Evaluating the Safety Isolation of the Package in an Integrated Power Device

Thomas Anthony Capobianco | Power Integrations, USA

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Abstract

Power devices that integrate a high-voltage switch and provide internal safety-rated isolation enable compact power supply solutions for automotive applications. To meet safety requirements in an automotive application, manufacturers are required to demonstrate that in the event of a fault condition, the system will not cause hazard or injury to the end-user.

In this paper, a method for evaluating package safety isolation is described. An artificially induced catastrophic failure of the power switch is used to cause package damage in the vicinity of the high-voltage switch. Post-failure isolation tests demonstrate that the integrity of the isolation barrier within the semiconductor device is maintained.

1 Introduction

Performance, reliability, and safety are three factors that are considered in the use of any product. These are of great significance not only to the end-users, but more immediately to original equipment manufacturers (OEMs), semiconductor manufacturers, and automotive companies.

A conventional ICE-based automobile utilizes a 12 V battery to power its auxiliary electronics systems. With the emergence of hybrid and electric vehicles, the voltage range for batteries has increased to 400 V or even 800 V. Devices with an integrated high-voltage switch and internal isolation enable compact power supply design for these new vehicles and provide significant benefits. Isolation within the package eliminates the need for an optocoupler, an integrated solution that includes a high-voltage switch, a primary side controller, and a secondary side controller. The isolation greatly reduces component count and increases performance uniformity across production. These benefits simplify design and can increase reliability.

With the move to high-voltage systems, ensuring that an electrical fault will not cause shock, harm, or injury to the end-user is critical. In this paper, a method to evaluate package safety isolation in the event of catastrophic power stage failure is proposed.

1.1 Industry Standards

Safety standards apply to both system designs and integrated circuits. Specific standards are also used for qualifying automotive products. Tests associated with the isolation barrier are described below.

1.1.1 UL 1577: UL Standard for Safety for Optical Isolators

UL 1577 [4] covers optical isolators, also known as optocouplers, and photocouplers. Aside from these, it also applies to non-optical devices that perform similar functions in terms of isolation and signal control. FluxLink™ technology employs magneto-inductive coupling (basically an isolation transformer forms the lead frame of the IC) used in the internal isolation of the InnoSwitch™ devices. Section 11 of the standard defines an important dielectric voltage-withstand test that is used to determine if a device is capable of withstanding — for 60 seconds without breakdown — a potential surge equal to the rated dielectric voltage. This is also commonly known as the High Potential (HiPot) test.

1.1.2 IEC 60747-17: Magnetic and Capacitive Coupler for Basic and Reinforced Insulation

In Section 6.4, isolation testing is described [3]. This test is used to verify the ability of a device to withstand the isolation test voltage. This test voltage can be a transient, repetitive, or continuous voltage under specified conditions. Passing criteria state that no external or internal flashover shall occur during testing. The unit must also pass post-testing isolation requirements. In this context, an appropriate definition of PASS / FAIL performance for post-stress testing is critical.

1.1.3 AEC-Q1000-007 Rev-B: Fault Simulation and Fault Grading

Fault simulation is of great importance to automotive qualification. In Attachment 7 of AEC-Q1000 [1], the purpose of proper fault modeling is described. As stated, the fault simulation should expose any manufacturing defects. The procedure must describe the fault coverage provided to manage failure expectations. Test conditions also need to be appropriately set such that the relevant environmental activation conditions are present. These activation conditions may be temperature-, voltage-, current-, or frequency-related.

1.2 Integrated Isolation Within Power Devices

The use of integrated devices has numerous benefits in power supply design and manufacturing. These include less dependency on discrete components, simplicity and ease of design, scalability, and a reduction in design-to-production time.

InnoSwitch3-EP (**Figure 1**) has the following functional blocks combined in a single IC: a 1700 V high voltage switch, driver, primary and secondary controllers, and protection circuitry. Secondary-side regulation is achieved using a proprietary feedback mechanism internal to the part — FluxLink [2]. Having internal isolation eliminates the need for an optocoupler, which reduces component count and increases system reliability.

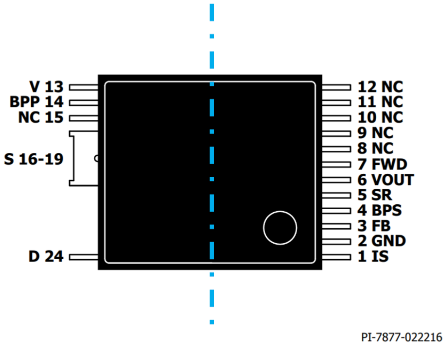

Figure 1 InnoSwitch3-EP pin configuration.

