Isolation in solar power converters: Understanding the IEC62109-1 safety standard

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Understanding the IEC 62109-1 safety standard for solar power converters enables you to pick the right isolation solutions for solar power conversion applications.

There is a pressing need to accelerate the development of advanced energy technologies in order to address the global challenges of clean energy, climate change and sustainable development [1]. Solar energy is the cleanest, most abundant renewable energy source available, and plays a key role in the development of sustainable energy systems. The solar power generation capability in the United States (U.S.) has gone through an exponential growth in the past decade. The U.S. has installed 1,393 megawatts (MW) of solar photovoltaics (PV) in the second quarter of 2015 to reach 22.7 gigawatts (GW) of total installed capacity. This is enough to power 4.6 million American homes [2]. Globally, by the end of 2015, the PV installation capability reached 233 GW.

Solar power conversion systems are used to convert solar energy to electrical energy, which is either fed to utility grids or used by off-grid electrical networks. In a solar power conversion system, solar panels are operated to convert solar energy to electrical energy, and power converters are employed to further process the harvested electrical energy. In a solar power converter, high-voltage and low-voltage circuits co-exist. Isolations are required between the high-voltage and low-voltage circuits for both functional and safety purposes. Fundamental isolation concepts and terminology are presented in references [3-4].

Digital isolators can be used to address the isolation requirements. In a solar power conversion system, different types of isolators are adopted to serve various functions. Isolated gate drivers are used to drive insulated gate bipolar transistors (IGBTs) or metal-oxide semiconductor field-effect transistors (MOSFETs) in the high-voltage power stage. Isolated analog-to-digital converters (ADCs) and isolated amplifiers are utilized to sense and convert analog front-end signals like voltages and currents for the purpose of close-loop controls. Isolated data links are applied to transfer information from circuits referenced to high voltage to ones referenced to earth.

The International Electrotechnical Commission (IEC) 62109-1 [5] is a safety standard for solar power converters. This standard defines the minimum requirements for the design and manufacture of power conversion equipment (PCE) for protection against electric shock, energy, fire, mechanical and other hazards. This standard provides general requirements applicable to all types of PV PCE.

This paper discusses the electrical aspects of the IEC 62109-1 safety standard and analyzes how its stipulations on insulation requirements translate into specifications for isolators used in solar power converters.

