Texas Instruments

HIGH VOLTAGE SEMINAR

WEI ZHANG

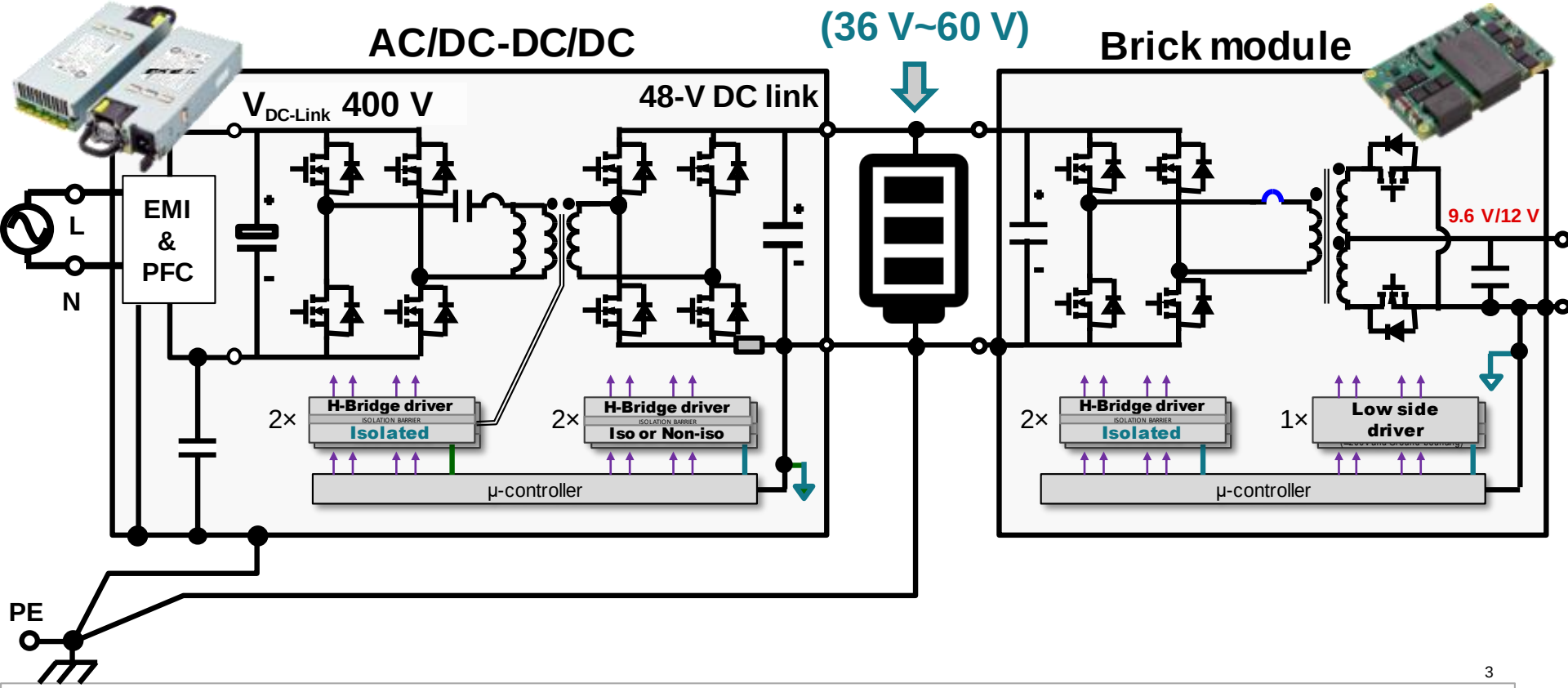
ISOLATED GATE DRIVERS

ISOLATED GATE DRIVER 101: FROM INSULATION SPEC TO END EQUIPMENT REQUIREMENTS

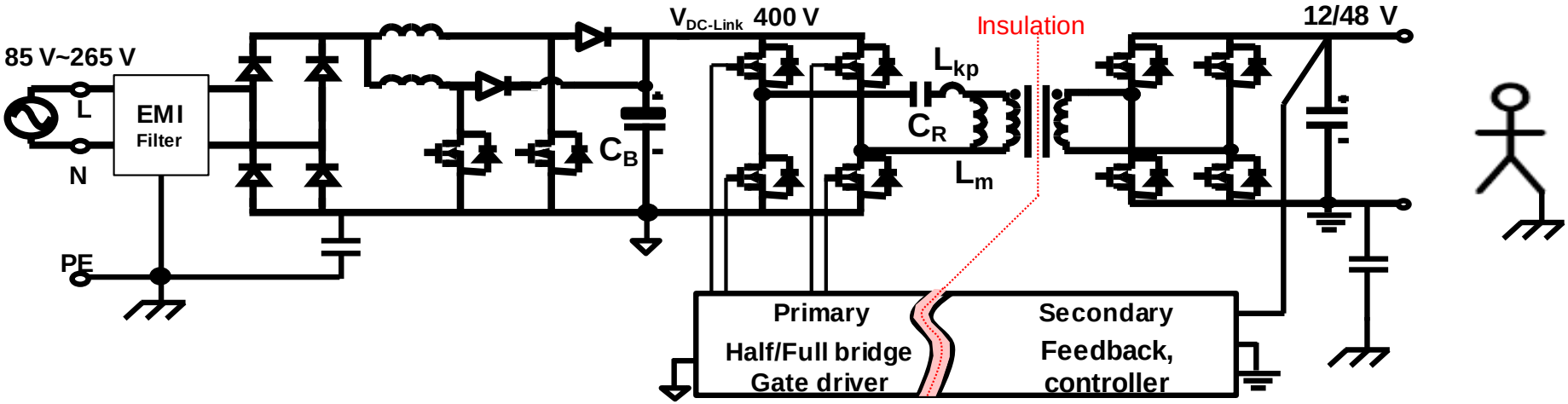
Agenda

- Isolated gate driver fundamentals
- Insulation specification and verification
- Requirements of isolated gate drivers in popular applications
- Questions

Isolated driver in server/telecom

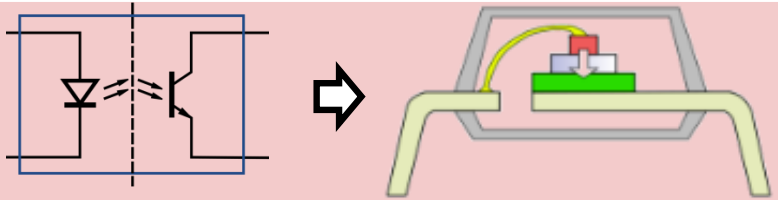
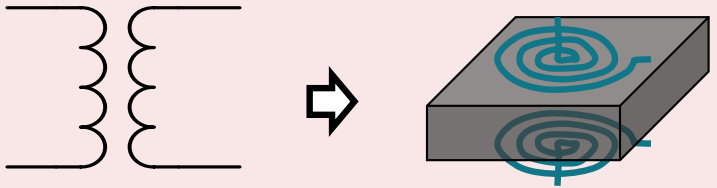
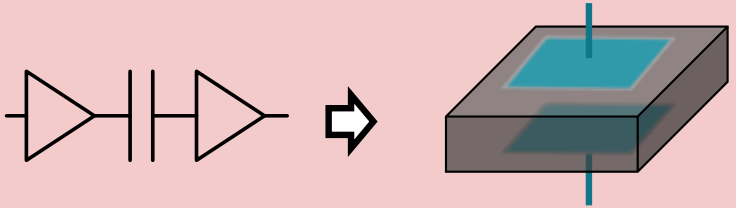


Why is isolation required?



1. Power delivery – $V_1/V_2=N_1/N_2$
2. Signal Communication
3. Safety
4. Breaking ground loop – CM noise
5. High voltage >800 V
6. Performance: high CMTI

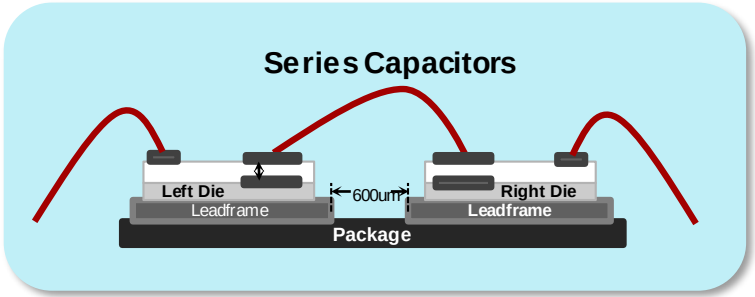
Types of isolation methods in gate drivers

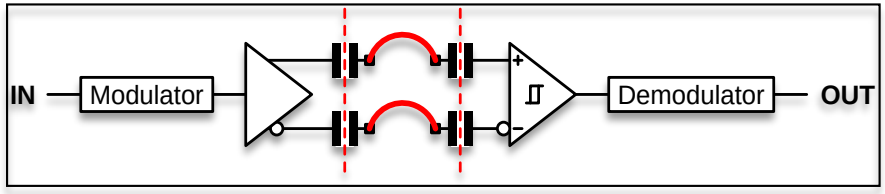
Technology	Advantages	Simplified diagram
Optical	➢ Long history ➢ Low emissions	
Inductive	❖ High speed data ❖ Low power ❖ CMTI ❖ Low ch-ch skew ❖ High temp	
Capacitive	❑ High speed data ❑ Low power ❑ CMTI ❑ Low channel-channel skew ❑ High temp ❑ **High working voltage**	

Types of isolation grades

- **Functional isolation**
  - ***For protecting circuits***
  - ***→Gnd bounce, high voltage, transient between secondary circuits***
- **Basic isolation**
  - Single level of isolation to protect against electric shock
- **Supplementary isolation**
  - Independent insulation if single level fails
- **Double isolation**
  - Basic + Supplementary → ***For human safety which requires redundancy***
- **Reinforced isolation**
  - **A single** insulation system that provides same ratings as double insulation

An example: reinforced capacitive isolation





- Reinforced isolation is realized by thick SiO_2 capacitors combined in series
  – Each channel uses high voltage isolation capacitors on both die
- Combined isolation capacitor thickness is >21 um
- 12.8 kV_{PK} surge voltage, 8 kV_{PK} transient over-voltage, 1.5 kV_{RMS} working voltage

