Design Guide: TIDA-00420

ADC-Based, Digitally-Isolated, Wide-Input, 16-Channel, AC/DC Binary Input Reference Design

TEXAS INSTRUMENTS

Description

This reference design showcases a cost-optimized and scalable ADC-based AC/DC Binary Input Module (BIM) architecture with reinforced isolation. The 16 channels of a 10- or 12-bit SAR ADC are used for sensing multiple binary inputs. The cost-optimized op amps, in addition to keeping the cost per-channel low, provide optimal signal conditioning for each input. A digital isolator (basic or reinforced) is used to isolate the host MCU or processor. A provision is available to measure temperature, humidity, and magnetic field for diagnostics. A reinforced isolation DC/DC power supply with configurable output provides the required supply for the binary module.

Resources

TIDA-00420	Design Folder
ADS7953, ADS7957, ADS7128	Product Folder
UCC12040, UCC12050	Product Folder
ISO6741, ISO1640, ISO7710	Product Folder
TLV6001, TLV6002, TLV70450	Product Folder
REF3425, REF5025	Product Folder
TPS25921A, LMZM23601	Product Folder

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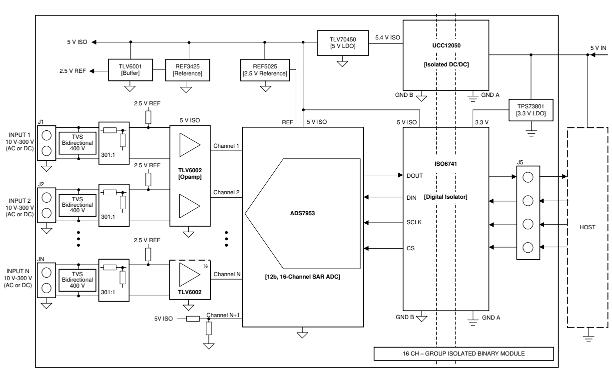
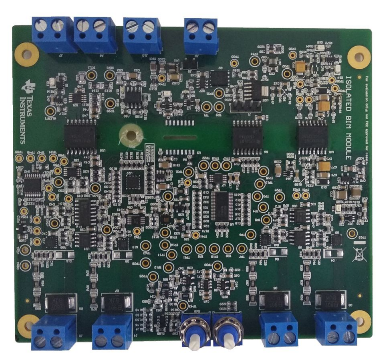
Features

- Scalable input AC/DC binary input module with ADC front end
  - ADS795x product family supports 4, 8, 12, or 16 channels in different packages
  - ADS7128 product family support programmable threshold setting using internal digital comparator
- Digital isolator based interface isolation
- Isolated DC/DC based power supply to isolate the host from the sensor side
- Improved system reliability from use of digital isolators over optocoupler based solution
- Wide input range from 10 V to 300 V and supports measurement in AC or DC input voltages
- Measurement of input voltage provides provision for programmable threshold
- Device selection optimized for low-cost per channel

Applications

- Binary input module
- Multifunction relay
- Merging unit
- Terminal unit
- Power quality analyzer





1 System Description

1.1 Binary Inputs or Digital Inputs

The inputs to the protection relay or substation controllers are called under different names:

- Binary input
- Digital input
- Control input
- Indication input

The names are based on the function performed. These inputs are referred to as binary inputs in this design guide. Binary inputs are sensed in a wide range of applications. The binary inputs are designed as one or more modules and based on applications with differing specifications unique to OEMs. A summary of some of the applications, functionalities, and specifications are shown in Section 1.1.1. Generally, optocouplers are used to achieve galvanic isolation between these inputs and internal circuitry. Each module typically consists of 4, 8, 16, or 32 binary inputs. Inputs may be shared to achieve *group isolation* or separate for *channel isolation* depending upon the application.

1.1.1 Binary Input Application Functionality

Some grid applications use binary inputs for the following functionalities:

- Substation battery monitoring
- Bay or substation interlocking
- Breaker status indication
- General interrogations
- LED test
- Diagnostics (self-test)
- Fault indication (alarm)
- Configuration change (operated with new settings to perform different functionality)

Common Specifications

- AC/DC input voltages: 24 V, 48 V, 110 V, and 230 V
- Basic isolation rating of 3 kV for signal and power
- Wide operating temperature range
- Threshold for assured and uncertain operation
- Response or reset time (software provides de-bounce time)
- Power consumption when energized
- Internal transient limiting protection for I/O terminals

1.2 Approaches to Binary Input Module Design

A traditional approach to binary input module design uses a combination of a resistor divider, Zener based reference, and an optocoupler to sense binary inputs. Based on the input rating, the Zener current is set to vary the voltage level being detected. This approach can be group or channel isolated with no change in design. This approach has larger variation in threshold voltages and drift overtemperature. The optocoupler performance over time and reliability is also a concern.

1.2.1 ADC Versus MCU Based Binary Input Module (BIM)

Some of the key advantages offered by ADC based BIM include:

Channel Scalability: The required number of binary inputs can be scaled easily by adding an ADC with minimum design efforts.

Performance scaling: Choice to scale between 10-bit and 12-bit provides flexibility to optimize performance in terms of measuring a wider input with higher accuracy.

Cost optimization: Use of ADC based approach optimizes onboard resources resulting in cost optimization.

