Application Note

Understand Safety Requirement and Isolation Needs for High-Voltage Application Part II: Key Considerations to Select ISO Devices and Demystify Clearance and Creepage Distance

Yang Wu, Severi Zhou

ABSTRACT

{Isolated components are widely used in High Voltage (HV) applications to protect users from dangerous voltages. However, it's usually confusing to know key considerations, such as isolation voltage, working voltage, clearance, creepage and certificate etc., and to select the most suitable isolated devices. This application note series can help engineers understand safety requirements and isolation needs for HV application, how to design the whole system isolation to satisfy the corresponding safety standards, and finally choose the right isolated devices. The series includes 3 parts, part II focuses on topics of key considerations to select the most suitable ISO devices and deep understanding on how clearance and creepage distance are required for ISO devices. More content can refer to part I: *Distinguish Different Safety Standards and Understand Basic Principles of Safety Requirements* and part III *Safety Regulation Design Examples of Solar and ESS System*.}

Table of Contents

1 Introduction.......2
2 Key Considerations to Select ISO Devices.......2
3 Insulation Influencing Factors.......7
4 Determine Clearances and Creepage Distance.......13
5 Methods to Change Creepage Distances Requirements.......19
6 Summary.......20
7 References.......21

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

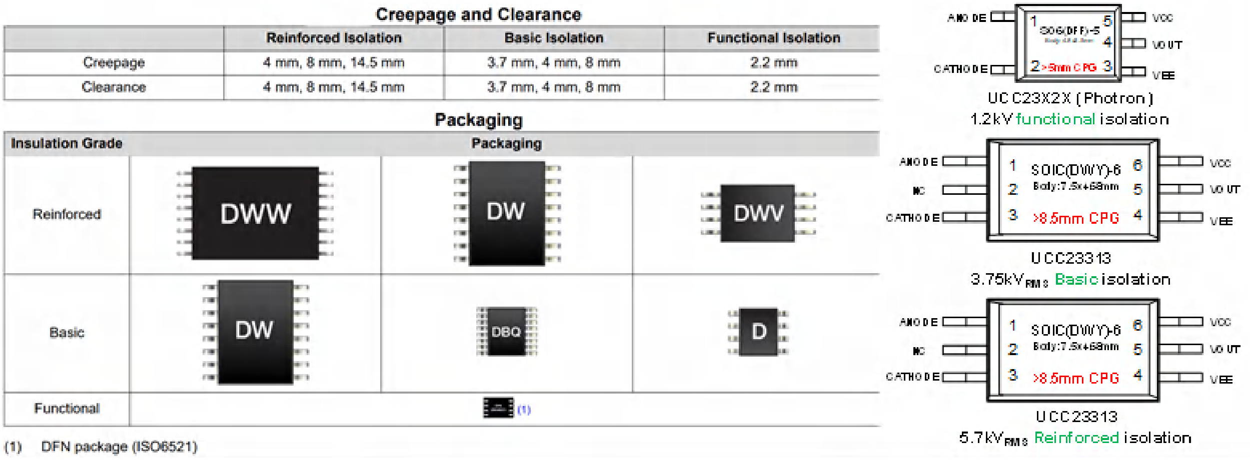
Understanding key specs of isolated devices and application safety regulation requirements are very important to disabuse engineers of choosing the most suitable isolated devices. This application note interprets key specs of ISO devices, key system level information to select ISO devices and demystifies clearance and creepage distance based on *IEC 62477-1:2022*.

Isolation and Insulation are often used interchangeably, isolation refers to the separation between two systems or voltage levels, while insulation refers to the actual medium being used to do the separation. While in this application note series, we regard it as having the same meaning.

2 Key Considerations to Select ISO Devices

1. Begin with Some Examples and Confusing Questions

   Figure 2-1 shows some TI examples of creepage and clearance values for reinforced, basic, and functional isolation, and different packages.



Creepage and Clearance

	Reinforced Isolation	Basic Isolation	Functional Isolation
Creepage	4 mm, 8 mm, 14.5 mm	3.7 mm, 4 mm, 8 mm	2.2 mm
Clearance	4 mm, 8 mm, 14.5 mm	3.7 mm, 4 mm, 8 mm	2.2 mm

Packaging

Insulation Grade	Packaging		
Reinforced	DWW	DW	DWV
Basic	DW	DBQ	D
Functional	(1)		

(1) DFN package (ISO6521)

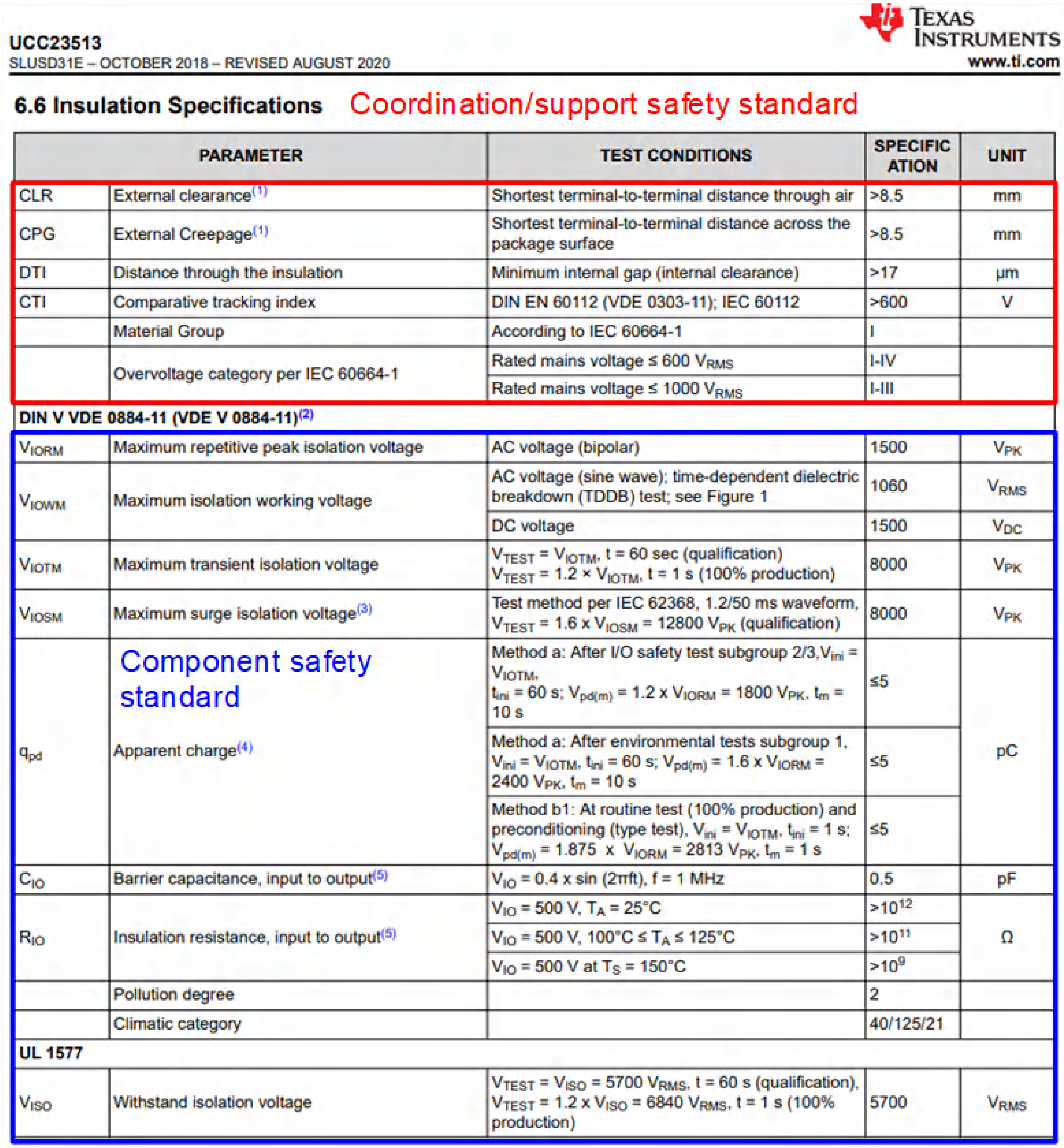
Figure 2-1. Some TI Example of Creepage, Clearance and Packaging

Engineers often get confused and there are some typical questions such as,

- What factors determine whether a device adopts functional insulation, basic insulation or reinforced insulation?
- Why do devices with the same insulation grade come in different packages to realize different clearance and creepage distance specifications?
- How to select suitable isolators for customers' safety protection applications? Should we refer to isolation voltage, working voltage, certification or relevant standards? What are the most critical considerations?

1. Key Insulation Specifications

   Figure 2-2 shows an example of key insulation specifications of ISO device and Table 2-1 lists the interpretation.



UCC23513
SLUSD31E – OCTOBER 2018 – REVISED AUGUST 2020
www.ti.com

6.6 Insulation Specifications

Coordination/support safety standard

PARAMETER		TEST CONDITIONS	SPECIFICATION	UNIT
CLR	External clearance[1]	Shortest terminal-to-terminal distance through air	>8.5	mm
CPG	External Creepage[1]	Shortest terminal-to-terminal distance across the package surface	>8.5	mm
DTI	Distance through the insulation	Minimum internal gap (internal clearance)	>17	μm
CTI	Comparative tracking index	DIN EN 60112 (VDE 0303-11); IEC 60112	>600	V
	Material Group	According to IEC 60664-1	I	
	Overvoltage category per IEC 60664-1	Rated mains voltage ≤ 600 V_{RMS}	I-IV	
		Rated mains voltage ≤ 1000 V_{RMS}	I-III	
DIN V VDE 0884-11 (VDE V 0884-11)[2]				
V_{IORM}	Maximum repetitive peak isolation voltage	AC voltage (bipolar)	1500	V_{PK}
V_{IOWM}	Maximum isolation working voltage	AC voltage (sine wave); time-dependent dielectric breakdown (TDDB) test; see Figure 1	1060	V_{RMS}
		DC voltage	1500	V_{DC}
V_{IOTM}	Maximum transient isolation voltage	$V_{TEST} = V_{IOTM}$, t = 60 sec (qualification) $V_{TEST} = 1.2 \times V_{IOTM}$, t = 1 s (100% production)	8000	V_{PK}
V_{IOSM}	Maximum surge isolation voltage[3]	Test method per IEC 62368, 1.2/50 ms waveform, $V_{TEST} = 1.6 \times V_{IOSM} = 12800\ V_{PK}$ (qualification)	8000	V_{PK}
q_{pd}	Component safety standard Apparent charge[4]	Method a: After I/O safety test subgroup 2/3, $V_{ini} = V_{IOTM}$, t_{ini} = 60 s; $V_{pd(m)} = 1.2 \times V_{IORM} = 1800\ V_{PK}$, t_m = 10 s	≤5	pC
		Method a: After environmental tests subgroup 1, $V_{ini} = V_{IOTM}$, t_{ini} = 60 s; $V_{pd(m)} = 1.6 \times V_{IORM} = 2400\ V_{PK}$, t_m = 10 s	≤5	
		Method b1: At routine test (100% production) and preconditioning (type test), $V_{ini} = V_{IOTM}$, t_{ini} = 1 s; $V_{pd(m)} = 1.875 \times V_{IORM} = 2813\ V_{PK}$, t_m = 1 s	≤5	
C_{IO}	Barrier capacitance, input to output[5]	$V_{IO} = 0.4 \times \sin(2\pi ft)$, f = 1 MHz	0.5	pF
R_{IO}	Insulation resistance, input to output[5]	V_{IO} = 500 V, T_A = 25°C	$>10^{12}$	Ω
		V_{IO} = 500 V, 100°C ≤ T_A ≤ 125°C	$>10^{11}$	
		V_{IO} = 500 V at T_S = 150°C	$>10^{9}$	
	Pollution degree		2	
	Climatic category		40/125/21	
UL 1577				
V_{ISO}	Withstand isolation voltage	$V_{TEST} = V_{ISO} = 5700\ V_{RMS}$, t = 60 s (qualification), $V_{TEST} = 1.2 \times V_{ISO} = 6840\ V_{RMS}$, t = 1 s (100% production)	5700	V_{RMS}

