Technical White Paper

A Comparative Analysis of Insulation Monitoring Device (IMD) Architectures in Bidirectional Onboard Chargers

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ABSTRACT

Bidirectional functionality in onboard chargers (OBCs) has emerged as a significant trend for electric vehicles (EV). This trend is enabling vehicle-to-everything (V2X) applications. Enhanced safety measures for vehicle-to-load (V2L) and vehicle-to-home (V2H) implementations are essential for protecting users from electrical shock hazards, which result from insulation failures. Consequently, insulation monitoring devices (IMDs) have become crucial components in bidirectional OBC systems. This document examines three prevalent IMD options for monitoring insulation: the basic architecture, dual-switch architecture, and active single-switch architecture—all options utilize electric bridge switch technology. This document thoroughly analyzes the advantages and limitations of each approach and presents comparative simulation results to evaluate the performance of each approach. Additionally, this document integrates theoretical analysis with specific device recommendations of Texas Instruments, offering a comprehensive reference guide for IMD circuit designs across various application scenarios.

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1 Introduction

1.1 Background

As electric vehicles evolve to deliver extended range and enhanced power capabilities, battery systems are increasingly adopting architectures of 800V or higher. User safety remains paramount in these high-voltage (HV) systems. Consequently, all HV components must maintain isolation from protective earth through high-resistance pathways. Insulation failures can arise from various causes; including wire harness deterioration, aging of power-handling components, or extreme electrical stress events, such as damage to Y-capacitors. The system enters an unsafe condition when any single insulation failure occurs. Electrical shock is not necessarily caused by an initial reduction in impedance *directly*, however, a reduction requires immediate warning as the condition presents a potential life-threatening risk if human contact occurs.

Isolated power systems, including DC fast-charging stations, must adhere to the applicable safety standards. These standards vary by region, as illustrated in Table 1-1.

Table 1-1. IMD Related Standard Across Different Regions

Region	Standard	Scope
Europe	IEC 61851-23	Defines the vehicle-side-monitor function that the OBC must support when communicating with a DC fast charger.
Europe	IEC 61557-8	General requirements for IMDs used in information technology systems, which are adopted for automotive OBCs
Europe	ISO 6469-3	Vehicle-wide safety requirements, referenced by ECE R100.
North America	UL 2231-1 | UL 2231-2	Specifies vehicle-side protection functions that must work with the IMD of the charger.
China	GB/T 18487.1	Chinese counterpart of IEC 61851-21 and IEC 61851-23.
China	GB/T 18487.4	Part 4 is the discharging requirements for electric vehicles.
Japan	JARI | JSAE Guidelines	Aligns with ISO 6469-3 and IEC 61557-8, adding Japanese environmental limits.
Other Regions (Australia (AS), New Zealand (NZ), Korea, India, and so forth)	National adoptions of IEC 61851-23, IEC 61557-8, and ISO 6469-3	Same functional scope as the European version with minor climate or labeling variations. For example, AS/NZS 61851-21-1, KS C-IEC 61851-21-1, BIS ISO 6469-3.

In IEC 61557-8 and GB/T 18487.1, the warning (500Ω / V d.c. – 2mA) and fault (100Ω / V d.c. – 10mA) thresholds are set for the resistance of the isolation barrier. The IMD circuit monitors the insulation resistance and reports a failure in the case of insufficient insulation resistance. In the event of insufficient insulation resistance, current leakage can potentially increase above the permissible limit.

Figure 1-1 illustrates that an insulation monitoring device (IMD) is installed on both the charger side and the vehicle side. The two IMDs cooperate to supervise the isolation barrier of the DC power-supply circuit throughout the entire charging process and while the vehicle is in operation.