Additional features: Based on ADC selection, additional feature like RMS computation, and digital thresholding with comparator are available. This reduces overhead on the host processor.

1.3 Measurement of Wide Inputs With Programmable Thresholds

An alternative approach to binary input module design is to use one of the two following solutions:

1. **MCU with internal ADC + digital isolation + isolated supply**

   A MCU based approach is showcased in TIDA-00847. Some of the advantages include scalability in features and reduction of host processing requirements. MCU based inputs have limitations in terms of ADC resolution scalability and the number of channels. The use of external ADC provides flexibility in choosing the number of channels and resolution.

   An ADC based approach provides multiple advantages over an MCU based approach including scalability in terms of channels and resolution making it simpler to design. The use of an ADC with internal computation and thresholding capabilities simplifies host processing.
2. **External ADC + digital isolation + isolated supply**

   This ADC based approach measures the input voltage, converts to digital sample value, and interfaces to the host to compute the parameters and compare against a set threshold to detect the binary input status. In some applications, an indication is also provided.

   Some of the key advantages with this approach includes wide input measurement, improved accuracy, scalability and improved isolation reliability due to use of digital isolators.

   This approach is optimized for group isolated module design where multiple inputs share a common reference. Higher channels means more cost optimization.

2 Design Features

The AC/DC binary input module measures the input voltage and converts the sampled values into ADC counts. The ADC counts are communicated to the host for further processing.

2.1 Electrical Specifications

Table 2-1. AC/DC Binary Input — Electrical Specifications

SERIAL NUMBER	PARAMETER	DESCRIPTION	COMMENT
1	Number of inputs	12–16	All inputs share common ground.
2	Input voltage range	10–300 V AC/DC	
3	Input voltage frequency	DC, 50 Hz and 60 Hz	
4	Measurement resolution	10-, 12-bit	Module can be configured for 10- or 12- bit configuration
5	Input voltage measurement accuracy	±1%	
6	Response time	< 1 ms DC, < 20 ms AC	Customer implemented
7	Isolator type	Digital Isolator	3.3-V isolated power supply is generated internally on the module.
8	Electrical isolation level	> 5 kV_{RMS}	