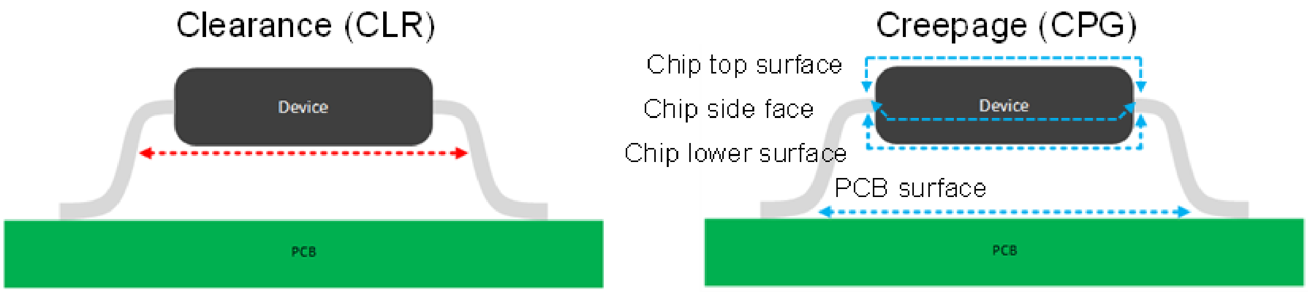
Figure 2-2. Key Insulation Specifications Example of ISO Device

Table 2-1. Key Insulation Specifications Interpretation of ISO Device

Parameter	**Definition**	**Interpretation**	**Customer Key Concerns**
Coordination/support safety standard			
CLR	Clearance	The shortest distance between two conductive materials (pins) measured through air	Whether the CLR of the device meets the safety requirements of the customer's system
CPG	Creepage	The shortest distance between two conductive materials (pins) measured along the insulating surface	Whether the CPG of the device meets the safety requirements of the customer's system
CTI	Comparative Tracking Index	A parameter describing the difficulty of charge migration on the insulator surface, only related to the material itself. A higher value indicates the material surface is less prone to leakage.	The higher the CTI rating (higher voltage), the lower the creepage distance requirement
OVC	Overvoltage Category	The operating environment of mains-powered electrical equipment is divided into four overvoltage categories according to surge protection levels	Whether the OVC of the device meets the safety requirements of the customer's system
Component safety standard			
V_{IORM}	Maximum Repetitive Peak Isolation Voltage (V_{PK})	The maximum repetitive voltage (peak) that an isolated device must withstand during its lifetime	Parameters that isolated devices must meet under normal operation
V_{IOWM}	Maximum Isolation Working Voltage (V_{RMS} or V_{DC})	The maximum continuous working voltage (rms or DC) that an isolated device must withstand during its lifetime	
V_{IOTM}	Maximum Transient Isolation Voltage (V_{PK})	The maximum transient voltage (usually non-repetitive) that an isolated device must withstand during its lifetime	Generally related to the actual required transient isolation voltage, operating bus voltage and corresponding OVC requirements
V_{IOSM}	Maximum Surge Isolation Voltage (V_{PK})	The maximum peak voltage that an isolated device can withstand based on 1.2us/50us standard surge waveform	Characterizes the lightning surge voltage immunity

2. Differentiate between Clearance and Creepage

   Figure 2-3 shows the differences between clearance and creepage. About clearance, it's easy to understand that the shortest distance between two conductive materials (pins) is measured through air. However, for creepage, note that the shortest distance between two conductive materials (pins) is measured along the insulating surface. The insulating surface can be the chip top surface, side face or lower surface.



The shortest distance between two conductive materials (pins) measured through air

The shortest distance between two conductive materials (pins) measured along the insulating surface

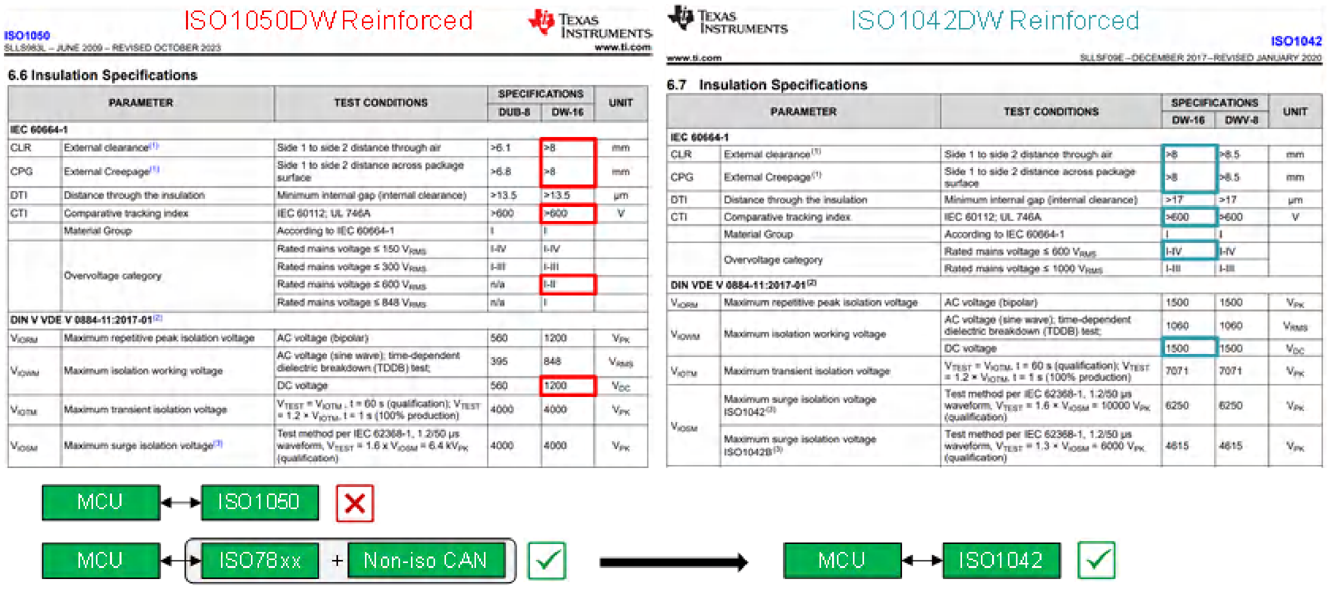
Figure 2-3. Clearance and Creepage Differences

3. Differentiate Component and System Level Insulation Requirements

Get back to those confusing questions in section 2.1, Does it mean that a reinforced isolated device can also make customer products reinforced? The answer is not always. Engineers must always differentiate component and system level insulation requirements.

- What factors determine whether a device adopts functional insulation, basic insulation or reinforced insulation?
  - Insulation grade is related to the insulation material, insulation layers and other properties of the chip. Different designs classify devices into functional, basic or reinforced insulation types, which further define the maximum isolation voltage the device can withstand.
  - There is a specific voltage limit for devices to comply with basic or reinforced insulation standards, indicating the voltage range within which the device meets corresponding insulation requirements.
- Why do devices with the same insulation grade come in different packages to realize different clearance and creepage distance specifications?
  - As mentioned above, insulation grade is determined by chip insulation materials and layers and is irrelevant to the actual achievable electrical clearance and creepage distance.
- How to select preferred isolators for customers' safety protection applications? Should we refer to isolation voltage, working voltage, certification or relevant standards? What are the most critical considerations?
  - Most importantly, do not confuse system-level safety specifications with the inherent insulation grade definition of isolated devices (components). A device with reinforced insulation does not mean the end application system can directly meet reinforced insulation requirements.
  - Customers focus on whether key parameters of isolators such as clearance and creepage distance can satisfy the safety requirements of their application systems. The compliance depends on operating voltage, overvoltage category, comparative tracking index, pollution degree, altitude and other practical factors.
  - It is quite common, especially in high-voltage applications, that customers adopt reinforced insulation devices to realize basic insulation or even functional insulation at the system level.

Figure 2-4 shows a 1500V solar or ESS example for ISO-CAN design. Both ISO1050 and ISO1042 are reinforced ISO-CAN transceivers. However, the maximum isolation working voltage of ISO1050 is 1200V which can't satisfy isolation requirements in 1500V system.



ISO1050DW Reinforced

ISO1050
SLLS983L – JUNE 2009 – REVISED OCTOBER 2023

www.ti.com

6.6 Insulation Specifications

PARAMETER		TEST CONDITIONS	SPECIFICATIONS		UNIT
			DUB-8	DW-16	
IEC 60664-1					
CLR	External clearance[1]	Side 1 to side 2 distance through air	>6.1	>8	mm
CPG	External Creepage[1]	Side 1 to side 2 distance across package surface	>6.8	>8	mm
DTI	Distance through the insulation	Minimum internal gap (internal clearance)	>13.5	>13.5	μm
CTI	Comparative tracking index	IEC 60112; UL 746A	>600	>600	V
	Material Group	According to IEC 60664-1	I	I	
	Overvoltage category	Rated mains voltage ≤ 150 V_{RMS}	I-IV	I-IV	
		Rated mains voltage ≤ 300 V_{RMS}	I-III	I-III	
		Rated mains voltage ≤ 600 V_{RMS}	n/a	I-II	
		Rated mains voltage ≤ 848 V_{RMS}	n/a	I	
DIN V VDE V 0884-11:2017-01[2]					
V_{IORM}	Maximum repetitive peak isolation voltage	AC voltage (bipolar)	560	1200	V_{PK}
V_{IOWM}	Maximum isolation working voltage	AC voltage (sine wave); time-dependent dielectric breakdown (TDDB) test;	395	848	V_{RMS}
		DC voltage	560	1200	V_{DC}
V_{IOTM}	Maximum transient isolation voltage	$V_{TEST} = V_{IOTM}$, t = 60 s (qualification); $V_{TEST} = 1.2 \times V_{IOTM}$, t = 1 s (100% production)	4000	4000	V_{PK}
V_{IOSM}	Maximum surge isolation voltage[3]	Test method per IEC 62368-1, 1.2/50 μs waveform, $V_{TEST} = 1.6 \times V_{IOSM} = 6.4\ kV_{PK}$ (qualification)	4000	4000	V_{PK}

ISO1042DW Reinforced

ISO1042
www.ti.com
SLLSF09E – DECEMBER 2017 – REVISED JANUARY 2020

6.7 Insulation Specifications

PARAMETER		TEST CONDITIONS	SPECIFICATIONS		UNIT
			DW-16	DWV-8	
IEC 60664-1					
CLR	External clearance[1]	Side 1 to side 2 distance through air	>8	>8.5	mm
CPG	External Creepage[1]	Side 1 to side 2 distance across package surface	>8	>8.5	mm
DTI	Distance through the insulation	Minimum internal gap (internal clearance)	>17	>17	μm
CTI	Comparative tracking index	IEC 60112; UL 746A	>600	>600	V
	Material Group	According to IEC 60664-1	I	I	
	Overvoltage category	Rated mains voltage ≤ 600 V_{RMS}	I-IV	I-IV	
		Rated mains voltage ≤ 1000 V_{RMS}	I-III	I-III	
DIN VDE V 0884-11:2017-01[2]					
V_{IORM}	Maximum repetitive peak isolation voltage	AC voltage (bipolar)	1500	1500	V_{PK}
V_{IOWM}	Maximum isolation working voltage	AC voltage (sine wave); time-dependent dielectric breakdown (TDDB) test;	1060	1060	V_{RMS}
		DC voltage	1500	1500	V_{DC}
V_{IOTM}	Maximum transient isolation voltage	$V_{TEST} = V_{IOTM}$, t = 60 s (qualification); $V_{TEST} = 1.2 \times V_{IOTM}$, t = 1 s (100% production)	7071	7071	V_{PK}
V_{IOSM}	Maximum surge isolation voltage ISO1042[3]	Test method per IEC 62368-1, 1.2/50 μs waveform, $V_{TEST} = 1.6 \times V_{IOSM} = 10000\ V_{PK}$ (qualification)	6250	6250	V_{PK}
	Maximum surge isolation voltage ISO1042B[3]	Test method per IEC 62368-1, 1.2/50 μs waveform, $V_{TEST} = 1.3 \times V_{IOSM} = 6000\ V_{PK}$ (qualification)	4615	4615	V_{PK}

Figure 2-4. 1500V Solar or ESS Example for ISO-CAN

4. Mandatory Asked Questions to Select Suitable ISO Devices

Table 2-2 lists mandatory asked questions to select the ISO devices. They will be discussed in detail in section 3 to determine clearance and creepage distance.