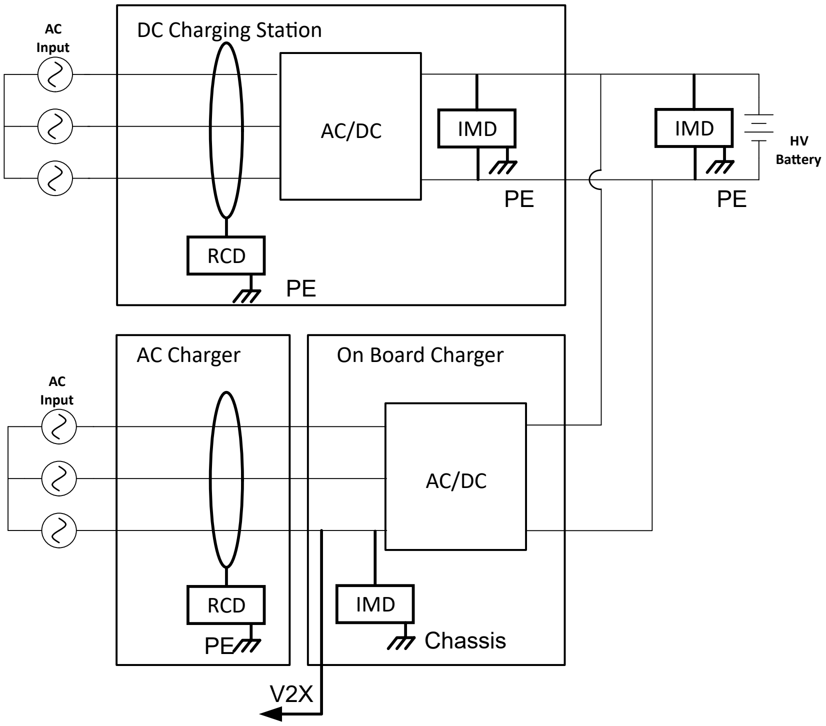

Figure 1-1. Use-Case of an IMD in a Automotive Application

According to GB/T 18487.1-2023, the following sequence and requirements apply:

- During the time frame from the vehicle coupler connection to the closing of the relay, the internal insulation monitoring (including charging cables) is completed by the charger.

- After the relay closes, the insulation monitoring of the entire charging system is completed by the electric vehicle in the energy transfer stage.

Therefore, these two IMD circuits work together to verify that the insulation resistance remains within the normal range during charging and driving, in both the charging end and vehicle end.

Whether AC is charging or DC is fast charging, there is generally a residual current detection (RCD) circuit on the AC side in both cases. There is a slight difference between the functions of the RCD and IMD circuits. The RCD circuit determines the insulation failure by monitoring the total leakage current, whereas, the IMD circuit monitors the insulation resistance. Table 1-2 presents a comparison between the IMD and RCD circuits.

Table 1-2. Difference Between the IMD and RCD Circuits

Method	RCD	IMD
Purpose	Detects an imbalance between phase and neutral, which indicates a fault-to-earth path and quickly disconnects the supply.	Verifies that the isolation barrier (HV ± to protective earth) remains above a prescribed resistance value.
Principle	Measures the sum of currents in the conductors. Any residual current larger than the set threshold trips the device. Rated current < 30mA DC current < 6mA	Measures the insulation resistance by injecting a test voltage through a high-ohmic path and reading the resulting current. Safe: > 500Ω / V Warning: ≅100Ω / V to 500Ω / V Fault: < 100Ω / V.
Locations	Typically installed upstream of the user-accessible load on the AC side. For DC fast-charging stations: An RCD can be placed on the DC link as an extra protection device.	• Charger-side IMD: Between charger HV bus and the mains connector (includes cable). • Vehicle-side IMD: Between vehicle HV bus and the DC inlet (covers cable, connector, on-board HV bus).
Response Time	≤30ms (typical) for 30mA devices.	≤10s (IEC 61557-8) for fault detection; many OEMs require ≤5s. Continuous monitoring at 0.5–1s interval is common.
Operation Mode	Instantaneous trip on the detection of residual current; does not perform a precharge insulation check.	Continuous monitoring of insulation resistance before and during power flow. Precharge verification is mandatory.
Options	Current transformer.	Electric bridge switch.
Reference Design	TIDA-010237	TIDA-010232 (DC side), *Design of Insulation Monitoring Device (IMD) in On-Board Charger System With Active Single-Switch Architecture* application note

The existing IMD and RCD circuits cover scenarios for unidirectional OBCs. However, with the emergence of bidirectional power flow capabilities in electric vehicle (EV) onboard chargers (OBCs), these systems not only enable traditional grid-to-vehicle charging but also reverse power flow in the applications. Enhanced safety measures are critical for protecting users from potential electrical shock hazards from insulation failures, as EVs increasingly function as mobile power sources. Therefore, new requirements on insulation monitoring exists:

- In a V2X configuration, the vehicle is neither attached to a DC fast-charger nor to an AC charging station, so the insulation monitoring functions provided by the RCD or the IMD circuits in the external charger cannot be used.
- When the OBC operates in reverse-power mode (DC to AC), the power-train adopts an isolated DC–AC topology; consequently, the IMD located on the BMS side can only detect faults on the DC side and is unable to sense insulation failures that potentially occur on the AC side of the converter.
- For these reasons, an insulation monitoring device must be integrated on the AC-input side of the onboard charger to maintain coverage of the V2X operating scenarios, as highlighted by the red block in Figure 1-1.