Example: insulation spec. of an isolated gate driver

6.6 Insulation Specifications

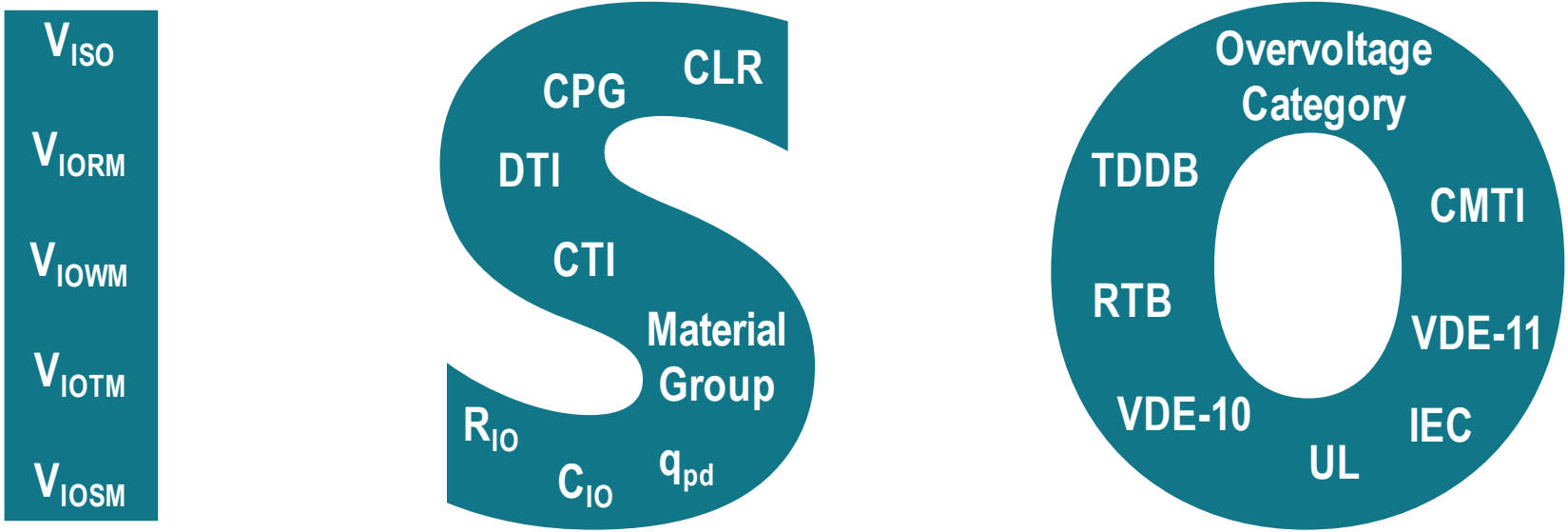
PARAMETER		TEST CONDITIONS
CLR	External clearance (1)	Shortest pin-to-pin distance through air
CPG	External creepage (1)	Shortest pin-to-pin distance across the pa
DTI	Dista	
CTI	Com	
	Mate	
	Ove IEC	
	Pollu	
	Clim	
UL 1577		
V_{ISO}	With	
$\lvert CM_H \rvert$	High-le immuni	
$\lvert CM_L \rvert$	Low-lev immuni	

DIN V VDE V 0884-11 (VDE V 0884-11): 2017-01 (2)			
V_{IORM}	Maximum repetitive peak isolation voltage	AC voltage (bipolar)	
V_{IOWM}	Maximum working isolation voltage	AC voltage (sine wave); time deper (TDDB), test (See Figure 1)	
		DC voltage	
V_{IOTM}	Maximum transient isolation voltage	$V_{TEST} = V_{IOTM}$, t = 60 sec (qualifica $V_{TEST} = 1.2 \times V_{IOTM}$, t = 1 s (100%	
V_{IOSM}	Maximum surge isolation voltage (3)	Test method per IEC 62368-1, 1.2/5 $V_{TEST} = 1.6 \times V_{IOSM} = 12800\ V_{PK}$ (	
q_{pd}	Apparent charge (4)	Method a, After Input/Output safety $V_{ini} = V_{IOTM}$, t_{ini} = 60s; $V_{pd(m)} = 1.2 \times V_{IORM} = 2545\ V_{PK}$, t_m	
		Method a, After environmental tests $V_{ini} = V_{IOTM}$, t_{ini} = 60s; $V_{pd(m)} = 1.6 \times V_{IORM} = 3394\ V_{PK}$, t_m	
		Method b1; At routine test preconditioning (type test) $V_{ini} = 1.2 \times V_{IOTM}$; t_{ini} = 1s; $V_{pd(m)} = 1.875 * V_{IORM} = 3977\ V_{PK}$	
C_{IO}	Barrier capacitance, input to output (5)	V_{IO} = 0.4 sin (2πft), f =1 MHz	
R_{IO}	Isolation resistance, input to output (5)	V_{IO} = 500 V at T_A = 25°C	
		V_{IO} = 500 V at 100°C ≤ T_A ≤ 125°C	
		V_{IO} = 500 V at T_S =150°C	

IEC/EN/DIN EN 60747-5-5 Insulation Characteristics* (Option

Description	Symbol
Installation classification per DIN VDE 0110/39, Table 1 for rated mains voltage ≤ 150V_{RMS} for rated mains voltage ≤ 300V_{RMS} for rated mains voltage ≤ 450V_{RMS} for rated mains voltage ≤ 600V_{RMS} for rated mains voltage ≤ 1000V_{RMS}	
Climatic Classification	
Pollution Degree (DIN VDE 0110/39)	
Maximum Working Insulation Voltage	V_{IORM}
Input to Output Test Voltage, Method b* $V_{IORM} \times 1.875 = V_{PR}$, 100% Production Test with t_m =1 sec, Partial discharge < 5 pC	V_{PR}
Input to Output Test Voltage, Method a* $V_{IORM} \times 1.6 = V_{PR}$, Type and Sample Test, t_m =10 sec, Partial discharge < 5 pC	V_{PR}
Highest Allowable Overvoltage* (Transient Overvoltage t_{ini} = 60 sec)	V_{IOTM}
Safety-limiting values – maximum values allowed in the event of a failure	
Case Temperature	T_S
Input Current	$I_{S, INPUT}$
Output Power	$P_{S, OUTPUT}$
Insulation Resistance at T_S, V_{IO} = 500V	R_S

Terminologies



What is the purpose?

- **Capability verification** for basic, supplementary and reinforced insulation barrier to withstand

  1. ***Electrical*** stresses
  2. ***Mechanical*** stresses

     as well as

  3. ***Thermal*** and ***environmental*** influences

which may occur during the anticipated life of the equipment

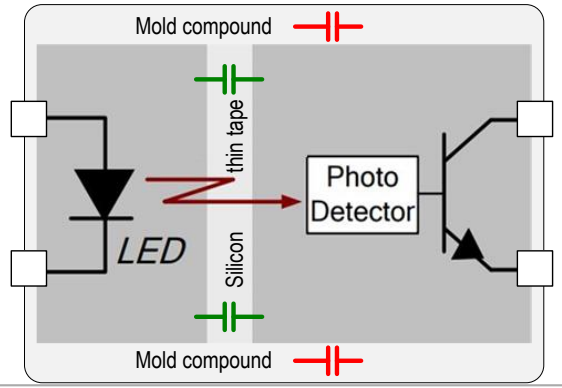
Standards – a broad categorization

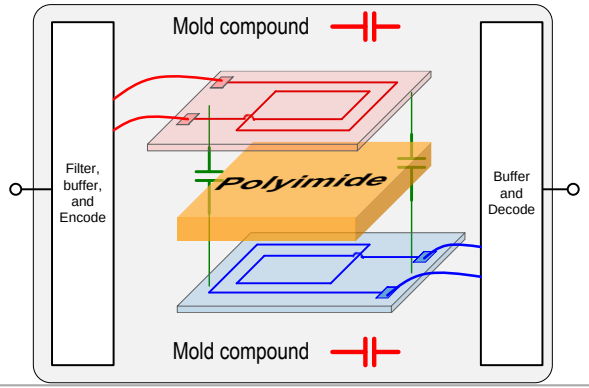
Category	Standards	Coverage	Terminologies
Component standard	IEC 60747-5-5 (VDE 0884-5-5)	Opto-couplers only	R_{IO}/C_{IO}, V_{ISO}/V_{IOTM}, V_{IORM}, V_{IOSM}, V_{IOWM}, CMTI, q_{pd}, CTI,
	IEC60747-17 (release soon)	Magnetic and capacitive coupler	
	VDE 0884-10, -11		Above spec "$-V_{ISO}$, +TDDB"
	UL 1577	Opto-couplers & digital isolator	V_{ISO}
Equipment standard	IEC 60601-1	Medical equipment	
	IEC 61010-1	Measurement, control and lab	
	IEC 60950-1 & IEC 62368-1	Information Technology up to 600 V	CLR, CPG, Pollution Degree, Material Group, Over voltage category
Supporting standard	IEC 60664-1	Insulation coordination for low-voltage systems	

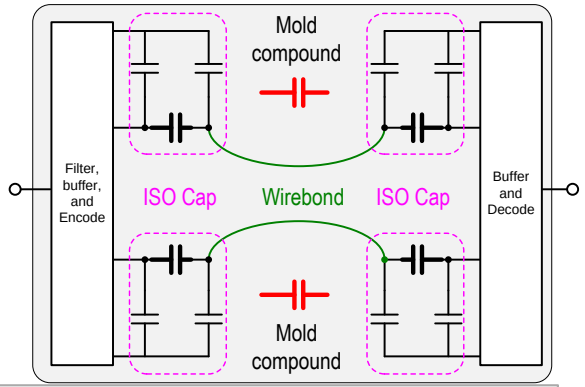
R_{IO}, C_{IO}

- C_{IO} – Input-to-output capacitance
  - The total capacitance between all input terminals connected together and all output terminals connected together
  - F = 1 MHz, I_F = 0, I_C = 0, V_{IO} = 0.4 sin(ωt)
  - Capacitance meter
  - Resistance meter (V_{IO}=500 V)

