TI Designs

Active Integrator for Rogowski Coil Reference Design With Improved Accuracy for Relays and Breakers

Design Overview

The TIDA-00777 is an op amp-based active integrator design that covers a wide input of current range measurement using a Rogowski coil with excellent accuracy, linearity, stability, and repeatability. The integrator uses a precision amplifier with very low offset and temperature drift. Two configurations of the integrator are shown: one for precision measurement with less than 3° phase error, and the other for fast response time (< 15 ms). While the output signal is bipolar, an optional level shifting stage can be used when unipolar output is required.

Design Resources

TIDA-00777	Design Folder
OPA2188	Product Folder
OPA188	Product Folder
LM4040-N	Product Folder
LP2951-N	Product Folder
TPS60403	Product Folder
TPS723	Product Folder

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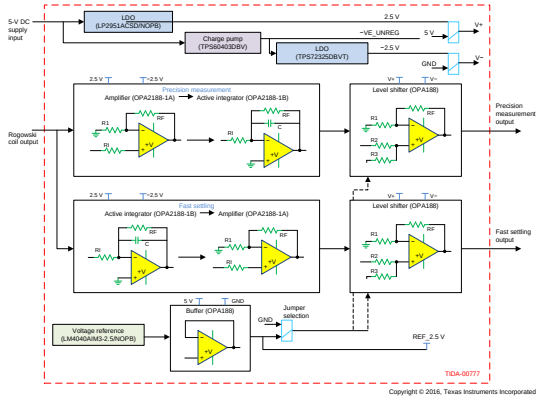
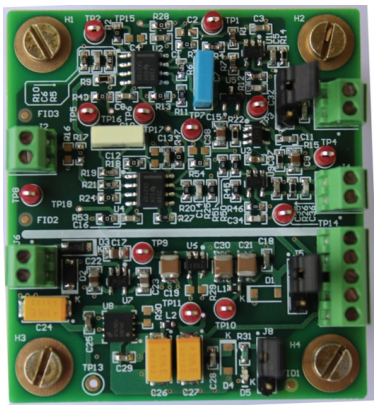
Design Features

- Current Measurement Using Rogowski (di/dt) Coil-Based Current Sensor:
  - 0.5 to 200-A for Precision Measurement Within ±0.5% Accuracy
  - 0.5 to 200 A for Fast Settling Within ±1% Accuracy of Final Measured Value
- Integration Achieved in Hardware With
  - RC, Low-Noise Density Op Amp Based Integrator Design
  - Parallel Paths With Low-Phase Shift Error and Fast Output Response Time
    - Phase Error < 3° for 50 and 60 Hz for Precision Measurement
    - Phase Error < 15° for 50 and 60 Hz for Fast Settling
- Op Amp Gains Designed for Integrating Rogowski Coil (Pulse, PA3209NL) Specification: 463 µV/A at 50 Hz;
  556 µV/A at 60 Hz
- Operates With a Single DC Input
- AFE Output Type:
  - Bipolar: V_{OUT} = ±2.5 V
  - Unipolar: V_{OUT} = 0 to 5 V, V_{CM} = 2.5 V
- Interfaced to MSP430F6779 Metering SoC for Accuracy Measurement and ADS131E08

Featured Applications

- Protection Relays and IEDs
- Circuit Breakers





1 Key System Specifications

Table 1. Key System Specifications

NO	PARAMETERS	SPECIFICATION	
1	Current sensor type	Rogowski coil	
2	Rogowski coil output specification	Pulse part number PA3209NL: • 463 µV/A at 50 Hz • 556 µV/A at 60 Hz	
3	Number of input currents	One	
4	Measurement frequency	50 or 60 Hz	
5	Integrator type	Active	
6	Integrator output	Two options: • Measurement path for reduced phase error • Fast settling path for fast response	
7	Output voltage scaling	Selectable unipolar or bipolar output: • 0 to 5 V with V_{CM} = 2.5 V • ±2.5 V	
		Precision measurement	Fast settling (±5% of final measured value)
8	AC current measurement range	0.25 to 200 A	0.5 to 200 A
9	Accuracy	< ±0.5%	< ± 1.0%
10	Current measurement linearity (from 1 to 200 A)	< ±0.3%	< ± 0.3%
11	Phase angle error	< 3°	< 15°
12	Temperature drift (–10°C to 60°C)	< ±150 PPM/°C	< ± 300 PPM/°C
13	Repeatability σ max (%)	< ±0.2%	< ±0.2%
14	Integrator time constant	~100 ms	~15 ms
15	External DC power supply input	5 V ± 0.1 V, ≤ 20 mA	

2 System Description

Grid infrastructure applications cover protection, control, and monitoring of systems that generate, transmit, and distribute power. These systems incorporate various sensor elements for measuring input voltages and currents accurately.

2.1 Protection Relays

Protection relays provide protection to grid equipment during fault conditions by monitoring multiple voltages and currents. If the relays detect a stressed condition, a trip signal is sent to the circuit breaker to isolate the faulty section from the power system. Protection relays accurately measure current inputs using current transformers (CTs), Rogowski coils, or shunts and voltage inputs using potential transformers (PTs) or potential dividers. Additionally, protection relays do precise measurement. They have auxiliary power (AC or DC).

2.2 Circuit Breakers

Circuit breakers use trip elements to provide circuit protection for different applications. These trip elements protect against thermal overloads, short circuits, and arcing ground faults. The trip unit is the brains of the circuit breaker. The function of the trip unit is to trip the operating mechanism in the event of a short circuit or a prolonged overload of current. Electronic trip units measure RMS current providing improved trip performance compared to conventional trip units.

Circuit breakers have a making current release (MCR) feature. MCR enables an instantaneous trip when a breaker is closed on a faulted circuit to open with no intended delay. The making current release functionality is active for only a short preset time after the circuit breaker is closed. In such a case, the breaker must power on, quickly detect the fault, generate trip signal, and disconnect. Fast settling is a key requirement.

Current sensors with a wide range is needed to measure currents from amperes in normal conditions to 100's of amperes in short-circuit conditions. A Rogowski coil is suitable because of its linear output range over a wide input current.

2.3 Rogowski Coil-Based Current Sensor

A Rogowski coil is an air cored (non-magnetic) toroidal windings placed round the conductor. An alternating magnetic field produced by the current in the primary conductor (I_P) induces a voltage (V_S) in the coil. Due to its non-magnetic core, the output of the coil does not saturate for a large primary current.

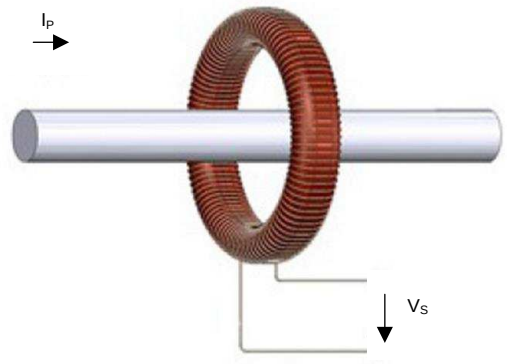


Figure 1. Rogowski Coil Operating Principle

The output voltage of a Rogowski coil is proportional to the rate of change of the current in the primary conductor, and it does not get affected by the DC current.

Rogowski coils with a wide current range can be used for both measurement and protection applications. They provide galvanic isolation from the primary circuit. Because Rogowski coils convert input current to an output voltage, no burden resistor is needed. This in turn reduces power consumption. Unlike current transformers, Rogowski coils are electrically safe when open.

Rogowski coils are of two types—rigid or flexible:

- Rigid Rogowski coils are wound on a toroidal shape core made of epoxy, plastic, or other non-magnetic materials.
- Flexible Rogowski coils are wound over flexible material such as silicone or a rubber tube.

Figure 2. Rigid (Left) and Flexible Rogowski Coils (Right)

2.4 Rogowski Coil Selection

While rigid coils have better accuracy, flexible coils are convenient for measuring current in large or non-round shaped conductors such as bus bars. Flexible coils are preferred when current carrying conductor interruption (electrical or mechanical) is not an option. The current measurement range of flexible coils can run into 1000's of amps.

Whether rigid or flexible coils are used, some of the key parameters to consider include:

- Dynamic range: Minimum to maximum current range that is required for the application
- Linearity: Linear output voltage for a specified range of current
- Accuracy: Output voltage accuracy for a specified range of current
- Secondary output voltage: Sensitivity of the coil specified as µV/A for a given frequency (for example: PA3209NL Rogowski coil from Pulse specifies 463 µV/A at 50 Hz, 556 µV/A at 60 Hz)
- Phase shift error: Specifies the phase difference between the output voltage and input current
- Primary-secondary isolation: Specifies the isolation barrier potential that the Rogowski coil can handle
- Inner diameter: Specified in mm depending on the current

3 System Design Theory

The voltage (V_S) induced at the output of a Rogowski coil is proportional to the time rate of change of current flowing in the primary conductor (I_P). The output voltage has a 90° phase shift and lags input for a sinusoidal input current.

$$V_S(t) = -M\frac{dI_P(t)}{dt}$$

Because the output of the Rogowski coil is proportional to the derivative of the instantaneous primary current, an integrator is required to retrieve the original current signal. The output voltage is linear, which can be used without integration in applications requiring only current measurement. For applications requiring measurement of power, the phase difference between current and voltage is important and requires phase shifting of the Rogowski current sensor output. This is done using an integrator. A Rogowski integrator can be implemented in two ways:

- Digital (software) integration: In a frequency domain, integration can be viewed as –20 dB/decade attenuation and a constant –90° phase shift. The phase angle correction can be highly accurate when done in the digital domain. This is because the phase and magnitude response of a digital integrator is very close to ideal. The limitation of such architecture is that this requires a high-performance MCU with digital filter implementation. This may delay processing during the start-up.
- Hardware integration: A hardware integrator can also be used for correcting the Rogowski current sensor phase shift. This can be achieved using a passive integrator (resistors, capacitors) or an active integrator (combination of active (op amp) and passive elements). This TI Design implements a stable op amp-based active integrator that can be used over the useful temperature range.

