## *TI Designs*

# *Voltage and Current (Power) Measurement AFE for mV Output Sensors Interfaced to SAR ADC*

## TI Designs

This TI design is a fixed gain amplifier stage for measuring low amplitude voltage and current inputs accurately over a wide dynamic range using SAR ADC for power measurement applications. This design provides amplification to the low-amplitude AC inputs from resistor network-based voltage dividers, current transformers, or split core current sensors with a 333-mV output. The output of the amplifier is compatible with ADS8688 input requirements. This application includes sub-metering, machine monitoring, calibration check of meters installed at consumer location, power measurement, power data logging and power quality analysis. This subsystem can be used in FTU, DTU, and RTU applications. The advantage of this TI design can be seen when interfaced with the ADS8688 or any other SAR ADC. The amplification stage ensures the use of the full range of ADC improving measurement accuracy.

## Design Resources

| | |
|---|---|
| TIDA-00493 | Design Folder |
| TPS65131RGET | Product Folder |
| OPA4180IPW | Product Folder |
| OPA180IDBVR | Product Folder |
| LM4041BIDBZ4 | Product Folder |
| TIDA-00307 | Tool Folder |

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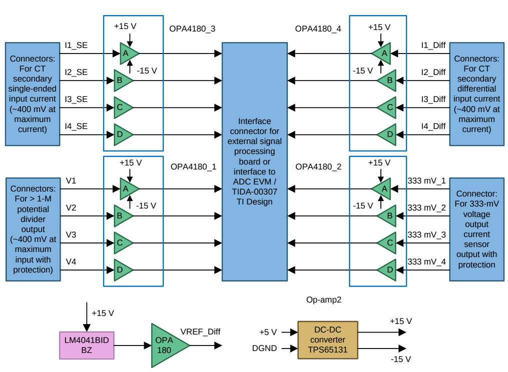
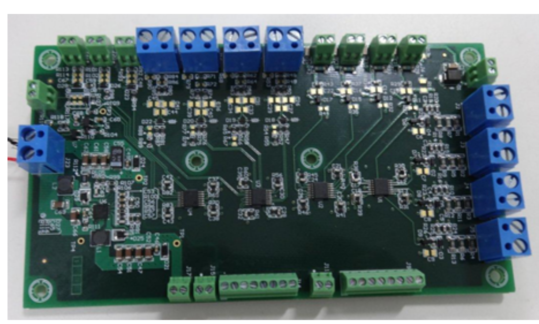
## Design Features

- Op-Amp Based Fixed Gain Amplifier Stage for Voltage and Current Inputs With Output Compatible to ADS8688 Input Range of ±2.56, ±5.12, and ±10.24 V
- Different Amplifier Configurations Provided for Measurement of Voltage and Current Inputs
- Configurations Provided:
  - Voltage Input With Resistor Divider > 1-MΩ Impedance (No External PT Required)
  - 333-mV AC Voltage Output Type Current Sensor Interface
  - CT Secondary Input With Burden Resistor: Single-Ended and Differential
- Operates From Single 5-V DC Input
- Generates ±15-V Power Supply Using Split-Rail Converter With Dual Outputs (Positive and Negative)
- Can be Interfaced With ADS8688-Based TI Design
- Onboard Programmable Reference Provided for Single-Ended Measurement Applications

## Featured Applications

- Multifunction Protection Relays
- RTU/DTU/FTU
- Bay Controllers
- Power Quality Analyzers
- Merging Units
- Energy Meters
- Solar Applications
- Data Logger with 333-mV Input



# 1 System Description

## *1.1 Introduction to Power Measurement*

Electrical power measurement is at the heart of numerous applications in the Grid Infrastructure sector for

1. Electrical power supply management,
2. Electricity usage control (sub-metering),
3. Condition monitoring, and
4. Portable power quality analysis.

Electrical power supply management is the primary application field, as it is essential to any industrial and business activity. It mainly concerns companies related to power generation and distribution, but also industry professionals monitoring their power quality and power factor to control rate of tariffs imposed by their utilities, especially when operating under low-power-factor loads.

Energy sub-metering is gaining importance among facility and plant managers as it allows tracking and allocating energy costs. Power supply sizing and billing is often dependent on the peak consumption, and a dynamic management of the overall system enables both cost reduction and failure prevention. Energy sub-metering is required to understand and manage the mains energy consumption. It also helps in identifying the energy wastes that are generally caused by defective appliances or inefficient facilities usage (for example, inappropriate lighting, heating, or air conditioning).

Condition monitoring requires immediate failure detection and reaction to prevent damage to equipment or interruption of critical processes. Electrical power measurement provides a comprehensive set of information (current, active power, power factor, frequency, and so on) that reflects the load behavior (for example, conveyer, bearing, pump, cutting tool, and so on). It often provides faster detection of abnormal behaviors than traditional sensors such as temperature, pressure, vibration, and so on. An analysis of these electrical parameters even enables the anticipation of failures, which allows for planning effective predictive maintenance.

Portable power quality analysis is used to measure, record, and detect power quality issues like harmonics, demand, inrush and power transients. Some of the power quality applications include:

- Measurement and recording of power system quantity (kW, VA, VAR)
- Determine harmonic problems originating from source or load
- Monitor phase balances
- Troubleshooting of power distribution panels and individual machinery
- Motor start-up analysis

## 1.2 Current Transformer / Current Sensor

Current transformers (CTs) aid in measuring alternating current. CTs provide a means of scaling a large primary (input) current into a smaller, manageable output (secondary) current for measurement and instrumentation. A CT uses the strength of the magnetic field around the conductor to form an induced current on its secondary windings. This indirect method of interfacing allows for easy installation and provides a high level of isolation between the primary circuit and secondary measurement circuits.

A CT is an "instrument transformer" that is designed to provide current in its secondary, which is accurately proportional to the current flowing in its primary. Some of the current transformers produce a 333-mV alternating voltage when the rated current is measured (either 30 A or 50 A). Some transducers produce a 5-V DC output or a 20-mA DC current output at the rated value.

### 1.2.1 Current Sensor Requirements

Some of the key specifications are

- Accuracy: In most applications, measurement accuracy directly impacts the efficiency of an overall system. The accuracy of the power calculation is dependent on the accuracy of the current sensors. A class 1 power meter requires current sensors with accuracy much better than 1%.
- Drift: The drift of a sensor is related to the sustainability of a reading over time. Some variations of its characteristics may be caused by changes in the ambient humidity and temperature, component aging, and so on.
- Linearity: The linearity of the sensor refers to the stability of its characteristics within the full operating mode. A high linearity of the analog-sensing part is essential to measure a wide range of primary currents accurately, especially at low current levels.
- Phase shift: The accuracy of the true active power or energy calculation is not only related to the accuracy and linearity of the AC current and voltage sensors in terms of amplitude, but also to the phase shift that may occur between the measurement of these correlated values. The phase shift should be as low as possible.
- Integration: Being self-powered, the CTs do not require any other wiring than a 2-wire output connection to the main power monitor unit. The typical 1-A and 5-A or 333-mV outputs are compatible with most standard power meters on the market. Current outputs are also almost insensitive to interferences and are preferable to voltage outputs when long cables are required to connect the sensors to the power meter.
- Price: The price of the sensors is important when accurate current sensors are required for 3-phase power measurement.

## 1.3 Current Transformer Types

- Precision solid-core CTs
- Split-core CTs
- Clamp-on current sensors
- Flexible or rigid Rogowski coil current sensor
- AC current transducers

### 1.3.1 Precision Solid-Core CTs

Power measurement systems generally implement contactless current sensors rather than shunts because the latter cause power losses as well as installation and safety issues. Traditional solid-core current sensors are based on the principle of a transformer, meaning the primary and secondary windings magnetically linked by a core. These basic CTs are designed to measure sinusoidal alternating currents in the typical 50- or 60-Hz range. Solid-core current transformers provide a low-amperage current output proportional to the line current and are for use in building automation and metering applications. Solid core CTs are very accurate (0.3% maximum error), small in size, and inexpensive. However, power must be turned off and the circuit opened, generally at a circuit breaker, so that the solid core CT can be slipped over the power line. After installation, the power wire must be reconnected to close the electrical circuit.

CTs are not suitable, however, for the numerous applications involving power monitoring of existing machines and facilities, where it would be necessary to shut down power and disconnect cables before retrofitting the solid-core sensors in all the places where they might be used. Installing power metering systems is generally not possible, prohibitively expensive, or even dangerous if it requires a service interruption, even for a short while (for example, stopping a production line, a telecom or datacenter power supply, some nuclear plant equipment, and so on).

**Figure 1. Precision Solid-Core CT**

Applications:

- 0.2 or 0.5 class meters in HVCT and MVCT for power plant, sub-station, and industrial complex
- Load sensor for the load center
- In-home display (home energy management)
- Inverters for solar and wind turbine systems

### 1.3.2 Split-Core CT

Split core transformers are intended for semi-permanent installations. They consist of a transformer where one of the legs can be opened or removed to place around the conductor and then be secured with a latch or some other type of fastener.

They can be installed in electrical control panels — thus avoiding complex wiring — to remotely monitor devices that sometimes operate in inaccessible or harsh environments. The beauty of the split-core transformers is that they can be retrofitted into a live installation without disturbing it, which often make them the unique choice for engineers designing power meters.

Split-core, or clamp-on, CTs provide an alternative to directly wiring to measurement or relay CTs in substation upgrade or retrofit applications when it is desired to add monitoring and SCADA data. This non-invasive approach provides for quicker installation with no disruption of service.

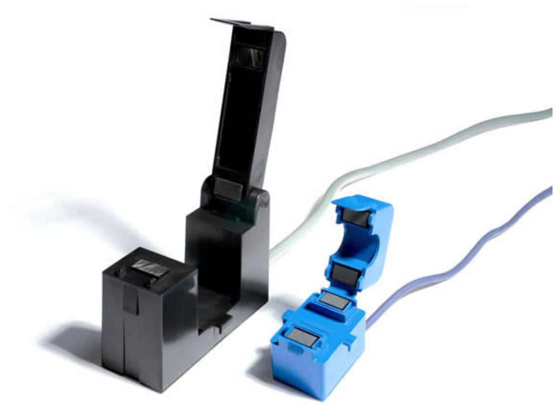


**Figure 2. Split-Core CT**

Applications:

- Sub-metering
- Data loggers to analyze building and machinery performance
- Digital fault recorders
- In-factory display or in-home display
- Inverters for solar and wind turbine systems
- Power measurement device for PLC

### 1.3.3 Flexible or Rigid Rogowski Coil Current Sensor

A Rogowski coil is a specially-wound toroidal coil that can be opened up and placed around a conductor carrying an AC. The alternating magnetic field generated by the AC induces a voltage in the coil. This voltage is proportional to the rate of change of current in the conductor. This voltage is then electronically integrated to provide an output voltage that mimics the current waveform in the conductor. Rogowski coils are suitable for measurement of currents up to thousands of amps, are not sensitive to positioning around the conductor, and can provide accurate phase response.

A Rogowski coil has a lower inductance than CTs and consequently a better frequency response because it uses a non-magnetic core material. It is also highly linear, even with high primary currents, because it has no iron core that may saturate. This kind of sensor is thus particularly well adapted to power measurement systems that can be subjected to high or fast-changing currents. For measuring high currents, it has the additional advantages of small size and easy installation, while traditional CTs are big and heavy.

**Figure 3. Flexible Rogowski Coil Current Sensor**

Applications:

- Electronic watt-hour meters (anti-tampering)
- Smart power meters for mobility application
- AC component fault detector of inverter in DC
- Electric mobility (automotive) and solar application

### 1.3.4 Clamp-On Current Sensors

Clamp-on current sensors are available in a variety of models and current ranges with either DC or AC voltage outputs. Clamp-on sensors are easy to use: simply open the clamp and place it around one of the current-carrying conductors. These sensors are ideal for temporary installations and can easily be moved from site to site, although they are somewhat more expensive than fixed CTs.

**Figure 4. Clamp-On Current Sensors**

Applications:

- Inverter monitoring and measurement
- Energy, power measurement, and monitoring
- DC motor control
- Uninterruptible power supplies
- Motor drives

### 1.3.5 AC Current Transducers

**Figure 5. AC Current Transducer**

A standard method of measuring AC for a power line-connected device is to use an AC current transducer, which converts an AC to a DC voltage or a 4- to 20-mA signal. Various outputs options are available:

Unipolar:

- 4 to 20 mA (500 Ω max)
- 0 to 20 mA (500 Ω max)
- 0 to 10 mA (1 kΩ max)
- 0 to 1 mA (10 kΩ max)
- 0 to 10 V (500 Ω min)
- 0 to 5 V (250 Ω min)
- 1 to 5 V (250 Ω min)
- 0 to 10-mV DC (250 Ω min)
- 0 to 100-mV DC (250 Ω min)
- 0 to 1-V DC (250 Ω min)

Bipolar:

- –20 to 20 mA (500 Ω max)
- –10 to 10 mA (1 kΩ max)
- –1 to 1 mA (10 kΩ max)
- –10 to 10 V (500 Ω min)
- –5 to 5 V (250 Ω min)

## 1.4 Potential Transformer and Voltage Transducer With 333-mV Output

The design can also interface with a voltage transformer with rated voltages of 110 V or 230 V extending up to 600 V with output of 333 mV at a rated voltage.

## 1.5 Voltage and Current Measurement AFE — TI Design Advantages

The ADS8684 and ADS8688 are 16-bit data acquisition systems with 4- and 8-channel analog inputs, respectively. Each analog input channel consists of an overvoltage protection circuit, a programmable gain amplifier (PGA), and a second-order, anti-aliasing filter that conditions the input signal before being fed into a 4- or 8-channel analog multiplexer (MUX). The output of the MUX is digitized using a 16-bit analog-to-digital converter (ADC), based on the successive approximation register (SAR) architecture. This overall system can achieve a maximum throughput of 500 kSPS, combined across all channels. The devices feature a 4.096-V internal reference with a fast-settling buffer and a simple SPI-compatible serial interface with daisy-chain (DAISY) feature. The devices operate from a single 5-V analog supply and can accommodate true bipolar input signals up to ±2.5 × $V_{REF}$. The devices offer a constant 1-MΩ resistive input impedance irrespective of the sampling frequency or the selected input range. The integration of multichannel precision analog front-end circuits with high input impedance and a precision ADC operating from a single 5-V supply offers a simplified end solution without requiring external high-voltage bipolar supplies and complicated driver circuits.