2.2 Block Diagram

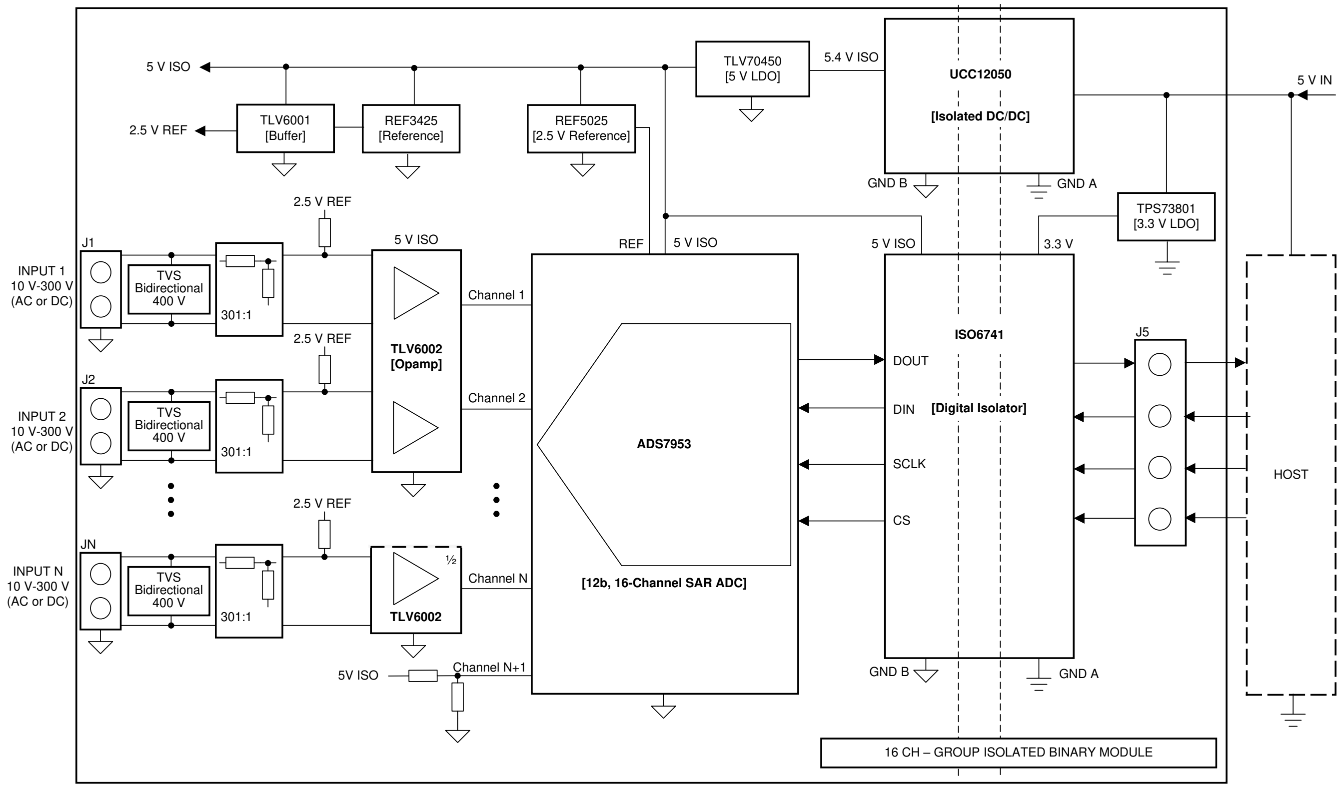


Figure 2-1. Block Diagram of ADC-based Binary Input Module

2.2.1 Analog-to-Digital Converter (ADC)

2.2.1.1 ADS795x SAR ADC Family

The ADS795x family of SAR ADCs has been considered in this design for its array of options providing ease-of-scalability for the user. Key configurations allow for system solutions of 4, 8, 12, and 16 AC/DC channels. System resolution can be adjusted by considering the 10-bit or 12-bit ADC option for desired accuracy. A REF5025 or REF3425 external reference can be used for the purpose of level shifting as well as driving the ADC reference input. A reference provides input conversion accuracy for the ADC.

Other ADC features Include:

- Wide supply voltage range: 2.7 V–5.25 V
  - Power-down current: 1 µA
- Low-power consumption: 14.5 mW
- SPI for easy connection to host processor
- Small package size: 32-pin VQFN (4 × 4 mm)
- Power down feature for power saving

2.2.2 Protection and Signal Conditioning

- **Input Protection:** The TVS diode is used for protecting the binary input module against transient inputs. Package selection is critical to ensure the device has low leakage with temperature variation.
- **Signal Conditioning:** The binary input voltage applied is divided by a resistor divider, which presents a constant resistance to the binary input. Multiple resistors are used to ensure the resistors reliably withstand the maximum input voltage. The output of the resistor divider is fed to the TLV6002 for signal scaling.

2.2.3 Digital Isolator

2.2.3.1 Host (SPI) Interfacing Using the ISO6741

The binary input module is isolated from the host interface. The ISO6741 reinforced digital isolator has been considered to achieve the required isolation. The high performance, quad-channel isolator provides a cost-optimized solution for communicating SPI data from the ADC to the host processor while shielding from noise currents.

2.2.4 DC Power Supply Isolator

The isolated DC power for the ADC, digital isolator, and the signal conditioning circuitry used for sensing the status of the binary inputs are generated using an isolated UCC12050 DC/DC converter. The reinforced isolated converter was selected to achieve 5 kV_{RMS} of isolation rating and supply a well-regulated output to core components. Integrated protection features such as short-circuit recovery and thermal shutdown increase overall system robustness. The host provides the 5-V nominal power supply voltage for the binary input module.

2.2.5 Design Alternative: ADC With Digitally Programmable Threshold

In applications requiring basic isolation and minimum off-the-shelf processing, consider using the ADS7128 (12-bit, 8-channel SAR ADC), ISO1640 (2-channel bidirectional I2C digital isolator), and ISO7710 (1-channel digital isolator for the ALERT function).

The ADS7128 ADC (see Figure 2-2) features an analog watchdog, enabling the use of a per channel programmable threshold. Individual thresholds can be programmed to alert the host MCU when a binary input reaches a desired voltage level, freeing the host to do operations elsewhere until notified, for increased processor bandwidth. The ISO1640 and ISO7710 digital isolators support I2C interfacing and a 3-kV_{RMS} isolation rating (basic isolation).

Unlike a typical optocoupler solution, a module implementing this threshold detection technology will have the ability to support AC/DC inputs of varying voltage levels with a single board. A user can easily program their desired threshold values and duplicate the design across grid sensing applications. The design has the added benefit of simplified implementation, increased scalability, and a reduction of component degradation over time.