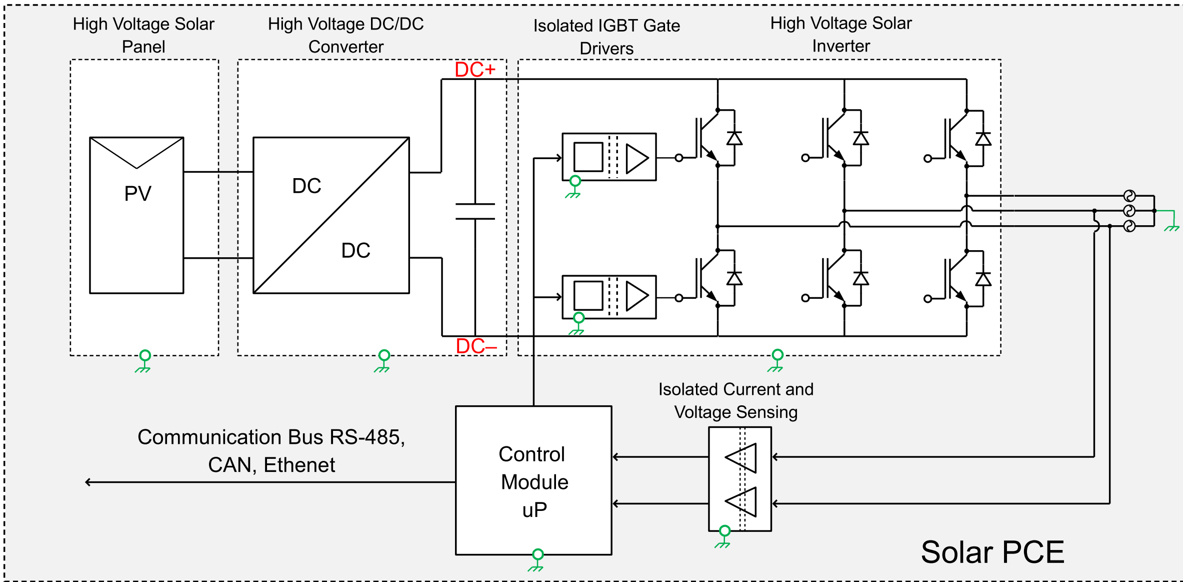

***Figure 1**. Typical system block diagram of a transformer-less solar power conversion system.*

This discussion is limited to a few select configurations and uses example cases to provide an understanding of the main principles of IEC 62109-1 relevant to isolators. For instance, we will discuss only three-phase systems with a rated system voltage of up to 1000 V_{RMS} and rated DC link voltage of 1500 V. For a more comprehensive understanding of these requirements, see the IEC 62109-1 standard [5].

Isolation in solar power converters

Figure 1 describes a simplified system block diagram of a transformer-less grid-tied solar power conversion system. The solar power is harvested by a PV panel and processed by post-stage DC/DC and DC/AC converters. The DC/DC converter is used to implement maximum power point tracking (MPPT) of the solar energy. The DC/AC inverter is utilized to convert DC power to AC power, which can be interfaced by a utility grid.

Conventionally, IGBTs with a switching frequency of tens of kilohertz are used to form the DC/AC converter. Nowadays, more and more SiC MOSFETs are applied to solar power conversion systems in order to achieve higher system efficiency, power density and cost-effectiveness. Isolated gate drivers provide the required drive voltage to turn IGBTs on and off. Typically, a gate-emitter voltage of 15 V is used to turn on IGBTs, and a negative gate-emitter voltage of –8 V is used for IGBTs turn off. The gate driver supply voltages for SiC MOSFETs are typically +20 V and –5 V. Isolated current and voltage sensors are used to sense the currents and voltages in order to realize a closed-loop control system.

A control module that contains a microprocessor or field-programmable gate array (FPGA) processes the feedback signals from the voltage and current sensors, and provides the right sequence of pulse-width modulated (PWM) control signals to the IGBT/SiC MOSFET gate drivers at the right frequency, which regulate the voltages and currents of the power converters. The voltage and current regulations are intended to realize MPPT and power-flow control to the grids.

The control module interfaces with the rest of the control network (for example, to a computer or human-machine interface ([HMI]) through standard communication interfaces such as RS-485, CAN or industrial Ethernet.

The control module has parts that are accessible to humans, for example, the connectors of the communication interface. Sufficient safety isolation is required between these exposed parts and the high-voltage circuits (circuitry connected to the DC buses and utility grids). This isolation can be achieved through isolated gate drivers and isolated voltage and current-sense amplifiers. In **Figure 1**, the human accessible control module, input side of the isolated gate drivers, and input side of the isolated amplifiers are referenced to the earth, which is safety-isolated from the high-voltage systems.

Additional isolation can be introduced between the control module and communication interface, as shown in **Figure 2**.

The control module, input side of the isolated gate drivers, and input side of the isolated amplifiers are referenced to the DC– bus in **Figure 2**.

In this case, additional digital isolation provides safety isolation between this control module (which is connected to high voltage) and a second control or communications module that is earth-referenced. The human-accessible parts or interfaces lie on the second control module. In this architecture, isolation is still required in both the gate drivers and the isolated current and voltage-sense modules – not from an electrical safety perspective but for functional purposes. Here, isolation allows the first control module (referenced to DC–) to communicate with the IGBTs and sensors, whose ground references are the inverter outputs that are switching high voltage with respect to the DC– bus.