Because of the internal isolation feature, the InnoSwitch3-EP requires package safety isolation testing. The goal of this qualification was to demonstrate safety not only during normal operation but also in the event of a catastrophic failure.

2 Methodology

2.1 Pre-Fault and Post-Fault HiPot Test

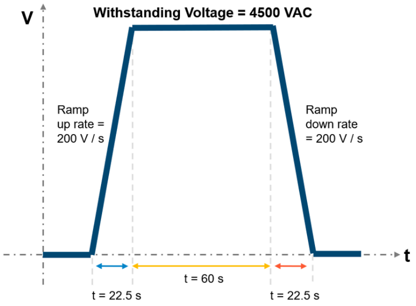

Figure 2 HiPot test (voltage vs. time).

In **Figure 2**, a voltage versus time plot illustrates the pre-fault and post-fault HiPot voltage stress applied during testing.

For each test, all the pins on the primary side of the IC are shorted together. The pins on the secondary side of the part are also shorted together on the opposite side. This forms a two-terminal device that is subjected to the HiPot test. The test voltage is ramped up at a rate of 200 V / s until it reaches the desired withstand voltage of 4500 VAC. The test lasts for 60 seconds before the voltage is ramped down at a rate of 200 V / s.

A failure condition is defined as the part exceeding a primary-to-secondary current of 2.0 mA and/or arcing is observed.

According to the datasheet of the InnoSwitch3-EP part under test, the UL1577 isolation voltage is 4000 VAC (max) [2]. Tests were performed at 12.5% above the rated voltage.

2.2 Test Setup

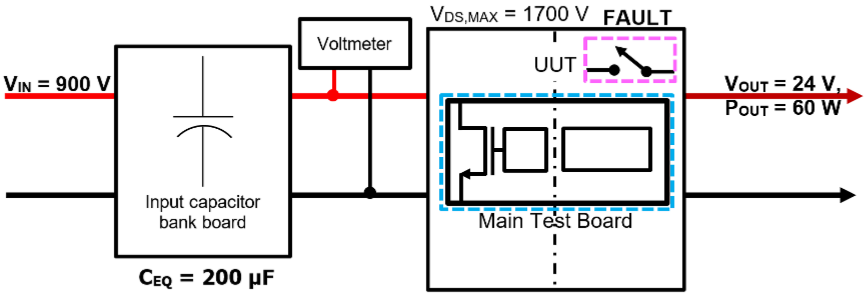

Figure 3 Test setup block diagram.

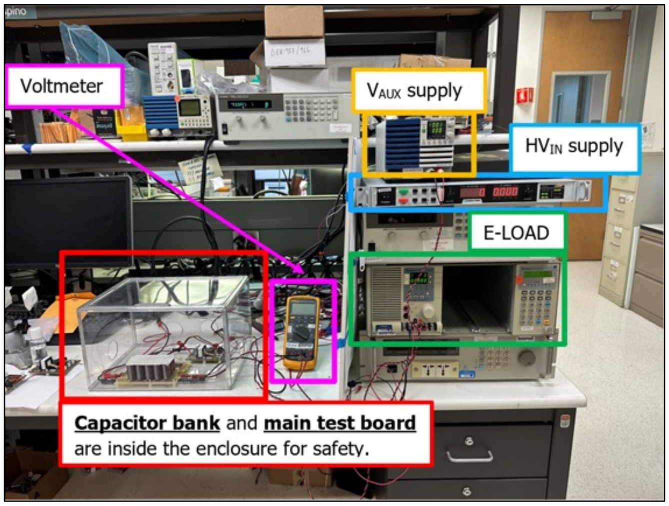

Figure 4 Test setup.

The following equipment was used in the setup as shown in **Figures 3** and **4**.

1. High-voltage DC supply: Magna-Power SL1000-1.5 / UI
2. Low-voltage DC supply: Kikusui PWR801ML
3. DC Electronic Load: Chroma 63108 module in Chroma 6314 mainframe
4. Dielectric Withstand Tester: Associated Research, Inc. HYPOT® III
5. Voltmeter: Fluke 87 True RMS Multimeter
6. Soundproof box (optional)

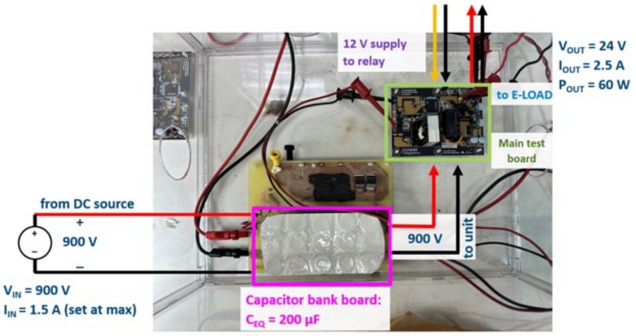

Figure 5 Test setup shown inside the safety enclosure.

