

Design Guide: TIDA-010065

High-Efficiency, Low-Emissions, Isolated DC/DC Converter Based Analog Input Module Reference Design



Description

This reference design is a simplified architecture for generating an isolated power supply for isolated amplifiers for measuring isolated voltages and currents. A fully integrated DC/DC converter with reinforced isolation operating from a 5-V input with configurable 5-V or 5.4-V output (headroom for low dropout regulator (LDO)) generates the isolated power. Shunts that are interfaced to ± 50 -mV input range isolation amplifiers configured as channel isolated inputs measure the current. Potential divider output interfaced to ± 250 -mV or ± 12 -V input range isolation amplifiers configured as group isolated inputs measure the voltage. The outputs of the isolation amplifiers interface directly to 24-bit delta sigma analog-to-digital converter (ADC) or are scaled to ± 10 V using gain amplifiers and interfaced to 16-bit SAR ADC for performance evaluation. On-board digital diagnostics improves reliability and enhances system performance.

Resources

[TIDA-010065](#)

[UCC12050](#), [ISO224](#), [AMC1302](#), [AMC1200](#)

[AMC1300](#), [AMC1311](#), [ISO7760](#), [ISO7720](#)

[ISO7721](#), [OPA2990](#), [OPA2180](#), [OPA2188](#)

[TLV704](#), [TLV6001](#), [TLV9062](#), [INA826](#)

[INA301](#), [INA333](#), [TPS2662](#), [TPS709](#)

[TPS65131](#), [TMP300](#), [DRV5032](#), [LM2903](#)

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Features

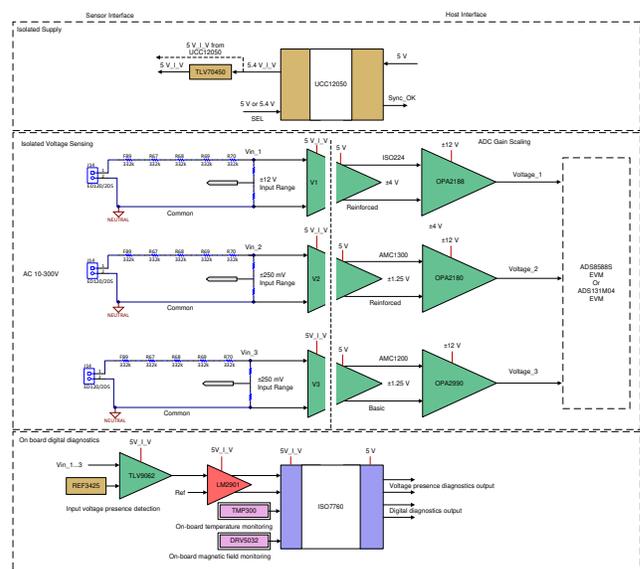
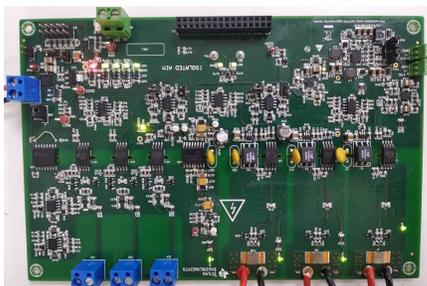
- Generation of high efficiency isolated supply of 5 or 5.4V (LDO head room) from 4.5 to 5.5 V input providing reinforced isolation
- Three group isolated voltage inputs with a range of 2 V to 350 V provide pin-compatible basic or reinforced isolation and three isolated current inputs from 40 mA to 12.5 A provide reinforced isolation
- ISO224, with an input range of ± 12 V, connects directly to a low-power current transformer output per IEC 60044-8
- Measurement of DC voltage and current with 1-us fast fault detection comparator path
- Gain scaling of isolation amplifier output to ADS8588H input range of ± 10 V using instrumentation, precision or general purpose amplifiers
- Achieves $\pm 0.2\%$ accuracy for both voltage and current using a 16-bit SAR or 24-bit delta-sigma ADC

Applications

- [AC analog input module](#)
- [Multifunction relay](#)



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1 System Description

Grid power systems include power generation, transmission, distribution, and consumption. Generation of power can be classified into renewable and nonrenewable including solar, coal, and nuclear. The generated power is transmitted over long distances using AC or DC transmission. Conventionally, AC transmission was commonly used for transmission but more DC transmission lines are being installed due to efficiency and economics. Power is transmitted at a higher voltage and is converted to lower voltages and transmitted further using substations.

Power system failure is one of the common problems faced by power generation, transmission, and distribution companies. Power outages result in loss of revenue and reduce generation capacity. Power utilities are working towards providing reliable power by using secondary equipment for protection, control, monitoring, and measurement systems to improve the efficiency and reliability of the power systems. High-end secondary equipment used in these systems include protection relay and terminal units such as remote terminal units, distribution terminal units, and feeder terminal units. Utility companies are also implementing protection algorithms and diagnostic schemes to protect the assets and predict failures as early as possible. An analog input module is important and is critical to protection relay trip performance and is one of the most commonly used modules. These are modules that are pluggable based on the application requirement. Currents and voltages are traditionally measured using transformers. Protection relays operate in high voltage and magnetic interference environment. The performance of a transformer is affected due to exposure to magnetic environments and the size must be increased, causing them to be bulky to operate in these environments. Adding more channels becomes a challenge due to bulky transformers. Also during a fault, the waveform has a DC component affecting the measurement performance. The simplest method of sensing the current in a electric circuit is by measuring the voltage drop across a known resistance in the current path. This resistor is commonly referred to as a shunt resistor. Similarly, voltage measurement can be performed using a resistor-based potential divider (PD). The utilization of shunt resistors for current sensing has several drawbacks. The resistor has to withstand the current, and will dissipate some power. A less obvious, but equally important disadvantage is that there is a direct connection between the primary circuit and the sensing circuit. There may be large common-mode voltage differentials between various parts of the circuit. When using PD and shunt for measurement, isolation is a challenge and the required isolation is provided using isolation amplifiers. Customers design analog input modules as an isolated voltage module, isolated current module, or isolated voltage and current module. The TIDA-010065 reference design features approaches to designing the aforementioned isolated analog input modules that can be leveraged during the design of an analog input module resulting in reduced design efforts, faster time to market, higher measurement accuracy, optimized cost, and smaller form factor.

Some key end-equipment applications requiring isolated analog input modules follow:

- *Protection Relay:* Protection relays detect defective lines, equipment, or other power system conditions that are abnormal or dangerous in nature. Digital protection relays detect and locate faults by measuring electrical quantities in the power system, which is different during normal and intolerable conditions. To measure and protect different end equipment, protection relays interface to different analog inputs including AC analog inputs for measuring current and voltages, DC analog input for control, digital input, monitoring and interlocking.
- *Substation Automation and Merging unit:* In substations, process-level primary equipment is monitored using terminal units and bay controllers. The inputs to this equipment includes AC analog inputs for measuring current and voltages, DC analog input or output for control, digital input or output for monitoring and interlocking. Merging units are used to sample AC analog values on the process level (near to the primary equipment such as a power transformer or circuit breaker) in a substation and transmit the sampled values (SV) to protection devices, bay control units (BCU), or electricity meters through a fiber optic Ethernet interface based on the IEC61850-9-2 protocol.

1.1 Key System Specifications

The primary objective of this reference design is to create an isolated analog input module showcasing isolated power-supply generation for isolated voltage measurement using a potential divider and isolated current measurement using a shunt (current sensor). The required isolated power supply is generated using a high-efficiency DC/DC power module with configurable output levels. The system architecture uses isolated amplifiers for the grouped voltages and each individual current channel. The output of the isolation amplifiers are scaled to ADC input range using gain amplifiers and are interfaced to a SAR ADC (with ± 10 -V input range) or directly to a delta-sigma ADC (with ± 1.25 -V or ± 2.5 -V input range).

Table 1. Isolated Analog Input Module Specifications

FUNCTION	DESCRIPTION	SECTION
Isolated power supply	Generation of Isolated supply for voltage measurement	Section 2.3.1 , Section 2.4.1
Isolated power supply	Generation of Isolated supplies for current measurement	Section 2.3.1 , Section 2.4.2
Non-isolated 5 V from DC supply input	Generation of non-isolated 5-V supply from 12- or 24-V input	Section 2.4.6
Non-isolated split-rail supply	Generation of regulated and non-isolated split-rail supply of ± 12 V from 5-V input	Section 2.4.7
Voltage measurement	Isolated measurement of voltage inputs with 5-V to 320-V range	Section 2.3.2 , Section 2.4.3
Current measurement	Isolated measurement of current inputs with 0.04-A to 12.5-A range	Section 2.3.2 , Section 2.4.4
Signal conditioning	Scaling of isolated amplifier outputs to ADC input range of ± 10 V	Section 2.4.3 , Section 2.4.4
DC voltage measurement	Isolated measurement of voltage inputs with 10-V to 900-V range	Section 2.3.5 , Section 2.3.8.1
DC voltage fault detection	Detection of overvoltage (> 800 V) or undervoltage (voltage < 350 V) using hardware window comparator with < 1 - μ s delay	Section 2.3.5 , Section 2.3.8.1
DC current measurement	Isolated measurement of voltage inputs with 0.1-A to ≥ 25 -A range using instrumentation amplifier	Section 2.3.5 , Section 2.3.8.2
DC current fault detection	Detection of bidirectional overcurrent ≥ 20 A using instrumentation with 50 gain and internal comparator option with 1- μ s delay	Section 2.3.5 , Section 2.3.8.2
Performance evaluation (measurement accuracy)	Interface to 16-bit ADC with ± 10 -V range or 24-bit ADC with ± 2.5 -V or ± 1.25 -V range	Section 2.1.6
Digital diagnostics	Diagnostics of onboard isolated power supply, temperature, magnetic field, and input voltage presence	Section 2.3.4 , Section 2.4.5

1.2 Device Mapping to Reference Design Functionalities

The following section provides details of device mapping to functionalities for the following subsystems:

- Measurement of isolated voltages
- Measurement of isolated currents
- Non-isolated power architecture and DC input supply protection

1.2.1 Measurement of Isolated Voltages

Table 2 provides details of the TI devices and functionalities implemented in this reference design for measurement of isolated voltages configured in group isolated configuration. A choice of pin-compatible basic or reinforced isolated amplifiers simplifies system design and increases design flexibility.

Table 2. Details of Functions and Devices Used for Implementing Isolated Voltage Measurement

FUNCTION	DEVICES	DESCRIPTION
Isolated supply for voltage measurement	UCC12050, TLV70450	Generation of isolated 5.4 V regulated by 5-V LDO or 5 V for direct operation of sensor-side circuit.
Isolated voltage measurement with basic isolation amplifiers	AMC1200, OPA2990	Measurement of isolated AC or DC voltages using isolation amplifier with ± 250 -mV input range and scaling the isolation amplifier output to ADC input range using precision- or general-purpose amplifiers.
Isolated voltage measurement with reinforced isolation amplifiers	ISO224, AMC1301, AMC1300, OPA2188, INA821	Measurement of isolated AC or DC voltages using isolation amplifier with ± 250 mV or ± 10 -V input range and scaling the isolation amplifier output to ADC input range using precision- or general-purpose amplifiers.
Digital diagnostics of input voltage	ISO7760, REF3425, TLV9062, LM2901	Input voltage presence detection by converting the AC input to zero cross output using a buffer and comparator and providing the output to the host through digital isolator.
Digital diagnostics of temperature and magnetic field	TMP300, DRV5032	Overtemperature detection using temperature switch and magnetic field presence detection using digital Hall switch.

NOTE: The UCC12050 device can be configured to generate 5-V output and the LDO can be removed or bypassed in this configuration.

1.2.2 Measurement of Isolated Currents

Table 3 provides details of the TI devices and functionalities implemented in this reference design for generating a non-isolated power supply for an analog input module. The availability of ± 50 -mV input range isolation amplifier improves performance by allowing use of lower value shunt resulting in reduced power dissipation due to shunt self-heating.

Table 3. Details of Functions and Devices Used for Implementing Isolated Current Measurement

FUNCTION	DEVICES	DESCRIPTION
Isolated supply for current measurement	SN6505B, TLV70450, TPS70950	Generation of isolated 5.5-V unregulated voltage and regulated by 5-V LDO for operation of sensor-side circuit.
Isolated current sensing and output scaling	AMC1302, OPA2188, OPA2990, INA821, INA826	Measurement of isolated AC or DC currents using isolation amplifier with ± 50 -mV input range and scaling the isolation amplifier output to ADC input range using instrumentation or precision amplifiers.

1.2.3 Measurement of DC Voltage and Current With Fast Fault Detection

Table 4 provides details of the TI devices and functionalities implemented in this reference design for generating the measuring and fault detection of DC voltage and current.

Table 4. Details of Functions and Devices Used for Implementing DC Voltage and Current Measurement

FUNCTION	DEVICES	DESCRIPTION
Measurement of DC voltage	AMC1311, TLV6001, TLV9001	Measurement of DC voltage in the range 10 to 900 V, using isolation amplifiers with 0-V to 2-V input range
Digital diagnostics of DC voltage fault	TLV3202, ISO7720	Detection of undervoltage and overvoltage DC voltage fault with < 1- μ s delay with hysteresis
Measurement of DC current	AMC1302	Measurement of DC current in the range 0.1 to \geq 25 A using isolation amplifiers with \pm 50-mV input range
Digital diagnostics of DC current overcurrent faults	INA301, ISO7721	Providing gain of 50 for the shunt output and detection of bidirectional DC current fault above 20 A with 1- μ s delay
Isolated power supply	TPS76350, TLV70433, SN6505B	Generation of isolated supply for isolation amplifiers, comparators, instrumentation amplifier, and digital isolator

1.2.4 Non-isolated Power Architecture and DC Input Supply Protection

Table 5 provides details of the TI devices and functionalities implemented in this reference design for generating a non-isolated power supply for AIM and input protection.

Table 5. Details of Functions and Devices Used for Implementing Power Supply for Analog Input Module

FUNCTION	DEVICES	DESCRIPTION
Sensor-side isolated supply monitoring	TPS3897	Voltage detector to monitor the unregulated 5.4 V of the isolated DC/DC converter
Generation of split-rail supply and 5-V reference for level shifting the amplifier output	TPS65131, TPS7A39, LM27762, REF3450	Generation of \pm 12 V or \pm 5 V from 5-V input using split-rail DC/DC converter, regulating the output of split rail and generation of 5-V reference. Use of Dual output LDO simplifies power supply design.
DC input voltage protection	LM74700-Q, TPS26624	Protection of 5-, 12-, or 24-V input supply rails against overload and input reversal
Generation of host-side power supply 3.3 V from 5 V or 5 V from 12 V or 24 V	LMZ14201, LMZ20501, TLV1117LV33	Generation of supplies for host side operation using power module with integrated inductor or LDO. Use of power modules simplifies the power supply design.
Input supply current monitoring	INA333	Monitoring of the power supply current using instrumentation amplifiers using external shunt

2 System Overview

2.1 Block Diagram for Analog Input Module

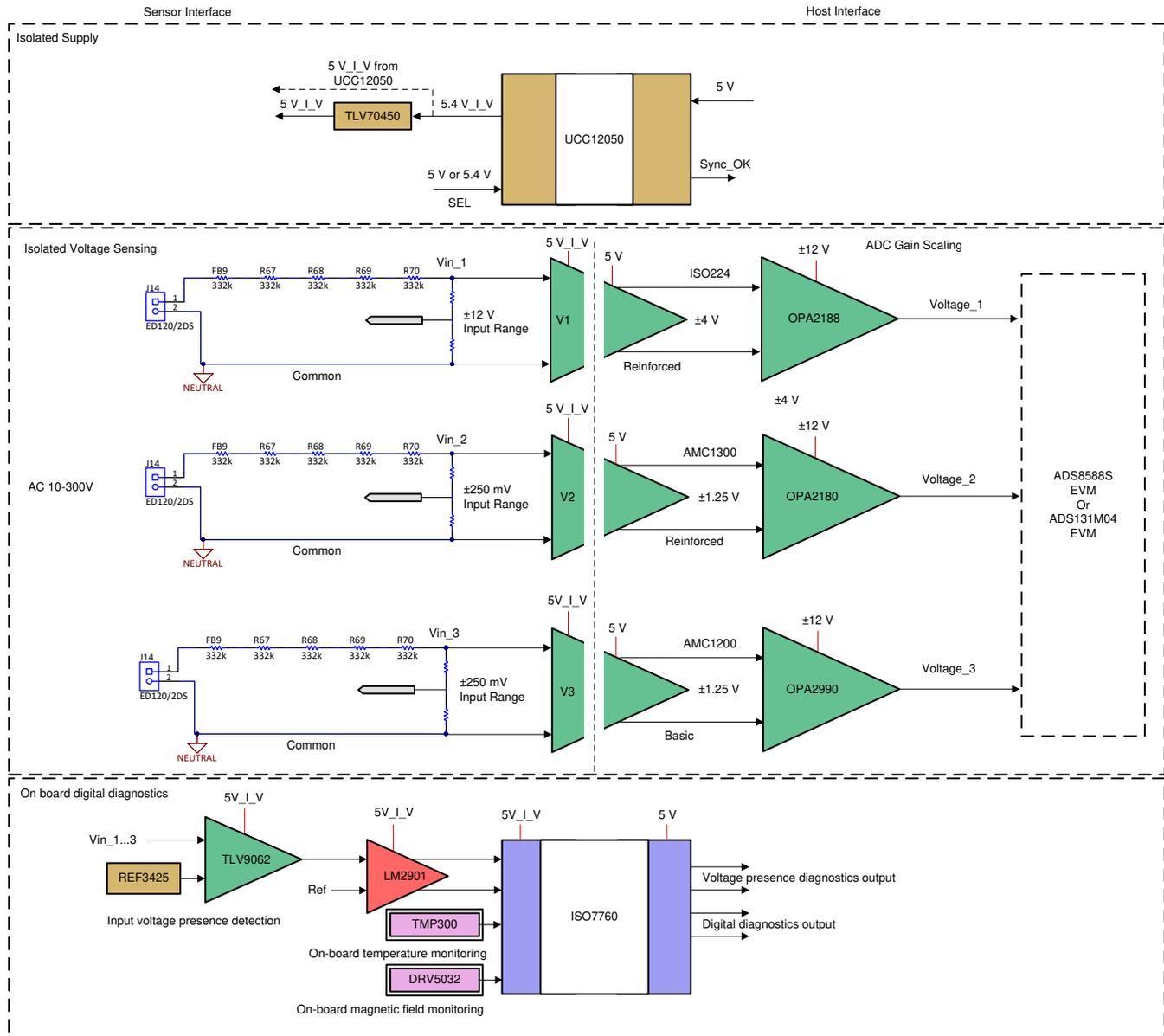
The explanation of key subsystems of an isolated analog input module and their functional blocks follow:

2.1.1 Generation of Isolated Supply and Measurement of Isolated Voltage Inputs

Figure 1 showcases the following:

- Isolated measurement of AC or DC input voltage using isolation amplifiers in group isolated configuration
- Scaling the isolation amplifier output to ADC input range
- Digital diagnostics of input voltage using zero cross detector connected through digital isolator and digital diagnostics of overtemperature and presence of a magnetic field

Figure 1. TIDA-010065 Voltage Measurement Subsystem



2.1.1.1 Generation of Isolated Supply

This design features the following functionality:

- Generation of 5- or 5.4-V DC (configurable) power supply from 5-V input using isolated DC/DC converter with reinforced isolation
- Regulation of the DC/DC converter using an LDO providing lower ripple supply to isolation amplifiers improving measurement accuracy
- Provision for configuring the DC/DC converter output based on the performance requirement

Use of isolated DC/DC integrated in an IC form factor improves reliability, reduces failures, and simplifies system design optimizing design and testing time. The DC/DC converter requires minimum external components and provides extra features such as an enable pin, synchronization of switching frequency among multiple devices, and selection of isolated output voltages. This is an excellent choice in height-constrained applications.