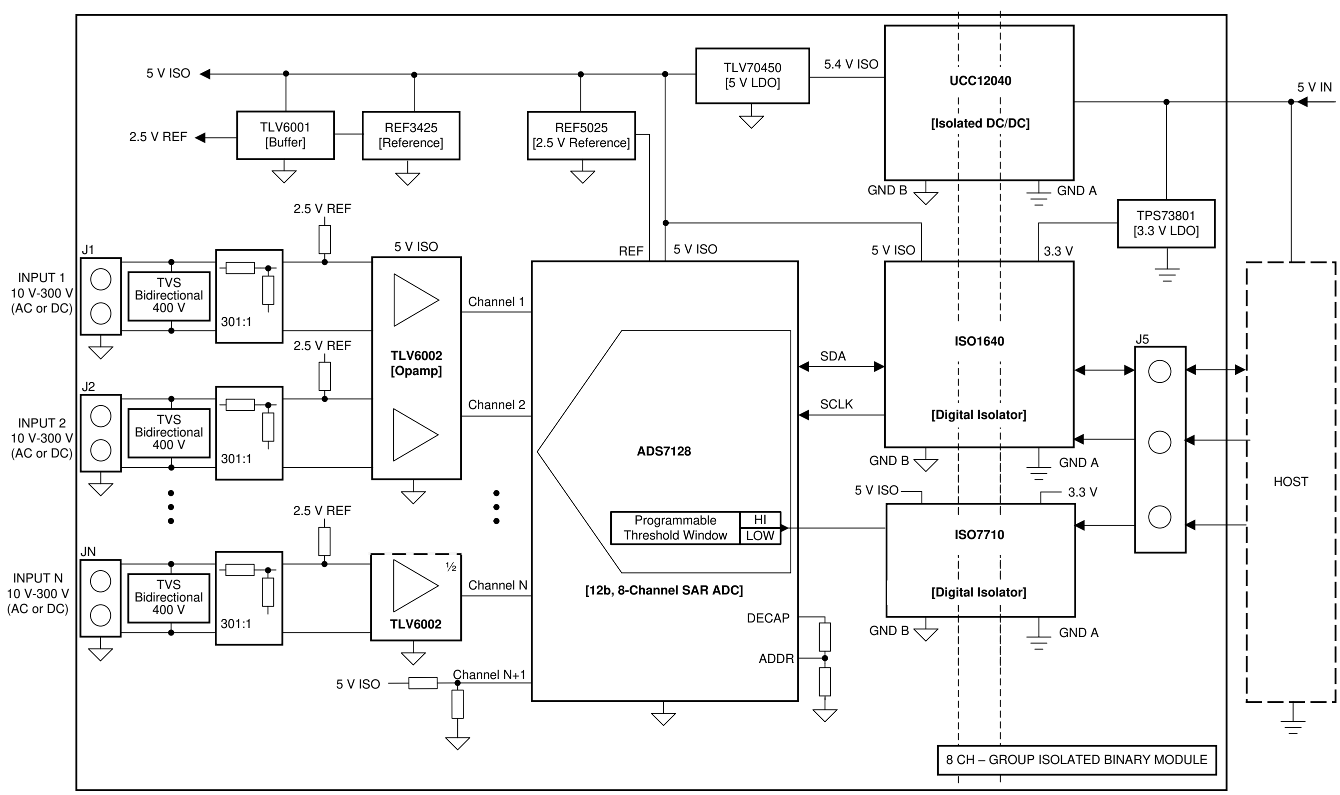


Figure 2-2. Block Diagram of ADC-based BIM Design (ADS7128)

2.2.5.1 ADS7128 SAR ADC With Programmable Threshold

The ADS7128 ADC can be considered for a system with limited processing capabilities. The eight individual channels of the SAR ADCs can be configured to support analog or digital signals for AC/DC input conversion to a host via I2C interface. Each channel implements an analog watchdog function for programmable HI and LO threshold triggered interrupts, along with hysteresis, and an event counter. An event-triggered interrupt can be sent via the ALERT pin to a host when a signal of interest leaves a specified range.

2.2.5.2 I2C Interfacing Using the ISO1640 and Optional Altert Interface Using ISO7710

To accommodate the bidirectional I2C protocol, consider the cost-optimized ISO164x family. Communication between the master processor and slave devices via the SDA and SCL lines are supported at several transfer rates ranging from standard (0–100kbps) up to high-speed (3.4 Mbps) modes. The ISO164x family also enables hot-swap ability on side 2 of the isolator to help prevent overloading of the I2C bus lines.

Use the ISO7710 1-channel digital isolator to isolate the alert output from the ADC to the host.

3 Circuit Design and Component Selection

3.1 Analog-to-Digital Converter (ADC)

To optimize binary input module cost profile, a 12-bit, 16-channel ADC is selected to perform binary input conversion to a host processor.

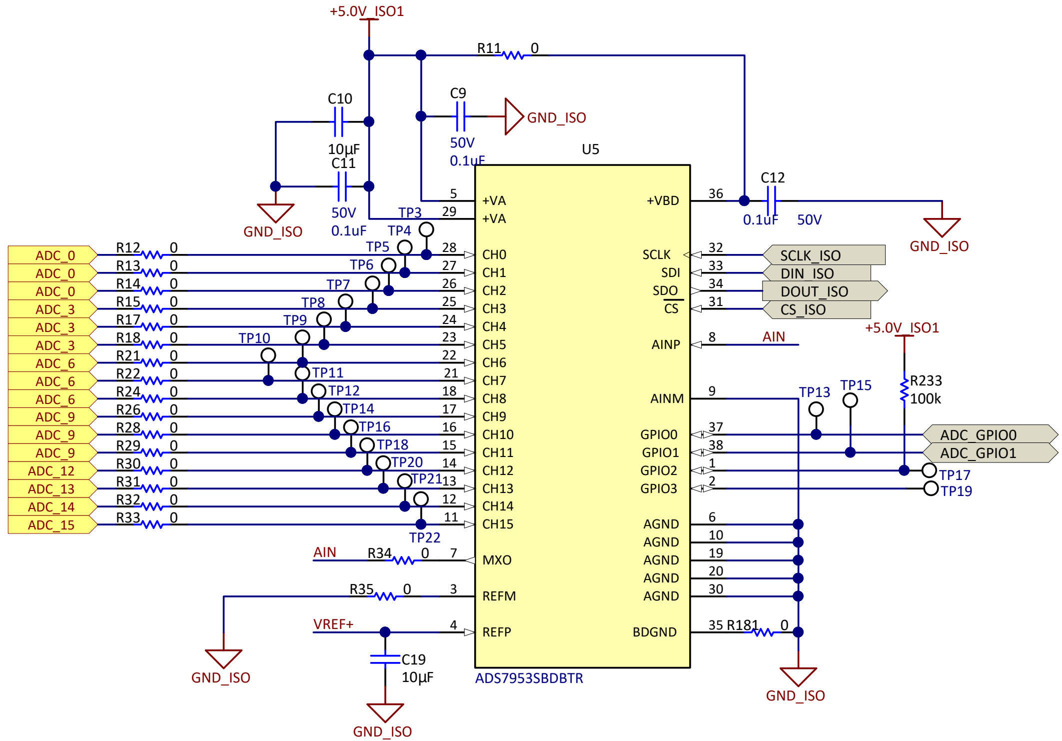


Figure 3-1. ADC Configuration for Measuring Multiple Channels

The ADC considered is the 12-bit, 16-channel, 1-MSPS, single-ended ADS7953 (see Figure 3-1). The 4–16 multichannel ADS795x family allows for auto or manual sequencing of preselected channels for the next conversion cycle. Typically at lower conversion speeds, these devices can draw 1-µA (typical) current while in power-down mode. If desired, additional signal conditioning circuitry may be applied to the MXO and AINP pins. Two programmable alarms may be utilized as well.

