Application Note

Basics of Solid-State Relays

Jose Rojo

ABSTRACT

Solid-state relays are switches with no moving parts that control loads with signals provided by an external device, such as an MCU. High voltage systems, like a high-voltage battery in an electric vehicle, need solid-state relays to control a high voltage load with a low voltage signal. These types of applications often require isolation to prevent two power domains forming an undesired ground loop due to a high potential difference as well as to monitor user protection from hazardous currents.

There are many methods available to achieve isolation for a solid-state relay. Photo or optical isolation technologies are well established in the industry for the last few years. New capacitive and inductive isolation technologies are able to provide advantages over photo isolation. This includes improved reliability, and the ability to quickly send and receive signals across the isolation barrier to allow for diagnostics information to inform the system of unexpected faults like over-current or over-temperature. This application note explores the different types of solid-state relays and their internal topologies.

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1 Introduction

A solid-state relay is an electronic switch that switches on or off when an external voltage is applied across the control terminals. Solid-state relays are typically used in the same applications as electromechanical relays; however, a key difference is that solid-state relays have no moving parts and can provide reliability benefits. Common examples of solid-state relays include optical or photo relays, or isolated switches and isolated switch drivers with capacitive or inductive isolation.

2 What Are Solid-State Relays?

2.1 History

2.1.1 Electromechanical Relays

Electromechanical relays were first invented in the mid-19th century. These devices functioned as electrically operated switches by using a coil in combination with movable metal contacts. These devices can experience failure as the metal contacts experience wear and tear, such as welding shut. As a result, the device has a limited number of switching cycles before experiencing complete failure, thus limiting overall reliability.

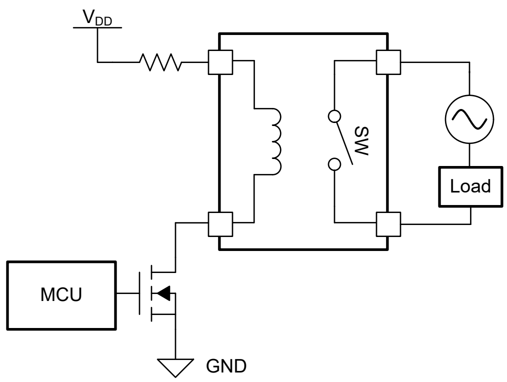

Figure 2-1. Block Diagram of an Electromechanical Relay

2.1.2 Solid-State Relays

Solid-state relays were developed to combat these failures, with the photo relay being one of the first solid-state relays to emerge as the leading design. Photo relays improved reliability by integrating MOSFETS within the device. As a result, photo relays allow for a higher amount of switching cycles, though are subject to failure in different ways as the internal LED degrades over time.

Newer alternative methods have been developed to improve solid-state reliability further. Capacitive and inductive based isolation technologies were developed to combat issues present in photo relays to provide robust reliability as well as high performance. Refer to Section 2.2 for more information.

Isolated switches are single-chip designs that have integrated MOSFETs, also, isolated switch drivers are chips that drive a control signal and power to an external array of MOSFETs. Both of these designs form a solid-state relay by leveraging capacitive and inductive isolation technologies

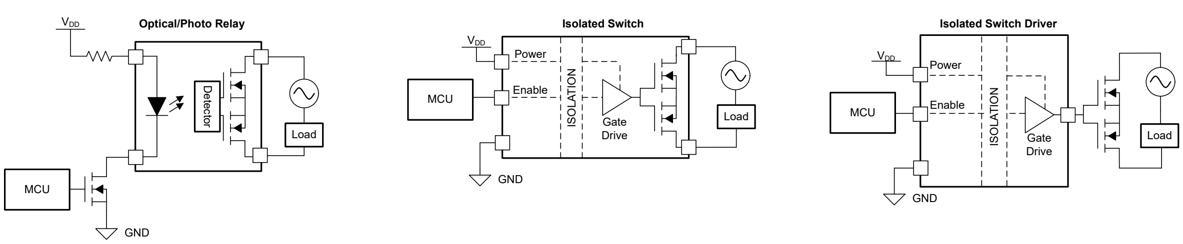

Figure 2-2. Block Diagram of Solid-State Relays

2.2 Isolation Technologies

2.2.1 Isolation Specifications

Solid-state relays typically have an isolation barrier between the primary and secondary sides of the device that can be achieved with various insulation materials. Refer to Table 2-1 for more information.