2.1.1.2 **Measurement of Isolated Voltages**

This design showcases the following functionality :

- Measurement of 3 × AC input voltages using isolation amplifiers in group-isolated configuration
- Three families of isolation amplifiers with ± 250 -mV or ± 12 -V input range is showcased in the design

Pin-compatible isolation amplifiers providing basic or reinforced isolation provides design flexibility and optimizes cost. A ± 12 -V input range enables interface to a sensor providing ± 10 -V input directly. Isolation amplifiers are used for isolated current and voltage sense and are typically used to measure phase currents (with shunt resistors) or phase voltages in three-phase power applications. The isolation amplifier provides analog output that can be interfaced to the ADC, similar to the approach used with a current transformer.

2.1.1.3 **Scaling of Isolation Amplifier Output**

This design showcases the following functionality:

- Scaling of the isolation amplifier output to SAR ADC input range of ± 10 V using general purpose or precision amplifiers
- Use of precision amplifiers for gain-scaling improves accuracy performance over a wide input and temperature range
- Use of general purpose amplifiers provides optimal performance and reduces the system cost
- The output of the gain scaling amplifier interfaces to the ADC for signal capture

2.1.1.4 **Interface to Precision ADC**

This design showcases the following functionality:

- Interfacing to a 16-bit single-ended SAR ADC with ± 10 -V input range providing true simultaneous sampling
- When a 16-bit SAR ADC is used, the differential output of the isolation amplifiers has to be converted to single-ended along with gain scaling to interface to the ADS8588H device
- Interfacing to a 24-bit delta-sigma ADC with ± 1.25 -, ± 2.5 -, or ± 4 -V differential input range
- Use of delta-sigma ADC with ± 1.25 -V input range limits the input voltage range to the isolation amplifier which has a fixed gain
- When a 24-bit delta-sigma ADC is used, the differential output of the isolation amplifier can be directly connected to the ADC, simplifying the design and optimizing the cost

The interface to the ADC and the availability of HMI for performance evaluation speeds up the isolation amplifier evaluation cycle reducing overall design and decision making time.

2.1.1.5 **Digital Diagnostics for Input Voltage Presence and Operating Environment**

This design showcases the following functionality :

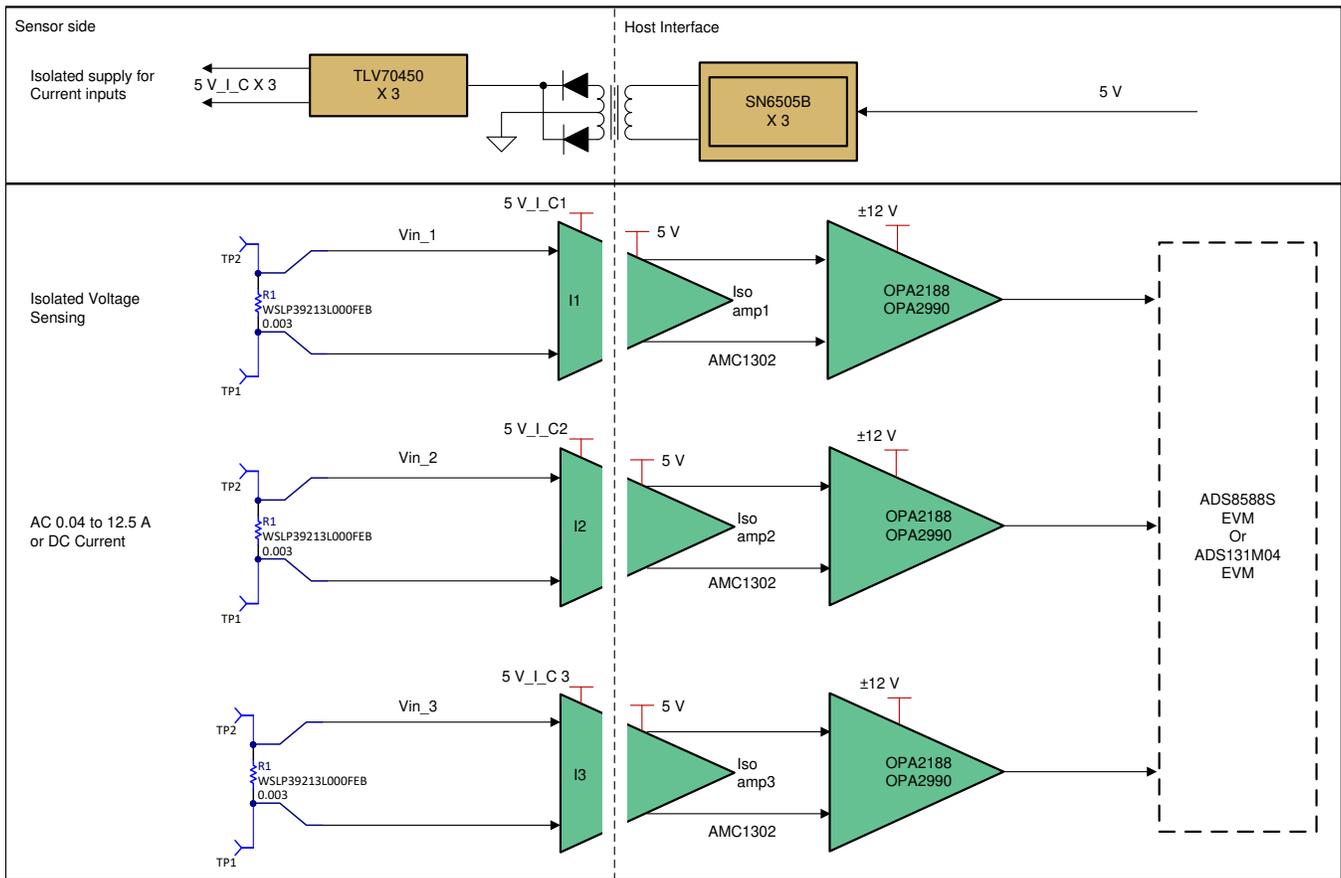
- Buffering the PD output and connecting the buffer output to a comparator for zero cross detection
- Isolating the zero cross output from the comparator to the host for implementing coherent sampling using a digital isolator
- Overtemperature detection using a temperature switch and an interface to the host through a digital isolator
- Magnetic field detection using a Hall switch and an interface to the host through a digital isolator

Implementing diagnostics digitally optimizes the cost, improves reliability, and enables continuous monitoring with minimal host processing.

2.1.2 **Generation of Isolated Supply and Measurement of Isolated Current Inputs**

Figure 2 features isolated measurement of AC or DC currents using isolation amplifiers in a channel-isolated configuration and scaling the isolation amplifier output to a SAR ADC input range.

Figure 2. TIDA-010055 Communication Power Module Block Diagram



2.1.2.1 Generation of Isolated Supply

This design showcases the following functionalities:

- Three isolated supplies with a low output current requirement for channel-isolated current measurement
- The supplies are generated using a transformer driver with the required isolation provided by the transformer
- The isolated supply output is regulated using an LDO to generate 5 V for operation of isolation amplifiers

The efficiency of the transformer-driver-based power supply is higher at lower load currents.

2.1.2.2 Sensing of Current Inputs

A low-value, low-drift current shunt is used to sense the current inputs. The shunt resistor value should be set in consideration of both power dissipation at the resistor and the sensing accuracy. Smaller shunt resistance is desired in terms of the power dissipation.

2.1.2.3 Measurement of Isolated Currents

This design showcases the following functionality:

- Measurement of 3 × AC or DC input currents using isolation amplifiers in channel isolated configuration
- Isolation amplifiers with ±50-mV input range reduces power loss and thermal heating
- The isolation amplifier provides reinforced isolation

2.1.2.4 Scaling of Isolation Amplifier Output

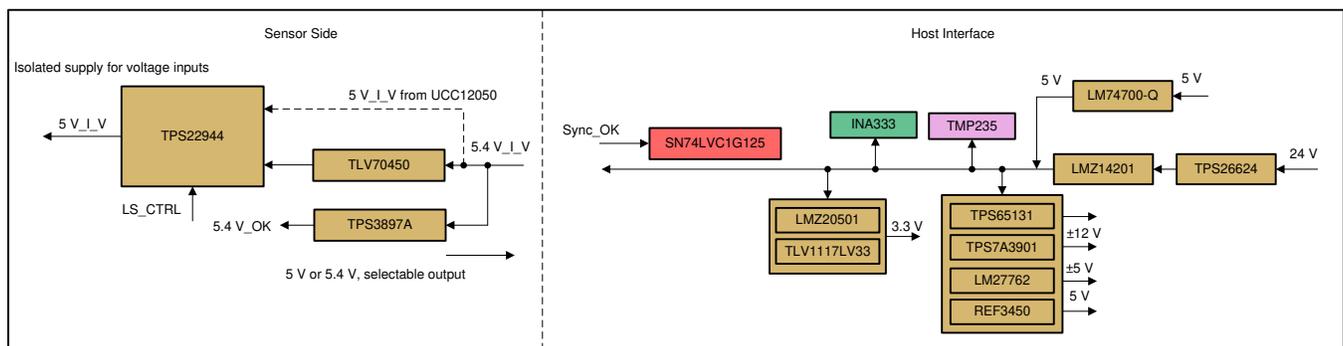
This design showcases the following functionality:

- Scaling of the isolation amplifier output to ADC input range using general purpose or precision operational amplifiers
- Scaling of the isolation amplifier output to ADC input range using precision instrumentation amplifiers for improved performance
- The output of the gain scaling amplifier interfaces to the ADC

2.1.3 DC Supply Input Protection and Non-isolated Power Architecture

Figure 3 illustrates generation of non-isolated supplies including split-rail supplies for the gain amplifiers and digital diagnostics of isolated supplies.

Figure 3. TIDA-010065 Power Architecture Input Protection



2.1.3.1 Input Reversal and Overload Protection

This design showcases the following functionality:

- The DC supply input is isolated during overload using an eFuse and is used for 24-V or 12-V input
- When connected to the 5-V input, protection against input reversal is showcased

2.1.3.2 Generation of Non-isolated Supplies From 5-, 12-, or 24-V Input

This design showcases the following :

- The analog input module is powered by the power supply from the backplane and can be 24 or 12 or 5 V
- The module can directly operate from 5 V (recommend using a current limited source during testing)
- When 24 or 12 V is available, the input is converted to 5 V using a DC/DC converter with an integrated inductor and can be connected as 5 V input

Use of DC/DC with an integrated inductor improves performance including output voltage accuracy, efficiency and simplifies design reducing the overall space.

2.1.3.3 Split-rail Supply Generation

This design showcases the following functionality:

- Generation of split-rail supply used to power the gain scaling amplifiers
- ± 14 -V non-regulated supply is generated using a split-rail DC/DC converter
- The DC/DC converter output is regulated to ± 12 V using dual LDO
- A 5-V reference is generated to level shift the isolation amplifier output for unidirectional 10-V operation

2.1.3.4 DC Input Supply (Load) Current Measurement and Supply Digital Diagnostics

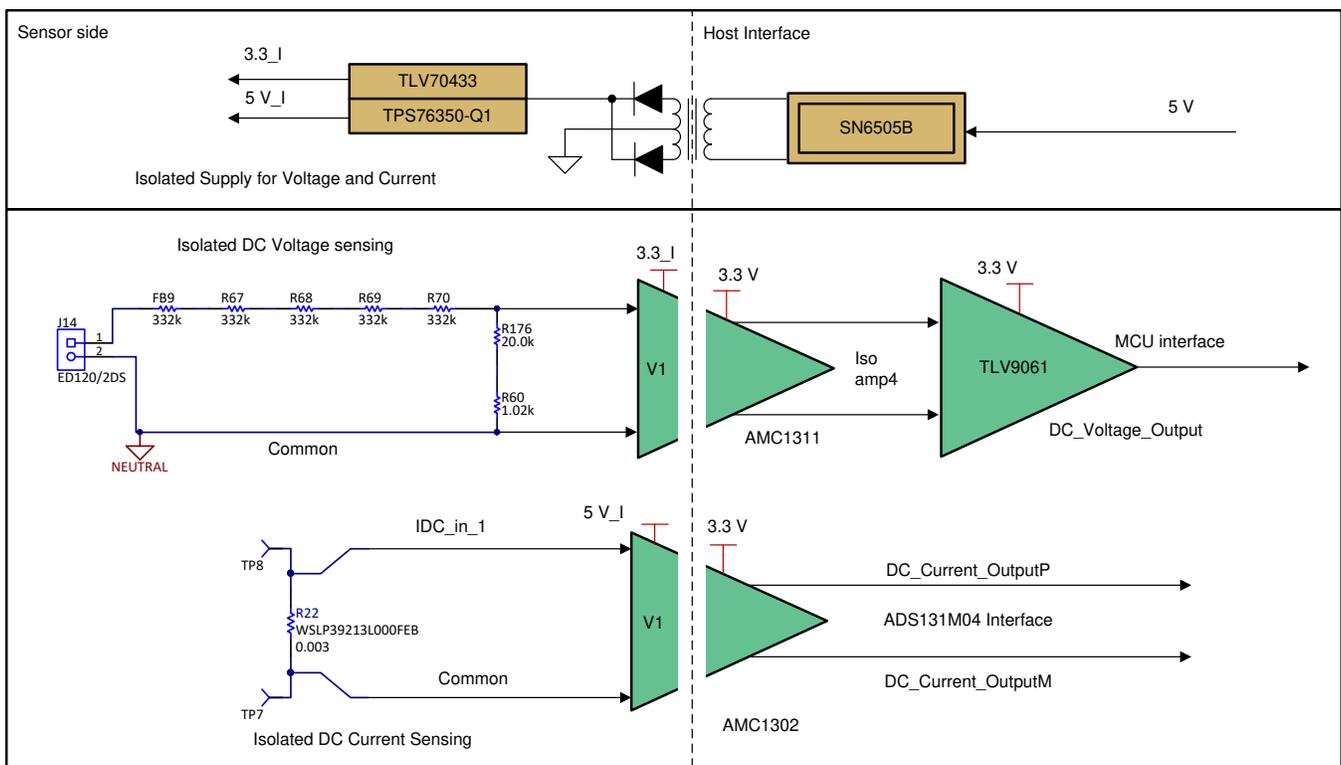
This design showcases the following functionality :

- Measurement of the analog input module current consumption at the DC supply input using precision instrumentation amplifier
- The unregulated output of the isolated supply is monitored using a voltage detector
- The DC/DC operating state indicated by the *sync_ok* is buffered to connect to the host
- The output of DC/DC is switched using a load switch for overload protection.

2.1.4 Measurement of DC Voltage and Current

Figure 4 showcases generation of isolated supply, measurement of isolated DC voltages, and measurement of isolated DC current.