1.2 System Requirements

The OBC must meet a number of insulation monitoring requirements to maintain safety during V2L and V2H operations. The most recent regulation addressing these needs is GB/T 18487.4-2025, *Electric Vehicle Conductive Charging and Discharging System – Part 4: Discharging Requirements for Electric Vehicles*. Published on 25th April 2025, the standard is scheduled for implementation on 1st November 2025. The standard expands the safety-related insulation monitoring rules, previously limited to charging (GB/T 18487.1/2), and now covers vehicle-to-load (V2L), vehicle-to-home (V2H), and vehicle-to-grid (V2X) discharging operations. The following list is a concise debrief of the insulation monitoring requirements on an OBC system:

- Applicability:

  - Applies to all conductive DC to AC or DC to DC discharging functions of an EV that can feed external loads, a building, or the grid.
  - Covers both stand-alone and integrated OBC architectures. The IMD circuit must be installed between Line | Neutral and PE.
  - Requires compliance for vehicles with nominal AC output voltages ≤ 250V and DC output voltages ≤ 1000V.
- Accuracy:
  - Insulation resistance is the minimum value of L to PE or N to PE.
  - Fault state: R < 500Ω/V; Safe state: R > 500Ω/V.
  - Both symmetric and asymmetric insulation failures must be identified by the IMD circuit.
- Response time:
  - Real-time IMD during the discharge stage.
  - Insulation monitoring period must be less than 10s.
  - Insulation monitoring response time must be less than 100ms.
- High-potential (Hi-pot) testing:
  - 2000 VAC or 2930 VDC when the working voltage is between 300V and 690V.
  - Test 60s or test 1s with 1.1 times of the rated voltage.
  - No failures during testing and leakage current is less than 10mA.

In addition to the above-mentioned requirements, there are requirements for the DC side IMD that are not explicitly mentioned in the AC side IMD, and requirements that depend on the OEMs of different regions worldwide.

- Insulation monitoring sequence during the pre-discharge stage, post-closure stage, and shutdown stage.
- Self-diagnostics: Power-up self-test, periodic self-test, CAN reporting, and fault memory.

Interaction with other safety devices: Interaction with an RCD circuit in the AC side or interaction with the IMD circuit in a battery management system (BMS) or chargers.

1.3 Typical Challenges

Unlike a DC type of insulation monitoring, an AC type of insulation monitoring faces additional difficulties due to the placement of AC insulation within the vehicle and the variety of operating scenarios. The following points outline the key challenges and provide a brief analysis of each challenge.

1.3.1 Influence of Y-Capacitors

The AC side of the onboard charger (OBC) typically incorporates a two-stage EMI filter, and a Y-type capacitor as a key element of that filter. In a V2L scenario, an external load is also equipped with an individual EMI filter on the load-side, adding further Y-capacitance to the circuit. Because the value of the Y-capacitor of the load is not known in advance, the combined capacitance can rise to as much as 100nF, which can significantly complicate the insulation-monitoring design.

The Y-capacitor influences the measurement in two ways, the capacitor introduces an error during transient periods and distorts the steady-state reading. Influence of Y-Capacitors illustrates a typical AC-voltage-sensing circuit. The waveform at the top shows the true AC voltage. In the lower panel, the green trace represents the voltage that is sensed if the Y-capacitor is ignored; whereas, the red trace shows the voltage that is actually sensed when the effect of the Y-capacitor is considered.

Influence of Y-Capacitors illustrates two distinct error mechanisms, introduced by the Y-capacitor, in the AC-voltage-sensing loop.

- Transient-state error (Figure 1-2): At the moment the measurement begins (t = 0.025s), the capacitor must charge through the sensing resistor. During this charging interval, the measured voltage deviates from the true value; only after the voltage has settled does the reading become accurate.
- Steady-state error (Figure 1-3): Since the Y-capacitor presents a frequency-dependent impedance, the sensed waveform is phase-shifted with regard to the actual AC voltage. The sensed voltage leads the true voltage, and the phase lead grows with increasing capacitance.