Table 2-1. Isolation Technology Specification Comparison

Isolation Type	Insulation Material	Dielectric Strength (1s)	Operating Temperature
Optical Isolation	Epoxy or Polyimide	approximately 20V_{RMS} / µm approximately 300V_{RMS} / µm	-40°C - 85°C
Inductive Isolation	Laminate or Polyimide	approximately 300V_{RMS} / µm	-40°C - 125°C
Capacitive Isolation	Silicon Dioxide	approximately 500V_{RMS} / µm	-40°C - 125°C

To learn more about the internal topologies of optical, capacitive, and inductive isolation, please reference *Addressing High-Voltage Design Challenges With Reliable and Affordable Isolation Technologies*.

2.3 Relay Evolution

Traditionally, electromechanical relays and photo relays require an external resistor to control current flow and an external MOSFET to drive a load through either the coil or LED. Isolated switches and drivers eliminate the need for an external resistor and MOSFET by incorporating transistor based inputs, such as TTL or CMOS logic. As a result, isolated switches or drivers reduce overall BOM compared to other isolation technologies.

Figure 2-3 displays an electromechanical relay, photo relay, and isolated switch or driver (left to right).

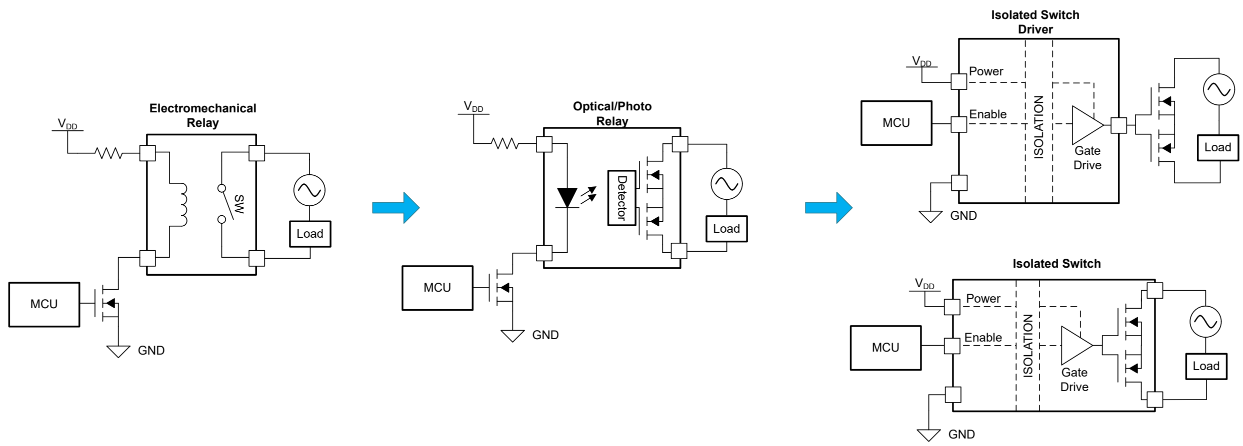

Figure 2-3. Relay Evolution Block Diagram

3 Failure Mechanisms

All solid-state relays and electromechanical relays can experience failure. A key difference in these faults are the failure mechanisms, which can vary for each device. This section explains the failure mechanisms found in electromechanical, photo, and capacitive/inductive technologies.

3.1 Arcing in an Electromechanical Relay

When an electromechanical relay switches to an open state from a closed state, the metal contacts can initially oscillate between both states. In combination with an inductive load, the metal contacts can experience an arcing phenomenon, the process in which electrons flow across the gap present between the metal contacts. After many cycles, there is a possibility that the metal contacts weld shut, leading to device failure. This failure mechanism limits the switching cycles of the device, thus limiting overall reliability.

