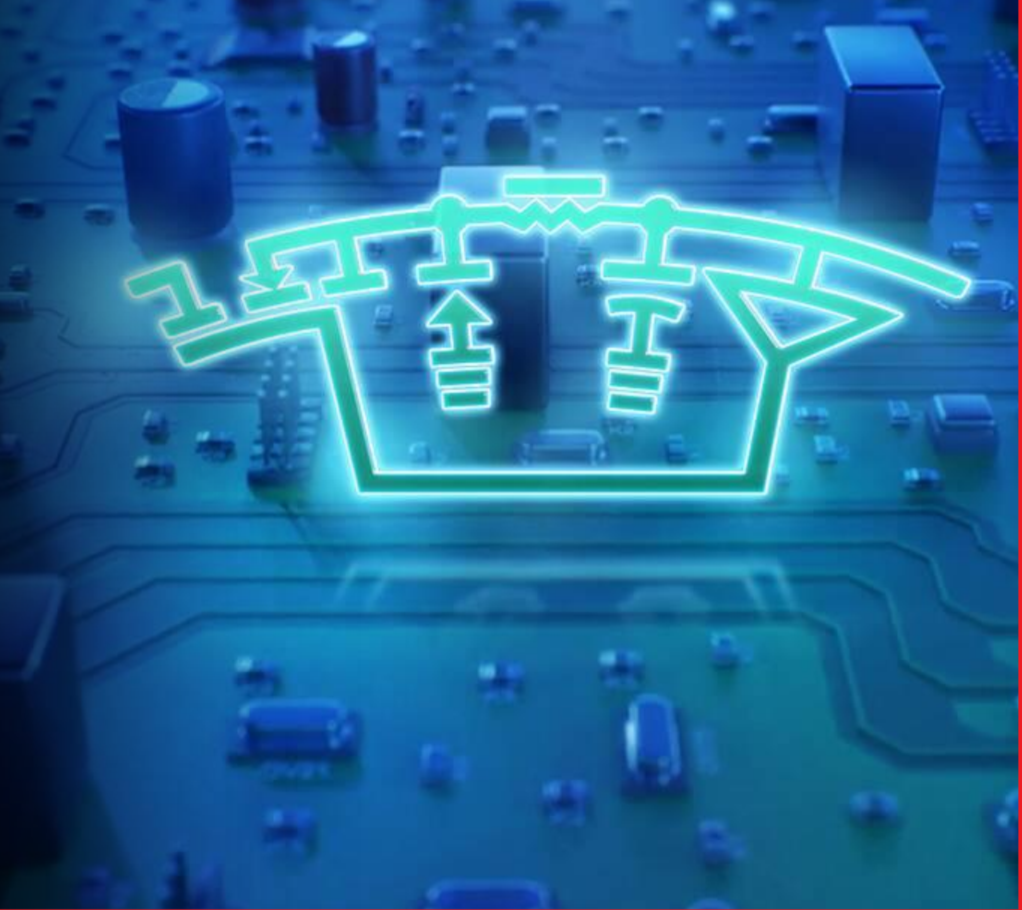
Texas Instruments

Power Supply Design Seminar

Demystifying clearance and creepage distance for high-voltage end equipment



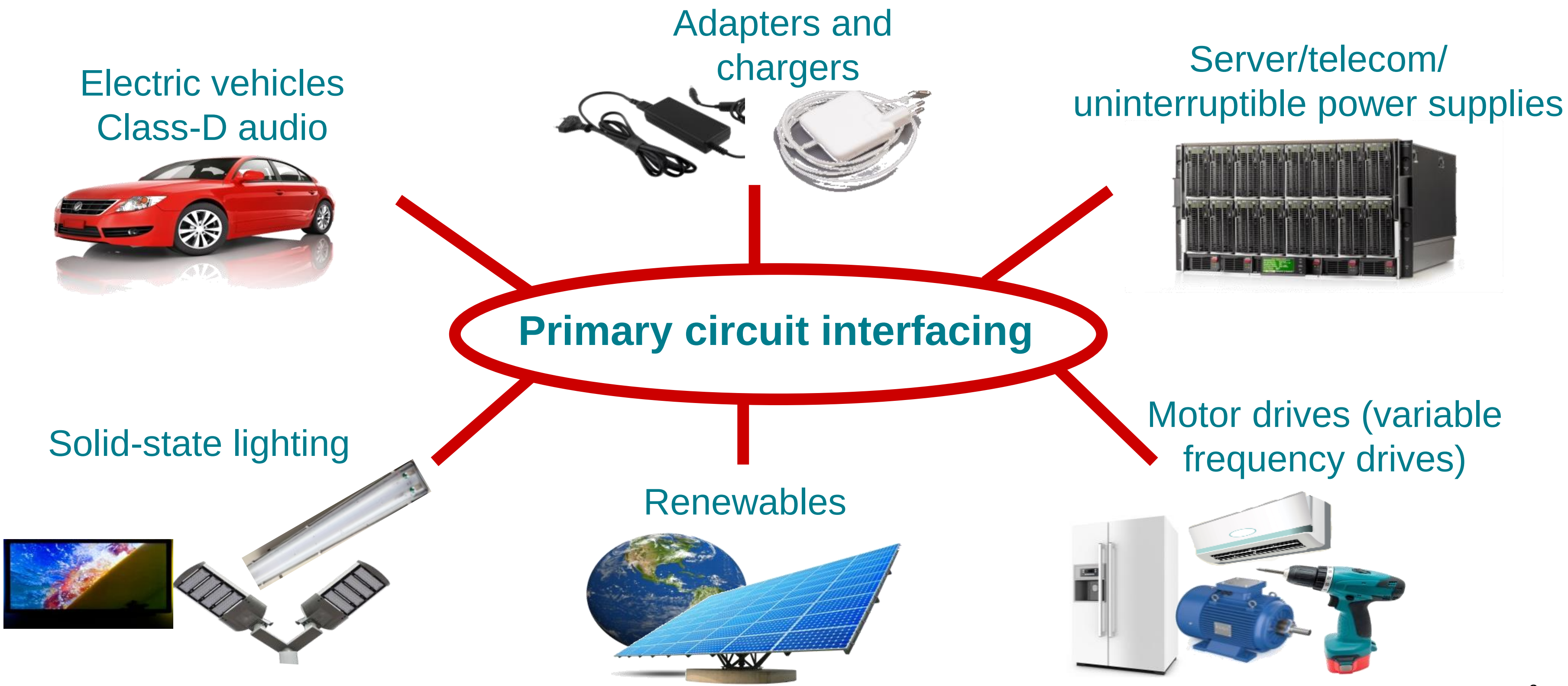
Authors

Wei Zhang and Thomas LaBella

Outline

- Definitions of creepage distance (CPG), clearance distance (CLR) and other relevant terms
- Different insulation grade levels and a selection guideline
- Flow chart to determine CLR and CPG, with end-equipment examples
- High-voltage printed circuit board (PCB) spacing standards and guidelines
- Other exceptions for high-voltage spacing