Table 1 lists the available ranges in the ADS8688:

**Table 1. ADS8688 Input Ranges**

| INPUT RANGE | POSITIVE FULL SCALE | NEGATIVE FULL SCALE | FULL-SCALE RANGE | LSB (µV) |
|---|---|---|---|---|
| ±2.5 × $V_{REF}$ | 10.24 V | –10.24 V | 20.48 V | 312.50 |
| ±1.25 × $V_{REF}$ | 5.12 V | –5.12 V | 10.24 V | 156.25 |
| ±0.625 × $V_{REF}$ | 2.56 V | –2.56 V | 5.12 V | 78.125 |
| 0 to 2.5 × $V_{REF}$ | 10.24 V | 0 V | 10.24 V | 156.25 |
| 0 to 1.25 × $V_{REF}$ | 5.12 V | 0 V | 5.12 V | 78.125 |

Table 1 indicates that the ADS8688 can measure bipolar and unipolar inputs. The TIDA-00310 demonstrates sensing *unipolar* and *bipolar* transducer outputs as described in Section 1.3.5.

TI design TIDA-00307 demonstrates measurement capabilities of the ADS8688 including daisy chaining. The power measurement AFE TIDA-00493 is a fixed gain amplifier stage that could be used along with the TIDA-00307 or TIDA-00310 to increase the measurement accuracy and use multiple measurement range capabilities of the ADS8688. Any type of AC current sensor or transducer input can be measured using combination of these TI designs.

The amplifier output is compatible to the ADS8688 input range. The AFE board can be wired to the ADS8688 ADC-based TIDA-00307, TIDA-00310, or the ADS8688 evaluation board easily.

## 2 Key System Specifications

**Table 2. Key System Specifications**

| SERIAL NUMBER | PARAMETERS | SPECIFICATION |
|---|---|---|
| 1 | Number of amplifier configurations | 4 |
| 3 | Channels per amplifier configuration | 4 |
| 3 | Direct AC voltage input | ≤ 350-V $AC_{RMS}$ (No external PT required) |
| 4 | Voltage output current sensor range | 10-mV to 333-$mV_{RMS}$ (400 mV max) |
| 5 | Current transformer secondary range | 10 mV, 400 mV with 22R secondary burden |
| 6 | Amplifier output voltage | ≤ 7 $V_{RMS}$ |
| 7 | Input frequency range | DC or 50/60 Hz (Application and current sensor dependent) |
| 8 | DC power supply input | 3-V to 5.5-V DC |
| 9 | DC power supply for amplifiers | Programmable from ±10-V to ±15-V DC |
| 10 | Voltage reference | Programmable: 1.5-V to 10-V DC |
| 11 | Input protection | ESD and Surge as per IEC61000-4-2, IEC61000-4-5 |
| 12 | Output interface | Screw-type connectors for Interface to ADS8688 ADC or other EVMs |

# 3 Block Diagram and Specifications

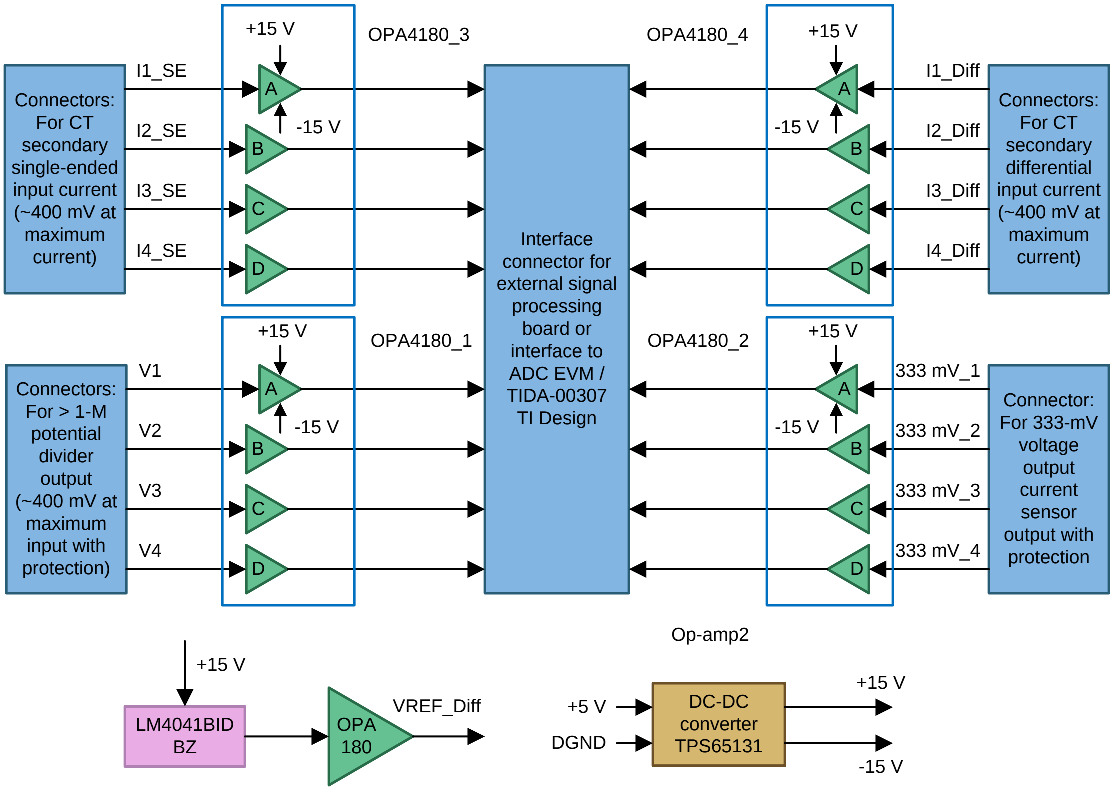



**Figure 6. Voltage and Current Measurement AFE**

The Voltage and Current (Power) Measurement AFE for mV Output Sensors design consists of

- Signal conditioning circuit including resistor voltage divider and amplifier for direct AC voltage input up to 350 $V_{RMS}$ (without an external potential transformer [PT])
- Amplifiers for a 333-mV voltage output current sensor
- Amplifiers for single-ended and differential current inputs

The output of the voltage divider and the current sensor are applied as input to the amplifiers that provide fixed gain amplification. The amplifier outputs are terminated to an interface connector for processing, including connecting to the ADS8688 ADC board.

The required positive and negative power supply for amplifier operation is generated using dual-output DC-DC converter, which operates from a single 3-V to 5.5-V input. The design provides a programmable reference for use with single-ended ADCs.

### 3.1 TPS65131

The ADS8688 has a maximum input voltage range of ±10.24 V. The op-amp chosen has to operate with a dual supply to provide an output voltage compatible with the input range of the ADS8688. The amplifier output must not saturate for an output voltage greater than ±10.24 V, which requires the supply voltage must be greater than ±10.24V. The TPS65131 multichannel output IC is used to provide both a positive and negative power rail. The input is a single 3-V to 5.5-V DC voltage, available in most systems. The output voltage is adjustable depending on the amplifier used to ensure the output is greater than ±10.24 V. This simplifies the input power supply rail requirement.

The TPS65131 is dual-output DC-DC converter generating a positive output voltage up to 15 V and a negative output voltage down to –15 V with output currents in a 200-mA range in typical applications, depending on input voltage-to-output voltage ratio. The TPS65131 has a total efficiency up to 85% and an input voltage range of 2.7 to 5.5 V. The TPS65131 comes in a small 4×4-mm QFN-24 package. Together with a minimum switching frequency of 1.25 MHz, it enables designing small power supply applications because it requires only a few small external components.

The converter operates with a fixed frequency PWM control topology and, if Power Save Mode is enabled, it uses a pulse-skipping mode at light load currents. It operates with only a 500-µA device quiescent current. Independent enable pins allow power up and power down sequencing for both outputs. The device has an internal current limit overvoltage protection and a thermal shutdown for highest reliability under fault conditions.

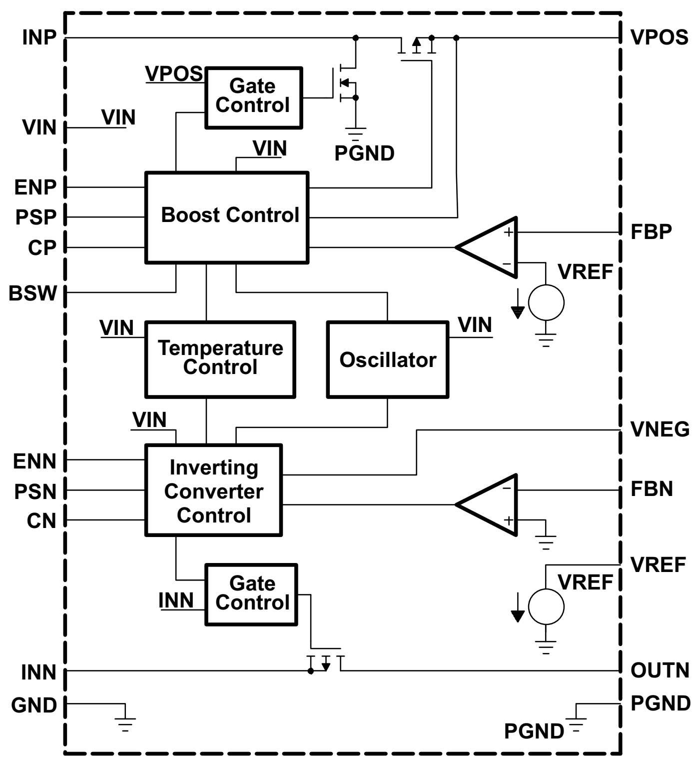



**Figure 7. TPS65131 Functional Block Diagram**

Features:

- Dual adjustable output voltages up to 15 V and down to –15 V
- 2-A typical switch current limit at boost and inverter main switches at TPS65131
- Up to 89% efficiency at positive output voltage rail
- Up to 81% efficiency at negative output voltage rail
- Power Save Mode for high efficiency at low load currents
- Independent enable inputs for power up and power down sequencing
- 2.7- to 5.5-V input voltage range
- Minimum 1.25-MHz fixed frequency PWM operation
- Thermal shutdown
- Overvoltage protection on both outputs
- 1-μA shutdown current
- Small 4×4-mm QFN-24 package (RGE)

### 3.2 OPA4180

TI has a wide range of quad op-amp portfolios. The OPA4180 quad amplifier has been selected in this application due to its performance and cost and has the required amplifier operating with ±12 to ±15 V.

The OPA4180 operational amplifiers use zero-drift techniques to simultaneously provide low offset voltage (75 µV) and near zero-drift over time and temperature. These miniature, high-precision, low-quiescent current amplifiers offer high input impedance and rail-to-rail output swig within 18 mV of the rails. The input common-mode range includes the negative rail.

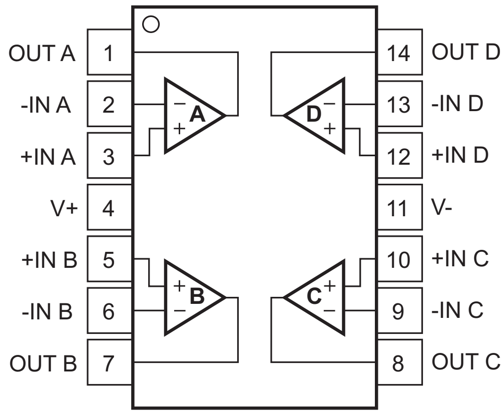



**Figure 8. OPA4180 Symbolic Diagram**

Features:

- Low offset voltage: 75 µV (max)
- Zero-drift: 0.1 µV/°C
- Low noise: 10 nV/√Hz
- Slew rate: 0.8 V/µs
- Gain bandwidth product: 2 MHz
- Current output / channel: 18 mA
- Very low 1 / f noise
- Excellent DC precision:
  - PSRR: 126 dB
  - CMRR: 114 dB
  - Open-loop gain ($A_{OL}$): 120 dB
- Quiescent current: 525 µA (max)
- Wide supply range: 4 to 36 V, ±2 to 18 V
- Rail-to-rail output: Input includes negative rail
- Low bias current: 250 pA (typ)
- RFI-filtered inputs
- Operating temperature: –40°C to 125°C

### 3.3 OPA180

The ADS8688, which is the target ADC for this design, accepts bi-directional signal input. There are ADCs that accept only unipolar inputs, and when using those ADCs, the AC input voltage is level shifted. The design provides a level shift to the ADC. The reference can be used to do the required level shifting. The reference output is programmable and can be set with resistors. The OPA180 is the buffer for the reference, and the output of the op-amp is connected to the amplifiers. Buffering is done to provide additional drive capability to connect reference to multiple inputs.

The OPA180 operational amplifiers use zero-drift techniques to simultaneously provide low offset voltage (75 µV) and near zero-drift over time and temperature. These miniature, high-precision, low-quiescent current amplifiers offer high input impedance and rail-to-rail output swing within 18 mV of the rails. The input common-mode range includes the negative rail. Either single or dual supplies can be used in the range of 4.0 to 36 V (±2 to ±18 V).

All versions are specified for operation from –40°C to 105°C.

Features:

- Low offset voltage: 75 µV (max)
- Zero-drift: 0.1 µV/°C
- Slew rate: 0.8 V/µs
- Gain bandwidth product: 2 MHz
- Current output / channel: 18 mA
- Low noise: 10 nV/√Hz
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- Low bias current: 250 pA (typ)
- RFI-filtered inputs
- Operating temperature: –40°C to 125°C

### 3.4 LM4041

The LM4041-N precision voltage reference is available in the sub-miniature SC70 and SOT-23 surface-mount packages. The device's advanced design eliminates the need for an external stabilizing capacitor while ensuring stability with any capacitive load, thus making the LM4041-N easy to use. Further reducing the design effort is the availability of a fixed (1.225 V) and adjustable reverse breakdown voltage. The minimum operating current is 60 µA for the LM4041-N 1.2 and the LM4041-N ADJ. Both versions have a maximum operating current of 12 mA.

The LM4041-N uses fuse and Zener-zap reverse breakdown or reference voltage trim during wafer sort to ensure that the prime parts have an accuracy of better than ±0.1% (A grade) at 25°C. Bandgap reference temperature drift curvature correction and low dynamic impedance ensure stable reverse breakdown voltage accuracy over a wide range of operating temperatures and currents.