Figure 4. TIDA-010065 DC Voltage Current Measurement



2.1.4.1 Isolated Supply for DC Voltage and Current Measurement

This design showcases the following functionality:

- Generation of isolated supply using a transformer driver
- Generation of regulated 3.3 V and 5 V for isolation amplifier operation

2.1.4.2 Measurement of Isolated DC Voltage, DC Current and Gain Scaling

This design showcases the following functionalities:

- Measurement of DC voltage output from the PD using an isolation amplifier with 2-V input range specified for DC voltage measurement
- The output of the isolation amplifier is scaled to ADC (internal to microcontroller unit (MCU)) range using general purpose amplifiers
- Measurement of DC current output (millivolts) from the shunt sensor using isolation amplifier with ± 50 -mV input range

2.1.4.3 MCU Interface

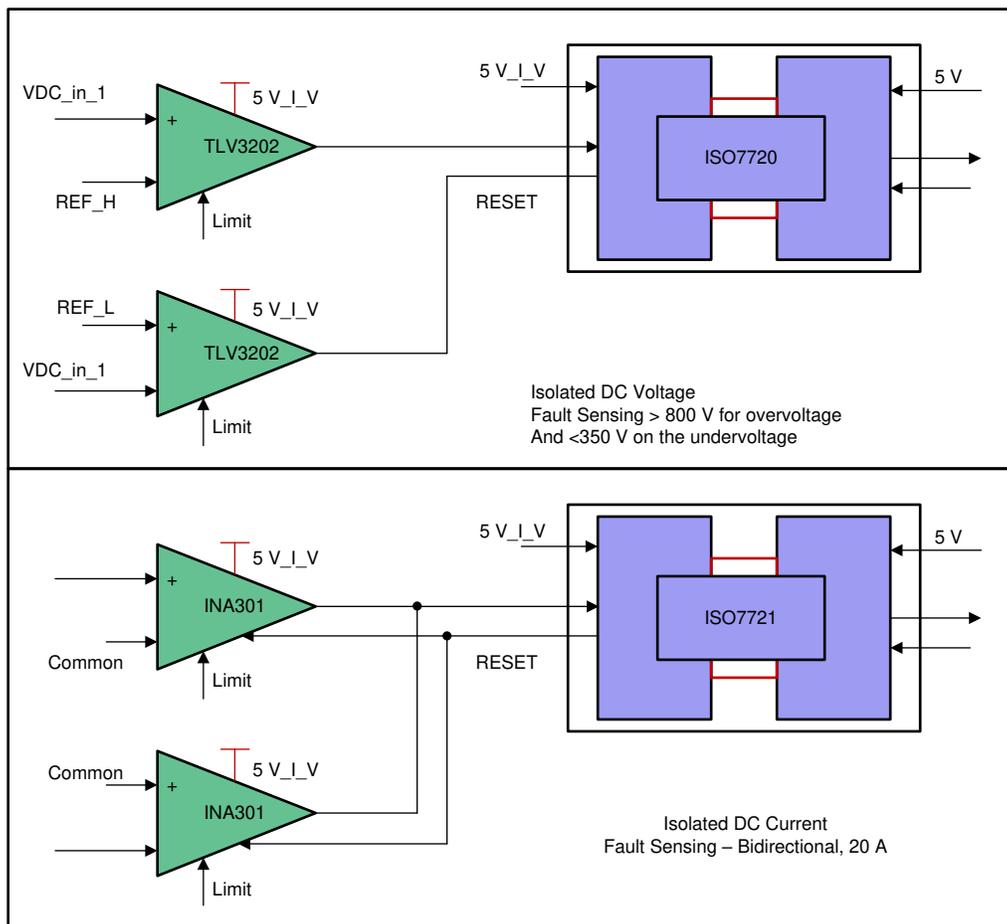
This design showcases the following functionality:

- Interfacing the gain-scaled output of the voltage measurement section to the MCU with internal ADC for sampling and processing
- Interfacing the differential output of the current measurement isolation amplifier to the MCU with differential input

2.1.5 Fault Detection of DC Voltage and Current Inputs

Figure 5 showcases fault detection of DC voltage and current with fast response.

Figure 5. TIDA-010065 DC Voltage Current Fast Fault Detection



2.1.5.1 Detection of DC Voltage and DC Current Faults

This design showcases the following functionality:

- Detection of overvoltage or undervoltage fault using a window comparator with 100-ns response time and interfacing the comparator output to the host through a digital isolator to provide the required isolation
- Detection of bidirectional overcurrent by sensing the shunt output using an instrumentation amplifier with a fixed gain and a 1- μ s response internal comparator.
- Interfacing the comparator output to the host through a digital isolator to provide the required isolation

2.1.6 Interface to EVM

The design additionally provides the ability to connect to external EVMs and test the performance using evaluation modules. The AIM is interfaced directly to the ADS8588S EVM. The output of the isolation amplifier can be connected to the ADS131M04 device for performance testing.

2.2 Design Considerations

Some of the key design considerations when designing isolated AIM include:

- Channel-to-channel or group isolated voltage and current measurement
- Capability to measure AC or DC input voltage and current
- Portioning the system into sensor side (isolated) and the host side
- Choice of isolation (basic or reinforced), depending on the application and cost
- Fault diagnostics of DC input within 1 μ s
- Generation of isolated power supply for powering the isolation amplifiers and digital isolators
- Interface to ADC and host including DSP, processor, or FPGA with the capability to perform signal capture and processing in real time.
- Performance in terms of measurement accuracy, programmable sampling rate, and coherent sampling are key design challenges
- Easily expandable since there are a greater number of channels (4–8 channels or more)
- Digital diagnostics is a good to have feature and is being added in the next generation modules

The TIDA-010065 reference design provides a solution with optimized performance and cost in a smaller form factor for the previously-mentioned requirements, in addition to providing improved performance.

2.3 Highlighted Products

This section provides details of some of the focus TI products used in this analog input module reference design.

2.3.1 Isolated Power-supply Generation Supply Generation

This section provides details of the devices used to generate the isolated power supply for voltage and measurement isolation amplifiers and monitoring of the DC/DC converter unregulated output voltage.

2.3.1.1 Isolated Supply Generation for Voltage Measurement Using Isolated DC/DC

The isolated power-supply generation functionality for group-isolated voltage measurement isolation amplifiers is implemented using the following devices:

- UCC12050: 500-mW, high-efficiency, low-emissions, 5-kV_{RMS} isolated DC/DC converter
- TLV70450: 150-mA, ultra-low- I_Q low-dropout (LDO) regulators

The UCC12050 device is a high-isolation voltage, DC/DC converter designed to provide efficient isolated power to isolated circuits that require well-regulated supply voltages. It integrates a transformer and DC/DC controller with a proprietary architecture to achieve high efficiency with very low emissions. It also provides 500 mW (typical) of isolated output power at high efficiency. Requiring a minimum of external components and including on-chip device protection, the UCC12050 device provides extra features such as an enable pin, synchronization of switching frequency among multiple devices, and selection of isolated output voltages. Synchronization among multiple devices is achieved with a Johnson counter ex: CD74HC4017 and connecting the clock output from the counter to multiple devices reduces peak current and radiated emission. See [UCC12050](#) for more details.

2.3.1.2 Isolated Supply Generation for Current Measurement Using Transformer Driver

The isolated power-supply generation functionality for channel-isolated current measurement isolation amplifiers is implemented using the following devices:

- SN6505B: Low-noise 1-A, 420-kHz transformer driver for isolated power supplies
- TLV70450: 150-mA, ultra-low- I_Q low-dropout (LDO) regulators
- TPS70950: 150-mA, 30-V, ultra-low- I_Q wide-input low-dropout (LDO) regulator with reverse current protection

2.3.1.3 Isolated Supply Digital Diagnostics

Power-supply digital diagnostics functionality is implemented with the following devices:

- TPS3897, Single-Channel Ultra-Small Adjustable Supervisory Circuit With Active-High Open-Drain Output
- SN74LVC1G125, Single Bus Buffer Gate With 3-State Outputs

2.3.2 Measurement of Voltage Inputs

This section showcases measurement of group-isolated voltage inputs using isolated amplifiers with ± 250 -mV or ± 12 -V input range and using the PD as the voltage sensing element. Additionally, the approach to scale the isolation amplifier gain to ADC input range is shown.

2.3.2.1 Measurement of Channel Isolated Voltage Inputs

The preferred approach for measuring voltage, is to use resistor dividers. The voltage divider with the specified ration is used to measure the input voltage. Using a voltage divider simplifies the voltage measurement, improves the measurement accuracy, and reduces the solution size. The resistor divider does not provide isolation between the input and output and an isolation amplifier is used to provide the required isolation. Isolation choice can be basic or reinforced isolation. A pin-compatible isolation amplifier solution with basic or reinforced isolation simplifies design of analog input modules with the capability to switch between basic and reinforced isolation. The isolated voltage measurement functionality was implemented using the following devices:

- AMC1200: ± 250 mV-input basic isolated amplifier
- AMC1300: ± 250 mV-input precision reinforced isolated amplifier
- AMC1311: 2-V input, reinforced isolated amplifier with high CMTI for voltage sensing
- ISO224: ± 12 -V input, reinforced isolated amplifier for voltage sensing

The ISO224 is a precision isolated amplifier with an output separated from the input circuitry by an isolation barrier with high immunity to magnetic interference. This barrier is certified to provide reinforced galvanic isolation of up to 5 kV_{RMS} with an exceptionally long lifetime and low power dissipation. When used with isolated power supplies, this device separates parts of the system that operate on different common-mode voltage levels and protects lower-voltage devices from damage. The input of the ISO224 device is optimized for accurate sensing of ± 10 -V signals that are widely used in industrial applications. The device operates on a single supply on the high-side. This unique feature simplifies the design of the isolated power supply and reduces the system cost. The integrated high-side supply voltage detection feature simplifies system-level diagnostics. The ± 4 -V output of the ISO224 amplifier allows lower-cost analog-to-digital converters (ADCs) to be used. The differential structure of the output supports high immunity to noise. See [ISO224](#) for more details.

2.3.2.2 Gain Scaling of Isolation Amplifier Output

The conversion of differential output of the isolation amplifier to single-ended output and gain scaling functionality was implemented using the following devices:

- OPA2990: Dual 1-MHz, 40-V rail-to-rail input/output, low-offset-voltage, low-power op amp
- OPA2180: 0.1- $\mu\text{V}/^\circ\text{C}$ drift, low-noise, rail-to-rail output, 3-V zero-drift op amp

Use of precision amplifiers improves the performance over a wide temperature range. Use of a general purpose amplifier optimizes performance and cost.

2.3.3 Measurement of Isolated Current Inputs

This section describes the measurement of channel-isolated current inputs using isolated amplifiers with a ± 50 -mV input range and a shunt as the current sensing element.

2.3.3.1 Isolated Current sensing and measurement

The isolated current inputs are measured using a low shunt. A shunt is a low-value resistor with excellent thermal behavior designed to measure AC or DC current inputs. The limitations of using a shunt is that they are self-heating and they increase power dissipation. To minimize power dissipation and self-heating, the lowest possible value shunt is chosen. The AMC1302 device has a ± 50 -mV input range resulting in selection of low values resulting in lower power dissipation and improved measurement accuracy. The isolated current-sensing functionality was implemented using the AMC1302 device. This device is a ± 50 -mV input high-precision reinforced isolated amplifier for current sensing.

The AMC1302 is a precision isolated amplifier with a capacitive isolation barrier that has high immunity to magnetic interference. This barrier provides reinforced isolation of $5 \text{ kV}_{\text{RMS}}$ (maximum) with a very long lifetime and low power dissipation. When used with isolated power supplies, this device isolates components that operate on different common-mode voltage levels. Furthermore, it also protects lower-voltage devices from damage. The input of the AMC1302 device is optimized for direct connection to shunt resistors or other low voltage-level signal sources. The ± 50 -mV input voltage range allows significant reduction of the power dissipation through the shunt. Additionally, the low high-side supply current and voltage of the AMC1302 allow use of low-cost isolated power-supply solutions. The performance of the device supports accurate current control resulting in system-level power savings and in low torque ripple that is particularly important in motor control applications. The integrated input common-mode overvoltage and missing high-side supply voltage detection features of the AMC1302 device simplify system-level diagnostics. See [AMC1302](#) for more details.

2.3.3.2 Gain Scaling of Isolation Amplifier Output Using General Purpose Amplifiers

The gain scaling and differential to single-ended output conversion functionality was implemented using the following devices:

- OPA2990: Dual 1-MHz, 40-V rail-to-rail input/output, low-offset-voltage, low-power op amp
- OPA2180: 0.1- $\mu\text{V}/^\circ\text{C}$ drift, low-noise, rail-to-rail output, 36-V zero-drift op amp
- TLV6001: 1-MHz, low-power operational amplifier for cost-sensitive systems

The OPAX990 is a family of high voltage (40-V) general purpose operational amplifiers. These devices offer excellent DC precision and AC performance, including rail-to-rail input/output, low offset ($\pm 300 \mu\text{V}$, typ), and low offset drift ($\pm 0.6 \mu\text{V}/^\circ\text{C}$, typ). Unique features such as differential and common-mode input voltage range to the supply rail, high short-circuit current ($\pm 80 \text{ mA}$), high slew rate ($4.5 \text{ V}/\mu\text{s}$), and shutdown make the OPA2990 an extremely flexible, robust, and high-performance op amp for high-voltage industrial applications. See [OPA2990](#) for more details.

2.3.3.3 Gain Scaling of Isolation Amplifier Using Instrumentation Amplifier

An alternative approach to gain scaling is to use an instrumentation amplifier. Using instrumentation amplifiers simplifies the design and improves performance over a wide temperature minimizing the drift. The gain scaling functionality is implemented using the following devices:

- INA826: Precision, 200- μA supply current, 36-V supply instrumentation amplifier
- INA821: 35- μV offset, $7\text{-nV}/\sqrt{\text{Hz}}$ noise, low-power, precision instrumentation amplifier

The INA821 device is a high-precision instrumentation amplifier that offers low power consumption and operates over a wide single-supply or dual-supply range. A single external resistor sets any gain from 1 to 10,000. The device has high precision as a result of super-beta input transistors, which provide low input offset voltage, offset voltage drift, input bias current, and input voltage and current noise. Additional circuitry protects the inputs against overvoltage up to $\pm 40 \text{ V}$. The INA821 device is optimized to provide a high common-mode rejection ratio. At $G = 1$, the common-mode rejection ratio exceeds 92 dB across the full input common-mode range. The device is designed for low-voltage operation from a 4.5-V single supply, and dual supplies up to $\pm 18 \text{ V}$.

2.3.4 Digital Diagnostics of Input Voltage and Operating Environment

This section showcases approaches for digital diagnostics of the analog input module including input voltage presence, overtemperature, and presence of a high magnetic field.

2.3.4.1 Buffering and Zero Cross Detection of AC Input

The aforementioned functionality was implemented using the devices listed in this section:

- TLV9062: 10-MHz, low-noise, RRIO, CMOS operational amplifier for cost-sensitive systems
- LM2901: Quad-differential comparator

2.3.4.2 Onboard Temperature, High Magnetic Field Detection and Digital Output Isolation

The previously-listed functionality was implemented using the devices listed in this section. Use of a digital switch simplifies system design and the temperature range can be programmed using resistors. The ISO776x family of devices provides high-electromagnetic immunity, low emissions, and low-power consumption:

- TMP300: Resistor-programmable, up to 18-V capable temperature switch and analog out sensor
- DRV5032: Ultra-low power 1.65-V to 5.5-V Hall-effect switch
- ISO7760: High-speed, robust EMC six-channel digital isolator

2.3.5 Fault Detection of DC Voltage Input, DC Current Input and Interface to Digital Isolators

The aforementioned functionality was implemented using devices listed in this section. The TLV3202 device is used in a wide variety of applications including HVDC where response time is critical:

- TLV3202: Dual, 40-ns, microPower, rail-to-rail input comparator with push-pull outputs
- ISO7720: High-speed, robust EMC reinforced dual-channel digital isolator
- INA301: 36-V, low-, or high-side, voltage output CSA with comparator
- ISO7721: High-speed, robust-EMC reinforced dual-channel digital isolator

2.3.6 Generation of Non-isolated Supplies From DC Input and Protection

This section provides details of the devices used to generate different non-isolated power-supply rails for AIM from 24-, 12-, or 5-V input with overload protection.

2.3.6.1 Generation of 5-V Supply From 12- or 24-V Input and 3.3-V Output for Host

The devices listed in this section were used to generate the required supply rails:

- LMZ14201: SIMPLE SWITCHER® 6-V to 42-V, 1-A power module in leaded surface mount TO package
- LMZ20501: 2.7-V to 5.5-V, 1-A high-density nano module
- TLV1117LV33: 1-A, positive fixed voltage, low-dropout regulator

2.3.6.2 Measurement of Input Supply Load Current and Temperature

The devices listed in this section were used to generate the required supply rails. Use of an instrumentation amplifier for current measurement simplifies design and improves measurement accuracy over a wide input current.

- INA333: Low-power, zero-drift, precision instrumentation amplifier
- TMP235: $\pm 2.5^{\circ}\text{C}$ analog output temperature sensor, with 10-mV/ $^{\circ}\text{C}$ gain

2.3.6.3 Generation of Split-rail Supply From 5 V, Reference and Regulation of Split-rail Supply

This section provides details of the devices used to generate split-rail supply from 5 V and regulating the split-rail supplies using LDOs. The devices listed in this section are used for generating and regulating split-rail supplies.

- TPS65131: Split-rail converter with dual, positive and negative outputs (750-mA typ)
- TPS7A39: Dual, 150-mA, wide- V_{IN} , positive and negative low-dropout (LDO) voltage regulator
- LM27762: Low-noise positive- and negative-output charge pump with integrated LDO

2.3.7 Interface to External Evaluation Module EVM

For evaluation purposes, the analog input module output can be interfaced to external ADC or MCUs with an internal ADC. When improved performance is required, the module is interfaced to precision 16- or 24-bit ADCs. [Table 6](#) provides details of the EVMs that can be interfaced to the AIM for performance testing.