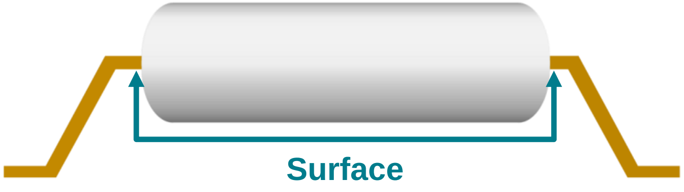
High-voltage applications



CPG and CLR

CPG
No insulation breakdown or tracking at a working voltage
(long term)

CLR
No air ionization or arcing to withstand required transients
(short term)



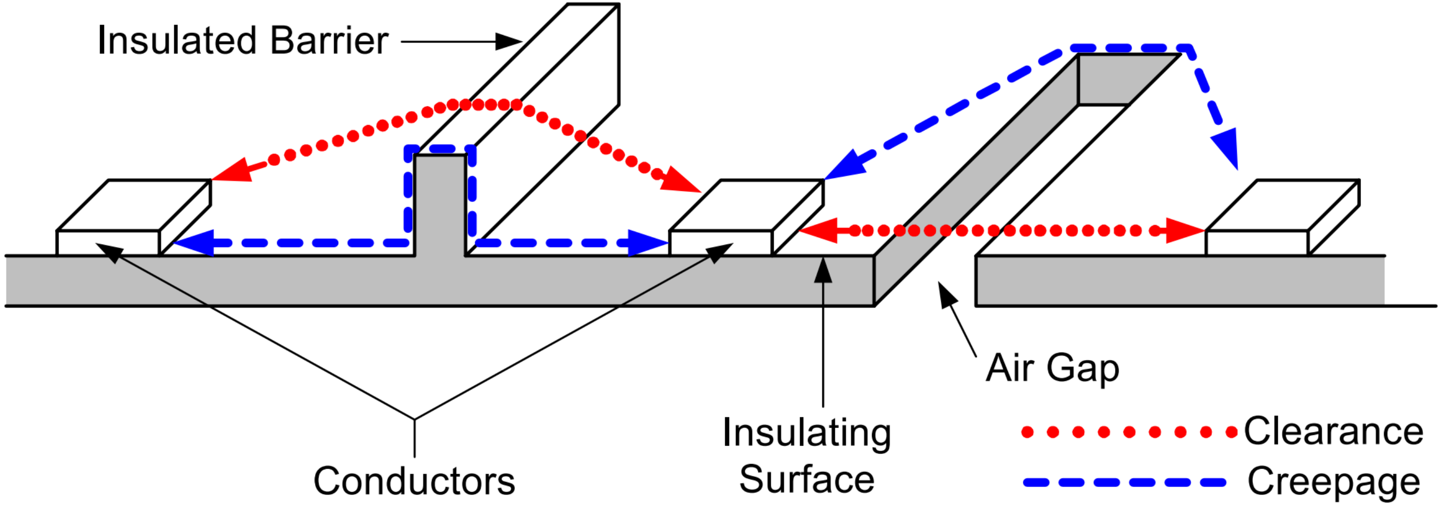
- Shortest distance **along the surface** of a solid insulating material between two conductive parts
- **Pollution, humidity, condensation** matter most
- Dimensioned for:
  - **Root-mean square (RMS) working voltage**
  - **Pollution degree**
  - **Material group** (no flashover or breakdown of insulation will occur)

- Shortest distance in **air** between two conductive parts
- **Air pressure (altitude), temperature** matters most
- Dimensioned for:
  - **Transient overvoltages***
  - **Pollution degree**
  - **Altitude** (Multiplication factor 2,000 m above sea level; e.g. ×1.48 at 5,000 m)

*Transient voltage – short duration overvoltage of a few milliseconds or less

CPG and CLR relationship

- There is no physical relationship between CPG and CLR
  - In most cases, CPG requirements will not be less than associated CLR
- **What is good enough?** Maximize whenever possible vs. size and cost



Material groups and the CTI

- **Material groups** depend on the comparative tracking index (CTI)
- CTI is the maximum V_{RMS} at which an insulating material withstands 50 drops (per 30 s) of contaminated water (0.1% ammonium chloride)
  - No tracking (<0.5 A) (formation of conductive paths)

Material groups	CTI range (V_{RMS})
Material group I	CTI ≥ 600
Material group II	400 ≤ CTI < 600
Material group IIIa	175 ≤ CTI < 400
Material group IIIb	100 ≤ CTI < 175 or if not specified

TI isolated integrated circuits

Most FR4 PCBs

*Material group is verified by an evaluation of the test data according to International Electrotechnical Commission IEC 60112

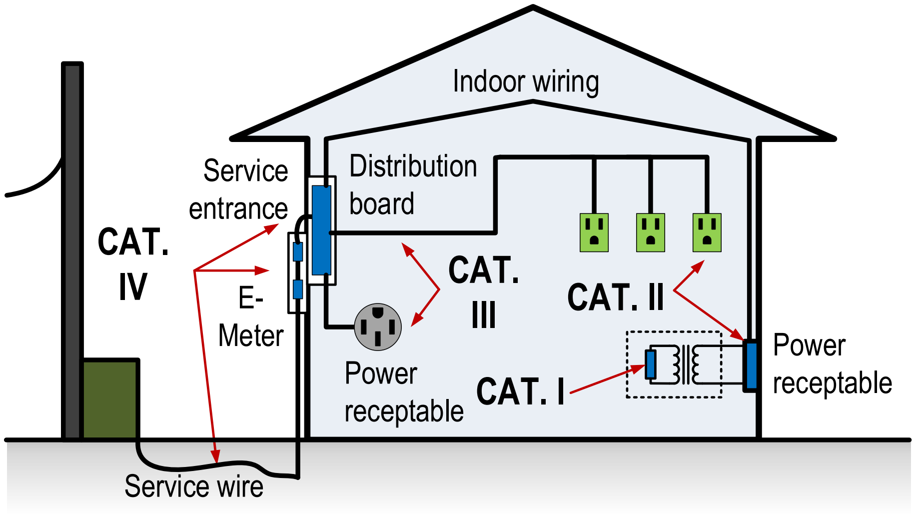
Pollution degrees

Classes	Descriptions	Examples
Pollution degree 1	• There is no pollution or only dry, nonconductive pollution	• **Sealed** components (coated PCB), clean room
Pollution degree 2	• Temporarily becomes conductive because of occasional condensation	• Telecom enclosure by IEC 60950-1 or IEC 62368-1 • Lab, office
Pollution degree 3	• Subject to conductive pollution • Nonconductive pollution that could become conductive **from expected condensation**	• Industrial, unheated factory rooms and farming
Pollution degree 4	• Continuous conductivity occurs because of conductive dust, rain or other wet conditions	• Outdoor applications