An ideal hardware integrator would introduce a 90° phase shift; however, there are practical limitations when designing a hardware integrator that results in a phase error with respect to the expected phase shift of 90°. Carefully choosing components minimizes the phase error variations.

3.1 Passive Integrator

A series resistor-capacitor (RC) network acts as an integrator for a larger output range Rogowski coil. The value of an RC is dependent on the phase error that is acceptable for the application. The relationship between the RC and the phase error can be established using the phasor diagram of an RC network as shown in Figure 3.

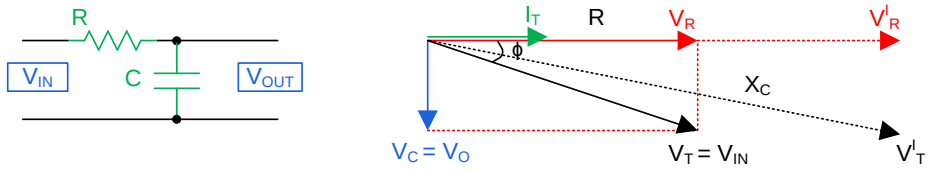


Figure 3. Passive Integrator (Left) and Phasor Diagram (Right)

As shown in the phasor diagram in Figure 3, V_R and V_C represent the drop across the resistor (R) and capacitor (C). The drop across the resistor will be in phase and the capacitor will lag by 90° with regard to the net current (I_T) in the network. The output voltage (V_O) is the voltage across the capacitor, and the input voltage (V_{IN}) is the vector sum of voltage drop across the resistor and capacitor.

The phase angle between V_O (V_C) and V_{IN} (V_T) is the phase difference between the integrator's input and output, which should be close to 90°. The phase error, which is the deviation from an ideal value of 90°, is represented by φ in Figure 3. The larger the drop across the resistor (V'_R) compared to the capacitive impedance, the smaller the phase angle error will be.

The values of R and C can be estimated based on the following equations:

$$\tan\Phi = \frac{X_C}{R} = \frac{1}{2\times\pi\times f\times C\times R} \quad (1)$$

where

- φ = Target phase error for the design
- X_C = Capacitive impedance
- R = Resistance
- f = Input mains frequency

$$R\times C = \frac{1}{2\times\pi\times f\times\tan\Phi} \quad (2)$$

Table 2 shows the cutoff frequency (RC) required to achieve various phase angle errors using Equation 2.

Table 2. Required RC for Different Phase Angle Errors

Θ	tan(φ)	RC	RC 50 Hz (ms)	RC 60 Hz (ms)
0.5°	0.009	18.2/f	364.7	304.0
1.0°	0.017	9.1/f	182.4	152.0
1.5°	0.026	6.1/f	121.6	101.3
2.0°	0.035	4.6/f	91.2	76.0
2.5°	0.044	3.6/f	72.9	60.8
3.0°	0.052	3.0/f	60.7	50.6

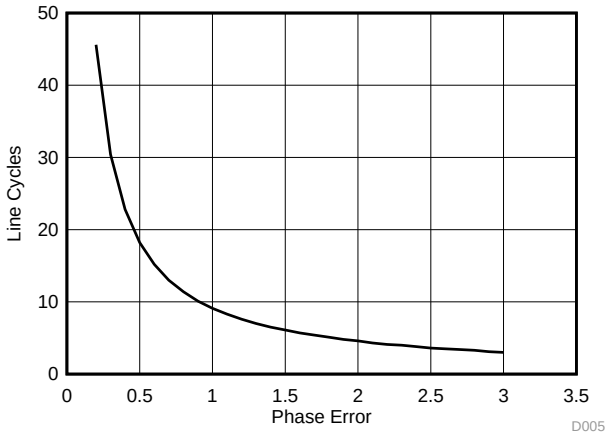


Figure 4. Cutoff Frequency (RC)

To achieve a 3° phase error, the RC product should be three line cycles. As seen from Figure 4, reducing the phase error entails increasing the RC product exponentially. To achieve an exact 90° phase difference (or 0° phase error) between the input and output, the RC product must be infinite. Depending on the application, designers choose a very low phase error value (< 3°) where measurement accuracy is important, such as protection relays, and a higher phase error value (< 15°) where response time is important, such as breakers.

The output of the Rogowski coil has a limited current drive capability. Passive RC integrators are often followed by DC level shift with amplification that helps drive the input stage of analog-to-digital converters (ADCs).

3.2 Active Integrator

To target a 3° phase error, the design uses a RC of 100 ms as per Table 3, which shows various combinations of R and C values for a 100-ms RC as an example.

Table 3. R and C combinations to Achieve 100-ms RC

RC	RESISTOR	CAPACITOR	X_C at 50 Hz	X_C : R
100 ms	100 kΩ	1 µF	3.2 kΩ	1:31
100 ms	500 kΩ	200 nF	15.9 kΩ	1:31
100 ms	1 MΩ	100 nF	31.8 kΩ	1:31

The RC network acts as an attenuator. The drop across the capacitor gets attenuated by a factor of 32. This is a problem, especially at low-current levels when the output voltage of the Rogowski coil will be less than 100's of µV. This results in poor signal levels at the input of the ADC, causing accuracy and repeatability issues at low-input current levels.

This problem can be solved using an active integrator as shown in Figure 5 where the RC element is in the feedback path of an amplifier. Additionally, the –90° phase shift caused by the Rogowski coil can be corrected and the output scaled using R_1.

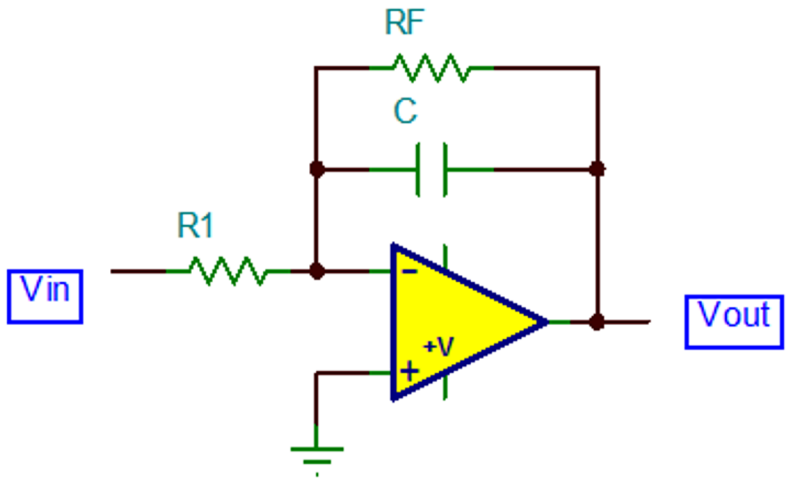


Figure 5. Active Integrator

The equations for computing the integrator elements (R_F, C) remain the same as shown in Section 3.1.

The gain of the amplifier can be adjusted using Equation 3, such that the output of the amplifier swings full scale for the entire input range.

$$GAIN_{INV} = \frac{VOUT_{MAX} - VOUT_{MIN}}{VIN_{MAX} - VIN_{MIN}} = -\frac{R_F \,||\, X_C}{R_1} \quad (3)$$

3.2.1 Inverting Amplifier Configuration

The input impedance of the amplifier is now dependent on the resistor R_1, which in turn is dependent on the previously mentioned gain requirements. For the parallel combination of R_F and X_C shown in Equation 3, the capacitive impedance dominates (see Table 3) as it is much smaller compared to the resistance. This parallel combination translates to a much smaller feedback resistance at line frequency. This lowers the value of R_1 that is required to meet the gain requirements of the circuit.

A typical Rogowski coil does not have enough drive capability at its output. If the value of R_1 is too low (in 10's of kΩ), it introduces a gain error at the output of the coil. This can be partially addressed by increasing X_C, for a given RC cutoff frequency, thereby increasing R_1. Not all Rogowski coils are able to drive such loads.

3.2.2 Non-Inverting Amplifier Configuration

A non-inverting amplifier is introduced in this design between the output of the Rogowski coil and the inverting amplifier. The high-input impedance of a non-inverting amplifier is used to overcome the challenge mentioned in Section 3.2.1. Additionally, the highest possible gain that is attainable is introduced in this stage for better noise performance.

The gain of this stage can be computed using the maximum output swing that the amplifier can handle (based on the loading from the next stage) and the maximum input swing. For better linearity, ensure that the output does not exceed the datasheet specification on how close it can go to the rail under maximum loading condition.

$$GAIN_{NON-INV} = \frac{VOUT_{MAX} - VOUT_{MIN}}{VIN_{MAX} - VIN_{MIN}} = 1 + \frac{R_F}{R_1} \quad (4)$$

Arriving at the system gain of the circuit ($GAIN_{NON-INV} \times GAIN_{INV}$) is an iterative process that involves

- Optimizing the capacitance and resistance value for a given RC cutoff frequency
- Selecting R_{1INV} such that the $GAIN_{INV}$ is able to handle the overall output swing and input swing requirement and that the Rogowski coil is able to drive it
- Introducing a non-inverting amplifier between the Rogowski coil and the integrator if R_{1INV} is too low. This stage should handle most of the gain.
- Adjusting R_{1INV} such that the combined gain ($GAIN_{NON-INV} \times GAIN_{INV}$) meets the output and input swing requirements

3.3 Component Selection

3.3.1 Integrator R and C Selection for Precision Measurement Path

This design has a target phase error of 3°.

