Isolation in AC Motor Drives: Understanding the IEC 61800-5-1 Safety Standard

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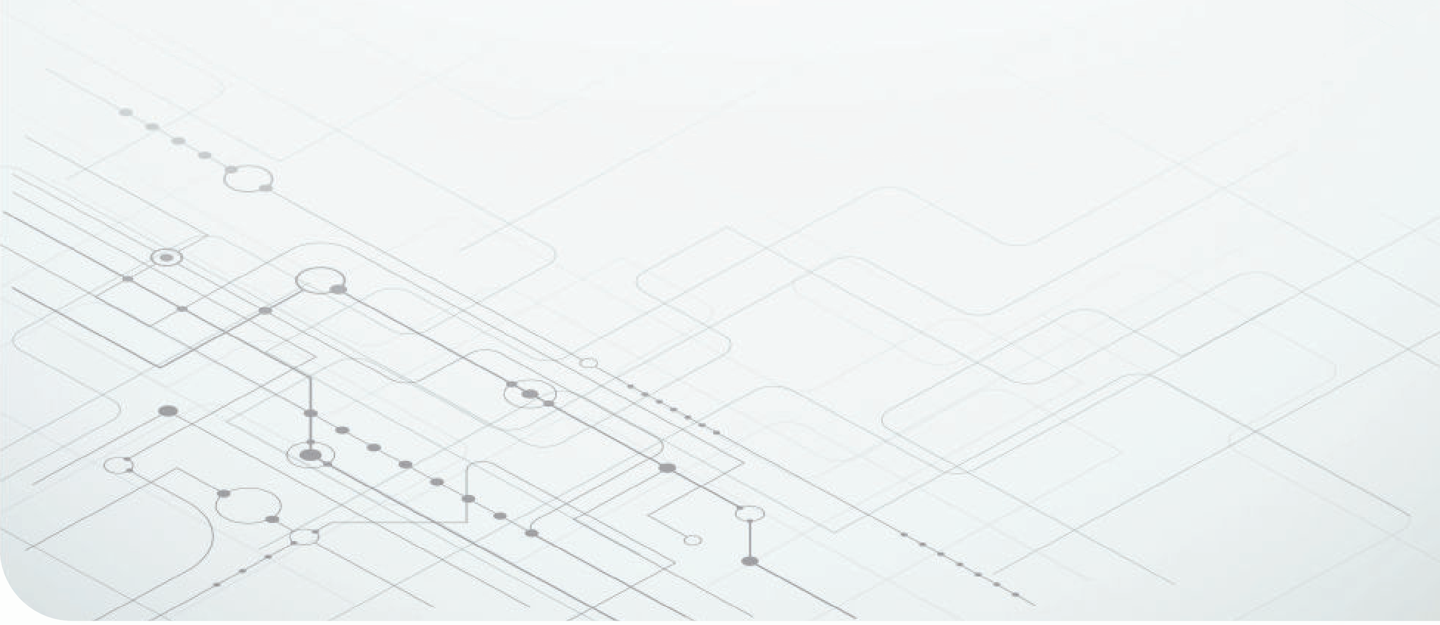

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Understanding the IEC 61800-5-1 safety standard for adjustable-speed electrical power-drive systems enables you to pick the right isolation solutions for AC motor drive applications.

Electric motors are ubiquitous in industrial applications. They are used in fans, conveyor belts, printing presses, paper mills, cranes, mixers, hoists, lifts, cooling and recirculating pumps, blowers, compressors, factory robotics, and many other applications. More than 300 million industrial electric motors are in use worldwide, with the number growing steadily every year.

Adjustable-speed electrical power-drive systems, also known as variable-frequency drives or AC motor drives, are smart motor-control systems. These systems use sophisticated power electronics to control the speed, torque and position of a motor versus running the motor at a fixed speed and using mechanical elements to control these parameters. Used widely in motor drive applications, adjustable-speed drives vastly improve the efficiency and control of motor drive systems.

Electric motor drive systems deliver output power in the range of a few to thousands of kilowatts. They operate off of AC line voltages in the range of hundreds to thousands of volts. Because such high voltages and power levels are involved, it is imperative that designers take measures to ensure the safety of humans involved in motor drive system operation.

The International Electrotechnical Commission (IEC) 61800-5-1 is a safety standard for adjustable-speed electrical power drive systems. It covers electrical, thermal and energy safety. As part of electrical safety, this standard defines the requirements for ensuring adequate insulation between circuits connected to voltages higher than 50 V and any drive system parts or connectors that may be accessible to humans.