Transient overvoltage category

- The overvoltage category is also referred to as the required impulse withstand voltage
- A **probabilistic implication** used for equipment energized directly from low-voltage mains

Category	Descriptions	Examples
IV	Original installation	• Electricity meters • **4 kV_{PK}***
III	Fixed installation where availability is subject to special requirements	• Utility panel • Distribution board • **2.5 kV_{PK}***
II	Energy-consuming equipment supplied from fixed installation	• Outlets, 10-m away from III • **1.5 kV_{PK}***
I	Connection to circuit in which measures are taken to limit transient voltage to a low level	• Thermostat, sprinkler with 24 V_{AC} • **0.8 kV_{PK}***



*Residential 120/240 V_{AC} line to neutral

No single standard for different voltage classes and end equipment

User safety in an insulation system		PCB
• IEC 60664-1 – insulation coordination for $<1.5\text{-kV}_{DC}$ or $<1\text{-kV}_{AC}$ systems • CPG and CLR, electric strength testing		For proper or functional operation only
IEC 62368-1 (IEC 60950-1)*	Telecommunications, server, audio, video, communication, cloud computing	Institute of Printed Circuits (IPC) • IPC 2221 – general requirements • IPC 9592 – computer/telecommunications
IEC 61800-5	Motor drives	IEC 60664-1 CPG guidance for PCBs
IEC 62109-1	Solar	IEC 62368, separation distance for uncoated, coated

*IEC 60950-1 had been withdrawn in December, 2020

CPG and CLR – insulation parameters that matter

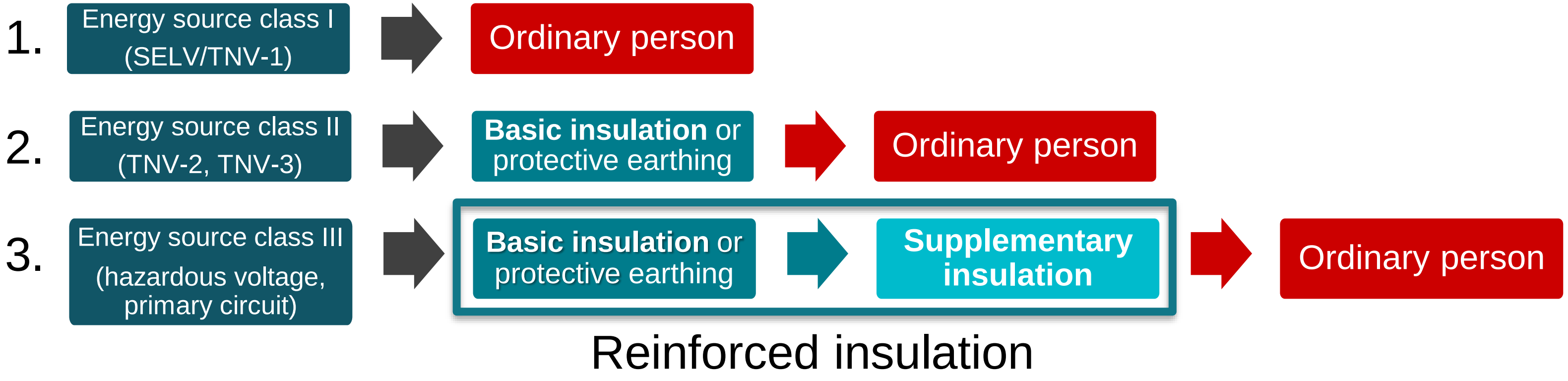
- Insulation standards for isolated components (such as an isolated gate driver) **do not address CPG and CLR.** Instead, they address the **insulation barrier's** capability to withstand electrical, mechanical stresses, and thermal and environmental influences. Examples include:
  - IEC 60747-1 (Verband der Elektrotechnik [VDE] 0884-11) for Europe; Underwriters Laboratories (UL) 1577 for U.S.; China Quality Certification Center (CQC) GB4943.1 for China. These component insulation standards addresses V_{IOSM}, R_{IO}, C_{IO}, q_{pd}, distance through insulation (DTI), common-mode transient immunity (CMTI), etc.

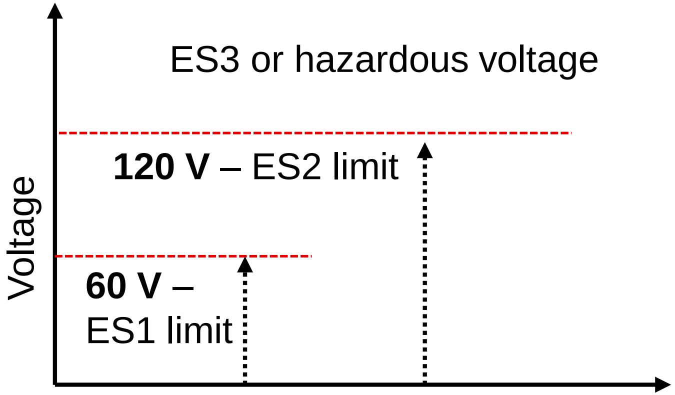
- However, **insulation grades** – basic, reinforced, functional insulation – **do matter** for CPG and CLR

Types of insulation grades

- **Functional insulation** or PCB high-voltage spacing
  - For proper functioning of the circuit – ground bounce, high voltage, transient between secondary circuits
- **Basic insulation**
  - Single level of insulation to protect against electric shock under both normal and abnormal operating conditions
- Supplementary insulation
  - Independent insulation applied in addition to Basic insulation
- Double insulation
  - Basic plus supplementary for normal, abnormal and **single-fault conditions**
- **Reinforced insulation**
  - A single insulation system that provides the same ratings as double insulation

Insulation grade guidelines

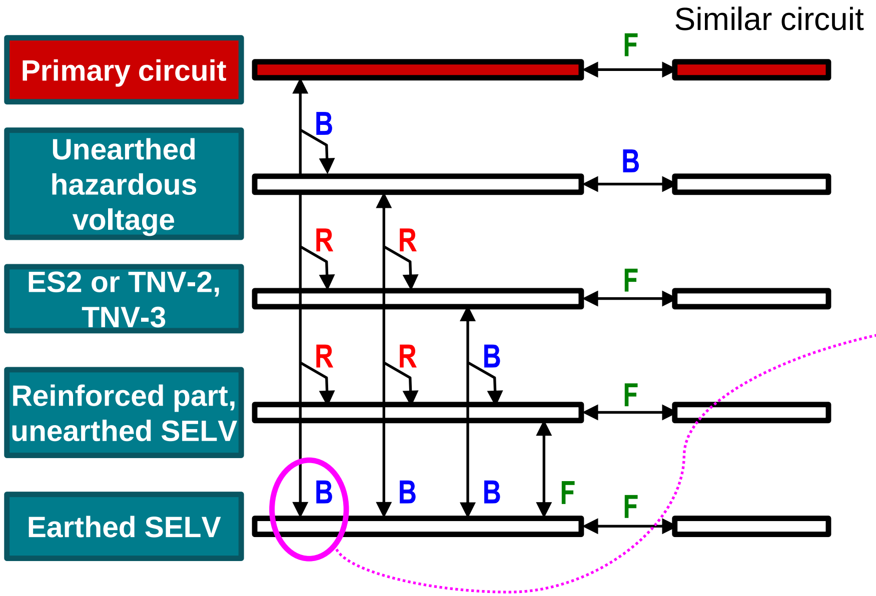




IEC 62368-1	IEC 60664-1, IEC 60950-1
ES1	**TNV-1,** Safety extra-low voltage (SELV)
ES2	**TNV-2, TNV-3***
ES3	Hazardous, primary circuit (connect to AC mains)
Ordinary person	User

