Design Guide: TIDA-010008
Flat-Clamp TVS Based Reference Design for Protection Against Transients for Grid Applications

TEXAS INSTRUMENTS

Description

This reference design features multiple approaches for protecting AC or DC analog input, DC analog output, AC or DC binary input, high-side or low-side drive digital output, LCD bias supply, USB power and data and onboard power supplies with 24-, 12-, or 5-V input used in grid applications against overvoltage, input or output overload, input reversal and transients (1.2/50 µs, 42-Ω) using bi-/uni-directional flat-clamp surge protection devices, ESD devices, eFuse or a load switch. The design monitors temperature, humidity, magnetic fields and power supplies for diagnostics.

Resources

TIDA-10008	Tool Folder
TPS2660, TPS2596, TPS25921A, TPS2595,	Product Folder
TPS22946 , TPS22965, TPS2662, TPS22810	Product Folder
TPS22944, TPS2051B, TPS2553, TPS2121	Product Folder
LM74700-Q1, LM74610-Q1	Product Folder
TPD1E10B06, TPD2E007, TPD4S012	Product Folder
TVS1401, TVS0701, TVS3300, TVS1400	Product Folder
CSD17577Q3A	Product Folder

TI E2E™ Community
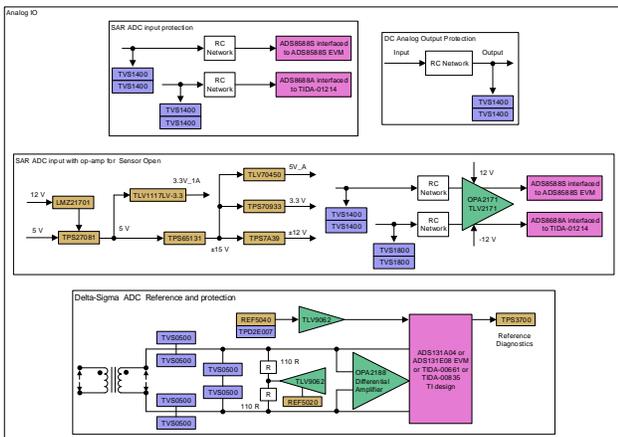
ASK Our E2E Experts
WEBENCH® Calculator Tools

Features

- Protecting AC or DC analog inputs or DC analog outputs against overvoltage and transients (±1.5 kV) interfaced to the ADS8688 (±20-V) , ADS8588S (±15-V) input, and DAC8771 with ±15-V output using bi-/uni-directional TVS
- Input overvoltage and current sensor open protection for AC inputs interfaced to the ADS131E08 or ADS131A04 with a ±4-V input range using bi-/uni-directional TVS
- 24-V, 12-V, or 5-V DC input reversal and output overload protection with configurable load current
- Protecting 24-V or 48-V rated voltage detector or self-powered isolated digital input receiver digital inputs against overvoltage and transients up to ±2 kV and 24-V digital output driver with high-side or low-side drive
- Generation of analog power supplies including dual supply for AC analog input measurement from 5-V input and accurate, stable references

Applications

- Industrial Applications – Circuit breakers, protection relays
- Substation Automation – RTU, bay controllers, merging unit, Gateways and remote IOs

⚠ An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

1   Features (continued)

- Protecting onboard power supplies against transients and overload including ±12 V, LCD bias supply configured for 18 V, USB power supply with programmable or fixed output current limit and differential USB data lines
- 5-V power supply for board functioning generated from 12 V or 24 V using high-efficiency power modules

2   Resources (continued)

TVS3301, TVS2701, TVS2201, TVS1801, TVS0500	Product Folder
TVS2700, TVS2200, TVS1800, SN74LVC1G125	Product Folder
HDC1080, TMP75, LMT84, DRV5032	Product Folder
TPS3700, TPS3710, LM8364, TPS3803, TLV3201	Product Folder
ISO1212, ISOW7821, DRV8803, TPS27S100, ISO5451	Product Folder
LMZ14201, LMZ21701, TPS61041, TPS65131	Product Folder
TLV1117LV, TLV704, TPS709, TPS7A39, TLV702	Product Folder
OPA2171, TLV9062, OPA2188, REF5040, REF5020, REF3440	Product Folder
SN74LVC1G17, SN74LVC1G14, SN74LVC1G08, CSD17571Q2	Product Folder

3   System Description

Failure of power systems 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 protection, control, monitoring, and measurement systems to improve the power systems efficiency and reliability.

Causes of failure:
- Wrong operation of the equipment
- Faulty component
- Hardware design (minimal or no design margin, type of component used and their performance)
- Equipment performance with ageing (drift)
- Manufacturing defect
- Effect of environment – temperature and vibration
- Failures due to exposure to sustained EMC environment including electric transients and magnetic field

This design showcases different approaches for protecting analog digital IOs against overvoltage and transients and generation of the required power supplies for operation of analog front-end (AFE) from a single 5 V. This design generates 5 V from 12-V or 24-V high-efficiency power modules. Additionally, the monitors the supplies using window comparator and diagnostics to improve performance and reliability of IO modules using temperature, humidity, and magnetic sensors. The design also showcases generation and protection of LCD bias voltage and protection of USB interface against ESD and overload.

The design can be used in multiple applications including:
- *Protection Relay*: Digital 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 IOs including the following:
  - AC analog inputs for measuring current and voltages
  - DC analog input or output for control
  - Digital input or output for monitoring and interlocking
  - Interface including RS232, RS485, and USB for networking
  - HMI including LCD display or LEDs

- *Substation Automation and Merging unit*: In substations, process-level primary equipment is monitored using RTU, bay controllers. The inputs to these 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. Multiple communication options are also provided in this equipment for implementing automation protocols. Since this equipment is installed in harsh environments, they are exposed to EMC and are required to be protected against transients or other EMC for proper operation. Merging units are used to sample AC analog values on the process level in a substation and transmit the sampled values (SV) to protection devices, bay control units (BCU), or electric meters through fiber optic Ethernet interface based on the IEC61850-9-2 protocol. Since this equipment is installed near to the primary equipment, they are exposed to EMC and required to be protected against transients or other EMC for proper operation.

3.1   Key System Specifications

The primary objectives of this design are to create a platform to showcase different approaches for protection of analog or digital IOs, HMI interface, and generation of power supplies required from a single 5 V for different IO modules. The design additionally provides an option for diagnostics of IO and power. Table 1 shows a summary of the key specifications.

Table 1. Specifications for Protection and Power Supply for IOs

PARAMETER	DESCRIPTION	SECTION
5-V power supply	Generated from 12 V or 24 V using buck converters	Section 4.4.1
Bipolar ±15-V power supply	Generated using split rail converter from a single 5 V	Section 4.4.1
Regulation of analog supply including ±15-V input	Using LDOs including dual-output LDO	Section 4.4.1
Power supply protection	Transient suppressor up to 1 kV on 24V supply input and load switch	Section 4.4.1
Isolated digital input with self-power	24-V or 48-V AC or DC input with self-powered digital input receiver protection using bi-/uni-directional TVS	Section 4.4.3
Isolated digital input with isolated power	Comparator or voltage detector, interfaced to host using digital isolator with integrated power	Section 4.4.3
Digital input protection	Transient protection up to 2 kV with external current limiting resistor, comparator output gated with isolated power	Section 4.4.3
Digital output	Two-channel, 24-V, low-side driver	Section 4.4.3
Digital output	24-V output, with high-side driver	Section 4.4.3
Digital output protection	Output protected against overvoltage and transients up to 1 kV	Section 4.4.3
Protection of SAR ADC ADS8688 or ADS8688A	Input overvoltage protection and transient protection up to 1.5 kV using bi-/uni-directional TVS , sensor open buffering	Section 4.4.1
Protection of SAR ADC ADS8588S	Input overvoltage protection and transient protection up to 1.5 kV using bi-/uni-directional TVS , sensor open buffering	Section 4.4.1
Protection of Delta-Sigma ADC ADS131E08 or ADS131A04	Current transformer open protection, input overvoltage protection, differential to single-side conversion using op-amp	Section 4.4.1
Generation of reference	4.096 V and 2.048 V for SAR and Delta-Sigma ADC with ESD protection	Section 4.4.1
HMI and USB interface protection	USB supply output overload protection with programmable or fixed current and transient protection	Section 4.4.4
DC input supply protection	Input reversal and overload protection with configurable load currents	Section 4.4.4
Status indication	LEDs for power supply operation indication	Section 4.4.4
Diagnostics	Temperature, humidity, magnetic field, window comparator for ISOW7821 power supply output monitor and reference monitoring	Section 4.4.4

3.2 TI Device Mapping to Design Functionalities

Table 2 provides details of the functionalities implemented in this design and TI devices used to implement the functionality.

Table 2. Details of Functions and Devices Used in the Design

FUNCTION	DEVICES	DESCRIPTION
Interface to SAR ADC	OPA2171, TVS1400, TVS1800, TVS1401, TVS1801, ADS8588S, ADS8688, ADS8688A	Protection of SAR ADC with ±10-V input against transients and overvoltage. Buffering of analog inputs for normal operation during sensor open.
Delta-Sigma ADC interface, differential to single-ended conversion, reference and monitoring	OPA2188, TVS0500, TVS0701, REF5040I, REF3020AI, TPS3700D, TLV9062, TPD2E007, ADS131A04, ADS131E08,	Protection of Delta-Sigma ADCs with ±4-V input against overvoltage. Protection against current transformer open. Generation of reference and ESD protection of reference output.
DC analog output	DAC8775, DAC8771, TVS1400, TVS1401	Protection against overvoltage and transients
Power supply 12 V or 5 V to analog supply	LMZ21701SILR, TPS22810, TVS3300, TVS0500, TPS65131, TPS7A3901, TPS70933, TLV70450, TLV1117LV33	Generation of dual power supplies for signal conditioning the AC inputs and other supplies for operation of ADCs from 5-V or 12-V DC input.
Digital input with voltage detector or comparator	LM8365BALMFX27, TPS3803, SN74LVC1G08, TLV3201AI, TPS3710, SN74LVC1G17, ISOW7821, TPS22944, TPD1E10B06, TVS3300	24-V binary input module implemented using comparator or voltage detector with different thresholds. Output of the voltage detector, comparator interfaced to host using digital isolator with integrated power. Monitoring of the Isolated power. Protection against transients.
Digital input with isolated digital input receiver	ISO1212, TVS2200, TVS3300, TVS2201, TVS3301, SN74LVC1G07	24-V or 48-V AC or DC binary input module with hysteresis. Protection against transients.
2 × digital output low side	DRV8803, TVS2700, TVS3300	Digital output with low-side drive. Protection of digital output against overvoltage and transients
1 × digital output high side	TPS27S100A, TVS2700,	Digital output with high-side drive. Protection of digital output against overvoltage and transients
Digital IO power supply	LMZ14201TZ-ADJ, TLV70233	Generation of 5 V and 3.3 V from 24-V input
USB overload switch	TPS2553, TPS2051B, TPD4S012, SN74LVC1G14, TVS0500	Protection of USB power output against overload, ESD and Transient with programmable current and output fault indication
LCD bias power supply	TPS61041, TVS1800	Protection of LCD bias power supply output against overvoltage, ESD and Transient
Diagnostics sensors	DRV5032, HDC1080, LMT84, TMP75B	Analog or Digital temperature sensor and Analog or digital magnetic sensor for AC analog input diagnostics and Humidity sensor for Binary input module wetting current control and diagnostics
5-V input reversal and output overload protection	TVS0500, LM74610-Q1, CSD17577Q3A, TPS25921A, TPS259521, TPS22946, TPS22965	Protection of 5-V input against transients and input reversal using ideal diode controller, protection of output against transients, overload using eFuse and switch output load based on the requirement with over load protection using load switch.
12-V input reversal and output overload protection	TVS1400DRVR, LM74700-Q1, CSD18543Q3A, TPS2121, TPS259631	Protection of 12-V input against transients and input reversal using ideal diode controller, switching between two 12-V inputs using power mux, protection of output against transients, overload using eFuse.
24-V input transient and output overload protection	TVS3300, TPS26600, TPS7B6933Q	Protection of 24-V input against input transient and output overload with configurable current limit.

4 System Overview

This design is intended for use in IO modules including analog IO, digital IO and HMI for protection relay, terminal units, circuit breakers and other grid application. The design has the following functional blocks:

- Analog input protection against overvoltage, transients and sensor open buffering for ADS8688, ADS8688A or ADS8588S ADCs using flat clamp TVS
- Overvoltage or current sensor open protection for Delta-Sigma ADC
- Protection of 24V or 48V rated binary input and 24-V rated digital output with high side or low side drive against overvoltage and transients using flat clamp TVS
- Generation of 5-V power supply from 12-V or 24-V input
- Generation of multiple supply outputs including ±15-V output for analog front-end from 5-V input
- Regulation of supply voltages using dual-output LDOs to generate ±12 V
- Protection of the power supply using a load switch or eFuse or flat-clamp surge suppressor diode

- 24-V or 48-V, AC or DC binary input module implementation using digital input receiver
- 24-V rated digital input using voltage detector or comparator and digital isolator with integrated power
- High-side or low-side digital output driver
- Generation of 4-V and 2-V reference and buffering for Delta-Sigma ADC and SAR ADC
- Monitoring of isolated Power supply
- Diagnostics of IO modules and performance enhancement using temperature, humidity and magnetic field sensors.

4.1 Block Diagram

Figure 1 shows different approaches for the design of analog IO and digital IO, generation of requires power supplies and protection using ESD or flat-clamp surge devices.

4.1.1 Digital Input, Digital Output, LCD Bias Supply, USB Protection and Sensors for Diagnostics

Figure 1 illustrates the following:

- 24-V or 48-V binary input module protection using flat-clamp surge protection
- Multiple approaches to binary input module design with 24-V or 48-V input rating
- Implementation of high-speed digital output protection including transient and overvoltage protection
- Generation of power supply for digital IO using DC/DC power module and LDOs
- Generation of LCD bias power supply and overvoltage protection
- USB power supply overload protection with configurable current, overvoltage protection for USB power output and ESD protection for data and power lines
- Diagnostics and wetting current control using a humidity sensor with integrated temperature sensor
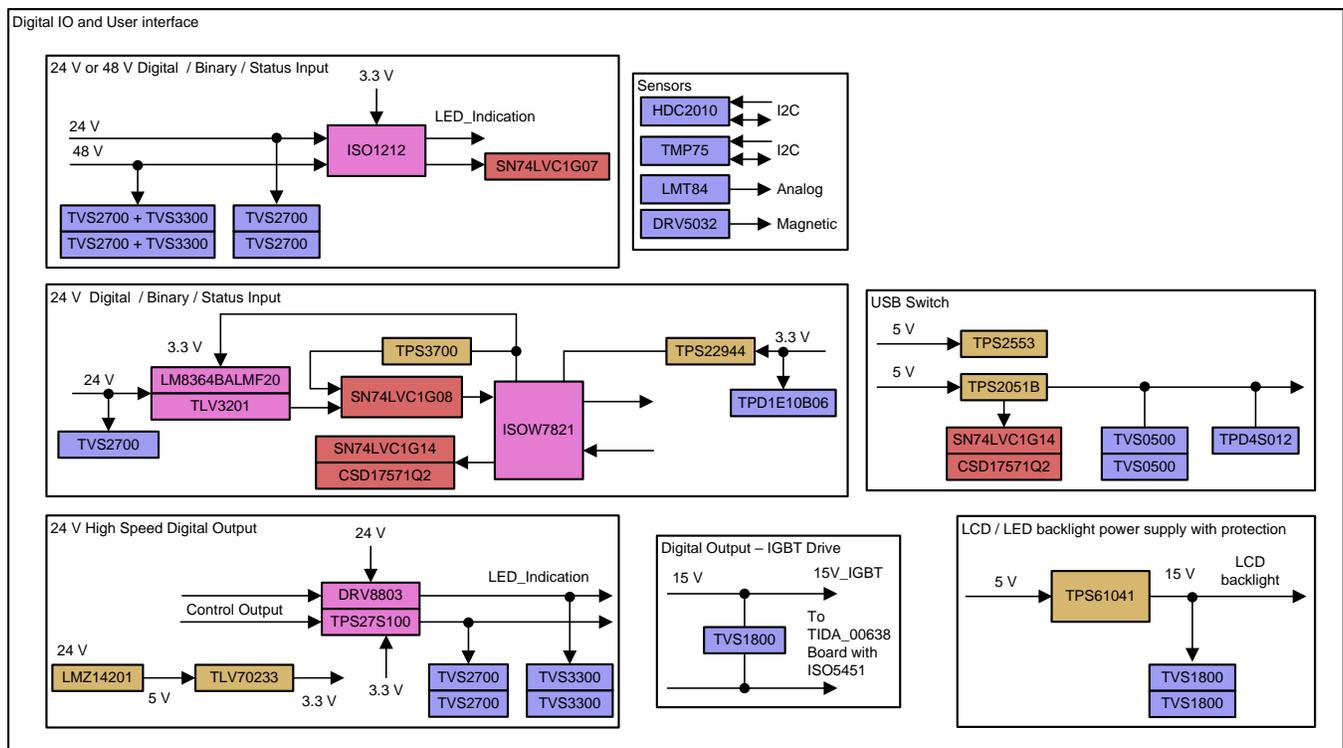