Table 6. Details of Reference Designs Interfaced to AIM

NUMBER	DESCRIPTION
ADS131M04EVM	ADS131M04 24-bit 32-kSPS 4-channel simultaneous-sampling delta-sigma ADC evaluation module
ADS131A04EVM	ADS131A04 evaluation module
ADS131E08EVM-PDK	ADS131E08 performance demonstration kit
ADS8588SEVM-PDK	ADS8588S 16-bit high-speed 8-channel simultaneous-sampling ADC EVM performance demonstration kit (PDK)
ADS8688EVM-PDK	ADS8688 PDK
TIDA-01576	Isolated 16-channel AC analog input module reference design using dual simultaneously sampled ADCs

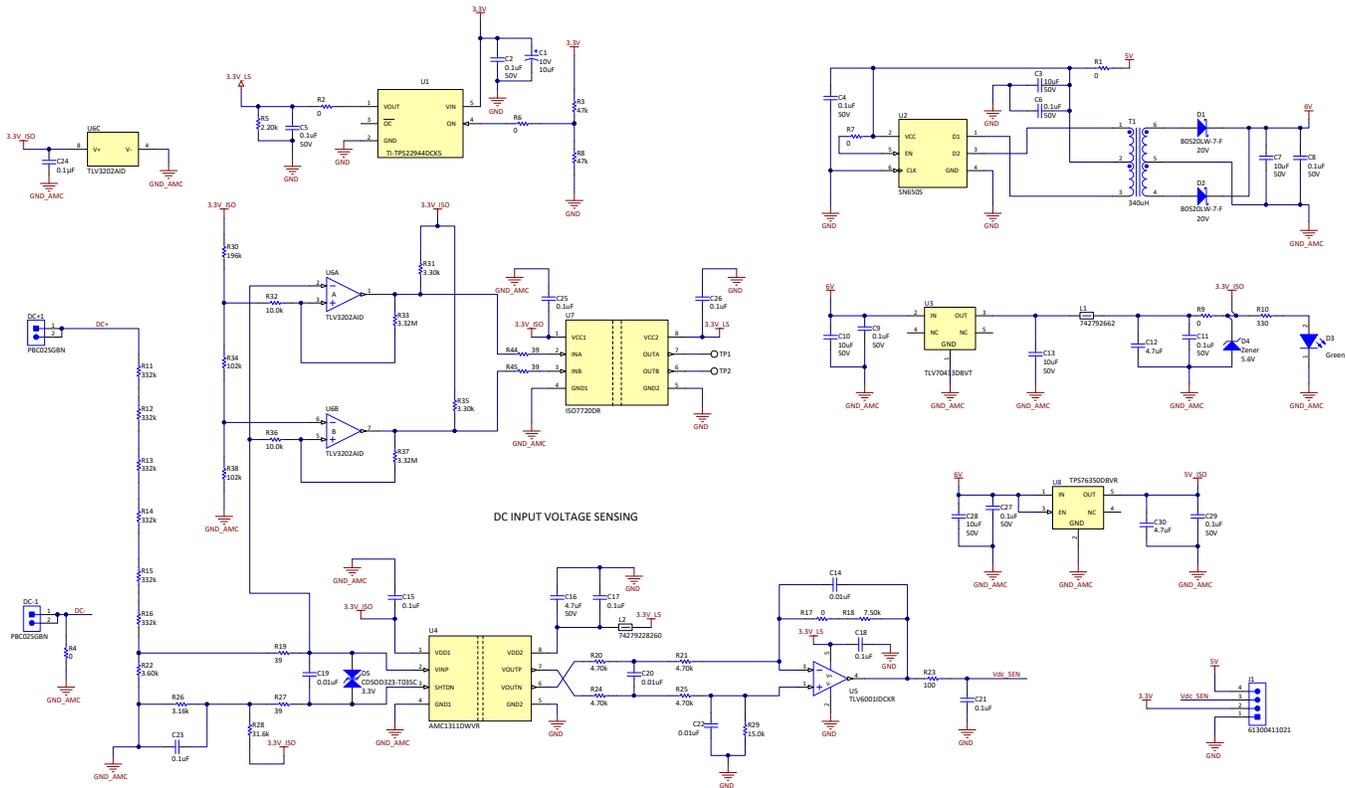
2.3.8 Enhancements

This section provides information on some of the design enhancements that can be considered during the design of the processor power modules and also provides a few commonly-used devices.

2.3.8.1 Measurement of DC Voltage Inputs With Fault Detection

In some of the application in grid, isolated DC voltage measurement is a common requirement in some of the grid applications including high-voltage direct transmission (HVDC). For improved performance in HVDC applications, a measurement path and a fast fault detection path is used for measurement of the input voltages. [Figure 6](#) provides details of the measurement and fast fault detection path.

Figure 6. DC Input Voltage Measurement



2.3.8.1.1 DC Voltage Measurement Path

An AMC1311, 0 to 2-V input, reinforced isolated amplifier with high CMTI for voltage sensing is used to measure the DC voltage. The HVDC voltage is attenuated using resistor divider to a range of 0 V–2 V and connected to the AMC1311 amplifier for measurement. The output of the isolation amplifier is scaled to interface to an MCU or ADC with a 3.3-V input range. The attenuation ratio is selected to ensure the required input range is measured within the specified accuracy.

2.3.8.1.2 DC Voltage Fast Fault Detection Path

The IEC61869-9 (IEC standard for Digital interface for instrument transformers) introduces 96000-Hz sampling for DC control applications which is translated to a sampling time of approximately 10 μ s and the AMC1311 device has a phase delay of approximately 3 μ s. When faster detection of a fault is required, an alternative comparator path with fast response time can be considered. The fault can be detected within 1 μ s translating to a 1-MHz sampling rate. Based on the configured values, the comparator detects undervoltage or overvoltage fault and provides a digital output to the host to indicate a DC voltage fault within 1 μ s. The fault detection range can be higher than the measurement range for a short time as the resistor divider are rated for short time overvoltage and do not saturate. The fault is detected within 500 ns and the comparator output is interfaced to the host using digital isolators.

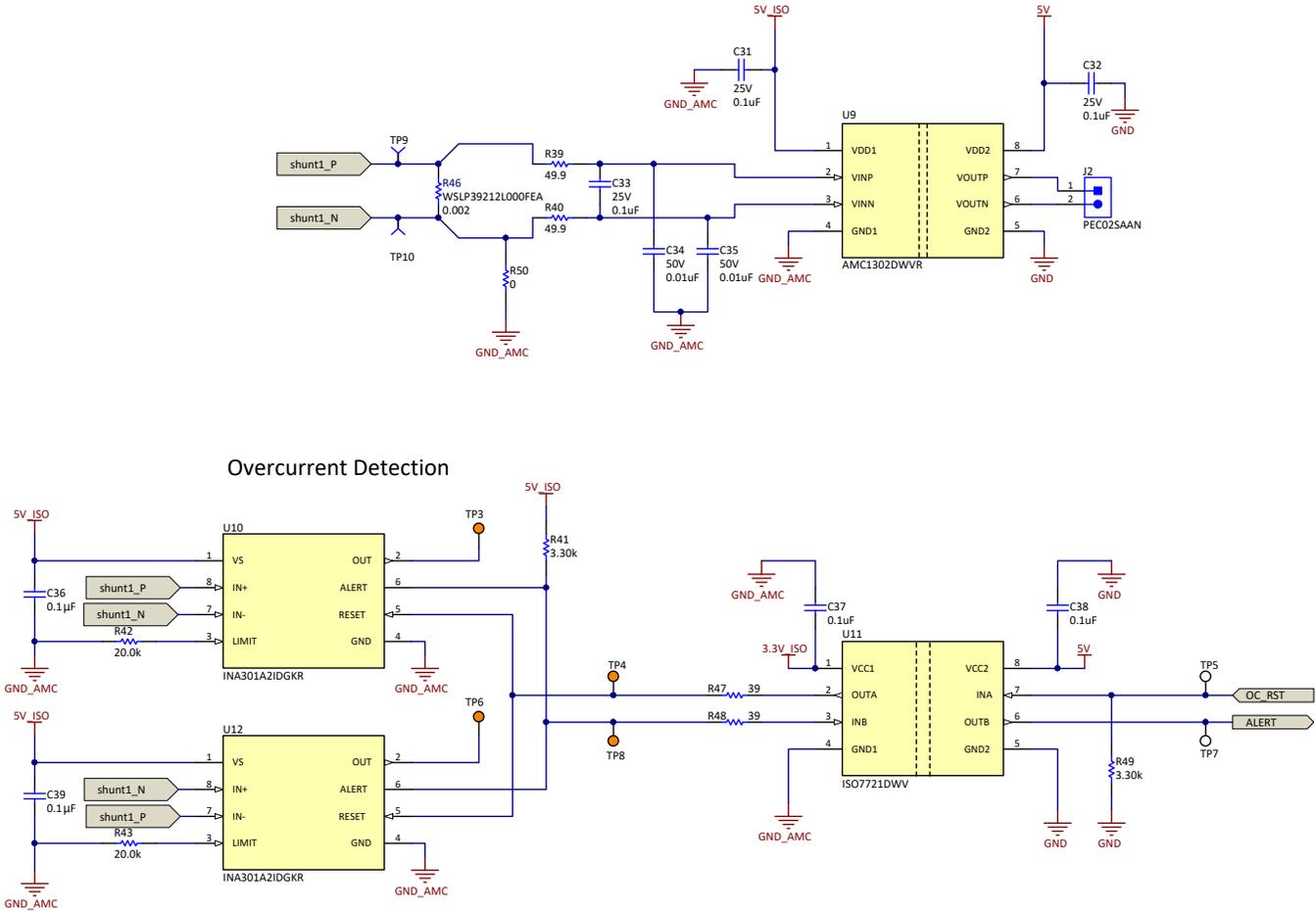
2.3.8.1.3 Digital Isolator

Two outputs of the window comparator are interfaced to the digital isolators. Use this approach when a comparator with push-pull output is used for fast fault detection. When a comparator with open collector or open drain is used, both the comparator outputs can be tied together with a common output to the digital isolator.

2.3.8.2 Measurement of DC Current Inputs With Fast Fault Detection

In HVDC applications, use a measurement path and a fast fault detection path for measurement of the input currents and detection of faults. Figure 7 provides details of the measurement and fast fault detection path.

Figure 7. DC Input Current Measurement



2.3.8.2.1 DC Current Measurement Path

The AMC1302 device has ± 50 -mV input range and provides reinforced isolation. The HVDC current is sensed using a shunt with Kelvin connection for improved accuracy and the output is connected to isolation amplifier for measurement. The AMC1303 device can measure bidirectional current. The output of the AMC1302 device can be interfaced directly to a delta-sigma ADC without gain scaling.

2.3.8.2.2 DC Current Fault Detection Path and Response Time

The AMC1302 device has a phase delay of approximately 3 μ s and when faster detection during fault is required, an alternative comparator path with a fast response time is used. Since the voltage drop across the shunt is low, additional gain is required before detection of the fault by the comparator. Use of an instrumentation amplifier with comparator output provides the required gain and also detects the fault within 1 μ s. The current during fault increases and so overcurrent fault detection is implemented. Bidirectional overcurrent fault can be detected using two instrumentation amplifiers. The current limit is set using a single resistor. The output from the shunt is reversed at the instrumentation amplifier input to detect reverse current. The output of the comparator is isolated using digital isolators. Provision to latch the output of the instrumentation amplifier is provided and controlled by the host interfaced through the digital isolator. The alert output response was tested using a function generator and the response time was observed to be approximately 500 ns for input varying from 0 to 50 mV.

2.3.8.5 Interfacing to the MCU for DC Input Signal Capture and Processing

There are multiple approaches to processing the analog signal and computing voltages and currents. A common approach for optimizing the cost and performance is to use an MCU with an internal ADC.

[Table 8](#) provides a list of TI MCUs that can be considered:

Table 8. MCU Selection for DC Signal Processing

MCU FAMILY	DEVICE	DESCRIPTION
Delfino™	TMS320F28335	Delfino 32-bit MCU with 150 MIPS, FPU, 512KB flash, EMIF, 12b ADC
	TMS320F28374	Delfino 32-bit MCU with 800 MIPS, 2 x CPU, 2 x CLA, FPU, TMU, 512KB flash, EMIF, 12b ADC
	TMS320F28377	Delfino 32-bit MCU with 800 MIPS, 2 x CPU, 2 x CLA, FPU, TMU, 1024KB flash, EMIF, 16b ADC
	TMS320F28379	Delfino 32-bit MCU with 800 MIPS, 2 x CPU, 2 x CLA, FPU, TMU, 1024KB flash, CLB, EMIF, 16b ADC
Piccolo™	TMS320F28035	Piccolo 32-bit MCU with 60 MHz, 128KB flash, CLA
	TMS320F28069	Piccolo 32-bit MCU with 90 MHz, FPU, VCU, 256KB flash, CLA
Other MCUs	TM4C1290NCPDT	High performance 32-bit Arm® Cortex®-M4F based MCU
	TM4C1292NCPDT	IoT enabled high performance 32-bit Arm Cortex-M4F based MCU
	TM4C1294KCPDT	IoT enabled high performance 32-bit Arm Cortex-M4F based MCU
SimpleLink™ wired MCU	MSP432P401	SimpleLink ultra-low-power 32-bit ARM Cortex-M4F MCU with precision ADC, 256KB flash and 64KB RAM
Other MSP430 MCUs	MSP430F6779	Polyphase metering SoC with 7 sigma-delta ADCs, LCD, real-time clock, AES, 512KB flash, 32KB RAM

2.3.8.6 Interfacing to ADC for DC Input voltage measurement

There are multiple approaches to capturing the analog signal. An alternative approach to an MCU is to use an external SAR ADC for improved performance. [Table 9](#) provides list of TI ADCs that can be considered. Selection of a single channel simplifies the channel isolated interface.

Table 9. SAR ADC Selection for DC voltage measurement

DEVICE	DESCRIPTION
ADS7057	14-bit, 2.5-MSPS, differential input, small-size low-power SAR ADC
ADS7056	14-bit 2.5-MSPS ultra-low-power ultra-small-size SAR ADC with SPI
ADS7054	14-bit, 1-MSPS, differential input, small-size low-power SAR ADC
ADS7052	14-bit, 1-MSPS, single-ended input, small-size low-power SAR ADC
ADS8861	16-bit, 1-MSPS, serial interface, microPower, miniature, truly-differential input, SAR ADC

2.3.8.7 Current Sensor Options for Analog Input Module

Some of the commonly-used sensors for measurement of currents in analog input module application include:

2.3.8.7.1 Current Transformers (CT)

This is the most commonly-used approach for current measurement. CT provides isolation but has some saturation concerns. Some of the reference designs showcasing current measurement using CTs are listed in [Table 10](#):

Table 10. Current Transformer-based Reference Designs

REFERENCE DESIGN	DESCRIPTION
TIDA-00834	High-accuracy analog front end using 16-bit SAR ADC with ± 10 -V measurement range reference design
TIDA-00454	Three-phase AC voltage and current transducer with isolated DC analog outputs reference design
TIDA-00753	Three-phase AC current measurements using current transformer reference design

2.3.8.7.2 Rogowski Coil-based Current Sensor

An alternative to using the current transformer for current measurement is an air core based Rogowski coil. They do not measure DC current and need integration to measure when used for power calculation. Some of the reference designs with current measurement using Rogowski coils are listed in [Table 11](#):

Table 11. Reference Designs for Rogowski Sensors

REFERENCE DESIGN	DESCRIPTION
TIDA-00777	Active integrator for Rogowski coil reference design with improved accuracy for relay and breaker
TIDA-01063	High-accuracy AC current measurements reference design using PCB Rogowski coil sensor

2.3.8.7.3 Hall or Fluxgate Sensors

The DC saturation challenges of a current transformer are solved using Hall or fluxgate sensors. Hall or flux gate sensors provide isolation but are bulky and have drift concerns. Some of the reference designs with current measurement using hall or flux gate sensors are listed in [Table 12](#):

Table 12. Hall or Flux Gate Based Reference Designs

REFERENCE DESIGN	DESCRIPTION
TIDA-00368	Reference design for interfacing current output Hall sensors and CTs with differential ADC and MCU
TIDA-00316	Interfacing current output Hall sensors and CTs with pseudo-differential ADC and MCU reference design
TIDA-00208	Single-ended signal conditioning circuit for current and voltage measurement using fluxgate sensors
TIDA-00201	Differential-signal conditioning circuit for current and voltage measurement using fluxgate sensors
TIPD205	± 100 -A bus bar current sensor using open-loop fluxgate sensors reference design

2.3.8.8 Shunt Current Sensor

Using a shunt enables the accurate measurement of symmetric and asymmetric currents. The limitation of shunt-based current sensor is the requirement for isolation. Some of the reference designs with current measurement using shunt are listed in [Table 13](#):

Table 13. Shunt Sensor-based Reference Designs

REFERENCE DESIGN	DESCRIPTION
TIDA-00445	Shunt-based 200-A peak current measurement reference design using isolation amplifier
TIDA-00912	Shunt-based high current measurement (200 A) reference design with reinforced isolation amplifier
TIDA-020018	Automotive shunt-based isolated current sensor reference design for DC/DC and OBC applications
TIDA-01598	Low-side, high bandwidth current amp and fault detection for solar inverters reference design
TIDA-03050	Automotive, mA-to-kA range, current shunt sensor reference design
TIDA-01543	Isolated current sense reference design (± 300 A) for traction inverter with overcurrent detection
TIDA-01590	Reference design for 1200-V isolated I2C high-side current sensing for solar combiner boxes
TIDA-01608	Isolated current sense with integrated shunt resistor and I2C interface reference design

2.3.8.9 Voltage Sensing Using Resistor (Potential) Divider

Some of the commonly used sensors for measurement of voltages include potential transformers and potential dividers. Potential transformers measure voltages and provide isolation, but the disadvantages include phase shift and size. Potential dividers are used to measure AC or DC input voltages and they are resistive and do not have phase shift. The disadvantage to potential dividers is that they do not provide isolation. Some of the reference designs with voltage measurement using a potential divider are listed in [Table 14](#):

Table 14. Potential Divider-based Reference Design

REFERENCE DESIGN	DESCRIPTION
TIDA-00661	High resolution, fast startup analog front end for air circuit breaker reference design
TIDA-00834	High accuracy analog front end using 16-bit SAR ADC with ± 10 V measurement range reference design
TIDA-00810	Reference design to measure AC voltage and current in protection relays with delta-sigma chip diagnostics

2.3.8.10 Phase Delay and Bandwidth

Some of the key isolation amplifier specifications include bandwidth and phase error. Phase error was not tested in this reference design. The maximum specified bandwidth and phase error for different families of isolation amplifiers are listed in [Table 15](#)!~.

Table 15. Isolation Amplifier Bandwidth and Phase Error Summary

DEVICE	BANDWIDTH kHz	PHASE ERROR (μ s)
AMC1200	100	3.15
AMC1300B	310	1.6
AMC1301	210	1.6
AMC1302	280	1.6
AMC1311	275	1.6
ISO224	275	2.2

When higher bandwidth is required along with isolation for enhanced performance, use isolated delta sigma modulators. Some of the common isolated delta-sigma modulator family devices and the bandwidth are listed in [Table 16](#):

Table 16. Delta-Sigma Modulator Bandwidth and Clock Summary

DEVICE	BANDWIDTH kHz	MODULATOR CLOCK
AMC1303M0510	430	10 MHz
AMC1303M0520	800	20 MHz
AMC1304	800	5 MHz to 20 MHz
AMC1305	800	5 MHz to 20 MHz
AMC1306	800–900 (250 mV)	5 MHz to 20 MHz
AMC1106	800	5 MHz to 20 MHz
AMC1336	> 800	9 MHz to 20 MHz

Use the following reference designs with analog input module functionality based on delta-sigma modulators for designing higher performance AIM.