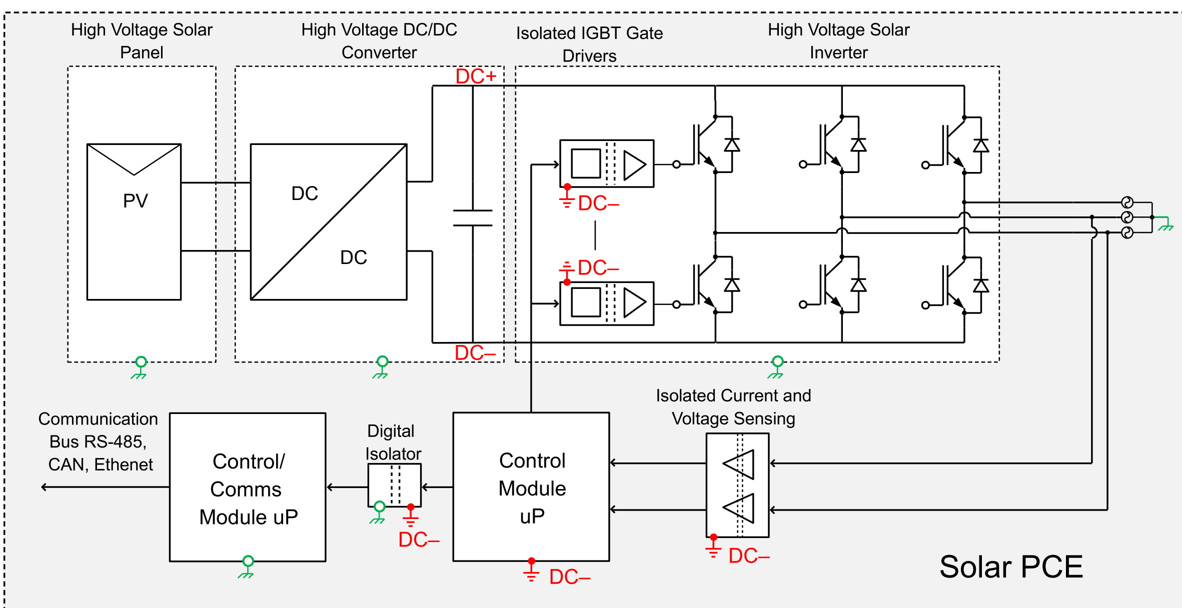

Figure 2. *Alternative system block diagram of a transformer-less solar power conversion system.*

Shown in **Figure 3** is a system diagram of a transformer-based, grid-tied solar converter. In this architecture, a high-frequency transformer is used to implement high-voltage isolation between the PV circuits and grid-tied circuits, which adds additional safety margins. However, inclusion of the isolation transformer brings extra power loss and accounts for further board space, which means more cost. The isolation requirements of the PV circuits and grid-tied circuits need to be considered separately for this case. More details will be presented later in this paper.

IEC 62109-1 definitions

1. System voltage – In a solar power system, there are two sub-circuits, which are PV circuits and grid-tied circuits. The system voltages of the PV circuits and grid-tied circuits are determined separately.

2. PV circuits – The system voltage is the open circuit voltage of the PV panels.

3. Grid-tied circuits – The system voltage depends on the ground-earthing patterns [6].

- TN and TT systems – The root-mean-square (RMS) value of the rated voltage between a phase and earth.
  In TN and TT systems, both line frequency transformer (or generator) neutral and equipment frames are earthed. In a TT system, equipment frames are earthed locally, and are not connected to the line neutral. In a TN system, the equipment frames are earthed by connecting to the line neutral.
- A TN system is called corner-earthed system if one phase earthed. The system voltage is the RMS value of phase-to-phase voltage

4. IT systems.

- The RMS value of the rated voltage between a phase and an artificial neutral is used to determine the impulse voltage.
- The RMS value of the rated voltage between phases is used to determine the temporary overvoltage.