Influence of Y-Capacitors

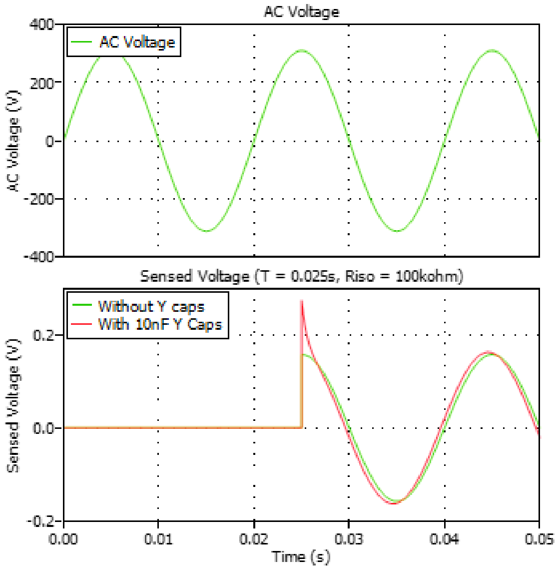

Figure 1-2. Transient-State Error Settling Time

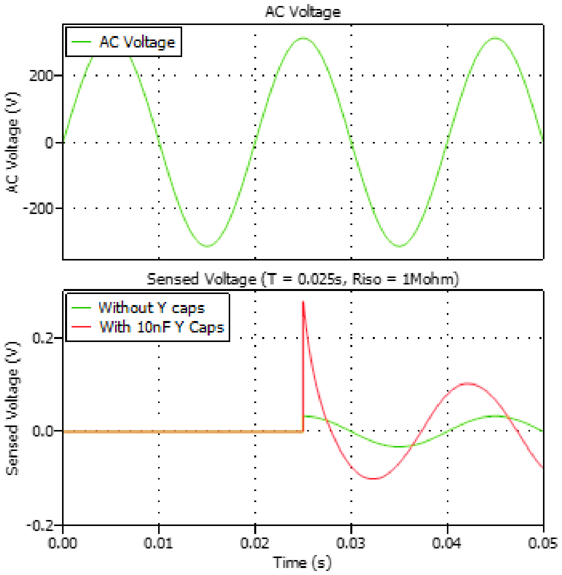

Figure 1-3. Steady-State Error Phase Delay

The time constant (τ = R × C) governs the severity of both effects. A larger τ lengthens the *charge-and-discharge* periods, prolonging the settling time and amplifying the phase deviation. For a given Y-capacitance, reducing the resistance in the measurement network of the IMD (for example, lowering R) shortens τ, and therefore, improves measurement accuracy.

1.3.2 High Potential Testing

Typically, a Hi-pot test is performed between the AC side of the onboard charger and protective earth. Figure 1-4 illustrates the standard Hi-pot test setup. According to GB/T 18487.1-2023, a test voltage of two 830V DC is applied when the rated insulation voltage of the equipment is between 690V and 800V. The Hi-pot test imposes two principal requirements on the IMD circuit:

- Withstand voltage: The IMD must tolerate the full stress of two 830V DC without degradation or failure.
- Leakage current limit: During the voltage application, the measured current leakage must remain below the threshold specified by the standard.

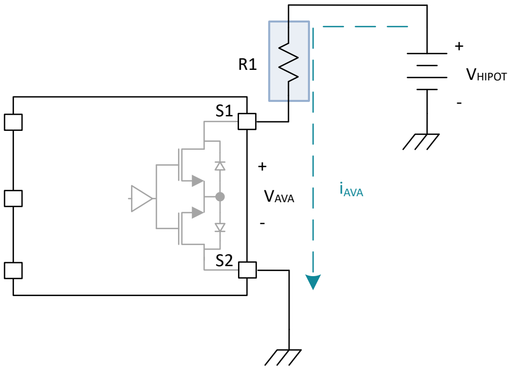

Figure 1-4. Diagram of Hi-pot Testing

1.3.3 Wide AC Voltage Range

If the IMD circuit does not include a dedicated voltage source, the circuit must rely on the individual AC-line voltage as the excitation. This reliance creates two potential difficulties:

- Resolution at the voltage peak: Accurate monitoring of insulation requires the measurement to be taken near the peak of the waveform, where the signal-to-noise ratio is highest. If the measurement is performed at a zero-crossing, the sensed voltage is essentially zero and the input offset of the op-amp dominates the reading, resulting in large errors. Consequentially, maintaining sensing that occurs very close to the AC peak is a challenge.
- Variable AC amplitude: In a V2H operation the output of the inverter must track the grid voltage, which can vary over a wide range. Since the reference voltage used to judge an insulation failure is derived from the AC line, the threshold for *acceptable* leakage must adapt to the instantaneous amplitude. Defining a robust, voltage-independent fault criterion under these changing conditions is therefore challenging.

2 Insulation Monitoring Architectures

There are three common IMD options (according to different insulation monitoring requirements): basic architecture, dual-switch architecture, and active single-switch architecture.

2.1 Basic Architecture

Figure 2-1 shows the block diagram and the equivalent circuit of the basic architecture. R_{isoL} is the insulation resistance between Line and PE. R_{isoN} is the insulation resistance between Neutral and PE. R_{stL} and R_{inL} are the resistor dividers between Line and PE. R_{stN} and R_{inN} are the resistor dividers between Neutral and PE.