Using Equation 2:

- RC ≥ 3.0/f (3° phase error)
- RC ≥ 60 ms (50-Hz line frequency being the worst case)

Considering a design margin for component tolerances, an RC time constant of ~100 ms is selected. A 150-nF standard capacitor and a 680-kΩ resistor that results in 102 ms are used for this integrator.

Integrator capacitor should have low (< ±5%) tolerance and lower temperature drift. Polyester film capacitors have good frequency response and temperature stability. This design uses polyester film capacitor with ±5% tolerance. The resistors used in precision measurement path have a ±0.1% tolerance to improve accuracy and repeatability.

3.3.2 Integrator R and C Selection for Fast Settling Path

For the fast settling signal path where response time has to be minimized, this TI Design has a target phase error of 15° to have integrator time constant of less than a cycle.

Using Equation 2:

- RC ≥ 0.6/f for 15° phase error
- RC ≥ 11.8 ms (50-Hz line frequency being the worst case)

Considering a design margin for component tolerances, an RC time constant of ~14 ms is targeted. A 100-nF standard capacitor value and a 137-kΩ resistor that results in 13.7 ms are used for this integrator.

As explained in Section 3.3.1, this design uses the same polyester film type capacitor with a ±5% tolerance. However, to optimize cost for fast settling branch, ±1% tolerance resistors are used in the design except integrator feedback resistors (±0.1%).

3.3.3 Gain for Precision Measurement Path (Non-Inverting Amplifier + Inverting Integrator)

Some of the amplifiers have approximately 100 to 250 mV of non-linear region of operation close to the rail. This design uses an output swing of ±2.5 V – 0.35 V (with a 100-mV margin). For a current range of 0.25 to 200 A, the Rogowski coil gives output of 115 µV to 92.6 mV. This design uses an input swing of 100 µV to 100 mV, which results in an overall system gain of less than 15.

3.3.3.1 $GAIN_{NON-INV}$

To improve AC performance at a lower current, the Rogowski coil output is amplified before applying to the integrator. Most of the gain is achieved in non-inverting amplifier stage.

Using Equation 4:

- $GAIN_{NON-INV} < 15$
- A 150-kΩ feedback resistor (R_F) and 11.3-kΩ gain resistor (R_1) that result in 14.3 for $GAIN_{NON-INV}$.

3.3.3.2 $GAIN_{INV}$

$GAIN_{INV}$ must be < 1.05 to have a system gain ($GAIN_{INV} \times GAIN_{NON-INV}$) of 15.

Using Equation 3:

- $R_1 > 20.2$
- A 680-kΩ integrator resistor (R_F), a 150-nF integrator capacitor (C), and a 20.5-kΩ gain resistor (R_1) that result in 1.04 for $GAIN_{INV}$.

As a result, $GAIN_{NON-INV} \times GAIN_{INV} = 14.8$ for precision measurement.

3.3.4 Gain for Fast Settling Path (Inverting Integrator + Non-Inverting Amplifier)

The combined system gain of all two stages will be same as the explanation in Section 3.3.3 for the precision measurement path.

3.3.4.1 $GAIN_{INV}$

Peak current during fault condition will be higher. In order to capture the current peak, the inverting integration stage is introduced first. To minimize the Rogowski coil gain error because of R_1, R_1 is selected as 30.9 kΩ.

Using Equation 3:

- $GAIN_{INV}$ = 1.0
- A 137-kΩ integrator resistor (R_F), a 100-nF integrator capacitor (C), and a 30.9-kΩ gain resistor (R_1) that result in 1.0 for $GAIN_{INV}$.

3.3.4.2 $GAIN_{NON-INV}$

$GAIN_{NON-INV}$ must be < 15 to have a system gain ($GAIN_{INV}$ × $GAIN_{NON-INV}$) of 15.

Using Equation 4:

- $GAIN_{NON-INV}$ < 15
- A 150-kΩ feedback resistor (R_F) and a 11-kΩ gain resistor (R_1) that result in 14.6 for $GAIN_{NON-INV}$.

3.3.5 DC Level Shifter

In case unipolar measurement is required, the DC level shifter stage is needed. The DC level shifter is after the integrator stage for precision measurement and after the amplifier stage for fast settling. The bipolar (±2.5 V) output needs to be DC level shifted to have unipolar (0 to 5 V) output with output common-mode voltage (V_{CM}) of 2.5 V.

4 Block Diagram

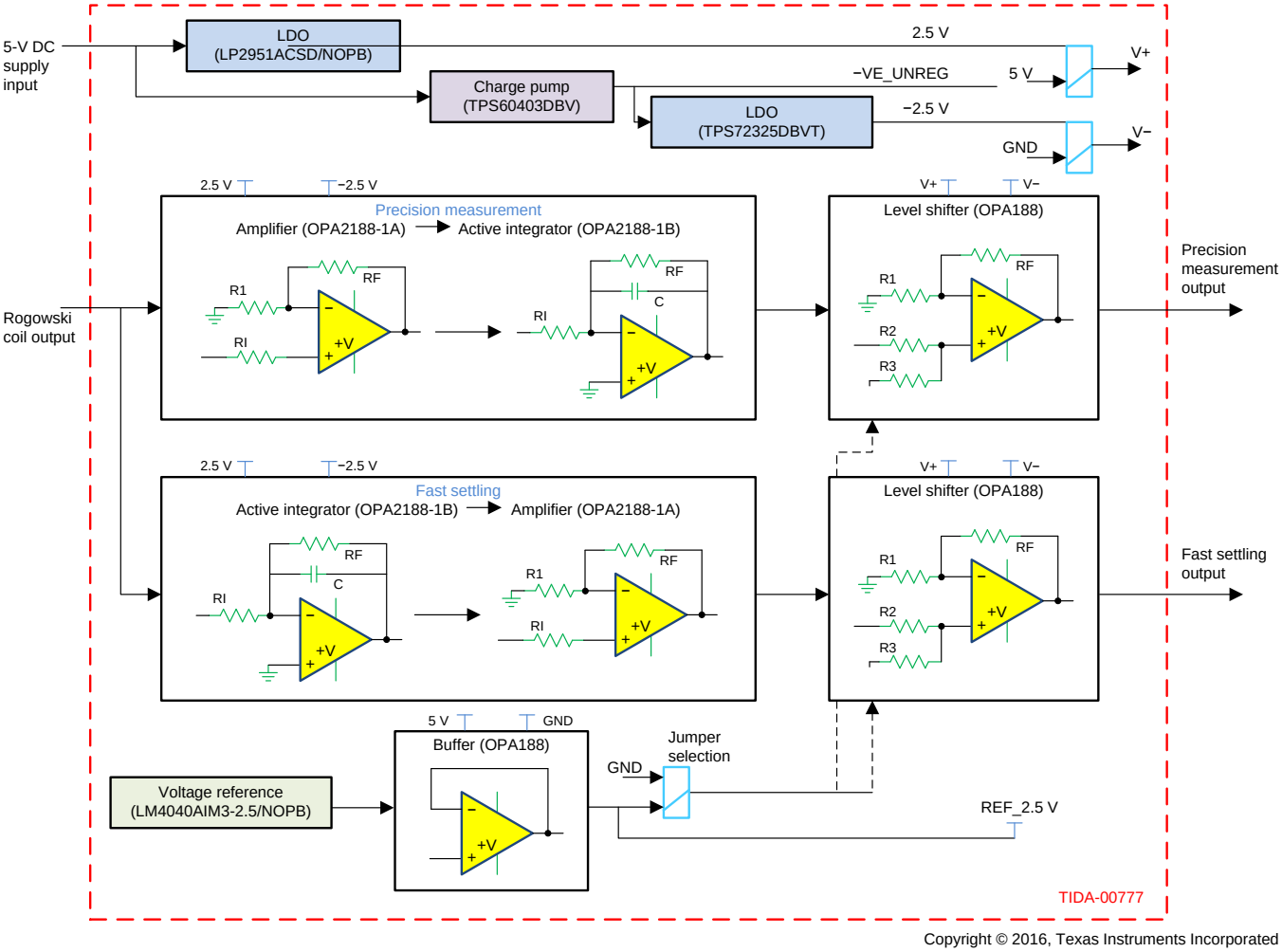


Figure 6. TIDA-00777 Block Diagram

The TIDA-00777 consists of four sections:

- Precision measurement
- Fast settling
- Voltage reference and buffer
- Power supply

4.1 Precision Measurement

Precision measurement consists of three stages:

- Gain stage
- Integrator stage
- DC level shift stage

To measure wide range of current, the Rogowski coil is used. To accurately measure output voltage at lower currents, the output voltage is amplified first before applying to integrator to improve AC performance at lower currents. This is because integrator attenuates the input signal. Most of the gain is achieved in gain stage so as to amplify Rogowski coil output before integrating it. This path has a non-inverting gain stage (14.3) followed by an inverting integrator (gain = 1.04, phase error < 3°) followed by DC level shift stage where DC level shift is selectable as 2.5 V for a 0- to 5-V output voltage range or 0 V for a ±2.5-V output voltage range. Dual op amp is used for gain and integrator stage and has a fixed ±2.5-V supply. The DC level shift stage supply can be selected as ±2.5 V or 0 to 5 V using jumpers available on the board.