A capacitor bank with capacitance of 200 µF was used. This is 66% more than the 120 µF bulk capacitor for a typical 60 W design. This, along with the main test board, is placed inside a safety enclosure as shown in **Figure 5**.

2.3 Evaluation Board

A flyback converter that has an InnoSwitch3-EP part at its core was used as the evaluation platform. It is based on RDR-919Q [5], an automotive reference design from Power Integrations. This power supply has a rated output power of 60 W, and a nominal voltage of 24 V. External protection circuitry was removed, as well as the diode in the RCD primary clamp.

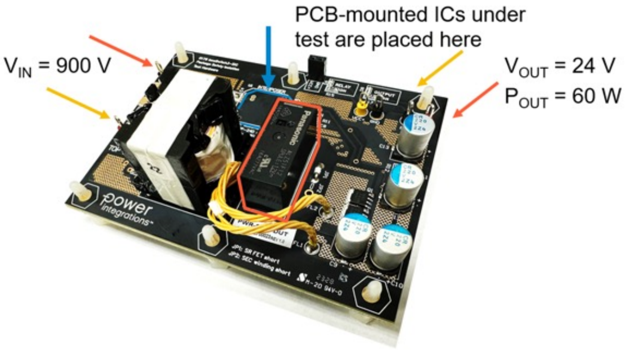

Figure 6 Main test board image.

As seen in **Figure 6**, the InnoSwitch3-EP part is loaded on the main evaluation board. This part is PCB-mounted with male connector pins at the bottomside. These mate with female socket pins on the evaluation board. The high-voltage DC supply is ramped up initially to 50 V.

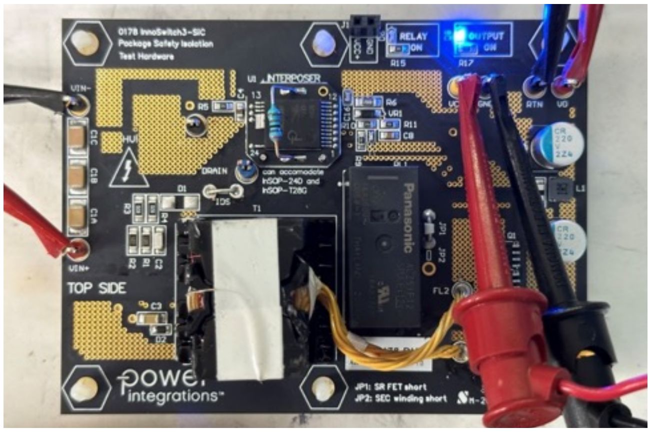

Figure 7 Blue LED turns on at VIN = 50 V.

The blue LED indicates output voltage of 24 V as seen in **Figure 7**. The input voltage is then ramped up further to 300 VDC.

Measure	P1:max(C1)	P2:max(C2)	P3:- - -	P4:min(C1)	P5:min(C2)	P6:- - -
value	1.647 kV	2.094 A		-40 V	-409 mA	
status	✓	✓		✓	✓	

C1 DC1M
500 V/div
-1.500 kV
2.690 kV
1.700 kV
Δy -990 V

C2 DC
1.000 A/div
1.000 A ofst
1.38 A
-600 mA
Δy -1.98 A

HD
12 Bits

Timebase 0.0 µs
20.0 µs/div
500 kS 2.5 GS/s

Trigger C1 DC
Stop 1.355 kV
Edge Positive

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Figure 8 Drain voltage and current waveforms. Pink is the primary switch current (1 A per division); Brown is the VDS of the primary power switch (500 V per division); Time base is 20 us per division.

The electronic load is then turned on, and set to draw 2.5 A output current, allowing 60 W operation. The input voltage is again ramped up and set to 900 V.

Prior to part failure, the drain voltage is operating just below the stated 1700 V maximum device voltage specified for the device as shown in **Figure 8**.