Table 17. Delta-Sigma Modulators-based Reference Design

REFERENCE DESIGN	DESCRIPTION
TIDA-00080	Shunt-based AC/DC current and voltage sensing for smart grid applications with reinforced isolation
TIDA-00738	Extended current and voltage measurement using shunts for protection relays reference design
TIDA-00171	Isolated current shunt and voltage measurement reference design for motor drives
TIDA-01543	Isolated current sense reference design (± 300 A) for traction inverter with overcurrent detection
TIDA-00209	Isolated current shunt and voltage measurement reference design for motor drives using AM437x

2.3.8.11 Similar Family Devices

Functionalities for isolation amplifiers, instrumentation amplifiers, precision amplifiers, and general purpose amplifiers are utilized in this reference design. The devices selected are a family of pin compatible devices with varying specifications including performance and cost. Designers have the flexibility to choose a family of devices based on performance and cost requirements. [Table 18](#) provides a list of devices used in this reference design and pin-compatible family devices. Performance tests for these families of devices were performed in this reference design.

Table 18. Devices Used in This Design and Similar Family Devices

DEVICES USED IN TIDA-010065	SIMILAR FAMILY DEVICES
AMC1200	AMC1100
AMC1300	AMC1300B
ISO224	ISO224B
TLV9061	TLV6001
OPA2990	OPA2171
OPA2180	OPA2277, OPA2188
SN6505B	SN6505A
ISO7760	ISO7761, ISO7762
INA826	INA821
INA333	INA118, INA188
TLV3202	LMV393

2.4 System Design Theory

Key subsystems in the design include:

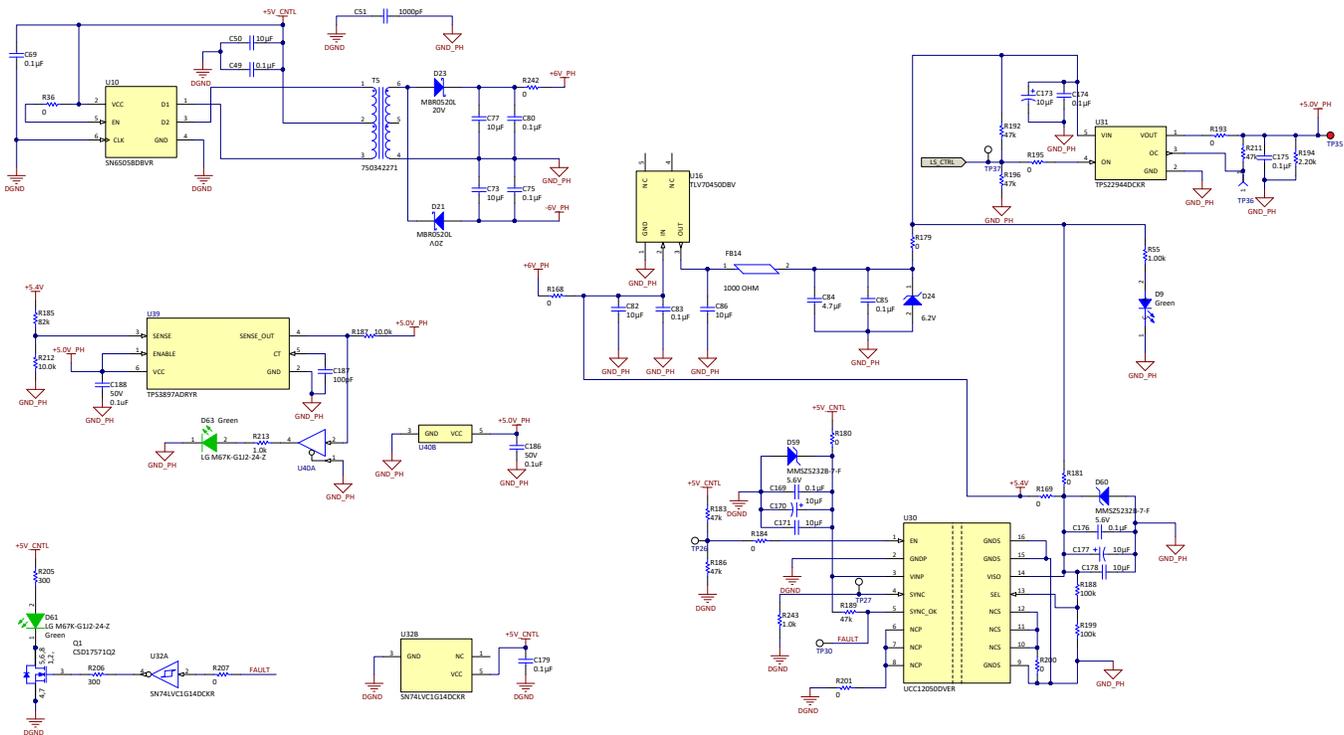
- Isolated supply for voltage measurement
- Isolated supply for current measurement
- Measurement of isolated voltages
- Measurement of isolated currents
- Digital diagnostics of voltage inputs
- Generation of non-isolated supply for the host from 12-, 24-, or 5-V input
- Generation of split-rail supply for scaling the isolation amplifier to ADC input range of ± 10 V

The following sections provide details of the circuit design and implementation:

2.4.1 Isolated Supply for Voltage Measurement

This section provides design details for the devices used to generate isolated power supply for voltage measurement using isolation amplifiers and monitoring of the DC/DC converter unregulated output voltage. A single supply is used to power three isolation amplifiers configured in group isolation mode.

Figure 9. Isolated Power Supply for Group Isolated Voltage Measurement



2.4.1.1 Isolated Supply Generation for Voltage Measurement Using Isolated DC/DC Converter

This section provides design details for generation of isolated supply for voltage measurement including device configuration and functionality.

- The UCC12050 device, an isolated DC/DC converter, is used to generate the required isolated supply for measurement of isolated voltage inputs. It can be configured to generate 5.4 V or 5 V and powers three isolation amplifiers, signal scaling amplifiers, and a digital isolator used for digital diagnostics. In this design, the output is configured for 5.4 V by connecting 100 k Ω between the supply and EN pin. When the DC/DC is configured to generate 5.4 V, an external LDO is used to regulate the output to 5 V. Key considerations for selection of the UCC12050 isolated DC/DC converter include solution simplicity, reliability, isolation, diagnostics, synchronization, and output configurability.
- The TLV70450 LDO is used to generate a fixed 5-V output from 5.4-V input for powering the devices on the sensor side.

Measurement accuracy and repeatability over a wide input range and temperature are the key specifications for analog input modules. The power supply ripple plays an important role in achieving the measurement accuracy and repeatability. When higher accuracy is required over a wide input range and temperature, an LDO is used to regulate the output of the isolated DC/DC converter ensuring lower ripple.

2.4.1.2 UCC12050 Output Configuration

This section provides details for configuring the UCC12050 output voltage based on the application requirement. [Table 19](#) summarizes the options for configuring the output.

Table 19. UCC12050 Functional Modes Configuration

EN	SEL	ISOLATED SUPPLY OUTPUT VOLTAGE (VISO) SETPOINT
HIGH	Shorted to VISO	5.0 V
HIGH	100 k Ω to VISO	5.4 V
HIGH	Shorted to GNDS	3.3 V
HIGH	100 k Ω to GNDS	3.7 V
HIGH	OPEN	UNSUPPORTED
LOW	X	0 V

2.4.1.3 Isolated Supply Digital Diagnostics

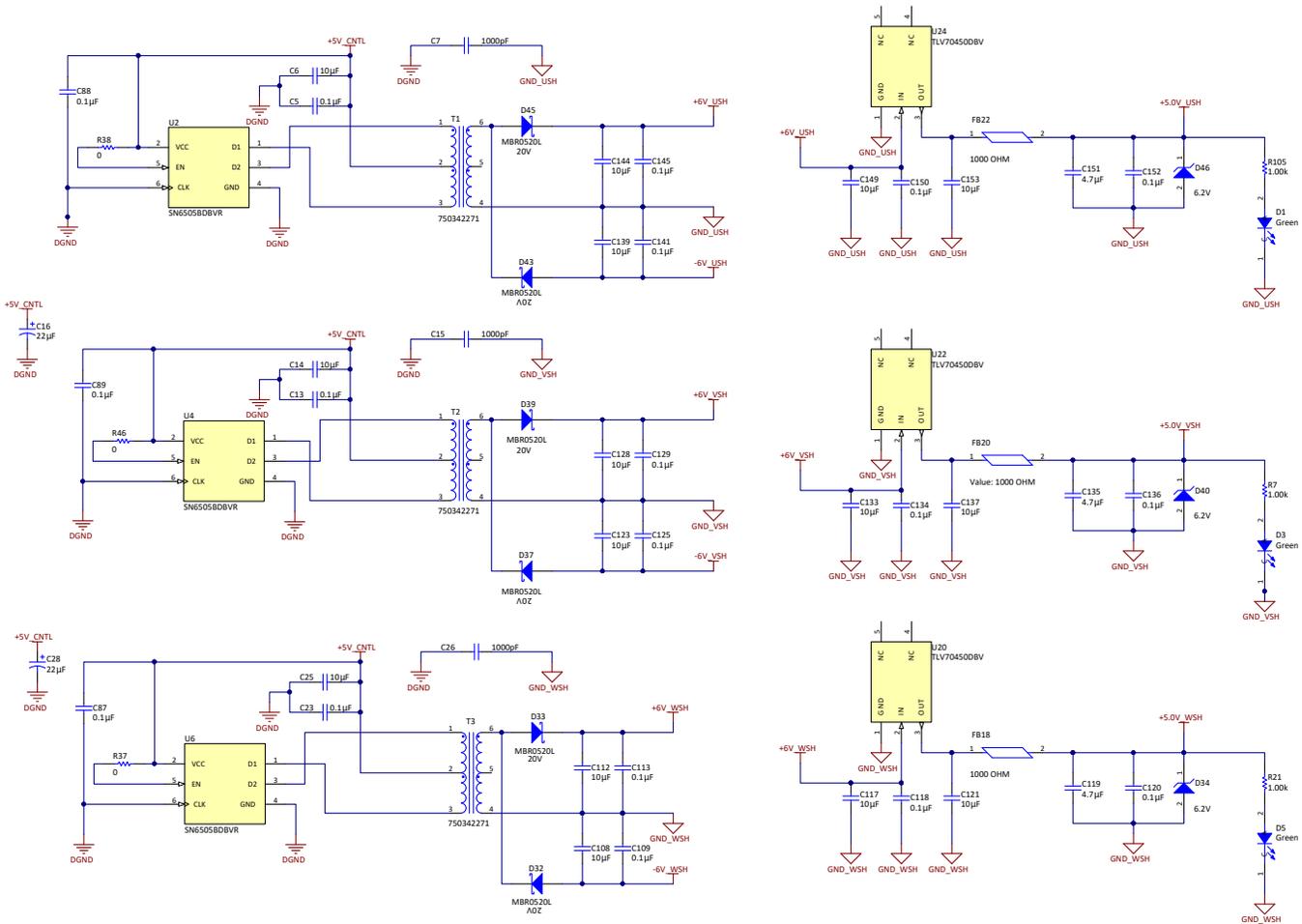
This section provides design details for isolated supply voltage digital diagnostics including monitoring the unregulated voltage level and indicating sync_ok output with the buffer.

- The TPS3897 device is used to monitor the 5.4-V output of the isolated DC/DC converter. It has a threshold of 500 mV and the detection voltage is set to approximately 4.7 V.
- The SN74LVC1G125 device is a buffer with enable. The Sync_Out can be buffered to drive an LED or connected to the host for indicating the status of the DC/DC supply.

2.4.2 Isolated Supply for Current Measurement

This section provides design details for the devices used to generate isolated power supply for current measurement using isolation amplifiers. Three separate supplies (one per channel) are used to power three isolation amplifiers configured in channel isolation mode. The implementation is illustrated in [Figure 10](#).

Figure 10. Isolated Power Supply for Channel Isolated Current Measurement



2.4.2.1 Isolated Supply Generation for Current Measurement Using Transformer Driver

This section provides design details for generation of isolated supply for current measurement including device configuration and functionality.

- The SN6505B device, an isolated transformer driver is used to generate the required isolated supply for measurement of isolated current inputs. Three transformer drivers are used to generate the three supplies used to power three channel isolated current measurement isolation amplifiers. The output of the transformer driver is an unregulated DC output with ripple. The key consideration for selection the SN6505B is the low load current efficiency and radiated emission.
- The TPS70950 device is used to regulate the output of the SN6505B device to 5 V for regulating the transformer driver output and powering the devices on the sensor side to improve measurement performance.

Table 20. Device Mounting Options for Reference Design TIDA-010065 Voltage Measurement Isolation Amplifiers

MOUNTED DEVICES	COMPONENTS TO BE MOUNTED	RESISTOR TO BE UNMOUNTED
AMC1100, AMC1200, AMC1300, AMC1300B, AMC1301	R87, R75, R64, R257, R258, R259	R66, R78, R88
ISO224, ISO224B	R66, R78, R88	R87, R75, R64 R257, R258, R259

2.4.3.2 Gain Scaling of Isolation Amplifier Output

This section provides design details for scaling of the isolation amplifier output using precision or general purpose op amps. An explanation of the implementation follows:

- The OPA2990 general purpose op amp is used to scale the output of the isolation amplifiers to the ADC input range. The gain scaling is $\times 4$ for all the isolation amplifiers with the exception that the scaling is $\times 3$ for the ISO224 device to match the input range up to ± 10 V. Adjust the gain to $\times 2.5$ to increase the ISO224 input range to ± 12 V.
- The OPA2180 precision op amp is used to scale the output of the isolation amplifiers to the ADC input range. The gain scaling is $\times 4$ for all the isolation amplifiers with the exception that the scaling is $\times 3$ for the ISO224 device to match the input range up to ± 10 V. Adjust the gain to $\times 2.5$ to increase the ISO224 input range to ± 12 V.

The choice of gain amplifier depends on the performance requirement over temperature. Precision amplifiers provide improved performance over temperature and general purpose amplifiers provide optimized cost.

2.4.3.3 Voltage Sensor (Potential Divider) Interface

A resistor divider with impedance greater than 1.5 M Ω is used in this design. Five resistors of 332 k Ω are connected in series for dividing the input voltage. The input to the isolation amplifier is derived for different isolation amplifiers using the following resistors values:

- A 1.02-k Ω resistor used for an isolation amplifier with ± 250 -mV input
- A 21.02-k Ω resistor used for isolation amplifier with ± 12 -V input

The use of multiple resistors improves the reliability and also limits the voltage stress on each resistor to be within the specified range including derating requirements during input transient condition as per IEC61000-4-5.

2.4.3.4 Offset Compensation

When a resistor divider is used to measure the voltage input, while using the AMC1300 family of devices, the DC offset might be observed at the output of the isolation amplifiers. This offset can be minimized by adjusting the gain resistor R119. Alternatively, R97 also can be mounted to reduce the output DC offset.

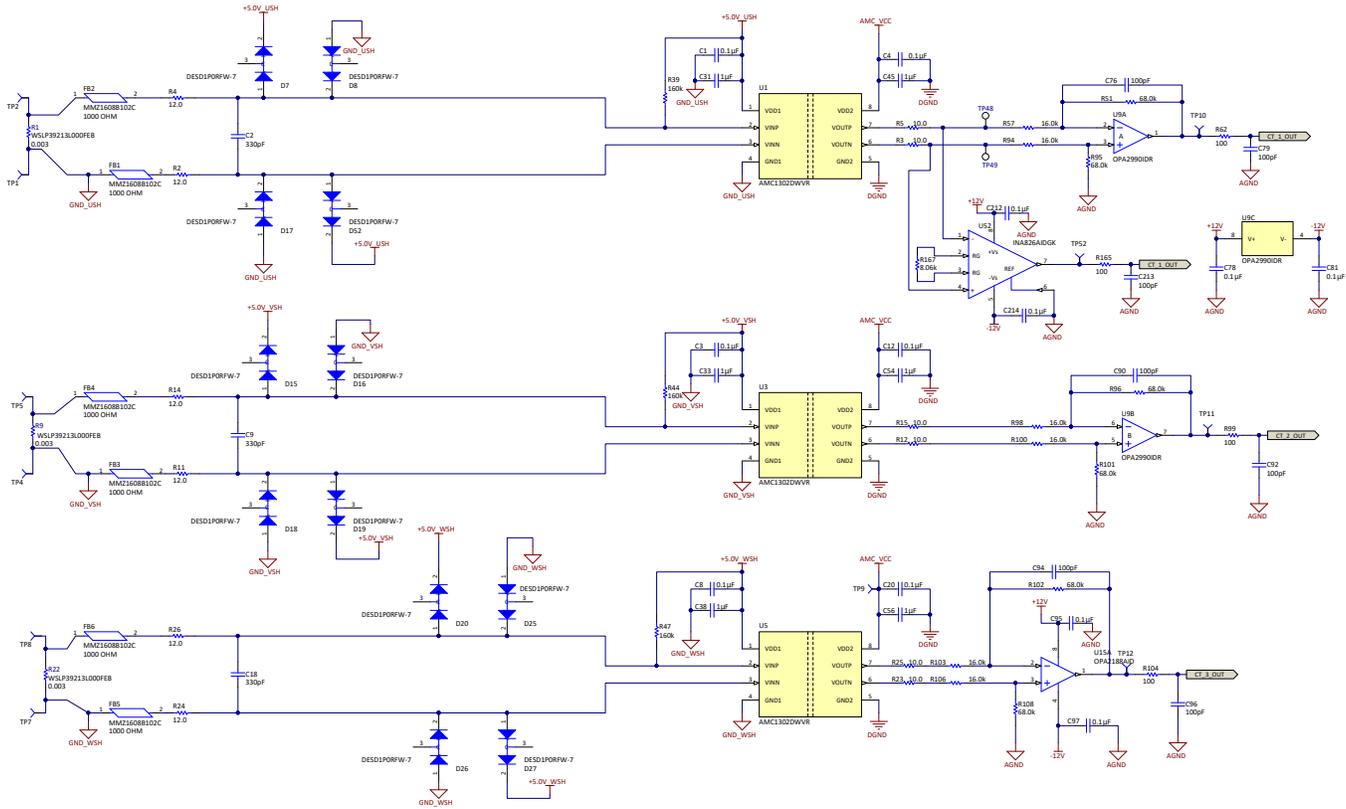
2.4.3.5 Isolation Amplifier Phase Reversal

Resistor dividers do not have phase shift or isolation. The required isolation is provided using isolation amplifiers. The isolation amplifiers do not have 180° phase shift that is provided by a conventional current transformer. When a shunt based approach is used for measurement of current, for the voltage divider output to be in phase, the isolation amplifier output has no phase shift as the reference design shows.