5. Single-phase IT systems – This is the RMS value of the rated voltage between phase conductors.

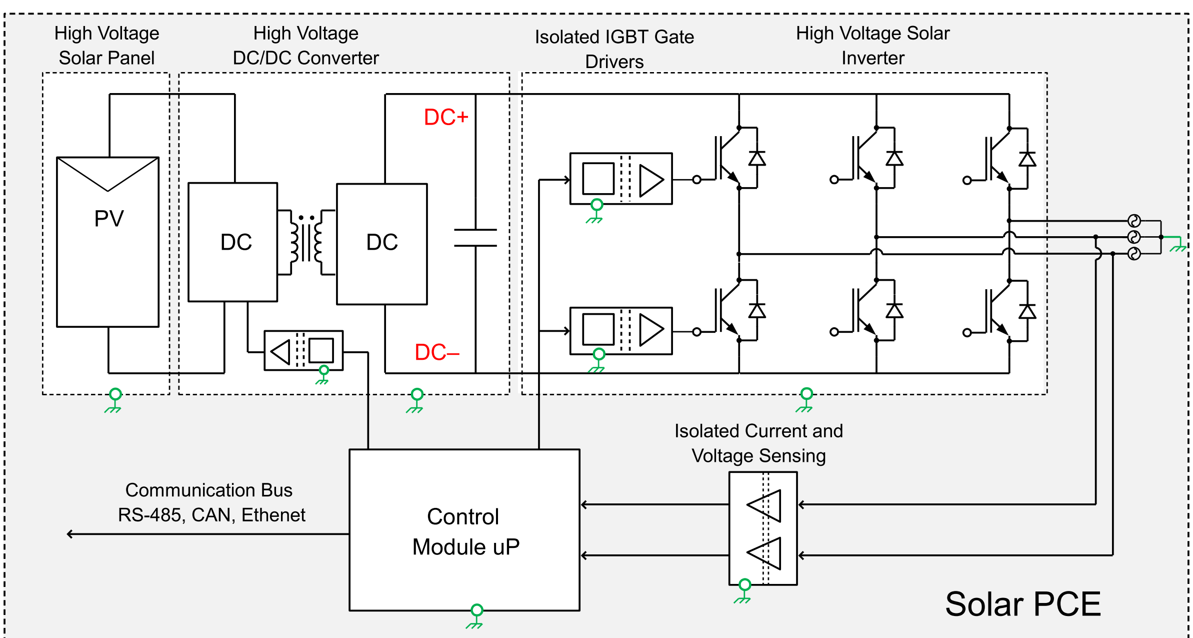

Figure 3. *System block diagram of a transformer-based solar power conversion system.*

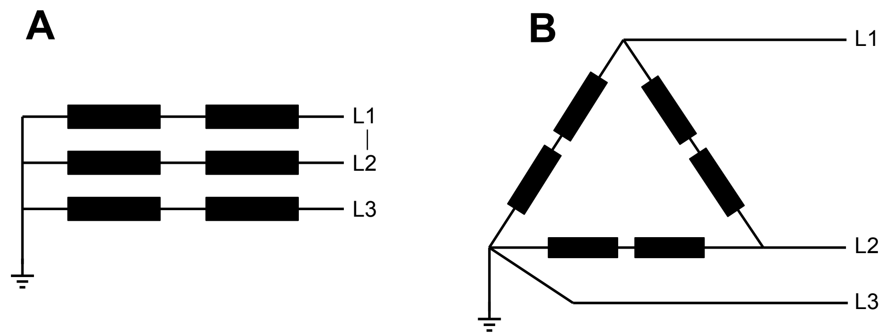

Figure 4. (a) A star-earthed TN system that is neutral-earthed; and (b) a corner-earthed TN system where one phase is earthed.

6. Overvoltage category (OVC) – addresses the transient voltages. According to the IEC 62109-1 standard, equipment falls into one of these four categories:

- Category I: Applies to equipment connected to a circuit where measures are taken to reduce surges and transient overvoltage.
- Category II: Applies to portable tools and plug-connected equipment not permanently connected to the mains.
- Category III: Applies to equipment connected permanently to supply mains downstream of the distribution board.
- Category IV: Applies to equipment permanently connected at the origin of the installation upstream of the main distribution board.

Equipment in a higher OVC category sees higher voltage disturbances with higher possibilities, so the equipment needs to address a higher requirement on the surge voltage and temporary overvoltage. In a solar power conversion system circuits connected to the PV panels belong to OVC II, while the circuits connected to the grid fall under OVC III.