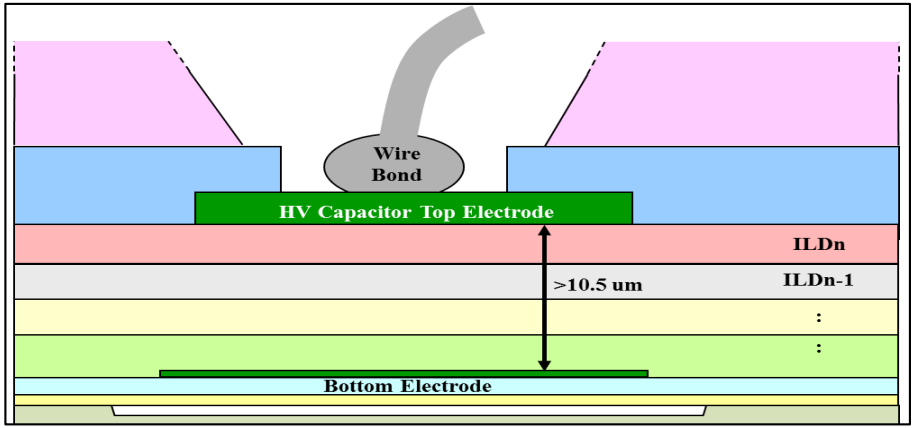
Temp	Requirement
T_{amb}	>10^{12} Ω
$T_{amb.max}$	>10^{11} Ω
T_S	>10^9 Ω

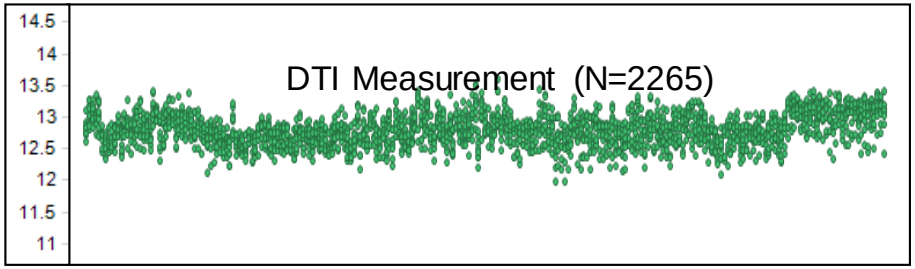






DTI: Distance Through Insulation



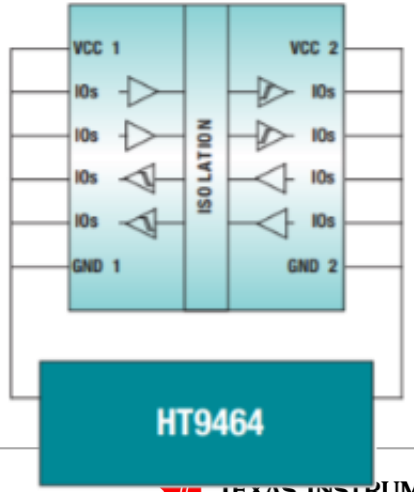


Mean = 12.79vum w/ 0.25vum StDev, CPK=3.1

- **Thickness** is directly related to breakdown voltage
- **Reinforced** barrier consists of **two** high voltage capacitors
  - HV Caps on each die
- Each capacitor has a thick **SiO_2** dielectric > 10.5 µm

V_{ISO}, V_{IOTM}: isolation withstand voltage

- V_{ISO} – Maximum withstanding isolation a.c. (r.m.s.) voltage for 1min
  - UL1577 specifies test either using DC or AC voltage source
- V_{IOTM} – Maximum transient isolation voltage (A peak value) = 1.414 × V_{ISO}
  - **Purpose** – verify the ability of the device to withstand the isolation test voltage under specified conditions for a short period, i.e. arcing, load change
  - AC voltage with commercial frequency for 1 min
  - **Routine test**
    - IEC: 1 s or 2 s is at 100% or maximum 120% of 1 min rating
    - UL: 1 s at ≥120%
  - T_A=25 °C
  - Requirements
    - Ext. or int. flash-over shall not occur during the test
    - Shall **pass the post-test measurements**



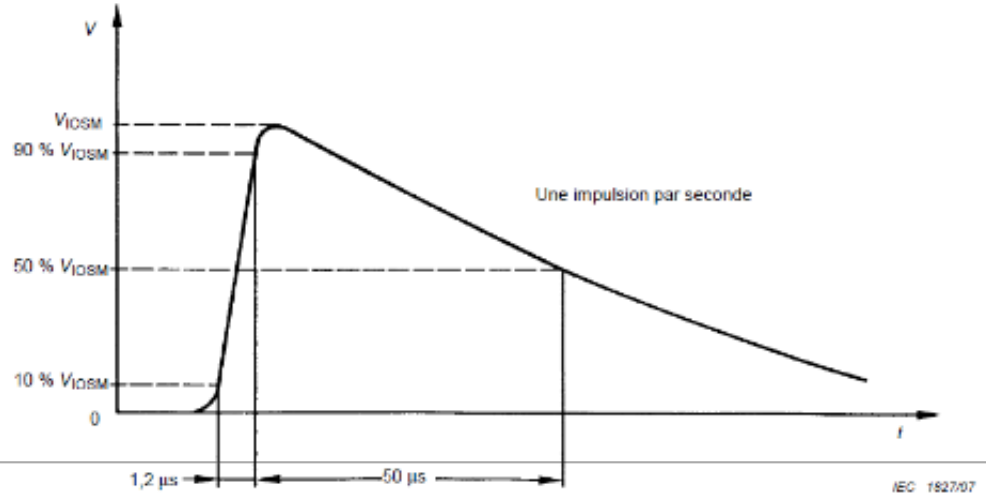
V_{IOWM} and V_{IORM}

- V_{IOWM} – Maximum working isolation voltage
  - Characterizing the specified **long term or the working voltage** withstand capability of the isolation
  - **r.m.s voltage** includes equivalent d.c. voltage

- V_{IORM} – Maximum repetitive **peak** isolation voltage
  - A repetitive **peak value** of withstand voltage, characterizing the specified withstand capability of its isolation against repetitive peak voltages
  - **$V_{IORM} = 1.414 \times V_{IOWM}$ for most datasheets**
  - The degradation of the galvanic isolation **depends normally on the peak voltage**, V_{IORM} is the repetitive peak value of the absolute envelop voltage over time.

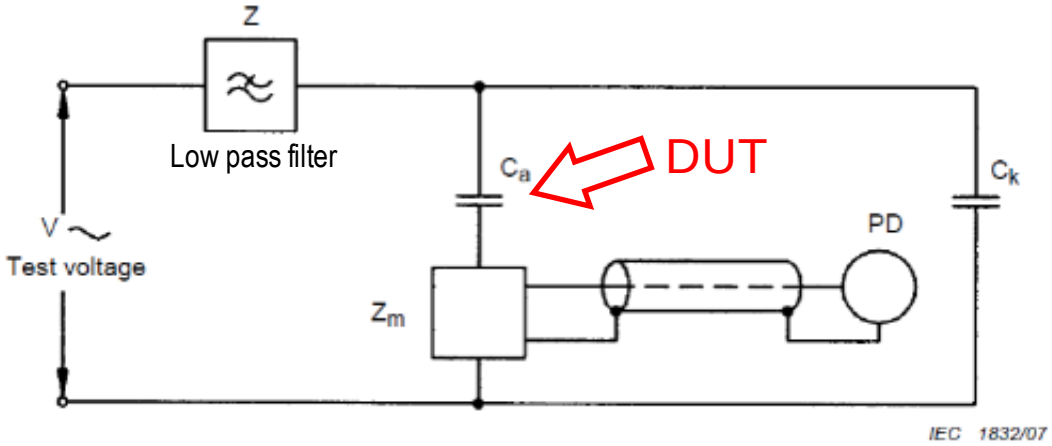
V_{IOSM}

- V_{IOSM} – Maximum surge isolation voltage **(type test only)**
  - The **highest instantons value of an isolation voltage pulse** with short time duration and of specified wave shape
  - **Goal:** Verifies the DUT's immunity to very high voltage levels over a short period of time, e.g. lightening strike
  - One pulse per second, 50 consecutive surge pulses



Q_{pd}: apparent charge caused by partial discharge

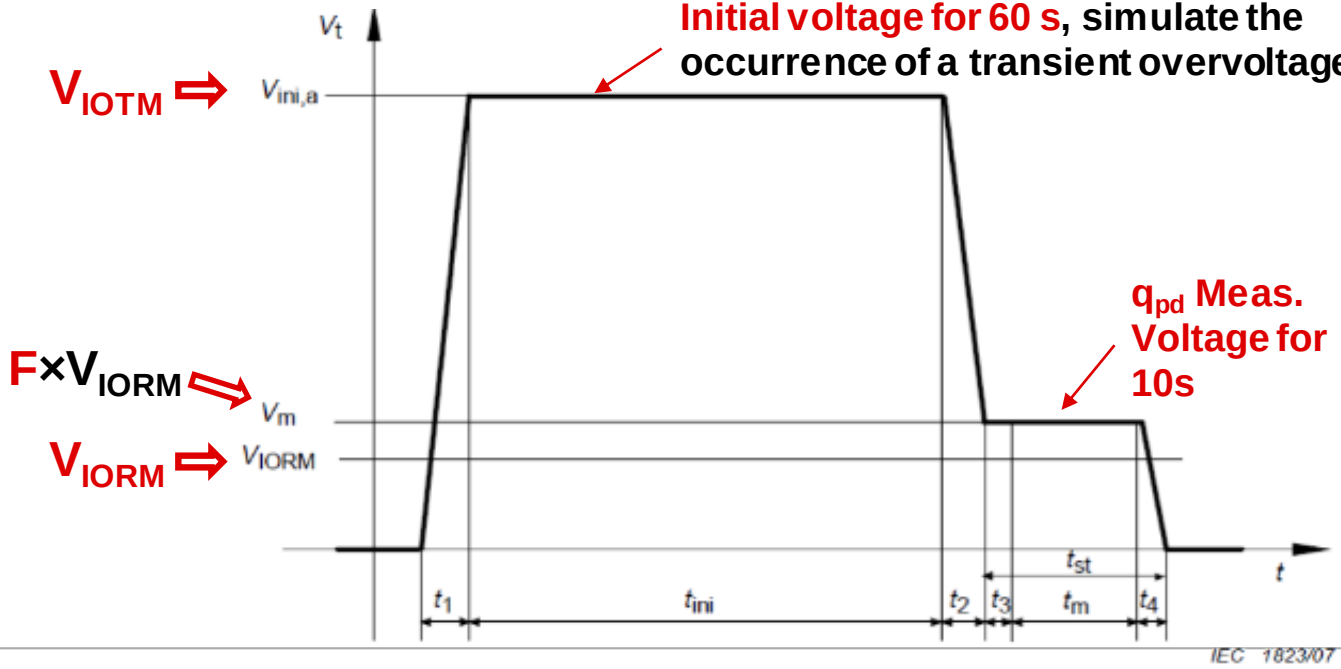
- An electric discharge that only partially bridge the insulation between conductors
- **Goal** – to verify the performance of insulation between input and output of a insulator by measuring the partial discharge level under specified conditions
- Requirement: <5 pC



Term	Meanings
Ca	Device under test, modeled as a capacitor
Ck	Bypassing capacitor
Zm	Measuring circuit (impedance, surge limit, others)
PD	Partial discharge measuring instrument

q_{pd} test: method a), type test

- Sample tested – Must Be Tested From Random Production Lot Once / Quarter
  - No failures, Perform if new package material, lead frame, package construction.