2.4 Inducing Failure While Part Is in Normal Operation

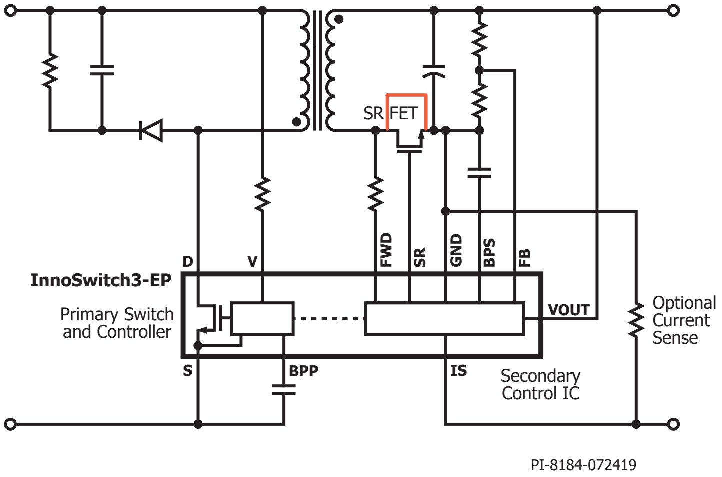

Figure 9 Simplified flyback schematic showing InnoSwitch3-EP.

A hard short between the drain and source pins of the secondary side MOSFET using a relay was then introduced to induce part failure. At the onset of the fault, the electronic load will continue to deplete the output capacitor. The short circuit on the secondary rectifier appears as a short across the primary winding of the transformer which results in a rapid di/dt rise (limited only by the leakage inductance of the primary winding). The primary overcurrent limit then activates, but the very fast di/dt of the primary switch drain current will overshoot. The primary switch is turned off by the protection circuit resulting in a very high voltage appearing across the leakage inductance of the primary winding and causing catastrophic switch failure. This all happens quickly. Catastrophic failure and localized package damage in the vicinity of the high-voltage switch occur.

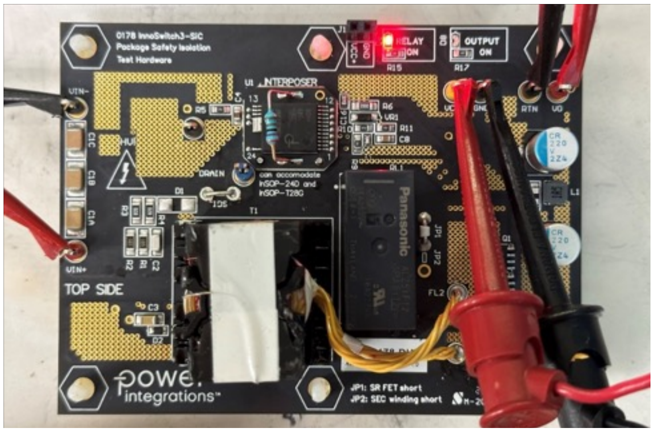

Figure 10 Red LED turns on when the short is performed.

When shorting the SR MOSFET, a red LED indicates that a secondary side short has occurred. There is no new hazard associated with the short as the isolation is intact. This is shown in **Figure 10**.

This test was repeated on three (3) different production lots, twenty (20) samples per lot, for a total of sixty (60) total samples tested.

3 Results

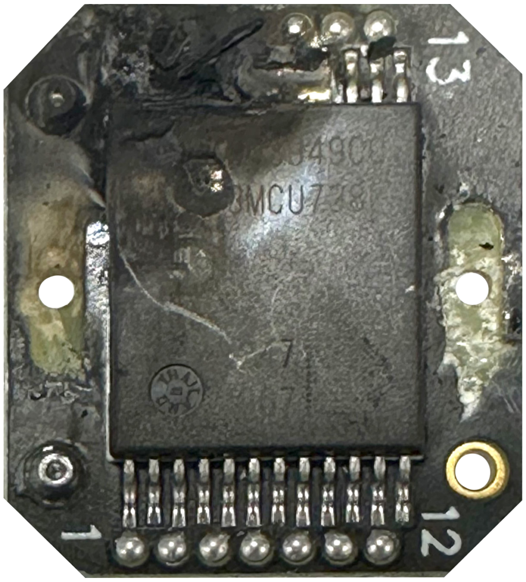

Figure 11 INN3949CQ, LOT: 03MCU738E, SN#4.

Figure 11 shows an InnoSwitch3-EP part after the catastrophic failure. A decapped part is also shown: the damage on the package is near the high voltage DRAIN pin of the power switch.

