Robust Construction of the Optoisolator

White Paper

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Chapter 1: Introduction

The concept of functional safety revolves around the assurance that a system will behave in a predictable and safe manner, even when faced with internal faults or external disturbances. In the context of motor drives, this process entails implementing measures to mitigate the risks associated with electrical, mechanical, and software failures. The goal is to ensure that the system operates reliably under all foreseeable circumstances and to prevent injury, damage, or even loss of life.

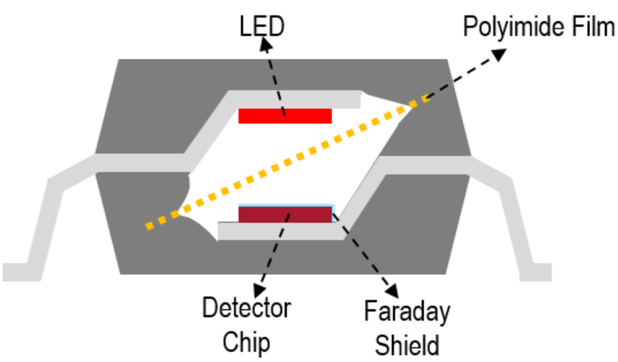
In this document, we will discuss how a single point failure with the power supply can lead to uncontrolled movements. The other aspect of this failure is damage to the galvanic insulation barrier. This damage can lead to electric shock because motor drives deliver high power, operating off AC line high voltages in the range of hundreds to thousands of volts. To minimize the likelihood of accidents and optimize operational efficiency, we will look at how robust construction in a high-voltage optoisolator can help mitigate such disastrous consequences from a power supply failure.

Chapter 2: Isolator Construction

Before looking into a single point failure of the power supply, we will look at the construction of an optical and capacitive galvanic isolated gate driver. Gate drivers are used extensively to drive power semiconductors such as insulated-gate bipolar transistors (IGBTs) in motor drives. They provide reinforced galvanic insulation between high-voltage IGBTs and control circuits. Their ability to reject high common mode noise is important to prevent erroneous driving of the IGBTs. Therefore, the robust construction of an isolated gate driver is critical to drive the motor in a fail-safe manner during a fault.

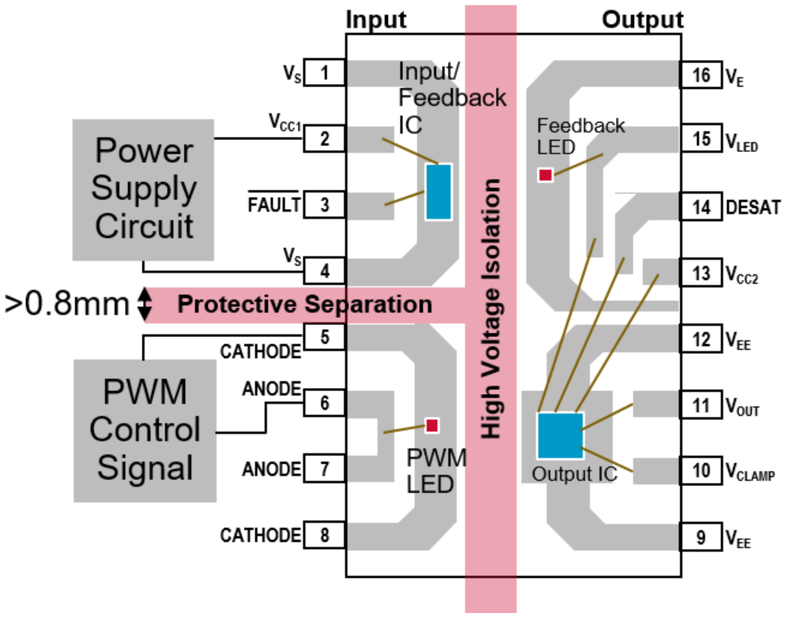
An optoisolator provides reinforced insulation via a wide distance through insulation (DTI) between the LED and the detector with three layers of insulation barriers. The three layers of insulation are made up of silicone, polyimide film, and silicone as shown in Figure 1. Polyimide film is developed specifically to withstand the damaging effects of partial discharge, which can cause ionization and a breakdown of insulation material. Polyimide has the unique properties of a high dielectric strength and a wide temperature range. These properties allow it to be used extensively in electrical insulation applications, from locomotives to aerospace. The polyimide film used in the ACPL-334J gate drive optocoupler has a typical dielectric strength of 300 kV/mm and can withstand temperatures as low as –200°C and as high as 400°C. The DTI of the ACPL-334J gate drive optocoupler is 0.5 mm.