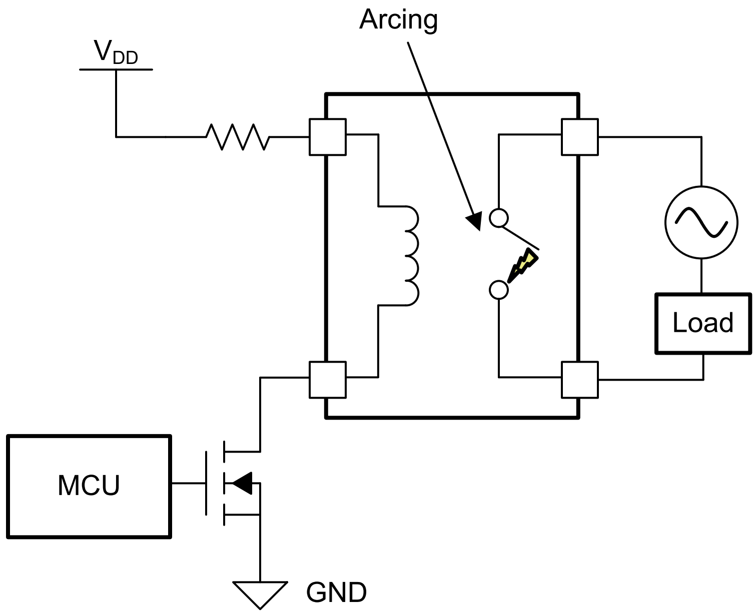

Figure 3-1. Arcing in an Electromechanical Relay Block Diagram

3.2 Photo-degradation in Photo Relays

Photo relays experience failure due to potential complications with the internal LED. To elaborate, an LED is subject to light decay, which in the case of a photo relay is the reduction of light output capacity due to extreme conditions, such as over-temperature or over-current. As a result, the LED within a photo relay does not have enough luminosity to drive a gate voltage, which limits the switch functionality of the device.

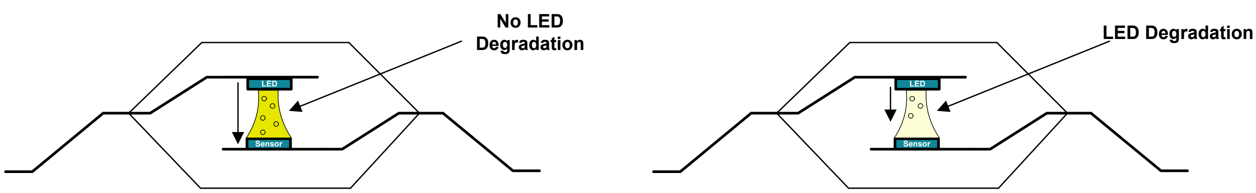

Figure 3-2. Optical Relay LED Failure Block Diagram

3.3 Partial Discharge

The insulation material used in solid-state relays has defects known as internal voids. This allows for localized ionization, the process by which an atom gains a negative or positive charge by losing or gaining electrons when a high voltage rating is applied. As a result, the dielectric strength of the insulation material can breakdown, thus reducing the isolation rating of the device. This process is known as partial discharge (PD), and is applicable to most solid-state relays.