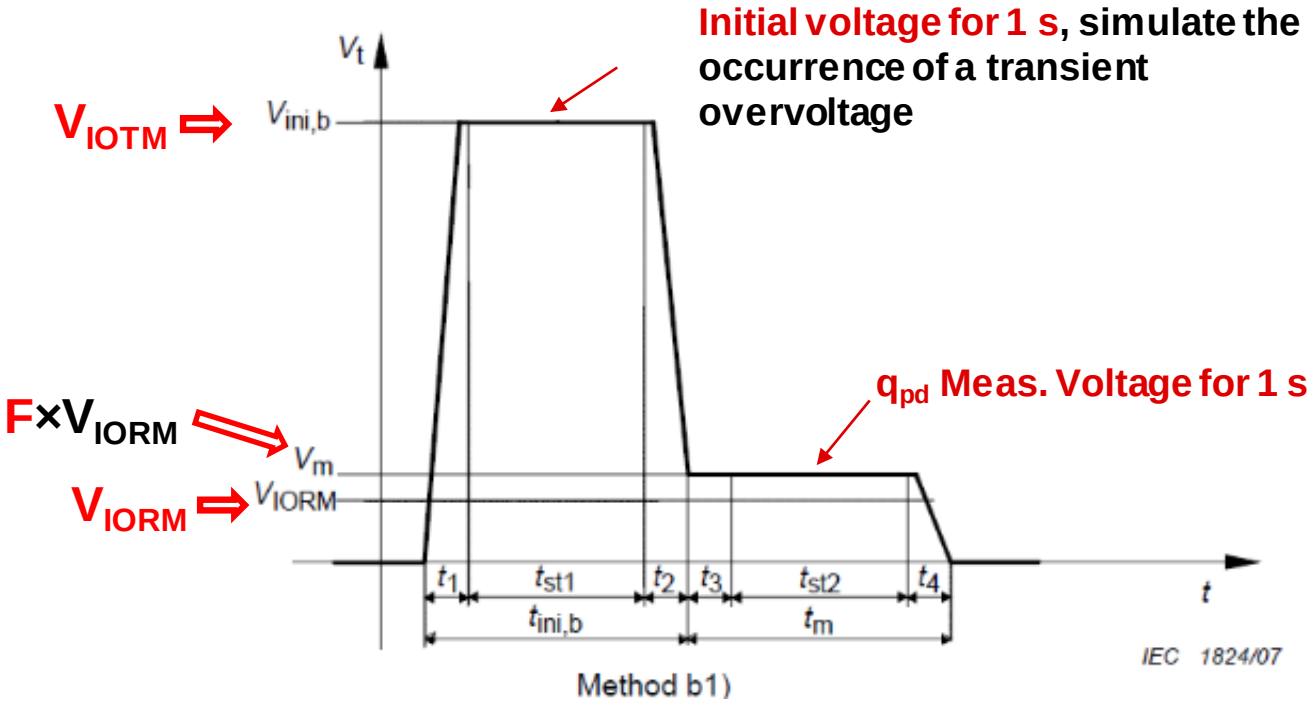
Subgroup 1:
F = 1.6 for reinforced iso and 1.2 for basic

Subgroup 2:
F = 1.2 for basic and reinforced

Requirement: **≤5 pC**

q_{pd} test: method b1), routine test

- Routine tested



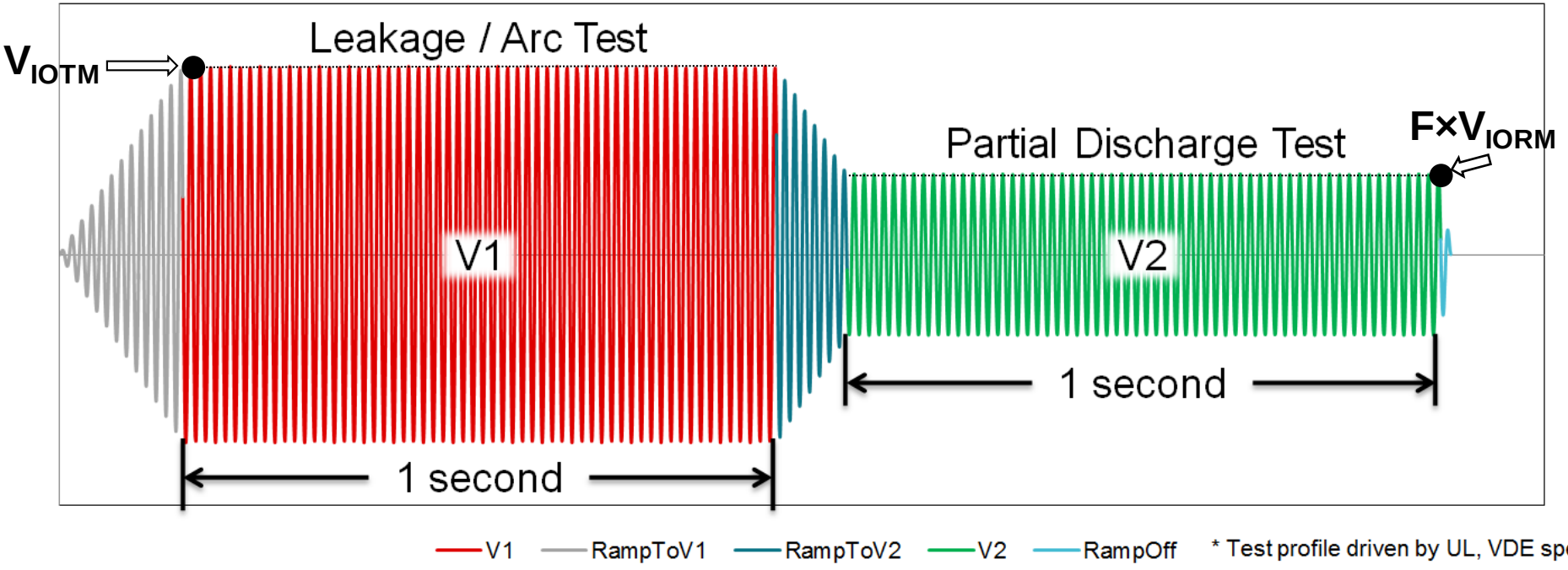
F = 1.875 reinforced iso
= $F_1 * F_2 * F_3$
F = 1.5 for basic iso
= $F_1 * F_2$

Requirement: **<5 pC**

IEC 60664-1:

- F_1: 1.2, environment factor (Temp.);
- F_2: 1.25, PD hysteresis factor;
- F_3: 1.25, Safety factor for reinforced isolation
- F_4: 1.1, Deviation factor from normal voltage

q_{pd} test: method b1), an example waveform



TDDB: Time Dependent Dielectric Breakdown

- Aging affect observed in isolators using SiO_2 or silica based materials to provide internal solid insulation
- Accelerated lifetime testing of the isolation barrier
  - Weibull statistics at each voltage
  - Multiple voltages, fit to model