2.4.4 Measurement of Current Inputs

This section provides design details for the devices used for measurement of channel isolated current inputs using isolated amplifiers with a ± 50 -mV input range and using a shunt as the current-sensing element. An addition approach is to scale the isolation amplifier gain to the ADC input range and the device configurations are detailed. The implementation is illustrated in [Figure 12](#).

Figure 12. Channel Isolated Current Measurement



2.4.4.1 Measurement of Isolated Current Inputs

This section provides design details for measurement of channel isolated current inputs using isolation amplifiers including input range and the output gain. An explanation of the implementation follows:

- The AMC1302 device has an input range of ±50 mV with reinforced isolation and the resistor divide output is connected for measuring the input voltage.
- The AMC1300 and AMC1301 devices provide differential output with common-mode voltage, an internal gain of 42 and high CMTI

Lower input range reduces power dissipation due to the resistive losses across the shunt make the solution suitable to measure wide current input ranges providing improved performance.

2.4.4.2 Gain Scaling of Isolation Amplifier Output Using Op Amp

This section provides design details for scaling of the isolation amplifier output using a precision or general purpose op amp. An explanation of the implementation follows:

- The OPA2990 device is a general purpose op amp used to scale the output of the isolation amplifiers to the ADC input range. The gain scaling is x 4 for all the isolation amplifiers with the exception that the scaling is x 3 for ISO224 to match the inputs.
- The OPA2180 precision op amp is used to scale the output of the isolation amplifiers to the ADC input range. The gain scaling is x 4 for all the isolation amplifiers with the exception that the scaling is x 3 for the ISO224 amplifier to match the inputs.

The choice of op amp depends on the performance requirement over temperature. Precision amplifiers provide improved performance over temperature and the general purpose amplifiers provide optimized cost.

2.4.4.3 Gain Scaling of Isolation Amplifier Output Using Instrumentation Amplifier

This section provides design details for the scaling of the isolation amplifier output using a precision instrumentation amplifier. An explanation of the implementation follows:

- Use the INA821 and INA826 precision instrumentation amplifiers for gain scaling. The required gain can be configured using a single resistor improving the performance. Instrumentation amplifiers have low offset and excellent noise performance. The output can be connected to the ADC by disabling the gain scaling op amp output and connecting the instrumentation amplifier output. These are done using resistors.

2.4.4.4 Current Sensor Interface

In this design, a 3-m Ω shunt (Manganin[®] alloy based) is used for current measurement. The voltage drop across the shunt is sensed as a Kelvin connection and interfaced to the isolation amplifier. The isolation amplifier is protected against overvoltage. The use of lower shunt values with increased input current improves the thermal performance and reduces self-heating of the shunt improving measurement accuracy. The current input range is limited by the shunt and the isolation amplifier inputs. When higher input currents are required to be measured, select a lower shunt value.

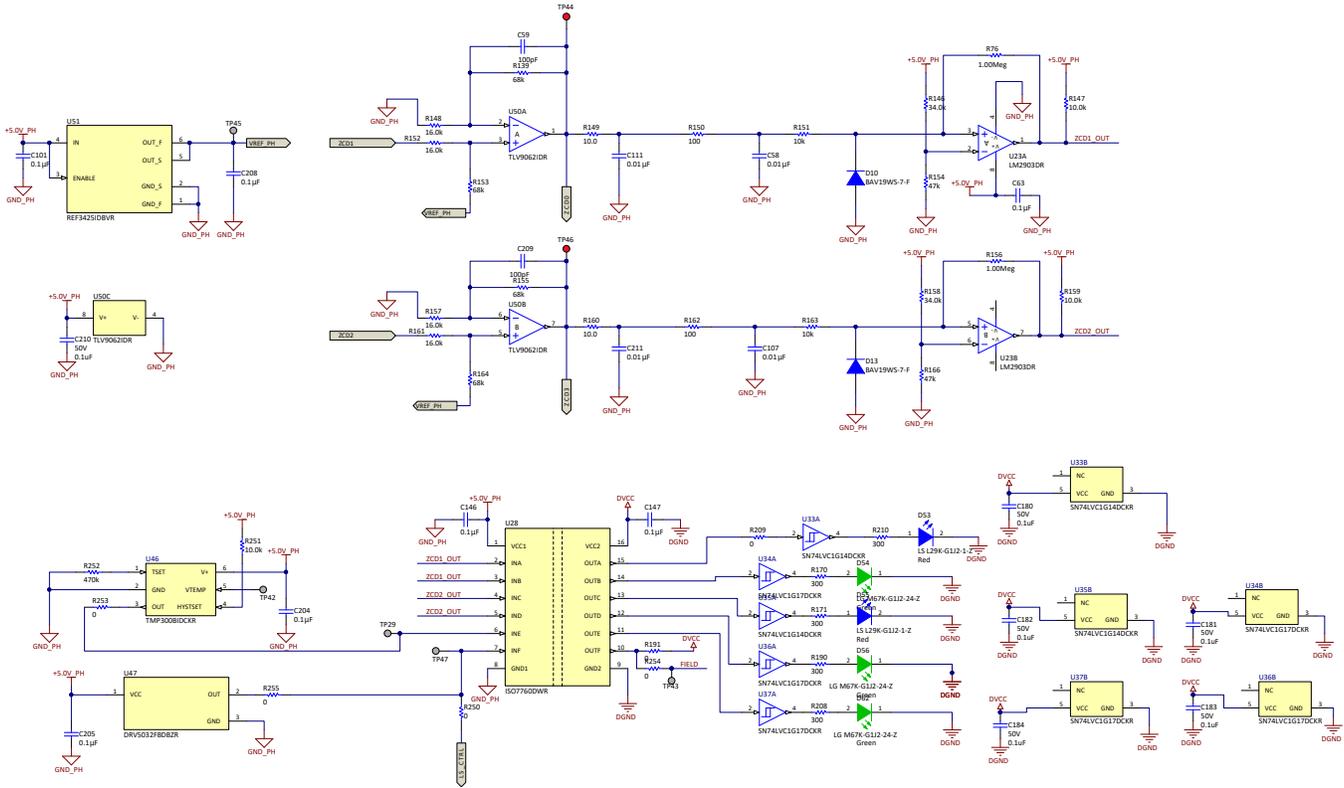
2.4.4.5 Isolation Amplifier Phase Reversal

Shunts do not have phase shift or isolation. The required isolation for the current inputs are provided using isolation amplifiers. The isolation amplifiers do not have 180° phase shift that is provided by a conventional current transformer. When a potential transformer approach is used for measurement of voltage, for the shunt output to be in phase, the isolation amplifier output is reversed as this reference design shows.

2.4.5 Digital Diagnostics Including Input Voltage Presence Detection

This section showcases design details for implementing digital diagnostics of the analog input module including input voltage presence, overtemperature and high magnetic field. An explanation of the implementation follows:

Figure 13. Voltage Input Presence and Environment Digital Diagnostics



2.4.5.1 Buffering and Zero Cross Detection of AC Input Voltages

This section provides design details for zero cross detection by converting the input AC voltage to square wave output. An explanation of the implementation follows:

- The TLV9062 dual-channel general purpose amplifier is used to buffer or provide gain to the resistor divider output before connecting to the comparator. The AC input is level shifted by VCC/2 before feeding to the comparator.
- Two inputs are used in the design and the same can be extended to all the channels.
- The LM2903 dual comparator is used to generate zero cross output from the AC input. The required reference to the comparator is generated using resistor divider and hysteresis is provided to the comparator to avoid multiple waveforms.

2.4.5.2 Alternative Approaches to Setting the Comparator Reference

In this design, the comparator reference is set using the resistor divider and this is a fixed reference. To increase the design flexibility and improve the diagnostics performance, use a programmable DAC. Using DAC can help optimize ADC channel requirements. Table 21 provides details of different DACs that can be considered.

Table 21. Diagnostics DAC Selection

DEVICE	DESCRIPTION
DAC101C081	10-bit micro-power digital-to-analog converter with an I2C-compatible interface
DAC101C085	10-bit micro-power DAC with I2C-compatible interface and external reference
DAC121C081	12-bit micro-power digital-to-analog converter with an I2C-compatible interface
DAC121C085	12-bit micro-power DAC with I2C-compatible interface and external reference

2.4.5.3 Onboard Temperature and Magnetic Field Detection

This section provides design details for detection of onboard overtemperature and the presence of a magnetic field. An explanation of the implementation follows:

- The TMP300 is a low-power, resistor-programmable, digital output temperature switch. The device allows a threshold point to be set by adding an external resistor. The output of the TMP300 device is connected to the digital isolator.
- The DRV5032 is an ultra-low-power, digital-switch, Hall-effect sensor. When the applied magnetics flux density exceeds the magnetic threshold operate point (B_{OP}), the device outputs a low voltage. The output stays low until the flux density decreases to less than the magnetic threshold release point (B_{RP}), and then the output either drives a high voltage or becomes high impedance, depending on the device version.

2.4.5.4 Isolation of ZCD and Diagnostics Sensor Outputs to the Host Using Digital Isolators

This section provides design details for interfacing the zero cross output to the host and providing the required isolation. An explanation of the implementation follows:

- The ISO7760 is a high-speed, robust EMC six-channel digital isolator providing reinforced isolation. The voltage diagnostic inputs, temperature, and magnetic field sensor outputs are connected to the digital isolators.

A range of digital isolator solutions are available to implement diagnostics. Some of the available devices are listed in [Table 22](#).

Table 22. Digital Isolator Selection for Diagnostics

DEVICE	DESCRIPTION
ISO7741	High-speed, low-power, robust EMC quad-channel digital isolator
ISO7740	High-speed, low-power, robust EMC quad-channel digital isolator
ISO7761	High-speed, robust-EMC six-channel digital isolator
ISO7762	High-speed, robust EMC six-channel digital isolator
ISO7841	High-immunity, 100-Mbps, 5.7-kV _{RMS} reinforced quad-channel 3/1 digital isolator

2.4.6.3 Input Reversal and Overload Protection

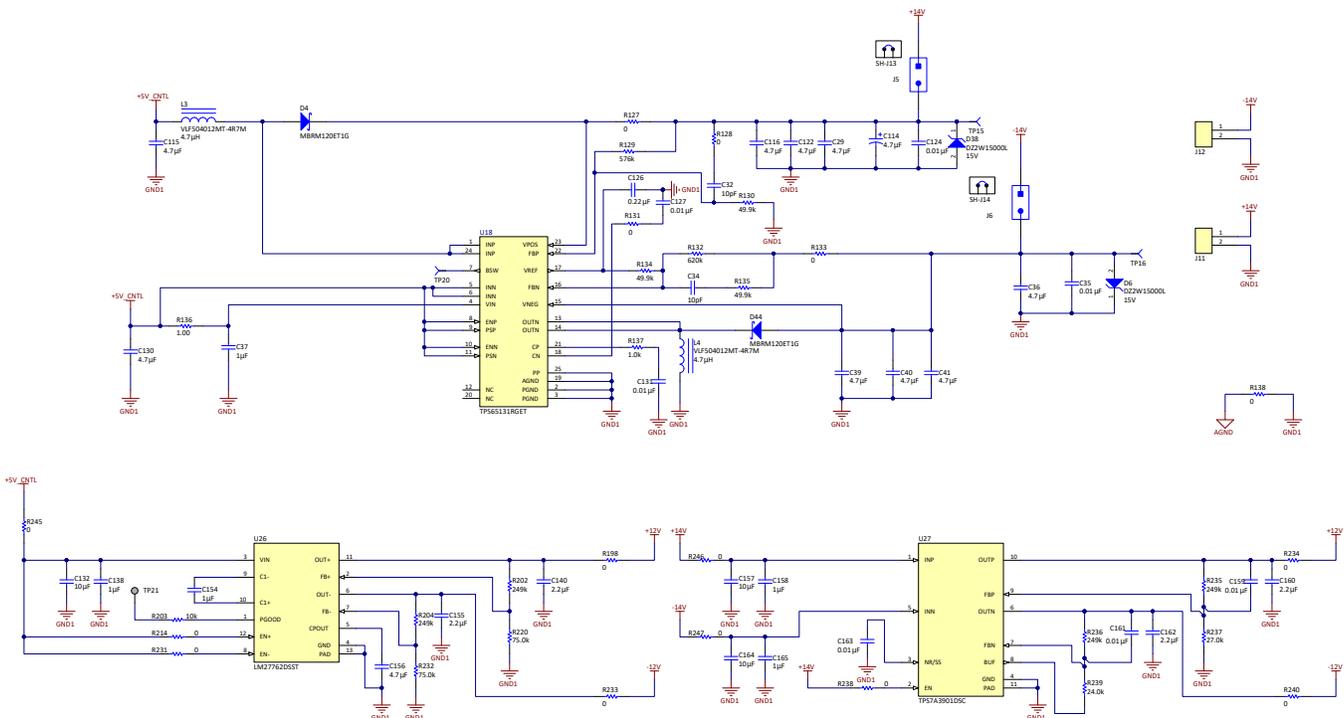
This section provides design details for protecting the DC input against reversal and overload. An explanation of the implementation follows:

- The LM74700-Q1 device is a low I_{OQ} , ideal diode controller used for protection of the AIM against input reversal.
- The TPS26624 device is a 60-V, 800-mA industrial eFuse with integrated reverse polarity protection. The output load current is settable and is set to 250 mA. Resistors are provided to set the currents from 25 mA to 800 mA.

2.4.7 Generation of Split-rail Supplies for Gain Amplifiers

This section provides details of the device configuration to generate the split-rail supply from 5 V and the regulation the split-rail supplies using an LDO to ± 5 V or ± 12 V.

Figure 15. Split-rail Supply Generation With Dual LDO



2.4.8 Board Layout

This section provides power supply recommendations and guidelines for isolated DC/DC supply.

Some of the generic guidelines for configuring the DC/D converter outputs based on application include:

- See the device data sheet for configuring the output, including calculations.
- The board is designed for optimal space and performance. When thermal is a concern, see the device EVM and data sheet and provide the required copper area.

2.4.8.1 Power Supply Recommendations

The recommended input supply voltage (VINP) for the UCC12050 device is from 4.5 V to 5.5 V. To ensure reliable operation, adequate decoupling capacitors must be located as close to supply pins as possible. Put local bypass capacitors between the VINP and GNDP pins at the input, and between the VISO and GNDS at the isolated output supply. Low ESR, ceramic surface mount capacitors are recommended. Put two such capacitors: one with a value of 10 μ F for supply bypassing, and an additional 100-nF capacitor in parallel for high-frequency filtering. The input supply must have an appropriate current rating to support the output load required by the end application.

2.4.8.2 Layout Guidelines

The UCC12050 integrated isolated power solution simplifies system design and reduces the board area usage. Proper PCB layout is important to achieve optimum performance. The layout recommendations follow:

- Place decoupling capacitors as close as possible to the device pins. For the input supply, place the capacitors between pin 3 (VINP) and pin 2 (GNDP). For the isolated output supply, place the capacitors between pin 14 (VISO) and pin 15 (GNDS). This location is of particular importance to the input decoupling capacitor, because this capacitor supplies the transient current associated with the fast switching waveforms of the power drive circuits.
- Because the device does not have a thermal pad for heat-sinking, the device dissipates heat through the respective GND pins. Ensure that enough copper — preferably a connection to the ground plane — is present on all GNDP and GNDS pins for best heat-sinking.
- If space and layer count allow, TI recommends connecting the VINP, GNDP, VISO, and GNDS pins to internal ground or power planes through multiple vias of adequate size. Alternatively, make traces for these nets as wide as possible to minimize losses.
- As a good practice, TI recommends grounding the no-connect pins (NC) to their respective ground planes. Connect pins 6, 7, and 8 to GNDP. Connect pins 10, 11, and 12 to GNDS. This allows more continuous ground planes and a larger thermal mass for heat-sinking.
- A minimum of four layers is recommended to accomplish a low-EMI PCB design. Space inner layers closer than outer layers and then they can create a high-frequency bypass capacitor between GNDP and GNDS to reduce radiated emissions. Ensure proper spacing, both inter-layer and layer-to-layer, is implemented to avoid reducing isolation capabilities. These spacings will vary based on the PCB construction parameters, such as dielectric material and thickness.
- Pay close attention to the spacing between primary ground plane (GNDP) and secondary ground plane (GNDS) on the outer layer of the PCB. The effective creepage and or clearance of the system will be reduced if the two ground planes have a lower spacing than that of the UCC12050 package.
- To ensure isolation performance between the primary and secondary side, avoid placing any PCB traces or copper below the UCC12050 device on the outer copper layers.

For more details see the *Layout* section of the [UCC12050 500-mW, High-Efficiency, Low-Emissions, 5-kV_{RMS} Isolated DC/DC Converter Data Sheet](#).