Isolators are one of the key electronic components used in adjustable-speed electrical power drives. As isolated gate drivers, isolators control turning power transistors (insulated gate bipolar transistors [IGBTs] or metal-oxide semiconductor field-effect transistors [MOSFETs]) on and off in the power stage. As isolated analog-to-digital converters (ADCs) and isolated amplifiers, isolators convey voltage and current feedback from the inverter output. As general-purpose communication links, isolators transfer information from circuits referenced to high voltage, to earthed circuits and components. Isolators also act as insulators between the high voltage and parts accessible to humans. Thus, insulation is one of two functions of an isolator.

This paper discusses the electrical aspects of the IEC 61800-5-1 safety standard and analyzes how its stipulations on insulation requirements translate into specifications for isolators used in motor drives. This discussion is limited to a few select configurations and uses example cases to provide an understanding of the main principles of IEC 61800-5-1 relevant to isolators. For instance, only three-phase systems with rated power supply of up to 1000 V_{RMS} are discussed. For a more comprehensive understanding of these requirements, see the **IEC 61800-5-1 standard** .

Fundamental isolation concepts and terminology

This section briefly discusses fundamental concepts and terminology related to isolation.

- Basic isolation (or insulation) protects against high voltage as long as the insulation or isolation barrier remains intact. Safety standards such as IEC 61800-5-1 require a secondary isolation barrier for redundancy. The additional barrier provides safety protection, even if the first barrier fails. This is called double isolation.

- Reinforced isolation by itself, as far as safety against high voltage is concerned, is as good as double isolation. Damage to a reinforced isolation barrier can endanger human lives, necessitating stricter requirements.
- Temporary overvoltage is a short-duration high voltage (five seconds according to IEC61800-5-1) that an isolator must endure without breaking down. This represents overvoltage that can be present on supply-grid lines due to load switching, faults or arcing.
- Surge or impulse voltage is the peak value of a waveform of a particular transient profile (1.2/ 50 µs, see IEC 60060-1 or IEC 61000-4-5) that represents voltages induced on power-supply lines during direct and indirect lightning strikes.
- Working voltage is the continuous voltage across the isolator that is present throughout the equipment's operating life as part of its normal functioning.

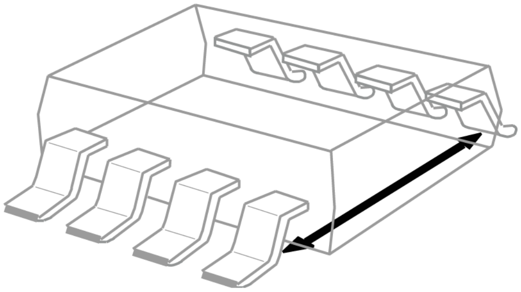

Figure 1. *Illustration of clearance.*

- Clearance is the shortest distance through the air from the pins on the high-voltage side to the pins on the low-voltage side of the isolator integrated circuit (IC) (**Figure 1**). The clearance must be high enough to prevent the peak values of impulse voltage and temporary overvoltage from causing the air between the pins to ionize and arc. Breakdown through the air is a fast phenomenon; the requirement on clearance depends on peak voltages that could occur in the system.