Features:

- Small packages: SOT-23, TO-92, and SC70
- No output capacitor required
- Tolerates capacitive loads
- Reference type: Shunt
- Output type: Fixed or adjustable
- Current output: 12 mA
- Temperature coefficient: 150 ppm/°C
- Operating temperature: –40°C to 85°C ($T_A$)
- Current Cathode: 70 µA

# 4 System Design Theory

## 4.1 DC Power Supply (Dual Output)

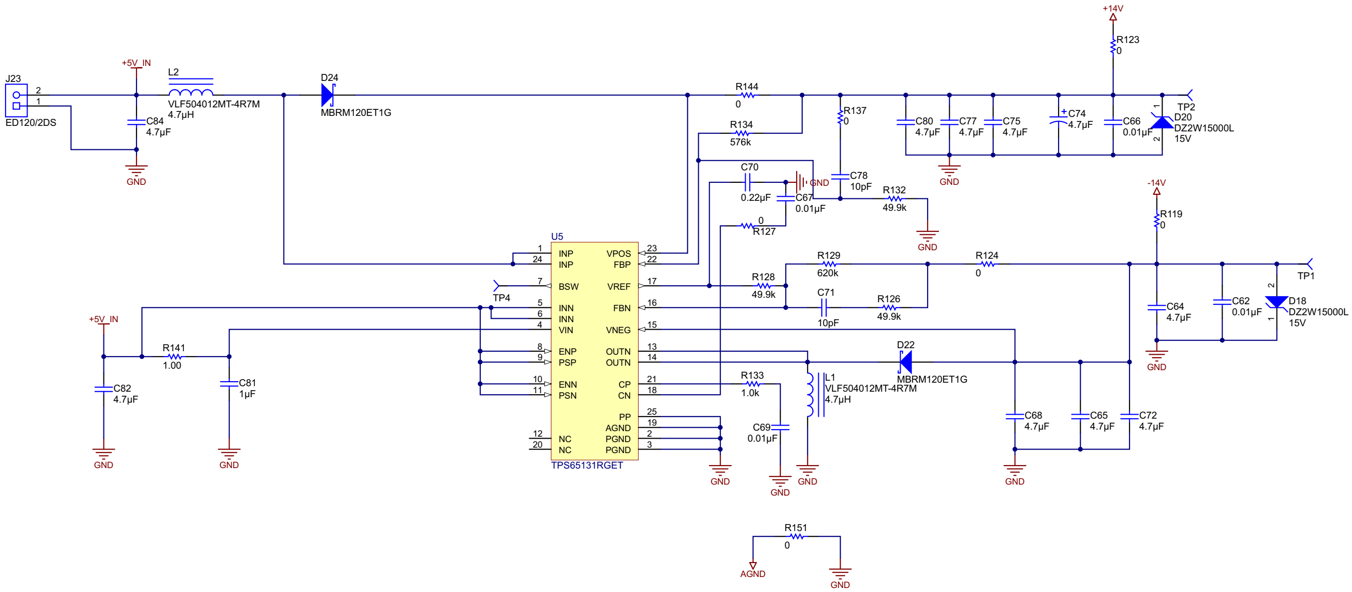


**Figure 9. Dual Output DC Power Supply**

The TPS65131 operates with an input voltage range of 2.7 to 5.5 V and can generate both a positive and negative output. Both converters work independently of each other. They only share a common clock and a common voltage reference. Both outputs are controlled separately by a fixed-frequency, pulse-width-modulated (PWM) regulator. In general, each converter operates at continuous conduction mode (CCM). At light loads, the negative converter can enter discontinuous conduction mode (DCM). As the load current decreases, the converters can enter a power save mode if enabled. This works independently at both converters. Output voltages can go up to 15 V at the boost output and down to –15 V at the inverter output.

The PSN and PSP can be used to select different operating modes. To enable power save mode for the corresponding converter, the dedicated PS pin must be set high. Power save mode can be used to improve efficiency at light load. In power save mode, the converter only operates when the output voltage falls below a set threshold voltage. It ramps up the output voltage with one or several operating pulses and goes again into power save mode once the inductor current goes discontinuous. The power save mode can be disabled separately for each converter by setting the corresponding PS pin low.

Design Procedure

The TPS65131 DC-DC converter is intended for systems typically powered by any regulated supply voltages between 2.7 and 5.5 V. It provides two independent output voltage rails, which are programmed as follows.

### 4.1.1 Programming Output Voltage

**Boost Converter**

The output voltage of the TPS65131 boost converter stage can be adjusted with an external resistor divider connected to the FBP pin. The typical value of the voltage at the FBP pin is the reference voltage, which is 1.213 V. The maximum recommended output voltage at the boost converter is 15 V. To achieve appropriate accuracy, the current through the feedback divider should be about 100 times higher than the current into the FBP pin. Typical current into the FBP pin is 0.05 μA, and the voltage across R2 is 1.213 V. Based on those values, the recommended value for R2 should be lower than 200 kΩ in order to set the divider current at 5 μA or higher. Depending on the needed output voltage ($V_{POS}$), the value of the resistor R1 can then be calculated using Equation 1:

$$R1 = R2 \times \left( \frac{V_{POS}}{V_{REF}} - 1 \right) \quad (1)$$

**NOTE:** Replace R1 with R134 and R2 with R132 in the current design.

The output voltage is programmed to 15 V in the design.

**Inverting Converter**

The output voltage of the TPS65131 inverting converter stage can also be adjusted with an external resistor divider. It must be connected to the FBN pin. In difference to the feedback divider at the boost converter, the reference point of the feedback divider is not GND but $V_{REF}$. So, the typical value of the voltage at the FBN pin is 0 V. The minimum recommended output voltage at the inverting converter is –15 V. Feedback divider current considerations are similar to the considerations at the boost converter. For the same reasons, the feedback divider current should be in the range of 5 μA or higher. The voltage across R4 is 1.213 V. Based on those values, the recommended value for R4 should be lower than 200 kΩ to set the divider current at the required value. The value of the resistor R3, depending on the needed output voltage ($V_{NEG}$), can be calculated using Equation 2:

$$R3 = R4 \times \left( \frac{V_{REF} - V_{NEG}}{V_{REF}} - 1 \right) \quad (2)$$

**NOTE:** Replace R3 with R129 and R4 with R128 in the current design.

The output voltage is programmed to –15 V in the design.

**Soft Start**

Both converters have implemented soft-start functions. When each converter is enabled, the implemented switch current limit ramps up slowly to its nominal programmed value in about 1 ms. Soft start is implemented to limit the input current during start-up to avoid high peak currents.

**Overvoltage Protection**

Both built-in converters have implemented overvoltage protection. If the feedback voltage under normal operation exceeds the nominal value by typically 5%, the corresponding converter shuts down immediately to protect any connected circuitry from possible damage.

**Undervoltage Lockout**

An undervoltage lockout prevents the device from starting up and operating if the supply voltage at $V_{IN}$ is lower than the programmed threshold. The device automatically shuts down both converters when the supply voltage at $V_{IN}$ falls below this threshold.

### 4.1.2 Input Capacitor

At least a 4.7-µF input capacitor is recommended for the input of the boost converter (INP) and for the input of the inverting converter (INN) to improve transient behavior of the regulators and EMI behavior of the total power supply circuit. A ceramic capacitor or a tantalum capacitor with a smaller ceramic capacitor (100 nF) in parallel, placed close to the input pins, is recommended.

### 4.1.3 Output Voltage Connector

15 V and –15 V are connected to J16 and J18, respectively. This can be used to power external subsystems. In case an external DC voltage is available, these connectors can be used to connect the external inputs by disabling the internal DC-DC converter. Zener protection has been provided for both output rails.

## 4.2 Reference and Buffer

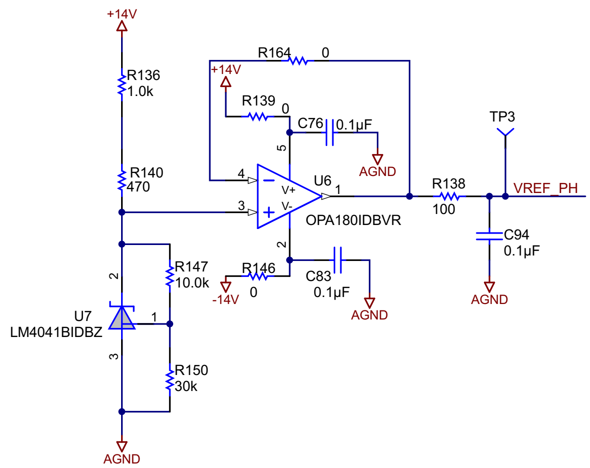


**Figure 10. Reference and Buffer**

The LM4041-N is a precision micro-power curvature-corrected bandgap shunt voltage reference. For space critical applications, the LM4041-N is available in the sub-miniature SOT-23 package. The LM4041-N has been designed for stable operation without the need of an external capacitor connected between the "+" pin and the "−" pin. If, however, a bypass capacitor is used, the LM4041-N remains stable. Design effort is further reduced with the choice of either a fixed 1.2 V or an adjustable reverse breakdown voltage. The minimum operating current is 60 µA for the LM4041-N 1.2 and the LM4041-N ADJ. Both versions have a maximum operating current of 12 mA.

The LM4041-N ADJ's output voltage can be adjusted to any value in the range of 1.24 through 10 V. It is a function of the internal reference voltage ($V_{REF}$) and the ratio of the external feedback resistors. The output voltage is found using the equation

$$V_O = V_{REF}\left[\left(\frac{R2}{R1}\right) + 1\right]$$

where

- VO is the output voltage (3)

The actual value of the internal $V_{REF}$ is a function of VO. The "corrected" $V_{REF}$ is determined by

$$V_{REF} = \Delta V_O \left(\frac{\Delta V_{REF}}{\Delta V_O}\right) + V_Y$$

where

- VY = 1.240 V
- ΔVO = (VO − VY) (4)

In the current application, the reference is set to 5 V.

### 4.3 Voltage Input Amplifier

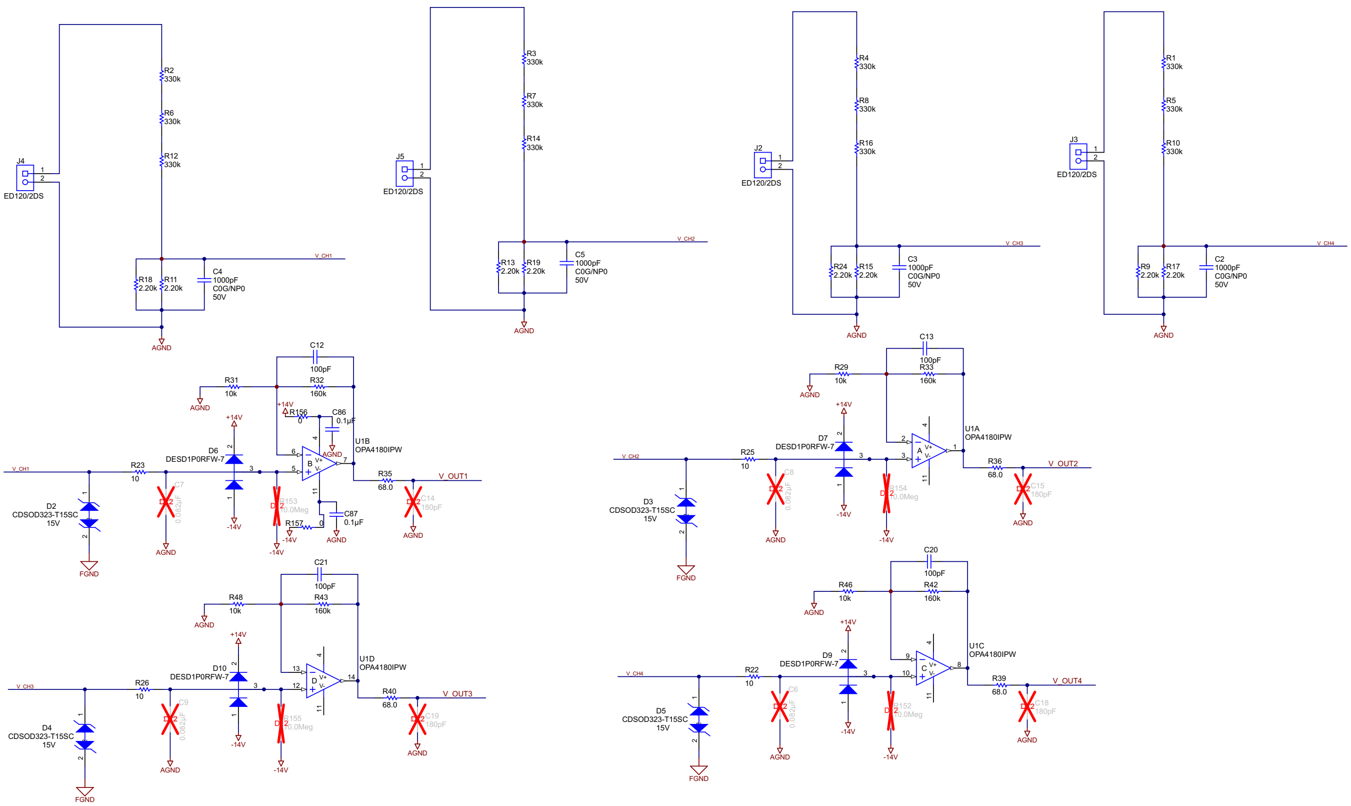


**Figure 11. 350-V AC Input Potential Divider and Amplifier**

The AC input voltage applied is divided by a resistive potential divider. Multiple resistors are used to increase reliability and also withstand the surge input. The resistor divider is selected to have input impedance is >= 1 MΩ. The input voltage is divided by 1:990 ratio. The inputs are protected for ESD and Surge. The max input is 350 $V_{RMS}$ and the divider output is 350 mV. This is amplified by the non inverting amplifier with X17 gain. There are in total four amplifiers to measure the AC voltage.

**NOTE:** Use of multiple resistors as voltage divider increases surge withstand capability and system reliability. The divider output is protected against surge and ESD.

### 4.4 333-mV Input Amplifier

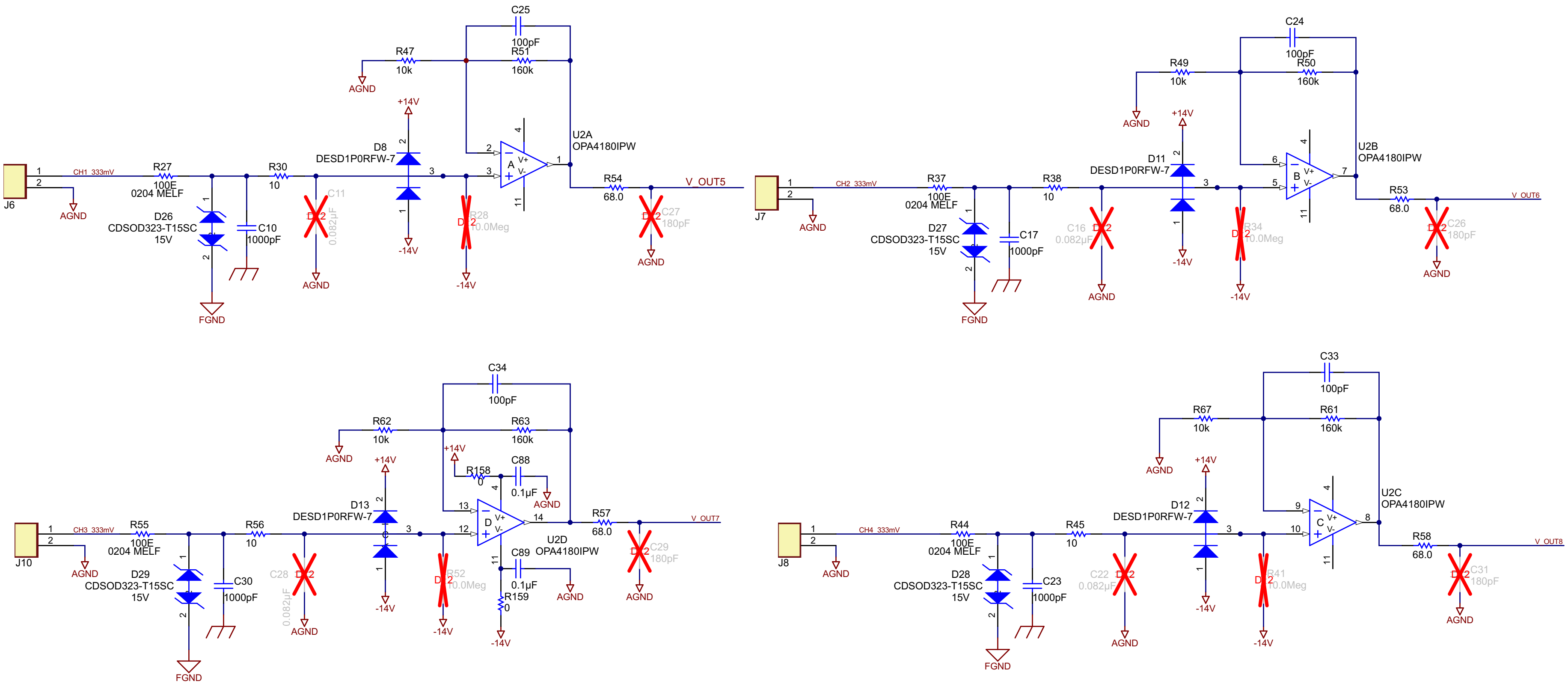


**Figure 12. 333-mV Voltage Output Current Sensor Input**

The 333-mV input is amplified by the non inverting amplifier with X17 gain. The inputs are protected for ESD and Surge. The output from the 333-mV output current sensor can be directly connected to the inputs. There are in total four amplifiers to measure the 333-mV voltage inputs. The divider output is protected against surge and ESD.