Figure 1: Optoisolator Barrier Structure with Three Layers of Insulation



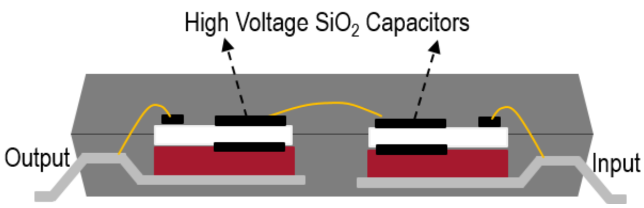
The IEC defines a separated extra-low voltage (SELV) circuit as an electrical circuit in which the voltage cannot exceed extra-low voltage under normal and single-fault conditions. A SELV circuit must have electrical protective separation from all other circuits. In motor drives, the power supply circuit at the input should be separated from the pulse-width modulation (PWM) control circuit. The lead frame at the input of the ACPL-334J gate drive optocoupler is designed with a protective separation distance of more than 0.8 mm as shown in Figure 2.

Figure 2: Lead-Frame Structure of the ACPL-334J Gate Drive Optocoupler with Protective Separation



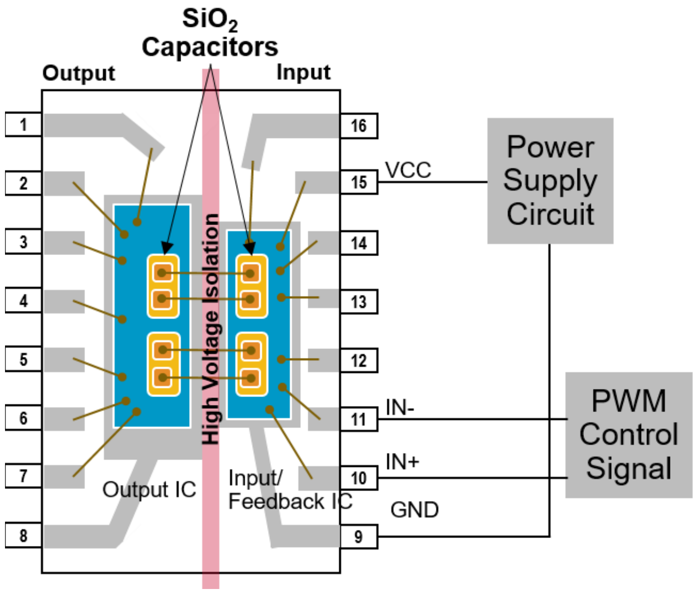
The capacitive isolator uses silicon dioxide (SiO_2) as a dielectric for the on-chip insulation. The isolation circuit is integrated on the same chip along with other circuitry in a monolithic process. High-voltage isolation is achieved using two thick SiO_2 capacitors in series, one on the input side and the other on the output side. The high-voltage capacitors use the same process as the CMOS production. The thickness of the SiO_2 or DTI of a capacitive isolator is between 0.014 mm and 0.028 mm.

Figure 3: Capacitive Isolator Structure with Two SiO_2 Capacitors in Series



The construction of a gate driver using capacitive isolation in a two-chip module is shown in Figure 4. The input and output ICs have isolation capacitors to increase the high-voltage capability. As this construction is a monolithic process, the input IC of the gate driver consists of the power supply circuit, PWM control circuit, and SiO_2 capacitor in a single chip.