The ADC can operate with an external 2.5 V, ±10-mV reference that produces a clean, low-noise, and well-coupled signal. The REF5025 voltage reference with a 10-µF ceramic decoupling capacitor provides sufficient analog integrity for reliable operation.

3.2 Input Signal Conditioning

Figure 3-2 illustrates the signal conditioning op amp and voltage divider circuit.

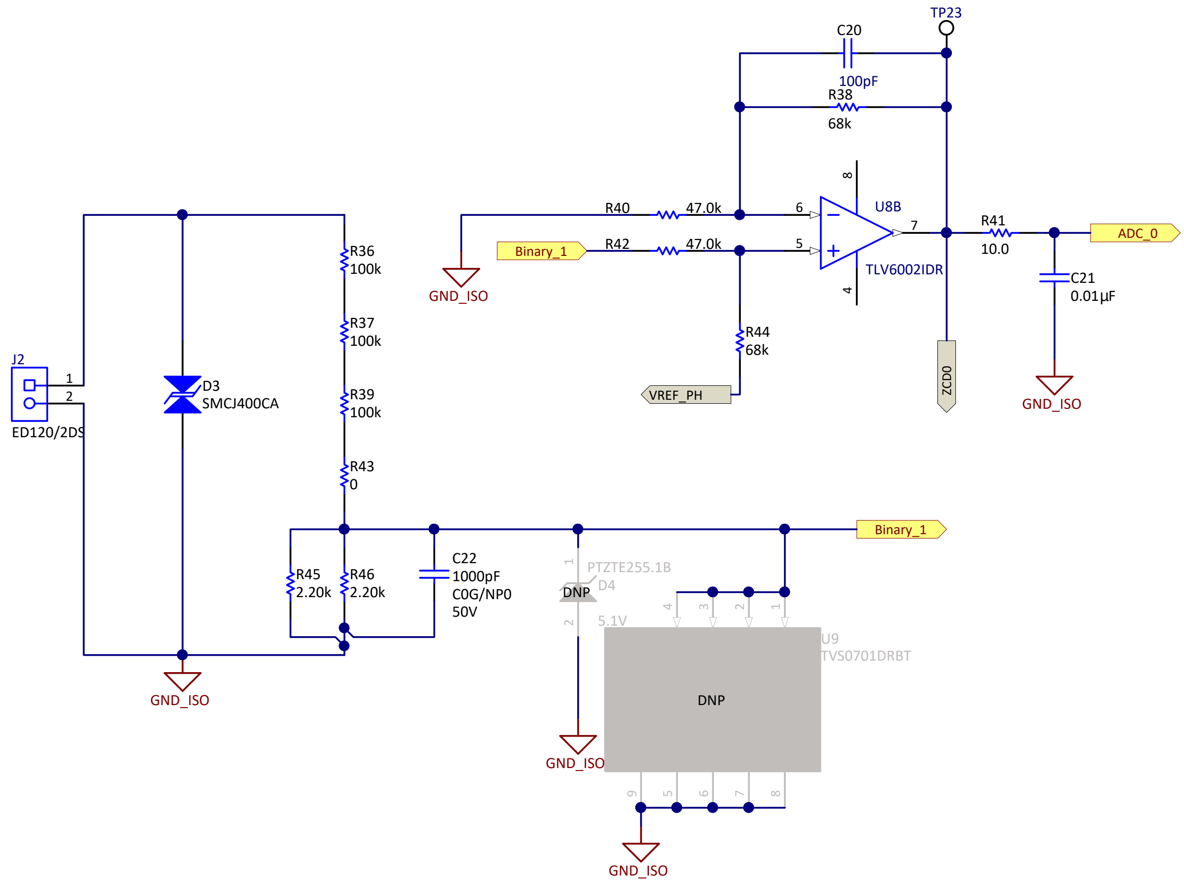


Figure 3-2. Signal Conditioning Operational Amplifier and Voltage Divider

3.2.1 Voltage Divider

The transient-protected signal is passed to 100-kΩ 1206 package series resistors selected for this application. Each can withstand a maximum voltage of 200 V. The resistor tolerance and temperature drift can be selected based on the accuracy requirement.

3.2.2 TLV6002 Operational Amplifier

The TLV6002 industry-leading general purpose 2-channel op amp was considered for this design to provide an attractive balance between cost and performance. The device provides a gain of 1.45 V/V to the input signal, which is then supplied to the ADC input channel. The op amp is the most cost-effective solution for single-ended and level-shifting conversion. Key benefits of using this device are minimal power consumption (75 µA typical), noise (28 nV/√Hz at 1 kHz), and bias current (±1 pA typical).