$$L = c \cdot e^{-k \cdot V^{-n}}$$

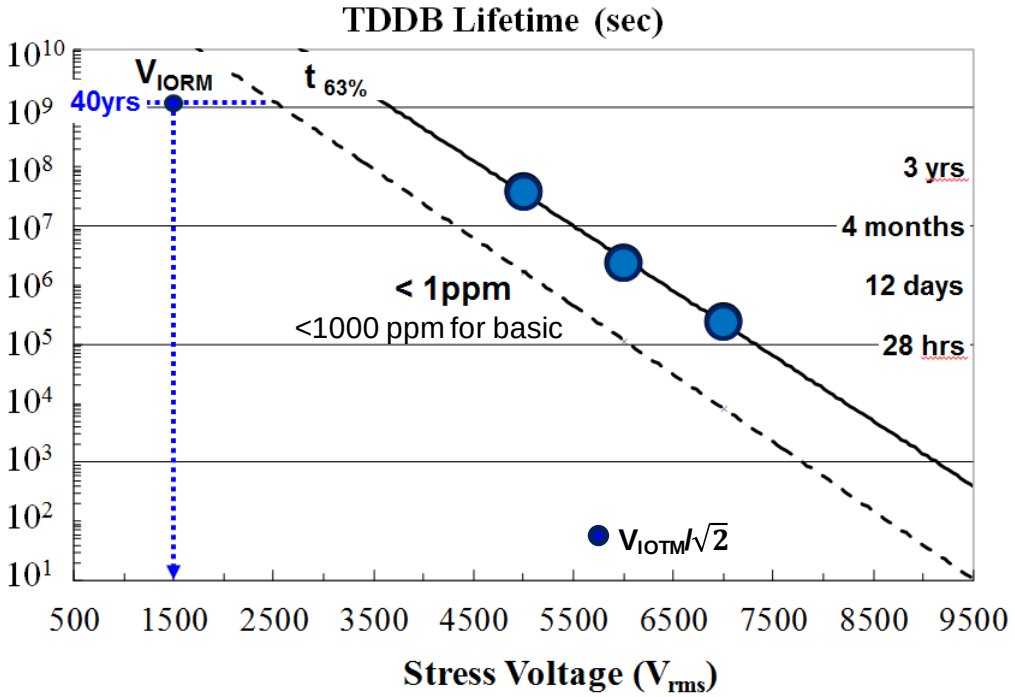
$L - time\ to\ failure;$

<2 MΩ at 500 V_{DC} for basic

<4 MΩ at 500 V_{DC} for reinforced

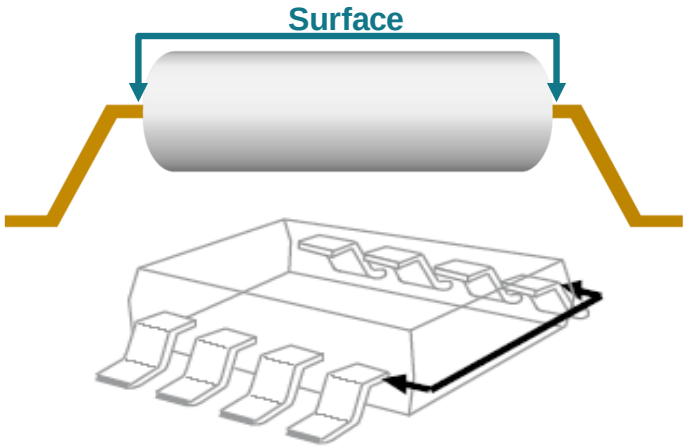
$V\ is\ test\ voltage$

$c, n, k\ are\ constant$



CPG and CLR

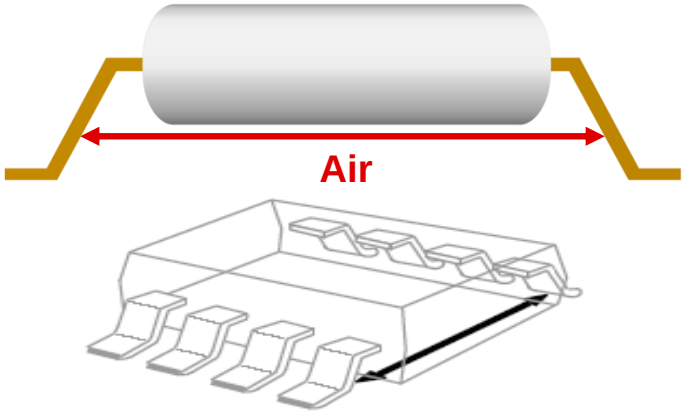
Creepage distance (CPG)



Shortest distance **along the surface** of a solid insulating material between two conductive parts

- **Pollution, humidity, condensation** matters most

Clearance distance (CLR)

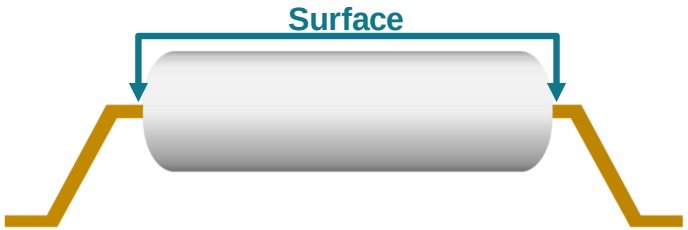


Shortest distance **in air** between two conductive parts

- **Air pressure (altitude), temperature** matters most

CPG and CLR

Creepage distance (CPG)



- Dimensioned for a giving **1) RMS working voltage, 2) pollution degree, 3) material group,**
- No flashover or breakdown of insulation will occur

Clearance distance (CLR)

- Dimensioned for the likelihood of breakdown due to **1) temporary voltage, 2) transient voltages, 3) recurring peak voltages**
- Multiplication factor above 2000 m
  - ×1.48 @5000 m

Material group and CTI

- **Material groups** depend on the comparative tracking index (CTI)
- **CTI** – the maximum voltage V_{AC} (in Volts) 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)
  - An accelerated simulation of conditions of surface in equipment using insulating material

Material groups	CTI range
Material group I	CTI ≥ 600
Material group II	400 ≤ CTI < 600
Material group IIIa	175 ≤ CTI < 400
Material group IIIb	100 ≤ CTI < 175

If not specified

* Material group is verified by evaluation of the test data according to IEC 60112

Pollution Degree

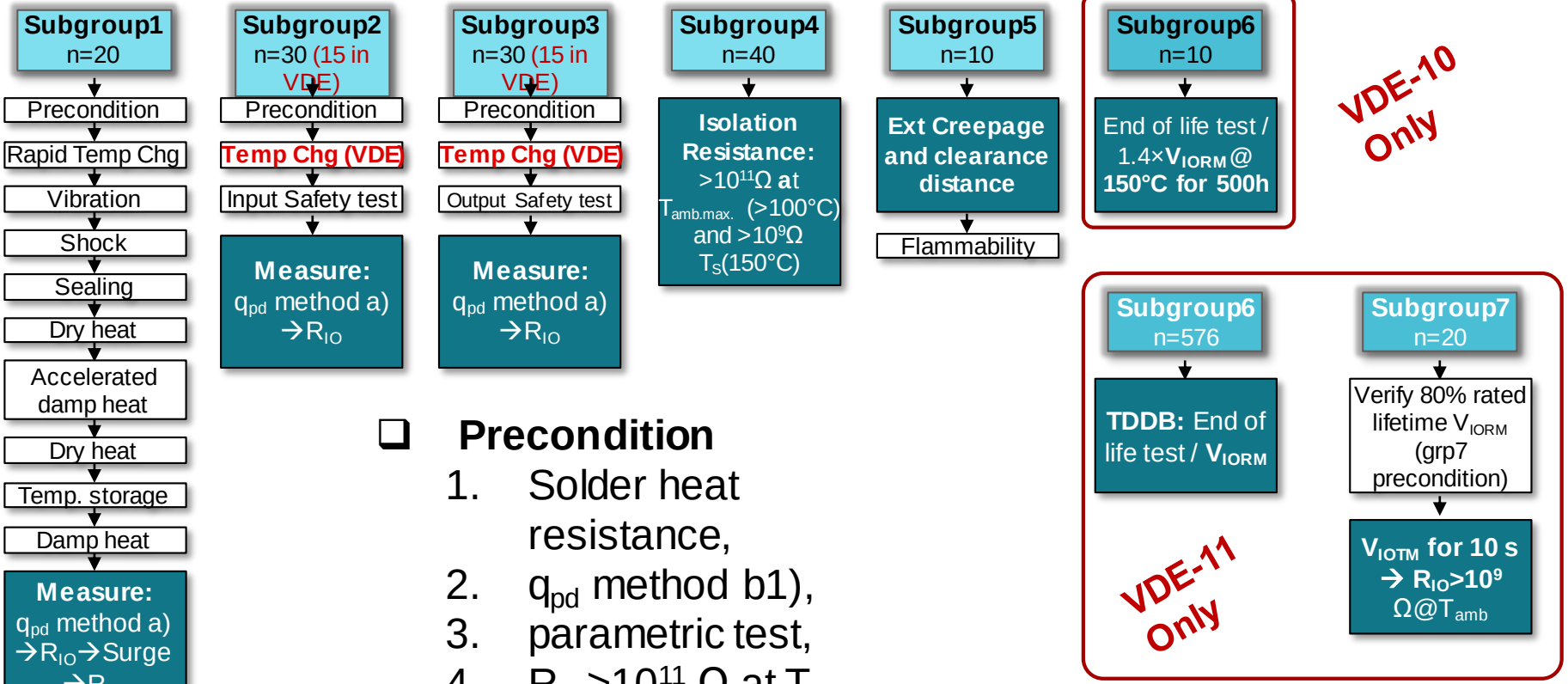
Classes	Descriptions	Examples
Pollution degree 1	• There is no pollution or only dry, non-conductive pollution	• **Sealed** components, equipment or subassemblies
Pollution degree 2	• Temporarily become conductive due to occasional condensation	• IEC 60950/62368 • Lab, office
Pollution degree 3	• Subject to conductive pollution • Non-conductive pollution that could become conductive **due to expected condensation**	• Industrial and farming
Pollution degree 4	• Continuous conductivity occurs due to conductive dust, rain or other wet conditions	• Outdoor applications

Impulse withstand voltage or overvoltage category

- **A probabilistic implication** used for equipment energized directly from low voltage mains
- Over voltage category ←synonymous→ Impulse withstand category

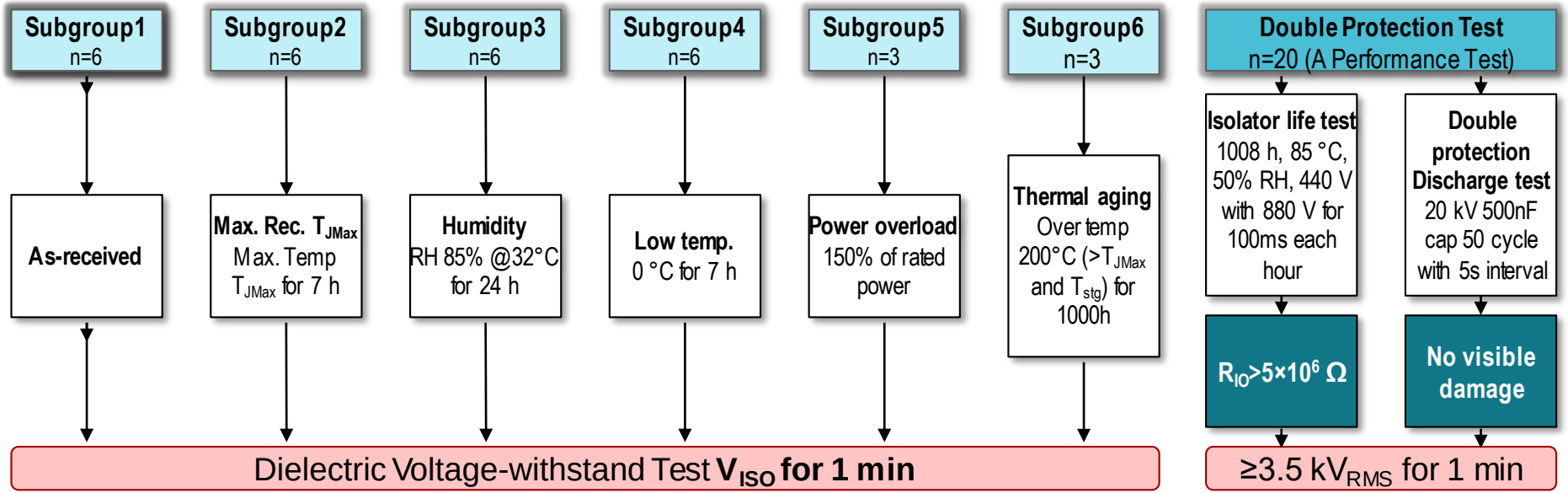
Categories	Descriptions	Examples
CAT. **4**	• Original of installation	• Electricity meters • Utility transformers
CAT. **3**	• Fixed installation where reliability and availability is subject to special requirements	• Utility panel • Distribution board
CAT. **2**	• Energy consuming equipment supplied from fixed installation	• Outlets • 10m away from III
CAT. **1**	• Equipment for connection to circuit in which measures are taken to limit transient voltage to a low level	• Thermostat, • Office printer