4.1.1 Fast Settling

Fast settling consists of three stages:

- Integrator stage
- Gain stage
- DC level shift stage

A high rate of change of current is expected during short circuit. An integrator is used at the first stage to capture the short-circuit currents. This path has an inverting integrator (gain = 1, phase error < 15°) followed by non-inverting gain stage (14.6) followed by DC level shift stage where DC level shift is selectable as 2.5 V for a 0- to 5-V output voltage range or 0 V for a ±2.5-V output voltage range.

A dual op amp is used for the gain and integrator stages and has a fixed ±2.5-V supply. A DC level shift stage supply can be selected as ±2.5 V or 0 to 5 V using jumpers available on the board.

DC level shift stage supply selection is common for both precision measurement and fast settling.

4.1.2 Voltage Reference and Buffer

A precise voltage reference of 2.5 V with low temperature drift and output voltage tolerance of ±0.1% is selected. A V_{CM} of 2.5 V is required for the unipolar output voltage level. Voltage reference is passed through buffer and is used in conjunction with DC level shifting op amp as shown in Figure 6.

4.1.3 Power Supply

This design takes single external DC supply of 5 V. Using a linear regulator, 2.5 V is generated. A negative supply is required for a bipolar output. Voltage is inverted using a charge pump voltage inverter. A negative linear regulator is used to generate –2.5 V.

4.2 Highlighted Products

4.2.1 OPA2188/OPA188

An op amp is used at each stage of precision measurement and fast settling. Selecting an op amp is critical for the design.

Key specifications for selecting an op amp for an integrator design include:

- Low offset and offset drift helps in minimizing calibration as well as degradation in performance over temperature.
- Low bias current helps in minimizing the loading of the Rogowski coil, thereby reducing gain error.
- Low voltage noise density improves repeatability and accuracy at low input currents of the Rogowski coil.

The OPA2188 dual op amp is used in this design for integrator and gain stage. The OPA188 single op amp is used in this design for the DC level shift stage and to buffer voltage reference. Table 4 lists key specifications:

Table 4. Key Specifications of OPA2188 and OPA188

PART NUMBER	OPA2188	OPA188
Number of channels	2	1
Total supply voltage (min)	4	4
Total supply voltage (max)	36	36
GBW (typ; MHz)	2	2
Slew rate (typ; V/µs)	0.8	0.8
Rail-to-rail	In to V–, Out	In to V–, Out
V_{OS}, Offset voltage at 25°C (max; mV)	0.025	0.025
Offset drift (typ; µV/C)	0.03	0.03
V_N at 1 kHz (typ; nV/rtHz)	8.8	8.8
I_Q per channel (typ; mA)	0.385	0.425
I_O (typ; mA)	18	18
CMRR (typ; dB)	114	114
Operating temperature range (°C)	–40 to 105	–40 to 105
I_{IB} (max; pA)	850	1400

4.2.1.1 Precision Measurement

The following gain stage circuit is in a non-inverting amplifier configuration. R5 and R10 are used to calculate gain using Equation 2. R32 is a design provision and must not be assembled.

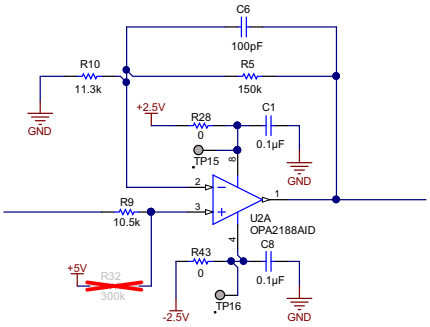


Figure 7. Gain Stage for Precision Measurement

The following circuit is in an inverting integrator configuration. R6 and C7 are the integrator resistor and capacitor, respectively. R6, C7, and R11 are used to calculate gain using Equation 3. R34 is a design provision and must not be assembled.

NOTE: Place R6 and C7 (integrator components) as close to the op amp as possible.

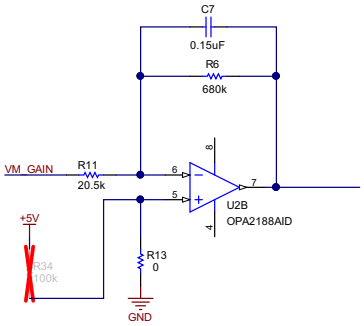


Figure 8. Integrator Stage for Precision Measurement

The following circuit is a DC level shift circuit with unity gain. Supply V+, V–, and reference voltage (V_REF) are selectable to have unipolar or bipolar output.

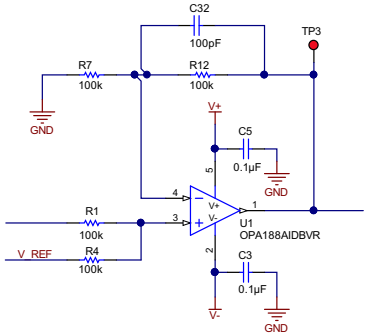


Figure 9. DC Level Shift Stage for Precision Measurement

4.2.1.2 Fast Settling

The following circuit is in inverting integrator configuration. R19 and C10 are the integrator resistor and capacitor, respectively. R19, C10, and R21 are used to calculate gain using Equation 3.

NOTE: Place R6 and C7 (integrator components) as close to the op amp as possible.

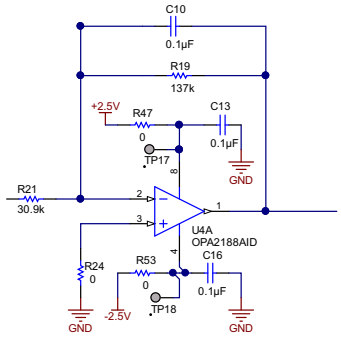


Figure 10. Integrator Stage for Fast Settling

The following circuit is in non-inverting amplifier configuration. R20 and R25 are used to calculate gain using Equation 2. R37 is a design provision and must not be assembled.

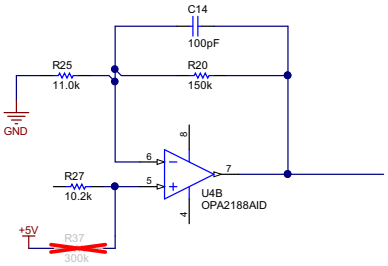


Figure 11. Gain Stage for Fast Settling

The following circuit is a DC level shift circuit with unity gain. Supply V+, V–, and reference voltage are selectable to have unipolar or bipolar output.

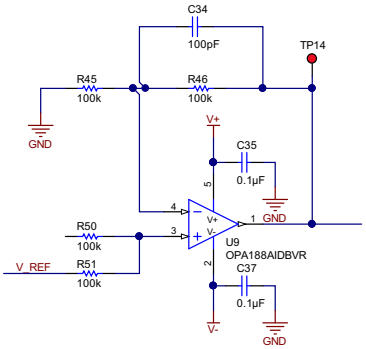


Figure 12. DC Level Shift Stage for Fast Settling

4.2.2 Voltage Reference

This TI Design provides a precise 2.5-V reference used for precision measurement and fast settling unipolar output. It features the LM4040AIM3-2.5/NOPB, a 2.5-V precision micropower shunt voltage reference. The same voltage reference is connected to DC level shift circuit of both precision measurement and fast settling. Reference voltage output is buffered using an op amp and is available on pin 1 of header J3. Short pin 2 of J3 with pin 3 of J3 for a 0- to 5-V output. Short pin 2 of J3 with pin 1 of J3 for a ±2.5-V output.

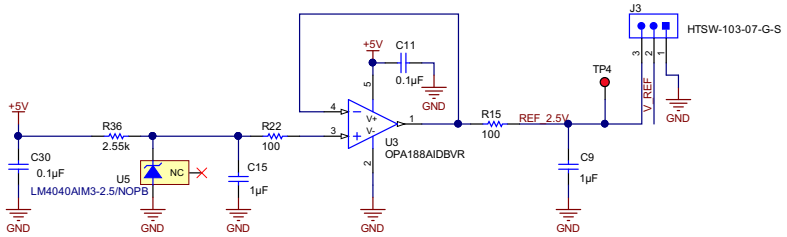


Figure 13. Circuit Diagram for 2.5-V Voltage Reference

4.2.3 2.5-V Supply

An external 5-V DC supply must be connected on the J6 terminal block. The LP2951 family of voltage regulators is used to generate the required positive supply. The LP2951ACSD/NOPB is configured to generate 2.5 V. A design option is provided for a positive supply of the DC level shift stage of precision measurement and fast settling op amp (V+) to be 2.5 V or 5 V. V+ will be 2.5 V if pin 1 and 2 of header J8 are short. V+ can be switched to 5 V if pin 2 and 3 of header J8 are short. Green LED is available for visual indication. To change the rail voltage from 2.5 V, the resistor value of R41 and R40 must be changed.