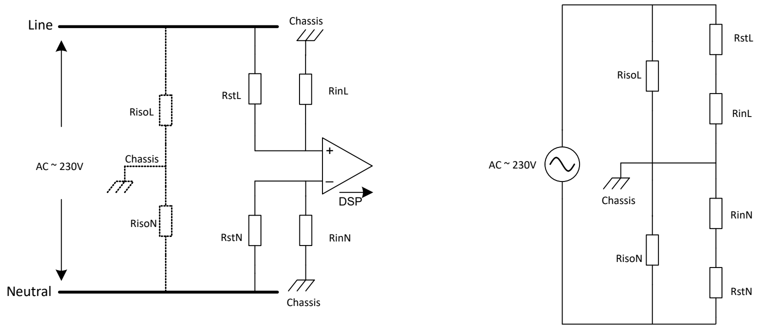

Figure 2-1. Block Diagram and the Equivalent Circuit of the Basic Architecture

The basic working principle of this architecture is that two-series resistors measure two voltages, and then the operational amplifier converts the differential voltage to a single-ended voltage.

2.2 Dual-Switch Architecture

Figure 2-2 shows the block diagram and the equivalent circuit of the dual-switch architecture. The key difference between dual-switch architecture and basic architecture is the use of two switches between Line and Neutral.

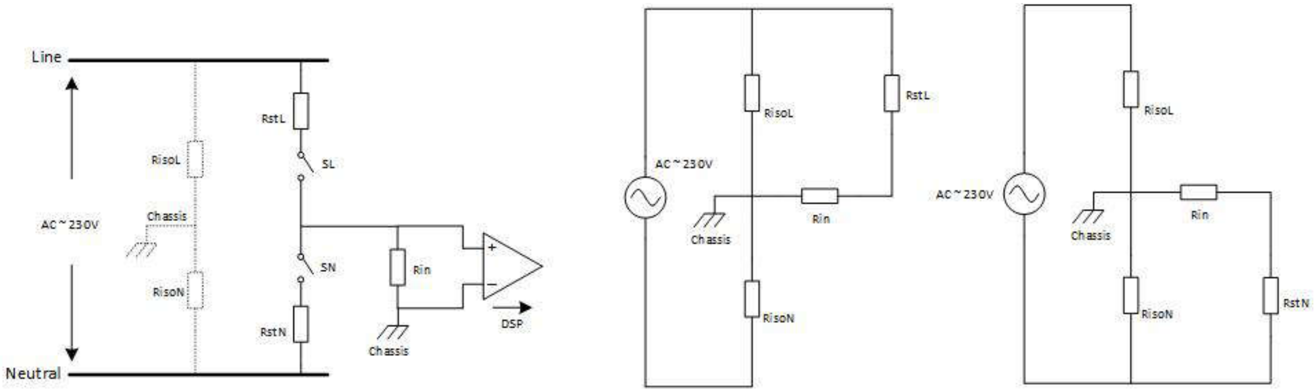

Figure 2-2. Block Diagram and the Equivalent Circuit of the Dual-Switch Architecture

The basic working principle is to close these two switches alternately, forming two different equivalent circuits. The two equivalent circuits correspond to two different equations, thus solving for the values of the two insulation resistances, R_{isoL} and R_{isoN}. TIDA-010232 is a reference design based on this architecture.

2.3 Active Single-Switch Architecture

Figure 2-3 shows the typical block diagram and the equivalent circuit of the active single-switch architecture. In the figure, the IMD circuit is connected to neutral, while the circuit can also be placed in line or chassis. This architecture is characterized by having one switch and one external bias supply.

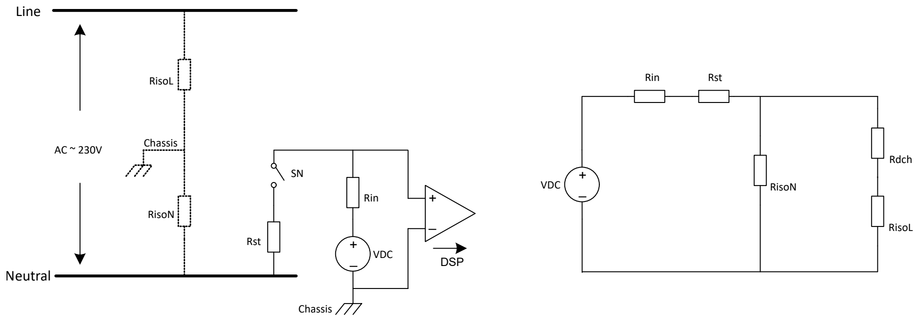

Figure 2-3. Block Diagram and the Equivalent Circuit of the Active Single-Switch Architecture

The basic working principle is based on the equivalent circuit when SN closes. The DC bias supply is the voltage source of the circuit. The effective insulation resistance of the system can be solved according to the resistor divider.

2.4 Architecture Comparison

Based on the previous analysis and equivalent circuit, Table 2-1 summarizes the characteristics of the three IMD architectures.