Figure 1. Power Digital IO

4.1.2 Analog Input Reference Generation, Buffering, Power Supply Generation and Protection

Figure 2 shows the following functionality:

- Overvoltage and transient protection for 16-bit SAR ADCs including ADS8688 or ADS8588S
- Input overvoltage and current transformer open protection for ADS131E08, 24-bit Delta-Sigma ADC
- Differential to single-ended conversion of AC analog input
- Generation of dual-supply ±12 V for interfacing analog inputs to ±10-V input SAR ADCs
- Generation of reference for SAR and Delta-Sigma ADCs including 4 V or 2 V with an op amp configured as a buffer and ESD protection
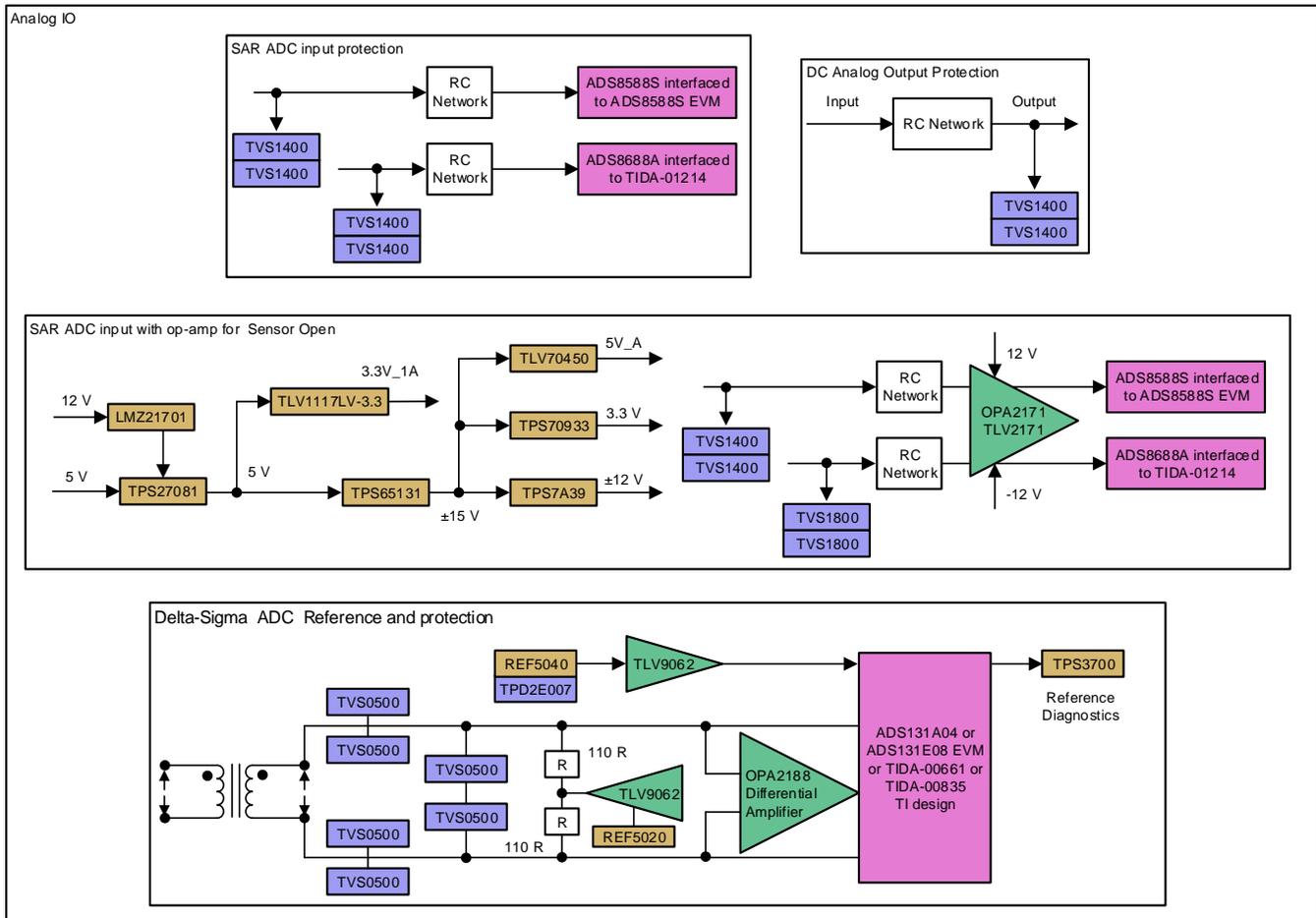- Buffering of sensors interfaced to 16-Bit SAR ADC to overcome DC offset and monitoring of reference

Figure 2. Power Analog IO

4.1.3 DC Input Transient, Reversal and Output Overload Protection

Figure 3 showcases the following:

- 5-V input reversal, output overload protection and load switching with protection
- 12-V input reversal and output overload protection
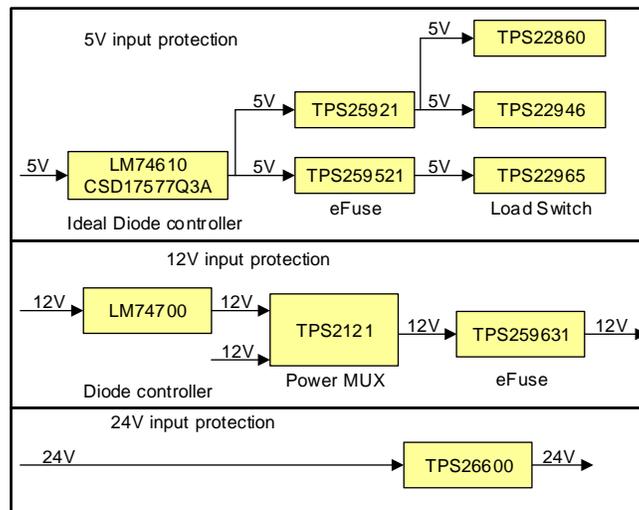- 24-V input transient and output overload protection

Figure 3. DC Input Supply Protection

4.2 Design Considerations

Some of the key considerations for TIDA-010008 include:

- Overvoltage and transient protection of analog inputs interfaced to 16-bit SAR ADCs including ADS8688, ADS8688A and ADS8588S with an input range up to 10.24 V
- Overvoltage protection of 24-bit Delta-Sigma ADCs including ADS131E08 and ADS131A04
- Generation, sensing, and protection of binary input and digital output against overvoltage and transients
- Efficient approach to generating 5 V from 12-V or 24-V input and generation of 5 V or 3.3 V using LDOs
- Generation of dual-output ±12 V from a single 5 V using a split-rail converter, dual LDO and protection of the power supply for overvoltage and transients
- Generation of stable references for precision 16-bit or 24-bit ADCs with ESD protection
- Isolated interface using digital isolators with integrated power and protection of the digital isolator supply output against overload using load switch
- Monitoring of isolated power supply and reference using window comparators
- Sensor for diagnostics and performance improvement of analog or digital IOs
- Protection of USB interface for ESD, overvoltage and overload with option for configurable current
- Generation of LCD bias supply and protection against overvoltage and transients

This is a generic design focusing on protection of analog or digital inputs and other interfaces including USB and LCD bias. This design can be used across other end equipment in grid infrastructure and other adjacent sectors including motor drives, and factory and building automation. Additional monitoring and diagnostics features are provided for improving system performance.

4.3 *Highlighted Products*

This section provides details of some of the focus TI products used in this design.

4.3.1 Uni-directional Transient Voltage Suppressor

Use of uni-directional transient voltage suppressor (single or dual) increases the transient current withstand capability. This design uses the following uni-directional flat-clamp surge protection devices for transient protection:

- TVS3300, 33-V flat-clamp surge protection device
- TVS2700, 27-V flat-clamp surge protection device
- TVS2200, 22-V flat-clamp surge protection device
- TVS1800, 18-V flat-clamp surge protection device
- TVS1400, 14-V flat-clamp surge protection device
- TVS0500, 5-V flat-clamp surge protection device

See *ESD Protection and TVS Surge Diodes – Products*, for more details on flat-clamp surge protection diodes.

4.3.2 Bi-directional Transient Voltage Suppressor

Use of bi-directional transient voltage suppressor simplifies system design and reduces complexity. This design uses the following bi-directional flat-clamp surge protection devices for transient protection:

- TVS3301, 33-V bi-directional flat-clamp surge protection device
- TVS2201, 22-V bi-directional flat-clamp surge protection device
- TVS1801, 18-V bi-directional flat-clamp surge protection device
- TVS1401, 14-V bi-directional flat-clamp surge protection device
- TVS0701, 7-V bi-directional flat-clamp surge protection device

See *ESD Protection and TVS Surge Diodes – Products*, for more details on flat-clamp surge protection diodes.

4.3.3 ESD Protection

This reference design uses the following devices for showcasing ESD protection:

- TPS1E10B06, single-channel ESD in 0402 package with 10-pF capacitance and 6-V breakdown
- TPD2E007, 2-channel ESD protection array for AC signal data interface
- TPD4S012, 4-channel USB ESD solution with power clamp

See *ESD protection and TVS surge diodes*, for more details on ESD devices.

4.3.4 eFuse, Load Switch, Power Mux, and Ideal Diode Controller

This reference design uses the following devices for output overload or short-circuit protection:

- TPS26624, 60-V, 800-mA industrial eFuse with integrated reverse polarity protection
- TPS22810, 18-V, 3-A, 79-mΩ load switch with adjustable rise time, adjustable quick output discharge, and thermal shutdown
- TPS22944, 5.5-V, 0.2-A, 500-mΩ, 100-mA current limit load switch
- TPS2051B, 0.7-A, 2.7- to 5.5-V single high-side MOSFET, fault report, active-high enable
- TPS2121, 2.7-22-V, 56-mΩ, 4.5-A, priority power mux with seamless switchover
- TPS26600, 60-V, 2-A industrial eFuse with integrated reverse-input polarity protection
- TPS259631, 2.7-V to 19-V, 0.13-A to 2-A, 85-mΩ eFuse with accurate current monitor and fast overvoltage protection
- TPS25921A, 18-V, 1.6-A, 90-mΩ eFuse with adjustable ±2% accurate current limit
- TPS259521, 2.7-V to 18-V, 4-A, 34-mΩ eFuse with fast overvoltage protection

- TPS22946, 5.5-V, 0.2-A, 400-mΩ selectable current limit load switch
- TPS22965, 5.7-V, 6-A, 16-mΩ load switch with adjustable rise time and optional quick output discharge
- LM74700-Q1, low Iq, ideal diode controller
- LM74610-Q1, zero Iq reverse polarity protection smart diode controller
- TPS2553, adjustable, active high, constant-current, current-limited power-distribution switch

See *Load Switches*, for more details on eFuse and load switches.

4.3.5 Voltage Detector, Window Comparator, and Configurable Comparator

This reference design uses the following devices to showcase monitoring of reference, isolated power and detection of binary input:
- TPS3700 Window comparator with overvoltage and undervoltage detection
- TPS3710 Wide-VIN voltage detector
- LM8364 Active-low voltage monitor with low quiescent current and 2.5% threshold accuracy
- TPS3803 Low-power voltage detector
- TLV3201 40-ns, micro-power, rail-to-rail input, single-channel comparator with push-pull outputs

See *Design with comparators*, for more details on comparators.

4.3.6 Isolated Binary Input and Digital Output

This reference design uses the following devices to showcase implementation of isolated digital interface and digital output:

- ISO1212, Isolated 24-V to 60-V digital input receivers for digital input modules
- ISOW7821, High-efficiency, low-emissions, reinforced digital isolator with integrated power
- DRV8803, Unipolar stepper motor or 1-A quad solenoid and relay driver (PWM Ctrl)
- TPS27S100 40-V, 80-mΩ single-channel smart high-side switch

See *Digital Isolators*, for more details on digital isolators.

4.3.7 DC/DC Converter and Power Module

This reference design uses the following DC/DC converters:

- LMZ21701, 3-V to 17-V, 1-A, high-density, nano module
- LMZ14201, SIMPLE SWITCHER® 6 V to 42 V, 1-A power
- TPS65131, split-rail converter with dual, positive, and negative outputs
- TPS61041, 28-V, 250-mA switch boost converter in SOT-23 for LCD applications

See *Non-Isolated Module – Products*, for more details on non-isolated modules.

4.3.8 Single or Multichannel LDOs

This reference design uses the following LDOs for generating the required analog or digital power supply:

- TLV1117, 3.3-V, single-output LDO, 800-mA, fixed and adjustable, internal current limit, thermal overload protection
- TPS70933, 150-mA, 30-V ultra-low-Iq wide-input low-dropout (LDO) regulator with reverse current protection
- TPS7A05, 1-µA, ultra-low-Iq, 200-mA, low-dropout regulator in a 1-mm × 1-mm package
- TLV70450, 24-V input voltage, 150-mA, ultra-low-Iq low-dropout (LDO) regulators
- TPS7B69-Q1, automotive high-voltage ultra-low-IQ low-dropout (LDO) regulator
- TPS7A3901, dual, 150-mA, wide-V_{IN}, positive and negative low-dropout (LDO) voltage regulator

See *Overview for Linear Regulator*, for more details about LDOs.

4.3.9 Op-Amp and Reference

This reference design uses the following op-amps and references:

- TLV9062, 10-MHz, low-noise, RRIO, CMOS operational amplifier for cost-sensitive systems
- OPA2171, 36V, Low Power, RRO, General Purpose Operational Amplifier in MicroPackages
- TLV2171, 36-V, Low-power, RRO, general purpose operational amplifier
- OPA2188, 0.03-µV/°C, 6 µV Vos, low noise, rail-to-rail output, 36-V zero-drift operational amplifier
- REF5040, Low-noise, very low drift, precision series voltage reference
- REF5020, Low-noise, very low drift, precision series voltage reference
- REF3440 4.1V Low-Drift Low-Power Small-Footprint Series Voltage Reference

See *Differentiate & innovate using the industry's best op amps*, for more details on op-amps.

4.3.10 Temperature, Humidity, and Magnetic Sensors

The following temperature, humidity, and magnetic field sensors are used in this design:

- LMT84, 1.5-V capable, 10-µA analog output temperature sensor in SC70 and TO-92
- TMP075, Temperature sensor with I2C, SMBus interface in industry-standard LM75 form factor and pinout
- HDC1080, Low-power, high-accuracy, digital humidity sensor with temperature sensor

- DRV5032, Ultra-low-power, 1.65-V to 5.5-V Hall-effect switch sensor

See *Temperature sensors for any need*, for more details about temperature sensors.