Table 2-2. Mandatory Asked Questions to Select the Preferred ISO Devices

Question	Comments
1. What is the system voltage (AC or DC)?	Used to determine CLR.
2. What is the OVC?	
3. Is it allowed to reduce the impulse withstand voltage by some methods (such as SPD)?	
4. What is the pollution degree?	
5. What is the maximum working altitude that the EE can support?	
6. What is the working voltage (AC or DC)?	Used to determine CPG.
7. What is the pollution degree and is potting acceptable to decrease it?	
8. What is the CTI?	

3 Insulation Influencing Factors

This section discusses insulation influencing factors based on *IEC 62477-1:2022*.

IEC 62477-1:2022 applies to power electronic converter systems (PECS), any specified accessories, and their components for electronic power conversion and electronic power switching, including the means for their control, protection, monitoring and measurement, such as with the main purpose of converting electric power, with rated system voltages not exceeding 1000VAC or 1500VDC.

In the field of new energy, IEC 62477 is suitable for power generation applications such as solar, wind, tidal, etc. in power electronic converter systems. Specific standards for products such as photovoltaic, energy storage systems, and charging piles refer to this standard to a large extent.

Note that in 2022, IEC 62477-1: 2022 was published to replace the former version IEC 62477-1: 2012 (and its revised version IEC 62477-1: 2016). The most important update related to insulation and our ISO product is impulse withstand voltage and temporary overvoltage versus system voltage. For 1500VDC system voltage, the impulse withstand voltage in IEC 62477-1: 2022 is one step higher than that in IEC 62477-1:2012. The impulse withstand voltage of IEC 62477-1: 2022 and IEC 60664-1:2020 are aligned.

Referring to IEC 62477-1: 2022, there are a lot of influencing influencing factors and complex guidelines for determination of clearance and creepage distances are also provided. We are not to discuss all factors, only focus on these most related to common high-voltage applications, including,

- System voltage and working voltage
- Overvoltage category (OVC)
- Impulse withstand voltage and temporary overvoltage
- Insulating material groups
- Pollution degree
- Altitude

1. System voltage and working voltage

    System voltage is the rated voltage of the whole system used to determine insulation level and clearance, fixed and unchanged regardless of operating conditions. For example, an ESS with 690VAC and 1500VDC system voltage.

    Working voltage is the maximum actual voltage (DC mean, AC RMS and repeat peak voltage) occurring between two points of local circuits under normal and worst-case operating conditions and used to determine creepage distances, varying with working status. For example, the voltage across the DC link capacitor, voltage across the IGBT.

    Typical system voltage and working voltage are the same, however, there are also exceptions. For example, solar inverter's system voltage is 1500V (MPPT max input voltage), but the working voltage can be up to 1600V (after the boost circuit and voltage across the DC link capacitor), as shown in Figure 3-1.

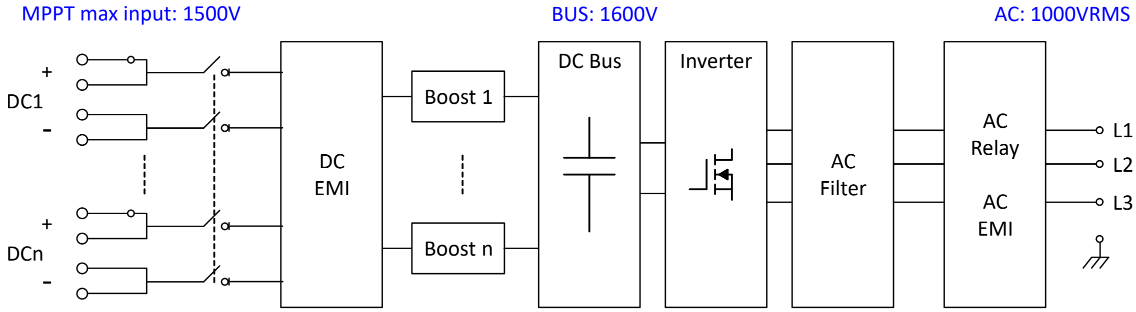


Figure 3-1. Solar inverter Example about System Voltage and Working Voltage

2. Overvoltage Category (OVC)

   The operating environment for mains-powered electrical equipment is separated into four overvoltage category (OVC) areas according to their level of surge protection. Figure 3-2 shows the diagrammatic representation of the OVC IV to OVC I environments.

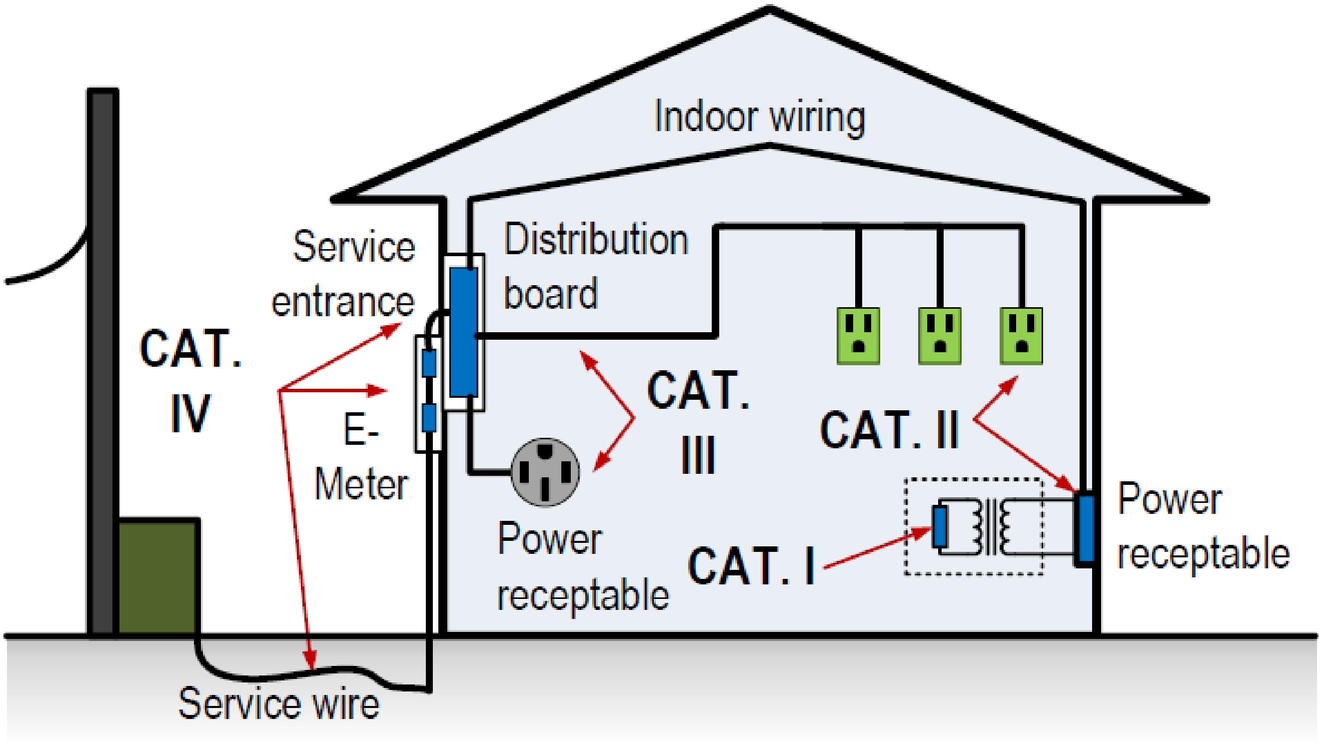


Figure 3-2. Diagrammatic Representation of the OVC IV to OVC I Environments

In residential, commercial and factory environments where devices draw power from wall outlets, the mains supply is generally relatively stable, free from excessive voltage transients that could damage terminal equipment. However, moving upstream along power distribution wiring towards distribution boards and building main AC inlets, the risk of overvoltage surges rises significantly. Such hazards mainly stem from external disturbances including lightning strikes and sudden load shedding on the public power grid.

Certain applications, such as solar inverter and ESS, are hardwired directly to central distribution boards. Exposed to transients of higher amplitude and greater energy intensity, these converters require enhanced overvoltage protection compared with conventional plug-in power adapters.

Table 3-1 lists OVCs according to *IEC 60664-1:2020*. Usually in most customer applications, AC requires OVC III and DC requires OVC II.

Note that in some cases, the isolation design is difficult to satisfy the required impulse withstand voltage under the corresponding OVC level and customers will reduce the impulse withstand voltage by some methods, such as OVC reduction by Surge Protection Device (SPD) which will be discussed in section 4.4.

Table 3-1. OVCs According to IEC 60664-1:2020

Overvoltage Category	Relevant Equipment
OVC I	Equipment for connection to circuits in which measures are taken to limit transient overvoltage to an appropriately low level.
OVC II	Energy-consuming equipment to be supplied from the fixed installation. Examples of such equipment are appliances, portable tools and other similar household loads.
OVC III	Equipment in fixed installations and for cases where reliability and the availability of the equipment is subject to special requirements. Examples of such equipment are switches in the fixed installation and equipment for industrial use with permanent connection to the fixed installation.
OVC IV	Equipment connected at the origin of the installation. Examples of such equipment are electricity meters and primary overcurrent protection equipment.

3. **Determination of Impulse Withstand Voltage and Temporary Overvoltage**

   Figure 3-3 shows steps of using the system voltage and overvoltage category of the circuit under consideration to determine the impulse withstand voltage. The system voltage is also used to determine the temporary overvoltage for mains supplies.

   As highlighted in red lines, interpolation of system voltage is not permitted when determining the impulse withstand voltage for mains supply. Interpolation of system voltage is permitted when determining the temporary overvoltage for mains supply. For example, actual system voltage of the residential inverter typically is 1100VDC, it must refer to 1250VDC system voltage in the table to determine the impulse withstand voltage. Interpolation between 900VDC and 1250DC to get the interpolated impulse withstand voltage is not permitted.