3.3 Isolated Interface

The ISO6741 was considered in this design to provide a cost-sensitive reinforced isolation solution for ADC-to-host interfacing. Each isolation channel has a logic input and output buffer separated by TI's double capacitive silicon dioxide (SiO_2) insulation barrier.

An isolation barrier separates the two isolator sides, allowing each side to be sourced independently with any voltage within recommended operating conditions. EN pins can be utilized on either side to set respective outputs in a high impedance state for multimaster applications. Figure 3-3 illustrates the ISO6741 isolator.

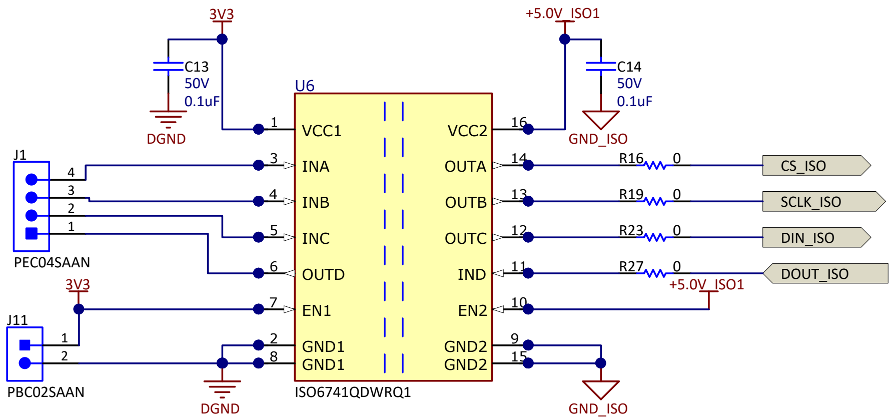


Figure 3-3. Reinforced Digital Isolator for Host Interface (SPI)

3.4 Isolated DC Power Supply

3.4.1 Reinforced Power Isolator: UCC12050 High-Efficiency 500-mW DC/DC Converter

The UCC12050 500-mW converter was considered for this application. The DC/DC converter was specifically designed for isolated voltage sensing applications relating to protection relays and smart breakers. It features 5-kV_{RMS} rated reinforced isolation and an adjustable 3.3-, 3.7-, 5.0-, or 5.4-V output, ideal for safe and dependable power output to an LDO, voltage reference, or other.

A convenient 5-V nominal input voltage and wide-body SOIC package is ideal for binary input module applications requiring cost-effective safety features. Some features include Under Voltage Lock-Out (UVLO), thermal shutdown, and output voltage selection. Figure 3-4 shows the reinforced isolation DC/DC converter power supply circuit.

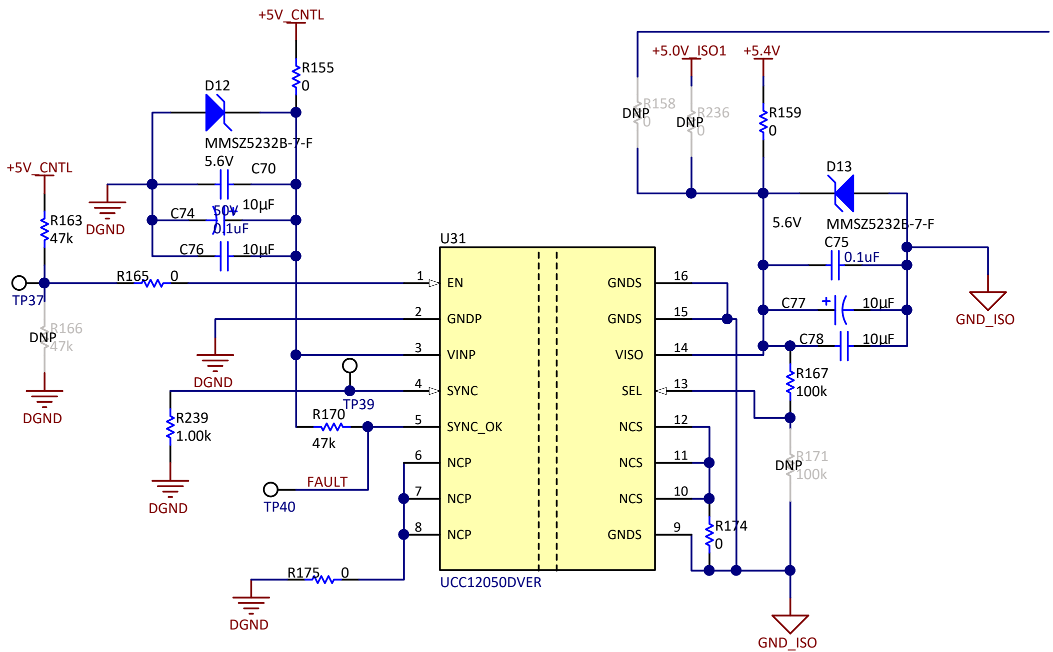


Figure 3-4. Reinforced Isolation DC/DC Converter Power Supply

3.5 Enhancements

Multiple options are available for selection of binary inputs based on the configured functions and monitored primary equipment. Modules can be integrated into the end equipment or externally connected. The modules operate from a 5- or 12-V DC rail.