Working voltage – Working voltage is the continuous voltage presenting across the insulation barrier of an isolator whenever the equipment is in operation. This value is not directly related to the system voltage. Instead, it depends on system architecture and operation conditions.

Applying the IEC62109-1 standard to a solar power converter design

Now that you have an understanding of isolation with earthing concepts and terms, you can apply the IEC 62109-1 requirements to a solar power conversion system design step-by-step. Unless specified otherwise, we use OVC III for grid-tied circuits and OVC II for PV circuits, and pollution degree 2 in this discussion. Also, this document only covers requirements for isolators versus other components in a solar inverter system, such as power modules and heat sinks.

Step 1: Identify the isolators present in the system and determine if each needs functional, basic or reinforced isolation.

Sufficient safety isolation (or protective separation in IEC 62109-1) is required between circuitries connected to high voltage and parts that are accessible to humans. A designer can achieve protective separation either by two basic isolators in series or through one reinforced isolator.

In the solar power conversion system (**Figure 1**), the isolated gate drivers and isolated voltage and current-feedback circuits both need to support reinforced isolation. Basic isolation is sufficient if another basic isolation is inserted through the isolated data links. In the solar power conversion system (**Figure 2**), the digital isolator needs to support reinforced isolation because the isolated gate drivers and amplifiers are referenced to DC–, and only functional isolations are implemented.

Step 2: Determine system voltage

As discussed, system voltages for PV circuits and grid-tied circuits are defined separately. For PV circuits, the system voltage is the open circuit voltage of the PV panels. For grid-tied circuits, the system voltage depends on the earthing scheme. A three-phase 400 V_{RMS} TN grid voltage that is neutral-earthed has a system voltage of 230 V_{RMS}. A three-phase 480-V_{RMS} corner-earthed system has a system voltage of 480 V_{RMS}.

Step 3: Determine the requirement for temporary overvoltage and impulse/surge voltage for each isolator from the IEC62109-1 standard.

a. For the grid-tied circuits, the impulse and temporary overvoltage can be determined according to the system voltage and overvoltage category (OVC III is assumed). Interpolation of the system voltage is not allowed for the grid-tied circuits, thus the next higher system voltage needs to be used. For example, a system voltage of 230 V_{RMS} is treated as a 300 V_{RMS} based on IEC62109-1.

b. For PV circuits, OVC II is assumed. The minimum requirement of the impulse withstand voltage is 2500 V. Different from the grid-tied circuits, system voltage interpolation is allowed for PV circuits.

c. For solar power conversion systems with galvanic isolation between the grid-tied circuits and PV circuits (**Figure 3**), the impulse voltage rating of the grid-tied circuits and PV circuits are determined in the previous two bullets. The isolation transformer between the PV circuits and grid-tied circuits can reduce the OVC. The OVC reduction needs to follow the approach below:

- The impulse voltage from the grid-tied circuits on the PV circuits is derived based on the system voltage of the grid-tied circuits with an OVC that is one level lower than the grid-tied circuits.
- The impulse voltage rating of the PV circuits is the higher one of (b) and the value calculated.
- The impulse voltage from the PV circuits on grid-tied circuits is determined based on PV system voltage and with an OVC that is one level lower than the PV circuits.
- The impulse voltage rating of the grid-tied circuits is the higher one of (a) and the value calculated.

d. For solar power conversion systems (**Figures 1-2**) not providing galvanic isolation between the grid and PV circuits, the impulse withstand voltage ratings of the grid-tied circuits and PV circuits are determined as in (a) and (b), and the higher value is used for the combined circuits. The impulse voltage rating of the combined circuits also applies to the circuits which are connected to the combined PV circuits without galvanic isolation.

IEC62109-1 lists the requirements for basic isolation. For reinforced isolation, use the next-higher impulse voltage and a temporary overvoltage of 2 times the basic requirement. To determine clearances (Step 4) for reinforced isolation, use a temporary overvoltage of 1.6 times (not double) the basic requirement and the next-higher impulse voltage.