IEC60747-5-5 and VDE 0884-10 and -11 type tests



- **Precondition**
  1. Solder heat resistance,
  2. q_{pd} method b1),
  3. parametric test,
  4. $R_{IO}>10^{11}$ Ω at T_{ambmax}
- **No Failures**

UL 1577 type tests

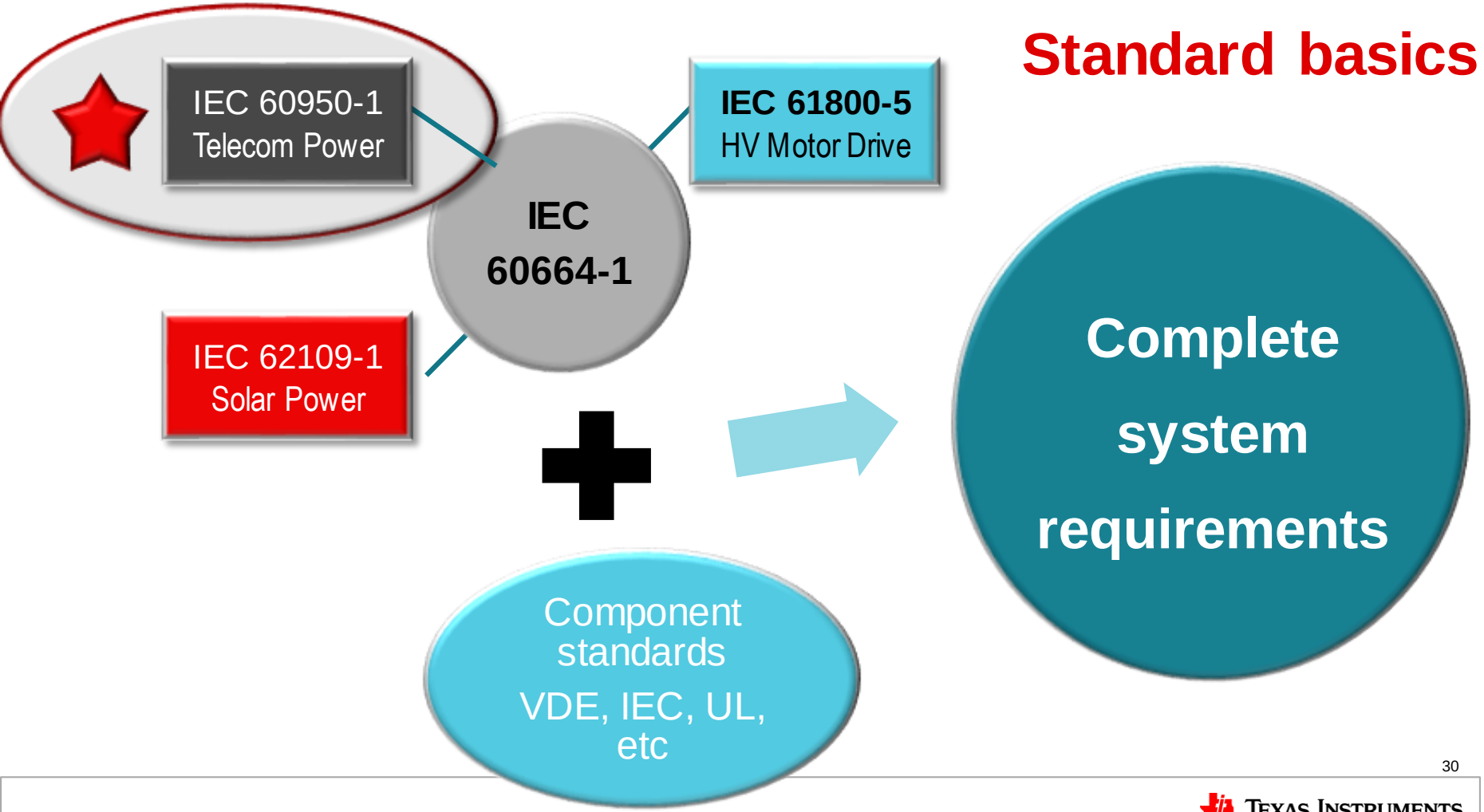


No Isolation Breakdown

Device standards comparison (UL, IEC, VDE)

Reinforced ISO		UL 1577	IEC60747-5-5	VDE 0884-10	VDE 0884-11 (new)
Type		Opto-couplers or digital isolator	Opto-couplers	Magnetic and capacitive coupler	
Production Test	V_{ISO}	1.2×V_{ISO} for 1 s	1.0× or 1.2×V_{ISO} for 1 s or 2 s	Not specified	
	q_{pd}	Not specified	1.875×V_{IORM} for 1 s	1.875×V_{IORM} for 1 s	
V_{IOWM}		Not specified	Based on q_{pd} test **No TDDB**	**No TDDB** submission required	**TDDB** (T_A&T_{JMAX}, 3lots, 3 data points differ by 2 orders of magnitude)
Min Rate Lifetime @ V_{IOWM}		Not specified	Not specified	No specified	**37.5 years w 20% margin**
Life Verification		1008 h, 85°C T_A, RH ≤50%, 440 Vac (w/ 0.1s 880Vac per h)	No specified	500h at 1.4×V_{IORM} at 150 °C	80% rated lifetime + V_{IOTM} for 10 s + R_{IO}
Surge		Not specified	V_{IOSM}, min. 10kV	1.6×V_{IORM}, min. 10 kV	

Standard basics



What is IEC 60664-1 about?

- **Insulation coordination for equipment within low-voltage systems**
  - **Up to 1000 $V_{a.c}$ (<30 kHz)** or
  - **1500 $V_{d.c}$**

1. **Clearance, creepage distance**
2. **Electric strength testing**

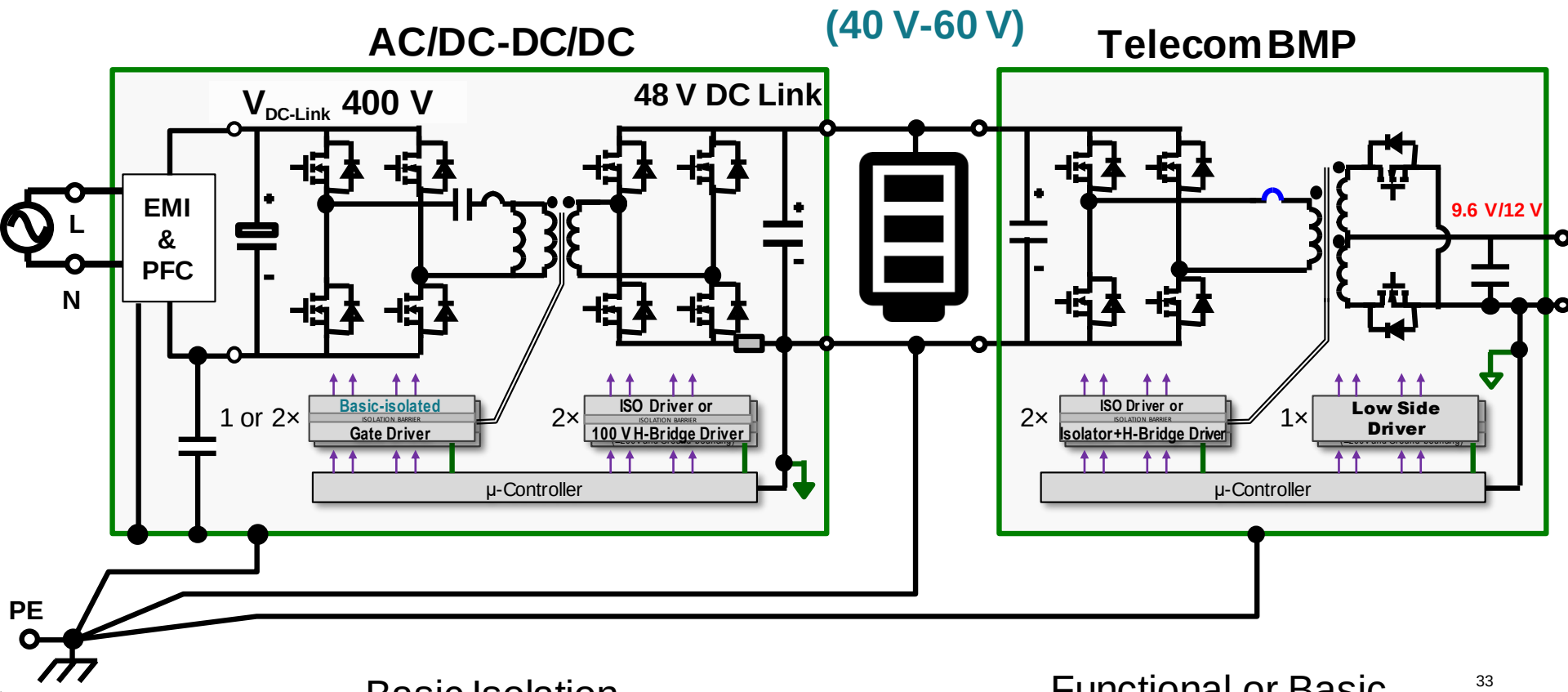
- **Guidance of insulation requirements for equipment**