For a 12-V DC input, a DC/DC converter is used to reduce to a 5-V rail. The 12-V DC input can optionally be protected against overload using eFuse.

This design showcases TPS25921A for protection, the input DC voltage against overload, and the LMZM23601 step-down DC/DC power module simplifying design and enhancing reliability.

4 Testing

This section provides details of the test setup and board connection details such as voltage input, power supply, and the communication interface used for functional and performance testing of the TIDA-00420.

4.1 Test Setup and Connection Diagram

The setup shown in Figure 4-1 consists of a DC supply with current limit used for accurately powering the TIDA-00420 board. The DC supply is also used as a programmable voltage source for testing the measurement accuracy of captured samples of the interface board. The board is interfaced to the GUI for processing the samples and configuring the ADC.

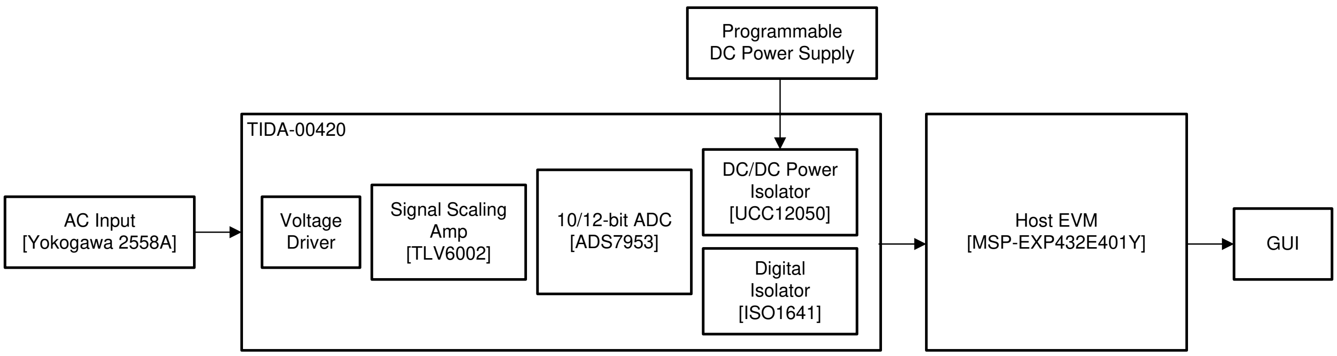


Figure 4-1. Test Setup Layout

Figure 4-2 shows the connection diagram used for board testing. Connectors are provided to connect the AC or DC voltage inputs. Screw type terminals are provided to connect the DC supply communication interface connector (header-male type) to the ADC, and then to the host.

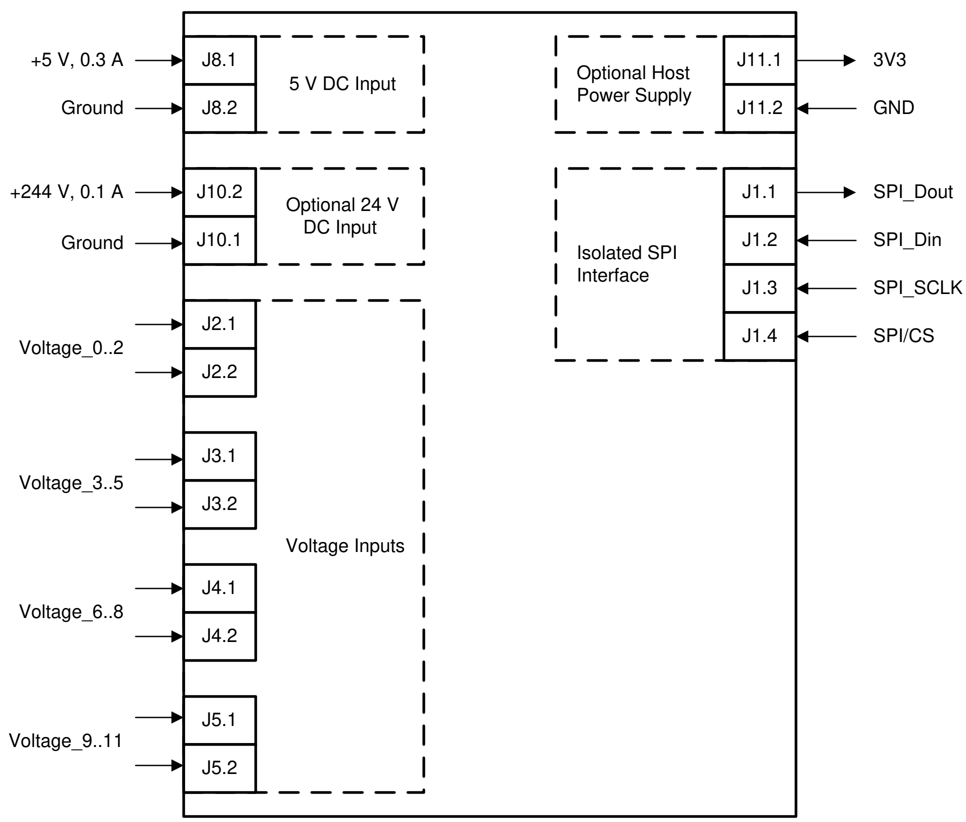


Figure 4-2. Connections for Performance Testing

4.2 Test Data

This section provides details of the functional and performance tests performed on the TIDA-00420 BIM board and the observations.