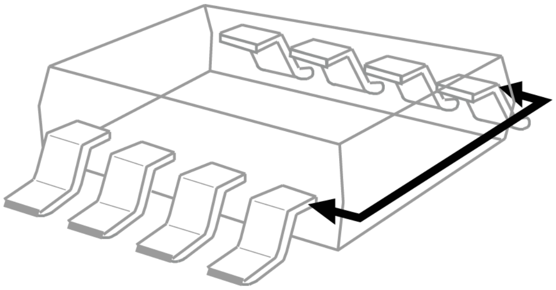

Figure 2. *Illustration of creepage.*

- Creepage is the distance along the surface of the isolator package from the high-voltage side to the low-voltage side (**Figure 2**). Creepage requirements are proportional to the root-mean-square (RMS) value of the working voltage that appears across the isolator according to the system's operating conditions. In some cases, you may need to increase creepage to meet clearance requirements. Creepage distance depends on pollution degree and the comparative tracking index (CTI) of the package-molding compound or material.
- Pollution degree represents the amount of dust, moisture or precipitation that may exist in the environment where the isolator is expected to work. A pollution degree of 2 is typical for an industrial environment where normally only nonconductive pollution occurs; however, conductive pollution can occur when the system is not in operation. A higher pollution degree increases the requirement on creepage and clearance.
- CTI is a property of insulation material that indicates its ability to resist degradation along its surface. Such degradation could lead to the formation of a conductive leakage path, if continuous high voltage is applied across it. Materials are classified into four groups based on CTI. Materials with a higher CTI (lower material group number) can tolerate a higher working voltage for the same creepage. Conversely, material with higher CTI can have a lower creepage length (smaller package dimensions) for a given working voltage.
  - Material group I: 600 V < CTI

- Material group II: 400 V < CTI < 600 V
- Material group IIIa: 175 V < CTI < 400 V
- Material group IIIb: 100 V < CTI < 175 V

Component-level standards for isolators (for example, VDE 0884-10 or IEC 60747-5-5) and system-level standards (for example, IEC 60664-1) define both the isolation parameters and methodologies used to test them. Reference [2 and 3] discusses these parameters and test methodologies in detail. Digital isolator data sheets clearly specify the values for these parameters. These values can be compared against requirements set by end-equipment standards such as IEC 61800-5-1.

Isolation in motor drives

Figure 3 describes a simplified example block diagram for an adjustable speed motor drive system.

An input power supply or grid input, usually three-phase, provides electrical power to the system. This is the grid or mains supply. Example voltages are 400 V_{RMS}, 690 V_{RMS} or 830 V_{RMS} at frequencies 50 Hz or 60 Hz. A rectifier stage of power diodes converts the input AC voltage into DC power rails (DC+ and DC–). High-voltage DC link capacitors provide both filtering to the rectifier and switching currents to the inverter stage. An IGBT module, or a bank of IGBTs, forms a three-phase inverter. MOSFETs can be used instead of IGBTs, although in this paper IGBTs are used as the example. Isolated gate drivers provide the required drive voltage to turn the IGBT on and off. Typically, a gate-emitter voltage of 15 V is used to turn on the IGBT, and a negative gate-emitter voltage of –8 V is used to turn it off. Isolated current and voltage-sense elements provide current and voltage feedback to the closed-loop control system. An encoder module provides feedback about the position and speed of the motor shaft.

The motor drive provides a three-phase output that is connected to the electric motor. The amplitude and frequency of this three-phase output is very different from the incoming grid supply, and depends entirely on the speed and torque output required from the electric motor. Simply put, this difference is how the adjustable-speed drive is able to control the electric motor’s mechanical output without needingmechanical elements such as gears or belts.

A control module that contains a microprocessor or field-programmable gate array (FPGA) provides the right sequence of pulse-width modulated (PWM) controls to the IGBT gate drivers at the right frequency, which controls the voltage and current waveforms produced at the motor drive output. These waveforms control the speed and torque output from the electric motor. The motor drive is a closed-loop system. The control module receives feedback from the voltage and current-sense circuits, and in some applications positions and speeds feedback from the encoder.

The control module interfaces with the rest of the control network (for example, to a programmable logic controller [PLC], 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 and the input port of the encoder interface. Sufficient safety isolation is required between these exposed parts and the high-voltage circuits (circuitry connected to the DC buses and the incoming supply lines). This isolation can be achieved through isolated gate drivers and isolated voltage and current-sense amplifiers. Additional isolation can be introduced between the control module and communication interface, but this is not shown in Figure 3. The lines shown in blue in Figure 3 are low-voltage or safe signals that are safety-isolated from the high voltage.