*Section 2.3 of IEC 60950-1 defines TNV-1, TNV-2 and TNV-3

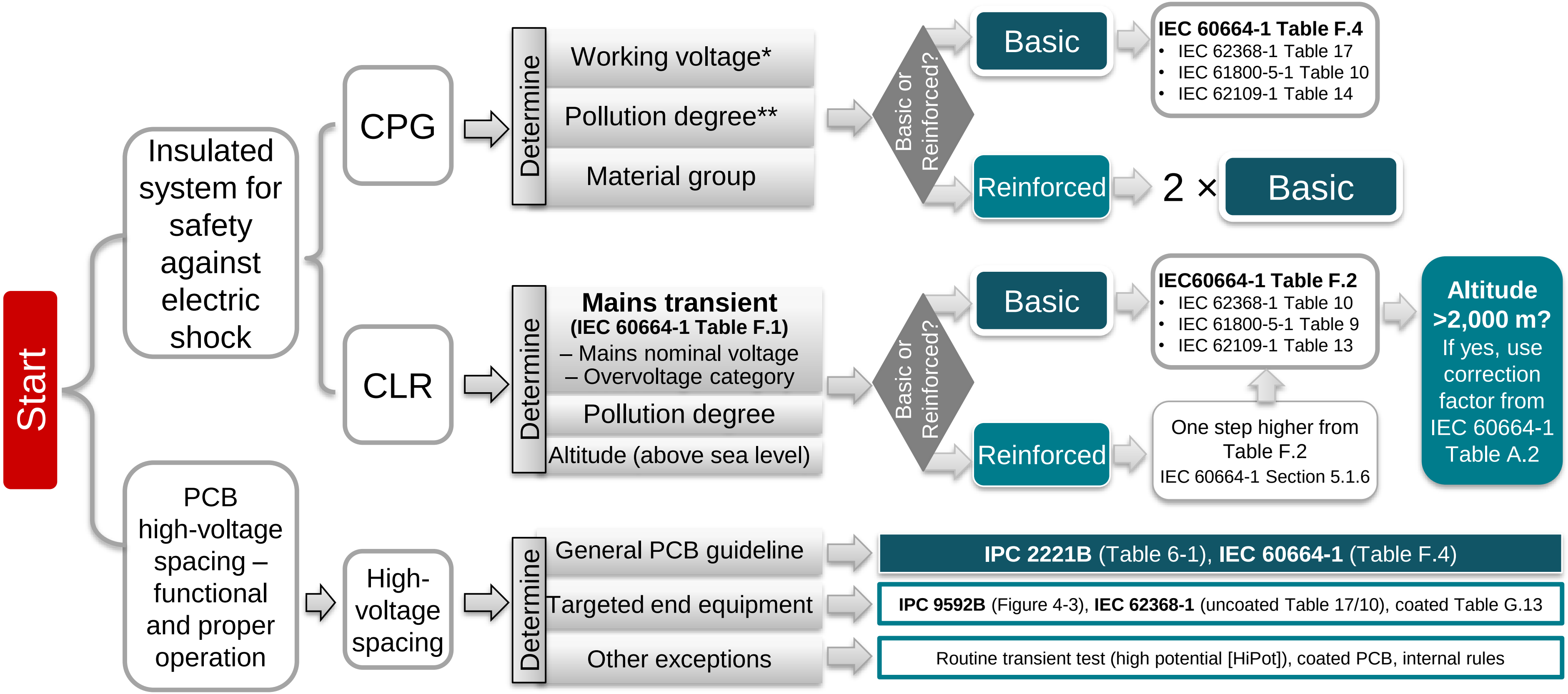
Insulation grade examples



Grades	Parts being separated		Example
F	SELV	SELV	<60-V brick module
	Reinforced part		
B	Primary, ES2, TNV-2/-3 hazardous voltage	SELV earthed	• >60-V DC/DC • AC to DC rectifiers with earthed 12-V output • On-board battery charger
	Primary	Unearthed hazardous	
R	Primary or hazardous voltage	SELV unearthed	AC to DC rectifiers with −48-V output
	ES2, TNV-2/-3		>60-V DC/DC
	Primary circuit	Reinforced part	On-board battery charger

- F: functional insulation; B: basic insulation; R: reinforced insulation
- Figure 2H IEC 60950-1 2013

Flow chart to determine CPG and CLR



*Working voltage: highest RMS value of the AC or DC voltage across insulation, IEC 60664-1 Section 3.5

**Coated PCB can help reduce to pollution degree 1 per IEC 62109-1 (follow IEC 60664-3) or IEC 62368 reduce the CPG distance using Table G.13

Mains transient voltage – IEC60664-1 Table F.1

- Determine transient voltage from **AC mains**
  - For all other end equipment, specify the transient voltage with reference from IEC 60664-1

Voltage line to neutral up to and including V_{RMS}	**Mains transient / rated impulse voltage (V_{PK})***			
	Overvoltage category			
	I	II	III	IV
• **≤50**	330	500	800	1,500
• **≤150**, for example, 120 (U.S., Japan)	800	1,500	2,500	4,000
• **≤300**, for example, 230 (EU, China)	1,500	**2,500**	**4,000**	6,000
• **≤600** for example, industrial motor or ship power	2,500	4,000	6,000	8,000

- Determining transient voltage from **short temporary overvoltages**:
  - Nominal line-to-neutral voltage +1,200 V for duration up to 5 seconds (IEC 60664-1 5.3.3.2.3)

*The impulse withstand test is carried out with a voltage having a 1.2/50-µs waveform

Clearance – IEC 60664-1 Table F.2

Required transient voltage (kV_{PK})	Minimum clearances (mm)*		
	Pollution degree		
	1	2	3
0.5	0.04	0.2	0.8
1.5	0.5 (0.76)		0.8
2.5	1.5 (1.8)		
4.0	3.0 (3.8)		
6.0	5.5 (7.9)		