4.3.11 Digital Logic and MOSFET

The following logic gates are used in this design for buffering or gating of signals:

- SN74LVC1G08, single 2-input positive-AND gate
- SN74LVC1G17, single Schmitt-trigger buffer
- SN74LVC1G07, single buffer, single driver with open-drain output
- SN74LVC1G14, single Schmitt-trigger inverter
- SN74LVC1G125, single bus buffer gate with 3-state outputs
- CSD17577Q3A, 30-V, 4.0-mΩ, SON 3.3 mm × 3.3 mm NexFET power MOSFET
- CSD18543Q3A, 60-V N-Channel NexFET™ Power MOSFET

See digital logic *Gates*, for more details on logic gates.

4.3.12 Enhancements

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

4.3.12.1 Building Blocks

This design has multiple building blocks that are typically used in customer end-equipment designs and showcases the application of these building blocks in implementing digital and analog IO, generation of power supply, protection and diagnostics. Table 3 lists the building blocks used.

Table 3. Building Block Devices and Application in this design

BUILDING BLOCK PRODUCTS	APPLICATIONS
Temperature, humidity, current and magnetic sensing	Diagnostics and adjustment of temperature drift
MUX, signal switches, digital isolator with isolated power, transceiver interface	Used to provide isolated interface to the host and control of wetting current
General purpose amplifiers, LP amplifiers and comparators	Used to implement sensor open buffer, differential amplifier and reference buffering
Voltage references and supervisors, linear and low-dropout regulators	Used to provide reference to ADS8588S, ADS8688, ADS8688A and ADS131E08 ADCs and to regulate the DC/DC converter output
Integrated protection devices and power switches	Used for protection of the IO module against overload and short circuit
Buck DC/DC switching regulators, low-power DC/DC	Used for generation of the required power supply for IO functioning using 12- or 24-V input
Standard logic and high reliability, standard logic	Used for buffering of power good output and gating of signals for diagnostics

4.3.12.2 Driving High-Speed Binary Output for ARC Flash Applications Using IGBT (TIDA-00638)

IGBT-based high-speed digital outputs are used in protection relays with focus on ARC flash applications for tripping the breaker in less than 1 ms. The TIDA-00638 design consists of a single module with a reinforced, isolated IGBT gate driver with a dedicated gate drive power supply. This compact reference design has the ability to control IGBTs for applications including protection relay. The ISO5451 reinforced isolated IGBT gate driver with high CMTI and Miller clamp simplifies the gate driver design for IGBT (see *Reference Design for Isolated Gate Driver Power Stage with Active Miller Clamp for Solar Inverters*).

Flat-Clamp TVS Based Reference Design for Protection Against Transients for Grid Applications

4.3.12.3 SAR ADC Analog Input Protection

This design has a protection and sensor open buffer implementation circuit that can be used with ADC with an input capability up to ±10.24 V and specified for higher overvoltage protection. TI provides a wide selection of ADCs and the same approach can be used. Table 4 lists some of the recommended devices.

Table 4. Precision SAR ADC Selection

ADC	DESCRIPTION
ADS8688	16-bit 500-kSPS, 8-channel single-supply SAR ADC with bipolar input ranges
ADS8688A	16-Bit, 500kSPS, 8-Ch SAR ADC With Bipolar Inputs Using 5V Supply and Low-Drift Vref
ADS8555	16-bit 6-channel simultaneous-sampling ADC
ADS8588S	16-bit, six-channel, simultaneous sampling analog-to-digital converter

4.3.12.4 Delta-Sigma ADC Protection

This design features overvoltage protection of ADC input for the ADS131E08 device. TI provides a wide selection of ADCs and the same approach can be used for all the ADCs. Table 5 lists some of the recommended devices.

Table 5. Precision Delta-Sigma ADC Selection

ADC	DESCRIPTION
ADS131E08	24-bit, 64-kSPS, 8-channel (simultaneous) Delta-Sigma ADC for power monitoring, control and protection
ADS131E08S	24-bit, 64-kSPS, 8-channel (simultaneous) Delta-Sigma ADC with fast start-up for monitoring and protection
ADS131A04	24-bit, 128-kSPS, 4-channel, simultaneous-sampling Delta-Sigma ADC
ADS131A02	24-bit, 128-kSPS, 2-channel, simultaneous-sampling, Delta-Sigma ADC

4.3.12.5 DAC Output Overvoltage and Transient Protection

This design showcases protection of DC analog outputs using (DACs with ±10-V or ±20-mA output) using flat-clamp surge protection diodes. TI provides a wide selection of DACs and the same approach can be used for all the DACs. Table 6 lists some of the recommended devices.

Table 6. DAC With Configurable Current or Voltage Output Selection Table

DAC	DESCRIPTION
XTR300	Industrial analog current, and voltage output driver
DAC8760	16-bit single-channel programmable current, voltage output DAC for 4- to 20-mA current loop applications
DAC8771	Single-channel 16-bit voltage- and current-output DAC with adaptive power management
DAC8775	16-bit quad-channel programmable current-output and voltage-output digital-to-analog converter (DAC)

This design with protection and connectors can be interfaced to, Reference Design for Power-Isolated Ultra-Compact Analog Output Module for performance testing (see *Reference Design for Power-Isolated Ultra-Compact Analog Output Module*).

4.3.12.6 DC Input Overload Protection Using eFuse

The IO modules can be protected against short circuits, flow of reverse current, reverse voltage input or overload using eFuse. This design showcases using load switch to protect the input power supply. TI provides a selection of load switches and eFuses that can be used during the design of IO modules. Table 7 details the recommended devices.

Table 7. eFuse Selection

eFuse	DESCRIPTION
TPS2421	20 V, 5 A, 33 mΩ eFuse with PG
TPS25921A	18-V, 1.6-A, 90-mΩ eFuse with adjustable ±2% accurate current limit
TPS25200	6.5-V, 2.8-A eFuse with overvoltage clamp
TPS2660	60-,V 2-A industrial eFuse with integrated reverse-input polarity protection

4.3.12.7 Digital Isolator Selection for Binary Input Interface to Host

Isolated digital input based on comparator or voltage detector is interfaced to the host through digital isolator. A dual-channel digital isolator can be used to implement channel-channel isolated binary input along with wetting current control. A two channel binary input can be implemented as an alternative approach. TI provides wide selection of dual-channel digital isolators. Table 9 lists some of the recommended devices.

Table 8. Dual-Channel Digital Isolator Selection

DIGITAL ISOLATOR	DESCRIPTION
ISO7221B	Dual-channel, 1/1, 5-Mbps digital isolator
ISO7720	High-speed, robust EMC reinforced dual-channel digital isolator
ISO7721	High-speed, robust EMC reinforced dual-channel digital isolator
ISO7821	High-immunity, 5.7-kV$_{RMS}$ reinforced dual-channel 1/1 digital isolator, 100 Mbps
ISO7820	High-immunity, 5.7-kV$_{RMS}$ reinforced dual-channel 2/0 Digital Isolator, 100 Mbps

4.3.12.8 Hall-Based Magnetic Sensor for Diagnostics

These magnetic field sensing switches can be used in protection relay or other grid equipments to detect exposure of the equipment to continuous magnetic field generated by transformers or motors or generator that may result in performance degradation including variation in measurement accuracy. Indicating the level may be the simplest approach for performance improvement when the device is operated in harsh environment. Measurement of the flux intensity levels can further provide data to improve shielding of the equipment. DRV5032 device is an ultra-low-power digital-switch Hall-effect sensor. The device is offered in multiple magnetic thresholds, sampling rates, output drivers. When the applied magnetic flux density exceeds the BOP threshold, the device outputs a low voltage. The output stays low until the flux density decreases to less than BRP, and then the output either drives a high voltage or becomes high impedance, depending on the device version. By incorporating an internal oscillator, the device samples the magnetic field and updates the output at a rate of 20 Hz, or 5 Hz for the lowest current consumption. Omnipolar and unipolar magnetic responses are available. DRV5056 is a linear Hall-effect sensor that responds proportionally to flux density of a magnetic south pole. The device can be used for accurate position sensing in a wide range of applications. DRV5053 device offers a magnetic sensing solution with superior sensitivity stability overtemperature and integrated protection features. The 0- to 2-V analog output responds linearly to the applied magnetic flux density, and distinguishes the polarity of magnetic field direction.

See *Linear Hall Effect Sensors – Products* for more details on Hall-effect sensors.

4.3.12.9 Voltage Detector

In this design, the binary input module has been designed using a voltage detector with a fixed threshold. The limitation of the fixed threshold is that the input voltage divider must be changed, based on the rated input voltage. The solution is to use a voltage detector with a configurable threshold. Additionally, to increase the system performance, a dual-voltage detector can be used to monitor the power output of the digital isolator with integrated power along with the input voltage. Table 9 provides some of the devices that can be considered along with the binary input module.

Table 9. Voltage Detector Selection

VOLTAGE DETECTOR	DESCRIPTION
TPS3780	Low-power, dual-voltage detector in a small µSON package
TPS3805	Dual-voltage detector

4.4 System Design Theory

This design is divided into the following major functional blocks:

- Protection of SAR and Delta-Sigma ADC analog inputs, reference generation and ESD protection
- Protection of digital input and digital output and generation of power supply for digital IO
- Power supply generation for analog Input signal conditioning from 5 V
- LCD bias supply, USB protection and sensor for diagnostics

This section provides details on the circuit design implementation.

4.4.1 Protection of SAR or Delta-Sigma ADC Analog Inputs

This section describes protection of ADC AC analog inputs against overvoltage and transients connected to SAR or Delta-Sigma ADCs.

4.4.1.1 Input Protection and Sensor Open Buffer for 16-bit SAR ADC ADS8588S

This section describes interfacing the AC signal output from a current transformer or potential transformer to the ADS8588S device, 16-bit high-speed 8-channel simultaneous-sampling ADC with bipolar inputs on a single supply. The ADC accepts input up to ±10 V and is rated for a maximum voltage of ±15 V. Flat-clamp surge protection diodes can be used at the input to protect against overvoltage and transients resulting in improved performance. An approach to showcase operation of the ADC without malfunctioning with input sensor open has been showcased by buffering the AC input using OPA2171 or TLV2171 Op-amp. TVS1400 has been used in this design to showcase overvoltage and transient protection. Bi-directional protection has been implemented for bipolar analog input. Design has been done to simplify connection to present ADC boards or EVM.
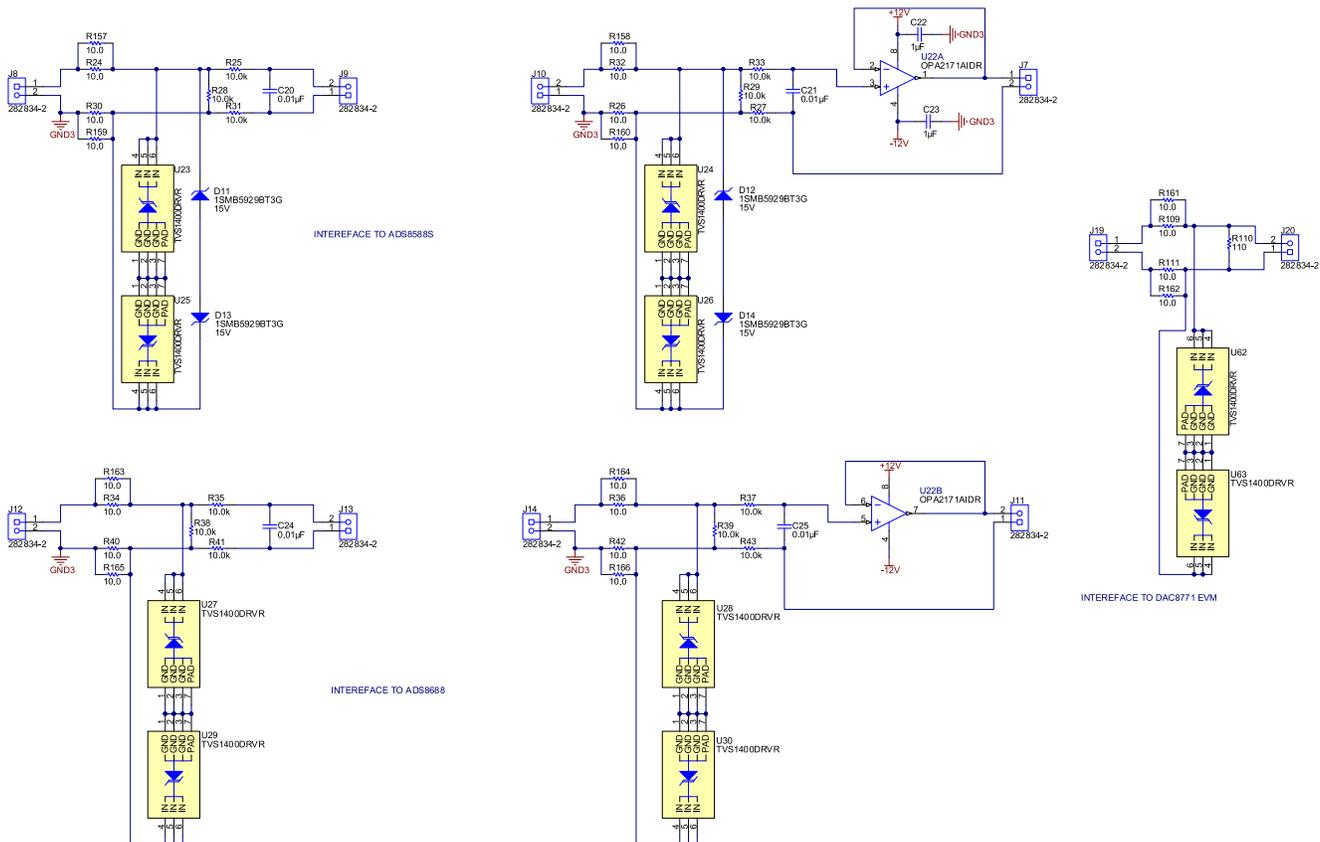

Figure 4. ADS8588S Interface Configuration Using Unidirectional TVS

Unidirectional TVS can be replaced with bidirectional TVS. U23 and U25 can be replaced with a single TVS, TVS1401, simplifying protection design. Similarly, U24 and U26 can be replaced with a single TVS, TVS1401. Figure 5 shows input protection using bidirectional TVS. Refer to the TVS surge current specification during the input protection design and series resistor selection.
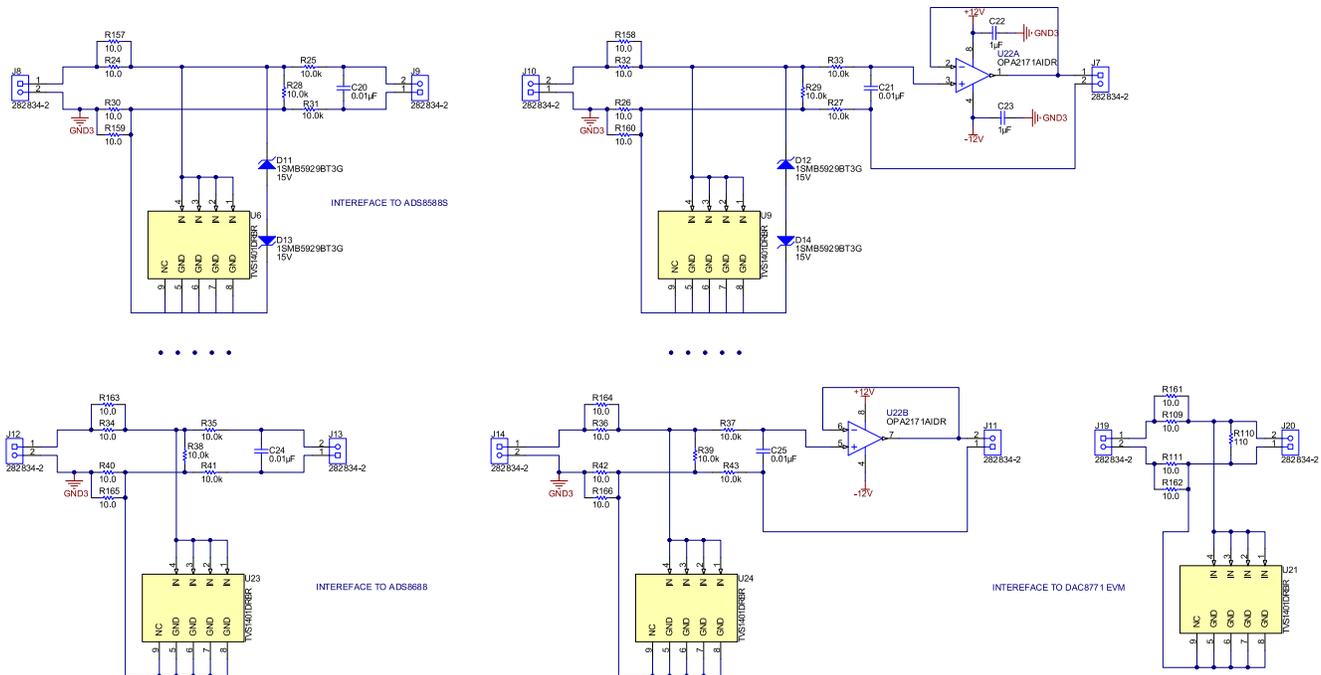