## 4.5 Current Input — Differential

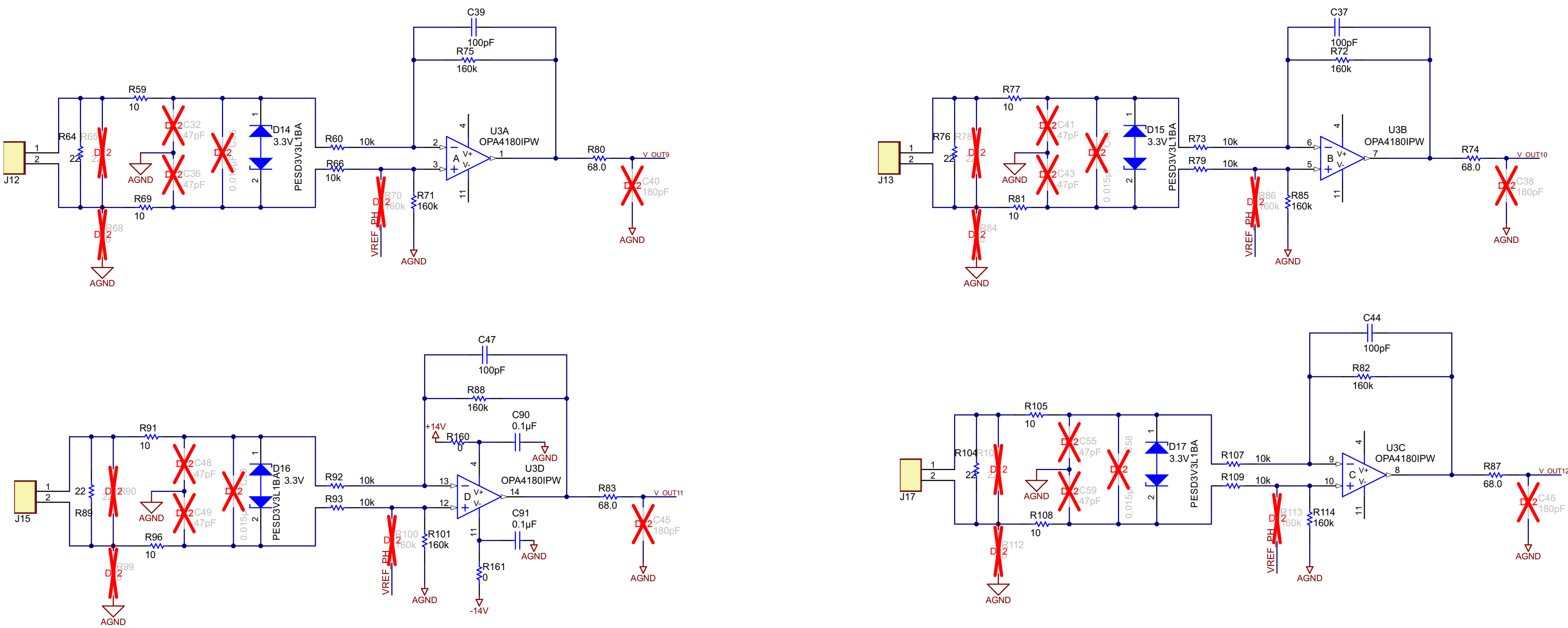


**Figure 13. Current Transformer Differential Input**

The current input is connected through an external current transformer (the board does not have an onboard current transformer). The secondary output of the current transformer is connected to the inputs. 22R is the secondary burden resistor. The secondary current has to be approximately 18 mA. The 400 mV across the burden resistor is amplified by differential amplifier with X16 gain. There are in total four amplifiers to measure the currents.

The ability to configure the op-amp as single-ended by DC level shifting the input has been provided.

**NOTE:** Do not directly connect the AC current input. Always use a CT and connect the secondary of the current transformer to the inputs.

The CT input is protected against overvoltage in case the burden resistor opens. To ensure this condition does not occur, the ability to populate two burden resistors have been provided. The required burden resistor can be a combination of two resistors.

## 4.6 Current Input — Single-Ended

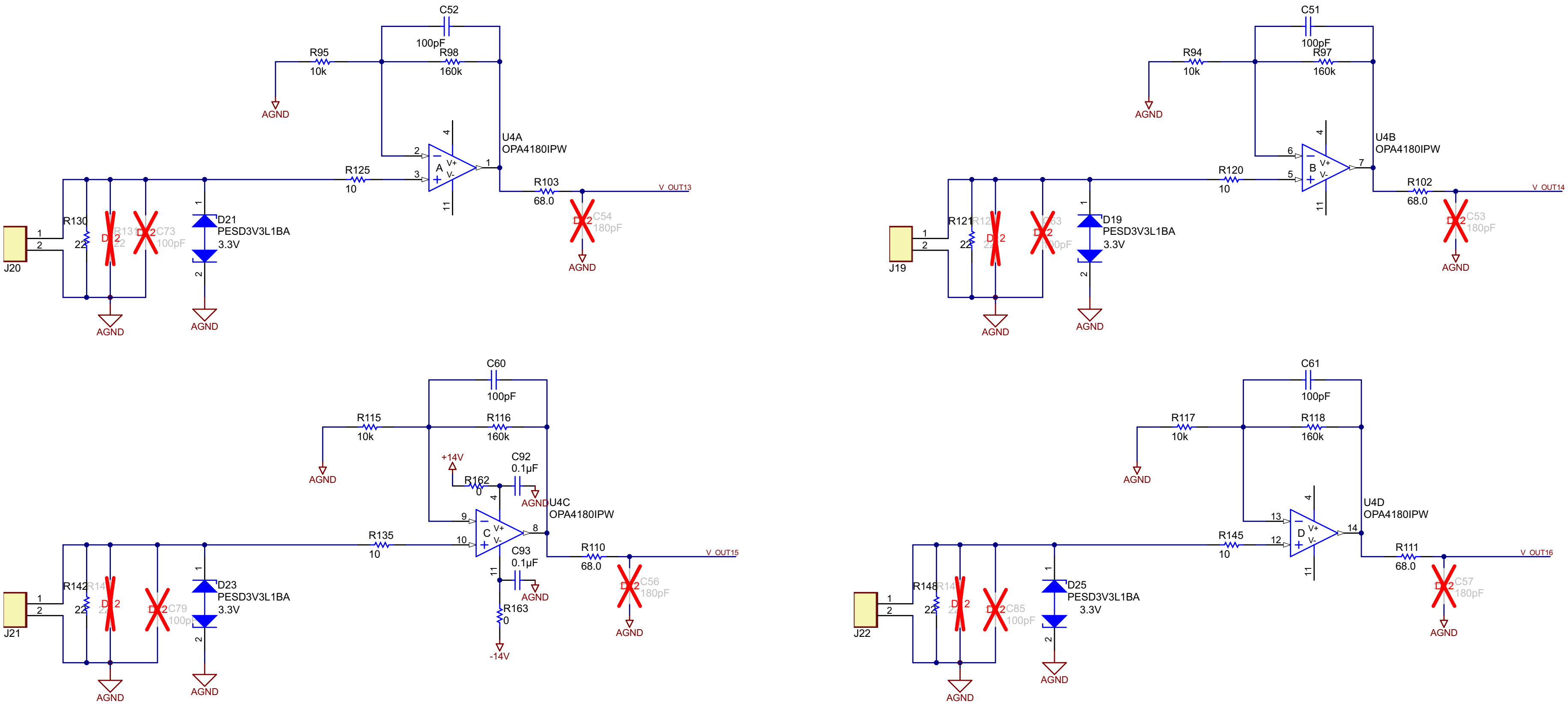


**Figure 14. Current Transformer Single-Ended Input**

The current input is connected through an external CT (the board does not have an onboard CT) . The secondary output of the CT is connected to the inputs. 22R is the secondary burden resistor. The secondary current has to be approximately 18 mA. The 400 mV across the burden resistor is amplified by the non-inverting amplifier with X17 gain. There are in total four amplifiers to measure the currents.

**NOTE:** Do not directly connect the AC current input. Always use a CT and connect the secondary of the CT to the inputs.

The CT input is protected against overvoltage in case the burden resistor opens. To ensure this condition does not occur, the ability to populate two burden resistors have been provided. The required burden resistor can be a combination of two resistors.

## 4.7 Interface to ADS8688

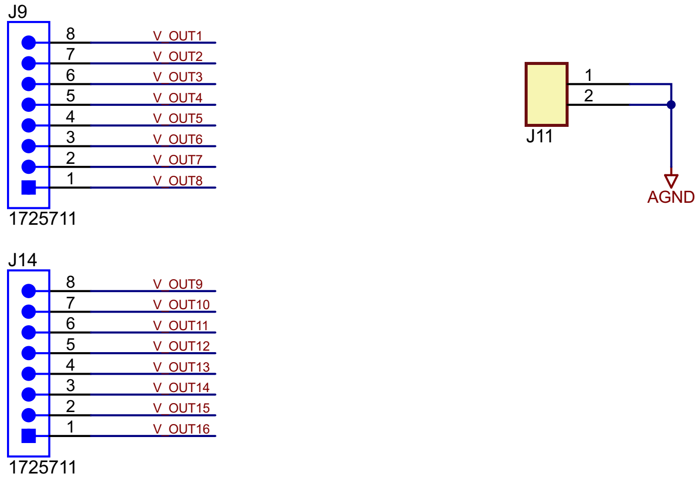


**Figure 15. External ADC Interface Connector**

A total of 16 amplifier outputs are connected to two 8-pin screw-type output connectors. The outputs can be interfaced to the TIDA-00307 TI design or ADC board as required.

## 4.8 Improving Accuracy

### 4.8.1 Choice of Op-Amp

The OPA4180 op-amp is used in this TI design. TI has a wide range of quad op-amp portfolio. There are devices with cost lower than the OPA4180 if cost is a critical factor. This design is targeted for class 0.5S accuracy. If a more accurate performance is required, more stable and expensive op-amp are available. Similarly, most of the resistors used are 1% tolerance resistors. Lower tolerance and lesser PPM drift resistors can be chosen based on the application's need.

Some of the devices that can be considered are listed in Table 3.

**Table 3. LM324 Specifications**

| PARAMETER | VALUE |
|---|---|
| Number of circuits | 4 |
| Output type | — |
| Slew rate | 0.5 V/µs |
| Gain bandwidth product | 1.2 MHz |
| Current — Input bias | 20 nA |
| Voltage — Input offset | 3 mV |
| Current — Supply | 1.4 mA |
| Current — Output / channel | 60 mA |
| Voltage — Supply, single or dual (±) | 3 to 32 V, ±1.5 to 16 V |
| Operating temperature | 0°C to 70°C |

**Table 4. OPA4170 Specifications**

| PARAMETER | VALUE |
|---|---|
| Number of circuits | 4 |
| Output type | Rail-to-rail |
| Slew rate | 0.4 V/µs |
| Gain bandwidth product | 1.2 MHz |
| Current — Input bias | 8 pA |
| Voltage — Input offset | 250 µV |
| Current — Supply | 110 µA |
| Current — Output / channel | 20 mA |
| Voltage — Supply, single or dual (±) | 2.7 to 36 V, ±1.35 to 18 V |
| Operating temperature | –40°C to 125°C |

### 4.8.2 Choice of Current Sensor

The measurement accuracy also depends upon the current sensor or transducer used. If a higher accuracy is required, select a current sensor with the lowest linearity and phase angle error.

### 4.8.3 Capacitor Filters

Provision to mount an RC filter has been provided on the outputs of all the amplifiers. Mounting these components improves the performance and can be used based on the requirement.

## *4.9 TPS65131 Layout Guidelines*

As with all switching power supplies, the layout is an important step in the design, especially at high peak currents and high switching frequencies. If the layout is not done carefully, the regulator could show stability problems as well as EMI problems. Therefore, use wide and short traces for the main current paths and for the power ground tracks. The input capacitors, the output capacitors, the inductors, and the rectifying diodes should be placed as close as possible to the IC to keep parasitic inductances low. Use a common ground node for power ground and a different node for control grounds to minimize the effects of ground noise. Connect these ground nodes at any place close to one of the ground pins of the IC.

The feedback dividers should be placed as close as possible to the control ground pin (boost converter) or the VREF pin (inverting converter) of the IC. To layout the control ground, it is recommended to use short traces as well, separated from the power ground traces. This avoids ground shift problems, which can occur due to superimposition of power ground current and control ground current.

# 5 Getting Started: Hardware

The following section explains different connectors on the AFE board and their usage.