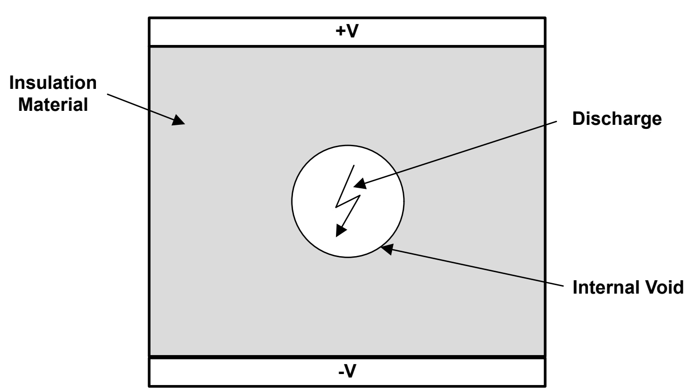

Figure 3-3. Internal Void Block Diagram

3.4 Time-Dependent Dielectric Breakdown in Capacitive and Inductive Isolation

Similar to photo relays, capacitive and inductive isolation technologies are subject to partial discharge. As a result, this phenomenon can be quantified to time-dependent dielectric breakdown (TDDB), the standard test method to verify the lifetime of any dielectric. Data can be gathered on a device's time-dependent dielectric breakdown (TDDB) performance to characterize the expected failure rate.

As an example, here is the insulation lifetime projection data for the TPSI3050-Q1. The breakdown data is collected at various high-voltage ratings, displaying a relationship between fail time and V_{RMS}.

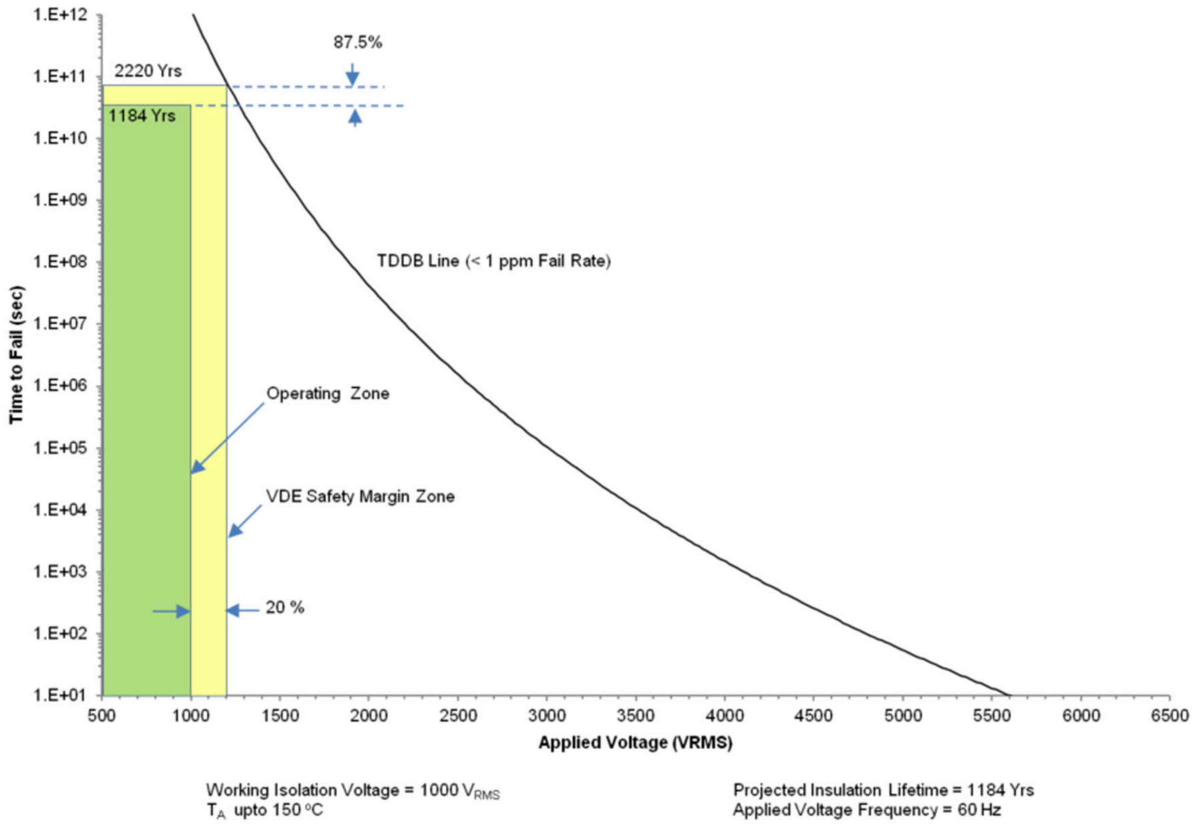

Figure 3-4. TPSI3050-Q1 Insulation Lifetime Projection Data

4 Electromechanical vs. Photo vs. Capacitive or Inductive

All solid-state relays share the same common feature of having no moving parts, which enables high switching speeds and a high number of switching cycles. However, because there are many methods to achieve isolation, every device has different limitations.