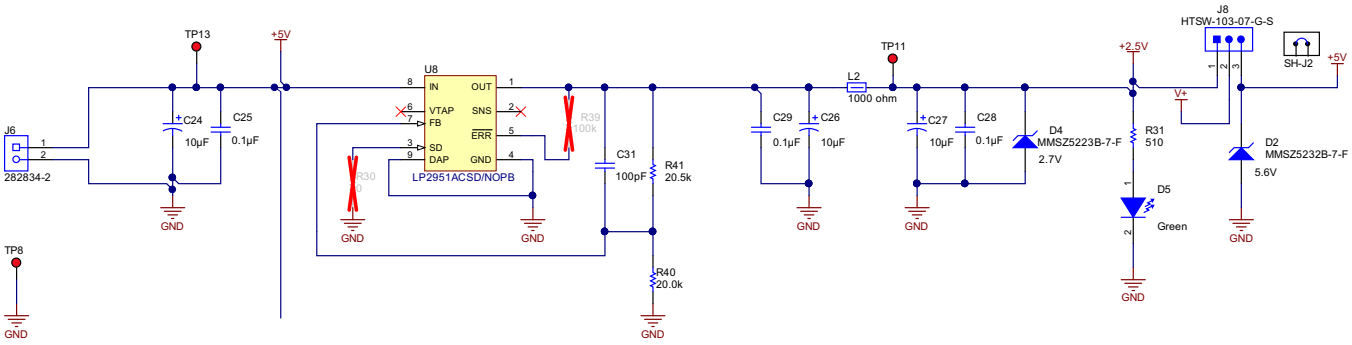


Figure 14. Circuit Diagram for 2.5-V Supply

4.2.4 –2.5-V Supply

This TI Design features the TPS60403DBVR, a 250-kHz fixed frequency charge pump voltage inverter to generate a negative output voltage from an input voltage. The input voltage range of the TPS60403 is 1.8 to 5.5 V. The external input supply voltage is 5 V. To increase the margin from the maximum input voltage of the TPS60403, diode D3 is added for additional voltage drop.

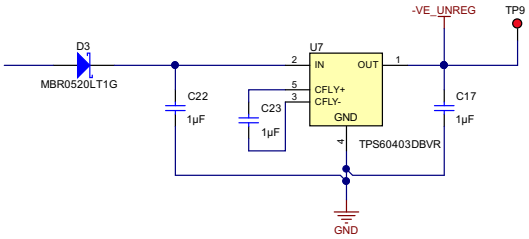


Figure 15. Circuit Diagram for Voltage Inverter

This TI Design uses the TPS72325DBVT, a fixed –2.5-V negative output low-dropout linear regulator to generate the required –2.5-V negative power supply and is available on pin 1 of header J7. A design option is provided for a negative supply of the DC level shift stage of precision measurement and fast settling. The op amp (V–) will be –2.5 V or GND. V– will be –2.5 V if pin 1 and 2 of header J7 are short. V– can be switched to GND if pin 2 and 3 of header J7 are short. To change the rail voltage from –2.5 V, the TPS72301DBV, an adjustable linear regulator from same family, can be used. R29 and R38 are used with adjustable linear regulator for adjusting output voltage.

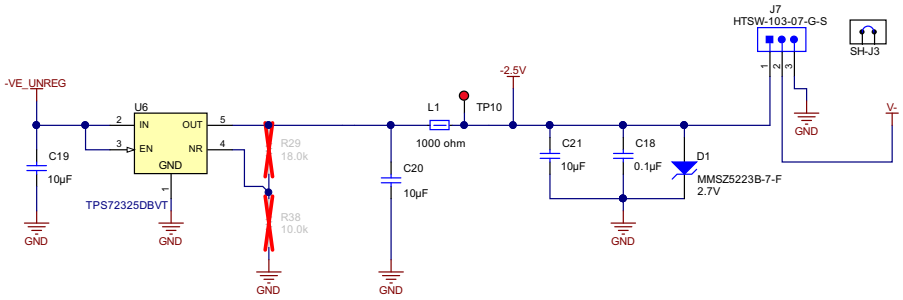


Figure 16. Circuit Diagram for –2.5-V Supply

4.2.5 DC Level Shifter Output

The DC level shift stage for precision measurement is required to convert output voltage from bipolar to unipolar. When only bipolar output is required, R33 can be used to bypass the DC level shift stage. When R33 is used, remove DC level shift stage components U1, R1, R12, and C32 from the board. DC level shift section output passes through an anti-aliasing filter and is available on terminal block J1.

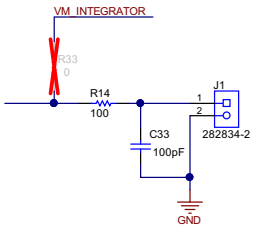


Figure 17. Precision Measurement Output Connector

The DC level shift stage of fast settling is required to convert output voltage from bipolar to unipolar. When only bipolar output is required, R49 can be used to bypass the DC level shift stage. When R49 is used, remove DC level shift stage components U9, R50, R46, and C34 from the board. DC level shift section output passes through an anti-aliasing filter and is available on terminal block J4.

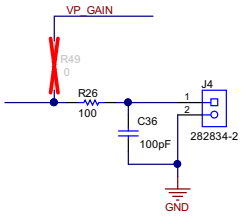


Figure 18. Fast Settling Output Connector

5 Getting Started Hardware

This section provides details of different connectors that are provided on the TIDA-00777 and TIDA-00222 boards and their applications.

5.1 Connectors

Table 5 provides connection information for the TIDA-00777.

Table 5. TIDA-00777 Board Connector Details

INPUT OR OUTPUT TYPE	SPECIFICATION	CONNECTOR
Input terminal block	Rogowski coil output	J2.1 – J2.2
Output terminal block	For precision measurement	J1.1 – J1.2
	For fast settling	J4.1 – J4.2
For ±2.5-V output range (same for both precision measurement and fast settling output)	Select V_REF = 2.5 V	Short J3.2 – J3.1
	Select V+ = 2.5 V	Short J8.2 – J8.1
	Select V– = -2.5 V	Short J7.2 – J7.1
For 0- to 5-V output range (same for both precision measurement and fast settling output)	Select V_REF = 0 V	Short J3.2 – J3.3
	Select V+ = 5 V	Short J8.2 – J8.3
	Select V– = 0 V	Short J7.2 – J7.3
External power supply input terminal block	5-V DC	J6.1 – J6.2
Interface terminal block	Supply and reference voltages	J5.1 – 2.5 V J5.2 – GND J5.3 – 2.5 V J5.4 – 5 V J5.5 – Reference 2.5 V

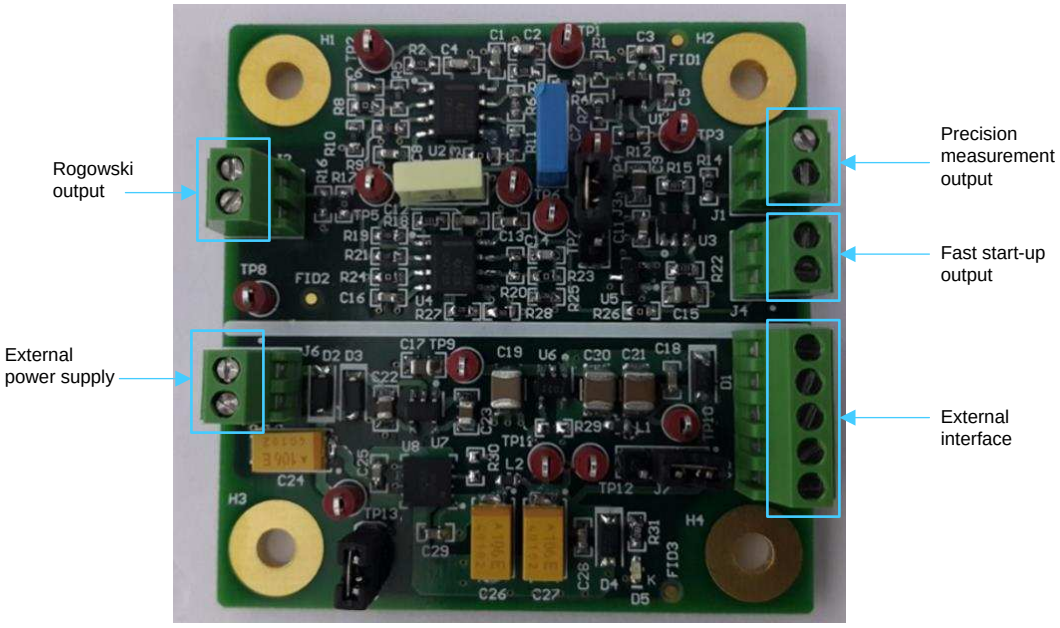


Figure 19. Connectors on TIDA-00777 Board

Table 6 provides connection information for the TIDA-00222.

Table 6. TIDA-00222 Board Connector Details

INPUT OR OUTPUT TYPE	SPECIFICATION	CONNECTOR
Phase A: Current channel Input terminal block	Output from TIDA-00777 board	J10.1 – J10.2
Phase A: Voltage channel Input terminal block	Potential divider output(1)	J13.1 – J13.2
External power supply input terminal block	5-V DC	J9.1 – J9.2
UART interface connector for GUI communication	PM_UCA0TXD (Tx) PM_UCA0RXD (Rx) GND	J1.1 J1.2 J1.4

(1) Potential divider output circuit: The circuit shown in Figure 20 is the external potential divider. The output of the potential divider is interfaced to the TIDA-00222 board for voltage measurement.