## 5.1 Connectors

**Table 5. Description of Different Connector on Measurement AFE**

| VOLTAGE INPUT TYPE | INPUT CONNECTORS | OUTPUT |
|---|---|---|
| Direct AC voltage input | J4 – AC input 1 | J9 – Pin8 |
| | J5 – AC input 2 | J9 – Pin7 |
| | J2 – AC input 3 | J9 – Pin6 |
| | J3 – AC input 4 | J9 – Pin5 |
| AC voltage output (333 mV) current sensor | J6 – 333mV AC input 1 | J9 – Pin4 |
| | J7 – 333mV AC input 2 | J9 – Pin3 |
| | J10 – 333mV AC input 3 | J9 – Pin2 |
| | J8 – 333mV AC input 4 | J9 – Pin1 |
| Current transformer connected in differential configuration | J12 – Differential current input1 | J14 – Pin8 |
| | J13 – Differential current input2 | J14 – Pin7 |
| | J15 – Differential current input3 | J14 – Pin6 |
| | J17 – Differential current input4 | J14 – Pin5 |
| Current transformer connected in single-ended configuration | J20 – SE current input1 | J14 – Pin4 |
| | J19 – SE current input2 | J14 – Pin3 |
| | J21 – SE current input3 | J14 – Pin2 |
| | J22 – SE current input4 | J14 – Pin1 |
| ±15-V DC power supply output | J16 (15 V) | J16 – Pin1 |
| | J18 (–15 V) | J18 – Pin1 |
| DC input | J23 | J23 – Pin2 |

## 5.2 DC Power Supply Input Voltage Range

The power supply operates from 3 to 5.5 V. In case an external ±12 V or more is available, disconnect R119 and R123 and connect the voltages across ±15-V DC output. The initial inrush current is more and care has to be taken if the power supply used has current limit set.

**NOTE:** Please ensure the positive and negative terminals are connected with the right polarity before powering the module.

## 5.3 Direct AC Voltage Input Range

An AC voltage of 50 Hz or 60 Hz, ≤ 350 $V_{RMS}$ can be applied for measurement. Apply the voltage across the AC voltage terminals in the above table.

## 5.4 333-mV Input

333 mV can be applied using a 333-mV voltage output current sensor (solid or split-core type). Alternatively, the 333-mV input can be applied using a function generator for testing.

## 5.5 AC Current Input

The AC current is applied using an external CT. The external CT can be solid or split or clamp type.

**NOTE:** Do not leave the secondary of the CT open and apply the current.

## 6 Test Setup

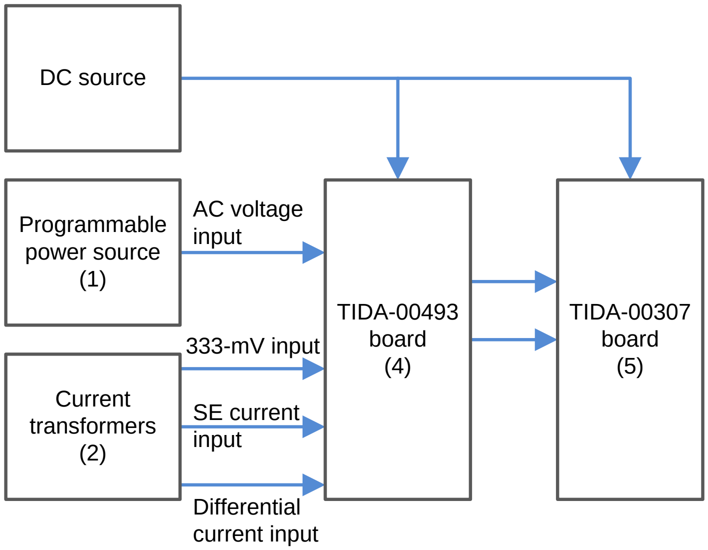


**Figure 16. Test Setup for Performance of Measurement AFE**


**Figure 17. 5-V DC Source Setup**


**Figure 18. Programmable Power Source Setup**

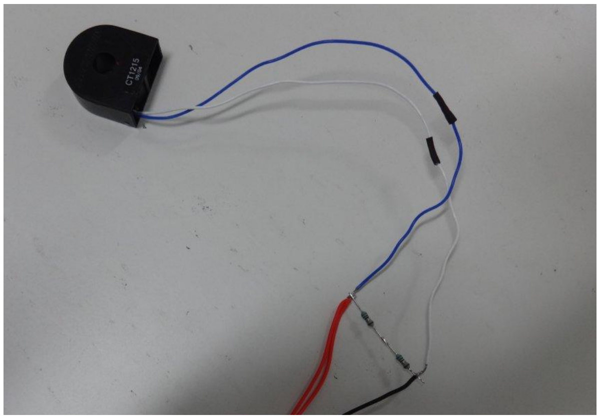

**Figure 19. Voltage Output Current Transformer**

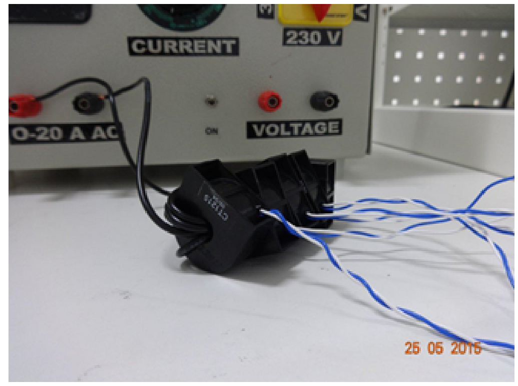


**Figure 20. Current Output Current Transformer**

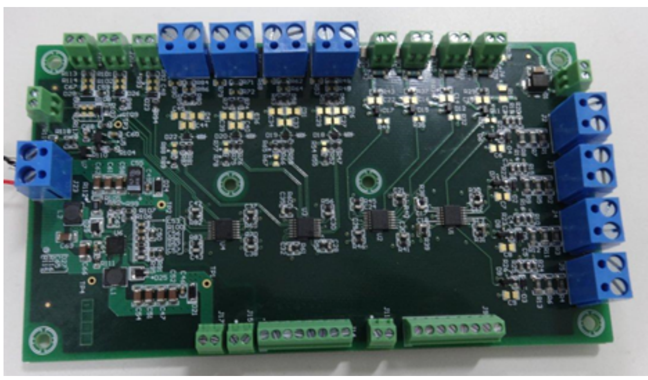

**Figure 21. TIDA-00493 Board**

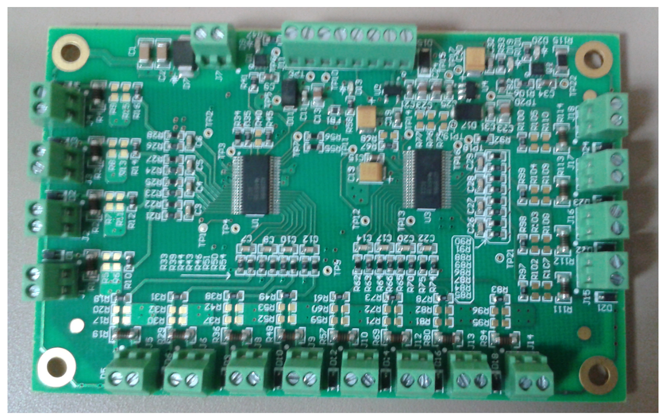

**Figure 22. TIDA-00307 Board**

# 7 Test Data

Notes:

- All the testing has been done with 50 Hz at 25°C.
- The error below includes CT Gain and Non-Linearity errors.
- Measurement is done with 6½ digit fluke Multimeter.

## 7.1 Functional Testing

**Table 6. Functional Testing**

| PARAMETER | MEASURED PARAMETER | OBSERVATION |
|---|---|---|
| Power supply | 15-V DC output | 15.28 |
| | Minus 15-V DC output | –15.11 |
| Reference out | 5 V | 5.01 |
| Undervoltage lockout | 2 V | OK |
| Op-Amp1-a output | X17 Gain | Ok |
| Op-Amp1-b output | X17 Gain | Ok |
| Op-Amp1-c output | X17 Gain | Ok |
| Op-Amp1-d output | X17 Gain | Ok |
| Op-Amp2-a output | X17 Gain | Ok |
| Op-Amp2-b output | X17 Gain | Ok |
| Op-Amp2-c output | X17 Gain | Ok |
| Op-Amp2-d output | X17 Gain | Ok |
| Op-Amp4-a output | X16 Gain | Ok |
| Op-Amp4-b output | X16 Gain | Ok |
| Op-Amp4-c output | X16 Gain | Ok |
| Op-Amp4-d output | X16 Gain | Ok |
| Op-Amp3-a output | X17 Gain | Ok |
| Op-Amp3-b output | X17 Gain | Ok |
| Op-Amp3-c output | X17 Gain | Ok |
| Op-Amp3-d output | X17 Gain | Ok |

**Table 7. DC Output versus DC Input**

| DC INPUT (V) | DC OUTPUT (15 V) | DC OUTPUT (–15 V) |
|---|---|---|
| 5.5 | 15.3 | –15.10 |
| 5.0 | 15.3 | –15.10 |
| 4.5 | 15.3 | –15.10 |
| 3.6 | 15.3 | –15.06 |
| 3.3 | 15.3 | –15.02 |
| 3.0 | 15.3 | –15.01 |
| 2.7 | 15.3 | –15.01 |

**Table 8. Power Measurement AFE Current Consumption**

| DC INPUT | POWER | NOTE |
|---|---|---|
| 5 V | 130 mA | With all amplifiers functional |

## 7.2 Performance Testing

### 7.2.1 AC Voltage Measurement

**Table 9. AC Voltage Measurement**

| AC VOLTAGE | ACTUAL OUTPUT | V_Out1 OUTPUT | Op-Amp1 ERROR (%) | V_Out2 OUTPUT | Op-Amp2 ERROR (%) | V_Out3 OUTPUT | Op-Amp3 ERROR (%) | V_Out4 OUTPUT | Op-Amp4 ERROR (%) |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 0.189 | 0.188 | –0.201 | 0.187 | –0.181 | 0.192 | 0.030 | 0.191 | 0.066 |
| 20 | 0.377 | 0.377 | –0.175 | 0.375 | –0.208 | 0.384 | –0.048 | 0.382 | 0.066 |
| 50 | 0.943 | 0.941 | –0.212 | 0.937 | –0.224 | 0.959 | –0.074 | 0.954 | –0.018 |
| 100 | 1.887 | 1.884 | –0.148 | 1.874 | –0.181 | 1.920 | 0.030 | 1.910 | 0.066 |
| 150 | 2.830 | 2.826 | –0.148 | 2.812 | –0.146 | 2.879 | –0.005 | 2.863 | –0.004 |
| 200 | 3.774 | 3.770 | –0.095 | 3.750 | –0.128 | 3.840 | 0.030 | 3.820 | 0.066 |
| 250 | 4.717 | 4.715 | –0.042 | 4.687 | –0.139 | 4.800 | 0.030 | 4.775 | 0.066 |
| 300 | 5.660 | 5.660 | –0.007 | 5.630 | –0.039 | 5.763 | 0.082 | 5.735 | 0.153 |
| 350 | 6.604 | 6.604 | 0.003 | 6.570 | –0.014 | 6.730 | 0.179 | 6.694 | 0.200 |
| Gain factor | | 1 | | 1.005 | | 0.983 | | 0.9885 | |

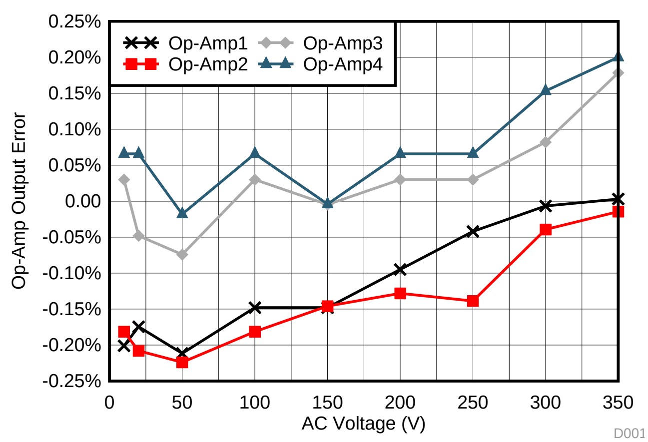


**Figure 23. AC Voltage Input versus Amplifier Output**

### 7.2.2 333-mV Voltage Output Current Sensor

**Table 10. 333-mV Voltage Output Current Sensor Input**

| AC INPUT (mV) | ACTUAL OUTPUT | V_Out5 OUTPUT | Op-Amp1 ERROR (%) | V_Out6 OUTPUT | Op-Amp2 ERROR (%) | V_Out7 OUTPUT | Op-Amp3 ERROR (%) | V_Out8 OUTPUT | Op-Amp4 ERROR (%) |
|---|---|---|---|---|---|---|---|---|---|
| 10.75 | 182.75 | 182.4 | –0.1915 | 180.2 | –0.212 | 180.4 | –0.200 | 183.0 | –0.064 |
| 21.45 | 364.65 | 364.2 | –0.1234 | 359.8 | –0.146 | 360.5 | –0.051 | 365.6 | 0.060 |
| 53.50 | 909.50 | 909.0 | –0.0550 | 898.5 | –0.024 | 899.5 | –0.012 | 912.5 | 0.129 |
| 106.80 | 1815.60 | 1815.0 | –0.0330 | 1795.0 | 0.0518 | 1798.0 | 0.120 | 1820.0 | 0.042 |
| 160.80 | 2733.60 | 2733.0 | –0.0219 | 2695.0 | –0.229 | 2703.0 | –0.032 | 2741.0 | 0.070 |
| 214.40 | 3644.80 | 3640.0 | –0.1317 | 3593.0 | –0.238 | 3603.0 | –0.060 | 3653.0 | 0.025 |
| 268.00 | 4556.00 | 4553.0 | –0.0658 | 4492.0 | –0.222 | 4504.0 | –0.054 | 4567.0 | 0.041 |
| 321.50 | 5465.50 | 5460.0 | –0.1006 | 5397.0 | –0.068 | 5403.0 | –0.056 | 5480.0 | 0.065 |
| 375.00 | 6375.00 | 6370.0 | –0.0784 | 6295.0 | –0.070 | 6305.0 | –0.010 | 6392.0 | 0.066 |
| Gain factor | | 1 | | 1.012 | | 1.011 | | 0.998 | |