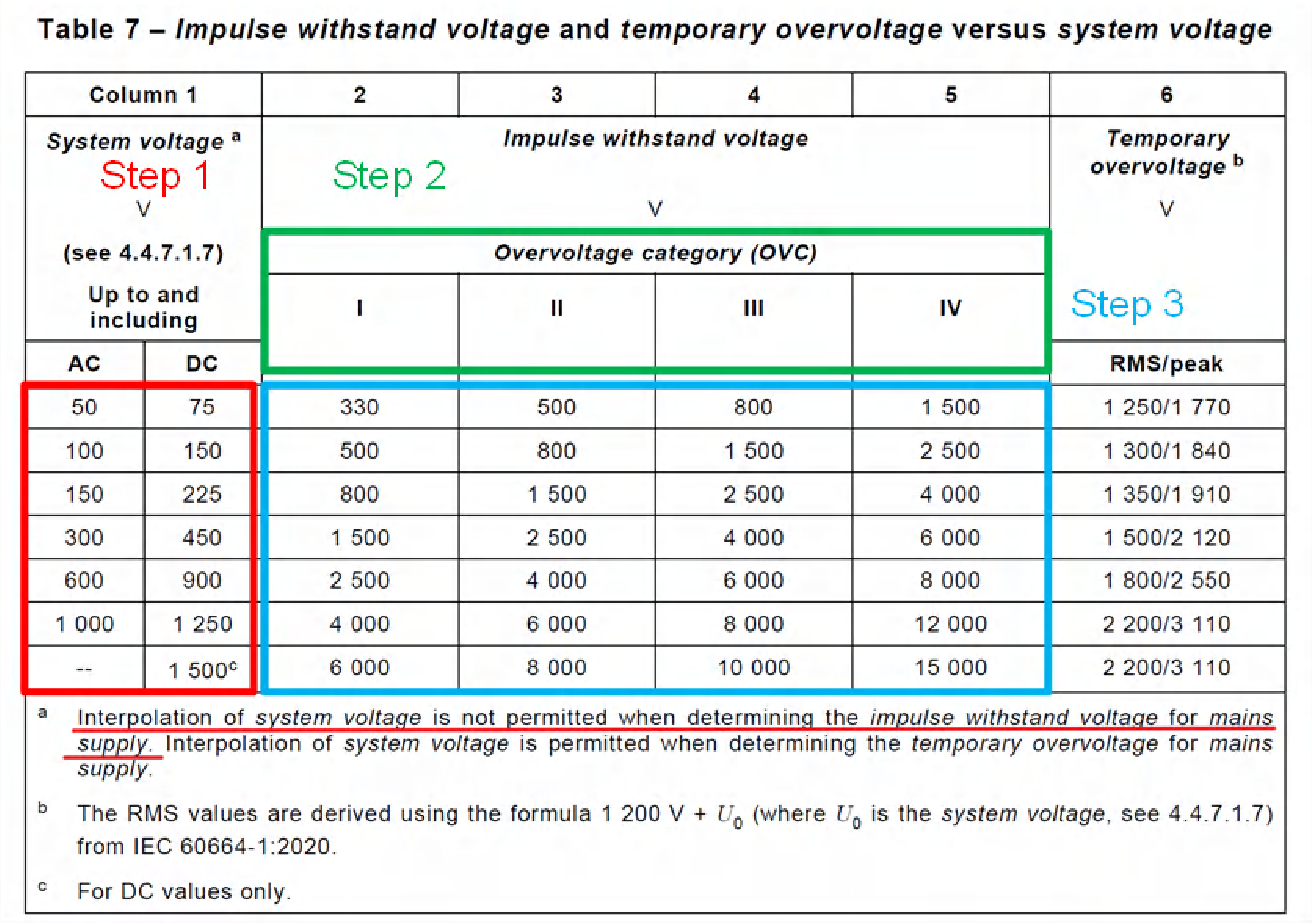


Table 7 – *Impulse withstand voltage* and *temporary overvoltage* versus *system voltage*

Column 1		2	3	4	5	6
System voltage [a] V (see 4.4.7.1.7) Up to and including		*Impulse withstand voltage* V				*Temporary overvoltage* [b] V
		Overvoltage category (OVC)				
		I	II	III	IV	
AC	DC					RMS/peak
50	75	330	500	800	1 500	1 250/1 770
100	150	500	800	1 500	2 500	1 300/1 840
150	225	800	1 500	2 500	4 000	1 350/1 910
300	450	1 500	2 500	4 000	6 000	1 500/2 120
600	900	2 500	4 000	6 000	8 000	1 800/2 550
1 000	1 250	4 000	6 000	8 000	12 000	2 200/3 110
--	1 500[c]	6 000	8 000	10 000	15 000	2 200/3 110

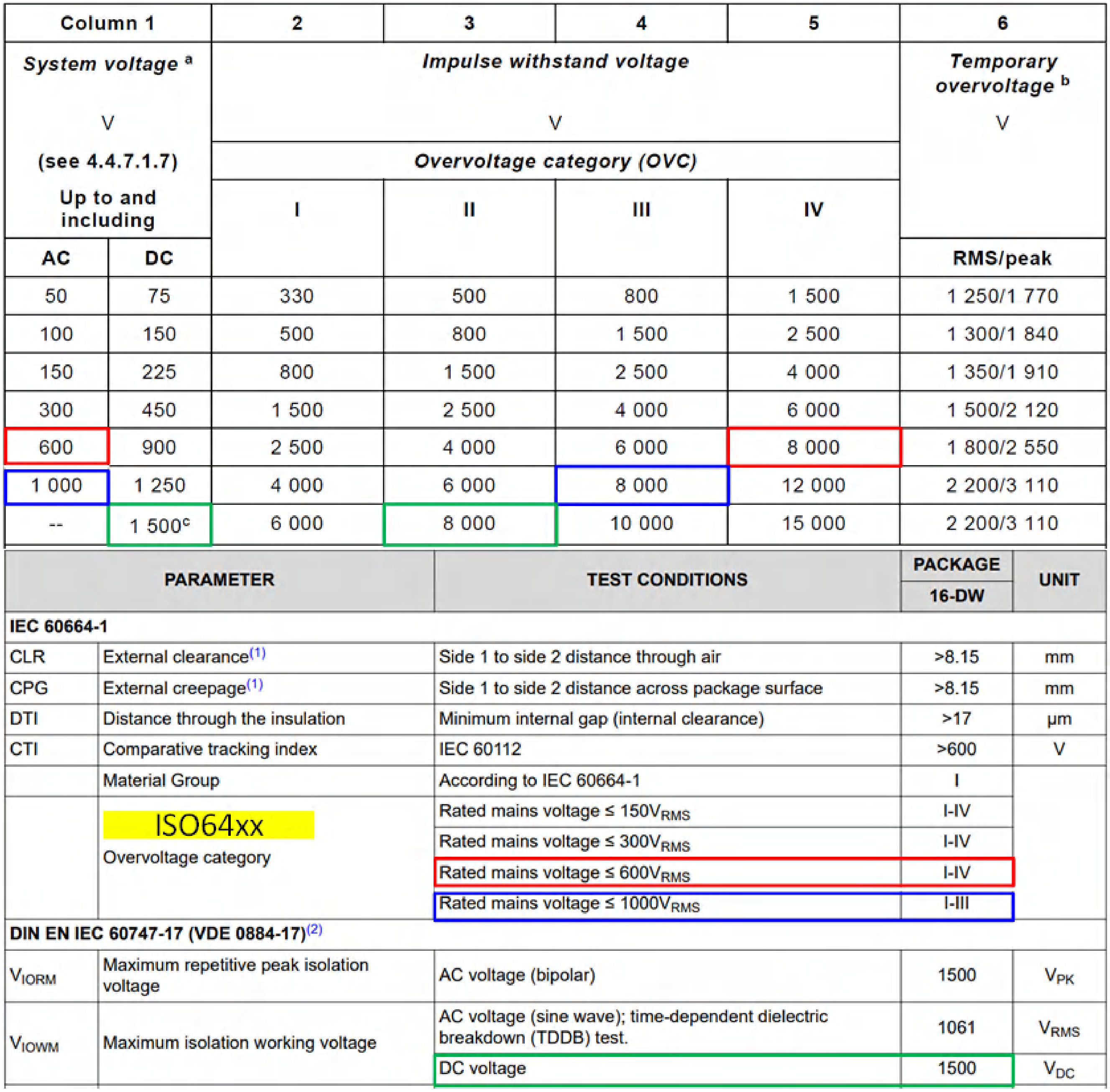
[a] Interpolation of *system voltage* is not permitted when determining the *impulse withstand voltage* for *mains supply*. Interpolation of *system voltage* is permitted when determining the *temporary overvoltage* for *mains supply*.

[b] The RMS values are derived using the formula 1 200 V + U_0 (where U_0 is the *system voltage*, see 4.4.7.1.7) from IEC 60664-1:2020.

[c] For DC values only.

Figure 3-3. Steps to Determine Impulse Withstand Voltage and Temporary Overvoltage

Figure 3-4 shows ISO64xx overvoltage category example. Note that not all test conditions are listed in the datasheet. Designers can only take care about the maximum value, for example, 8000V impulse withstand voltage at test conditions of rated mains voltage ≤ 600VRMS and ≤ 1000VRMS. Even though the datasheet does not list test condition of mains voltage ≤ 1500VDC, the maximum isolation working voltage is 1500VDC and can align with the 8000V impulse withstand voltage at OVC II. Finally, the impulse withstand voltage determines insulation level and clearance.



Column 1		2	3	4	5	6
System voltage [a] V (see 4.4.7.1.7) Up to and including		Impulse withstand voltage V				Temporary overvoltage [b] V
		Overvoltage category (OVC)				
		I	II	III	IV	
AC	DC					RMS/peak
50	75	330	500	800	1 500	1 250/1 770
100	150	500	800	1 500	2 500	1 300/1 840
150	225	800	1 500	2 500	4 000	1 350/1 910
300	450	1 500	2 500	4 000	6 000	1 500/2 120
600	900	2 500	4 000	6 000	8 000	1 800/2 550
1 000	1 250	4 000	6 000	8 000	12 000	2 200/3 110
--	1 500[c]	6 000	8 000	10 000	15 000	2 200/3 110

PARAMETER		TEST CONDITIONS	PACKAGE 16-DW	UNIT
IEC 60664-1				
CLR	External clearance(1)	Side 1 to side 2 distance through air	>8.15	mm
CPG	External creepage(1)	Side 1 to side 2 distance across package surface	>8.15	mm
DTI	Distance through the insulation	Minimum internal gap (internal clearance)	>17	µm
CTI	Comparative tracking index	IEC 60112	>600	V
	Material Group	According to IEC 60664-1	I	
	ISO64xx Overvoltage category	Rated mains voltage ≤ 150V_{RMS}	I-IV	
		Rated mains voltage ≤ 300V_{RMS}	I-IV	
		Rated mains voltage ≤ 600V_{RMS}	I-IV	
		Rated mains voltage ≤ 1000V_{RMS}	I-III	
DIN EN IEC 60747-17 (VDE 0884-17)(2)				
V_{IORM}	Maximum repetitive peak isolation voltage	AC voltage (bipolar)	1500	V_{PK}
V_{IOWM}	Maximum isolation working voltage	AC voltage (sine wave); time-dependent dielectric breakdown (TDDB) test.	1061	V_{RMS}
		DC voltage	1500	V_{DC}

Figure 3-4. ISO64xx Overvoltage Category Example

4. **Insulating Material Groups**

Insulating materials are classified into four groups corresponding to their comparative tracking index (CTI) when tested according to IEC 60112:2020, Clause 11:

- Insulating material group I: CTI ≥ 600;
- Insulating material group II: 600 > CTI ≥ 400;
- Insulating material group IIIa: 400 > CTI ≥ 175;

- Insulating material group IIIb: 175 > CTI ≥ 100.

CTI is an index used to measure the electric tracking breakdown performance of insulating materials. Electric tracking occurs on the surface of insulating materials. Due to dielectric loss, the dielectric generates heat and temperature rises, which causes the dielectric to decompose and carbonize. Eventually, the carbonized track extends to electrodes and leads to short circuits.