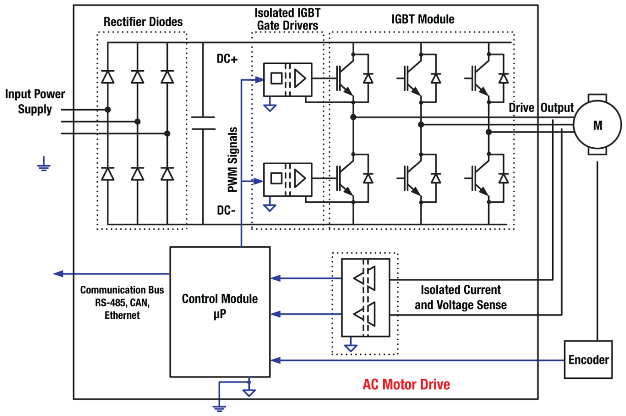

Figure 3. *Typical block diagram of an AC motor drive.*

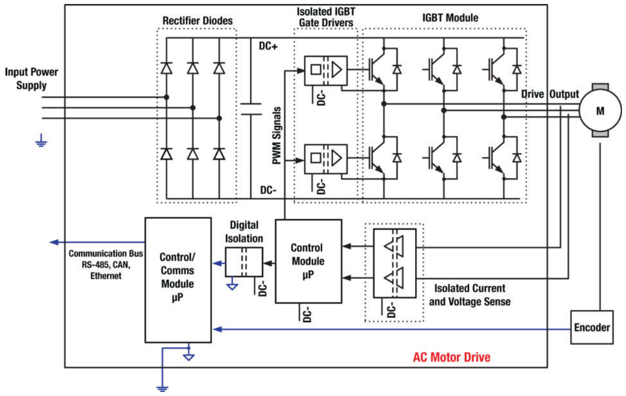

Figure 4. *Alternative isolation scheme for an AC motor drive.*

Figure 4 shows another possible configuration where the control module is not earth-referenced. Instead it is biased to the DC bus. 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 sense elements, whose ground references are the inverter outputs that are switching high voltage with respect to the DC-bus.

IEC 61800-5-1 definitions

When applying the IEC 61800-5-1 standard to any given motor drive design, a designer needs to understand the following definitions.

System voltage

This is the RMS voltage between a phase of the input or grid supply and earth. The system voltage has a strong dependence on the supply system's earthing scheme. For a star-earthed TN grid (Figure 5**a**), the RMS voltage between a phase and earth is the phase-phase voltage divided by √3. However, for a corner-earthed TN system (Figure 5**b**), the system voltage is the same as the phase-phase voltage. Safety requirements on the isolation (or insulation) depend directly on the system voltage.

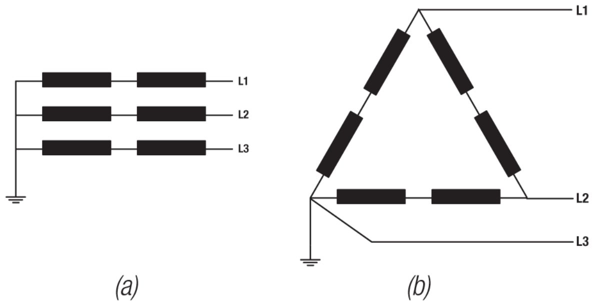

Figure 5. *Star-earthed TN system that is neutral-earthed (a); and a corner-earthed TN system where one phase is earthed (b).*

Overvoltage category

According to IEC 61800-5-1 standard, equipment is classified into four categories based on how it is connected to the supply mains:

- 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 category is more likely to see higher voltage disturbances. Therefore, it needs to meet a higher requirement on temporary overvoltage and impulse or surge voltage.

Most industrial motor drives fall under Category III.

Working voltage

Working voltage is the voltage continuously present across an isolator whenever the equipment is in operation. This value does not directly follow from the system voltage, or from the phase-phase voltage of the incoming supply. Instead, it depends on the architecture of the drive itself. This is discussed more in the next section.

Applying IEC 61800-5-1 standard to a motor drive design

Now that you have an understanding of isolation with earthing concepts and terms, you can apply the IEC 61800-5-1 requirements to a given motor drive design step-by-step. Unless specified otherwise, we use overvoltage Category III and pollution degree 2 in this discussion. Also, this document only covers requirements for isolators versus other components in a gate-drive 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 61800-5-1) is required between circuitry connected to high voltage and any parts or connectors accessible to humans. A designer can achieve protective separation by: 1) two basic isolators in series (double isolation); or 2) through one reinforced isolator.

In the motor drive system shown in **Figure 3** , the isolated gate drivers and isolated voltage and current-feedback circuits both need to support reinforced isolation. Basic isolation is sufficient, if you introduce additional basic isolators (such as an isolated RS-485) in the path of signals that proceed to external interfaces or connectors. In the motor-drive system shown in **Figure 4** , the digital isolator needs to support reinforced isolation. In **Figure 4** , the isolated gate drivers and isolated feedback circuits, being DC bus-referenced, have high voltage on either side and do not need to be designed for protective separation.