Step 4: Determine the clearance required from every isolator used in the design

IEC 62109-1 lists the clearance requirements for a given temporary overvoltage and surge/impulse voltage. Using this information, you can obtain the clearance requirement based on the temporary overvoltage and surge requirements determined at Step 3.

IEC 62109-1 presents isolation requirements for altitudes of up to 2000 m. To operate at higher altitudes, clearance needs to be increased by a certain degree to account for the fact that air breaks down more easily at higher altitudes. This correction factor for higher altitudes is defined in IEC 62109-1.

For example, to operate at 5000 m, increase the clearance obtained from this standard by a factor of 1.48.

Step 5: Determine working voltage (both PK and RMS) based on the actual operating condition of an isolator

The working voltage does not directly follow from the system voltage, but depends on the system structure and operations of the solar power conversion system. A sinusoidal PWM-modulated bipolar voltage having a swing between DC+ and DC– is applied to the barrier of the high-side isolated gate drivers in **Figure 1**. However, the high-side isolated gate driver sees a unipolar voltage swing between 0 to 2 VDC+ in **Figure 2**.

The earthing scheme also plays a role in the working voltage. For the case in **Figure 2**, the DC– bus is at a pretty steady voltage with respect to earth potential when the grid is star-earthed while the DC- sees a high voltage swing if the grid is corner-earthed.

The operations of the converter affect the working voltage in another way. For example, a higher modulation depth of the inverter forces a higher working voltage across the barriers of the high-side isolated gate drivers in **Figure 1**. All of these factors complicate accurately determining working voltage. Generally, a working voltage equal to the DC link voltage covers most cases for solar converters.

However, some margin provides a buffer for the effects for various working-voltage-transient profiles to increase design robustness and reliability.

Step 6: Determine creepage based on RMS values of working voltage expected according to IEC62109-1

IEC62109-1 presents the results for basic isolation. For reinforced isolation, double the creepage requirement. The creepage requirement depends on the pollution degree and comparative tracking index (CTI) of the isolator.

Conformal coating or potting can be used to reduce the creepage and clearance requirement by reducing the pollution degree under the coating and blocking the path for arcing between pins. However, these methods add cost, need additional inspection steps to check the quality of the coating, and have limitations on the maximum voltage levels supported. Choosing an isolator with a higher CTI and higher values of creepage and clearance is often the cheaper and more reliable alternative.

For cases where the creepage requirement is lower than the clearance requirement, you need to increase creepage to meet the clearance. This adjustment is necessary because the creepage path along the package surface is also a path along which air breakdown can occur.

AC phase - phase voltage (V_{RMS})	DC link voltage (Vdc)	Earthing scheme	System voltage (V_{RMS})	System voltage per IEC62109-1	Basic/ reinforced	Temporary overvoltage (V_{RMS}/V_{PK})	Impulse/ surge voltage (V_{PK})	Minimum clearance (mm)	Working voltage (V_{PK})	Minimum Material group I	Minimum Material group II	Minimum Material group III
480	1500	Neutral-earth	277	300	Basic	1500/2120	4000	3.0	1500	5	7.1	10
480	1500	Neutral-earth	277	300	Reinforced	3000/4240	6000	5.5	1500	10	14.2	20
480	1500	Comer-earth	480	600	Basic	1800/2550	6000	5.5	1500	5	7.1	10
480	1500	Comer-earth	480	600	Reinforced	3600/5100	8000	8.0	1500	10	14.2	20

Table 1. *Summary of requirements per the IEC 62109-1 for our example system.*

Step 7: Choose isolator that meets V_{ISO}, V_{SURGE}, working voltage, creepage and clearance requirements obtained above

Table 1 summarizes these requirements for an example transformer-less solar power conversion systems under different system configurations, with OVC III for grid-tied circuits and OVC II for PV circuits, pollution degree 2, and altitude <2000 m. For the example solar power conversion system, the AC phase-to-phase voltage is 480 V_{RMS}, the DC link voltage is 1500 V_{DC}, and the open circuit voltage of the PV panel is 848V_{DC}. With the open circuit voltage of 848 V_{DC}, the surge voltage requirement is determined to be 4000 V_{PK}. The working voltage is assumed the same as the DC link voltage, which covers most architectures. However, the actual working voltage required from the isolator depends on where the isolator fits in the system architecture.