Altitude (m)	Correction factor
2,000	1.0×
3,000	1.14×
4,000	1.29×
5,000	**1.48×**
6,000	1.70×
10,000	3.02×

- Clearance in parenthesis is from IEC 62368-1 Table 10 for **server telecommunications**
- The clearance assumes inhomogeneous field from IEC 60664-1 Table F.2 for basic insulation for use in altitudes up to 2,000 m
- For reinforced insulation, dimension CLR as specified the rate impulse voltage in Table F.2 but **one step higher**
- For all other end equipment, specify the clearance with reference from IEC 60664-1

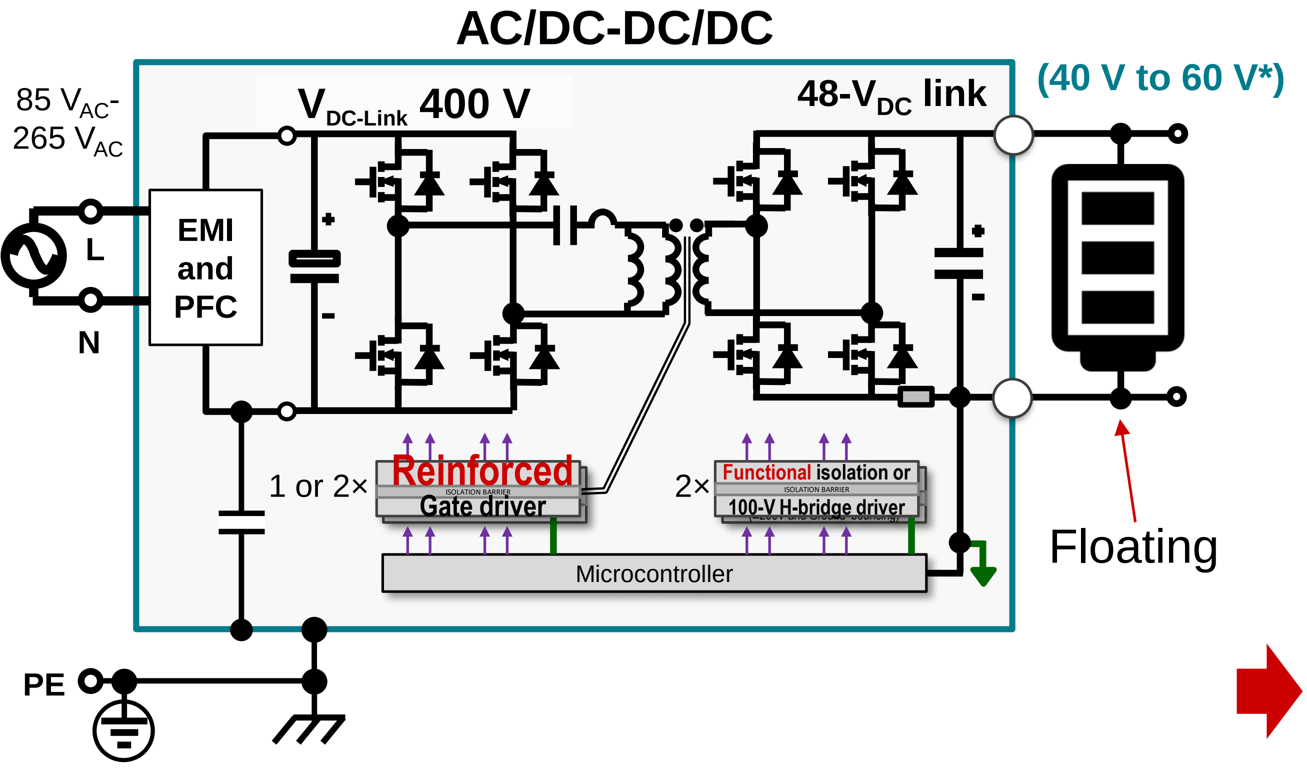
Creepage – IEC60664-1 Table F.4

V_{RMS}* (V)	CPG to avoid failure caused by tracking (mm)**			
	Pollution degree			
	1	2		
	All material groups	Material group		
		I	II	III
63	0.20	0.63	0.90	1.25
400	1.0	**2.0**	2.8	**4.0**
800	2.4	4.0	5.6	8.0
1,000	3.2	5.0	7.1	10.0

- CPG for **reinforced insulation** shall be **twice** the CPG for basic insulation from Table F.4
- The values of Table F.4 are based on existing empirical data and are suitable for the majority of applications. However, for functional insulation, values of CPG other than those in Table F.4 may be appropriate
- For all other end equipment, specify the creepage with reference from IEC 60664-1

*The voltage selected shall be appropriate for the highest rated voltage of the equipment
**It is possible to use linear interpolation between the nearest two points