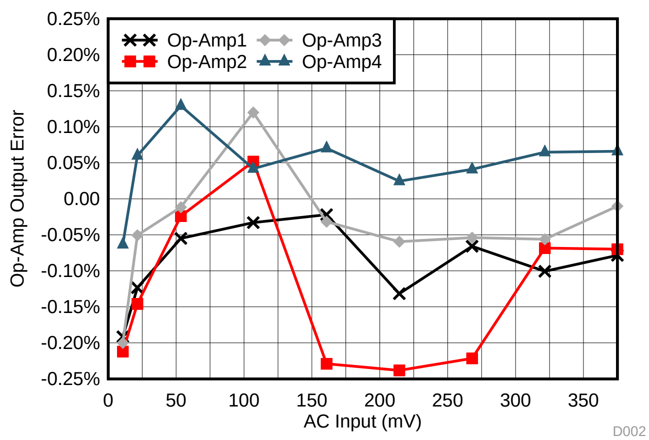


**Figure 24. 333-mV Input versus Amplifier Output**

### 7.2.3 Differential Current Input

**Table 11. Differential Current Input**

| AC CURRENT INPUT (mA) | ACTUAL OUTPUT (mV) | V_Out9 OUTPUT (mV) | Op-Amp1 ERROR (%) | V_Out10 OUTPUT (mV) | Op-Amp2 ERROR (%) | V_Out11 OUTPUT (mV) | Op-Amp3 ERROR (%) | V_Out12 OUTPUT (mV) | Op-Amp4 ERROR (%) |
|---|---|---|---|---|---|---|---|---|---|
| 100 | 70.4 | 70.95 | 0.0758 | 70.06 | 0.015 | 71.1 | 0.0150 | 71.7 | 0.0873 |
| 200 | 140.8 | 141.8 | 0.0053 | 140 | –0.071 | 142.3 | 0.1558 | 143.5 | 0.1850 |
| 500 | 352.0 | 354.2 | –0.0794 | 350 | –0.071 | 355.5 | 0.0854 | 358.5 | 0.1152 |
| 1000 | 704.0 | 709.6 | 0.0899 | 700 | –0.071 | 710.5 | 0.0150 | 716.7 | 0.0733 |
| 2000 | 1408.0 | 1418.0 | 0.0053 | 1400 | –0.071 | 1422.0 | 0.0854 | 1432.5 | 0.0105 |
| 3000 | 2112.0 | 2127.0 | 0.0053 | 2098 | –0.166 | 2132.0 | 0.0384 | 2148.0 | –0.0244 |
| 5000 | 3520.0 | 3542.0 | –0.0794 | 3496 | –0.185 | 3553.0 | 0.0291 | 3580.0 | –0.0244 |
| 7500 | 5280.0 | 5308.0 | –0.1734 | 5250 | –0.071 | 5322.0 | –0.1117 | 5370.0 | –0.0244 |
| 10000 | 7040.0 | 7080.0 | –0.1358 | 6995 | –0.142 | 7100.0 | –0.0554 | 7153.0 | –0.1222 |
| Gain factor | | 0.993 | | 1.005 | | 0.991 | | 0.983 | |

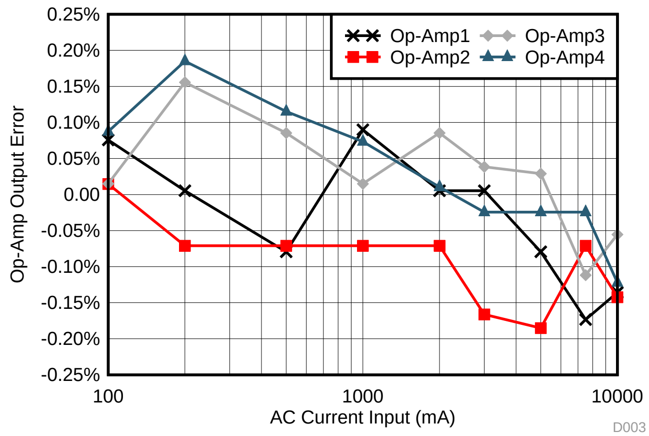


**Figure 25. AC Current Input versus Amplifier Output**

### 7.2.4 Single-Ended Current Input

**Table 12. Single-Ended Current Input**

| AC CURRENT INPUT (mA) | ACTUAL OUTPUT (mV) | V_Out13 OUTPUT (mV) | Op-Amp1 ERROR (%) | V_Out14 OUTPUT (mV) | Op-Amp2 ERROR (%) | V_Out15 OUTPUT (mV) | Op-Amp3 ERROR (%) | V_Out16 OUTPUT (mV) | Op-Amp4 ERROR (%) |
|---|---|---|---|---|---|---|---|---|---|
| 100 | 74.8 | 75.9 | 0.1515 | 74.1 | 0.0053 | 78.9 | 0.1945 | 73.9 | 0.0676 |
| 200 | 149.6 | 151.9 | 0.1845 | 148.0 | –0.1297 | 157.8 | 0.2072 | 147.8 | 0.0811 |
| 500 | 374.0 | 379.5 | 0.1515 | 370.5 | 0.0053 | 394.0 | 0.0802 | 369.5 | 0.0811 |
| 1000 | 748.0 | 758.0 | 0.0195 | 741.0 | 0.0053 | 789.0 | 0.2072 | 738.5 | 0.0134 |
| 2000 | 1496.0 | 1516.0 | 0.0195 | 1482.0 | 0.0053 | 1577.0 | 0.1437 | 1476.0 | –0.0543 |
| 3000 | 2244.0 | 2275.0 | 0.0635 | 2220.0 | –0.1297 | 2365.0 | 0.1225 | 2215.0 | –0.0091 |
| 5000 | 3740.0 | 3792.0 | 0.0723 | 3702.0 | –0.0757 | 3940.0 | 0.0802 | 3686.0 | –0.1626 |
| 7500 | 5610.0 | 5690.0 | 0.1075 | 5558.0 | 0.0143 | 5913.0 | 0.1310 | 5538.0 | –0.0001 |
| 9000 | 6732.0 | 6820.0 | –0.0098 | 6668.0 | –0.0097 | 7093.0 | 0.0943 | 6645.0 | –0.0091 |
| Gain factor | | 0.987 | | 1.0095 | | 0.95 | | 1.013 | |

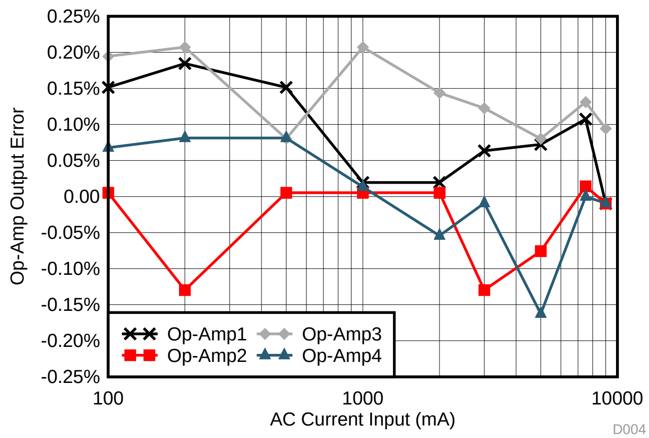


**Figure 26. AC Current Input versus Amplifier Output**

## 7.3 ADS8688 Interface and Measurement

### 7.3.1 ADS8688 Interfaced to TIDA-00493 Board

1. Ensure that the analog input is connected to both inputs for any of the channels for measurement because the two ADCs are daisy chained.
2. Aux channel is permanently wired to 3.3 V. No external connection is available.
3. The output of TIDA-00493 is connected to the ADC inputs of TIDA-00307.

**Table 13. TIDA-00307 Input Connectors**

| ADC CHANNELS | CONNECTOR | MEASURED | CONNECTOR | MEASURED |
|---|---|---|---|---|
| Channel 1 | J2 | Pin 1: in_AIN0_Signal | J13 | Pin 1: 2in_AIN0_Signal |
| | | Pin 2: Ground | | Pin 2: Ground |
| Channel 2 | J1 | Pin 1: in_AIN1_Signal | J14 | Pin 1: 2in_AIN1_Signal |
| | | Pin 2: Ground | | Pin 2: Ground |
| Channel 3 | J5 | Pin 1: in_AIN2_Signal | J15 | Pin 1: 2in_AIN2_Signal |
| | | Pin 2: Ground | | Pin 2: Ground |
| Channel 4 | J6 | Pin 1: in_AIN3_Signal | J16 | Pin 1: 2in_AIN3_Signal |
| | | Pin 2: Ground | | Pin 2: Ground |
| Channel 5 | J8 | Pin 1: in_AIN4_Signal | J17 | Pin 1: 2in_AIN4_Signal |
| | | Pin 2: Ground | | Pin 2: Ground |
| Channel 6 | J9 | Pin 1: in_AIN5_Signal | J18 | Pin 1: 2in_AIN5_Signal |
| | | Pin 2: Ground | | Pin 2: Ground |
| Channel 7 | J4 | Pin 1: in_AIN6_Signal | J10 | Pin 1: 2in_AIN6_Signal |
| | | Pin 2: Ground | | Pin 2: Ground |
| Channel 8 | J3 | Pin 1: in_AIN7_Signal | J12 | Pin 1: 2in_AIN7_Signal |
| | | Pin 2: Ground | | Pin 2: Ground |
| Aux channel | Internally connected to 3.3 V | | Internally connected to 3.3 V | |

### 7.3.2 Measuring ADC Channels Performance With Analog Input Applied From TIDA-00493

**Table 14. ADS8666 ADC Performance at Different Ranges**

| ADC CHANNELS | RANGE | APPLIED VOLTAGE (mV) | CONNECTOR | MEASURED | CONNECTOR | MEASURED |
|---|---|---|---|---|---|---|
| Channel 9 to 10 | 10.24 | 5.925 | J1 | 5.924 | J2 | 5.925 |
| | 5.120 | 2.962 | | 2.964 | | 2.964 |
| | 2.560 | 1.482 | | 1.482 | | 1.482 |
| | 2.560 | 0.445 | | 0.445 | | 0.445 |
| Channel 11 to 12 | 10.24 | 6.044 | J5 | 6.041 | J16 | 6.040 |
| | 5.120 | 3.020 | | 3.020 | | 3.020 |
| | 2.560 | 1.510 | | 1.510 | | 1.511 |
| | 2.560 | 0.453 | | 0.453 | | 0.453 |
| Channel 13 to 14 | 10.24 | 5.985 | J8 | 5.982 | J9 | 5.981 |
| | 5.120 | 2.992 | | 2.991 | | 2.991 |
| | 2.560 | 1.496 | | 1.496 | | 1.496 |
| | 2.560 | 0.449 | | 0.449 | | 0.449 |
| Channel 15 to 16 | 10.24 | 5.970 | J3 | 5.971 | J14 | 5.969 |
| | 5.120 | 2.986 | | 2.985 | | 2.984 |
| | 2.560 | 1.494 | | 1.493 | | 1.493 |
| | 2.560 | 0.448 | | 0.448 | | 0.448 |
| Channel 1 to 2 | 10.24 | 5.209 | J13 | 5.205 | J14 | 5.208 |
| | 5.120 | 2.838 | | 2.836 | | 2.837 |
| | 2.560 | 1.418 | | 1.417 | | 1.417 |
| | 2.560 | 0.473 | | 0.472 | | 0.472 |
| Channel 3 to 4 | 10.240 | 5.197 | J15 | 5.194 | J16 | 5.193 |
| | 5.120 | 2.832 | | 2.830 | | 2.831 |
| | 2.560 | 1.416 | | 1.414 | | 1.415 |
| | 2.560 | 0.472 | | 0.471 | | 0.471 |
| Channel 5 to 6 | 10.240 | 5.172 | J17 | 5.169 | J18 | 5.168 |
| | 5.120 | 2.818 | | 2.817 | | 2.816 |
| | 2.560 | 1.408 | | 1.407 | | 1.409 |
| | 2.560 | 0.469 | | 0.469 | | 0.469 |
| Channel 7 to 8 | 10.240 | 5.180 | J3 | 5.176 | J12 | 5.176 |
| | 5.120 | 2.822 | | 2.820 | | 2.820 |
| | 2.560 | 1.411 | | 1.409 | | 1.409 |
| | 2.560 | 0.470 | | 0.470 | | 0.470 |
| Aux channel | 4.096 V | 3.297 | | 3.299 | | 3.296 |

### 7.3.3 Isolating the Measurement Module From the MCU

There are applications (such as modular systems) where the measurement module is isolated from the MCU (or processing module). The required isolation can be provided by TI digital isolators. The TI design TIDA-00300 has the required power and digital isolator components. The TIDA-00300 operates with a single 24-V input and generates isolated 15 V, –15 V, and 6 V. A combination of the TIDA-00493, TIDA-00307, and TIDA-00300 provides an option to design an isolated measurement module.

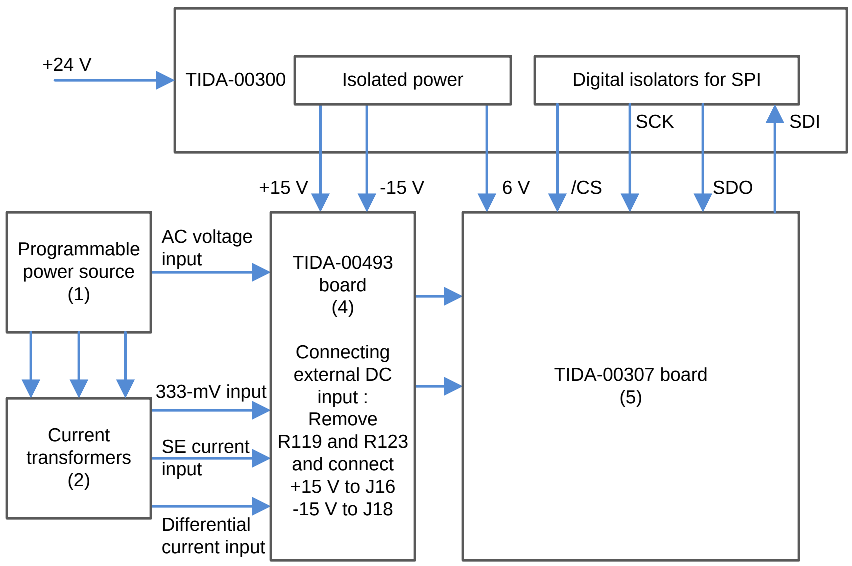


**Figure 27. Setup Diagram**

## *7.4 Additional Performance Tests*

### 7.4.1 AC Voltage Input

**Table 15. AC Voltage Measurement — Board 2**

| AC VOLTAGE (mV) | ACTUAL OUTPUT (mV) | V_Out1 OUTPUT (mV) | Op-Amp1 ERROR (%) | V_Out2 OUTPUT (mV) | Op-Amp2 ERROR (%) | V_Out3 OUTPUT (mV) | Op-Amp3 ERROR (%) | V_Out4 OUTPUT (mV) | Op-Amp4 ERROR (%) |
|---|---|---|---|---|---|---|---|---|---|
| 100 | 1.887 | 1.886 | –0.042 | 1.907 | –0.142 | 1.930 | 0.142 | 1.908 | –0.039 |
| 250 | 4.717 | 4.722 | 0.106 | 4.776 | 0.036 | 4.832 | 0.287 | 4.775 | 0.066 |
| 300 | 5.660 | 5.670 | 0.170 | 5.735 | 0.103 | 5.803 | 0.367 | 5.734 | 0.136 |
| Gain factor | | 1 | | 0.988 | | 0.979 | | 0.989 | |