The CTI value of materials is positively correlated with their insulation performance. A higher CTI value allows a smaller required creepage distance, enabling a shorter spacing between two conductors.

Usually in most HV applications, it requires CTI-I for isolated devices or components. However, FR4 PCB (CTI IIIa) are most used. So, the creepage requirements for isolated devices and PCB may be different.

5. Pollution Degree

The operating environment for mains-powered electrical equipment is separated into four overvoltage category (OVC) areas according to their level of surge protection. Figure 3-2 shows the diagrammatic representation of the OVC IV to OVC I environments.

Insulation is affected by pollution which occurs during the expected life cycle of the power electronic converter systems. The micro-environmental conditions for insulation shall be applied according to Figure 3-5.

The pollution degree shall be determined according to the environmental condition for which the product is specified.

Usually in most customer applications, it requires pollution degree 2. The lower the pollution degree (for example, the cleaner the environment with fewer impurities that may degrade insulation performance), the lower the insulation requirements will be.

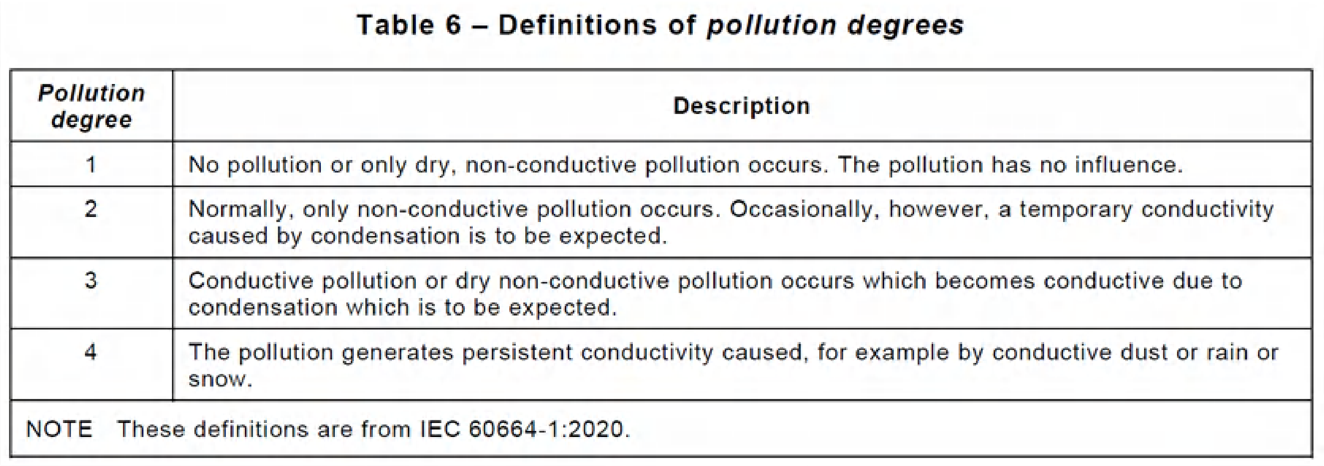


Table 6 – Definitions of *pollution degrees*

Pollution degree	**Description**
1	No pollution or only dry, non-conductive pollution occurs. The pollution has no influence.
2	Normally, only non-conductive pollution occurs. Occasionally, however, a temporary conductivity caused by condensation is to be expected.
3	Conductive pollution or dry non-conductive pollution occurs which becomes conductive due to condensation which is to be expected.
4	The pollution generates persistent conductivity caused, for example by conductive dust or rain or snow.
NOTE These definitions are from IEC 60664-1:2020.	

Figure 3-5. Definitions of Pollution Degrees

6. Altitude

Clearances are related to Altitude. Clearances for functional insulation, basic insulation or supplementary insulation and reinforced insulation for use at altitudes between 2 000 m and 20 000 m shall be calculated using a correction factor according to IEC 60664-1:2020, as shown in Figure 3-5.

Previously, solar inverters and ESS power stations commonly support maximum 4000m altitude. However, now increasingly solar inverter and ESS power stations will be deployed in 5000m altitude plateau areas. The previous products can't support full power running at 5000m altitude due to isolation design limit. If wants to support full power running at 5000m altitude, the clearance requirement will be higher (correction factor change from 1.29 to 1.48).

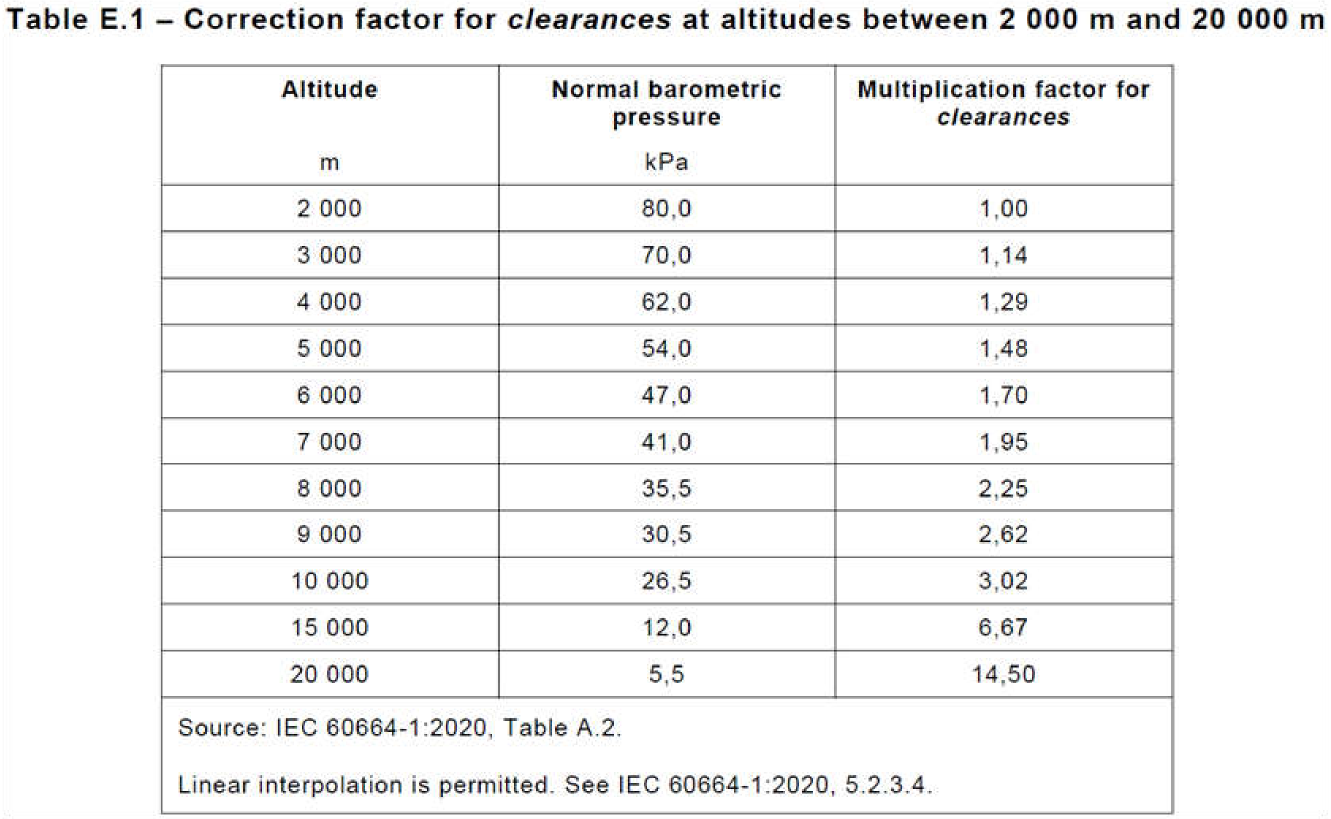


Table E.1 – Correction factor for *clearances* at altitudes between 2 000 m and 20 000 m

Altitude m	Normal barometric pressure kPa	Multiplication factor for *clearances*
2 000	80,0	1,00
3 000	70,0	1,14
4 000	62,0	1,29
5 000	54,0	1,48
6 000	47,0	1,70
7 000	41,0	1,95
8 000	35,5	2,25
9 000	30,5	2,62
10 000	26,5	3,02
15 000	12,0	6,67
20 000	5,5	14,50

Source: IEC 60664-1:2020, Table A.2.

Linear interpolation is permitted. See IEC 60664-1:2020, 5.2.3.4.

Figure 3-6. Altitude Correction for Clearances

4 Determine Clearances and Creepage Distance

This section demystifies clearances and creepage distance based on *IEC 62477-1:2022*.

1. Clearances

   Clearances shall be determined for functional insulation, basic insulation or supplementary insulation directly from Figure 4-

   The impulse withstand voltage for reinforced insulation is one step higher for that of basic insulation. For example, if the impulse withstand voltage is 6000V for basic insulation, then it should be 8000V for reinforced insulation.

   Note that it shows the minimum clearances in air up to 2000m above sea level. For altitude above 2000m applications, it needs to consider the altitude correction factor discussed in section 3.6.

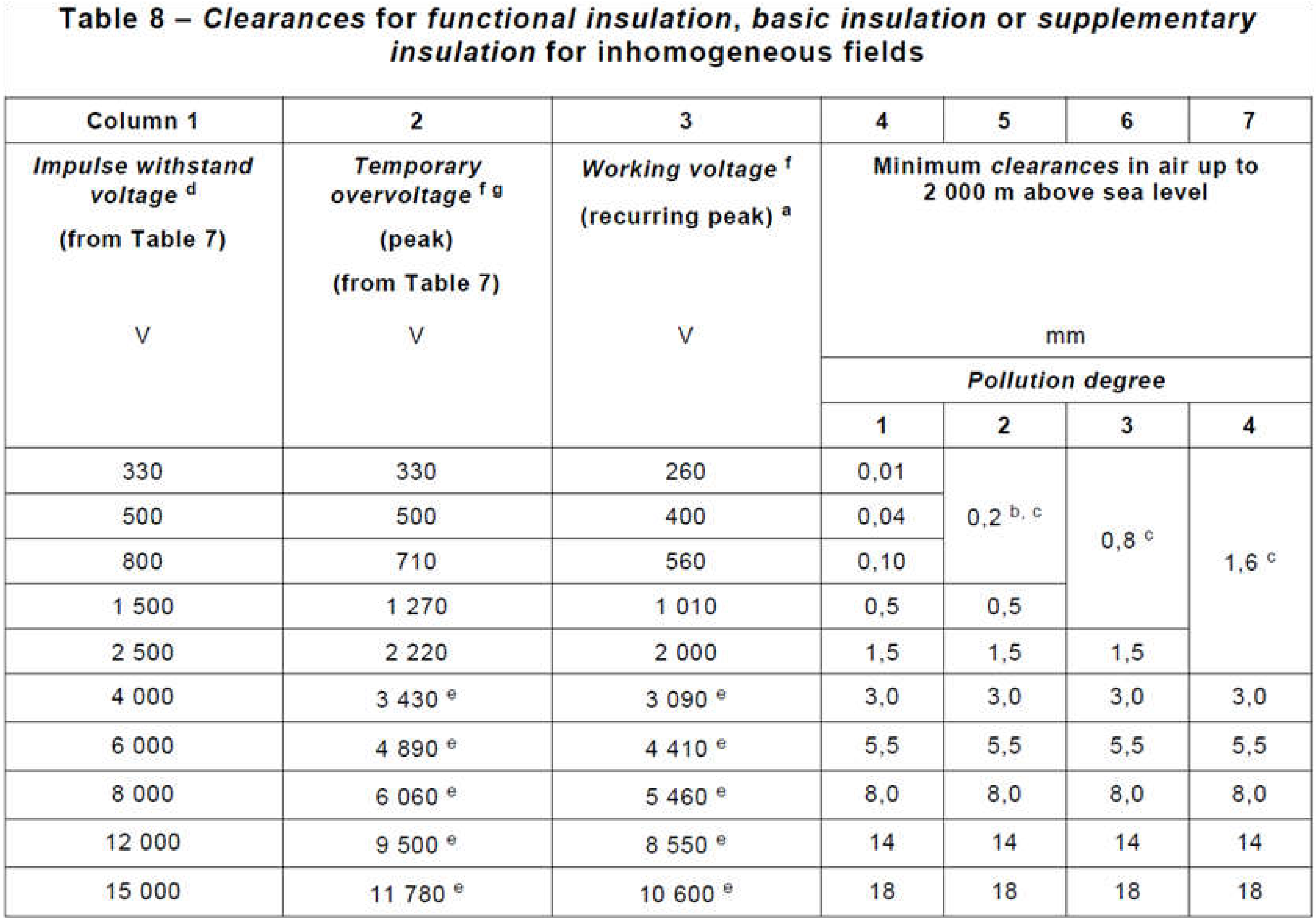


Table 8 – *Clearances* for *functional insulation*, *basic insulation* or *supplementary insulation* for inhomogeneous fields