3 Testing Requirements, and Test Results

This section provides the details of the setup and testing performed on the TIDA-010065 reference design for validating the performance:

- Required hardware and connection
- Functional testing
- Performance testing
- Summary of test results

3.1 Required Hardware and Connections

The following boards and equipment are required, validating the functionality and performance:

- TIDA-010065 AIM with all basic functional tests completed
- Programmable DC voltage source capable of varying voltage from 5 V to 30 V with programmable current limit up to 0.5 A
- Programmable voltage and current source
- ADS8588S EVM with an ADS8588H device mounted and PHI interface card for GUI interface

3.2 Testing and Results

Testing of this reference design includes the following:

- Functional testing
- Performance testing
- EMI testing

3.2.1 Test Setup

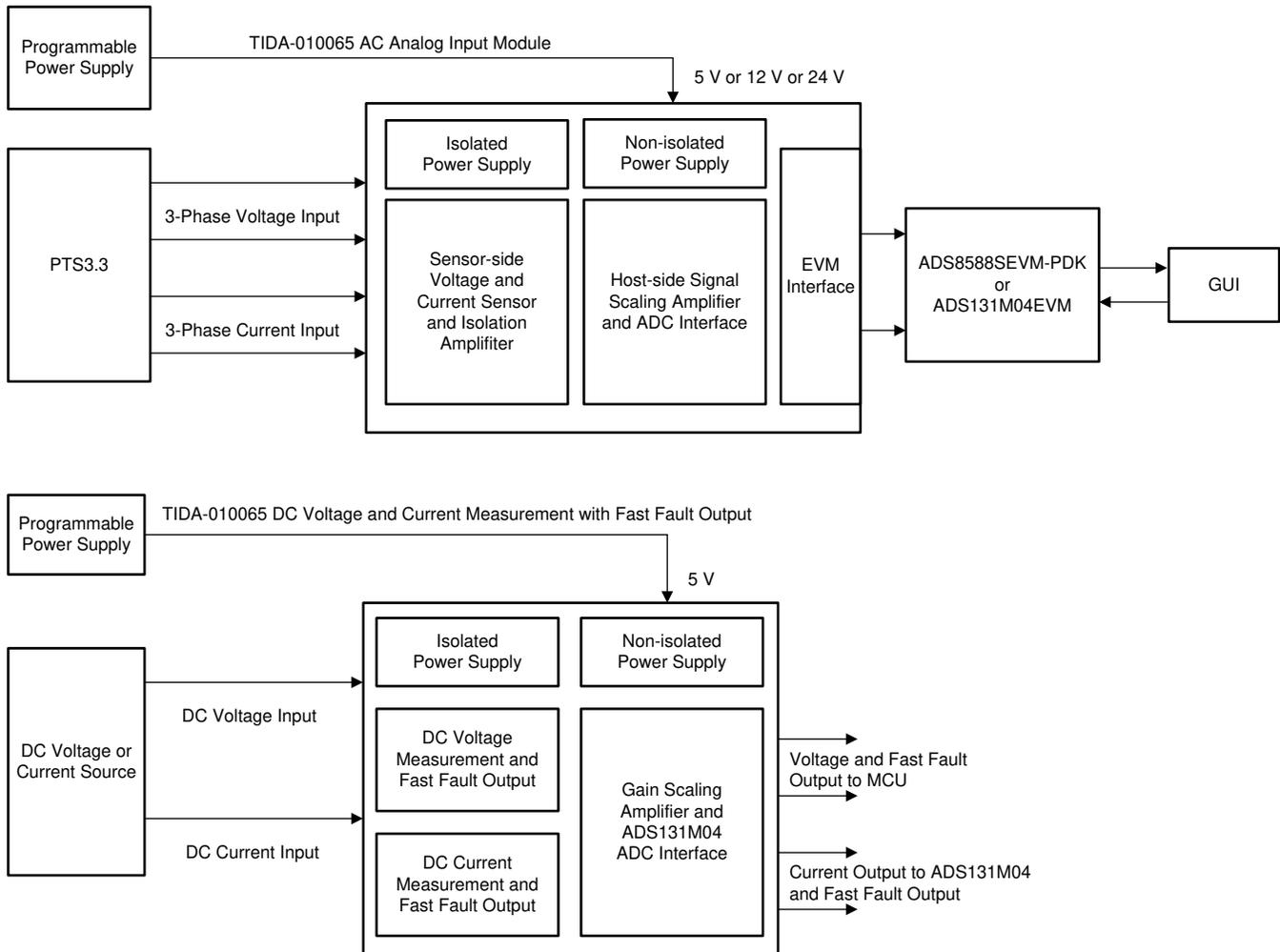
The design is broadly classified into these function blocks:

- Generation of isolated power supply
- Measurement of isolated voltage inputs
- Measurement of isolated current inputs
- Digital diagnostics of voltage inputs and operating environment
- Generation of non-isolated supply

3.2.1.1 Interfacing Between TIDA-010065 AIM, EVMs, and Source

This section provides details of different boards that are interfaced for testing the TIDA-010065 reference design functionality and performance. Figure 16 illustrates the interconnections between multiple boards for testing the functionality.

Figure 16. TIDA-010065 Functional Testing Setup



The setup includes the following:

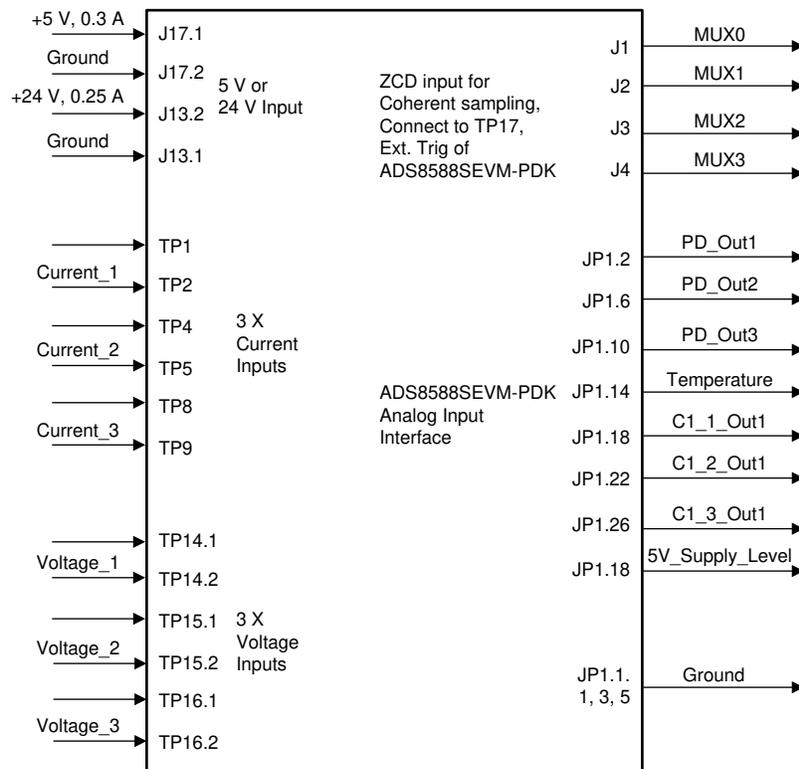
- DC power supply with programmable voltage and current outputs to power the AIM
- ADC interface including EVM and GUI interface for measuring isolated voltage and currents
- Programmable voltage, and current source for performance testing

3.2.1.2 Connections for TIDA-010065 Analog Input Module

This section provides connection details for the following:

- DC input supply for AIM module operation
- AC voltage inputs and current inputs
- ADC interface for performance testing
- ZCD outputs for coherent sampling

Figure 17. TIDA-010065 AIM Connections for Testing



3.2.2 Functional Testing

This section provides details of the functional tests done and test observations.

3.2.2.1 UCC12050 Testing

This section provides details of the tests that were performed on the UCC12050 device.

3.2.2.1.1 Isolated DC/DC Functional Testing

This section provides the test results for the common function of the UCC12050 device including undervoltage lockout (UVLO) and output configuration.

Table 23. Functional Testing and Protection Results

ISOLATED SUPPLY OUTPUT VOLTAGE (VISO) SETPOINT	MEASURED VOLTAGE
5.0 V	4.98
5.4 V	5.37
Device operation UVLO – Rising	4.3
Device shutdown UVLO – falling	3.7

3.2.2.1.2 Output Voltage Configuration and Outputs

Table 24 provides details of the UCC12050 output configurations. The configurations include options to configure the output voltages with head room or without headroom.

Table 24. Device Functional Modes and Observations

EN	SEL	ISOLATED SUPPLY OUTPUT VOLTAGE (VISO) SETPOINT	LOAD CURRENT	INPUT CURRENT	MEASURED VOLTAGE
HIGH	Shorted to VISO	5.0 V	100	173	4.98
HIGH	Shorted to VISO	5.0 V	150	281	3.71
HIGH	100 kΩ to VISO	5.4 V	100	206	5.37
HIGH	100 kΩ to VISO	5.4 V	10	55	5.37
HIGH	100 kΩ to VISO	5.4 V	5	49	5.37
HIGH	Shorted to GNDS	3.3 V	100	152	3.28
HIGH	100 kΩ to GNDS	3.7 V	100	149	3.67
HIGH	OPEN	UNSUPPORTED			
LOW	X	0 V		0	0

The input current of the DC/DC converter varies for different output voltage configurations. Table 25 summarizes the input current for different output configurations

Table 25. Input Current at no Load With Different Output Configuration

SEL CONFIGURATION	OUTPUT (V)	INPUT CURRENT (mA)
100kΩ to VCC	5.37	45
0R to VCC	4.98	50
100kΩ to ground (device warm)	3.68	79
0R to ground (device warm)	3.28	92

3.2.2.1.3 Additional Isolated DC/DC Converter Testing

This section provides details of the tests performed on the isolated DC/DC using a current limited source.

Table 26. DC/DC Converter Performance Results With Current Limited Source

INPUT VOLTAGE (V)	CURRENT LIMIT (mA)	INPUT CURRENT (mA)	OUTPUT SELECT	OUTPUT VOLTAGE (V)	OUTPUT CURRENT (mA)
5	50	49	5	4.97	No load
5	50	44	5.4	5.37	No load
5	120	98	5	4.97	50
5	150	101	5.4	5.37	50
5	230	169	5	4.98	100
5	250	194	5.4	5.37	100
5	230	181	5	3.18	200
5	400	242	5	0.05	short
5	400	242	5.4	0.05	short

3.2.2.2 AC Analog Input Module

This section provides details of the tests done and the test observations for AIM power supplies and comparator outputs used for coherent sampling.

Table 27. AIM Functional Testing

DEVICES	TEST POINT	ACTUAL	MEASURED
TPS26624DRCR Out	C47	24 V	23.92
LMZ14201	J8	5 V	5.02
LM74700 Output	TP18	5 V	4.983
TLV1117LV33	TP25	3.3 V	3.31
TPS65131	J5	P15 V	15.24
TPS65131	J6	N15 V	15.04
TPS7A3901	R234	P12 V	12.21
TPS7A3901	R240	M12 V	12.35
LM27762	R198	P5	4.99
LM27762	R233	M5	4.993
TLV70450 or TPS70950	R105, R7, R21, R55	5 V	4.975 to 5.010
TLV70450 or TPS70950	LED	Check across D1 and D3 and D5 and D9	OK
UCC12050	C177	5.4 V	5.423
UCC12050	Fault	D61	OK
TPS22944	TP35	5 V	4.965
TMP235	TP22	700 to 800 mV	763
LM2903D	J1	D57	Ok
LM2903D	J2	D57	OK
LM2903D	J3	D58	OK
LM2903D	J4	D58	OK
ISO7761	ZCD1Out and ZCD1Out Inv	D53	OK
ISO7761	ZCD1Out, ZCD2Out, ZCD3Out, ZCD4Out	D54, D55, D56, D57	OK

3.2.2.3 Other Hardware Features

This reference design provides additional hardware features used for input current monitoring, overtemperature detection, and magnetic field detection. Table 28 provides the description and observations.

Table 28. Summary of Additional Hardware Features

DEVICES	DESCRIPTION	OBSERVATION
TMP300	Resistor-programmable, up to 18-V capable temperature switch and analog out sensor	OK
DRV5032	Ultra-low power 1.65-V to 5.5-V Hall-effect switch	OK
INA333	Low-power, zero-drift, precision instrumentation amplifier	OK
TMP235	$\pm 2.5^{\circ}\text{C}$ analog output temperature sensor, with 10 mV/ $^{\circ}\text{C}$ gain	OK
TPS3897	Single-channel ultra-small adjustable supervisory circuit with active-high open-drain output	OK

3.3 Performance Testing

This section provides details of the performance tests including the EMI tests that were performed using the TIDA-010065 reference design.

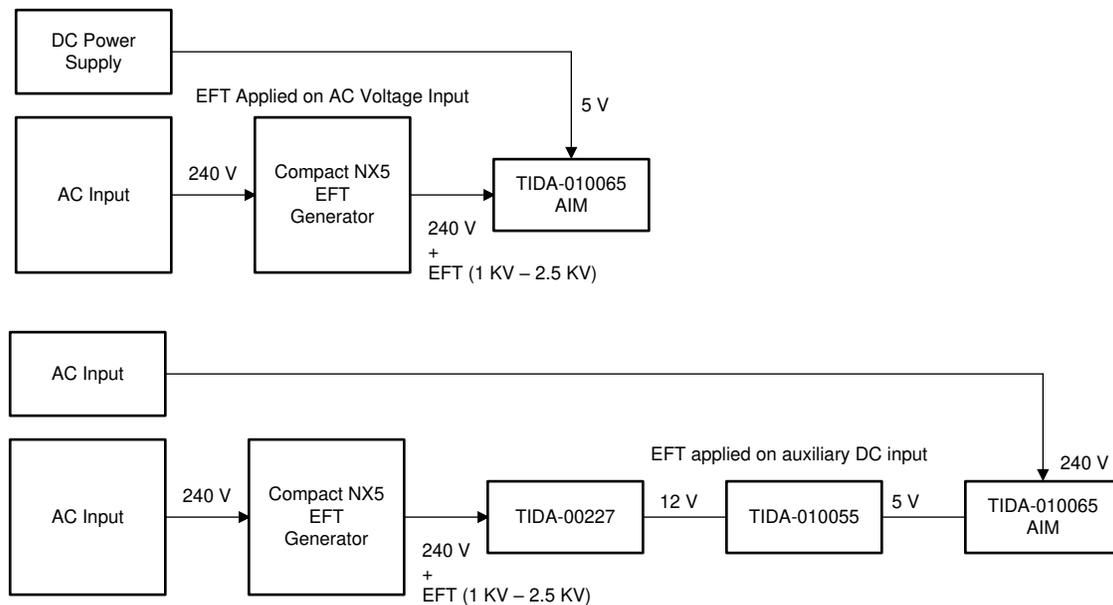
3.3.1 EMI Test Setup for Testing TIDA-010055 Power-Supply Board for Communication Module

The IEC 61000-4-4 is an IEC standard designed to test fast transient or burst immunity. A burst has a single pulse rise time/duration of 5 ns/50 ns from a source impedance of 50 Ω . Bursts of 15 ms duration with a repetition rate of 5 kHz (or 100 kHz) are applied every 300 ms. The standard defines four basic test levels, all with repetition frequencies of 5 or 100 kHz. The level voltage depends on equipment being tested includes power ports with 0.5 , 1, 2, 4 kV and signal or control ports: 0.25, 0.5, 1, 2 kV. Electrical fast transients (EFT) testing was done on the TIDA-010065 boards with the following test conditions:

- EFT applied on the AC voltage inputs
- EFT applied on the DC input supply

Figure 18 provides the details of the setup for testing EFT.

Figure 18. EFT Test Setup for Testing the TIDA-010065



3.3.1.1 EFT Testing on Voltage Inputs

The EFT test was applied on the isolated voltage inputs and the auxiliary power supply was connected without the EFT applied. [Table 29](#) summarizes the test results.

Table 29. Test Results With EFT Applied to AC Voltage Input

TEST TYPE AND STANDARD	VOLTAGE AMPLITUDE	MEASUREMENT BEFORE TEST	MEASUREMENT AFTER TEST
EFT IEC61000-4-4	±1 KV, 5 kHz, 100 kHz for 1 minute	ISO224 output - approximately 4.4 V	ISO224 output - approximately 4.4 V
EFT IEC61000-4-4	±2 KV, 5 kHz, 100 kHz for 1 minute	ISO224 output - approximately 4.4 V	ISO224 output - approximately 4.4 V
EFT IEC61000-4-4	±2.5 KV, 5 kHz, 100 kHz for 1 minute	ISO224 output - approximately 4.4 V	ISO224 output - approximately 4.4 V

3.3.1.2 EFT Testing on DC Supply Input

The EFT on the 5-V auxiliary supply was applied by connecting the output of the TIDA-010055 and TIDA-00227 reference designs. [Table 30](#) summarizes EFT test results for TIDA-010065 AIM applied on the auxiliary DC supply.

Table 30. Test Results With EFT Applied to DC Power Supply Input

TEST TYPE AND STANDARD	VOLTAGE AMPLITUDE	MEASUREMENT BEFORE TEST	MEASUREMENT AFTER TEST
EFT IEC61000-4-4	±1 KV, 5 kHz, 100 kHz for 1 minute	ISO224 output - approximately 4.4 V	ISO224 output - approximately 4.4 V
EFT IEC61000-4-4	±2 KV, 5 kHz, 100 kHz for 1 minute	ISO224 output - approximately 4.4 V	ISO224 output - approximately 4.4 V

3.3.2 Measurement Accuracy Performance Testing

This section summarizes the performance tests that were performed using the TIDA-010065 reference design.

3.3.2.1 Summary of Devices Used for Accuracy Testing

Accuracy tests were done using multiple combinations of isolation amplifiers, general purpose, and precision amplifiers. [Table 31](#) summarizes the devices used for performing accuracy tests.

Table 31. Summary of Devices Tested for Accuracy Performance

DEVICE FAMILY	DEVICES
Voltage measurement using Isolations amplifiers with basic isolation and ±250-mV input range	AMC1100, AMC1200
Voltage measurement using Isolations amplifiers with reinforced isolation and ±250-mV input range	AMC1300, AMC1300B, AMC1301, AMC1301S
Voltage measurement using Isolations amplifiers with reinforced isolation and ±12-V input range	ISO224A, ISO224B
DC voltage measurement using Isolations amplifiers with reinforced isolation and 0- to 2-V input	AMC1311
Current measurement using Isolations amplifiers with reinforced isolation and ±50-mV input range	AMC1302
Transformer driver	SN6505B, SN6501
Isolated DC/DC power supply	UCC12050
Isolated power converters	DCR010505, DCH010505, DCP010505
General purpose amplifiers	OPA2171, TLV2171, OPA2172, TLV9302, OPA2990
Precision amplifiers	OPA2180, OPA2188, OPA2227, OPA2277, OPA2210
Instrumentation amplifiers	INA821, INA826, INA827, INA819
Instrumentation amplifiers	INA188, INA818, INA828
SAR ADC interface with ±10-V input	ADS8588S, ADS8588H
Delta-Sigma ADC interface with ±1.25-V interface	ADS131M04, ADS131M02
Delta-Sigma ADC interface with ±2.5-V interface	ADS131A04, ADS131E08

3.3.2.2 Additional Performance Testing

Additional tests for DC voltage and current measurements were performed. The accuracy measurements were within $\pm 0.3\%$ for voltage input range of 10–400 V (due to the DC source accuracy) and $\pm 0.2\%$ for current input up to 5 A.