### 7.4.2 333-mV Sensor Output

**Table 16. 333-mV Voltage Output Current Sensor Input — Board 2**

| AC INPUT (mV) | ACTUAL OUTPUT (mV) | V_Out5 OUTPUT (mV) | Op-Amp1 ERROR (%) | V_Out6 OUTPUT (mV) | Op-Amp2 ERROR (%) | V_Out7 OUTPUT (mV) | Op-Amp3 ERROR (%) | V_Out8 OUTPUT (mV) | Op-Amp4 ERROR (%) |
|---|---|---|---|---|---|---|---|---|---|
| 53.3 | 905.3 | 917.2 | 0.003 | 910.2 | 0.1446 | 913.5 | –0.0978 | 922.2 | 0.1406 |
| 159.6 | 2713.2 | 2752.0 | 0.112 | 2731.0 | 0.2534 | 2741.0 | 0.0144 | 2769.0 | 0.3216 |
| 266.4 | 4528.8 | 4589.0 | 0.012 | 4554.0 | 0.1542 | 4570.0 | –0.0994 | 4617.8 | 0.2318 |
| Gain factor | | 0.987 | | 0.996 | | 0.990 | | 0.993 | |

### 7.4.3 Differential Current Input

**Table 17. Differential Current Input — Board 2**

| AC CURRENT INPUT (mA) | ACTUAL OUTPUT (mV) | V_Out9 OUTPUT (mV) | Op-Amp1 ERROR (%) | V_Out10 OUTPUT (mV) | Op-Amp2 ERROR (%) | V_Out11 OUTPUT (mV) | Op-Amp3 ERROR (%) | V_Out12 OUTPUT (mV) | Op-Amp4 ERROR (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1000 | 704 | 698.1 | 0.1536 | 688.2 | –0.0937 | 705.1 | –0.1442 | 705.1 | –0.1428 |
| 3000 | 2112 | 2094.2 | 0.1488 | 2064.5 | –0.0985 | 2115.0 | –0.1584 | 2115.0 | –0.1584 |
| 7500 | 5280 | 5236.0 | 0.1583 | 5162.1 | –0.0821 | 5289.1 | –0.1282 | 5289.0 | –0.1301 |
| Gain factor | | 1.01 | | 1.022 | | 0.997 | | 0.997 | |

### 7.4.4 Single-Ended Current Input

**Table 18. Single-Ended Current Input — Board 2**

| AC CURRENT INPUT (mA) | ACTUAL OUTPUT (mV) | V_Out13 OUTPUT (mV) | Op-Amp1 ERROR (%) | V_Out14 OUTPUT (mV) | Op-Amp2 ERROR (%) | V_Out15 OUTPUT (mV) | Op-Amp3 ERROR (%) | V_Out16 OUTPUT (mV) | Op-Amp4 ERROR (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1000 | 748 | 744.3 | –0.0966 | 760.2 | 0.0252 | 759.0 | –0.0515 | 761.2 | –0.1688 |
| 3000 | 2244 | 2232.5 | –0.1145 | 2280.0 | –0.0011 | 2274.3 | –0.1700 | 2283.2 | –0.1863 |
| 7500 | 5610 | 5584.0 | –0.0653 | 5701.0 | 0.0165 | 5693.0 | –0.0427 | 5707.0 | –0.2038 |
| Gain factor | | 1.004 | | 0.9842 | | 0.985 | | 0.981 | |

## 7.5 IEC EMC Pre-Compliance Testing

The following EMC tests have been performed.

**Table 19. EMC Tests**

| TESTS | STANDARDS |
|---|---|
| Electrostatic Discharge | IEC61000-4-2 |
| Surge | IEC61000-4-5 |

**Table 20. Performance Criteria**

| CRITERIA | PERFORMANCE (PASS) CRITERIA |
|---|---|
| A | The analog output module shall continue to operate as intended. No loss of function or performance even during the test. |
| B | Temporary degradation of performance is accepted.<br>After the test, the analog output module shall continue to operate as intended without manual intervention. |
| C | During the test loss of functions accepted, but no destruction of hardware or software.<br>After the test, the analog output module shall continue to operate as intended automatically, after manual restart or power off/power on. |

### 7.5.1 IEC61000-4-2 ESD Test

The IEC610004-2 electrostatic discharge (ESD) test simulates the electrostatic discharge of an operator directly onto an adjacent electronic component. Electrostatic charge usually develops in low relative humidity and on low-conductivity carpets, or vinyl garments. To simulate a discharge event, an ESD generator applies ESD pulses to the equipment under test (EUT), which can happen through direct contact with the EUT (contact discharge), or through an air-gap (air-discharge). This was applied across signal inputs only. A series of 10 negative and positive pulses were applied directly on the 333-mV and the AC voltage inputs (contact discharge). After the test, the AFE module was tested functionally.

**Table 21. ESD Test Observations**

| IMMUNITY TEST | STANDARD | PORT | TARGET VOLTAGE LEVEL | RESULT |
|---|---|---|---|---|
| ESD | IEC 61000-4-2, contact | AC voltage input and 333-mV input | ±4 kV | Meets Criteria B (After the test the AFE continued to operate as intended) |

**Table 22. ESD Test Steps**

| TEST NO | TEST MODE | OBSERVATION |
|---|---|---|
| 1 | Contact 2 kV | Pass |
| 2 | Contact –2 kV | Pass |
| 3 | Contact 4 kV | Pass |
| 4 | Contact –4 kV | Pass |

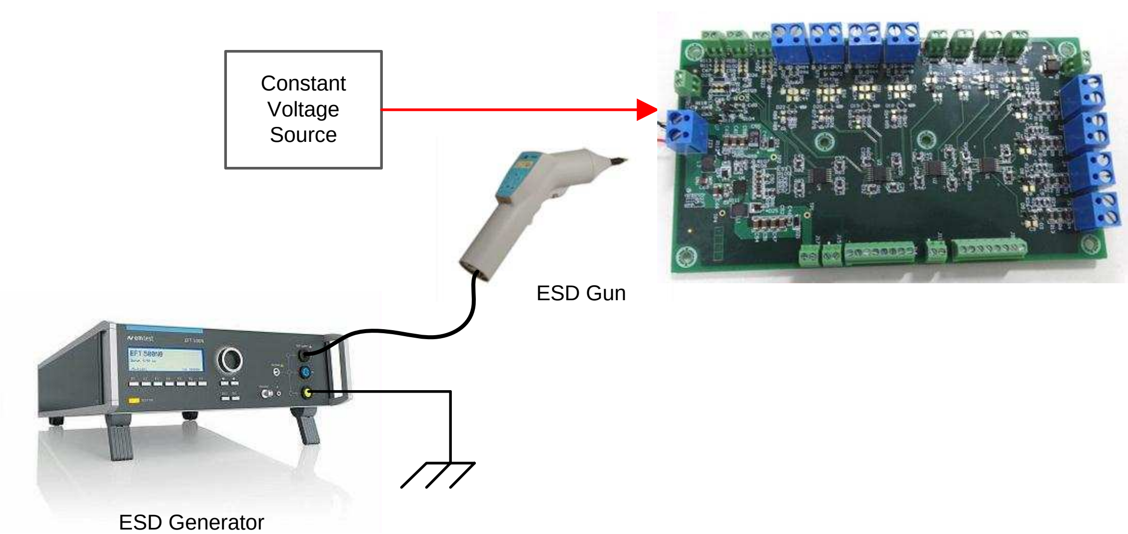


**Figure 28. ESD Setup for AFE**

### 7.5.2 IEC61000-4-5 Surge Test

The IEC61000-4-5 surge test simulates switching transients caused by lightning strikes or the switching of power systems including load changes and short circuits. The test requires five positive and five negative surge pulses with a time interval between successive pulses of 1 minute or less. The unshielded symmetrical data line setup as defined by the IEC61000-4-5 specification was used for this test. The test generator was configured for 1.2/50-µs surges and diode clamps were used for line-to-ground coupling. A series of five negative and positive pulses, with 10 seconds spacing between each pulse, were applied during the test. After the test, the AFE was tested for functionality.

**Table 23. Surge Test Observations**

| IMMUNITY TEST | STANDARD | PORT | TARGET VOLTAGE LEVEL | RESULT |
|---|---|---|---|---|
| Surge, DM | IEC 61000-4-5: (1.2 / 50 µs to 8 / 20 µs), 42 Ω–0.5 µF | AC voltage input and 333-mV input | ± 1 kV | Pass, Criteria B (After the test, the module continued to operate as intended) |

**Table 24. Surge Test Steps**

| TEST NO | TEST MODE | OBSERVATION |
|---|---|---|
| 1 | 0.5 kV | Pass |
| 2 | –0.5 kV | Pass |
| 3 | 1 kV | Pass |
| 4 | –1 kV | Pass |

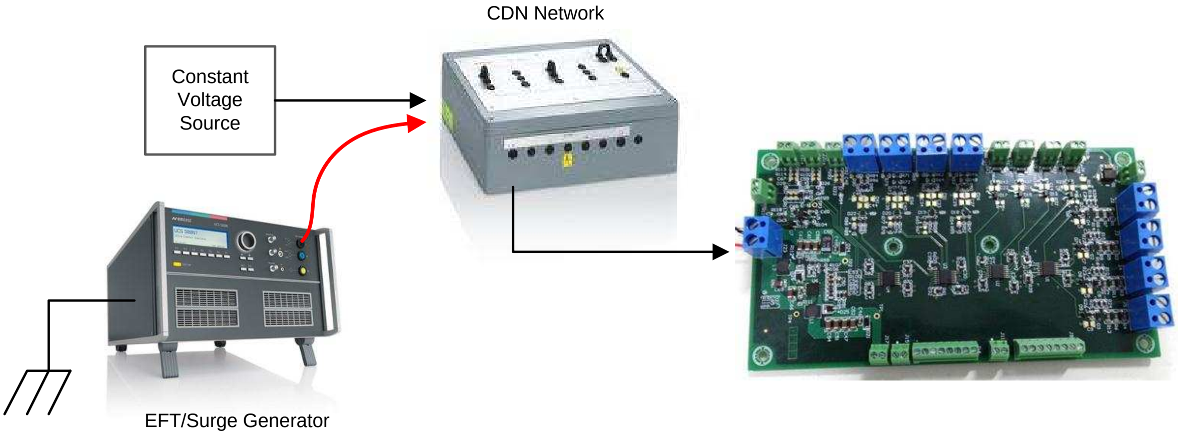


**Figure 29. Surge Setup for AFE**

## *7.6 Summary of Test Results*

**Table 25. Test Results**

| SERIAL NUMBER | PARAMETERS | RESULT |
|---|---|---|
| 1 | Power supply output 15 V, –15 V | Ok |
| 2 | Power supply operation over 3-V to 5.5-V DC input | Ok |
| 3 | Measurement of direct AC voltage Input | Ok |
| 4 | Measurement of 333-mV input | Ok |
| 5 | Measurement of current inputs | Ok |
| 6 | Measurement accuracy including source errors, sensor errors, and ADC measurement errors | < ±0.3% |

# 8 Design Files

## 8.1 Schematics

To download the schematics, see the design files at TIDA-00493.