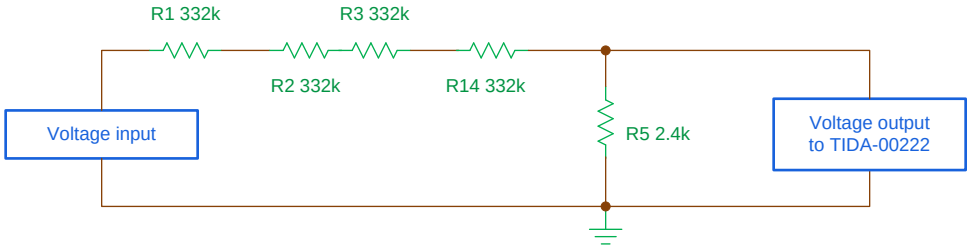


Figure 20. Potential Divider (Externally Connected) for Voltage Measurement on TIDA-00222

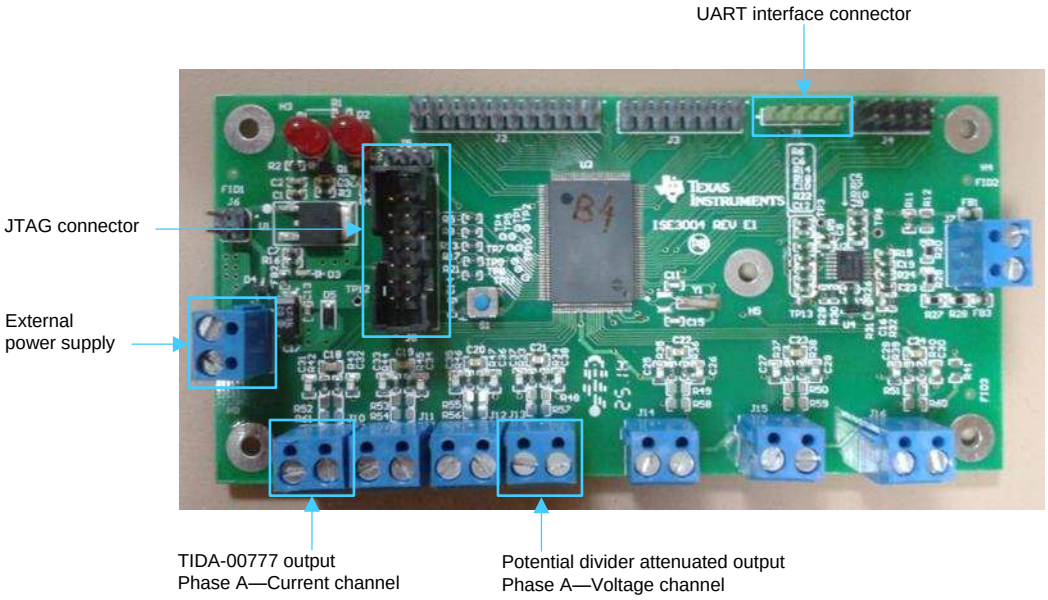


Figure 21. TIDA-00222 Board Connector Diagram

To interface the TIDA-00777 board, the following modifications are done on the TIDA-00222 board:

- Current measurement channel: Remove components R61, C31, C32, C18
- Voltage measurement channel: Remove components R57, C37, C38, C21
- Download firmware of available at http://www.ti.com/tool/TIDA-00454 to the TIDA-00222 board using JTAG programming connector J8. Voltage and current channels are configured as phase A in this software
- GUI is available at http://www.ti.com/lit/zip/slaa621

5.2 External DC Power Supply

The external 5-V DC power supply is required to power up the board on connector J6. Green LED (D5) will glow once the 2.5-V supply is generated. Check the 2.5-V (TP11 with respect to TP8) and –2.5-V (TP10 with respect to TP8) supplies before applying input current.

6 Test Setup

6.1 Test Setup Connection

Figure 22 shows the test setup for the TIDA-00777 board. The TIDA-00222 board is interfaced with the TIDA-00777 board. A programmable current and voltage source (PTS3.3C test system) is used for applying current to the TIDA-00777 board. Voltage is applied to the external potential divider, and output of the potential divider is connected to the TIDA-00222 board. A 5-V power supply connection is shown in Figure 22.

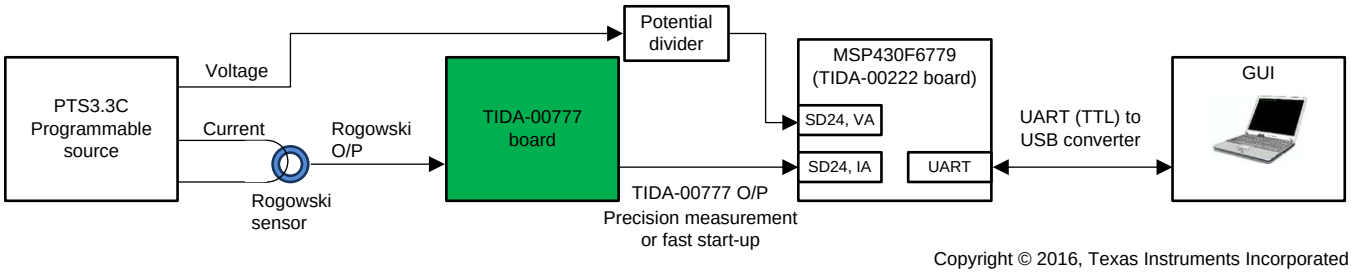


Figure 22. Test Setup to Connect TIDA-00777 and TIDA-00222

NOTE: Connect the Rogowski sensor output to connector J2 of the TIDA-00777 board before applying current.

6.2 TIDA-00222 Board

The current input range for this design is 0.5 to 200 A for fast settling and 0.25 to 200 A for precision measurement.

AC input parameters are measured using the TIDA-00222 MCU AFE board. The TIDA-00777 output of precision measurement or fast settling is interfaced with the TIDA-00222 MCU AFE to measure AC input current.

The following key features of the TIDA-00222 MCU AFE are used in this design:

- MSP430F6779 SoC with seven simultaneous sigma-delta ADCs. In this design, one current and one voltage channels are used
- AC input current measurement: Up to 90 A
- AC input voltage measurement: 230 V
- GUI support for monitoring and calibrating current, voltage, active power, and phase angle through a UART interface

6.2.1 AC Input Measurement

6.2.1.1 Current Measurement

The current is measured using the 24-bit sigma-delta (SD) ADC of the MSP430F6779, which is used in the TIDA-00222 TI Design with the modifications specified in Section 6.1. Phase A is used for measurement. At any given time, precision measurement or fast settling inputs can be taken.

6.2.1.2 Voltage Measurement

Although the TIDA-00777 TI Design is for current sensing, voltage measurement is required to compute the power and power factor, which is computed using cos φ = active power / apparent power, where φ is the phase angle.

6.2.2 Calibrating and Viewing Results From PC

See Section 7.2 from the TIDA-00601 design guide (TIDU845) for details on calibrating and viewing results.

6.3 Test System

PTS3.3C with an accuracy class of 0.05% is used for measurement, which provides minimum uncertainty during measurement.

Figure 23. Test System (Including Programmable Power Source)

7 Test Data

7.1 Functional Testing

Table 7. Functional Test Results

PARAMETERS	SPECIFICATIONS	OBSERVATION
Power supply	2.5-V DC	2.497-V DC
	Charge pump voltage inverter input	4.602-V DC
	Charge pump voltage inverter output	–4.561-V DC
	–2.5-V DC	–2.519-V DC
Reference voltage	2.5-V DC (REF_2.5V)	2.498-V DC
Precision measurement gain	Gain stage (× 14.3)	14.30
	Integrator stage (× 1.04)	1.05
	DC level shift stage (× 1.0)	1.00
Fast settling gain	Integrator stage (× 1.0)	1.02
	Gain stage (× 14.6)	14.70
	DC level shift stage (× 1.0)	1.00

7.2 Accuracy, Linearity, and Integrator Phase Error Testing

Voltage and current are applied using the PTS3.3-C. Accuracy of the current and active power is observed. Measurements were adjusted for gain and phase angle as required.

NOTE: Unless specified:

- AC voltage and current values are in RMS.
- The output voltage range is ±2.5 V.

7.2.1 Precision Measurement

The applied voltage is 230-V AC.

7.2.1.1 Test Data With 50-Hz Operating Frequency

7.2.1.1.1 Phase Error Observed

To test precision measurement at 50 Hz, the phase is corrected (compensated) for 90 µs.

Phase error = –90 µs × 360° × 50 Hz = –1.62°

7.2.1.1.2 Testing at Unity Power Factor (UPF)

Table 8. Current and Power Measurement Error at UPF

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.10	0.1005	0.53	23.0	23.10	0.45
0.25	0.2503	0.13	57.5	57.59	0.16
0.50	0.5002	0.04	115.0	115.09	0.07
1.00	1.0002	0.02	230.0	230.11	0.05
5.00	4.9981	–0.04	1150.0	1150.08	0.01
10.00	9.9992	–0.01	2300.0	2300.76	0.03
20.00	20.0034	0.02	4600.0	4602.89	0.06
50.00	49.9916	–0.02	11500.0	11502.60	0.02
75.00	74.9854	–0.02	17250.0	17250.90	0.01
90.00	89.9869	–0.01	20700.0	20700.00	0

Current linearity (from 1 to 90 A) = 0.06%

7.2.1.1.3 Testing at 0.5 Lag (60° Phase Lag Between Voltage and Current)

Table 9. Current and Power Measurement Error at 0.5 L

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.10	0.1004	0.42	11.50	11.59	0.76
0.25	0.2500	–0.01	28.75	28.81	0.19
0.50	0.4996	–0.07	57.50	57.50	0
1.00	0.9993	–0.07	115.00	114.99	–0.01
5.00	4.9950	–0.10	575.00	574.22	–0.14
10.00	9.9940	–0.06	1150.00	1149.33	–0.06
20.00	19.9920	–0.04	2300.00	2296.57	–0.15
50.00	49.9618	–0.08	5750.00	5739.72	–0.18
75.00	74.9416	–0.08	8625.00	8610.51	–0.17
90.00	89.9367	–0.07	10350.00	10332.80	–0.17

Current linearity (from 1 to 90 A) = 0.06%

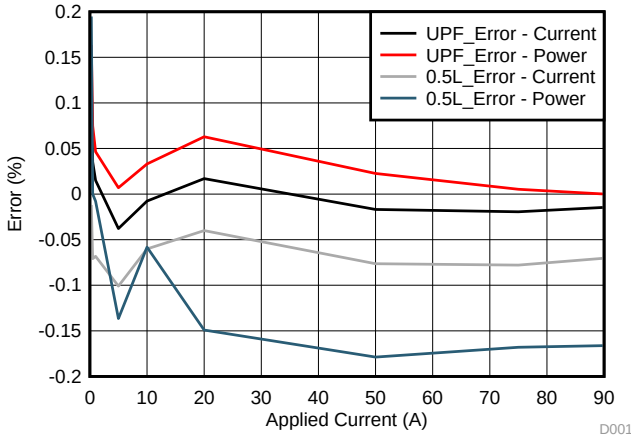


Figure 24. Precision Measurement Current and Power Accuracy for 50 Hz

7.2.1.2 Test Data With 60-Hz Operating Frequency

7.2.1.2.1 Phase Error Observed

To test precision measurement at 60 Hz, the phase is corrected (compensated) for 59.1 µs.