Foundation of insulation basics

Highlights from IEC 60664-1

- Table F.1 – **Rated impulse voltage** for equipment powered directly by low voltage mains
- Table F.2 – Dimensioning **CLR** to withstand transient voltage
  - Basic insulation follows Table F.2 directly
  - Reinforced insulation follows Table F.2 but one step higher →
    - 330 V, 500 V, 800 V, 1 500 V, 2 500 V, 4 000 V, 6 000 V, 8 000 V, 12 000 V.
- Table F.4 – Dimensioning **CPG** to avoid failure due to tracking
- Table A.2 – Altitude **correction factors** above 2000 m for CLR
- **Electric strength test**
  - Impulse withstand voltage, or
  - Partial discharge based on working voltage

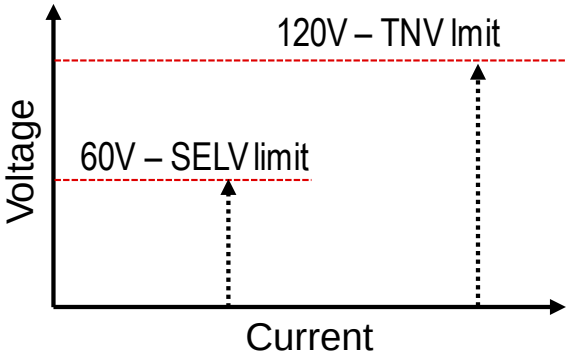
Telecom AC-DC with 36 V-60 V output

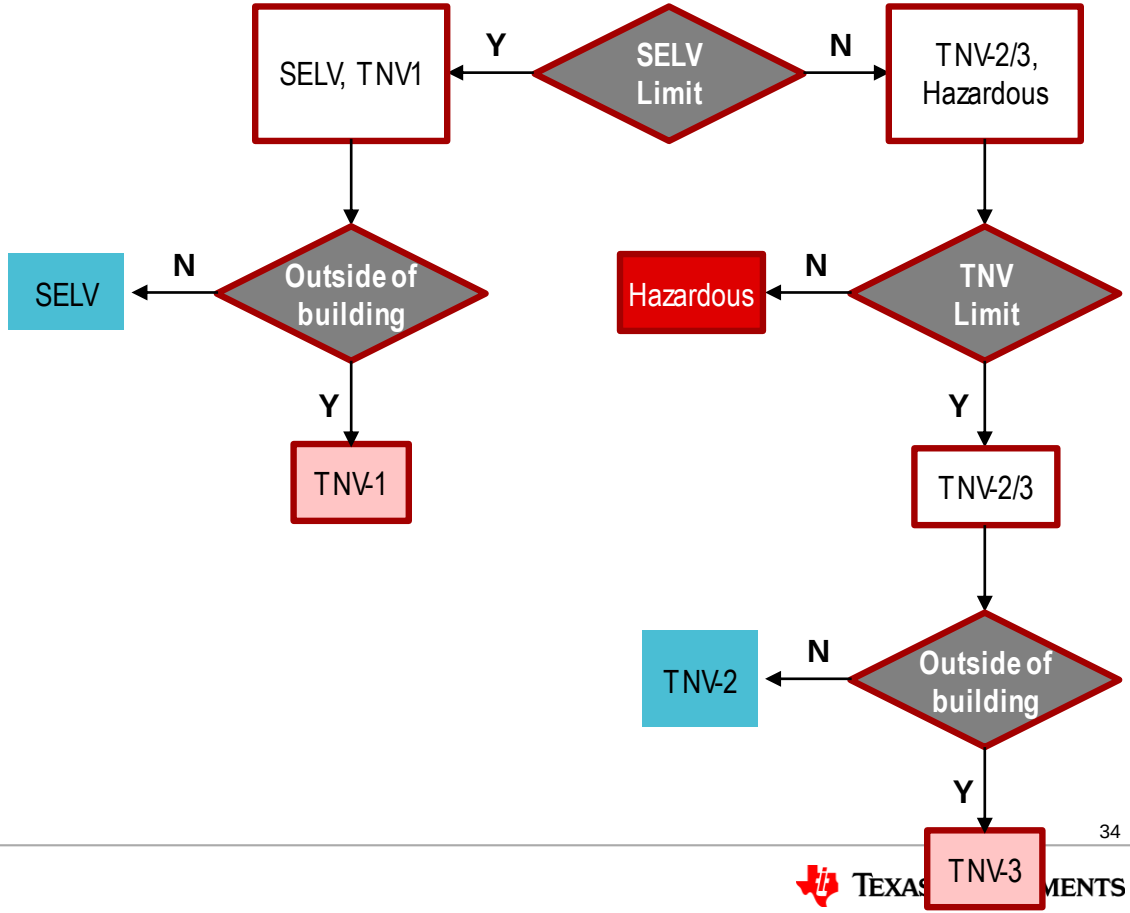


Primary — Basic Isolation — SELV — Functional or Basic Isolation — SELV

What is SELV and TNV?

Normal operating voltage limit



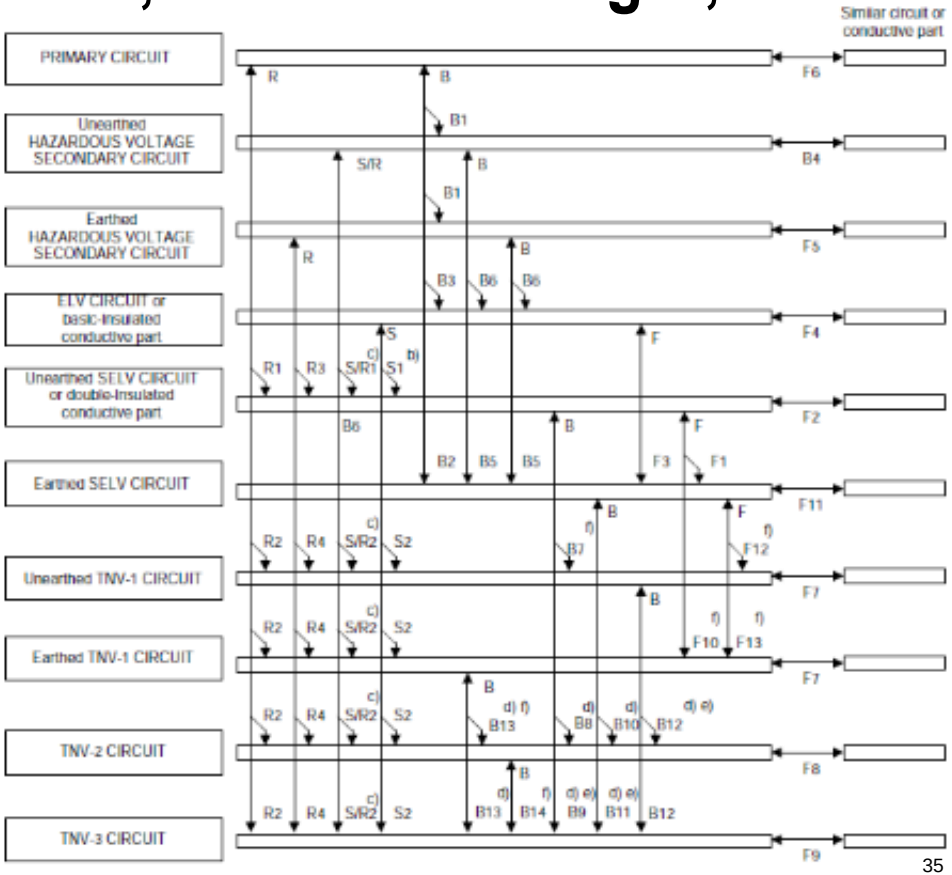


Or a combination of a.c. and d.c.

$$\frac{V_{a.c.}}{71\ V} + \frac{V_{d.c.}}{120\ V} \leq 1$$

Insulation grades: CLR, CPG, electrical strength, etc.

Grd	Parts being separated		Example
F	SELV	SELV	<60 V brick module
	SELV	TNV-1	
	SELV	Reinforced part	48V DC - DC
B	SELV	Primary, TNV -2/3	<120 V brick module
	SELV (E)	Hazardous	400 V-48 V
	TNV-2	TNV-1/3	<120 V to <120 V
R	Primary	SELV (U)	AC to DC 12 V or 48 V
	Primary	TNV-x	AC to DC <120 V
	Hazardous	SELV (U), TNV-x	400 V-48 V



F-Functional insulation; **B**-Basic insulation; **R**-Reinforced insulation *IEC 712/13*

Mains transient voltage: clearance distance

- Transient voltage from **AC mains**

AC MAINS SUPPLY voltage [a] (line to neutral voltage) V r.m.s.	MAINS TRANSIENT VOLTAGE [b] V peak			
	Overvoltage Category			
	I	II	III	IV
up to and including 50	330	500	800	1 500
over 50	500	800	1 500	2 500
over 100 Including 120/208 V, 120/240 V	800	1 500	2 500	4 000
over 150 Including 230/400 V, 277/480 V	1 500	2 500	4 000	6 000
over 300 Including 400/690 V	2 500	4 000	6 000	8 000

* IEC 60950-1 Ed2, Table 2J – AC mains transient voltage

- IEC 62368-1: 500 V_{PK} for DC power distribution system **earthed at a single point**, or 350 V_{PK} earthed at the source (5.4.2.3.2.3)

Minimum clearances: primary circuits

- In primary circuits and between primary to secondary **(mm)**, 2000m

Peak working voltage (V_{PK})	Mains transient					
	1500V			2500V		
	F	B	R	F	B	R
71 V	0.4	1.0 (0.5)	2.0 (1.0)	1.0	2.0 (1.5)	4.0 (3.0)
210 V	0.5			1.4		
420 V	1.5	2.0 (0.5)	4.0 (1.0)	1.5		