Step 2 – Determine the system voltage. As discussed, this depends on the incoming grid supply voltage as well as the earthing scheme. A three-phase 400 V_{RMS} TN supply, neutral-earthed, has a system voltage of 230 V_{RMS}. A three-phase 830 V_{RMS} corner-earthed system has a system voltage of 830 $V_{RMS.}$

Step 3 – Determine the requirement for temporary overvoltage and impulse/surge voltage for each isolator, using **Table 7** [4] from IEC 61800-5-1 [1]. This table does not allow for interpolation. The next higher system voltage, for example, 230 V_{RMS}, is treated as a 300 V_{RMS} system voltage, and 830 V_{RMS} is treated as a 1000-V_{RMS} system voltage.

Table 7 lists the requirements for basic isolation. For reinforced isolation, double the requirement on temporary overvoltage. For surge voltage, use the next-higher impulse voltage. 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. **Table 9** [4] from IEC 61800-5-1 [1] lists the clearance requirements for a given temporary overvoltage and surge/impulse voltage. Using this table, and based on the temporary overvoltage and surge requirements determined at Step 3, you can obtain the clearance requirement.

Table 9 shows values for altitudes of up to 2000 m. To operate at higher altitudes, increase the clearance by a certain factor to account for the fact that air breaks down more easily at higher altitudes. This correction factor for higher altitudes is defined in **Table D.1** [4] of IEC 61800-5-1. For example, to operate at 5000 m, increase the clearance obtained from **Table 9** by a factor of 1.48.

Step 5 – Determine the working voltage for every isolator used in the design. The working voltage does not directly follow from the system voltage or from the incoming supply's phase-phase voltage, but depends on the motor drive architecture. The gate driver of **Figure 2** , under maximum output voltage from the motor drive, sees a sinusoidal bipolar barrier voltage (modulated by a high-frequency trapezoidal PWM carrier frequency) having a swing between DC+ and DC –. Alternatively, the gate driver shown in **Figure 4** is biased to DC–. The gate-driver sees a unipolar voltage swing between 0 to 2 × DC+.

The earthing scheme also plays a role. For example, the voltage profile across the digital isolator in **Figure 4** depends on whether or not the incoming supply is either star- or corner-earthed. In the first case, the DC– bus is at a fairly steady voltage with respect to earth potential, while the DC– bus in the second case also sees a high-voltage swing.

Several factors complicate the computation of the working voltage. First, the high-frequency trapezoidal PWM modulation on the inverter output can change the RMS of the working voltage for the isolated gate drivers and isolated sense elements. Second, increasing DC bus voltage during motor braking can mean occasional higher voltage across the isolators. Therefore, determine the working voltage of every isolator carefully.

The isolator must sustain both peak and RMS values of the working voltage profiles throughout the equipment's expected life. Generally, isolators with RMS and DC working-voltage capability equal to the RMS and peak values of input phase-phase voltage should cover most cases. 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 using the RMS value of the working voltage according to **Table 10** [4] from IEC 61800-5-1. This table presents results for basic isolation. For reinforced isolation, double the creepage requirement.

The creepage requirement depends on the pollution degree and CTI of the isolator; this is reflected in **Table 10** .

Conformal coating or potting can help reduce the requirement for creepage and clearance by reducing the pollution degree under the coating, as well as blocking the path for arcing between pins. Note that 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.

Step 7 – Choose an isolator that meets all requirements called out in steps 3 through 6. **Table 1** summarizes these requirements for a few example three-phase systems with overvoltage Category III, pollution degree 2 and altitude <2000 m. The working voltage is assumed the same as the incoming phase-phase 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 motor drive applications

In response to these needs, Texas Instruments offers several isolation offerings for motor drive 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 **UCC23513** and **ISO5852S** reinforced isolated gate drivers and the ISO77xxDW and ISO78xxDWW families of digital isolators.

These families of isolators, with the exception of the ISO78xxDW family, have a 60-second temporary overvoltage of 5 $\mathrm{kV_{RMS}}$ or greater; bipolar, unipolar and DC working voltages of 1.5 $\mathrm{kV_{RMS}}$ and 2121 $\mathrm{V_{PK}}$; and a surge voltage of 12.8 $\mathrm{kV_{PK}}$. The ISO78xxDW family has an extra-wide 14.5-mm creepage and clearance package for higher voltage systems. 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.