Table 2-1. Architecture Comparison

Architecture		Basic	Dual switches	Active single switch
Components		Op-amp × 1	Switch × 2 + Op-amp × 1	Switch × 1 + Op-amp × 1 + DC bias × 1
Accuracy		Low	High	Medium
Effort on software		Low	High	Medium
Cost		Low	High	Medium
Influence of Y-capacitor		High	Medium	Low
Features	Symmetric | Asymmetric fault	No	Yes	Yes
	Detect fault location	Yes	Yes	No
	Calculate insulation resistance	No	Yes	No
	Operate without AC voltage present	No	No	Yes
Golden rule		$(R_{isoP} - R_{isoN}) \uparrow \rightarrow V_{in} \uparrow$	$R_{isoP} \downarrow \rightarrow V_{in} \downarrow$, $R_{isoN} \downarrow \rightarrow V_{in} \uparrow$	$R_{sys} \uparrow \rightarrow V_{in} \uparrow$

3 Key Components

High-voltage switches and voltage-sensing circuitry are the two critical elements of an insulation monitoring device (IMD). The switch changes the equivalent network of the IMD, so the microcontroller (MCU) can determine the system impedance. A commonly used switch is a mechanical relay, but relays are bulky, heavy, and tend to lose reliability over long-term operations.

Voltage sensing is usually performed with an operational amplifier or an isolated amplifier; the choice determines the achievable accuracy and isolation level. The series resistors in the measurement path also have a major influence on the precision of detection, so both the nominal values and tolerances must be selected to meet the overall accuracy specification.

Finally, the placement of the MCU is a key design decision. The following discussion assumes the MCU is located on the low-voltage side of the IMD and shares the vehicle chassis ground. This topology simplifies grounding and communication but imposes additional constraints on the high-voltage front-end design.

3.1 Solid-State Relay

A solid-state relay (SSR) uses a semiconductor FET to build high-voltage ability switches with an isolation barrier. Compared with conventional electromechanical relays, SSRs offer a number of distinct advantages.

- High reliability: With no moving contacts, SSRs are free from wear, arcing, and contact-bounce. The rated life of an SSR is typically 10–100 times greater than that of an electromechanical relay, and SSRs are immune to vibration, shock, dust, and humidity, and can operate in wide temperature ranges.
- Fast switching: Compared to mechanical relays switching in several milliseconds and exhibiting bounce, an SSR offers a microsecond-range switching-time and bounce-free operation that enables cleaner voltage on measurement and quicker fault detection.
- Predictable electrical parameters: The on-state resistance and leakage current of an SSR are tightly specified and remain stable throughout a lifetime, unlike the variable contact resistance and uncontrolled leakage of mechanical relays.
- Simple circuit: An SSR can be driven directly from a logic-level signal; an SSR does not require a dedicated driver or a separate power supply for coil excitation, reducing component count and design complexity.
- Compact size: SSRs integrate capacitive isolation within a small package, eliminating the bulky coil, driver, and auxiliary power components that are typical of electromechanical relays, and thereby, saving PCB area.

These benefits directly address the high-cycle, safety-critical requirements of insulation monitoring functions in onboard chargers, so SSRs are the preferred replacement for mechanical relays. Table 3-1 contains the side-by-side comparison of SSRs against traditional options.

Table 3-1. Comparison of SSRs Against Traditional Options

Specification	TI Solid-State Relay	PhotoMOS	Relay
Turn | Off time	<400µs	<4ms	≅10ms
$I_{Avalanche}$	<1mA	<1mA	x
On resistance	≅300Ω	≅500Ω	<1Ω
Size	Small	Small	Large
AEC	Qualified	Not Qualified	Qualified

The TPSI2140-Q1 is a single-channel, high-voltage solid-state switch from Texas Instruments that integrates MOSFET power devices with an isolated gate-drive interface. The diagram in Figure 3-1 shows the block architecture of the TPSI2140-Q1 device. The device provides the switching capability of one 200V ON/OFF switch and can tolerate an avalanche current of 1mA for up to 60 seconds, enabling high-potential (Hi-Pot) testing. The device is appropriate for implementation in both dual-switch and active single-switch architecture.

