacings, which go beyond the intention of this application note, here two important aspects in terms of electrical safety, which are usually under-estimated, are described.

The first to be discussed is the deposition of solder resist on top of the layers. Indeed, a simple solder resist deposition per gravity could lead to some imperfection reducing the thickness of the solder resist just in the corner edge of the PCB layers (especially for the thicker PCB layer above the 70 µm) exactly in the position, where there should be the need of more solder resist, as shown in Fig. 4.24b. Indeed an electrochemical deposition of solder resist can offer a very even deposition of the resist layer also on the corner edges, offering a higher degree of electrical safety (and also chemical protection) as shown in Fig. 4.24c.

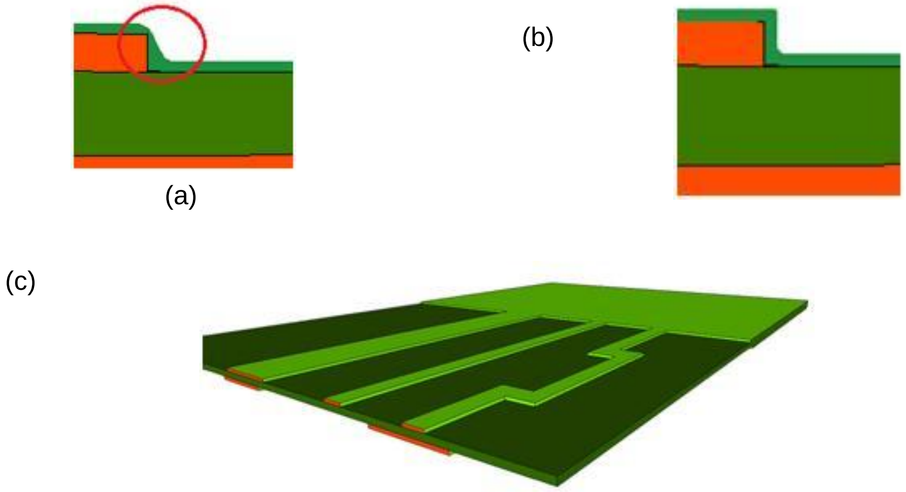


Fig. 4.24: Solder resist deposition on two layers PCB

4.2.11 Electrical Safety designing a four layer PCB

In this second case, the design of a 4-layer PCB is considered. 4-layer PCBs are quite common, especially in multilevel inverter topologies, where it is always suggested to arrange the different layers as shown in Fig. 4.25. The external layers in these converters are used as power layers for the positive and negative voltage rails (in this case the power to be dissipated externally is higher than what is possible in the inner layers, which are therefore used in parallel increasing the total copper size and reducing the losses and therefore the temperature which would have less possibility to be dissipated outside). Therefore, the inner layers are used both for the common or the neutral or the ground and the signals and low voltage power supplies.

In fact, practically a 4-layer PCB is made of two times two layers PCB “glued” using a special prepreg. Therefore, the isolation voltages offered by a thick FR4 (toward the external) are higher than the isolation capabilities offered by an internal prepreg. And at the same time, the parasitic coupling capacitances are also much lower than the one in the prepreg. Therefore, it is always suggested to keep the internal layers (separated just using few µm of prepreg) as common or ground layers which have a voltage drop not higher than 100V. Using higher voltage layers may be possible, but any overlap of inner layers must definitely be avoided.

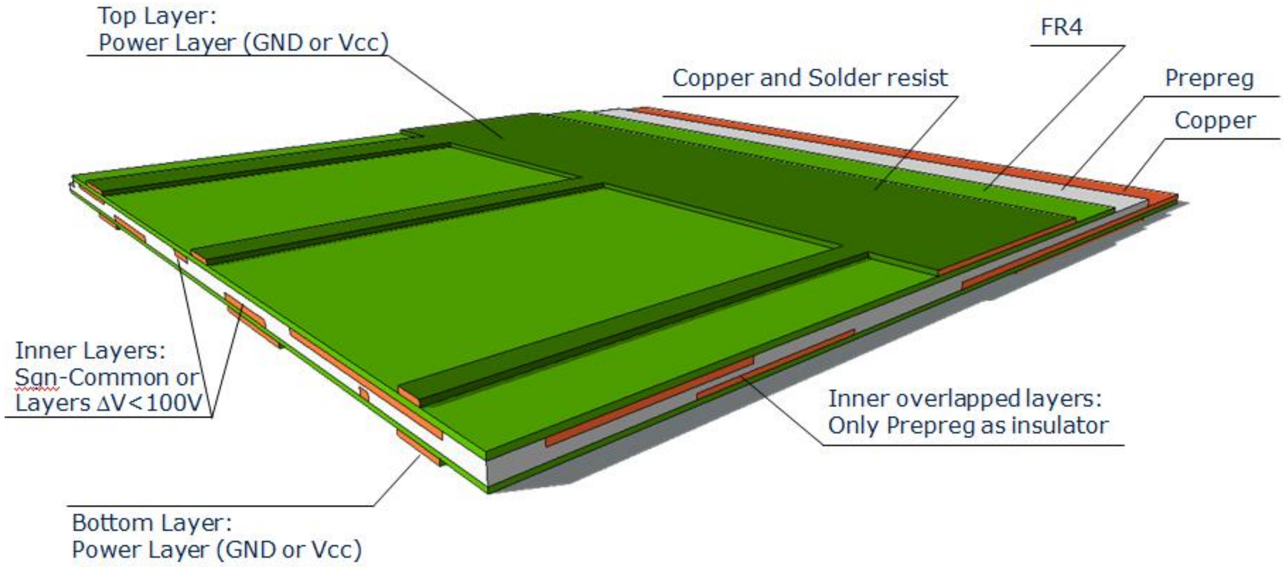


Fig. 4.25: Special embodiment of a 4 layer PCB.

5 Summary

This document gives an overview for basic understanding of safety related topics in electronic equipment and therefore educates the reader in a way, that people from different fields can have an effective communication. Furthermore, with this knowledge more in-depth material like standards or articles are more easy to read. In addition the document shows many design hints, which supports the daily work of the engineer.