3.3.2.3 Graphical User Interface (GUI) for Performance Evaluation

A customized GUI was developed to implement coherent sampling and compute RMS values for all the channels for the ADS8588H device. The GUI is customized and is available for evaluation, based on request. The ADS131M04 device was tested using the GUI available with the TIDA-010037 reference design.

3.3.3 Isolated Voltage Measurement Accuracy Performance Testing

This section provides a summary of the accuracy tests done for the voltage inputs. Measurement accuracy for three voltage inputs are shown.

3.3.3.1 Voltage Accuracy Testing Using 16-Bit SAR ADC

The accuracy test was done by capturing 256 samples per cycle and averaging for 5 cycles. One point gain calibration (common multiplication factor to all the measured values) is applied to compensate for the gain errors. The linearity error was observed to be within $\pm 0.2\%$ for voltages from 2 V to 410 V as [Table 32](#) shows.

Table 32. Isolated DC/DC With LDO + ISO224 Interfaced to ADS8588H

INPUT (AC, 50 Hz)	ACTUAL	CH1	CH2	CH3	CH1 ERROR	CH2 ERROR	CH3 ERROR
2	0.0355	0.035519	0.035522	0.035527	0.054561	0.063337	0.077964
5	0.0887	0.088756	0.08881	0.088748	0.008924	0.069773	-0.00044
10	0.1775	0.177385	0.177506	0.177427	-0.06304	0.004829	-0.03964
20	0.3550	0.354779	0.354968	0.354876	-0.0607	-0.00746	-0.0332
50	0.8875	0.887161	0.887476	0.887215	-0.03648	-0.00102	-0.03039
100	1.7750	1.773986	1.774664	1.774082	-0.05543	-0.01729	-0.05005
150	2.6625	2.661731	2.662821	2.661877	-0.02723	0.013722	-0.02173
200	3.5499	3.547631	3.549054	3.547731	-0.06506	-0.02498	-0.06225
250	4.4374	4.434442	4.435975	4.434564	-0.06725	-0.03271	-0.06449
300	5.3249	5.321795	5.32355	5.321883	-0.05852	-0.02556	-0.05688
375	6.6561	6.654151	6.655893	6.654255	-0.02986	-0.0037	-0.0283
410	7.2774	7.275955	7.27787	7.275882	-0.01956	0.006755	-0.02057

3.3.3.2 Voltage Accuracy Testing Using 24-Bit Delta-Sigma ADC

The accuracy test was done by capturing 80 samples per cycle and averaging for 5 cycles. The PGA gain was set 1 and one point gain calibration (common multiplication factor to all the measured values) is applied to compensate for the gain errors. The linearity error was observed to be within $\pm 0.2\%$ as [Table 33](#) shows.

Table 33. Voltage Measurements Accuracy Tests and Observations for ADS131M04

DEVICE COMBINATION	INPUT RANGE IN V (AC, 50 Hz)	MEASUREMENT ACCURACY OBSERVATIONS
AMC1300 + AMC1300B + AMC1301 + ADS131M04	2 to 380	-0.08 to 0.09
AMC1200 + ADS131M04	5 to 320	-0.08 to 0.09
ISO224 + ADS131M04	5 to 320	-0.06 to 0.05

The ADS131M04 device is a differential ADC and the input range is ± 1.25 V. The common-mode output can be selected from 1.29 V to 2.55 V for the AMC1200 device and is a fixed 1.44 V for the AMC1301 device. The potential divider selection must ensure that the mV input to the isolation amplifier is less than 150 mV peak-to-peak at 320 V. The ADS131M04 differential ADC has an input range of ± 1.25 V. The ISO224 device provides ± 4 -V differential output voltage for ± 12 -V input voltage. The potential divider selection must ensure that the mV input to the isolation amplifier is less than 3.5 V peak-to-peak at 380 V. The common mode is 2.5 V at 5 V VDD. Other delta-sigma ADCs with input voltages in the ± 2.5 -V or ± 4 -V range can be selected for utilizing the complete isolation amplifier range. Some of the delta-sigma ADCs that can be considered are listed in [Table 34](#).

Table 34. Delta-Sigma ADC Input Selection Table

DEVICE	DESCRIPTION	INPUT RANGE
ADS131A0x	2- or 4-channel, 24-bit, 128-kSPS, simultaneous-sampling, delta-sigma ADC	-VREF, Gain to VREF, Gain
	VREF_4V bit = 0	Reference output voltage=2.442 V
	VREF_4V bit = 1, AVDD – AVSS > 4.5 V	Reference output voltage= 4.0 V
ADS131E0x	4-, 6-, and 8-channel, 24-bit, simultaneously-sampling, delta-sigma ADC	-VREF, Gain to VREF, Gain
	VREF_4V bit = 0	Reference output voltage = 2.442 V
	VREF_4V bit = 1, AVDD – AVSS > 4.5 V	Reference output voltage = 4.0 V

Accuracy testing was done using the ADS131E08 device interfaced to the ISO224 isolation amplifier output and the measurement accuracy is summarized in [Table 35](#):

Table 35. Voltage Measurements Accuracy Tests and Observations for ADS131E08

APPLIED INPUT VOLTAGE (AC, 50 Hz)	MEASURED INPUT VOLTAGE	ERROR
3	2.9992	-0.06
10	9.9987	-0.08
30	29.9989	-0.08
150	149.998	-0.04
300	299.996	0.03
360	359.995	0.06

3.3.3.3 PGA Gain Testing With 24-Bit Delta-Sigma ADC

The ADS131M04 device features a programmable gain amplifier (PGA) with gains up to 128. Use PGA to increase the dynamic range. The absolute input voltage specified for Gain = 1, 2, or 4 is specified up to AVDDA. Performance test results for $\times 1$, $\times 2$ and $\times 4$ gain of the PGA is shown in [Table 36](#):

Table 36. ADS131M04 ADC PGA Gain Performance

INPUT VOLTAGE (V) (AC, 50 Hz)	PGA GAIN	ERROR
10	1	-0.042
10	2	-0.031
10	4	-0.089

NOTE: The common-mode input to the ADS131M04 device for gains greater than 4 is AVDD – 1.8 V limiting the application. When the isolation amplifier common-mode output is configured for less than 1.5-V output, use gains greater than four.

3.3.3.4 Summary of Other Accuracy Tests Done (With LDO)

Accuracy test for voltage inputs with a different combination of isolation amplifiers and gain scaling amplifiers were performed and the results are summarized in [Table 37](#). The output of the isolated supply was regulated using LDO to minimize the output ripple and connected to the isolation amplifier. A change in the initial DC offset value was observed for precision and general purpose amplifiers that was computed and subtracted from the measured value before computing the RMS value. The measurement accuracy for all combinations are shown after applying a single point gain calibration and the errors were observed to be within $\pm 0.2\%$. [Table 37](#) provides details of the performance tests done and test observations.

Table 37. Voltage Measurements Accuracy Tests and Observations

DEVICE COMBINATION	INPUT RANGE IN V (AC, 50 Hz)	MEASUREMENT ACCURACY OBSERVATIONS
AMC1300 + AMC1300B + AMC1301 + OPA2188 + OP2180 + SN6505B + TLV70450 + ADS8588H (Channel 1)	2 V to 330 V	-0.06 to 0.06
AMC1300 + AMC1300B + AMC1301 + OPA2188 + OP2180 + UCC12050 + TLV70450 + ADS8588H (Channel 2)	2 V to 330 V	-0.07 to 0.06
AMC1100 + AMC1200 + OPA2227 + OPA2277 + UCC12050 + TLV70450 + ADS8588H (Channel 1)	2 V to 330 V	-0.06 to 0.05
AMC1100 + AMC1200 + OPA2188 + OPA2180 + UCC12050 + ADS8588H (Channel 2)	2 V to 330 V	-0.06 to 0.05
ISO224A + ISO224B + OPA2227 + OPA2277 + UCC12050 + TLV70450 + ADS8588H (Channel 1)	2 V to 410 V	-0.07 to 0.06
ISO224A + ISO224B + OPA2180 + OPA2188 + UCC12050 + TLV70450 + ADS8588H (Channel 2)	2 V to 410 V	-0.07 to 0.06
ISO224A + ISO224B + OPA2180 + OPA2188 + UCC12050 + ADS8588H (amplifier gain changed to 2.5)	3 V to 480 V	-0.07 to 0.05

NOTE: The DC offset was computed for 64K samples and the DC offset was subtracted from all the measurements. Accuracy measurement tests in some of the selected combinations were repeated 3–5 times to test for repeatability. No change in measurement accuracy was observed.

3.3.3.5 Summary of Other Accuracy Tests Done (Without LDO)

Accuracy test for voltage inputs with a different combination of isolation amplifiers and gain scaling amplifiers were performed and the results are summarized in [Table 38](#). The output of the isolated supply was directly connected to the isolation amplifiers. The measurement accuracy for all combinations are shown after applying a single point gain calibration and the errors were observed to be within $\pm 0.2\%$. [Table 38](#) provides details of the performance tests done and test observations.

Table 38. Voltage Measurements Accuracy Tests and Observations Without Using LDO

DEVICE COMBINATION	INPUT RANGE IN V (AC, 50 Hz)	MEASUREMENT ACCURACY OBSERVATIONS
ISO224A + ISO224B + OPA2180 + OPA2188 + UCC12050 + ADS8588H	2 V to 410 V	-0.07 to 0.06
ISO224A + ISO224B + OPA2180 + OPA2188 + UCC12050 + ADS8588H (amplifier gain changed to 2.5)	3 V to 480 V	-0.06 to 0.05

NOTE: The DC offset was computed for 64 k samples and the DC offset was subtracted from all the measurements. Accuracy measurement tests in some of the selected combinations were repeated 3–5 times to test for repeatability. No change in measurement accuracy was observed.

3.3.4 Isolated Current Measurement Accuracy Performance Testing

This section provides summary of the accuracy tests done for the current inputs. Measurement accuracy for 3 current inputs are shown:

3.3.4.1 Current Measurement With AMC1302 + OPA2180 Interfaced to ADS8588H

The accuracy test was done by capturing 256 samples per cycle and averaging for 5 cycles. One point gain calibration (common multiplication factor to all the measured values) is applied to compensate for the gain errors. The linearity error was observed to be within $\pm 0.2\%$ for currents from 0.04 A to 12.5 A as [Table 39](#) shows.

Table 39. AC Current Measurement Accuracy

AC INPUT (AC, 50 Hz)	ACTUAL OUTPUT	CH7	CH6	CH5	CH7 % ERROR	CH6 % ERROR	C5 % ERROR
0.04	0.02091	0.021	0.021	0.021	-0.040	0.004	-0.024
0.1	0.05228	0.052	0.052	0.052	-0.062	-0.044	-0.013
0.25	0.13069	0.131	0.131	0.131	0.009	-0.024	-0.044
0.5	0.26138	0.261	0.261	0.261	-0.006	-0.055	-0.040
1	0.52275	0.523	0.523	0.523	0.013	-0.042	-0.036
2.5	1.30688	1.307	1.307	1.307	0.045	-0.017	-0.016
5	2.61375	2.615	2.614	2.614	0.064	0.006	0.014
7.5	3.92063	3.921	3.921	3.920	0.014	-0.001	-0.024
10	5.22750	5.227	5.226	5.224	-0.018	-0.030	-0.061
12.5	6.53438	6.531	6.529	6.531	-0.052	-0.075	-0.046

NOTE: The DC offset was computed for 64 k samples and the DC offset was subtracted from all the measurements.

3.3.4.2 Summary of Other Accuracy Tests Done

Accuracy tests for current inputs with different combination of gain scaling amplifiers including precision amplifiers and general purpose amplifiers were performed and the results are summarized in [Table 40](#). A change in the initial DC offset value was observed for precision and general purpose amplifiers that was computed and subtracted from the measured value before computing the RMS value. The measurement accuracy for all combinations of devices are shown after applying a single point gain calibration and the errors were observed to be within $\pm 0.2\%$. [Table 40](#) provides details of the performance tests done and test observations.

Table 40. AC Current Measurements Accuracy Tests and Observations

DEVICE COMBINATION	INPUT RANGE WITH 50 Hz (A)	MEASUREMENT ACCURACY RANGE MAX OF THREE CHANNELS (%)
AMC1302 + SN6505B + OPA2188 + TLV70450 + ADS8588H	0.04 to 12.5	-0.06 to 0.06
AMC1302 + UCC12050 + OPA2180 + TLV70450 + ADS8588H	0.04 to 12.5	-0.05 to 0.06
AMC1302 + SN6505B + OPA2990 + TLV70450 + TPS70950 + ADS8588H	0.04 to 12.5	-0.07 to 0.06
AMC1302 + SN6505B + OPA2171 + TLV70450 + TPS70950 + ADS8588H	0.04 to 12.5	-0.07 to 0.06
AMC1302 + SN6505B + INA821 + TLV70450 + ADS8588H	0.04 to 12.5	-0.04 to 0.05
AMC1302 + SN6505B + INA826 + TLV70450 + ADS8588H	0.04 to 12.5	-0.04 to 0.05

NOTE: The DC offset was computed for 64 k samples and the DC offset was subtracted from all the measurements. Accuracy measurement tests in some of the selected combinations were repeated 3–5 times to test for repeatability. No change in measurement accuracy was observed.

3.4 Summary of Test Results

Table 41 summarizes the tests that were performed on the AIM TI reference design and the observation of the tests.

Table 41. Summary and Observations of the Tests Performed

SERIAL NUMBER	PARAMETERS	OBSERVATIONS
1	24-V input with eFuse and DC/DC converter with 5-V output	OK
2	5-V input with input reversal	OK
3	3.3-V generation from 5 V using LDO or DC/DC	OK
4	Measurement of input current using Instrumentation amplifier	OK
5	Generation of split-rail supply and regulation to ± 5 V and ± 12 V	OK
6	Generation of isolated supply for voltage inputs	OK
7	Isolated supply monitoring and digital diagnostics	OK
8	Measurement of isolated voltage inputs and gain scaling	OK
9	Generation of isolated supply for current inputs	OK
10	Measurement of isolated current inputs and gain scaling	OK
11	Generation of Zero cross output using gain scaling amplifier output for voltages	OK
12	Generation of 5-V reference	OK
13	Gain scaling of Voltage and Current outputs from isolation amplifier	OK
14	Gain scaling amplifier interface to ADC	OK
15	Performance testing with SAR and delta-sigma ADCs	OK
16	Generation of ZCD for input voltage presence detection	OK
17	Interface of ZCD to digital isolators for digital diagnostics	OK
18	Temperature and magnetic field digital diagnostics	OK

3.4.1 Power Supply Related Reference Designs for Protection Relay Modules

Use these TI reference designs to design the power architecture for a modular protection relay with pluggable modules, multifunction relay, terminal unit, and other grid end equipment requiring wide input operation, isolated or not isolated output with high efficiency, optimized size and cost.

Table 42. Power Architecture and Focused Reference Design

REFERENCE DESIGN	FOCUS MODULE	DESCRIPTION
TIDA-00127	Auxiliary power supply module	Wide input AC/DC power supply with supply override time of 50 ms or more and 30-W output
TIDA-00227	Auxiliary power supply module	Wide input AC/DC power supply with supply override time of 50 ms or more and 12-W output
TIDA-00300	AC analog input module, communication module, DC analog input/output module	Isolated power supply using a DC/DC converter with integrated FET, DC/DC power module, Flyback DC/DC converter and transformer driver for analog input/output, binary input, and communication module
TIDA-010011	Processor module	Non-isolated power supply architecture using a DC/DC converter with integrated FET, DC/DC with integrated inductor, PMIC, DC/DC in hot rod package for processor module with high efficiency and fast load transient response
TIDA-010055	AC analog input module, communication module, DC analog input/output module	Non-isolated power supply using a DC/DC converter with integrated FET, DC/DC with integrated inductor, DC/DC in hot rod package for analog input/output, binary input, and communication module
TIDA-010008	AC analog input module, communication module, DC analog input/output module	Approaches for protecting AC or DC analog input, DC analog output, AC or DC binary input, digital output with a high-side or low-side driver, LCD bias supply, USB interfaces (power and data), and onboard power supplies with 24-, 12- or 5-V input

4 Design Files

4.1 Schematics

To download the schematics for each board, see the design files at [TIDA-0010065](#).

4.2 Bill of Materials

To download the bill of materials (BOM) for each board, see the design files at [TIDA-010065](#).

4.3 PCB Layout Recommendations

To download the layout prints for each board, see the design files at [TIDA-010065](#).

4.4 Altium Project

To download the Altium Designer® project files for each board, see the design files at [TIDA-0010065](#).

4.5 Gerber Files

To download the Gerber files for each board, see the design files at [TIDA-010065](#).

4.6 Assembly Drawings

To download the assembly drawings for each board, see the design files at [TIDA-0010065](#).

5 Related Documentation

See the following documents during design and testing of the power supplies for communication and analog IO modules:

- Texas Instruments, [±480-V isolated voltage-sensing circuit with differential output application report](#)
- Texas Instruments, [ISO224 Fail-Safe Output Feature Application Report](#)
- Texas Instruments, [High voltage isolation quality and reliability for AMC130x white paper](#)

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6 Terminology

I/O — Input or Output

AMI— Analog input module

ZCD — Zero cross detector

CT — Current Transformer

UVLO — Undervoltage lock out

EFT —Electrical fast transients

AFE —Analog Front End

IEC —INTERNATIONAL ELECTROTECHNICAL COMMISSION

PD — Potential divider (Resistor divider)

7 About the Authors

KALLIKUPPA MUNIYAPPA SREENIVASA is a systems architect at Texas Instruments where he is responsible for developing reference design solutions for the industrial segment. Sreenivasa brings to this role his experience in high-speed digital and analog systems design. Sreenivasa earned his bachelor of engineering (BE) in electronics and communication engineering (BE-E&C) from VTU, Mysore, India.

AMIT KUMBASI is a systems architect at Texas Instruments Dallas where he is responsible for developing subsystem solutions for Grid Infrastructure within Industrial Systems. Amit brings to this role his expertise with defining products, business development, and board-level design using precision analog and mixed-signal devices. He holds a master's in ECE (Texas Tech) and an MBA (University of Arizona).

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