AC phase-phase voltage ($\mathrm{V_{RMS}}$)	Earthing scheme	System voltage ($\mathrm{V_{RMS}}$)	System voltage ($\mathrm{V_{RMS}}$) per IEC61800-5-1	Basic / reinforced	Temporary overvoltage ($\mathrm{V_{RMS}}$ / $\mathrm{V_{PK}}$)	Impulse / surge voltage ($\mathrm{V_{PK}}$)	Minimum clearance	Working voltage ($\mathrm{V_{RMS}}$ / $\mathrm{V_{PK}}$)	Minimum creepage (mm)		
									Material group		
									I	II	III
400	Neutral-earthed	230	300	Basic	1500/2120	4000	3	400/566	2	2.8	4
830	Neutral-earthed	480	600	Basic	1800/2550	6000	5.5	830/1174	4.2	5.8	8.3
830	Corner-earthed	830	1000	Basic	2200/3110	8000	8	830/1174	4.2	5.8	8.3
1000	Corner-earthed	1000	1000	Basic	2200/3110	8000	8	1000/1414	5	7.1	10
400	Neutral-earthed	230	300	Reinforced	3000/4240	6000	5.5	400/566	4	5.6	8
830	Neutral-earthed	480	600	Reinforced	3600/5100	8000	8	830/1174	8.4	12.6	16.6
830	Corner-earthed	830	1000	Reinforced	4400/6220	12000	14	830/1174	8.4	12.6	16.6
1000	Corner-earthed	1000	1000	Reinforced	4400/6220	12000	14	1000/1414	10	14.2	20

Table 1. *Summary of requirements per IEC 61800-5-1 for a few example systems (Category III, pollution degree 2, altitude <2000 m).*

Table 2 summarizes the capabilities of these devices when applied to various requirements of the IEC 61800-5-1 standard. By combining intrinsic isolation strength with material group I mold compound in wide packages, TI devices can address products with a rated power supply up to 1000 $\mathrm{V_{RMS}}$, with margin to spare.

Conclusion

Isolators are essential components of modern motor drive systems and must be chosen carefully to ensure optimal insulation coordination. In this paper, we examined several aspects of isolator selection for motor drive systems to comply with IEC 61800-5-1. This includes requirements on transient overvoltage, impulse voltage, working voltage, 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 motor drive designs with rated supply voltages up to 1000 $\mathrm{V_{RMS}}$.

References

1. IEC 61800-5-1 Ed. 2.0. Adjustable speed electrical power drive systems, safety requirements, electrical, thermal and energy. July 2007.
2. Anant S Kamath, Kannan Soundarapandian. **High-voltage reinforced isolation: Definitions and test methodologies** . Texas Instruments White Paper, November 2014.
3. **Isolation glossary** . Texas Instruments, October 2014.
4. Referenced tables 7, 9, 10 and D.1 are available from the **IEC 61800-5-1** publication, which can be purchased from the IEC webstore.
5. Download these data sheets: **UCC23513** , **ISO5852SDW** , **ISO7741** and **ISO7841DWW** .
6. Signal Isolators with Integrated Power product folders **ISOW64xx**, **ISOW3080**, **ISOW1050**
7. Texas Instruments, ***Enhance Design Performance using Integrated Power and Digital Isolation Design*** , application brief.
8. Texas Instruments, ***Achieving Best EMC Performance for Signal Isolators with Integrated Power.***, application note.

Device	Function	Creepage / clearance (mm)	Basic / reinforced	System voltage supported up to V_{RMS}	Working voltage supported up to V_{RMS}/V_{PK}
UCC23513DWY ISO5852SDW	Gate driver	8	Basic	1000	1500/2121
			Reinforced	600	800/1130
ISO77xxDW	Digital isolator	8	Basic	1000	1500/2121
			Reinforced	600	800/1130
ISO78xxDWW	Digital isolator	14.5	Basic	>1000	1500/2121
			Reinforced	1000	1450/2050
ISOW64xx	Digital Isolator with integrated Power	8	Reinforced	1000	1000/1414
ISOW3080	Isolated RS485 with integrated Power	8	Reinforced	1000	1000/1414
ISOW1050	Isolated CAN with integrated Power	8	Reinforced	1000	1000/1414

Table 2. *TI isolation device capabilities per IEC 61800-5-1 (Category III, pollution degree 2, altitude <2000 m).*

[1]

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[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 [2]. For example, the intrinsic capabilities of the isolator can be realized at the system level through conformal coating or potting.

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