Figure 5. ADS8588S Interface Configuration Using Bidirectional TVS

4.4.1.2 Input Protection and Sensor Open Buffer for 16-bit SAR ADC ADS8688

This section describes interfacing the AC signal output from a current transformer or potential transformer to ADS8688, 16-bit 500-kSPS eight-channel single-supply SAR ADC with bipolar input ranges on a single supply. The ADC accepts input up to ±10.24 V and is rated for a maximum voltage of ±20 V. Flat-clamp surge protection diodes can be used at the input to protect against overvoltage and transients resulting in improved performance. An approach to showcase operation of the ADC with sensor open has been showcased by buffering the AC input using OPA2171 or TLV2171. TVS1800 has been used in this design to showcase overvoltage and transient protection. Bidirectional protection has been implemented as the AC analog input is bipolar. Design has been done to simplify connection to present ADC boards or EVM.
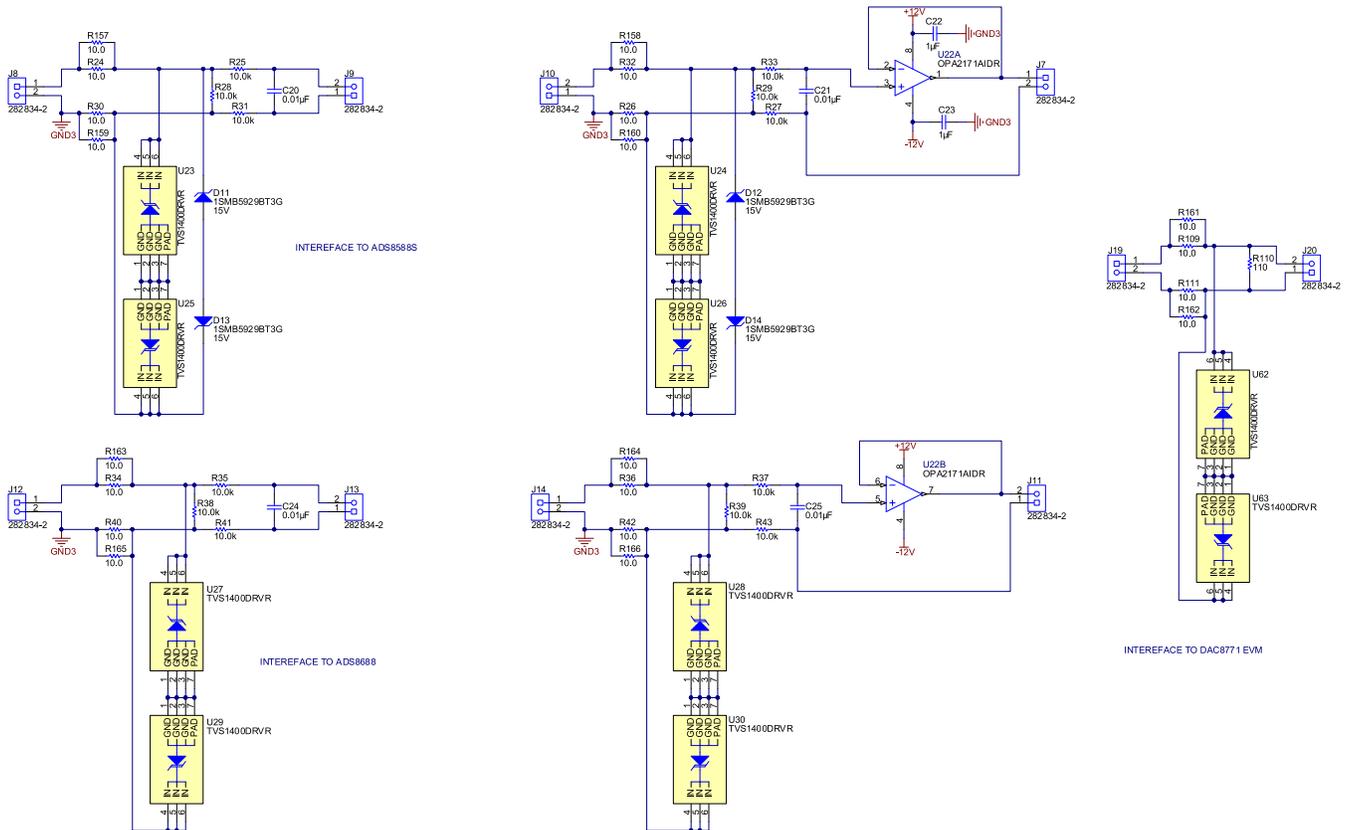

Figure 6. ADS8688 Interface Configuration Using Unidirectional TVS

Unidirectional TVS can be replaced with bidirectional TVS. U27 and U29 can be replaced with a single TVS, TVS1401, simplifying protection design. Similarly, U28 and U30 can be replaced with a single TVS, TVS1401. Refer to the TVS surge current specification during the input protection design and series resistor selection.
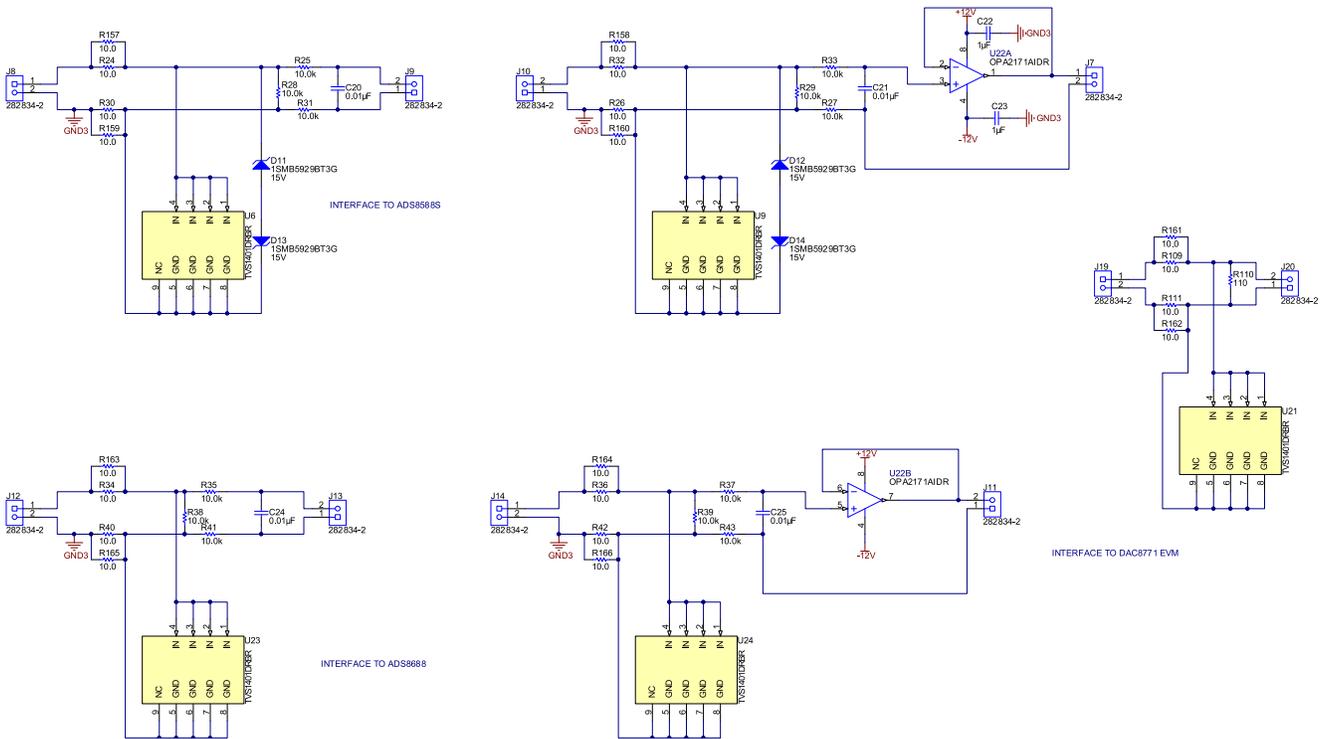
Figure 7. ADS8688 Interface Configuration Using Bidirectional TVS

4.4.1.3 Input Overvoltage Protection for 24-bit Delta-Sigma ADC

This section showcases protection of differential input SAR or Delta-Sigma ADCs against overvoltage. The design also showcases protection of the input against current transformer open condition using flat-clamp surge protection diodes. One of the two protection approaches can be used in the design. TVS0500 has been configured in back-back configuration for providing protection against overvotage. A differential to single-ended conversion has been showcased to interface differential input signals to a single-ended ADC. Design has been done to simplify connection to present ADC boards or EVM. In many applications bipolar input is converted to a single-ended output for measurement.
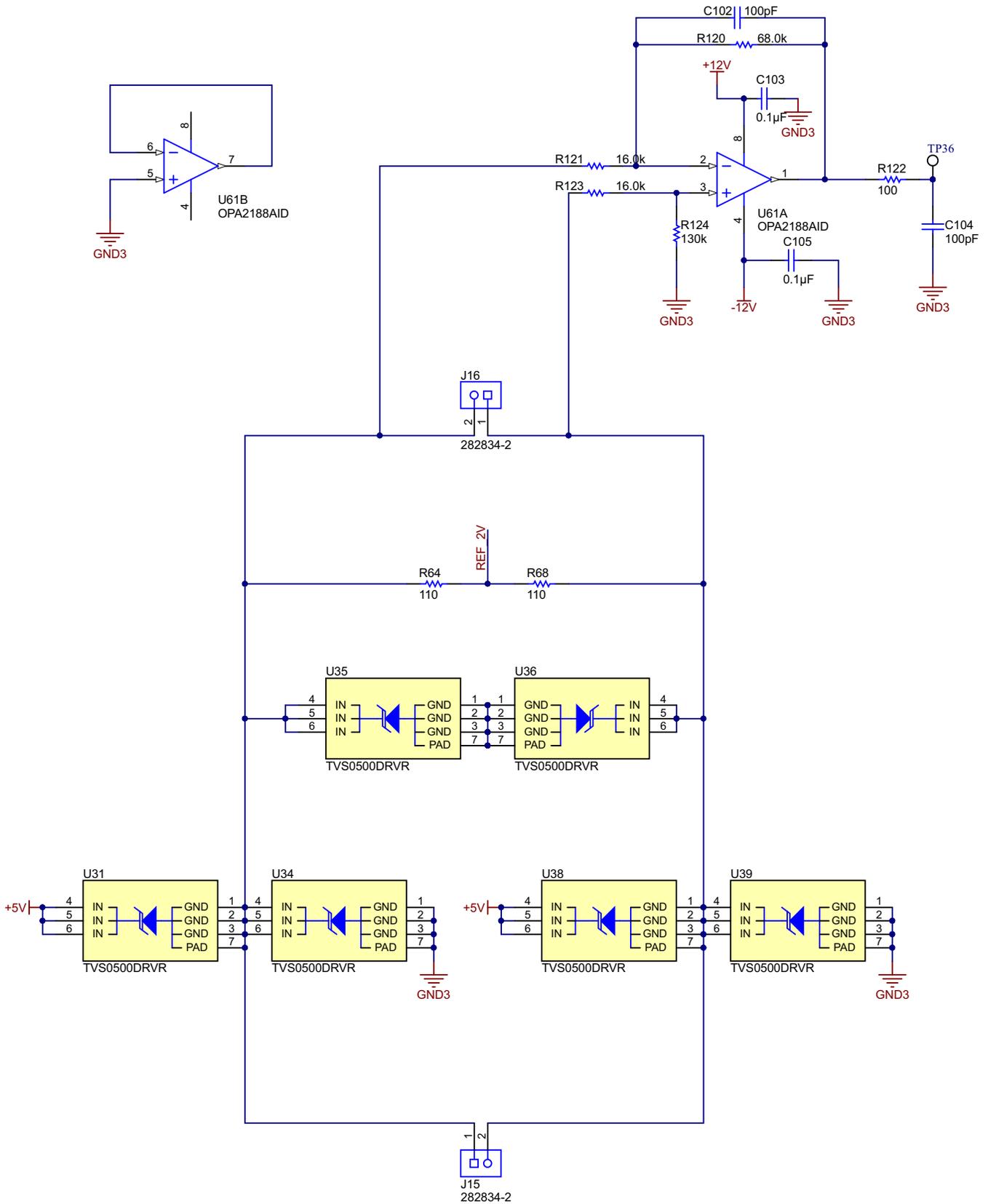
Figure 8. Delta-Sigma ADC Interface

> **NOTE:** U35 and U36 can be replaced with a single TVS0701, simplifying protection design.

4.4.1.4 *Reference Generation for precision ADCs, ESD Protection, and Monitoring*

This section showcases generation of high-accuracy, low-drift stable reference for connection to precision 16-bit SAR or 24-bit Delta-Sigma ADCs. SAR and Delta-Sigma ADCs require 4.094-V reference. When the Delta-Sigma ADC is configured for single-ended input configuration, the AC input has to be DC level shifted for measurement. The Output of the reference is buffered using Low-Noise, RRIO, CMOS op amp and the output is protected for ESD that can be used as an option depending on the placement of the reference. A Window comparator with under voltage and overvoltage detection is used to monitor the reference. In applications where differential interface is preferred THS4551 or THS4531 can be considered.
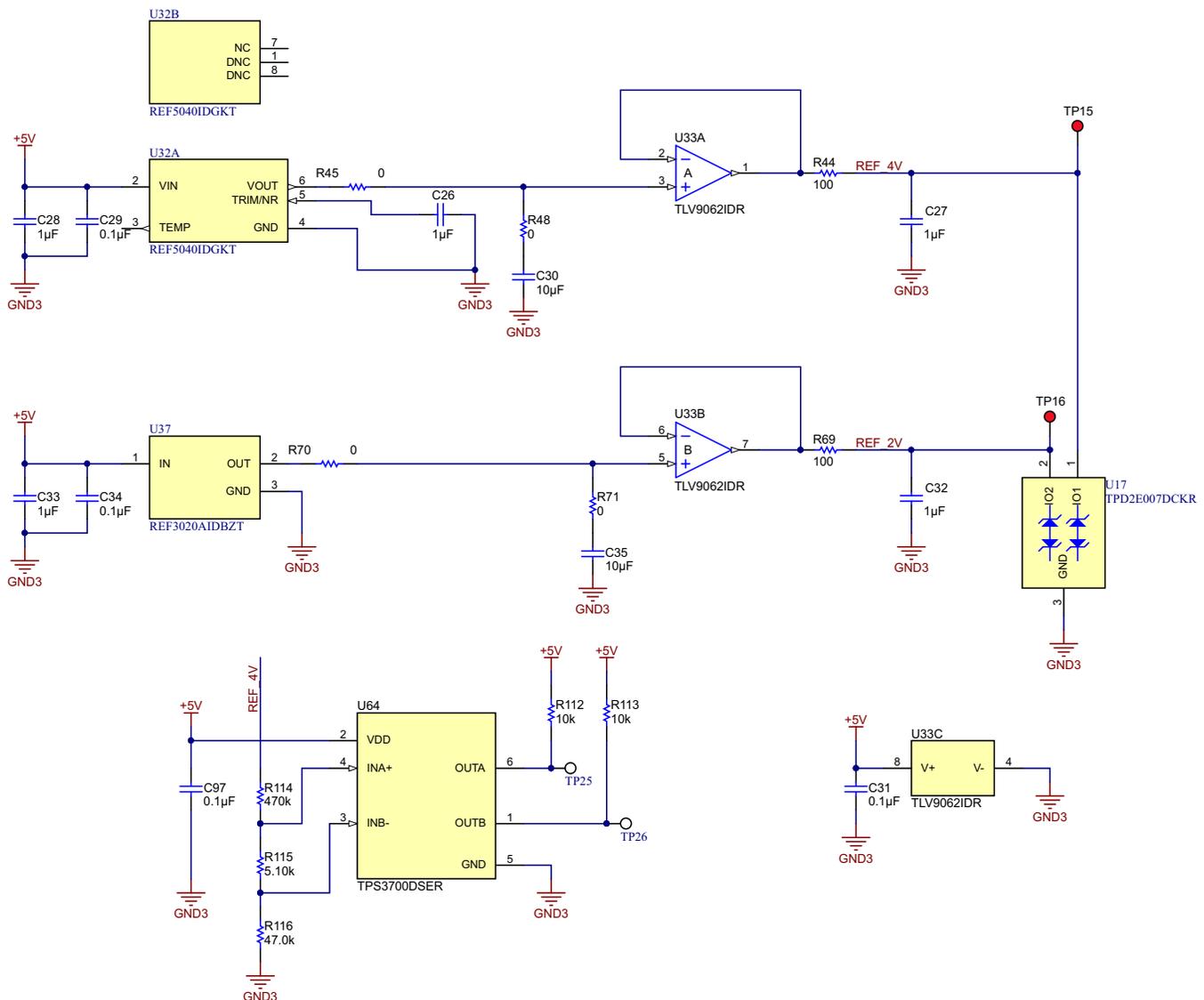

Figure 9. Delta-Sigma ADC Reference Buffer Protection

4.4.2   Binary Input Sensing and Digital Output Generation With Protection

This section describes the design and implementation of the binary input module and digital output modules.