Column 1	2	3	4	5	6	7
Impulse withstand voltage [d] (from Table 7) V	*Temporary overvoltage* [f g] (peak) (from Table 7) V	*Working voltage* [f] (recurring peak) [a] V	Minimum *clearances* in air up to 2 000 m above sea level mm			
			Pollution degree			
			1	2	3	4
330	330	260	0,01	0,2 [b, c]	0,8 [c]	1,6 [c]
500	500	400	0,04			
800	710	560	0,10			
1 500	1 270	1 010	0,5	0,5		
2 500	2 220	2 000	1,5	1,5	1,5	
4 000	3 430 [e]	3 090 [e]	3,0	3,0	3,0	3,0
6 000	4 890 [e]	4 410 [e]	5,5	5,5	5,5	5,5
8 000	6 060 [e]	5 460 [e]	8,0	8,0	8,0	8,0
12 000	9 500 [e]	8 550 [e]	14	14	14	14
15 000	11 780 [e]	10 600 [e]	18	18	18	18

Figure 4-1. Clearances Determination Table

2. **Creepage Distances**

   Creepage distances for functional insulation, basic insulation and supplementary insulation shall be dimensioned according to Figure 4-2.

   Creepage distances for reinforced insulation shall be twice the distances required for basic insulation. For example, if the creepage distance is 8mm for basic insulation, then it should be 16mm for reinforced insulation.

   Note that in all cases, the associated creepage distance is not permitted to be smaller than the required clearance (i.e. CPG always ≥ CLR).

Note that interpolation for working voltage is allowed. For example, 1500V is not listed here, but we can use interpolation between 1250V and 1600V to determine the creepage distance (interpolation between 6.3mm and 8mm, pollution degree 2, CTI I).

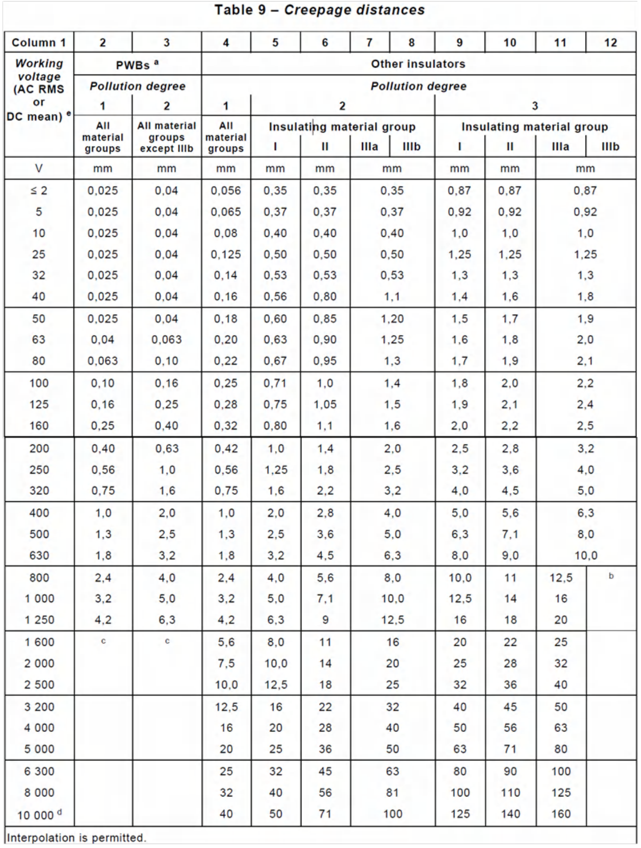


Table 9 – *Creepage distances*

Column 1	2	3	4	5	6	7	8	9	10	11	12
Working voltage (AC RMS or DC mean) [e]	PWBs [a]		Other insulators								
	Pollution degree		*Pollution degree*								
	1	2	1	2				3			
	All material groups	All material groups except IIIb	All material groups	Insulating material group				Insulating material group			
				I	II	IIIa	IIIb	I	II	IIIa	IIIb
V	mm	mm	mm	mm	mm	mm		mm	mm	mm	
≤ 2	0,025	0,04	0,056	0,35	0,35	0,35		0,87	0,87	0,87	
5	0,025	0,04	0,065	0,37	0,37	0,37		0,92	0,92	0,92	
10	0,025	0,04	0,08	0,40	0,40	0,40		1,0	1,0	1,0	
25	0,025	0,04	0,125	0,50	0,50	0,50		1,25	1,25	1,25	
32	0,025	0,04	0,14	0,53	0,53	0,53		1,3	1,3	1,3	
40	0,025	0,04	0,16	0,56	0,80	1,1		1,4	1,6	1,8	
50	0,025	0,04	0,18	0,60	0,85	1,20		1,5	1,7	1,9	
63	0,04	0,063	0,20	0,63	0,90	1,25		1,6	1,8	2,0	
80	0,063	0,10	0,22	0,67	0,95	1,3		1,7	1,9	2,1	
100	0,10	0,16	0,25	0,71	1,0	1,4		1,8	2,0	2,2	
125	0,16	0,25	0,28	0,75	1,05	1,5		1,9	2,1	2,4	
160	0,25	0,40	0,32	0,80	1,1	1,6		2,0	2,2	2,5	
200	0,40	0,63	0,42	1,0	1,4	2,0		2,5	2,8	3,2	
250	0,56	1,0	0,56	1,25	1,8	2,5		3,2	3,6	4,0	
320	0,75	1,6	0,75	1,6	2,2	3,2		4,0	4,5	5,0	
400	1,0	2,0	1,0	2,0	2,8	4,0		5,0	5,6	6,3	
500	1,3	2,5	1,3	2,5	3,6	5,0		6,3	7,1	8,0	
630	1,8	3,2	1,8	3,2	4,5	6,3		8,0	9,0	10,0	
800	2,4	4,0	2,4	4,0	5,6	8,0		10,0	11	12,5	[b]
1 000	3,2	5,0	3,2	5,0	7,1	10,0		12,5	14	16	
1 250	4,2	6,3	4,2	6,3	9	12,5		16	18	20	
1 600	[c]	[c]	5,6	8,0	11	16		20	22	25	
2 000			7,5	10,0	14	20		25	28	32	
2 500			10,0	12,5	18	25		32	36	40	
3 200			12,5	16	22	32		40	45	50	
4 000			16	20	28	40		50	56	63	
5 000			20	25	36	50		63	71	80	
6 300			25	32	45	63		80	90	100	
8 000			32	40	56	81		100	110	125	
10 000 [d]			40	50	71	100		125	140	160	

Interpolation is permitted.

Figure 4-2. Creepage Distances Determination Table

3. Simplified Flowchart to Determine CLR and CPG

Referring to IEC 62477-1: 2022, guidelines for determination of clearance and creepage distances are very complex because it needs to consider all scenarios. For most high-voltage applications, such as solar inverter and ESS, we can simplify them, as shown in Figure 4-3 and Figure 4-4.

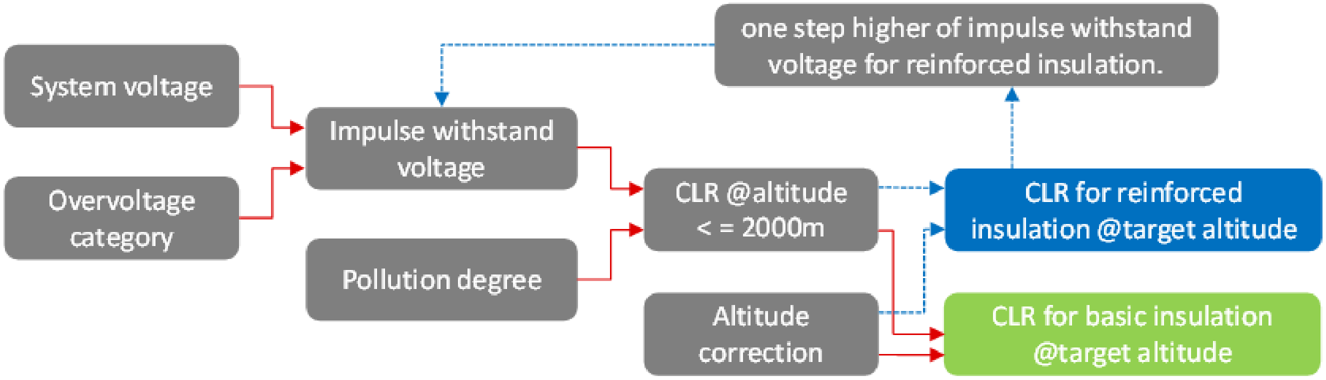


Figure 4-3. Simplified Flowchart to Determine CLR

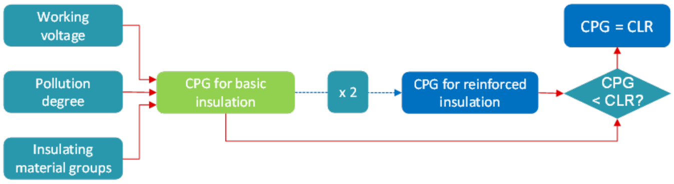


Figure 4-4. Simplified Flowchart to Determine CPG

4. CLR and CPG Determination Example

Figure 4-5 shows step-by-step clearance determination example for 1500VDC solar inverter or ESS.

Figure 4-6 shows step-by-step creepage distances determination example. In step 4, the interpolation is calculated as, (8 - 6.3) / (1600 - 1250) × (1500 - 1250) + 6.3 = 7.514mm.

Table 4-1 summarizes the results in conditions of 1500VDC, OVC II, CTI-I, pollution degree 2.