Phase error = –59.1 µs × 360° × 60 Hz = –1.28°

7.2.1.2.2 Testing at UPF

Table 10. Current and Power Measurement Error at UPF

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.10	0.1005	0.53	23.0	23.11	0.47
0.25	0.2502	0.10	57.5	57.56	0.11
0.50	0.4998	–0.03	115.0	114.98	–0.02
1.00	0.9994	–0.06	230.0	229.89	–0.05
5.00	4.9949	–0.10	1150.0	1149.07	–0.08
10.00	9.9909	–0.09	2300.0	2298.08	–0.08
20.00	19.9882	–0.06	4600.0	4598.39	–0.03
50.00	49.9583	–0.08	11500.0	11490.80	–0.08
75.00	74.9355	–0.09	17250.0	17233.90	–0.09
90.00	89.9264	–0.08	20700.0	20678.80	–0.10

Current linearity (from 1 to 90 A) = 0.04%

7.2.1.2.3 Testing at 0.5 Lag (60° Phase Lag Between Voltage and Current)

Table 11. Current and Power Measurement Error at 0.5 L

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.10	0.1004	0.37	11.50	11.58	0.73
0.25	0.2500	–0.01	28.75	28.81	0.22
0.50	0.4996	–0.08	57.50	57.52	0.04
1.00	0.9992	–0.09	115.00	114.95	–0.05
5.00	4.9948	–0.10	575.00	574.24	–0.13
10.00	9.9914	–0.09	1150.00	1148.87	–0.10
20.00	19.9909	–0.05	2300.00	2297.85	–0.09
50.00	49.9607	–0.08	5750.00	5742.41	–0.13
75.00	74.9390	–0.08	8625.00	8612.41	–0.15
90.00	89.9274	–0.08	10350.00	10334.40	–0.15

Current linearity (from 1 to 90 A) = 0.05%

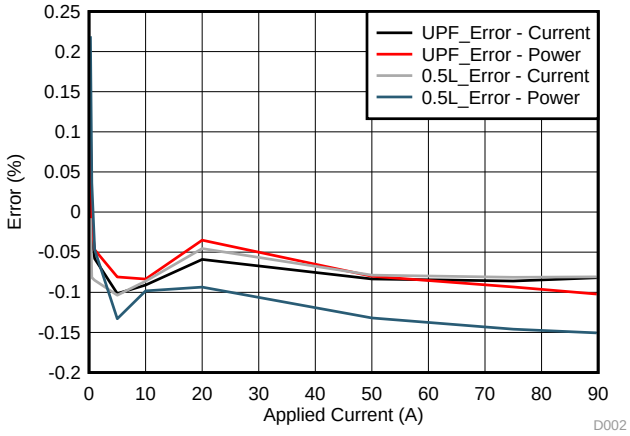


Figure 25. Precision Measurement Current and Power Accuracy for 60 Hz

7.2.2 Fast Settling

7.2.2.1 Test Data With 50-Hz Operating Frequency

7.2.2.1.1 Phase Error Observed

To test fast settling at 50 Hz, the phase is corrected (compensated) for 720 µs.

Phase error = –720 µs × 360° × 50 Hz = –12.96°

7.2.2.1.2 Testing at UPF

Table 12. Current and Power Measurement Error at UPF

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.25	0.2502	0.09	57.5	57.54	0.08
0.50	0.5000	0.01	115.0	115.00	0
1.00	1.0001	0.01	230.0	230.00	0
5.00	4.9981	–0.04	1150.0	1149.75	–0.02
10.00	10.0003	0	2300.0	2300.06	0
20.00	20.0052	0.03	4600.0	4601.08	0.02
50.00	49.9968	–0.01	11500.0	11498.10	–0.02
75.00	74.9932	–0.01	17250.0	17245.40	–0.03
90.00	89.993.0	–0.01	20700.0	20693.00	–0.03

Current linearity (from 1 to 90 A) = 0.07%

7.2.2.1.3 Testing at 0.5 Lag (60° Phase Lag Between Voltage and Current)

Table 13. Current and Power Measurement Error at 0.5 L

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.5	0.4999	–0.03	57.5	57.50	–0.01
1.0	0.9999	–0.01	115.0	115.05	0.04
5.0	4.9980	–0.04	575.0	574.62	–0.07
10.0	9.9999	0	1150.0	1150.12	0.01
20.0	20.0053	0.03	2300.0	2299.52	–0.02
50.0	49.9973	–0.01	5750.0	5745.74	–0.07
75.0	74.9954	–0.01	8625.0	8618.08	–0.08
90.0	89.9980	0	10350.0	10344.50	–0.05

Current linearity (from 1 to 90 A) = 0.07%

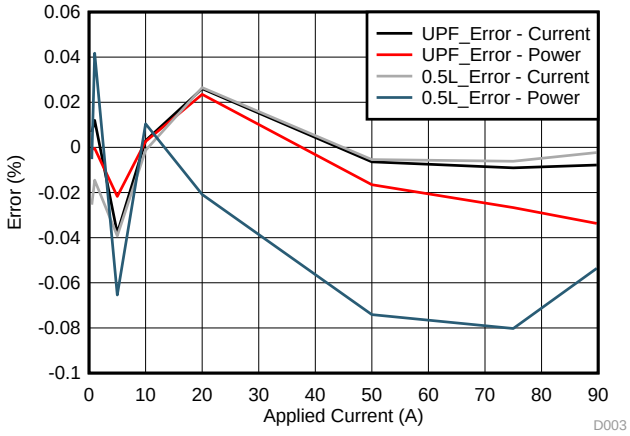


Figure 26. Fast Settling Current and Power Accuracy for 50 Hz

7.2.2.2 Test Data With 60-Hz Operating Frequency

7.2.2.2.1 Phase Error Observed

To test fast settling at 50 Hz, the phase is corrected (compensated) for 499.7 µs.

Phase shift = –499.7 µs × 360° × 50 Hz = –10.79°

7.2.2.2.2 Testing at UPF

Table 14. Current and Power Measurement Error at UPF

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.25	0.2495	–0.20	57.5	57.25	–0.43
0.50	0.4992	–0.16	115.0	114.78	–0.19
1.00	0.9990	–0.10	230.0	229.75	–0.11
5.00	4.9978	–0.04	1150.0	1149.59	–0.04
10.00	9.9985	–0.02	2300.0	2299.75	–0.01
20.00	20.0027	0.01	4600.0	4601.25	0.03
50.00	49.9987	0	11500.0	11498.80	–0.01
75.00	74.9962	–0.01	17250.0	17245.70	–0.02
90.00	89.9917	–0.01	20700.0	20691.90	–0.04

Current linearity (from 1 to 90 A) = 0.11%

7.2.2.2.3 Testing at 0.5 Lag (60° Phase Lag Between Voltage and Current)

Table 15. Current and Power Measurement Error at 0.5 L

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.5	0.4979	–0.42	57.5	57.41	–0.16
1.0	0.9979	–0.21	115.0	114.97	–0.03
5.0	4.9958	–0.09	575.0	575.02	0
10.0	9.9965	–0.04	1150.0	1150.74	0.06
20.0	20.0045	0.02	2300.0	2302.20	0.10
50.0	49.9979	0	5750.0	5753.55	0.06
75.0	74.9952	–0.01	8625.0	8629.11	0.05
90.0	90.0376	0.04	10350.0	10359.90	0.10

Current linearity (from 1 to 90 A) = 0.25%

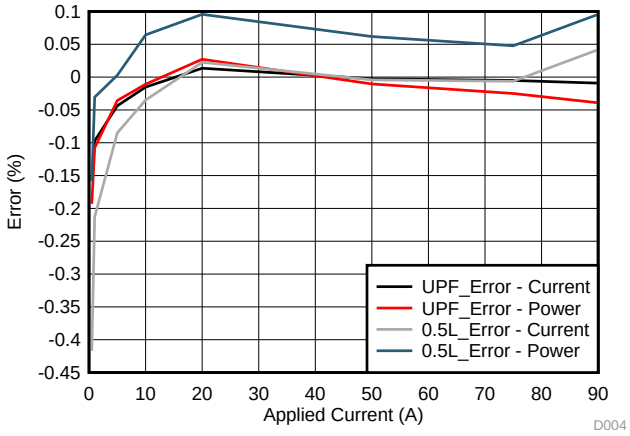


Figure 27. Fast Settling Current and Power Accuracy for 60 Hz

7.3 Accuracy and Linearity Testing for 0- to 5-V Range

Current is applied using the PTS3.3-C.