4.4.2.1   Isolated 24-V or 48-V AC or DC Binary Input Using Isolated Digital Input Receiver With Self-Power

This section details using the digital input receiver ISO1212 for designing binary inputs with voltage rating of 24-V or 48-V inputs. This is an isolated digital input receiver with integrated power simplifying the overall system design. This is an advantage when designing 8-channel or 16-channel binary input module reducing the board size. This design showcases one 24-V input channel and one 48-V input channel. This design can be used for designing channel-channel isolated binary input module or group isolated binary input module. ISO1212 provides hysteresis between input high and input low. The input high and input low can be configured using resistors. In the design the 24-V input detects an input high of 14 V and 48 V detects an input high of 25 V. The host interface is a simple digital logic output that can be read by an MCU for detecting the status of the binary input module. The digital output can be buffered to drive larger loads or longer distance. The Inputs are protected against overvoltage and transients using bi-directional transient suppressors. Unidirectional devices can be used in application where there is no negative input expected. Propagation delay time for low to high transition is 150 ns and Propagation delay time for high to low transition is 20 ns. The device can be used for counting high-frequency pulses up to 2 MHz without any measurement uncertainty for HVDC applications. The Input capacitor is used for slow signal inputs (DC or 50, 60 HZ AC).
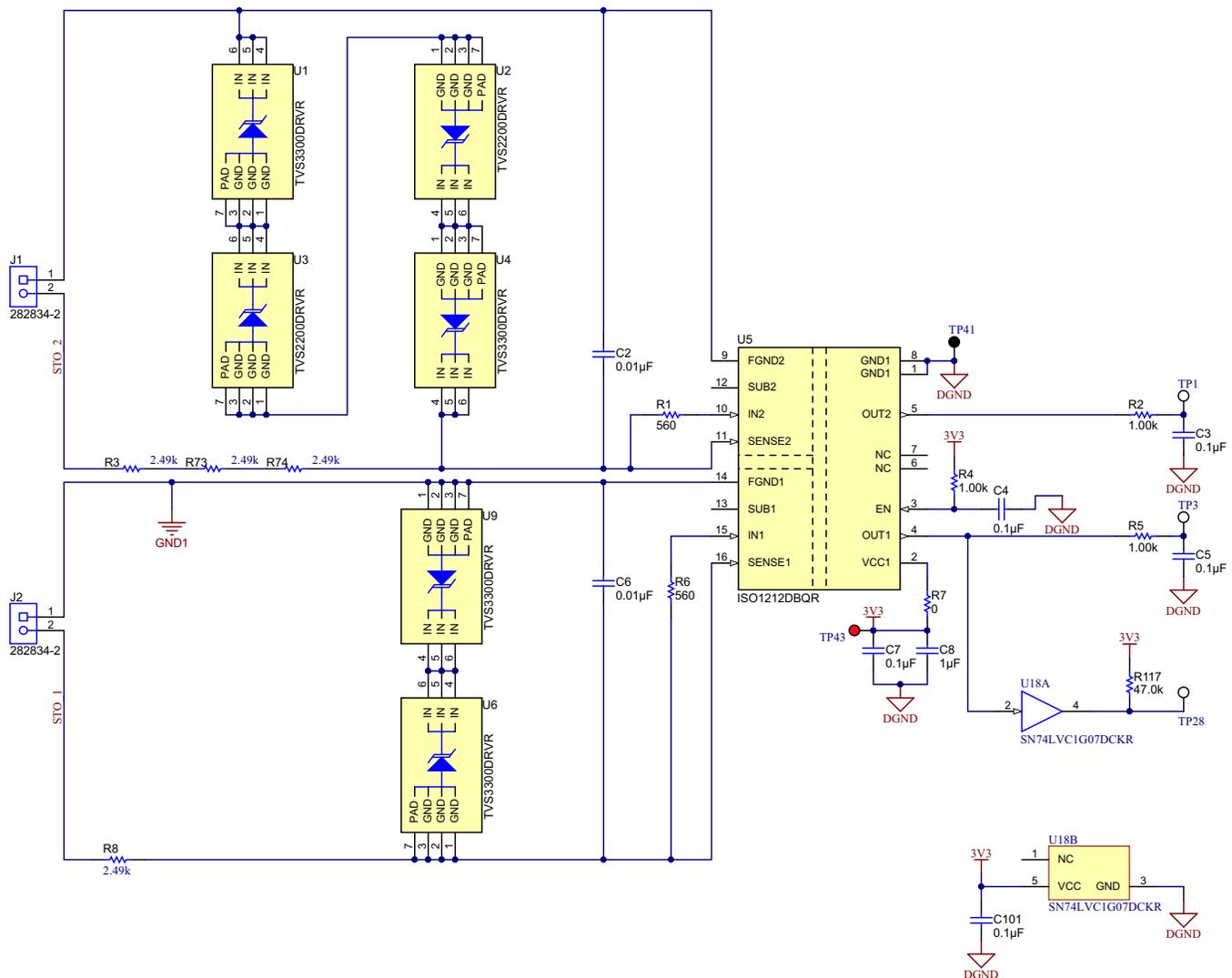
Figure 10. Isolated 24-V, 48-V Binary Input Receiver

> **NOTE:** U1 and U4 can be replaced with TVS3301 and U2 and U4 can be replaced with TVS2201 or TVS2701, simplifying protection design. Similarly, U9 and U6 can be replaced by TVS3301.

See the *Application and Implementation* section of *ISO121x Isolated 24-V Digital Input Receivers for Digital Input Modules* for more details and calculation of voltage input high and voltage input low. See *ISO1212 Isolated Digital-Input Receiver Evaluation Module* for designing 8-channel binary input modules.

The *Sub 1-W, 16-Channel, Isolated Digital Input Module Reference Design* has more details on the design of BIM

4.4.2.2 Voltage Detector or Comparator and Digital Isolator Based Binary Input with input Protection

This section showcases an alternative approach to designing Binary or Digital input module using a voltage detector or comparator. This can be used in interlocking applications or battery monitoring. The output delay is programmable and can be programmed using a capacitor and has been programmed as 10 ms while the voltage is increasing and has a fixed delay of 100 µs for decreasing voltage. The Detector threshold voltage is factory-programmed with multiple options. The device in the design detects voltage of 2.7 V (accuracy threshold voltage of ±2.5%) with Programmable Output Delay using an External Capacitor and Detector threshold hysteresis of less than 0.2 V. When programmable threshold is required, the

detect level and the hysteresis can be set using a comparator and this is shown as an alternative option in the following design. The Comparator has been set at a lower detect voltage to showcase design flexibility. The voltage detector output is interfaced to a digital isolator with integrated power. The Digital Isolator output supply is protected against overload using a load switch. The Load switch can be controlled externally. The resistor R89 can be mounted to power the device continuously. The Output of the voltage detector is gated with the isolated power for increases system performance. The voltage detector or the comparator does not withstand negative inputs and so a unidirectional transient suppressor is used for protection. Different options for threshold are available and can be chosen based on the input detection range and the output delay required. This design provides provision for TPS3803 for sensing a lower binary input voltage and when TPS3803 is used, SN74LVC1G32 is used instead of SN74LVC1G08.

See *TIDA-00847, Size and Cost Optimized Binary Module Reference Design Using Digital Isolator with Integrated Power* for alternative approaches to design of binary input modules.
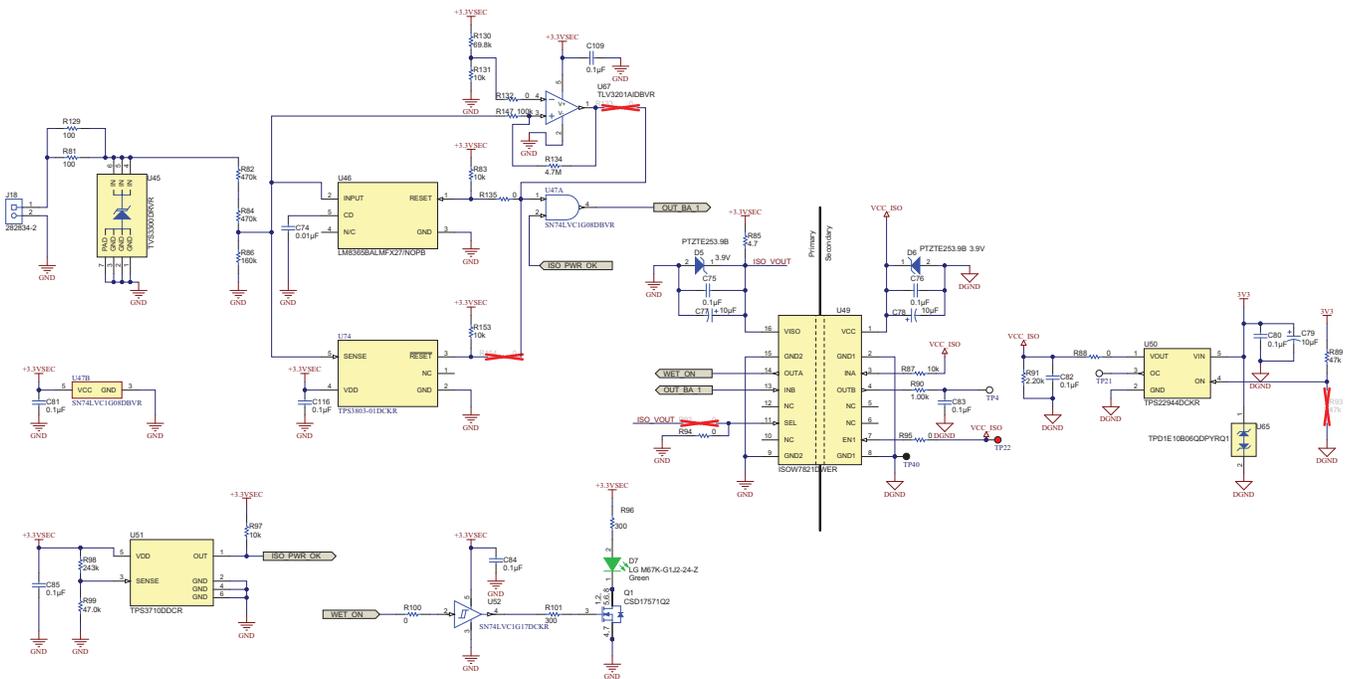

Figure 11. Voltage Detector Binary Input

4.4.2.3 Low-Side Digital Output Driver With Protection

This section showcases design of digital input module with low-side drive. This can be used to drive external relays or optocoupler for driving thyristors or coil of 24-V contactors in grid applications including an air circuit breaker. The DRV8803 device provides a 4-channel low-side driver with overcurrent protection. It has built-in diodes to clamp turnoff transients generated by inductive loads. Protection against overvoltage and transients are provided using flat-clamp transient suppressors. The device does not withstand negative inputs and so a unidirectional transient suppressor is used.
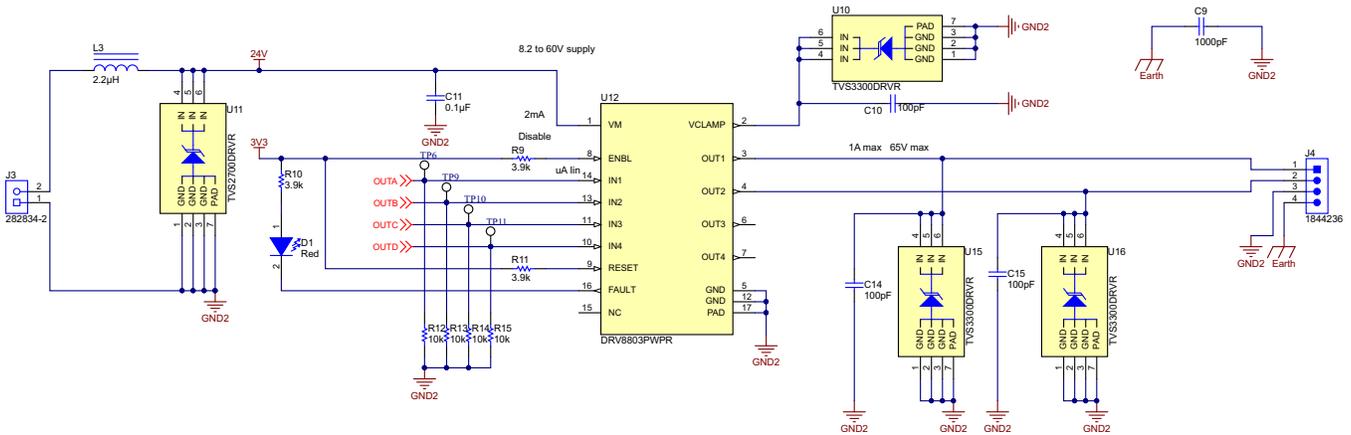