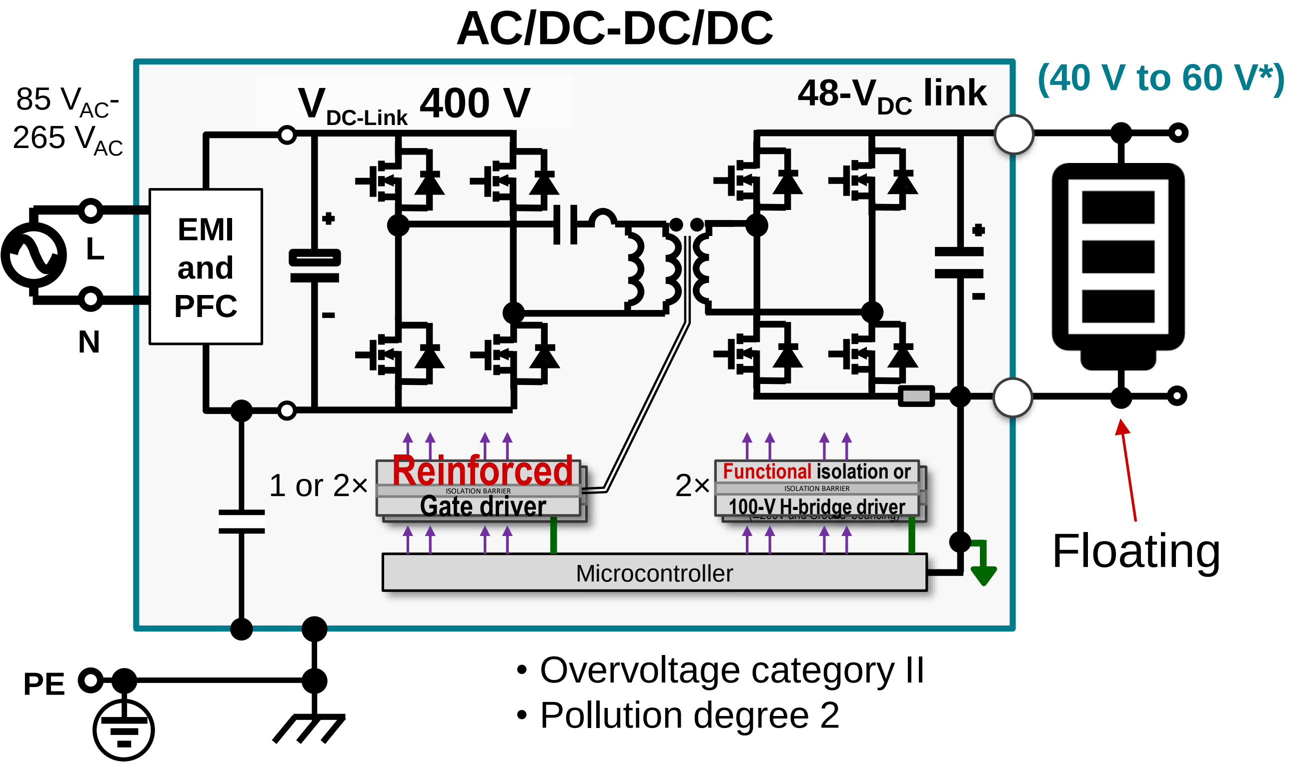
Example No. 1: Telecom AC/DC front end



Grade	Parts being separated	
F	SELV	SELV
	Reinforced part	
B	Primary, ES2, TNV-2, TNV-3, hazardous voltage	SELV earthed
	Primary	Unearthed hazardous
R	**Primary or hazardous voltage**	**SELV unearthed**
	ES2, TNV-2, TNV-3	

*−48 V_{DC} power system voltage range is **40.5 V_{DC} to 57 V_{DC}** (ETSI EN 300 132-2)

Example No. 1: Telecom AC/DC front end

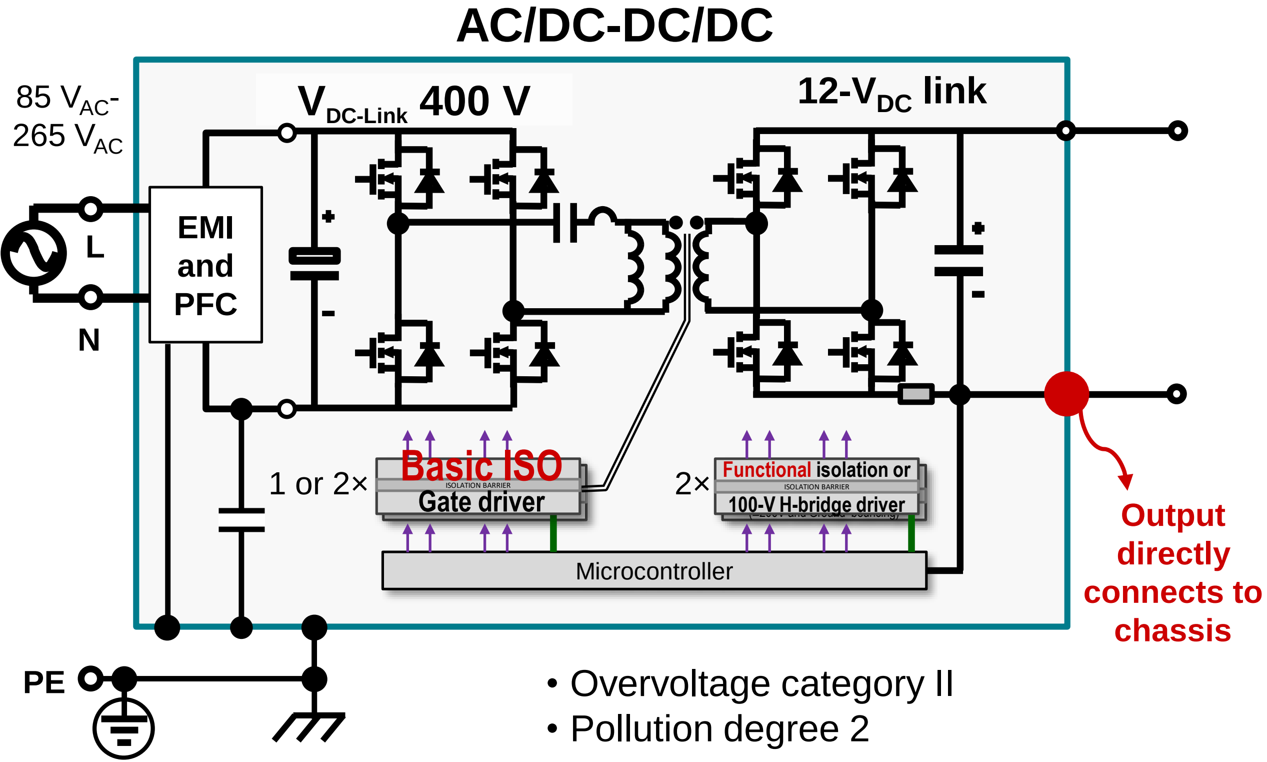


- Overvoltage category II
- Pollution degree 2

Item	Required
Insulation grade	Reinforced
AC mains transient	4,000 V
Clearance at 5,000 m	5.7 mm (3.8 mm × 1.48)
Creepage **(MG I)**	4.0 mm (2 mm × 2)
Creepage (MG II)	5.6 mm (2.8 mm × 2)
Creepage (MG III)	8.0 mm (4.0mm × 2)

*−48 V_{DC} power system voltage range is **40.5 V_{DC} to 57 V_{DC}** (ETSI EN 300 132-2)