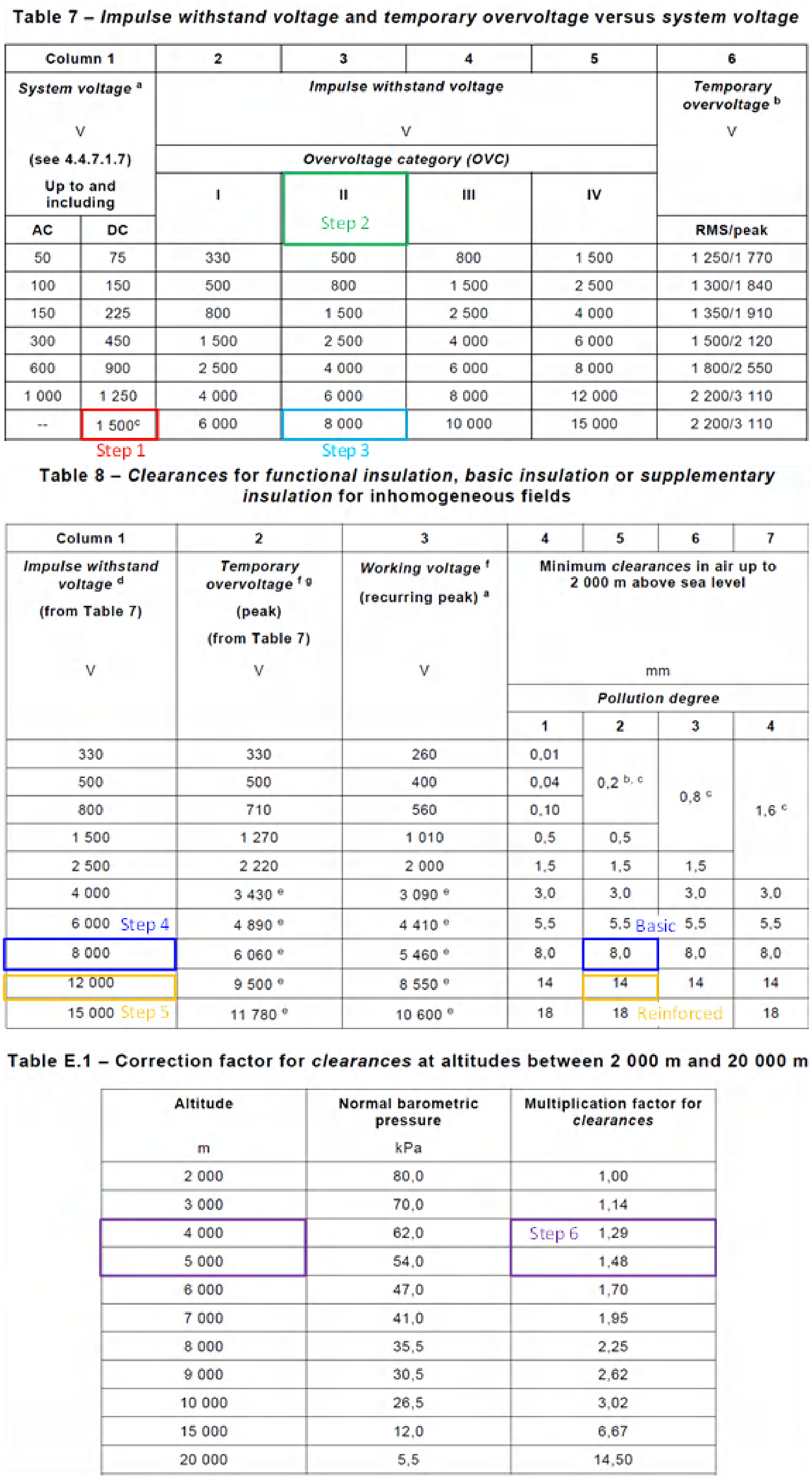


Table 7 – *Impulse withstand voltage* and *temporary overvoltage* versus *system voltage*

Column 1		2	3	4	5	6
System voltage [a] V (see 4.4.7.1.7) Up to and including		*Impulse withstand voltage* V				*Temporary overvoltage* [b] V
		Overvoltage category (OVC)				
		I	II Step 2	III	IV	
AC	DC					RMS/peak
50	75	330	500	800	1 500	1 250/1 770
100	150	500	800	1 500	2 500	1 300/1 840
150	225	800	1 500	2 500	4 000	1 350/1 910
300	450	1 500	2 500	4 000	6 000	1 500/2 120
600	900	2 500	4 000	6 000	8 000	1 800/2 550
1 000	1 250	4 000	6 000	8 000	12 000	2 200/3 110
--	1 500[c]	6 000	8 000	10 000	15 000	2 200/3 110
	Step 1		Step 3			

Table 8 – *Clearances* for *functional insulation*, *basic insulation* or *supplementary insulation* for inhomogeneous fields

Column 1	2	3	4	5	6	7
Impulse withstand voltage [d] (from Table 7) V	*Temporary overvoltage* [f g] (peak) (from Table 7) V	*Working voltage* [f] (recurring peak) [a] V	Minimum *clearances* in air up to 2 000 m above sea level mm			
			Pollution degree			
			1	2	3	4
330	330	260	0,01	0,2 [b, c]	0,8 [c]	1,6 [c]
500	500	400	0,04			
800	710	560	0,10			
1 500	1 270	1 010	0,5	0,5		
2 500	2 220	2 000	1,5	1,5	1,5	
4 000	3 430 [e]	3 090 [e]	3,0	3,0	3,0	3,0
6 000 Step 4	4 890 [e]	4 410 [e]	5,5	5,5 Basic	5,5	5,5
8 000	6 060 [e]	5 460 [e]	8,0	8,0	8,0	8,0
12 000	9 500 [e]	8 550 [e]	14	14	14	14
15 000 Step 5	11 780 [e]	10 600 [e]	18	18 Reinforced	18	18

Table E.1 – Correction factor for *clearances* at altitudes between 2 000 m and 20 000 m

Altitude m	Normal barometric pressure kPa	Multiplication factor for *clearances*
2 000	80,0	1,00
3 000	70,0	1,14
4 000	62,0	Step 6 1,29
5 000	54,0	1,48
6 000	47,0	1,70
7 000	41,0	1,95
8 000	35,5	2,25
9 000	30,5	2,62
10 000	26,5	3,02
15 000	12,0	6,67
20 000	5,5	14,50

Figure 4-5. CLR Determination Steps

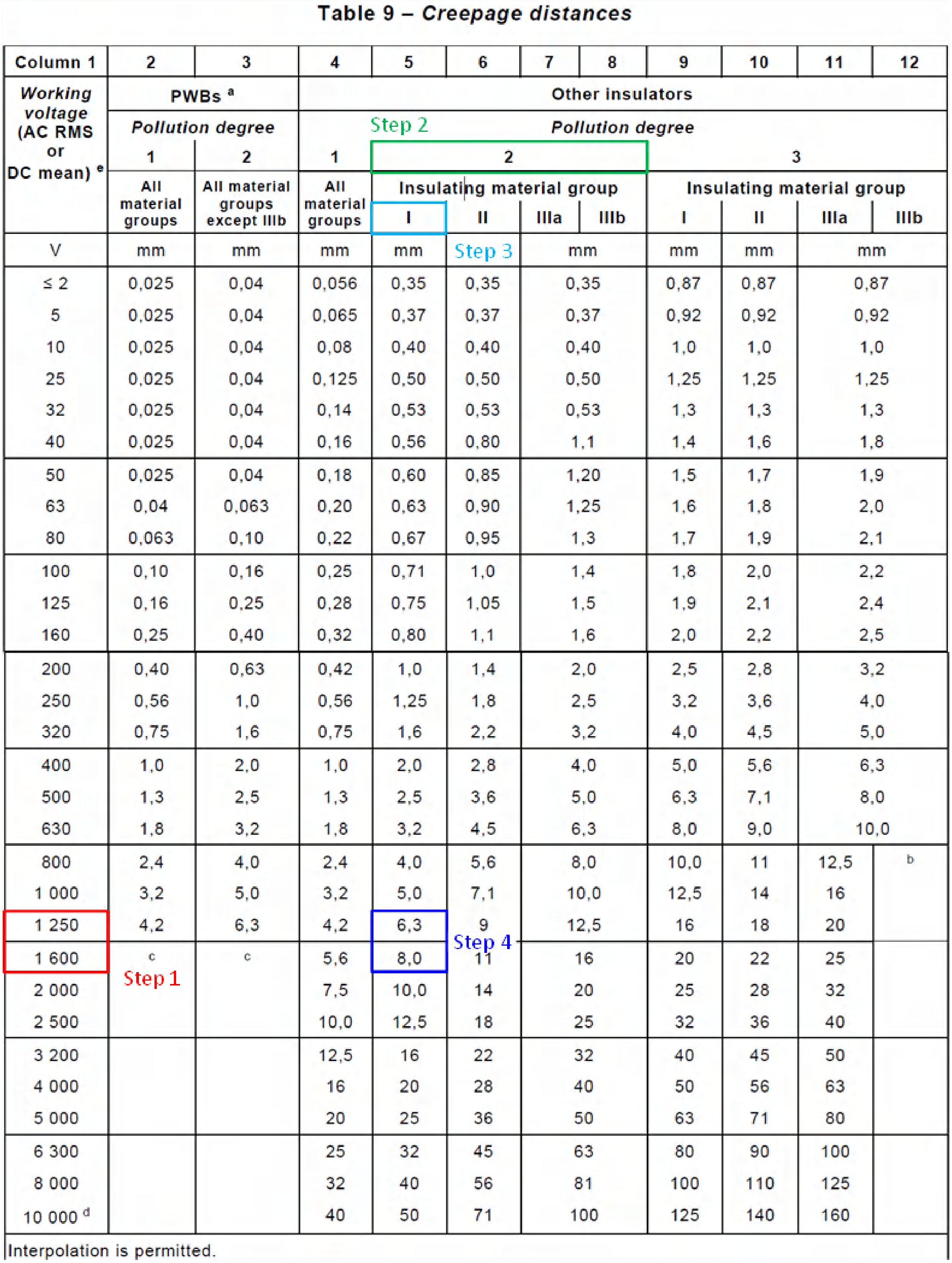


Table 9 – *Creepage distances*

Column 1	2	3	4	5	6	7	8	9	10	11	12
Working voltage (AC RMS or DC mean) [e]	PWBs [a]		Other insulators								
	Pollution degree		*Pollution degree*								
	1	2	1	2				3			
	All material groups	All material groups except IIIb	All material groups	Insulating material group				Insulating material group			
				I	II	IIIa	IIIb	I	II	IIIa	IIIb
V	mm	mm	mm	mm	mm	mm		mm	mm	mm	
≤ 2	0,025	0,04	0,056	0,35	0,35	0,35		0,87	0,87	0,87	
5	0,025	0,04	0,065	0,37	0,37	0,37		0,92	0,92	0,92	
10	0,025	0,04	0,08	0,40	0,40	0,40		1,0	1,0	1,0	
25	0,025	0,04	0,125	0,50	0,50	0,50		1,25	1,25	1,25	
32	0,025	0,04	0,14	0,53	0,53	0,53		1,3	1,3	1,3	
40	0,025	0,04	0,16	0,56	0,80	1,1		1,4	1,6	1,8	
50	0,025	0,04	0,18	0,60	0,85	1,20		1,5	1,7	1,9	
63	0,04	0,063	0,20	0,63	0,90	1,25		1,6	1,8	2,0	
80	0,063	0,10	0,22	0,67	0,95	1,3		1,7	1,9	2,1	
100	0,10	0,16	0,25	0,71	1,0	1,4		1,8	2,0	2,2	
125	0,16	0,25	0,28	0,75	1,05	1,5		1,9	2,1	2,4	
160	0,25	0,40	0,32	0,80	1,1	1,6		2,0	2,2	2,5	
200	0,40	0,63	0,42	1,0	1,4	2,0		2,5	2,8	3,2	
250	0,56	1,0	0,56	1,25	1,8	2,5		3,2	3,6	4,0	
320	0,75	1,6	0,75	1,6	2,2	3,2		4,0	4,5	5,0	
400	1,0	2,0	1,0	2,0	2,8	4,0		5,0	5,6	6,3	
500	1,3	2,5	1,3	2,5	3,6	5,0		6,3	7,1	8,0	
630	1,8	3,2	1,8	3,2	4,5	6,3		8,0	9,0	10,0	
800	2,4	4,0	2,4	4,0	5,6	8,0		10,0	11	12,5	[b]
1 000	3,2	5,0	3,2	5,0	7,1	10,0		12,5	14	16	
1 250	4,2	6,3	4,2	6,3	9	12,5		16	18	20	
1 600	[c]	[c]	5,6	8,0	11	16		20	22	25	
2 000			7,5	10,0	14	20		25	28	32	
2 500			10,0	12,5	18	25		32	36	40	
3 200			12,5	16	22	32		40	45	50	
4 000			16	20	28	40		50	56	63	
5 000			20	25	36	50		63	71	80	
6 300			25	32	45	63		80	90	100	
8 000			32	40	56	81		100	110	125	
10 000 [d]			40	50	71	100		125	140	160	

Interpolation is permitted.