Figure 4: Construction of a Gate Driver Using Capacitive Isolation in a Two-Chip Module

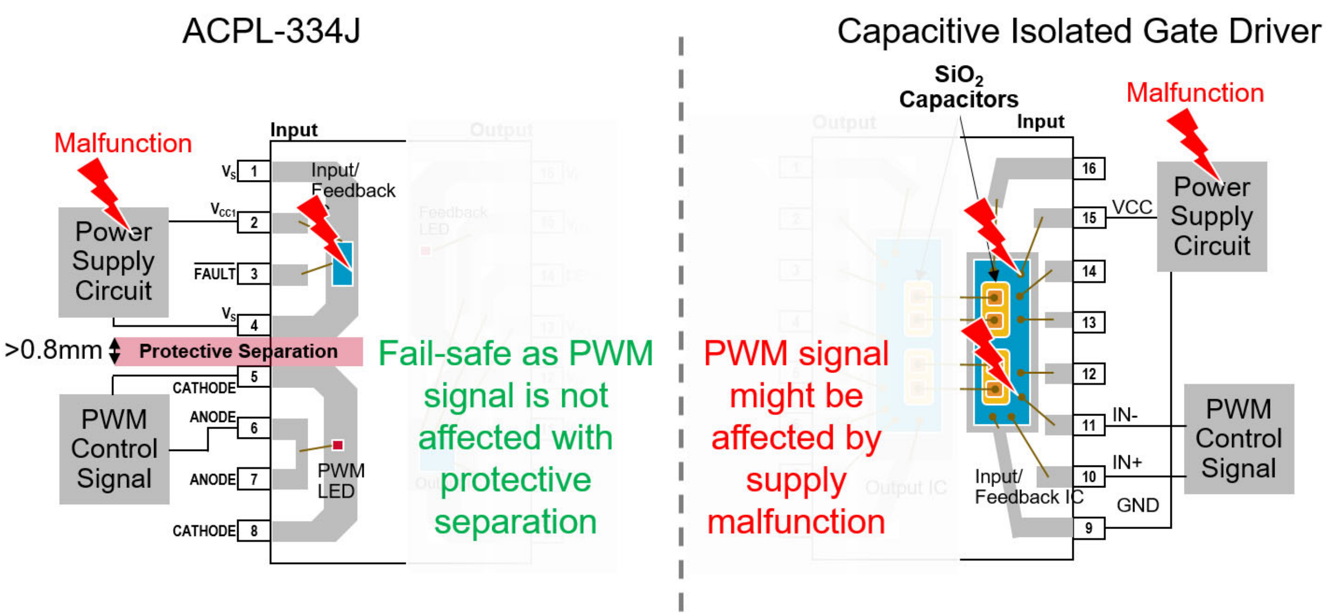


Chapter 3: Single Point Failure and Power Supply Fault

One of the primary reasons why functional safety is of utmost importance in motor drives is the catastrophic consequences during a fault. A single point power supply fault can lead to uncontrolled movements and compromise the isolation barrier. The PWM controller on its own cannot be considered safe when off. If there is a malfunction on the power supply and damage to the input IC, the ability to switch off the motor must be guaranteed.

However, in the single-chip architecture of the capacitor isolation, the power supply malfunction can cause input logic (IN+/IN–) to be in the wrong state and signal the wrong motor movements. Alternatively, the lead frame at the input of the ACPL-334J gate drive optocoupler provides a protective separation from the malfunctioned power supply. This redundancy in architecture provides a fail-safe condition in which the PWM LED will not transmit the wrong signal to the motor.