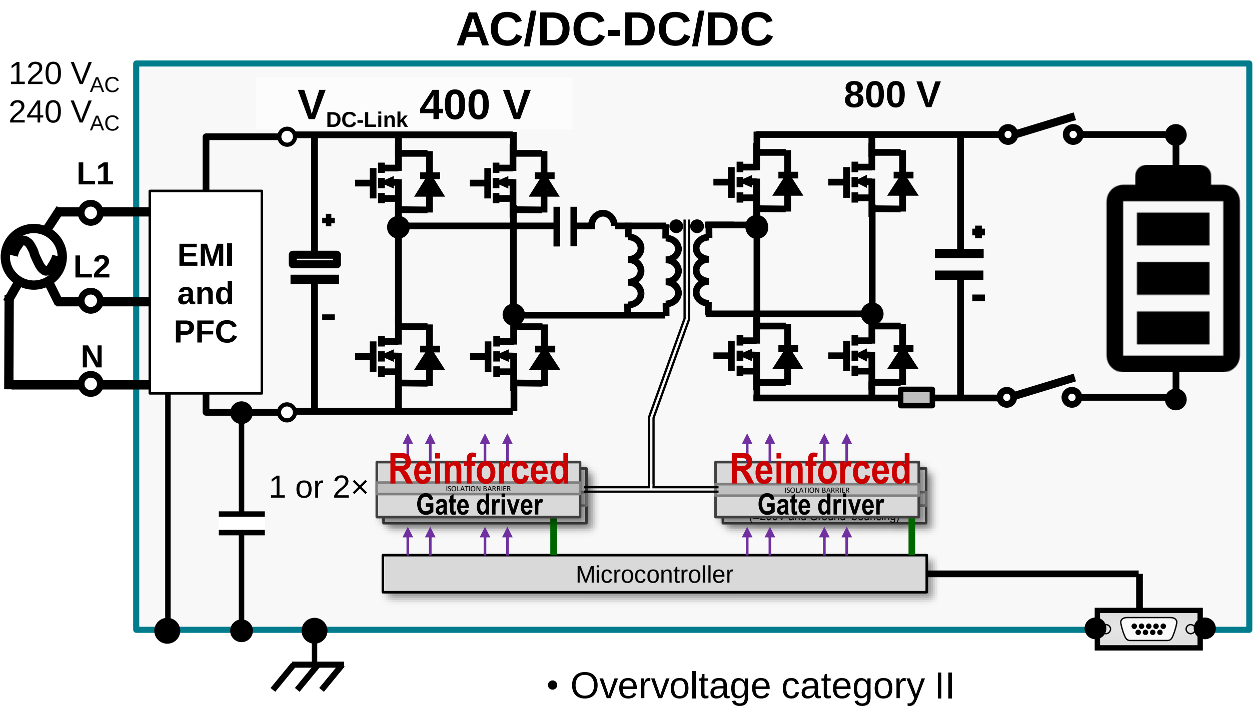
Example No. 2: Server with 12-V output



Item	Required
Insulation grade	Basic
AC mains transient	2,500 V
Clearance at 5,000 m	2.7 mm (1.8 mm × 1.48)
Creepage (MG I)	2 mm
Creepage (MG II)	2.8 mm
Creepage (MG III)	4.0 mm

- Overvoltage category II
- Pollution degree 2

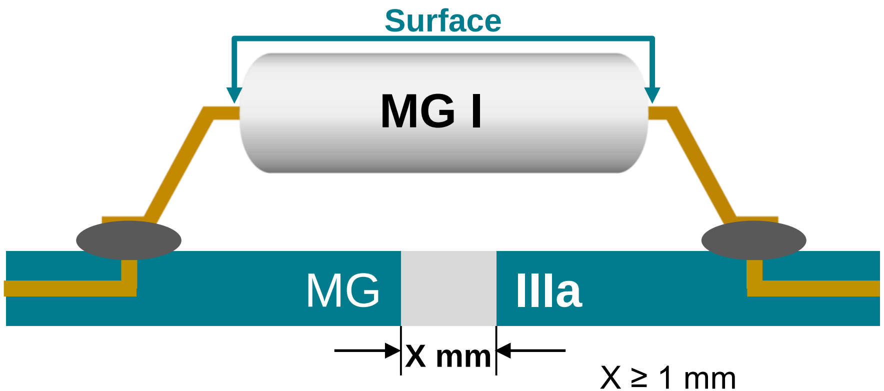
Example No. 3: Onboard battery charger



- Overvoltage category II
- Pollution degree 2

Item	Required
Insulation grade	Reinforced
AC mains transient	4,000 V
Clearance at 5,000 m	2.3 mm or 4.5 mm (1.5 or 3 mm × 1.48)
Creepage (MG I) 400 V	4.0 mm (2 mm × 2)
Creepage (MG II) 400 V	5.6 mm (2.8 mm × 2)
Creepage (MG I) 800 V	8.0 mm (4 mm × 2)
Creepage (MG II) 800 V	11.2 mm (5.6 mm × 2)

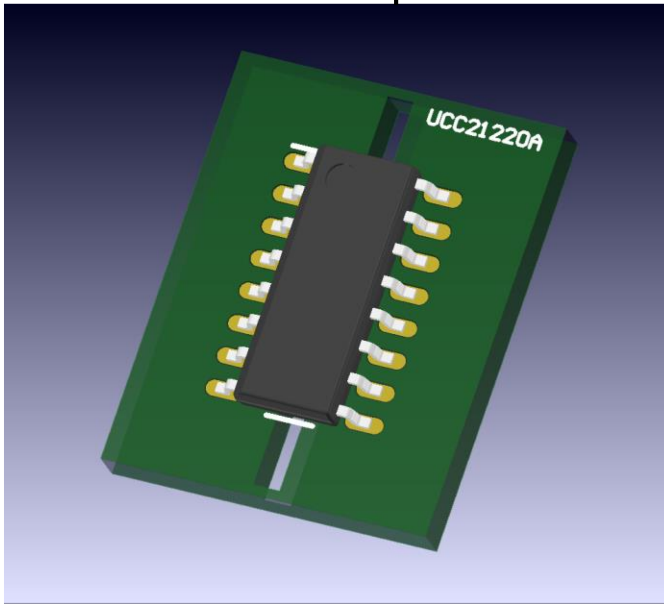
PCB cutout to increase the PCB creepage



X ≥ 1 mm

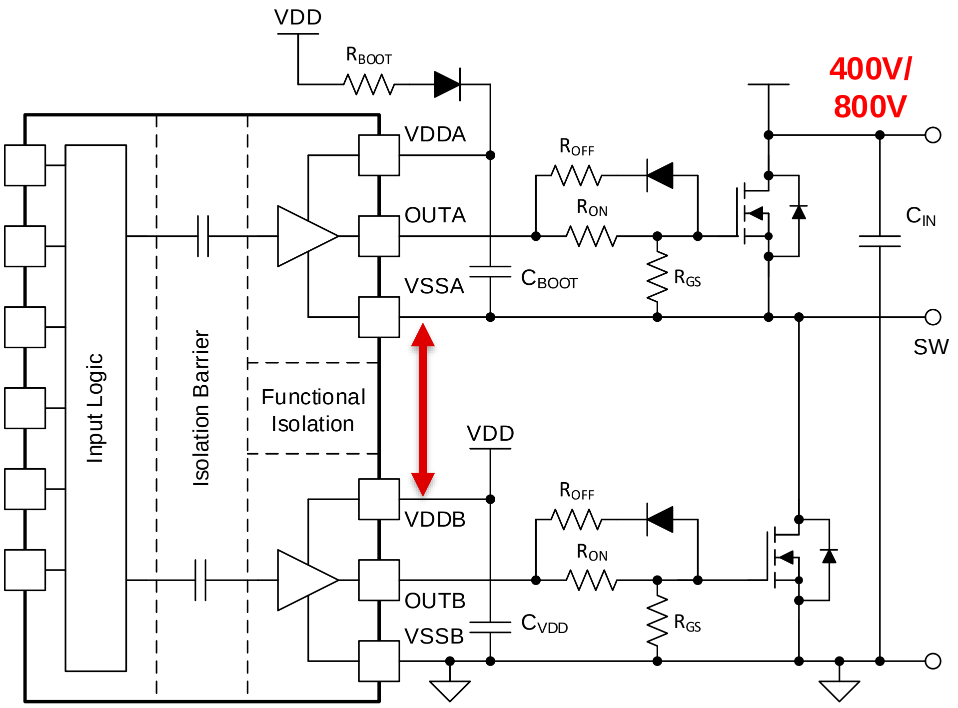
Pollution degree	Dimension × minimum value*
1	0.25 mm
2	1.0 mm
3	1.5 mm