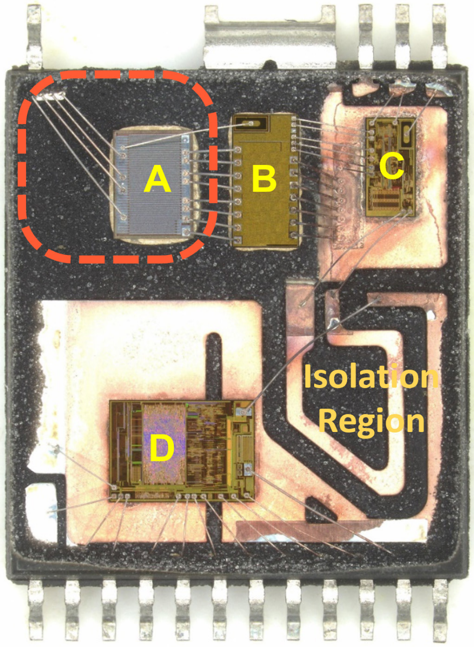

Figure 12 Decapped image of an InnoSwitch3.

Figure 12 is a decapped image of the InnoSwitch3-EP part. The different sections within the part are labelled from A to D. A is the high-voltage SiC device and B is the low-voltage MOSFET. Together, A and B form a cascode. C and D are the primary and secondary controllers, respectively, and FluxLink is realized using the lead frames in the area labelled as the Isolation Region.

All tested parts underwent post-fault HiPot tests. The setup and PASS/FAIL criteria were identical to those set during pre-fault HiPot tests. All parts passed post-fault HiPot tests. No arcing or flashover was observed during the tests. Tables 1 to 3 show the results for each part from the three (3) different lots.

INN3649C 03MCU738H 2306 H606	**Results**
SN#1	PASS
SN#2	PASS
SN#3	PASS
SN#4	PASS
SN#5	PASS
SN#6	PASS
SN#7	PASS
SN#8	PASS
SN#9	PASS
SN#10	PASS
SN#11	PASS
SN#12	PASS
SN#13	PASS
SN#14	PASS
SN#15	PASS
SN#16	PASS
SN#17	PASS
SN#18	PASS
SN#19	PASS
SN#20	PASS

Table 1 Lot 1 results

INN3949CQ 03MCU738E 2247 H907	**Results**
SN#1	PASS
SN#2	PASS
SN#3	PASS
SN#4	PASS
SN#5	PASS
SN#6	PASS
SN#7	PASS
SN#8	PASS
SN#9	PASS
SN#10	PASS
SN#11	PASS
SN#12	PASS
SN#13	PASS
SN#14	PASS
SN#15	PASS
SN#16	PASS
SN#17	PASS
SN#18	PASS
SN#19	PASS
SN#20	PASS

Table 2 Lot 2 results

INN3649C 03MCU738F 2247 H606	**Results**
SN#1	PASS
SN#2	PASS
SN#3	PASS
SN#4	PASS
SN#5	PASS
SN#6	PASS
SN#7	PASS
SN#8	PASS
SN#9	PASS
SN#10	PASS
SN#11	PASS
SN#12	PASS
SN#13	PASS
SN#14	PASS
SN#15	PASS
SN#16	PASS
SN#17	PASS
SN#18	PASS
SN#19	PASS
SN#20	PASS

Table 3 Lot 3 results

4 Conclusion

Safety standards in electrical designs cover both system-level circuitry and component parts. The main intent of these standards is to act as safeguards in protecting end-users from harmful voltages and currents. The voltage-withstand test was used to evaluate the internal isolation of the integrated power device in a flyback converter. The evaluation consisted not only of this test but also included system fault modelling. The single fault was constructed to be not only one that was a critical worst-case fault, but also best represented what may be encountered in a real application. Results showed that the fault was “successful” in causing catastrophic damage to the package of the integrated device. Post-fault tests show that despite this, the strength of the isolation barrier of the integrated power device was preserved.

References

[1] Fault Simulation and Fault Grading. AEC-Q100-007 Rev-B. Automotive Electronics Council. 2007.

[2] Power Integrations: InnoSwitch3-EP Family Off-Line CV/CC QR Flyback Switcher IC with Integrated Primary Switch, Synchronous Rectification and FluxLink Feedback. 2023. [accessed March 18, 2024]. https://www.power.com/sites/default/files/documents/innoswitch3-ep_family_datasheet.pdf

[3] International Standard Semiconductor devic es – Part 17: Magnetic and capacitive coupler for basic and reinforced insulation. IEC 60747-17. International Electrotechnical Commission (IEC). 2020.

[4] Standard for Safety Optical Isolators, AN-SI/UL 1577-2015. American National Stand ard. 2014.

[5] Power Integrations: Reference Design Report for a 60 W Isolated Flyback Power Supply Using InnoSwitch3-AQ INN3949CQ. [ac cessed March 18, 2024]. https://www.power.com/sites/default/files/documents/rdr-919q_60w_high_input_voltage_psu_automotive_innoswitch3-aq-1700v_sic.pdf

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