Figure 5: Protective Separation Provides a Fail-safe Condition during a Power Supply Fault



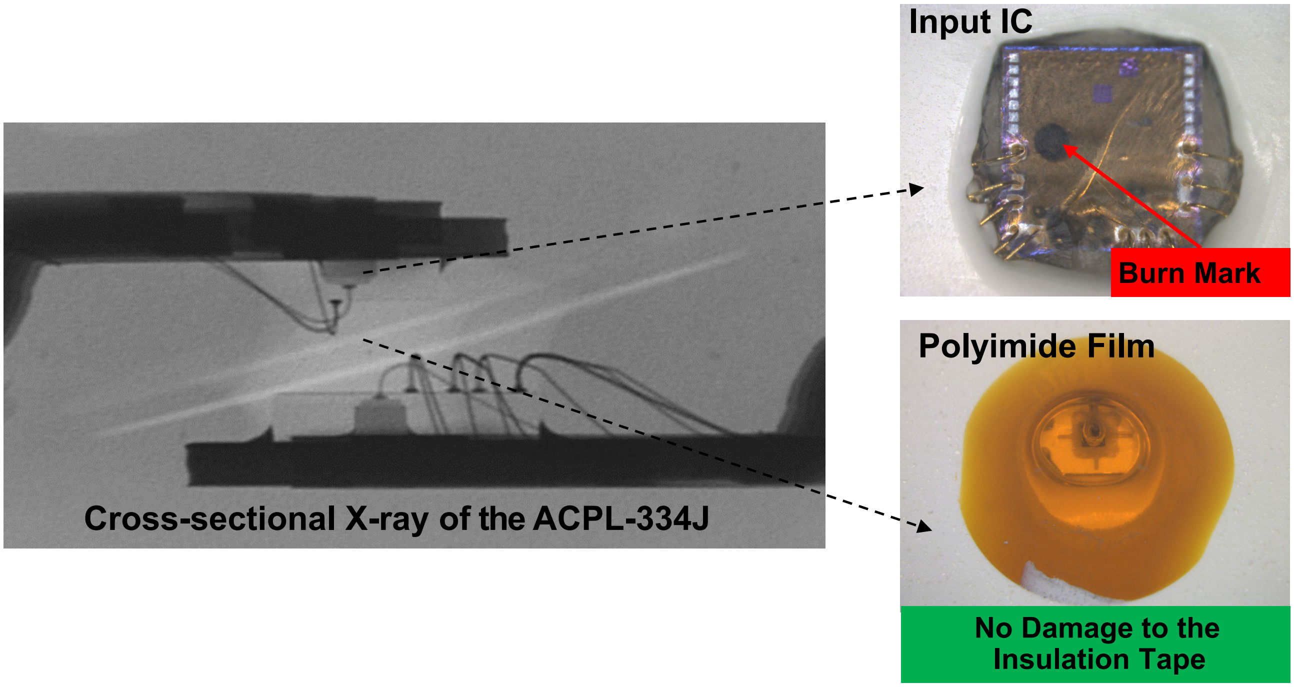
The other aspect is to study the impact of the power supply fault on the galvanic insulation barrier. A power supply destructive test was conducted by increasing the bias of the supply pins of the optical and capacitive isolated gate drivers until the input IC broke down. This test simulates a power supply fault with an uncontrolled current surge into the input IC. In accordance with the UL 1577 specification for optical isolators, the gate drivers were proof-tested by applying an insulation test voltage of 5 kV_{RMS} to detect leakage current and the I_{I-O} not exceeding 5 µA. Table 1 shows the test conditions and results of the power supply destructive test.