Table 4-1. Functional Test Plan and Observations

MODULE FUNCTION	PARAMETERS	OBSERVATIONS
Power Supply	Isolated 5.4 V	5.41 V
	Isolated and regulated 5 V	4.98 V
	Non-isolated 3.3 V	3.29 V
Signal Scaling	Voltage reference	2.491 V
	DC level shifted output	2.47–2.48 V
	Gain scale amplifier output ADC_0, ADC_3, ADC_6, ADC_9	OK
ADC Isolated SPI	ADS7953 12-bit, 16 channels	OK
	ADS7952 12-bit, 12 channels	OK
	ADS7957 10-bit, 16 channels	OK
	ADS7956 10-bit, 12 channels	OK
Accuracy Measurement Performance over Wide AC or DC Inputs	ADS7953 12-bit, 16 channels	OK
	ADS7952 12-bit, 12 channels	OK
	ADS7957 10-bit, 16 channels	OK
	ADS7956 10-bit, 12 channels	OK
ADC GPIO – Input	Isolated supply status	OK
ADC GPIO – Output	Isolated supply control	OK
Diagnostics	Temperature sensor output (0.7 (20°C) to 0.75 (25°C))	0.71 V
	Magnetic sensor output approximately 1 V (no field)	1.002 V
	LED indications for isolated power status, input supply and UCC12050 sync status	OK

4.2.1 Voltage Measurement Accuracy Testing

Table 4-2 summarizes the performance test results for the TIDA-00420 board configured for a 10-bit ADC.

Table 4-2. Voltage Measurement Accuracy for 10-bit ADC (ADS7957) from 10 V to 320 V

ADC CHANNEL	MEASUREMENT ERROR (%)		
	320 V	100 V	10 V
0	0.540	0.400	0.170
1	0.536	0.396	0.184
2	0.452	0.321	0.098
3	0.476	0.532	0.320
4	0.478	0.398	0.259
5	0.442	0.499	0.297
6	0.137	0.179	0.390
7	0.242	0.172	0.437
8	0.163	0.123	0.309
9	0.391	0.304	0.020
10	0.391	0.314	0.029
11	0.314	0.251	–0.019

Table 4-3 summarizes the performance test results for the TIDA-00420 board configured for a 12-bit ADC.

Table 4-3. Voltage Measurement Accuracy for 12-bit ADC (ADS7953) From 3 V to 320 V

ADC CHANNEL	MEASUREMENT ERROR (%)					
	320 V	250 V	100 V	10 V	5 V	3 V
0	0.410	0.349	0.295	0.554	0.836	0.757
1	0.411	0.350	0.295	0.558	0.842	0.786
2	0.331	0.273	0.255	0.476	0.740	0.709
3	0.217	0.147	0.101	0.312	0.546	0.573
4	0.216	0.148	0.100	0.289	0.575	0.491
5	0.154	0.088	0.048	0.221	0.484	0.438
6	0.134	0.065	0.054	0.248	0.537	0.563
7	0.135	0.113	0.115	0.263	0.493	0.591
8	0.130	0.108	0.153	0.237	0.437	0.550
9	0.002	0.040	0.093	0.171	0.492	0.564
10	0.002	0.040	0.095	0.165	0.472	0.588
11	0.002	0.044	0.086	0.137	0.448	0.576

Note

The measurements are within ±1% for wide voltage inputs.

4.3 Test Results Summary

Table 4-4 summarizes the observations for the functional and performance tests that were done on the TIDA-00420 board mounted with ADCs of varying channel counts and resolutions.

Table 4-4. AC/DC Binary Input Module Testing Summary

Tests	Observations
5-V power supply with input reversal protection	OK
Isolated supply output with headroom	OK
Isolated supply monitoring	OK
Non-isolated power supply output	OK
Reference for level shifting	OK
Scaling of voltage inputs and op amp output	OK
Isolated ADC interface to host	OK
12 or 16 channel 12-bit ADC functionality	OK
12 or 16 channel 10-bit ADC functionality	OK
Measurement accuracy over wide input 3 V to 320 V using a 12-bit ADC	OK
Temperature and magnetic sensor output	OK

5 Design Files

5.1 Schematics

To download the schematics, see the design files at TIDA-00420.

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00420.

5.3 Altium Project

To download the Altium project files, see the design files at TIDA-00420.

5.4 Gerber Files

To download the Gerber files, see the design files at TIDA-00420.

6 References

1. Texas Instruments, *MSP430™ Programming With the JTAG Interface User's Guide*
2. Texas Instruments, *The ISO72x Family of High-Speed Digital Isolators Application Report*

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7 About the Author

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8 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision B (September 2016) to Revision C (May 2021) **Page**

- This reference design has been adapted from a MCU based 2-channel DC Binary Input Module (BIM) to an ADC based 16-channel AC/DC BIM. The updated reference design includes Texas Instrument's latest IC technology to improve upon cost optimization, measurement accuracy, and more within BIM systems............1

Changes from Revision A (May 2015) to Revision B (September 2016) **Page**

- Added "EMC-Compliant" to title..1
- Added design-specific description to front page..1
- Deleted ISO7220A and added ISO7320C to Section Resources 1
- Added ISO7820 to Section Resources 1

Changes from Revision * (March 2015) to Revision A (May 2015) **Page**

- Changed from preview page..1