Isolators for solar power conversion applications

In response to these needs, Texas Instruments offers several isolation offerings for solar power conversion applications. These include isolated IGBT gate drivers, digital isolators, isolated delta-sigma ADCs and amplifiers, and isolated communication links such as isolated RS-485 and isolated CAN. Recent offerings include the ISO5851, ISO5852S, ISO5451 and ISO5452 reinforced isolated gate drivers, digital isolators ISO77xx, and isolated delta-sigma ADCs AMC1304x and AMC1305x in a 16-pin small-outline integrated circuit (SOIC) package, with 8-mm creepage and clearance.

Included are isolated gate drivers UCC53xx with basic isolation in 8D package and reinforced isolation in 8-DWV package. The isolated gate driver family has three different pin configurations featuring active miller clamp, split outputs, and bipolar power supply separately. Each pin configuration offers different options of drive strength. Digital isolators ISO78xx are available with an extra-wide 14.5-mm creepage and clearance package. These extra-wide package options are targeted to support high-voltage (1500 V_{DC}) solar power conversion applications.

These families of isolators have a 60-second temporary overvoltage of 5.7 kV_{RMS}; bipolar, unipolar and DC working voltages of 1.5 kV_{RMS} and 2121 V_{PK}; and a surge voltage of 12.8 kV_{PK}.

Device	Function	Creepage /Clearance (mm)	Basic /Reinforced	System voltage supported up to V_{RMS}	Working voltage supported up to V_{RMS}/V_{PK}
UCC53xxD	Gate Driver	4	Basic	300	800/1130
UCC53xxDWV	Gate Driver	8	Basic	600	800/1130
			Reinforced	1000	1000/1414
ISO585xDW	Gate Driver	8	Basic	600	800/1130
			Reinforced	1000	1500/2121
ISO77xxDW	Digital Isolator	8	Basic	300	450/637
			Reinforced	1000	1500/2121
ISO78xxDW	Digital Isolator	8	Basic	600	800/1130
			Reinforced	1000	1500/2121
ISO78xxDWW	Digital Isolator	14.5	Basic	1000	1450/2050
			Reinforced	> 1000	1500/2121

Table 2. *TI isolation device capabilities per IEC 62109-1 (OVC III, pollution degree 2, altitude < 2000m).*

Note 1: Occasionally package creepage and clearance limits the system and working voltage supported. For the intrinsic capability of the isolators, see the corresponding product data sheets and reference [7]. For example, the intrinsic capabilities of the isolator can be realized at the system level through conformal coating or potting.

Additionally, these devices use a CTI > 600 (Material Group I) package-mold compound, which enables them to operate at higher working voltages at the system level, compared to competing devices with the same creepage. The ISO78xx, ISO77xx, ISO58xx, and UCC53xx devices also feature high common-mode transient immunity (CMTI), low propagation delay, and split sink and source strength, which can support high-performance operations of SiC MOSFETs.

Table 2 summarizes the capabilities of these devices when applied to various requirements of the IEC 62109-1 standard. By combining intrinsic isolation strength with a Material Group I mold compound in wide packages, TI devices can address products with a rated system voltage of up to 1000 V_{RMS} and a rated DC link voltage of up to 1500 V_{DC}, with margin to spare.

Conclusion

Isolators are essential components of modern solar power conversion systems and must be chosen carefully to ensure optimal insulation coordination. In this paper, we examined several aspects of isolator selection for solar power conversion systems to comply with IEC 62109-1. This includes requirements on transient overvoltage, impulse voltage, working voltage, and creepage and clearance. A combination of intrinsic isolation strength, superior mold compound and availability of wide-package options enables TI devices to address the requirements of solar inverter designs with rated system voltage up to 1000 V_{RMS} and a rated DC link voltage of up to 1500 V_{DC}.

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