Figure 4-6. CPG Determination Steps

Table 4-1. Clearances and Creepage Distance Summary 1

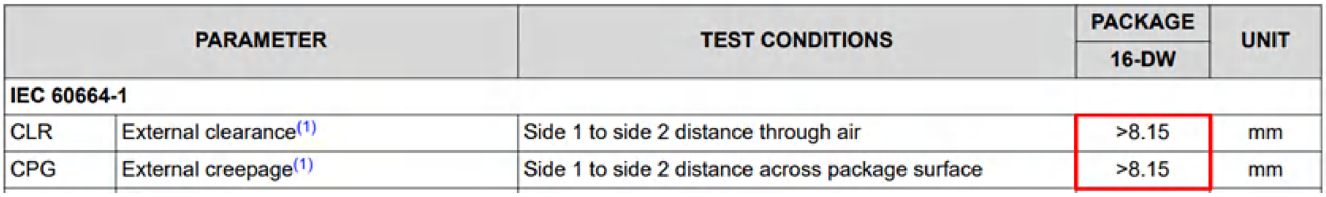
1500VDC, OVC II, CTI-I, Pollution Degree 2				
	Clearances		Creepage	
Altitude	Basic	Reinforced	Basic	Reinforced
4000m	10.32mm (8 1.29)	18.06mm (14*1.29)	7.514mm 10.32mm	15.028mm (7.514*2) 18.06mm
5000m	11.84mm (8*1.48)	20.72 mm (14*1.48)	7.514mm 11.84mm	15.028mm (7.514*2) 20.72mm

In some cases, the isolation design may be difficult to satisfy the required impulse withstand voltage under the corresponding OVC level. A practical way is to reduce the impulse withstand voltage a step lower, such as from 8000V to 6000V (OVC II to OVC I) by adding SPD to lower the isolation design difficulties. More examples can refer to Annex I (informative) Examples of *overvoltage category* reduction in *IEC 62477-1:2022*.

Table 4-2 summarizes the results of reducing OVC II to OVC I. Now we can see that 8.14mm clearance and creepage distance is required for Basic insulation at 5000m altitude. Now this is supported in TI latest digital isolator ISO64xx, as shown in Figure 4-7.

Table 4-2. Clearances and Creepage Distance Summary 2

1500VDC, OVC I, CTI-I, pollution degree 2				
	Clearances		Creepage	
Altitude	Basic	Reinforced	Basic	Reinforced
4000m	7.095mm (5.5*1.29)	10.32mm (8*1.29)	7.514mm	15.028mm (7.514*2)
5000m	8.14mm (5.5*1.48)	11.84mm (8*1.48)	7.514mm 8.14mm	15.028mm (7.514*2)



PARAMETER		TEST CONDITIONS	PACKAGE 16-DW	UNIT
IEC 60664-1				
CLR	External clearance[(1)]	Side 1 to side 2 distance through air	>8.15	mm
CPG	External creepage[(1)]	Side 1 to side 2 distance across package surface	>8.15	mm

Figure 4-7. ISO64xx Clearance and Creepage Distance

5 Methods to Change Creepage Distances Requirements

The definition of creepage distance is the shortest distance between two conductive materials (pins) measured along the insulating surface. It means that the creepage distance can be changed if it's not enough in some situations.

Figure 5-1 shows the PCB cutout method to increase the creepage distance. For example, if using CTI IIIa or CTI IIIb PCB to replace CTI I or CTI II PCB for saving cost, the PCB creepage distance may be not enough and PCB cutout is needed to increase the creepage distance.

Note that PCB cutout can only increase PCB creepage distance but can't increase the isolated devices or components creepage distance.

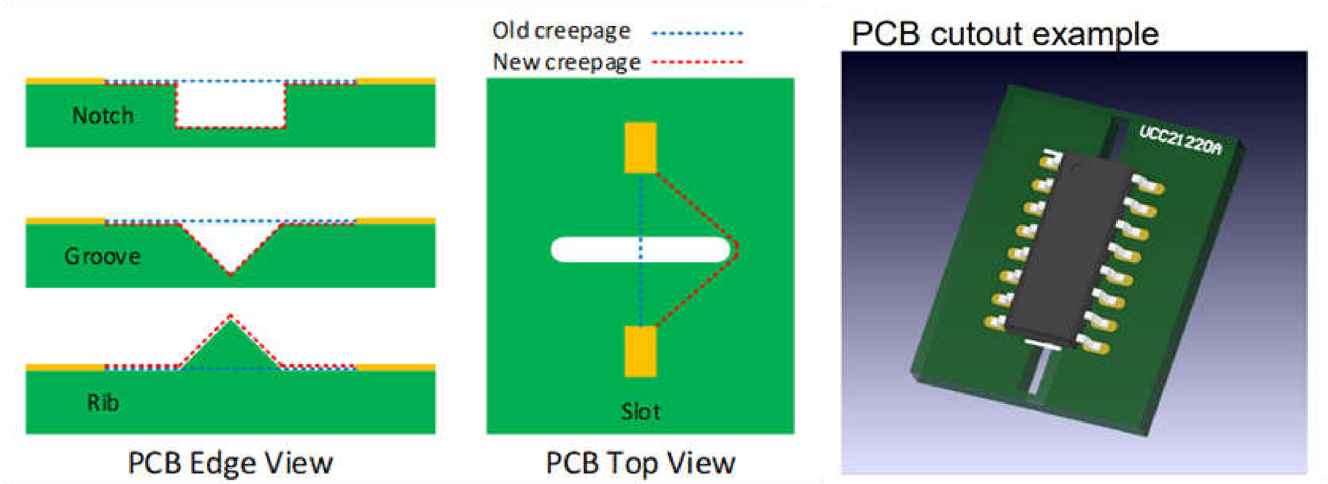


Figure 5-1. PCB Cutout Method to Increase Creepage Distance

Figure 5-2 illustrates the PCB conformal coating solution for lowering the pollution degree of PCB, which enables reduced creepage distance requirements.

This does not eliminate air gaps between conductive materials (pins), meaning the insulation form remains air-based. Under such protection, the clearance and creepage distance criteria for Pollution Degree 1 specified in Figure 4-1 and Figure 4-2 are applicable. Notably, only the pollution degree can be downgraded, while clearance values cannot be reduced. Furthermore, only Type 1 coating that meets the conditions for pollution degree downgrade can reduce the required creepage distance in accordance with pollution degree 1. Poor coating quality such as pinholes, air bubbles or incomplete coverage results in invalid safety compliance, and the original pollution degree shall still be adopted for calculation.

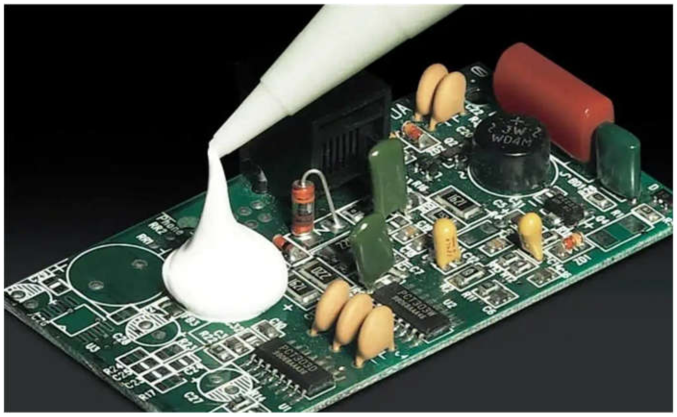


Figure 5-2. PCB Conformal Coating for Lowering the Pollution Degree

When air insulation design fails to meet specified clearance and creepage distance limits, the potting method shown in Figure 5-3 can be adopted to achieve solid insulation.

Potting is Type 2 protection (as defined in IEC 60664-3:2016) which replaces air insulation completely with solid insulation materials. Accordingly, the conventional clearance and creepage distance requirements stated in Figure 4-1 and Figure 4-2 are no longer applicable.

In general, potting delivers higher insulation performance than conformal coating, yet it involves additional design efforts, complicated manufacturing procedures and significantly higher costs. Besides, solid insulation compliance must be fully validated via official certification tests such as AC/DC withstand voltage test, impulse withstand voltage test, partial discharge test and thermal cycling test by authoritative bodies such as VDE and TUV, rather than relying solely on theoretical calculations.

For this reason, designers tend to select isolators and components that inherently meet insulation specifications instead of adopting potting solutions, unless no alternative design scheme is available.

Figure 5-3. Potting Method to Achieve Solid Insulation

6 Summary

Many engineers struggle with selecting appropriate isolated components and defining required clearance and creepage distances. This application note provides in-depth insights into key insulation characteristics of isolated devices, analyzes factors affecting insulation performance, and offers a step-by-step guide to calculating clearance and creepage distances.

7 References

1. Texas Instruments, *Key Considerations to Select ISO Devices and Demystify Clearance and Creepage Distance*, application note.
2. Texas Instruments, *Safety Regulation Design Examples of Solar and ESS System*, application note.
3. Texas Instruments, *Digital Isolator Design Guide*, application note.
4. Texas Instruments, *About This Isolation Glossary*, application note.
5. Texas Instruments, *ISO644x General-Purpose, Basic and Reinforced, Quad-Channel Digital Isolators*, datasheet.
6. Texas Instruments, *UCC23513, 4-A Source, 5-A Sink, 5.7-kVRMS Opto-Compatible Single-Channel Isolated Gate Driver*, datasheet.
7. Texas Instruments, *ISO1050 Isolated CAN Transceiver*, datasheet.
8. Texas Instruments, *ISO1042 Isolated CAN Transceiver With 70-V Bus Fault Protection and Flexible Data Rate*, datasheet.
9. Texas Instruments, *ISO774x High-Speed, Robust-EMC Reinforced and Basic Quad-Channel Digital Isolators*, datasheet.
10. Texas Instruments, *ISO7842x High-Performance, 8000VPK Reinforced Quad-Channel Digital Isolator*, datasheet.
11. IEC, *IEC 60747-17:2020*.
12. VDE, *VDE 0884-17:2021-10*.
13. UL, *UL 1577*.
14. IEC, *IEC 62368-1:2023*.
15. IEC, *IEC 61010-1:2010*.
16. IEC, *IEC 60601-1:2025 SER*.
17. National Standard of the People's Republic of China, *GB 4943.1-2022*.
18. IEC, *IEC 62477-1:2022*.
19. IEC, IEC 62477-2:2018.
20. IEC, *IEC 62109-1:2010*.
21. IEC, *IEC 60950-1:2005+AMD1:2009+AMD2:2013*.
22. VDE, *VDE 0884-5:2015-11*.
23. IEC, *IEC 60747-5-5:2020*.
24. IEC, *IEC 60664-1:2020*.
25. UL, UL 60950-1.

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you fully indemnify TI and its representatives against any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale, TI’s General Quality Guidelines, or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products. Unless TI explicitly designates a product as custom or customer-specified, TI products are standard, catalog, general purpose devices.

TI objects to and rejects any additional or different terms you may propose.

Copyright © 2026, Texas Instruments Incorporated

Last updated 10/2025