Value in parentheses applies based on IEC 62368-1

Table 2K, IEC 60950-1 Ed2 Amd1,

Altitude: 2000m. **For 5000m, multiplication factor is 1.48**

Minimum clearances: secondary circuits

- Clearance in **secondary circuits (mm), 2000m**

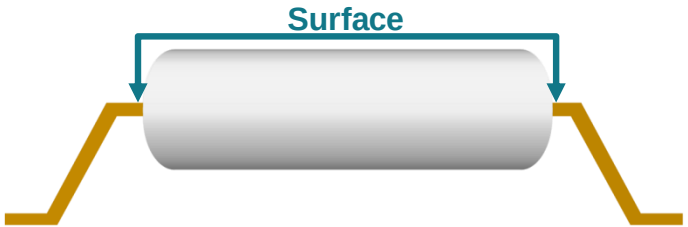
Peak working voltage (V_{PK})	Mains transient					
	1500 V			2500 V		
	F	B	R	F	B	R
71 V	0.5	1.0	2.0	1.5	2.0	4.0
140 V						
210 V						

Table 2M, IEC 60950-1 Ed2

Altitude: 2000m. **For 5000m, multiplication factor is 1.48**

Creepage distance

Creepage distance (CPG)



- Dimensioned for a giving **1) RMS working voltage, 2) pollution degree, 3) material group,**
- No flashover or breakdown of insulation will occur

*Pollution degree 2

Isolation grade	RMS working voltage (V)	Material group		
		I	II	III
Functional or basic isolation	80	0.67	0.9 (0.95)	1.3
	125	0.75	1.05	1.5
	400	2.0	2.8	4.0
Reinforced isolation	80	**2 ×** distance above		
	125			
	400			

Value in parentheses applies based on IEC 62368-1

DTI & electric strength

- ***No minimum DTI*** is required semiconductor device which is completely filled with insulation compound (semiconductor device), provided passing

1) Electric strength **TYPE** test

AND

2) Electric strength **ROUTINE** test *(insulation grade matters)*

A. Basic and reinforced isolation (5.2.2)

- **Peak working voltage** *Table 2B*; OR
- **Required withstand voltage** *Table 5C* (CAT III shall use Table 5C)

B. Functional isolation (5.3.4)

- **Same with above** if CPG&CLR is **NOT** met
  (< 707 V required withstand voltage when working voltage < $60V_{DC}$)

OR

- NOT required if CPG&CLR is met

Electric strength test B: based on required withstand voltage

IEC 60950-1 ed. 2.0, Table 5C, Amd2,

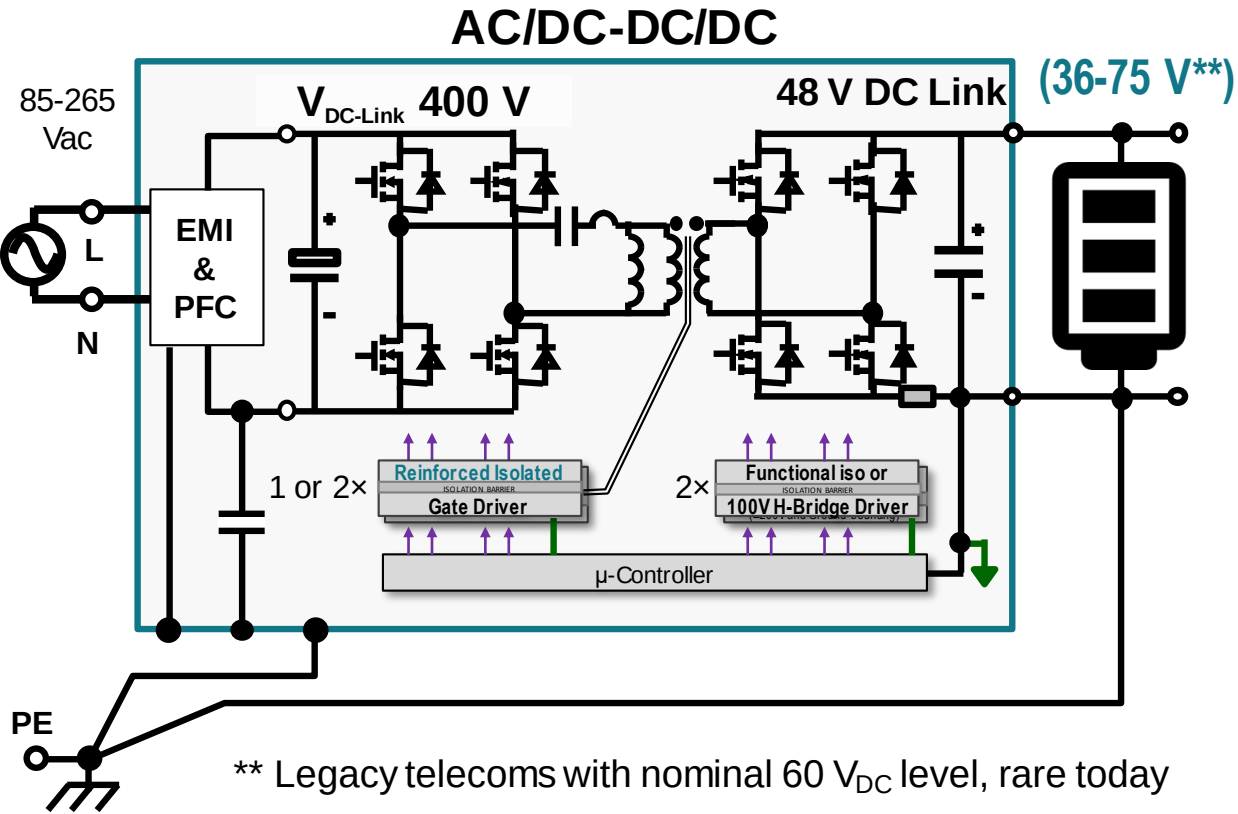
Required withstand voltage kV_{PK}	Test voltage for electric strength based on required withstand voltage	
	Functional or Basic (kV_{PK} or d.c.)	Reinforced insulation (kV_{PK} or d.c.)
0.8	0.9 (0.8)	1.5
1.5	1.5	2.5
2.5	2.5	4.0
4.0	4.0	6.0

CAT III shall use Table 5C

Value in parentheses applies based on IEC 62368-1

- **Routine test** allows test duration **reduced to 1s**, and test voltage (for Table 5C) **reduced by 10%**

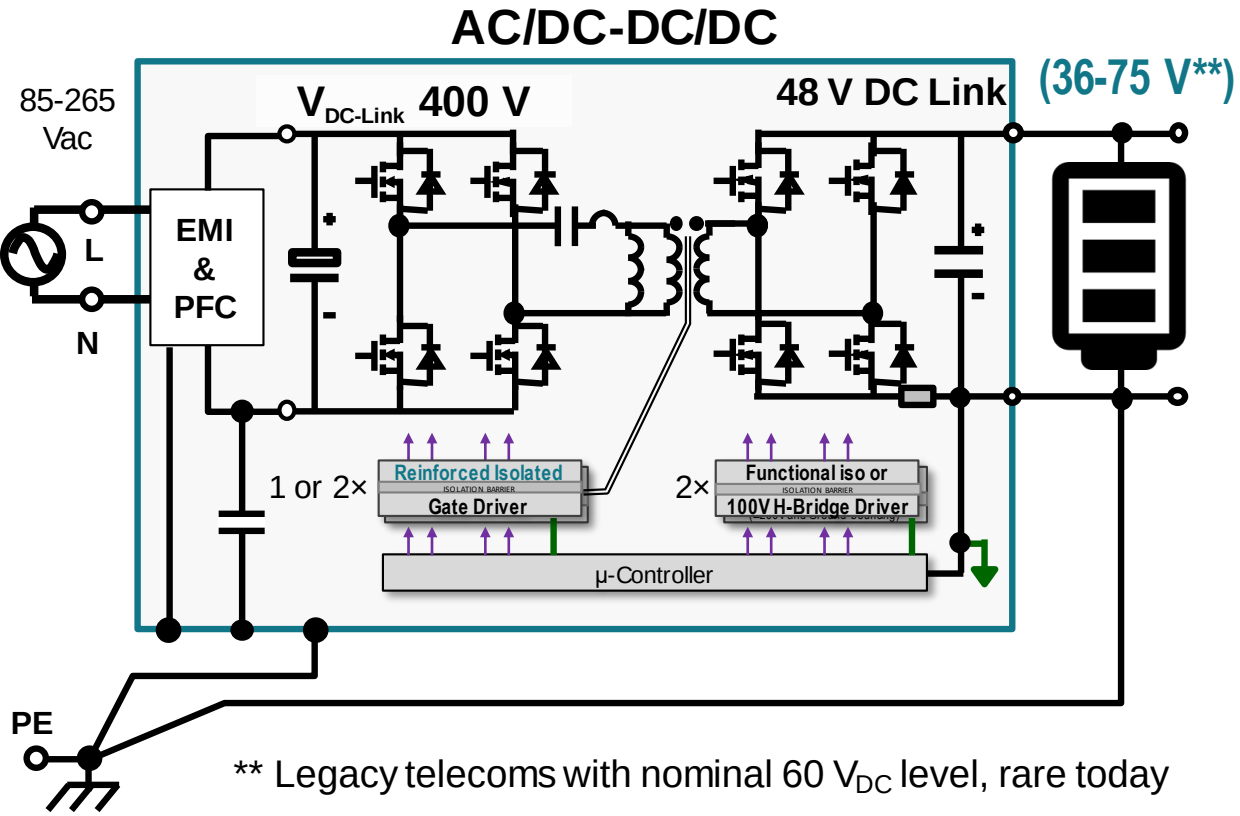
Case study 1b: isolated AC/DC (TNV-x)



** Legacy telecoms with nominal 60 V_{DC} level, rare today

Grd	Parts being separated	
F	SELV	SELV
	SELV	TNV-1
	SELV	Reinforced part
B	SELV	Primary, TNV -2/3
	SELV (E)	Hazardous
	TNV-2	TNV-1/3
R	Primary	SELV (U)
	Primary	TNV-x
	Hazardous	SELV (U), TNV-x

Case study 1b: isolated AC/DC (TNV-x)



** Legacy telecoms with nominal 60 V_{DC} level, rare today

Item	Minimum required
AC mains transient	2500 V CAT II
Clearance	4 mm
Clearance @5000m	6 mm
Creepage (MG I)	4 mm
Creepage (MG III)	8mm
Electric strength A	3.0 kV_{RMS} V_{ISO}
Electric strength B (Routine test)	4.0 kV_{PK} V_{IOTM}

Questions?

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