4.1 Electromechanical Relays

4.1.1 Advantages

4.1.1.1 No Leakage Current

Electromechanical relays use metal contacts instead of integrated or external MOSFETs. This allows for no leakage current within the device due to the ability to implement a pure mechanical disconnect. The same cannot be said of solid-state relays as leakage current can be present due to the nature of MOSFETs.

Figure 4-1 displays how leakage current is non-existent in electromechanical relays, and where leakage current is present in solid-state relays.

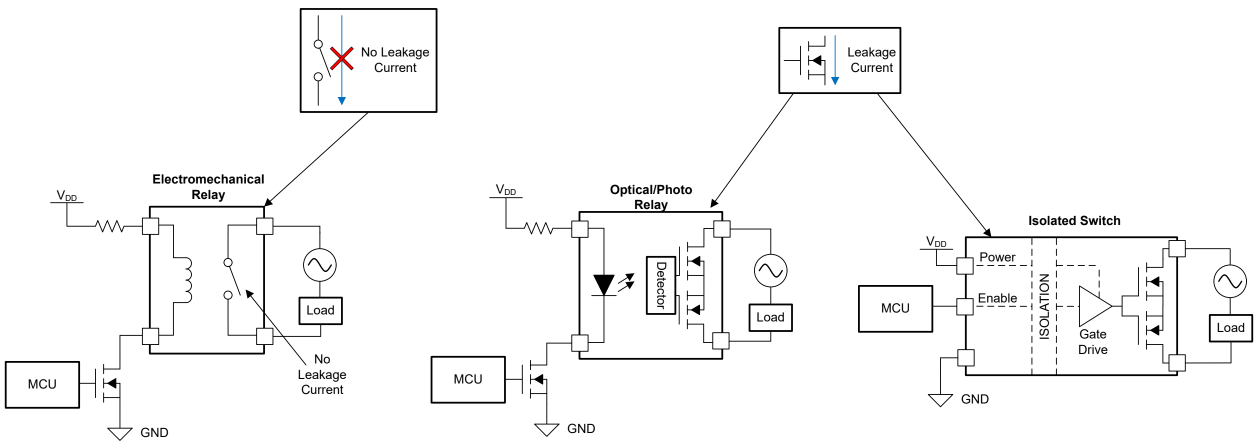

Figure 4-1. Leakage Current in All Relays Block Diagram

4.1.2 Limitations

4.1.2.1 Switching Speed

Electromechanical relays typically have slower switching speeds than solid-state relays. This is because the current flowing through the metal contacts must reach a certain condition before switching to an open/closed state. As an example, when switching from an open to a closed state, the metal contacts must stop oscillating before applying a current load. This is known as the settling time, and this phenomenon can be found in most electromechanical relays.

4.1.2.2 Package Size

Electromechanical relays usually have larger heights than solid-state relays. This is because the the package needs to accommodate space for all of the parts within the device, such as the metal contacts, coil, and spring.

Figure 4-2 compares the package size of an electromechanical relay and an isolated switch driver.