Figure 12. Low-Side Digital Output

4.4.2.4 High-Side Digital Output Driver With Protection and Digital IO Power

This section showcases design of digital input module with high-side drive using TPS27S100x 40-V, 80-mΩ single-channel high-side switch with open drain status output. The switch can drive up to 4-A load and the current limit can be set. The current limit is set to 1 A. The required control supply is generated from the 24-V input using SIMPLE SWITCHER 6-V to 42-V, 1-A power module which converts the 24-V input to 5 V and an LDO is used to convert the 5 V to 3.3 V. LMZ14201 can be configured for an output up to 6 V. The device does not withstand negative inputs and so a unidirectional transient suppressor is used. The turn-on delay time of the device is specified to be 50-µs maximum and the turn-off delay time is specified to be 80 µs maximum. The switching frequency that can be achieved is 5 kHz and suits most of the grip applications. The switch provides diagnostic features including Open Load Detection and output current limit for reliable operation of the device. The switch is protected for overvoltage using flat-clamp surge protection devices. The rating changes with the output and can be selected during the design.
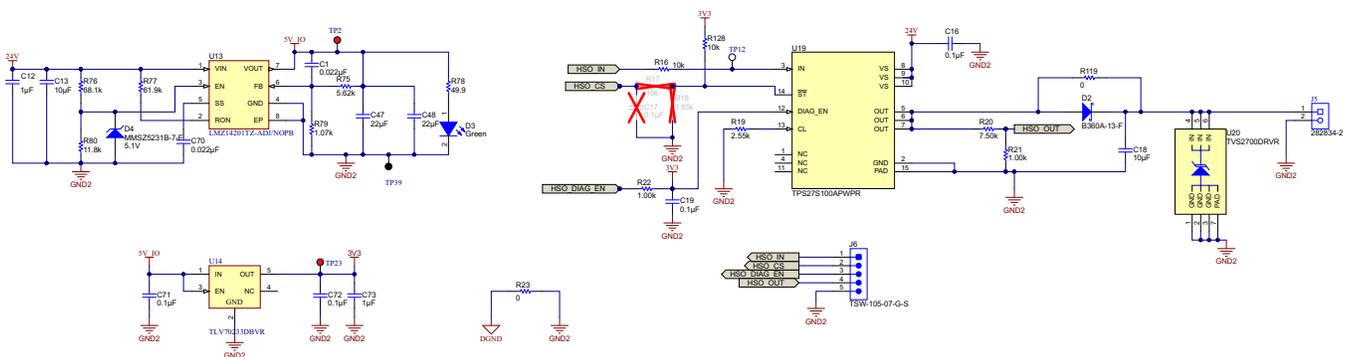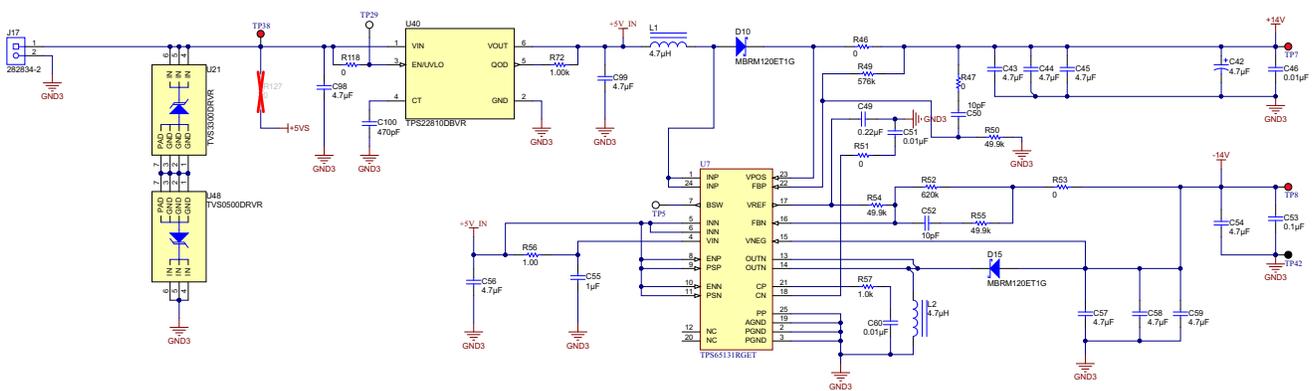

Figure 13. High-Side Digital Output Power

4.4.3 Power Supply Multi-Rail Generation From 5-V Input and Protection

This section describes generation of power supplies required for AFE operation used for measuring AC analog input using 16-bit SAR ADCs.

4.4.3.1 Load Switch and Split-Rail Converter

The ADS8688, ADS8688A and ADS8588S devices are specified to measure ±10-V input. For the purpose of signal condition, to power the op-amp, a dual supply is required. A commonly-available supply is a 5-V input and the required power supplies are generated from this supply. One of the simplest approaches to generate a dual supply is to use a split-rail converter with dual, positive and negative outputs – the TPS65131 device. The TPS65131 generates both positive and negative voltage outputs from a single supply. This converter has an internal boost converter control to step up the input voltage and an inverting converter control to derive negative voltage. External passives are designed to obtain ±14 V from the input. The inputs are protected against being overloaded using a load switch and protected against transients using bidirectional transients. The clamping voltage level for the negative input is lower and has been provided to avoid device failure when the DC supply has negative transients during power on or power off. In applications where there are no negative transients expected, single device can do the protection.

Figure 14. 5-V Dual-Output Supply

4.4.3.2 Bipolar Output LDO for Analog Input Op-Amps and LDOs for ADC Supply

The split-rail converter is followed by a dual-channel LDO TPS7A3901, consisting of a positive and negative LDO in a single package to simplify the system design. The output of the dual LDO is protected against overvoltage using transient suppressor working in overvoltage protection mode. Regulator outputs can be independently adjusted to obtain ±12 V. The 3.3-V and 5-V supplies required for operation of LDOs are generated using LDOs.

Figure 15. Dual-Supply ADC LDO

4.4.4 Other Hardware Features for Interface and Diagnostics

This section describes design and implementation of the following hardware features and can be used in multiple IO modules or compact or multifunction relay.

4.4.4.1 *USB Overload Switch With Overvoltage, Transient Protection Using TVS or ESD*

This section describes implementation of the following protections for USB interface:

- Overload protection using current distribution switch using fixed current or programmable current (programmed to 500 mA) switch with enable and fault output. Choose the overload switch based on the output current requirement.
- Overvoltage protection using flat-clamp surge protection diode
- ESD protection using 4-channel USB ESD solution with power clamp
- The overcurrent alarm output is buffered and connected to LED for indication of fault
- OC1 output is buffered to drive LED. SN74LVC1G14 is used to buffer. When LED control is required, SN74LVC1G125 single bus buffer with 3-state outputs can be used.

Figure 16. USB Overload ESD

4.4.4.2 *LCD Bias Supply With Output Protection and 12-V to 5-V DC/DC Nano Power Module*

The LCD bias is generated using a low-power DC/DC boost converter whose output can be programmed up to 28 V. In this design the output is programmed to 18 V. The output is protected for overvoltage and transient using the TVS1800 device , an 18-V flat-clamp surge protection diode. The 12-V to 5-V conversion is achieved by a SIMPLE SWITCHER nano module, an easy-to-use step-down DC/DC solution capable of driving up to 1000-mA load in space-constrained applications. Only an input capacitor, an output capacitor, a soft-start capacitor, and two resistors are required for basic operation. The input is protected against transients using flat-clamp surge protection diode. The output is configurable up to 6 V making it a choice for a number of IO module applications.

Figure 17. LCD Bias 12-V, 5-V Module

Flat-Clamp TVS Based Reference Design for Protection Against Transients for Grid Applications

4.4.4.3 5-V Input Reversal, Output Overload, and Load Switch

Some of the common protection provided on the DC input voltage includes input reversal protection, provision to isolate the input from the load during output overload, and output load switching with overload protection. This section showcases protection of 5-V input against transients using TVS and input reversal using ideal diode controller, protection of output against transients, overload using eFuse, and switching output load based on the requirement with overload protection using load switch. Some of the protections implemented include:

- LM74610-Q1, CSD17577Q3A, and TVS0500 for transient and input reversal protection
- TPS25921A, TPS259521 eFuse for overload protection with varying load current, accurate load monitoring, and fast overvoltage protection
- TPS22946, TPS22965 load switch with low ON resistance, selectable output current, and optional quick output discharge
- TVS0500, flat clamp TVS for input transient protection

    Figure 18 showcases different protection schemes for a 5-V input.
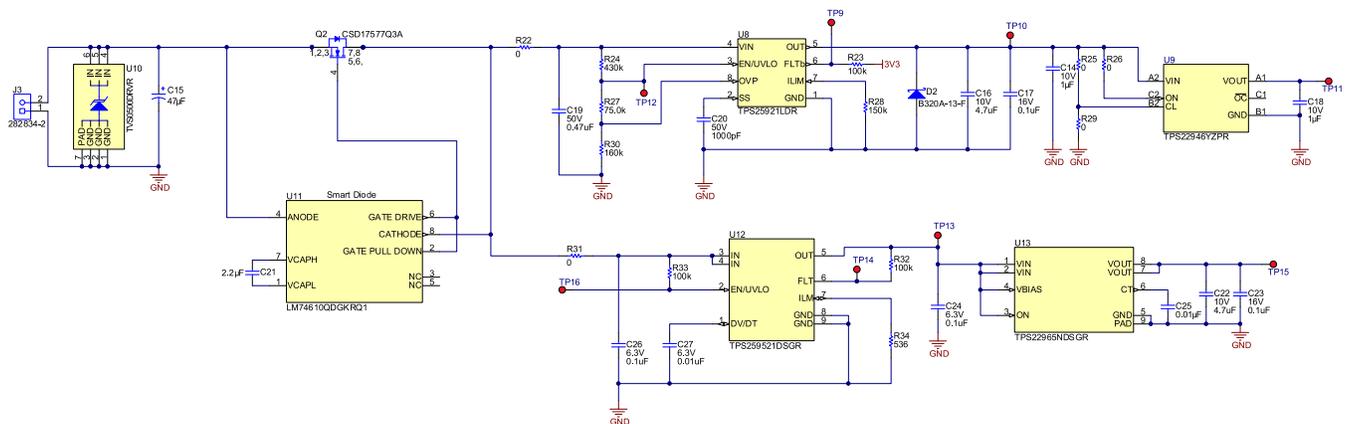
Figure 18. DC Input Protection for 5-V Input

4.4.4.4 12-V or 24-V Input Reversal and Output Overload Protection

Some of the common protection provided on the DC input voltage includes input reversal protection, provision to isolate the input from the load during output overload, and selection of DC input source using a power mux. For 12 V, the design showcases input reversal protection using ideal diode controller, output overload protection using eFuse, switching between two 12-V inputs using a power mux, input protection against transients using TVS, and overload using eFuse. For 24 V, the design showcases protection of input against transient and output overload with a configurable current limit. Some of the protections implemented include:

- LM74610-Q1, CSD18543Q3A for input reversal protection with low ON resistance
- TPS2121 for switching between two DC inputs
- TPS26600, TPS259631 eFuse for overload protection up to 60 V with programmable overload current, accurate monitoring, and integrated reversal protection
- TVS1400, TVS3300, flat clamp TVS for protection against transients

Figure 19 showcases different protection schemes for 12-V and 24-V inputs.
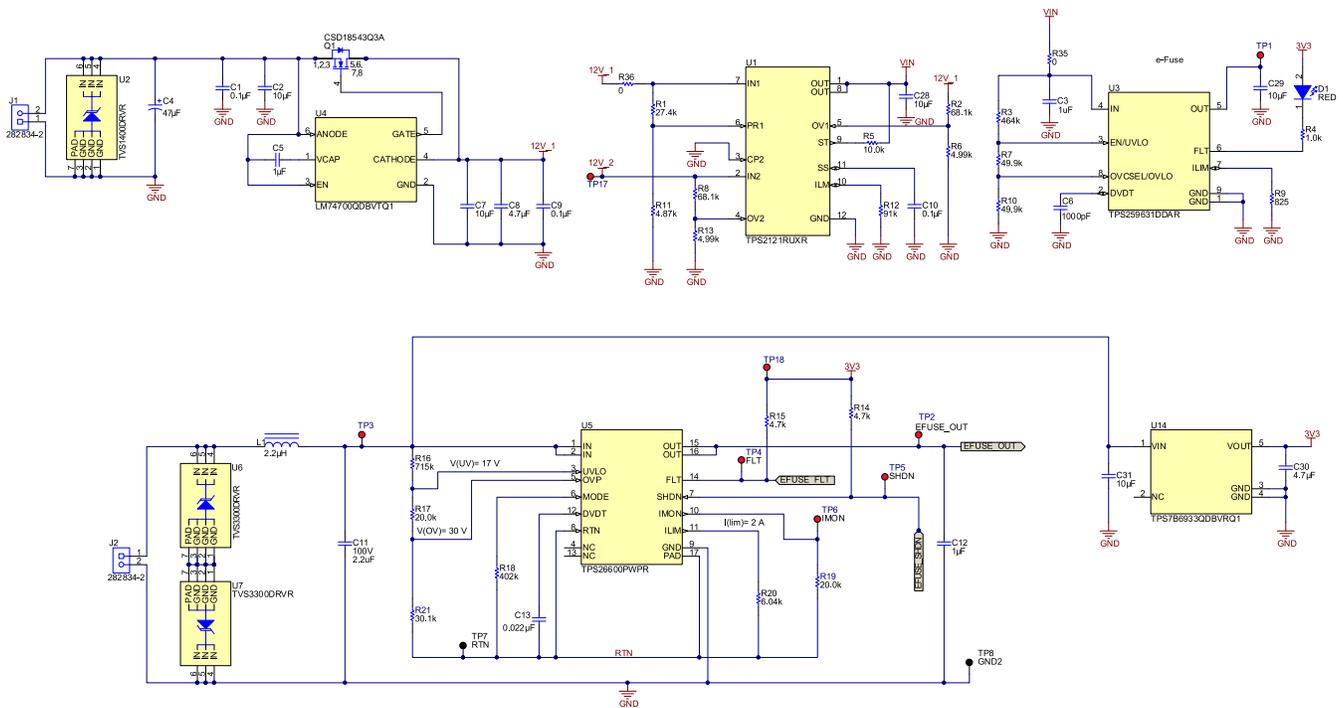
Figure 19. DC Input Protection for 12-V and 24-V Inputs

4.4.4.5 Sensors for Diagnostics

A description of multiple environment sensors that can be used for diagnostics and performance improvement of analog input or digital input or output modules follows:

A humidity sensor can be used along with the binary input module for control of the wetting current. The wetting current control is used to remove the oxidation on the contacts. The HDC1080 humidity sensor with temperature sensor can be used to dynamically configure the wetting control.

Temperature sensor and magnetic sensors can be used along with an AC analog input module for improving the performance including compensation of the errors due to temperature variation and detection of high magnetic field that influences the AC analog input module. The temperature sensor can be digital or analog depending on the interface and the magnetic sensor can be digital switch or analog output with indication of direction of the field.
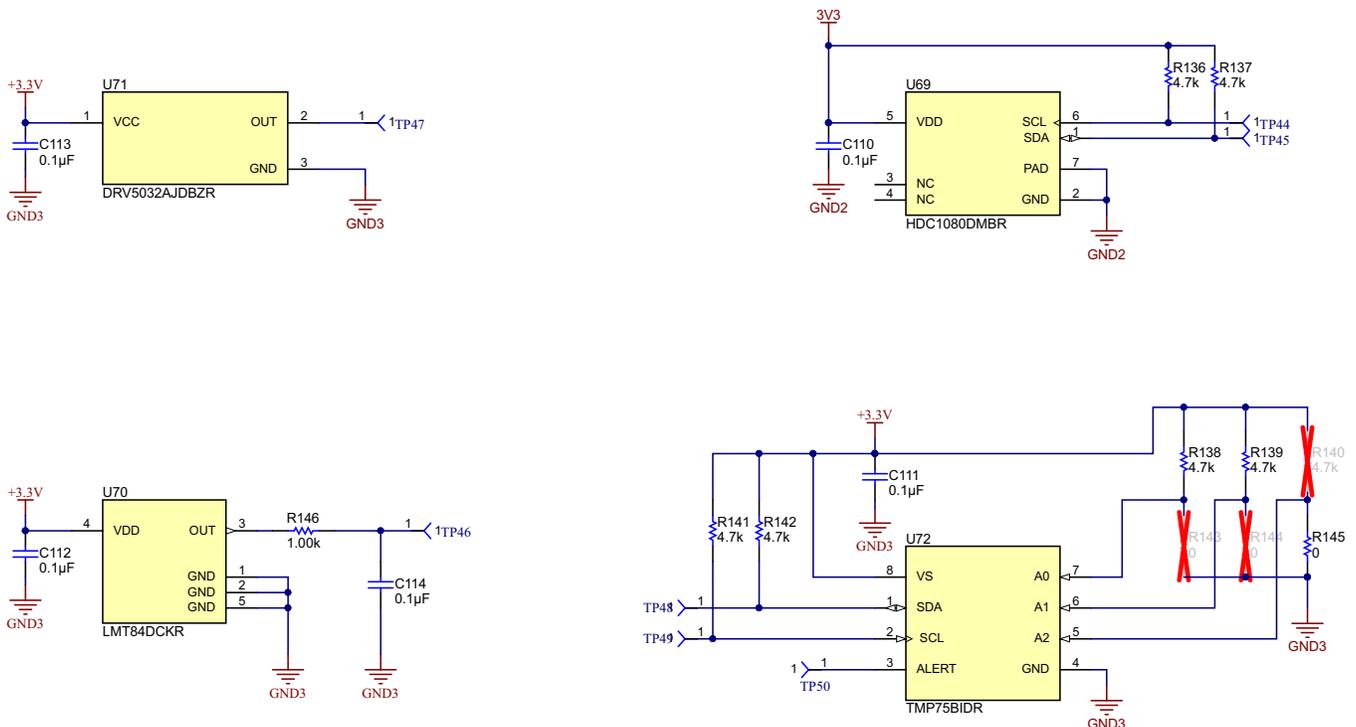
Figure 20. Sensor Diagnostics

4.4.5 Simulation of Circuit Functionality With Protection Devices

Simulations have been performed to analyze the flat-clamp surge clamping behavior of the surge protection diode family interfaced to:

* ADS8588S or ADS8688 or ADS8688A for overvoltage and transient behavior
* Binary input with voltage detector or isolated digital input receiver
* LDC bias power supply generation simulation with overvoltage protection

These simulations files can be used for analysis of the flat-clamp surge device behavior and surge currents amplitude for different levels of surge input for design of protections and board layout.