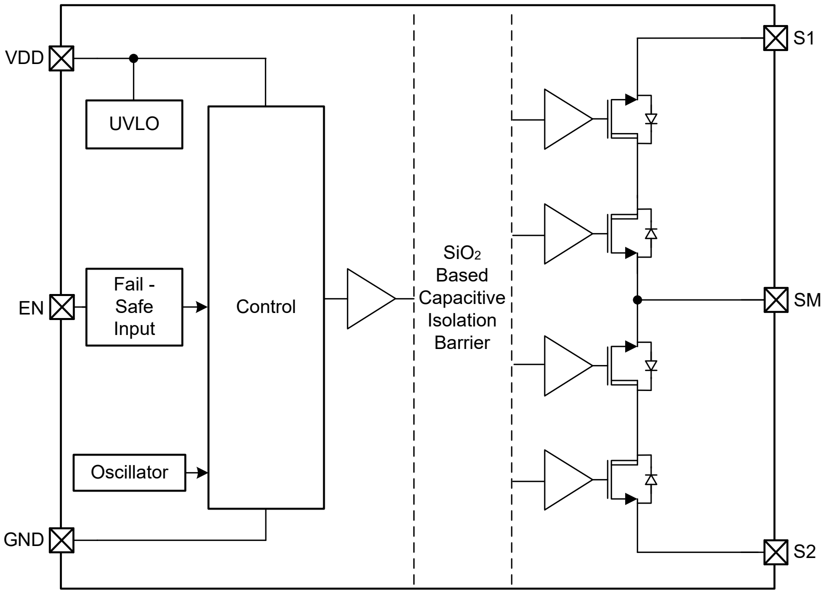

Figure 3-1. Unidirectional SSR TPSI2140-Q1 Block Diagram

The TPSI2072-Q1 is a dual-channel, high-voltage, solid-state switch from Texas Instruments that integrates a MOSFET power device with an isolated gate-drive interface. The device is appropriate for implementation in dual-switch architecture. The diagram of TPSI2072-Q1 is in Figure 3-2.

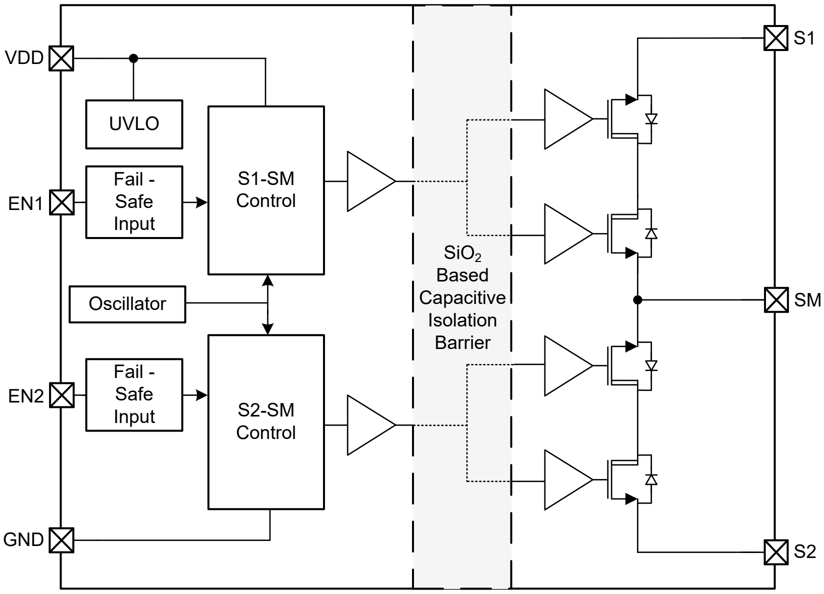

Figure 3-2. Bidirectional SSR TPSI2072-Q1 Block Diagram

Below are key specifications to consider when using a solid-state relay for IMD:

- Isolation barrier: In using semiconductor technology, the TPSI2140-Q1 and TPSI2072-Q1 devices can potentially support over 26 years of isolation under 1000Vrms AC or 1500V DC.
- Standoff voltage: If the external voltage applied on an SSR is lower than the standoff voltage, only 1uA of leakage current flows from S1 to S2 or S2 to S1. Therese is no concern for a sticky contact when compared with traditional relays.
- Avalanche current: This specification is challenged in a Hi-pot test. During a Hi-pot test, ≅2kV to 3kV apply on R_{st} and the SSR. Due to the 1.2kV standoff voltage of an SSR, R_{st} is required to limit the current and not exceed the avalanche current limitation of the SSR. The R_{st} selection is a trade-off in reliability and detection accuracy when considering Hi-pot testing.

- Turn ON/OFF time: A Y-capacitor significantly impacts settling time for a 50Hz or 60Hz system, based on the earlier analysis in Section 2. A Y-capacitor is helpful to suppress EMI in an OBC system, but a larger Y-capacitor leaves a shorter detection window for IMD. Therefore, the value of a Y-capacitor must be chosen carefully to have a balance between the benefits for EMI and the trade-offs for IMD during the design of the circuit.
- ON resistance: ON resistance impacts the accuracy of detection when the individual relay divides voltage from the main path.