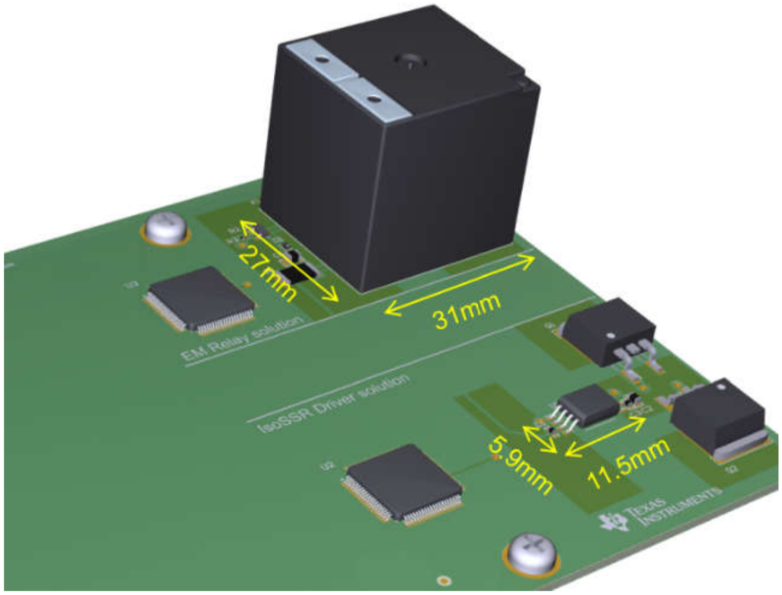

Figure 4-2. Electromechanical Relay's Package Size

4.2 Photo or Optical Relays

4.2.1 Advantages

4.2.1.1 Lower EMI

Photo relays can have a lower EMI rating than capacitive/inductive based relays. This is because photo relays do not need to modulate or demodulate signal and power across the isolation barrier, Instead, photo relays emit a constant light output from the LED to the sensor.

4.2.2 Limitations

4.2.2.1 Limited Temperature Range

Photo relays can have a lower operating temperature range compared to other relay designs. This is because the LED within a photo relay cannot exceed a certain temperature range without compromising high performance due to potential LED degradation. To achieve higher temperature ranges, most photo relays have to use more expensive materials, which is not practical in most applications.

4.3 Capacitive or Inductive Based Relays

4.3.1 Advantages

4.3.1.1 Auxiliary Power

Isolated switch drivers are able to provide an auxiliary power source on the secondary side of the device to drive additional external circuits. This allows for low voltage systems, such as current sense amplifiers, to be powered without requiring any external power source on the secondary side of the device.

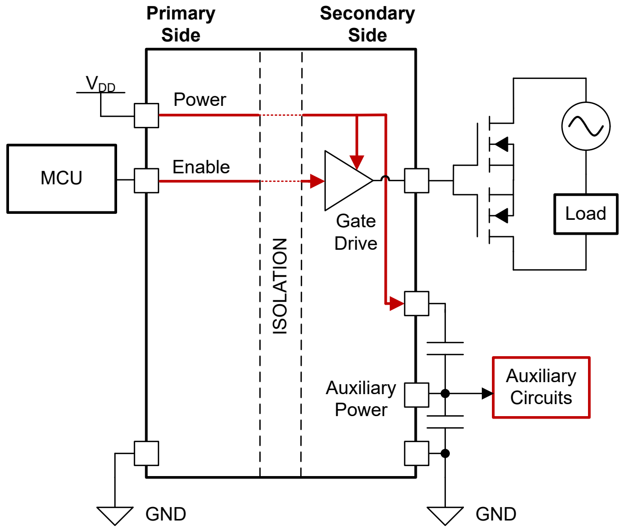

Figure 4-3. Isolated Switch Driver with Auxiliary Power Block Diagram

4.3.1.2 Bidirectional Communication

Capacitive and inductive isolation technologies are capable of implementing diagnostics and protection features. These technologies are able to send signals across the isolation barrier in both directions, allowing for bidirectional communication. As an example, TPSI3100-Q1 is able to send signal and power from primary to secondary side, as well as send diagnostics like fault and alarm signals from secondary to primary side. These diagnostic features can be used to detect system faults like over current or monitor system conditions like inrush currents. Optical designs are only able to send power from primary to secondary side allowing only unidirectional communication, unable to provide diagnostics to the system.