Table 1: High-Voltage Leakage Current Test after the Power Supply Destructive Test

Power Supply Destructive Test	**Input Biasing Conditions before IC Breakdown**	**$I_{I\text{-}O}$, 5 kV_{RMS} per UL 1577**
ACPL-334J control unit	—	3.2 µA
ACPL-334J device under test	V_{CC1} > 30V	3.2 µA (Pass)
Capacitive isolated gate driver control unit	—	1.6 µA
Capacitive isolated gate driver device under test	V_{CC} > 15V, I_{CC} > 13 mA	>99.9 µA (Fail tester limit)

The high-voltage leakage current test was applied to a control unit accompanying the device under test to see if there is any degradation of the insulation barrier. The ACPL-334J gate drive optocoupler using optical insulation shows that there is no change in leakage current after the power supply destructive test. This result is attributed to the robust insulation construction with a wide DTI and the three layers of insulation made up of silicone, polyimide film, and silicone as shown by the cross-sectional x-ray in Figure 6. Although it is obvious that the power supply has damaged the input IC, the polyimide film (insulation tape) remains unscathed due to its distance from the input IC.

Figure 6: Failure Analysis of the ACPL-334J Gate Drive Optocoupler after the Power Supply Destructive Test



The gate driver using capacitive insulation shows very high leakage current that exceeds the limit of the high-voltage tester. A failure analysis was conducted to see the extent of the damage that caused the high leakage current.

Figure 7: Failure Analysis of the Capacitive Isolated Gate Driver after the Power Supply Destructive Test

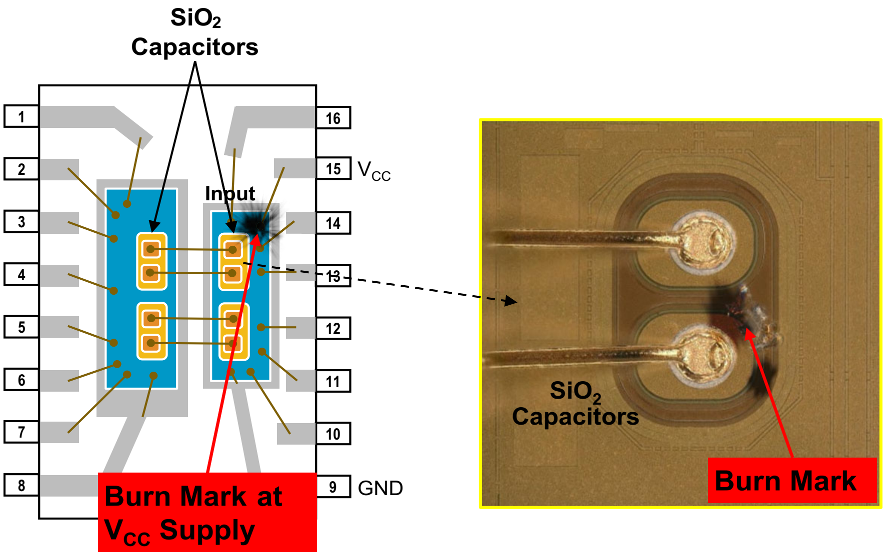


Figure 7 shows that the SiO_2 capacitor is damaged at the input IC and the insulation capability of the isolator is compromised. The insulation circuit being integrated on the same chip, along with the input circuitry in a monolithic process and a thin DTI, is the obvious reason for the insulation failure. This result shows that the single point failure of the power supply can damage the capacitive insulation barrier. This damage can lead to electric shocks and compromise safety.

Chapter 4: Conclusion

Both optical and capacitive isolators can do a very good job insulating against high voltage, protecting the low-voltage circuit and ensuring user safety. However, fault events at a peripheral circuit, such as the power supply fault described in this document, can damage the insulation barrier and compromise functional and electrical safety. The fundamental construction of the isolation barrier is crucial to determine how easily the fault can reach and damage the insulation barrier. The protective separation in the lead frame and the three layers of insulation in the ACPL-334J gate drive optocoupler create a gap that is impossible for the fault energy to reach. Alternatively, capacitive isolation construction uses a monolithic process that integrates electrical circuits and the SiO_2 capacitor on a single chip, allowing the fault to reach the insulation barrier easily.

Revision History

RCO-OPTO-WP101; November 22, 2024

- Updated the conditions and results for the power supply destructive test.

RCO-OPTO-WP100; August 15, 2024

Initial release.