3.2 Voltage Sensor

The voltage sensor provides the accurate, real-time voltage information that underpins every function of the insulation monitoring system:

- High sensitivity: A precise voltage sensor can resolve millivolt-level changes caused by a few megohm insulation faults, enabling early detection of degradation before dangerous current leakage develops.
- Fast response: A fast-response voltage sensor tracks transient voltage variations, allowing the IMD algorithm to filter out noise and maintain measurement accuracy.

The voltage sensor circuit consists of a high-voltage resistor divider and an operational amplifier. The resistor divider is the critical element of the IMD circuit that interfaces with the SSR. The high-voltage resistors not only set the measurement scale but also limit the avalanche current to satisfy the system-accuracy requirements. A standard operational amplifier, such as the LM2904B-Q1, is appropriate for this purpose. When the insulation monitoring function is implemented on the power-factor-correction (PFC) microcontroller, an isolated amplifier with an individual high-voltage supply must be used to maintain proper isolation between the HV side and the control side.

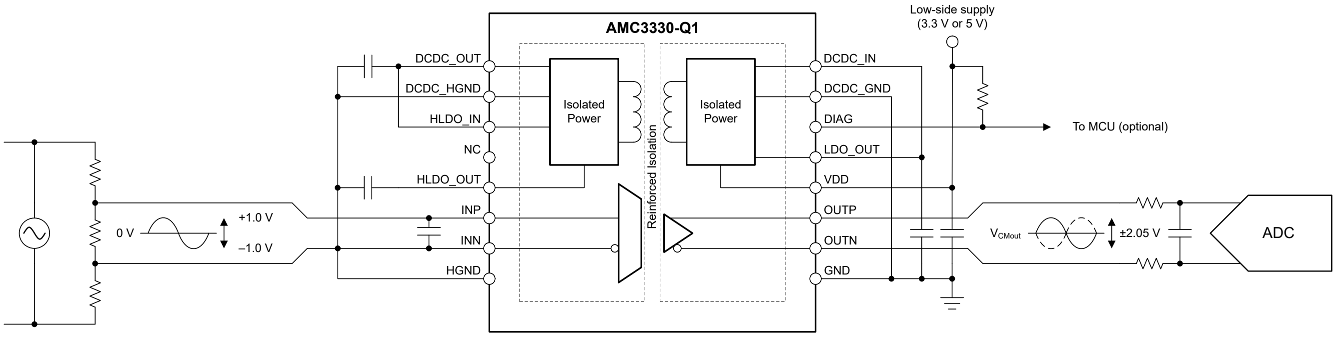

Figure 3-3. AMC3330-Q1 Typical Application

Figure 3-3 is the block diagram of the isolated amplifier. The AC voltage is measured on the high-voltage side with the PFC-side MCU; whereas, the IMD circuit is referred to the vehicle chassis. Using the AMC3330-Q1 eliminates the need for a separate isolated power supply on the high-voltage side, simplifying the design while maintaining the required isolation.

3.3 DC Power Supply

The DC supply is required only in the active-single-switch topology. A higher DC voltage generally improves the accuracy of detection because this type of voltage reduces the relative impact of the voltage of the AC line on the measurement. A boost converter is commonly employed to obtain this higher voltage from the low-voltage battery of the vehicle (typically 12V, with a range of 8V–16V).

The TPS61170-Q1 boost converter offered by TI operates at 1.2MHz, can deliver up to 38V, and maintains good efficiency even at light loads, making the device a potentially cost-effective way to generate a stable VDC for the insulation monitoring circuit.

Another alternative is to add an extra winding to the transformer that supplies isolated bias power for the gate drivers. While this alternative eliminates the need for a separate boost converter, this option complicates the transformer design and makes voltage regulation more difficult, especially under light-load conditions.

4 Summary

As adoption of electric vehicles accelerates, bidirectional onboard chargers (OBCs) with V2X capability have become essential. System-level analysis shows that neither an AC-side residual-current device (RCD), nor a DC-side insulation monitoring device (IMD) located in the BMS, can satisfy the insulation monitoring demands of V2X operations. By examining the V2X requirements for OBCs and the fundamentals of conventional DC-IMD, this document introduced three viable AC-IMD topologies and evaluated the advantages and compromises of those topologies using the included calculations.

The basic architecture *currently* provides a lower cost option, but the performance of the architecture is limited. The dual-switch architecture provides the highest performance at a cost that is *currently* comparatively higher. The active single-switch architecture requires an external power supply, but *currently* offers the better balance between performance and cost.

Integrating these detection schemes with an appropriate solid-state-relay device offered by TI enables designers to achieve an excellent balance of accuracy, speed detection, footprint, and reliability for V2X-enabled OBCs.

5 Reference

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4. Texas Instruments, TPSI2072-Q1 2-Channel 600V, 50mA, Automotive Isolated Switch with 2mA Avalanche Rating for Insulation Monitoring and High Voltage Measurements, datasheet
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