PCB cutout example



*IEC 60664-1 Section 6.2 Ed 2.0

High-voltage spacing: PCBs

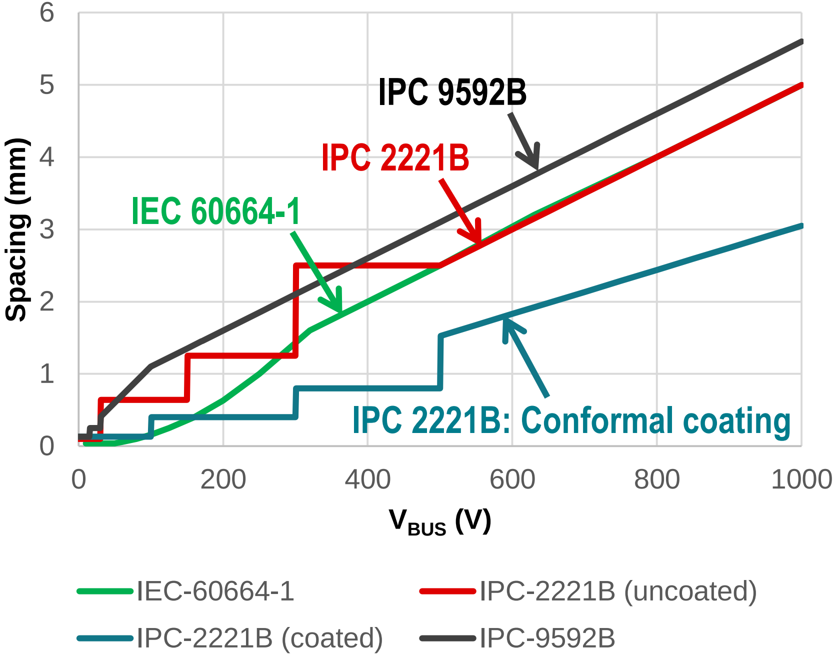


- IEC 60664-1 gives CPG guideline to avoid failure from tracking
- IPC-2221 “Generic standard on printed board design”
  - This standard gives extensive guidelines on PCB spacing based on environmental conditions and conformal coating
- IPC-9592 “Requirements for power conversion devices for the computer and telecommunications industries”
  - Provides guidelines for spacing requirements for uninsulated conductors

*UL 796, “Standard for Safety: Printed Wiring Boards” provides guidelines for vertical layer spacing

High-voltage spacing: PCB spacing requirements

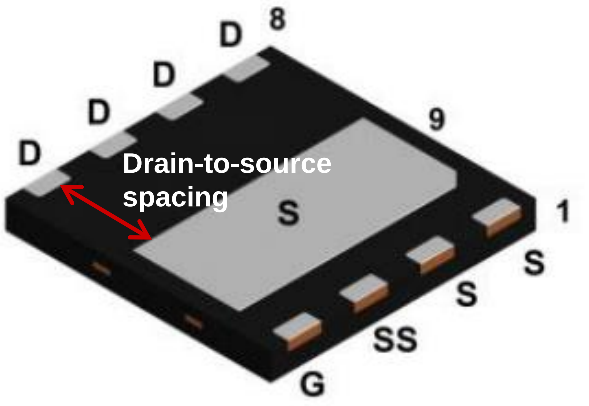
Voltage	IEC 60664-1	IPC 9592B $0.6 + V_{PK} \times 0.005$	IPC 2221B Uncoated	IPC 2221B Coated
(V)	(mm)			
20	0.04	0.7	0.1	0.13
32	0.04	0.75	0.64	0.13
63	0.063	0.9	0.64	0.13
125	0.25	1.2	0.64	0.4
400	**2**	**2.6**	2.5	0.8
800	**4**	4.6	**4**	2.44
1000	5	5.6	5	3.05



Existing high-voltage package examples

- There are inconsistencies in the industry, even for the same applications

Manufacturer	Package	Absolute maximum (DC)	High-voltage spacing
I1	8 × 8 DFN	650 V	2.325 mm
I2	8 × 8 DFN	600 V	2.8 mm
G1	8 × 8 DFN	650 V	2.8 mm
G2	8 × 8 DFN	650 V	2.74 mm
T1	8 × 8 DFN	650 V	2.5 mm
T1	TO247-3	650 V	2.7 mm
T1	TO220-3	650 V	1.11 mm
T2	7 × 9 QFN	650 V	2.1 mm



Other exceptions for high-voltage spacing

Functional insulation, to achieve proper operation for high-voltage environments, creepage and clearance, or **high-voltage spacing**, shall satisfy*:

- They meet the creepage and clearance requirements discussed above

or

- They withstand the electric strength **routine** test (the HiPot test)
  - The peak working voltage or the required withstand impulse voltage can decide the electric strength test voltage
    - Example: Phone or PC adapters can accept 1 kV/1 mm with the HiPot test

*Per the functional insulation description in IEC 60664-1 5.2.2.1 and 5.1.3.3, IEC 60950-1 5.3.4, and IEC 62368-1 B.4.4

Conclusions

- Reviewed definitions of critical terms, listing the impacts from each parameter to determine CPG and CLR with practical examples
- Summarized two approaches to determine CPG and CLR: insulation safety and high-voltage PCB spacing
- Introduced how to determine insulation grades
- Presented a flow chart to determine insulated system CPG and CLR and high-voltage spacing regarding PCBs, and reviewed critical tables used in the flow chart from IEC 60664-1
- Discussed three examples: telecommunications, server, and onboard battery charger
- Summarized and compared different high-voltage spacing from IPC and IEC standards
- Provided exceptions regarding functional insulation when not meeting the required CPG and CLR

Resources

- IEC 60664-1 Insulation coordination for equipment within low-voltage supply systems – part 1: principles, requirements and tests
- IEC 62368-1 Audio/video, information and communication technology equipment – part 1: safety requirements
- IEC 60950-1 Information technology equipment – safety – part 1: general requirements
- IEC 62109-1 Safety of power converters for use in photovoltaic power systems – part 1: general requirements
- IEC 61800-5-1 Adjustable speed electrical power drive systems – part 5-1: safety requirements – electrical, thermal and energy
- IPC 2221B Generic standard on printed board design
- IPC 9592B Requirements for power conversion devices for the computer and telecommunications industries

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