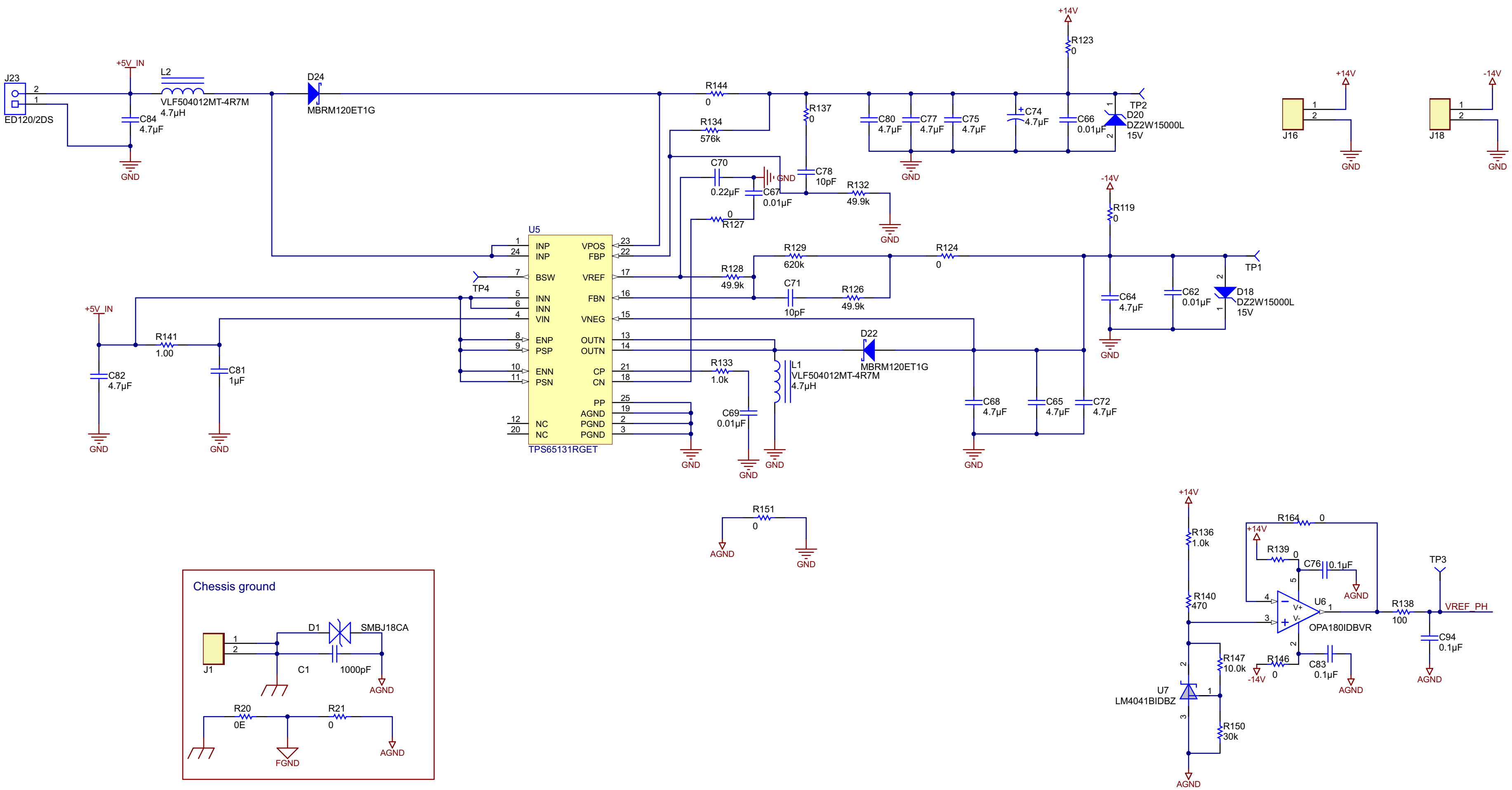


Figure 30. Split Rail Converter

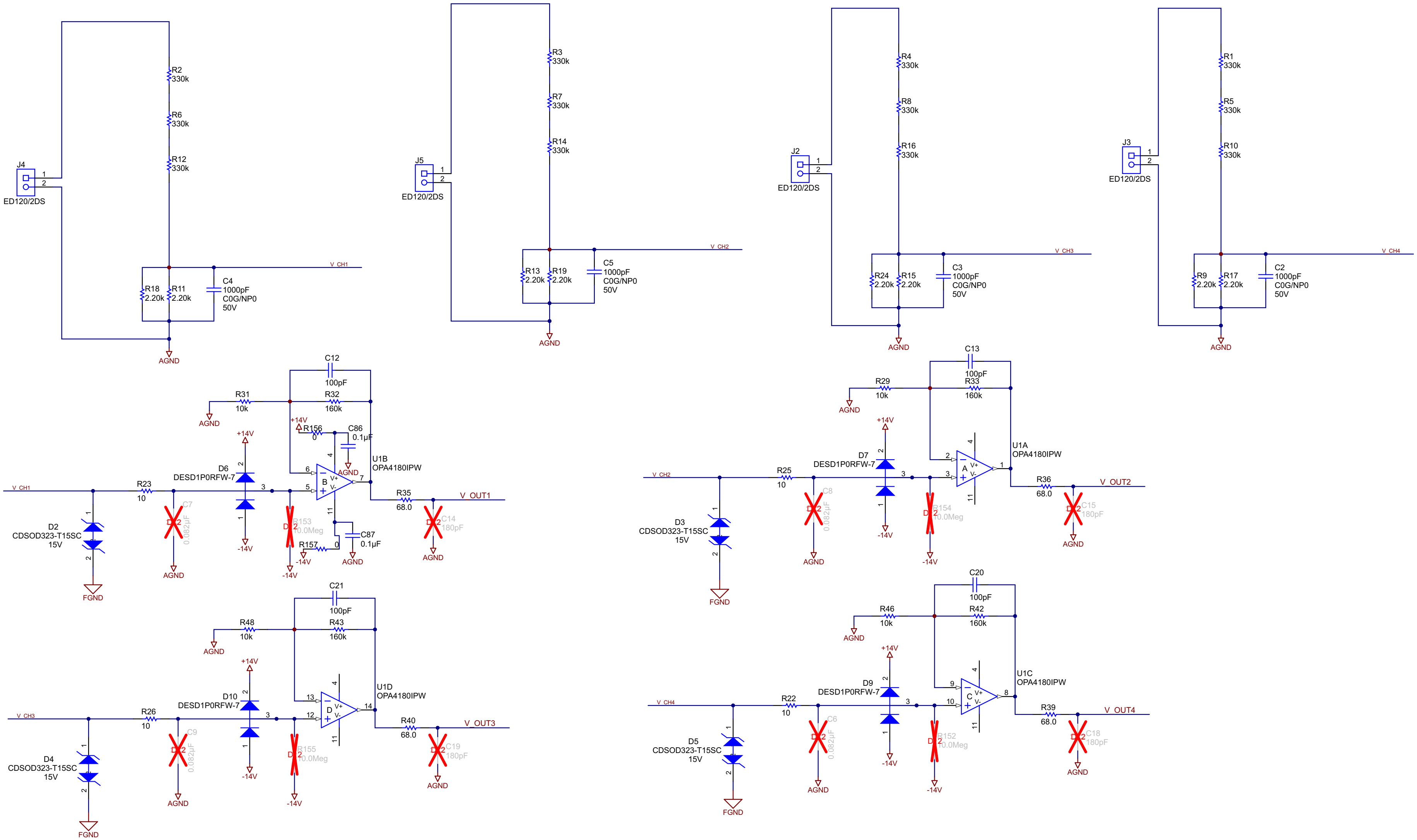

**Figure 31. 350-V AC Voltage Input Measurement**

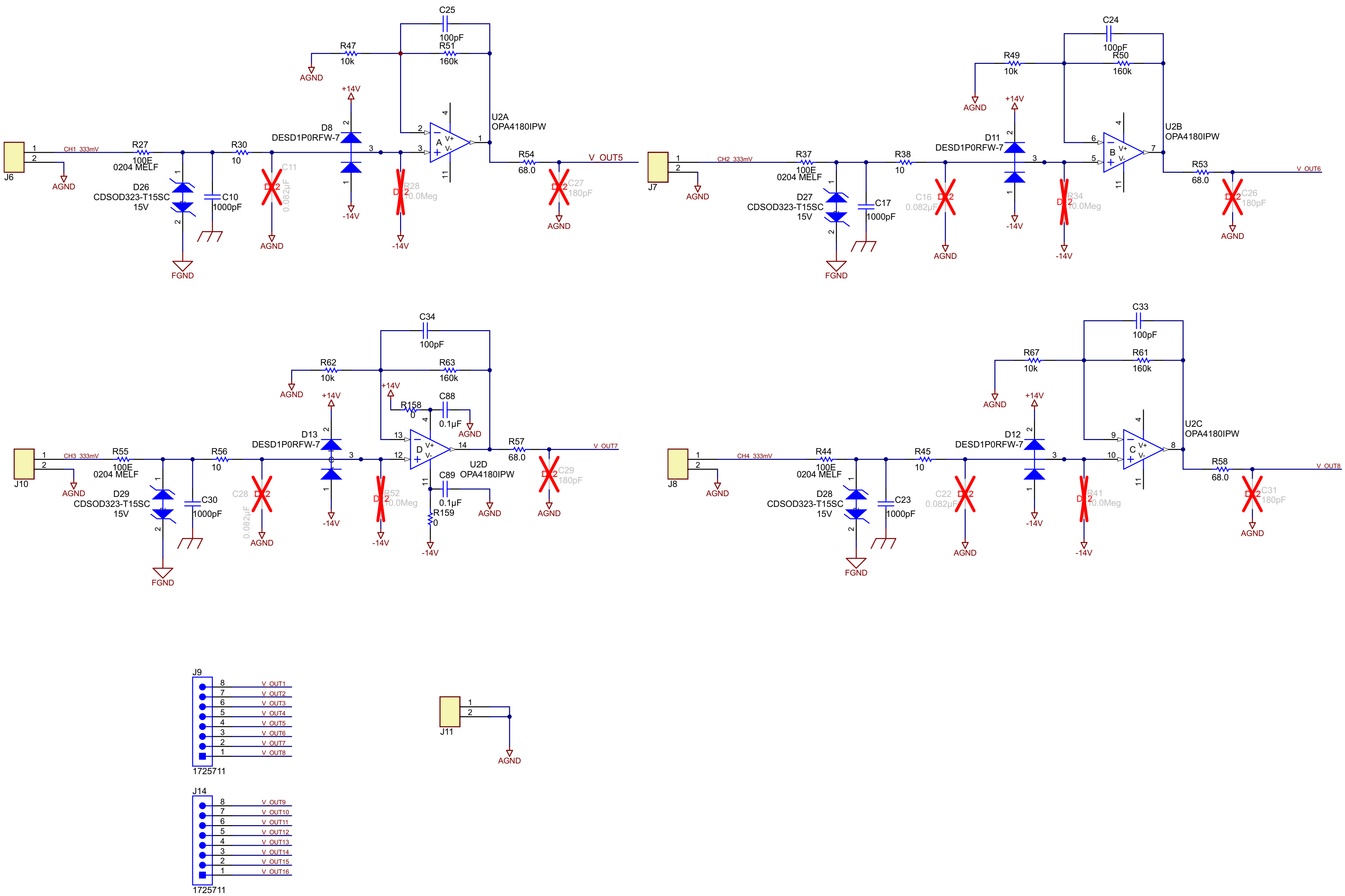

Figure 32. 333-mV Sensor Input

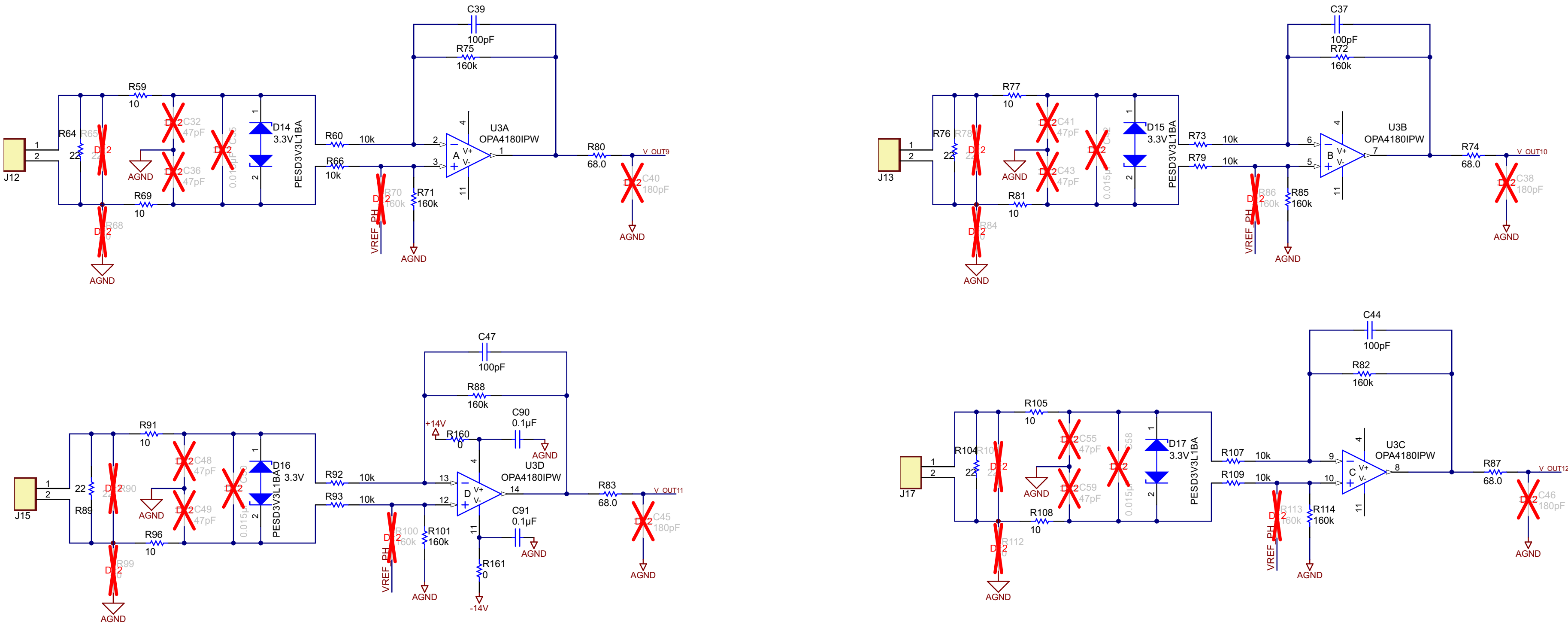


**Figure 33. Differential CT Input**

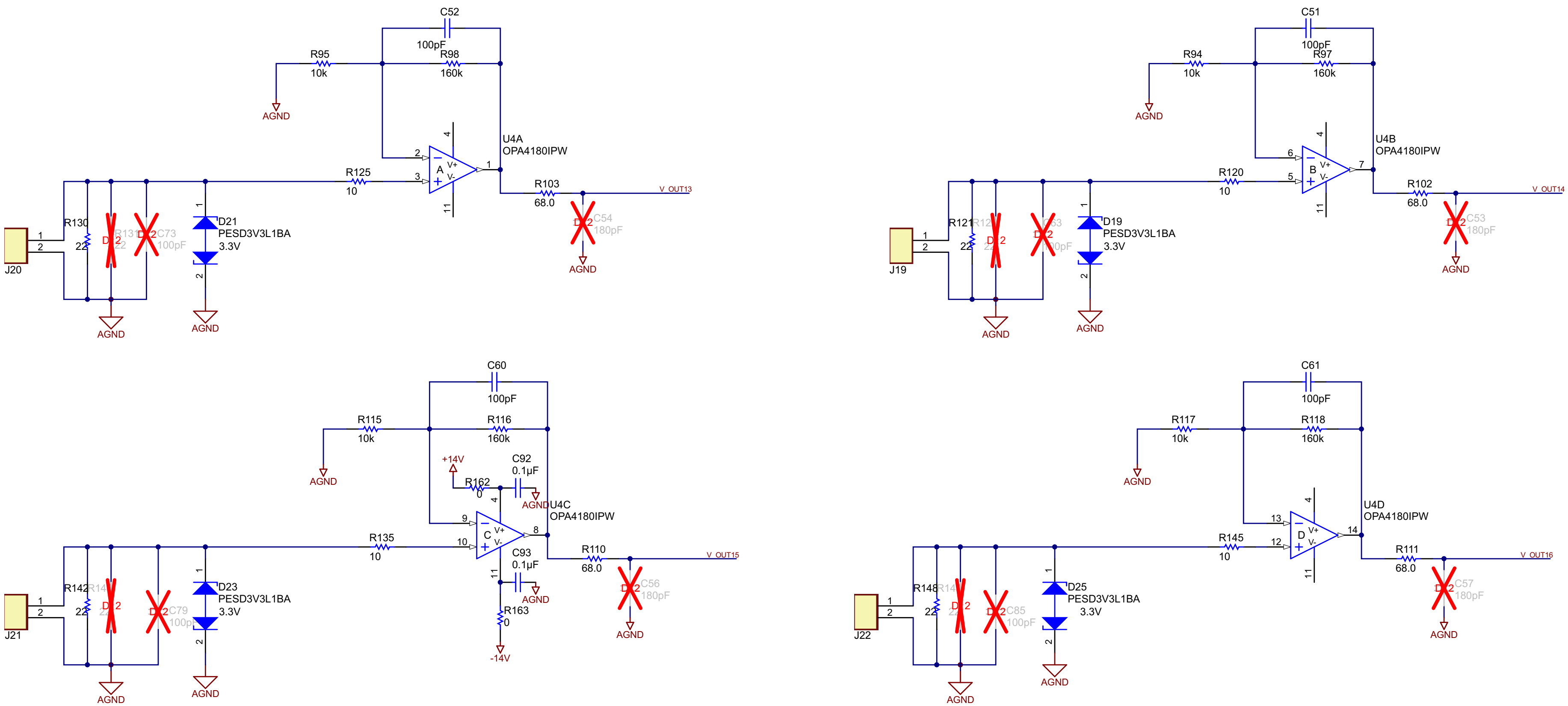


**Figure 34. Single-Ended CT Input**

### 8.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00493.

### 8.3 Layer Plots

To download the layer plots, see the design files at TIDA-00493.

### 8.4 Altium Project

To download the Altium project files, see the design files at TIDA-00493.

### 8.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00493.

## 9 References


1. Texas Instruments, *TPS65131EVM User's Guide* (SLVU119)
2. Texas Instruments, *ADS868x 16-Bit, 500-kSPS, 4- and 8-Channel, Single-Supply, SAR ADCs with Bipolar Input Ranges*, ADS8688 Datasheet (SBAS582)
3. Texas Instruments, *Sensor Inputs AFE for Merging Unit and Protection Relays Design Guide*, TIDA-00307 Design Guide (TIDU540)


## 10 Terminology

**RTU—** Remote terminal unit

**FTU—** Feeder terminal unit

**DTU—** Distribution terminal unit

**CT—** Current transformer

**PT—** Potential transformer

## 11 About the Author

**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 electronics (BE) in electronics and communication engineering (BE-E&C) from VTU, Mysore, India.

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