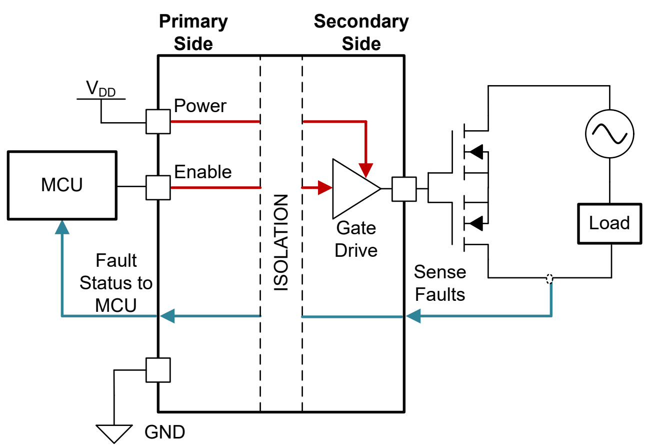

Figure 4-4. Isolated Switch Driver with Bidirectional Communication Block Diagram

4.3.2 Limitations

4.3.2.1 EMI

When sending power across a capacitive or inductive isolation barrier, switching modulation is required. These high frequency switching signals can couple through the board, which can result in higher EMI. In light of this, these newer technologies are designed with electromagnetic compatibility (EMC) to help minimize conducted and radiated emissions. These improved designs are able to meet rigorous automotive standards, such as CISPR 25 Class 5, or CISPR 32 for industrial applications.

There are additional system level techniques that designers can use to improve EMI performance. To learn more about low cost EMI mitigation techniques, please reference the *TPSI2140-Q1* data sheet.

4.4 Overall Comparison

Refer to Table 4-1 for comparisons among electromechanical relays, optical relays, and capacitive/inductive based relays.

Table 4-1. Performance Comparison

Type of Relay	Device	Power consumption at high temperature	Package size	Leakage current	# of Switching cycles	Reliability	Switching speed
Non Solid-State Relay	Electro-mechanical relays	Higher	Larger	None	Limited	Lower	Slow
Solid-State Relays	Photo-based relays	Higher	Smaller	Small leakage current	High	Better	Quick
	Capacitive/ Inductive based relays	Lower	Smaller	Small leakage current	High	Better	Quick

5 Summary

Solid-state relays are effective in high-voltage systems, providing overall better reliability and performance than electromechanical relays. Photo or optical based designs provided an initial improvement in reliability over EMRs, however newer technologies such as capacitive and inductive based isolation technologies have the capability to enable advanced protection features as well as further improving reliability. These next-generation solid-state relays have the ability to lay the foundation for innovation in many industries, pushing the limits in what can be achieved with an electronic switching device.

6 References

1. Texas Instruments, *How to Achieve Higher-reliability Isolation and a Smaller Solution Size with Solid-state Relays*, technical article.
2. Texas Instruments, *Why Pre-Charge Circuit are Necessary in High-Voltage Systems*, application brief.
3. Texas Instruments, *Cascoding Two TPSI3050 Isolated Switch Drivers to Increase Gate Drive Voltage*, application note.
4. Texas Instruments, *AFE for Insulation Monitoring in High-Voltage EV Charging and Solar Energy Reference Design*.
5. Texas Instruments, *Overcurrent and Overtemperature Protection for Solid State Relays Reference Design*.
6. Texas Instruments, *Zero-Cross Switching for Solid-State Relays Reference Design*.
7. Texas Instruments, *High Frequency TDDB of Reinforced Isolation Dielectric Systems*, technical white paper.
8. Texas Instruments, *Addressing High-Voltage Design Challenges With Reliable and Affordable Isolation Technologies*, marketing white paper.
9. Texas Instruments, *TPSI2140-Q1 1200-V, 50-mA, Automotive Isolated Switch With 2-mA Avalanche Rating*, data sheet.

For additional information, refer to Solid-State Relays.