4.4.6 Board Layout

This section describes the board layout approach and guidelines implemented in the design TIDA-010008.

4.4.6.1 *Board Segregation*

The board layout has been planned and segregated into two parts:

- Analog input and output including power and protection
- Digital input and output including power and protection plus interface protection

The two sections are laid out on the same PCB with V-grooves between the digital and the analog section. Figure 21 shows the portioning of the board and the power supply modules resulting in reduced board size and improved efficiency.

Digital Input With Isolated Digital Input Driver, Digital Isolator With Power, Digital Output
With Low-Side or High-Side Driver, LCD Bias and USB Overload Switch With ESD Protection

24-V Input Simple Switcher With 1-A Output Current

12-V Input Nano Module

Analog Input With Interface to ADCs, DACs, and TCS Protection
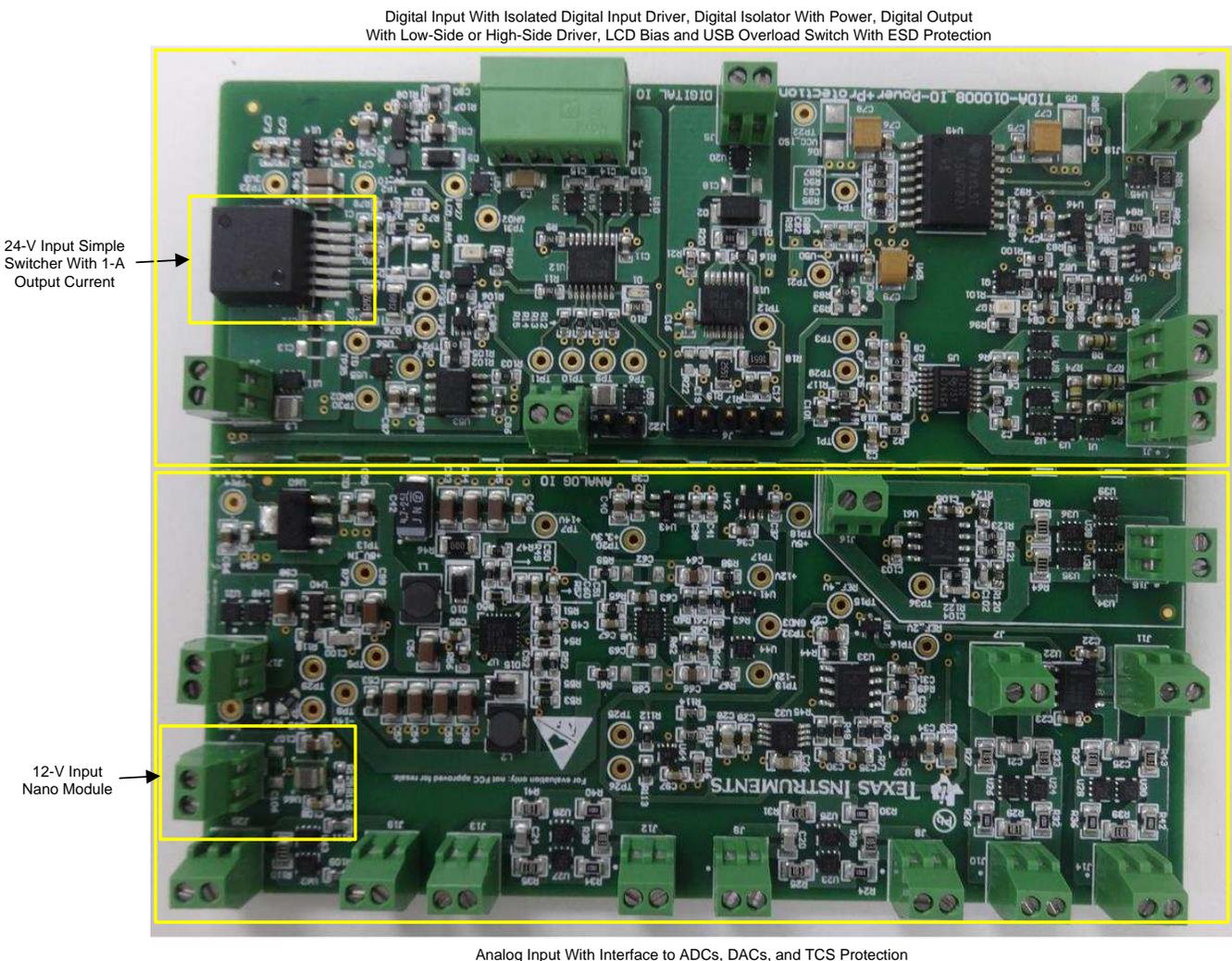
Figure 21. Board With Labels

4.4.6.2   PCB Layout for Flat-Clamp Surge Protection Device

The optimum placement of transient protection device is close to the connector. EMI during a surge event can couple from the trace being struck to other nearby unprotected traces, resulting in early system failures. The PCB designer must minimize the possibility of EMI coupling by keeping any unprotected traces away from the protected traces which are between the TVS and the connector. Route the protected traces straight. Eliminate any sharp corners on the protected traces between the Flat-Clamp Surge Protection Device and the connector by using rounded corners with the largest radii possible. Electric fields tend to build up on corners, increasing EMI coupling. Refer to the layout section of the *TVS3300 33-V Flat-Clamp Surge Protection Device Data Sheet* for more details.

4.4.7   TIDA-010008 Advantages

The TIDA-010008 design demonstrates the following functionalities and hardware features used in a number if grid and other industrial EEs:

- Protection of analog inputs (output of current transformer or potential transformer) used for measuring mains voltage in LV, MV, and HV grid applications using flat-clamp surge protection devices which additionally used also overvoltage protection
- Buffering of sensor input (Current or voltage) to avoid malfunctioning of the ADC input and output when the input sensor (Current or voltage) is open
- Simple way of generating ±12-V regulated DC power supply from a 5 V (commonly available voltage rail) for application using ADS8688 or ADS8688A and ADS8588S ADCs with input range up to ±10.24 V
- Showcases generation of 5 V form 24 V or 12 V which are the other common rails available increasing design flexibility and applications
- Generation of 4.096 and 2.048-V reference that can be used with most of the precision ADCs including ADS131E08, ADS131A04, ADS8588S, ADS8688 and ADS8688A and protection against ESD based on the application requirement.
- Conversion of differential input from a current transformer of potential transformer to single-ended output used with single-ended or pseudo differential ADCs including ADS8588S, ADS8688 or ADS8688A
- Interface to DAC with transient and overvoltage protection to testing DC analog interface output DACs including DAC8771 and DAC8775
- Input reversal protection with low power consumption
- Output overload protection and input isolation using eFuse for 5-V, 12-V, and 24-V inputs with varying load current
- Output load switching and overload protection using load switch
- Protection of binary input with voltage rating of 24 V or 48 V using flat-clamp transient protection devices
- Sensing of AC or DC binary input rated for 24 V or 48 V using isolated digital input receiver with self-power and sending the voltage input using voltage detector or comparator with provision to extend the input range up to 300 V by changing the potential divider values
- Protection of Digital output against transients and overvoltages and generation of digital output using high-side or low-side drivers with option to control the outputs and limit the current
- Protection of USB 5-V output against overload using overload switches with fixed or configurable current limit and ESD protection for both USB signals and power signals
- Protection of LCD bias supply output and generation of LCD bias supply using simple DC/DC boost converters

These hardware features are configurable and simple to design, have high efficiency and can be used in multiple IO modules in grid applications including protection relay, terminal unit, multifunction relay, recloser, generator monitoring and power quality analyzer.

5 Hardware, Software, Testing Requirements, and Test Results

This section provides the following test data for validating the design:

- Required hardware and software connection
- Functional testing
- Surge testing
- Summary of test results

5.1 Required Hardware and Software

The following setup is required for the functional testing of TIDA-010008:

- Tested TIDA-010008 board
- Programmable DC voltage source capable of varying between 5 V to 24 V
- Electronic load for testing the power supply output
- Digital multimeter for measuring the DC or AC voltages
- EVM as required to connect to the design for performance and surge testing

5.2 Testing and Results

This section provides connector details for testing the boards. Testing of the design includes the following:

- Functional testing
- Surge testing

5.2.1 Test Approach

The design is broadly classified into three major function blocks:

- Generation of power supply from 5 V or 12 V or 24 V, overload protection for USB, monitoring and diagnostics
- Analog input
- Digital input and output

5.2.1.1 Test Setup for Power Supply and Other Hardware Features

This section provides details of the connection and the test points for connecting the power supply input and measuring the power supply outputs.
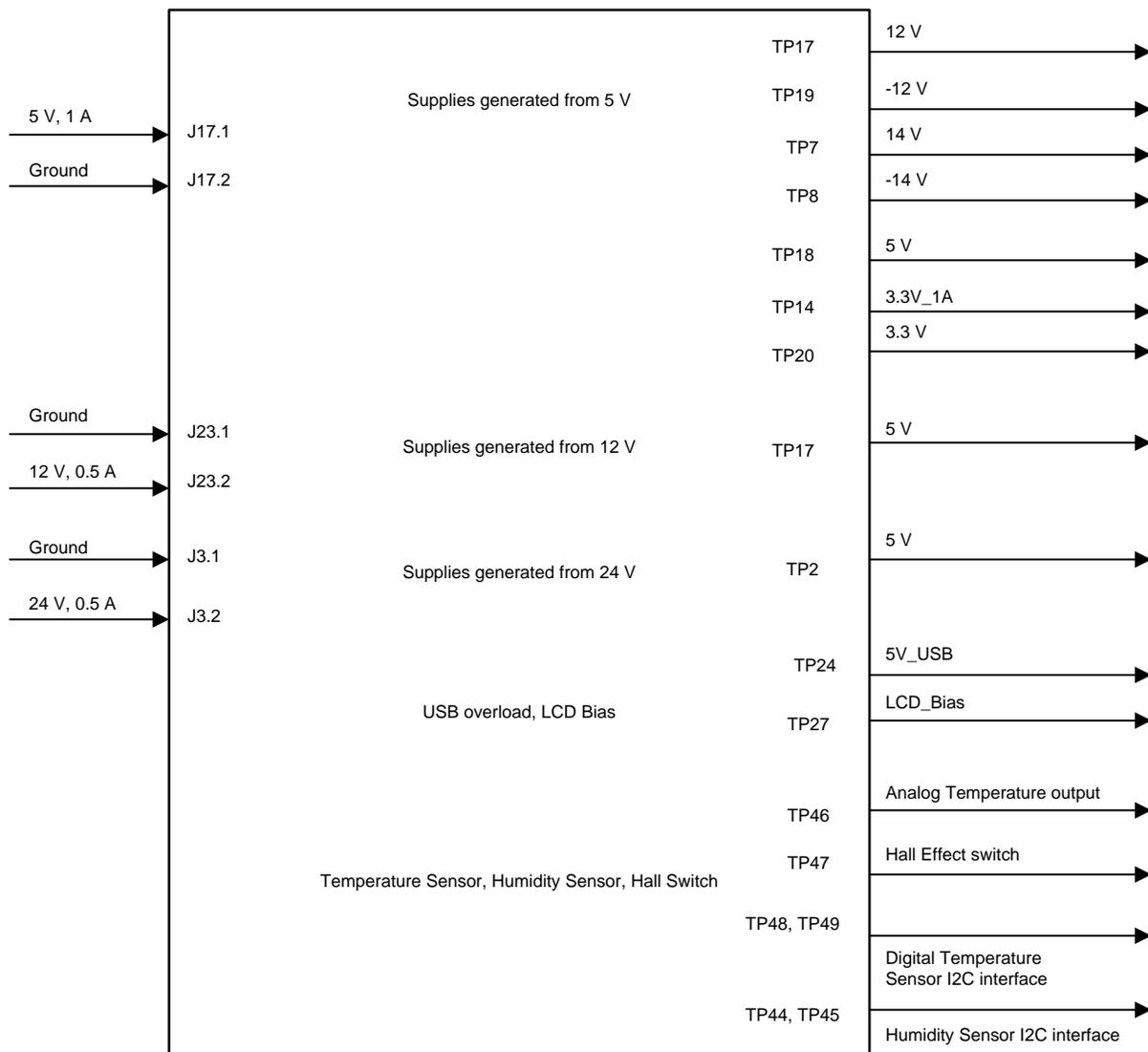
Figure 22. Setup Power Supply

5.2.1.2 *Test Setup for Analog Input Output Testing*

This section provides details of the connection and the test points for connecting the analog inputs for ADCs and outputs to DAC with protections for overvoltage and surge.

Figure 23. Setup AIO

Copyright © 2018–2019, Texas Instruments Incorporated
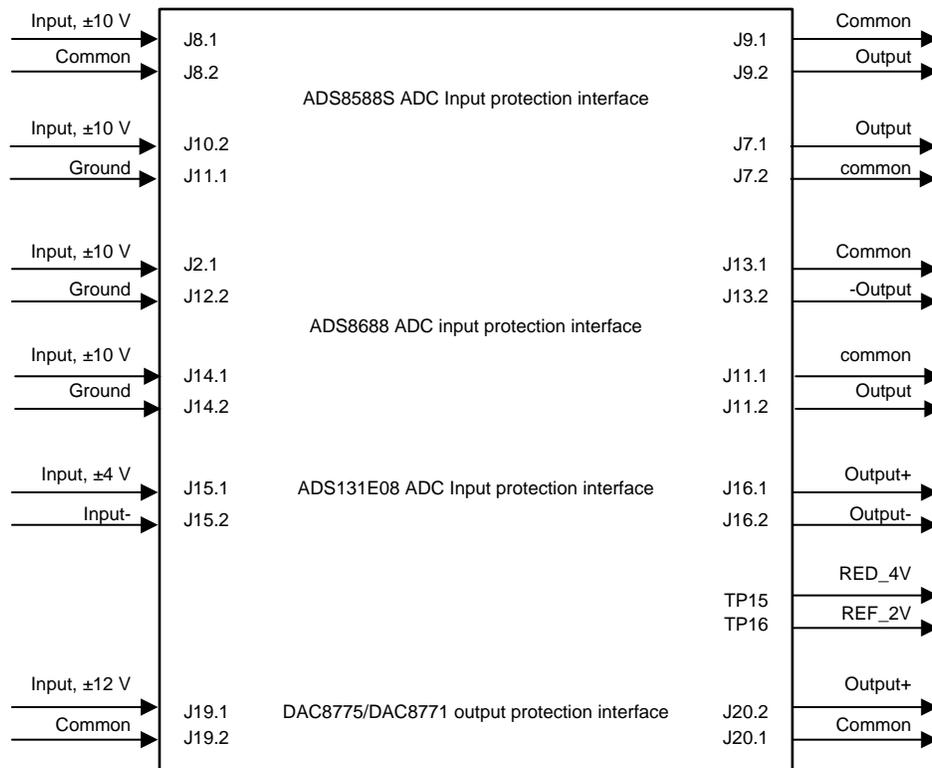
5.2.1.3 *Test Setup for Digital Input and Digital Output Testing*

This section provides details of the connection and the test points for connecting the digital input and digital output with protections for overvoltage and surge.

Figure 24. Setup DIO

Copyright © 2018–2019, Texas Instruments Incorporated
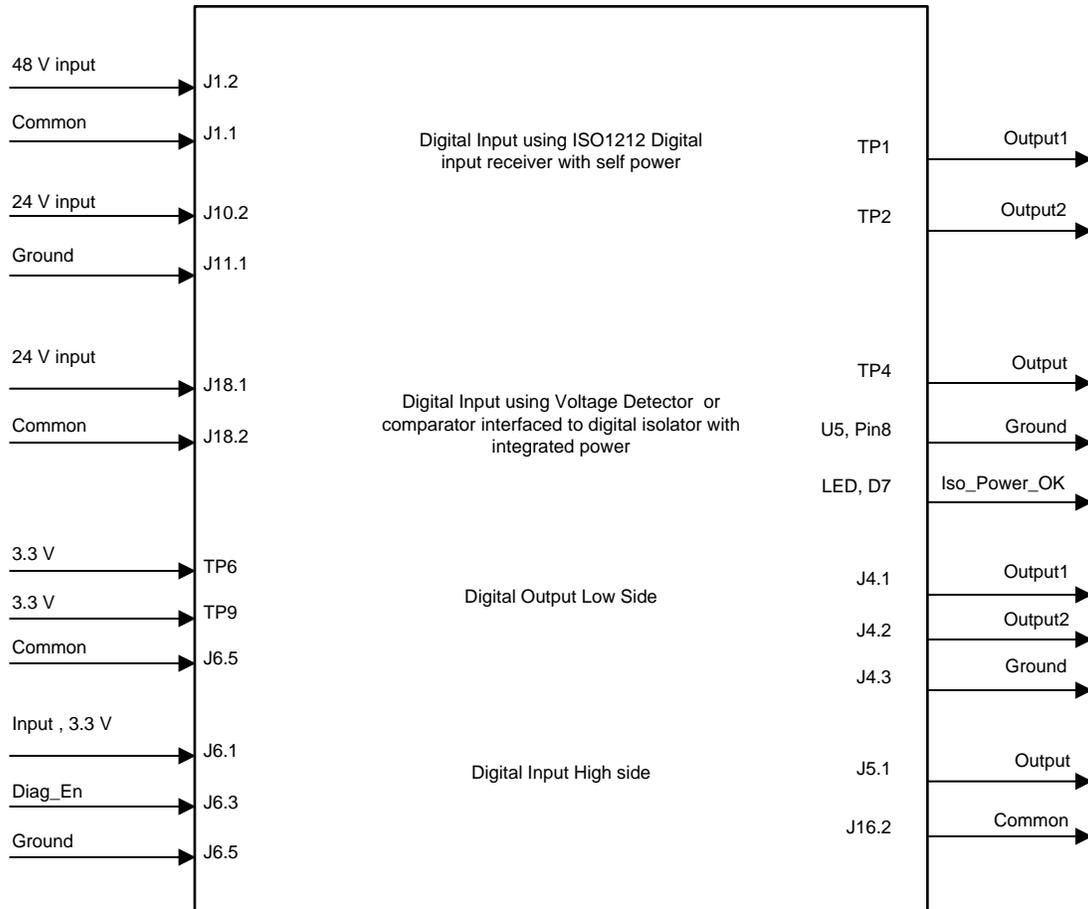
5.2.2 Functional Testing

This section provides details of the functional tests done with design TIDA-010008 and observations.

5.2.2.1 *Digital or Analog IO Power*

Table 10 details of the tests done and the test observations for the power supply section for analog and digital IO.

Table 10. Power Supply Functional Test Observations

SUPPLY TYPE	INPUT	OUTPUT	MEASUREMENT, V
5-V DC input for Analog IO	J17-1: Input	TP17: 12 V	11.55
	J17-2: Ground	TP7: 14 V	15.1
		TP19: –12 V	–11.85
		TP8: –14 V	–15.2
		TP18: +5 V	4.997
		TP14: 3.3V_1A	3.308
		TP20: 3.3 V	3.307
12-V input DC/DC for Analog IO	J23-1: Ground	TP17: 5-V output	4.85
	J23-1: 12-V input		
24-V input DC/DC for Digital IO	J3-2: Input	TP2: Output_5V	5.11
		TP23: Output_3.3V	3.30
	J3-1: Ground		
Digital Input Isolated Power Supply	J3-2: Input	U49–16: 3.3 V	3.33
		R97: Input OK	3.3
		Efficiency: 20–100 mA	39–47%
	J3–1: Ground	U49–9: 0 V	
LCD Bias	J3-2: Input	TP27: Output	18.58
	J3-1: Ground	TP31: Ground	
USB	J3-2: Input	TP24: Output	5.11
	J3-1: Ground	TP30: Ground	
Temperature	TP46	Analog Output	OK
	TP44, TP45	I2C interface for Humidity Sensor	OK
	TP48, TP49	I2C interface for digital temperature Sensor	OK
	TP47	Hall switch	OK

5.2.2.2 Digital Input and Digital Output Functionality

This section provides details of the tests done and the test observations for the digital input and digital output section of the design. Table 11 lists digital io functional test observations.

Table 11. Digital IO Functional Test Observations

IO TYPE	INPUT	OUTPUT	OBSERVATIONS
Digital input receiver, 48-V input	J1-1: Ground	TP1: Output	Output high: 25 V
	J1-2: 48-V input	U5 Pin 1: Ground	Output low: 23 V
Digital input receiver, 24-V input	J2-1: Ground	TP3: Output	Output high: 14 V
	J2-2: 48-V input	U5 Pin 1: Ground	Output low: 13 V
Voltage detector or comparator based digital input, 24 V	J18-1: Input	TP4: Output	Output high: 22 V
	J18-2: Ground	U49-8: Ground	Output low: 18 V
	D7, LED	Isolated power status indication	OK
		Wetting control output LED indication	OK
Digital output, low side	TP6: 3.3-V input	J4-1: Output1	Output low: OK
	TP9: 3.3-V Input	J4-2: Output2	Output low: OK
	Enable: R9 open		
	Reset: R11 removed	J4-3: Ground	
Digital output, high-side	J6-1: 3.3-V input	J5-1: Output	24 V
	J6-5: Ground	J5-2: Ground	

NOTE: The digital output, high side and low side was tested using an LED, 24-V rated relay, and external load.

Figure 25 shows the waveform for 50-Hz AC, Binary input waveforms with upper threshold and lower threshold. The AC input is overlapped with the digital output. Note that for AC input, the threshold is based on the peak value.
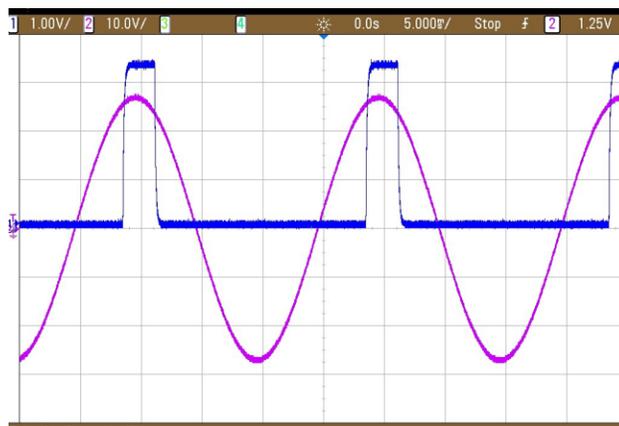
Figure 25. AC Binary Input

5.2.2.3 *Analog Input for SAR or Delta-Sigma ADC*

This section provides details of the tests done and the test observations for the analog input section of the design

Table 12. Analog Input Section Test Observations

IO TYPE	INPUT	OUTPUT	OBSERVATIONS
ADS8588S input	J8-1: Input	J9-2: Connector Output same as input	5.30 V
	J8-1: Input	J9-2: Connector Output clamped to 18 V	OK
	J8-2: Ground	J9-1: Ground	
ADS8588S with Buffer for sensor open	J10-2: Input	J7-1: Output	5.30 V
	J10-1: Ground	J7-2: Ground	
ADS8688 input	J12-1: Input	J13-2: Connector Output same as input	5.30 V
		J9-2: Connector Output clamped to 22 V	OK
	J12-2: Ground	J13-1: Ground	
ADS8688 with Buffer for sensor open	J14-1: Input	J1-2: Output	5.30 V
	J14-2: Ground	J11-1: Ground	
Delta-Sigma ADC interface	J15-1: Input+	J16-1: Output+	1.063 V
	J15-2: Input-	J15-2: Output-	1.063 V
		TP36: Op-amp output, Gain × 4 of input	3.995 V
Delta-Sigma ADC interface		TP15: REF4V_Output (REF5040 or REF3440)	4.094 V, 4.096 V
		TP16: REF2V_Output	2.043 V
		TP25, TP26 (Reference window comparator output)	OK

Figure 26 shows the waveform with input and output following each other when the applied voltage is less than the TVS breakdown threshold voltage.

Figure 26. ADC Input With TVS Below Breakdown

Figure 27 shows the output voltage clamping with respect to the input after the input voltage exceeds the breakdown threshold voltage of the TVS and also the flat clamping with increase in voltage.

Figure 27. ADC Input With TVS1400 Breakdown

5.2.2.4   Other Hardware Features for IO and Interface

This design provides additional hardware features used for LCD interface or USB interface protection or diagnostics. This section provides details of the tests done and the test observations.

Table 13. Hardware Features Functional Test Observations

DEVICES	DESCRIPTION	OBSERVATION
TPS26624	Interface of design 24 V to eFuse EVM with current limit programmed to 150 mA	Normal operation: OK Protection : OK
TPS22810	5-V input load switch	Normal operation: OK Protection : OK
TPS22944	Digital isolator supply output overload protection	Normal operation: OK
TPS61041	LCD power supply bias supply generation	Output voltage: >18.5 V
TPS2051B	USB, single, current-limited, power-distribution switch	Normal operation: OK Protection : OK
TPS2553	Adjustable, active high, constant-current, current-limited power-distribution switch	Normal operation: OK Protection : OK
HDC1080	HDC1080 low-power, high-accuracy digital humidity sensor with temperature sensor	Measurement performance as per specification including diagnostics
TMP75	Temperature sensor with I2C/SMBus interface in industry standard LM75 form factor and pinout	Measurement performance as per specifications
LMT84	1.5-V capable, 10-µA analog output temperature sensor in SC70 and TO-92	Analog output : OK
DRV5032	Ultra-low power 1.65-V to 5.5-V Hall-effect switch sensor	Digital output : OK
LM74700-Q1, LM74610-Q1, CSD17577Q3A, CSD18543Q3A	Smart diode or ideal diode controller for input reverse protection	DC output: OK
TPS26600	60-V, 2-A industrial eFuse with integrated reverse-input polarity protection used for 24-V input	DC output: OK
TPS259631, TPS25921A, TPS259521	18-V eFuse with configurable load current used for 12-V input	DC output: OK
TPS22946, TPS22965	5-V load switch with varying load current and output control	DC output: OK
TPS2121	12-V power mux	DC output: OK

Copyright © 2018–2019, Texas Instruments Incorporated

5.3 *Surge Testing*

Table 14 provides details of the surge testing that was performed on the design board. The surge was applied with 42-Ω impedance.

Table 14. Surge Test Observations for IOs and Power Supply

INPUT TYPE	SURGE LEVEL V	PERFORMANCE BEFORE SURGE TEST	PERFORMANCE AFTER SURGE TEST	OBSERVATIONS
TVS3300 or TVS3301 with output load resistor	100	Ok	OK	Criteria B
	250	OK	OK	Criteria B
	500	OK	OK	Criteria B
	1000	OK	OK	Criteria B
	1500	OK	OK	Criteria B
ADS8588S input with TVS1400 or TVS1401 input	200	OK	OK	Criteria B
	500	OK	OK	Criteria B
	1000	OK	OK	Criteria B
	1500	OK	OK	Criteria B
ADS8588S input to op-amp with TVS1401 or TVS1400 input with op-amp	200	OK	OK	Criteria A
	500	OK	OK	Criteria A
	1000	OK	OK	Criteria A
	1500	OK	OK	Criteria A
24-V input power supply	500	OK	OK	Criteria A
	1000	OK	OK	Criteria A
Digital input 48 V	500	OK	OK	Criteria A
	1000	OK	OK	Criteria A
	2000	OK	OK	Criteria A
Digital input 24 V	500	OK	OK	Criteria A
	1000	OK	OK	Criteria A
	2000	OK	OK	Criteria A
Digital Input with voltage detector, 24-V input	500	OK	OK	Criteria A
	1000	OK	OK	Criteria A
	2000	OK	OK	Criteria A

Observations:

- Combination waveform generator with capability to generate 1.2 / 50 μs, surge open-circuit waveform and 8 / 20 μs, surge short-circuit waveform used
- For criteria A, LED output was observed before, after, and during testing
- For criteria B, testing was done before and after application of transient and no degradation in performance was observed
- Five positive and five negative pulses were applied with 42-Ω impedance for testing at different voltage levels

5.4 Summary of Test Results

Table 15 summarizes the tests that have been performed on the design and observation.

Table 15. Summary of the Tests Performed and Observations

SERIAL NUMBER	PARAMETERS	OBSERVATIONS
1	SAR ADC input protection using bi-/uni-directional TVS	OK
2	Delta-Sigma ADC input protection	OK
3	Isolated digital input receiver based binary input module performance and protection using bi-/uni-directional TVS	OK
4	Voltage detector or comparator based binary input module using digital isolator with integrated power performance and protection	OK
5	Digital output, high-side and low-side performance	OK
6	Power supply, output rails for different DC/DC and LDOs	OK
7	Sensor open buffer output, differential amplifier output, reference output and reference diagnostics	OK
8	Diagnostics including temperature, humidity, magnetic sensor	OK
9	5-V input reversal and output overload protection	OK
10	12-V, 24-V input reversal, power mux and output overload protection	OK

6   Design Files

6.1   *Schematics*

To download the schematics for each board, see the design files at TIDA-0010008.

6.2   *Bill of Materials*

To download the bill of materials (BOM) for each board, see the design files at TIDA-010008.

6.3   *PCB Layout Recommendations*

To download the layout prints for each board, see the design files at TIDA-010008.

6.4   *Altium Project*

To download the Altium Designer® project files for each board, see the design files at TIDA-010008.

6.5   *Gerber Files*

To download the Gerber files for each board, see the design files at TIDA-010008.

6.6   *Assembly Drawings*

To download the assembly drawings for each board, see the design files at TIDA-010008.

7   Related Documentation

- Texas Instruments, *Flat-Clamp surge protection technology for efficient system protection*
- Texas Instruments, *System-Level ESD Protection Guide*
- Texas Instruments, *How to use isolation to improve ESD, EFT and surge immunity in industrial systems*
- Texas Instruments, *Low-Emission Designs With ISOW7841 Integrated Signal and Power Isolator*

7.1   *Trademarks*

SIMPLE SWITCHER is a registered trademark of Texas Instruments.
Altium Designer is a registered trademark of Altium LLC or its affiliated companies.
All other trademarks are the property of their respective owners.

8   Terminology

TVS— Transient Voltage Suppressor

AIO— Analog Input Output

DIO— Digital Input Output

AFE— Analog Front End

BIM— Binary Input Module

EE— End Equipment

MCU— Micro Controller

9   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).

Revision History

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

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to TI's Terms of Sale or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.