7.3.1 Precision Measurement

7.3.1.1 Test Data With 50-Hz Operating Frequency

Table 16. Current Measurement Error

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR — CURRENT (%)
1	1.0008	0.08
2	2.0008	0.04
5	4.9992	–0.02
10	10.0019	0.02
20	20.0045	0.02
50	49.9920	–0.02
75	74.9928	–0.01
90	90.0022	0.00

Current linearity (from 1 to 90 A) = 0.1%

7.3.1.2 Test Data With 60-Hz Operating Frequency

Table 17. Current Measurement Error

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR — CURRENT (%)
1	1.0012	0.12
2	2.0011	0.05
5	4.9992	–0.02
10	10.0001	0.00
20	20.0051	0.03
50	49.9916	–0.02
75	74.9889	–0.01
90	89.9923	–0.01

Current linearity = 0.14%

7.3.2 Fast Settling

7.3.2.1 Test Data With 50-Hz Operating Frequency

Table 18. Current Measurement Error

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR — CURRENT (%)
1	0.9991	–0.09
2	1.9996	–0.02
5	4.9983	–0.03
10	10.0010	0.01
20	20.0071	0.04
50	49.9913	–0.02
75	74.9941	–0.01
90	90.0032	0.00

Current linearity = 0.13%

7.3.2.2 Test Data With 60-Hz Operating Frequency

Table 19. Current Measurement Error

APPLIED CURRENT (A)	MEASURED CURRENT (A)	ERROR — CURRENT (%)
1	1.0003	0.03
2	2.0012	0.06
5	4.9995	–0.01
10	10.0013	0.01
20	20.0084	0.04
50	49.9956	–0.01
75	74.9978	0.00
90	90.0025	0.00

Current linearity = 0.07%

7.4 Repeatability Testing

The repeatability testing is performed with 1-, 5-, 20-, 50-, and 90-A input currents.

To test repeatability:

1. Power up the board and apply a 1-A current.
2. After 5 min, capture current and power readings with UPF and 0.5 L (LAG) for specified input currents.
3. Power off the board DC power supply for 15 min, including current input.
4. Repeat the measurement cycle.

Repeatability error is computed as standard deviation (σ (%)).

7.4.1 Precision Measurement

Table 20 is a summary of the standard deviation (σ (%)) at UPF and 0.5 L for the applied currents.

Table 20. Summary of Standard Deviation (σ (%)) at UPF and 0.5 L

APPLIED CURRENT (A)	UPF		0.5 L	
	ERROR CURRENT σ (%)	ERROR POWER σ (%)	ERROR CURRENT σ (%)	ERROR POWER σ (%)
1	0.007	0.011	0.004	0.036
5	0.007	0.029	0.009	0.045
20	0.015	0.022	0.015	0.030
50	0.010	0.019	0.012	0.039
90	0.007	0.020	0.009	0.055

7.4.1.1 Measurement Data

Table 21. Current Measurement Error at UPF

APPLIED CURRENT (A)	ERROR CURRENT (%)								ERROR CURRENT σ (%)
	REPEAT 1	REPEAT 2	REPEAT 3	REPEAT 4	REPEAT 5	REPEAT 6	REPEAT 7	REPEAT 8	
1	0.053	0.060	0.041	0.044	0.050	0.043	0.044	0.042	0.007
5	–0.034	–0.009	–0.017	–0.012	–0.016	–0.014	–0.017	–0.017	0.007
20	0.006	0.048	0.051	0.025	0.032	0.046	0.025	0.038	0.015
50	–0.019	0.012	0.009	–0.003	0	0.011	0	0.003	0.010
90	–0.008	0.015	0.012	0.008	0.010	0.011	0.005	0.008	0.007

Table 22. Current Measurement Error at 0.5 L

APPLIED CURRENT (A)	ERROR CURRENT (%)								ERROR CURRENT σ (%)
	REPEAT 1	REPEAT 2	REPEAT 3	REPEAT 4	REPEAT 5	REPEAT 6	REPEAT 7	REPEAT 8	
1	0.027	0.023	0.023	0.022	0.024	0.017	0.014	0.020	0.004
5	–0.034	–0.013	–0.021	–0.021	–0.024	–0.020	–0.002	–0.024	0.009
20	0.003	0.048	0.025	0.020	0.029	0.046	0.029	0.039	0.015
50	–0.024	0.011	0.008	–0.001	0.001	0.014	0	0.004	0.012
90	–0.009	0.017	0.014	0.014	0.008	0.013	0.006	0.016	0.009

Table 23. Power Measurement Error at UPF

APPLIED CURRENT (A)	ERROR POWER (%)								ERROR CURRENT σ (%)
	REPEAT 1	REPEAT 2	REPEAT 3	REPEAT 4	REPEAT 5	REPEAT 6	REPEAT 7	REPEAT 8	
1	0.080	0.087	0.102	0.099	0.096	0.100	0.094	0.070	0.011
5	–0.039	0.030	0.053	0.033	0.046	0.025	0.032	0.050	0.029
20	0.028	0.088	0.093	0.088	0.091	0.094	0.090	0.083	0.022
50	–0.007	0.050	0.043	0.042	0.050	0.043	0.053	0.032	0.019
90	–0.009	0.035	0.028	0.046	0.054	0.031	0.049	0.027	0.020

Table 24. Power Measurement Error at 0.5 L

APPLIED CURRENT (A)	ERROR POWER (%)								ERROR CURRENT σ (%)
	REPEAT 1	REPEAT 2	REPEAT 3	REPEAT 4	REPEAT 5	REPEAT 6	REPEAT 7	REPEAT 8	
1	0.050	0.056	0.130	0.139	0.135	0.115	0.128	0.132	0.036
5	–0.167	–0.096	–0.033	–0.096	–0.036	–0.090	–0.062	–0.037	0.045
20	–0.107	–0.058	–0.028	–0.033	–0.020	–0.059	–0.020	–0.067	0.030
50	–0.131	–0.096	–0.109	–0.047	–0.031	–0.099	–0.033	–0.110	0.039
90	–0.185	–0.100	–0.096	–0.031	–0.027	–0.103	–0.021	–0.099	0.055

7.4.2 Fast Settling

Table 25 is summary of the standard deviation (σ (%)) at UPF and 0.5 L for the applied currents.

Table 25. Summary of Standard Deviation (σ (%)) at UPF and 0.5 L

APPLIED CURRENT (A)	UPF		0.5 L	
	ERROR CURRENT σ (%)	ERROR POWER σ (%)	ERROR CURRENT σ (%)	ERROR POWER σ (%)
1	0.027	0.038	0.063	0.068
5	0.014	0.027	0.017	0.049
20	0.018	0.023	0.017	0.036
50	0.015	0.022	0.014	0.035
90	0.018	0.023	0.013	0.043

7.4.2.1 Measurement Data

Table 26. Current Measurement Error at UPF

APPLIED CURRENT (A)	ERROR CURRENT (%)								ERROR CURRENT σ (%)
	REPEAT 1	REPEAT 2	REPEAT 3	REPEAT 4	REPEAT 5	REPEAT 6	REPEAT 7	REPEAT 8	
1	–0.079	–0.057	–0.024	–0.003	–0.032	–0.014	–0.033	0.001	0.027
5	–0.052	–0.024	–0.027	–0.009	–0.005	–0.014	–0.021	–0.019	0.014
20	0.012	0.041	0.046	0.048	0.056	0.059	0.068	0.063	0.018
50	–0.011	0.016	0.012	0.030	0.026	0.032	0.036	0.029	0.015
90	0.001	0.017	0.064	0.034	0.034	0.036	0.039	0.032	0.018

Table 27. Current Measurement Error at 0.5 L

APPLIED CURRENT (A)	ERROR CURRENT (%)								ERROR CURRENT σ (%)
	REPEAT 1	REPEAT 2	REPEAT 3	REPEAT 4	REPEAT 5	REPEAT 6	REPEAT 7	REPEAT 8	
1	–0.250	–0.275	–0.179	–0.154	–0.200	–0.166	–0.154	–0.072	0.063
5	–0.068	–0.064	–0.053	–0.031	–0.027	–0.030	–0.037	–0.030	0.017
20	0.007	0.039	0.044	0.045	0.045	0.060	0.062	0.053	0.017
50	–0.008	0.007	0.014	0.028	0.025	0.031	0.032	0.026	0.014
90	–0.001	0.021	0.019	0.031	0.036	0.037	0.038	0.033	0.013

Table 28. Power Measurement Error at UPF

APPLIED CURRENT (A)	ERROR POWER (%)								ERROR CURRENT σ (%)
	REPEAT 1	REPEAT 2	REPEAT 3	REPEAT 4	REPEAT 5	REPEAT 6	REPEAT 7	REPEAT 8	
1	–0.106	–0.057	–0.049	–0.009	–0.037	–0.008	–0.036	–0.105	0.038
5	–0.071	–0.047	–0.040	–0.002	–0.023	–0.010	–0.021	–0.073	0.027
20	0.013	0.028	0.034	0.055	0.062	0.033	0.063	0	0.023
50	–0.014	–0.013	–0.008	0.024	0.019	–0.007	0.020	–0.039	0.022
90	–0.021	–0.027	–0.028	0.010	0.023	–0.006	0.003	–0.047	0.023

Table 29. Power Measurement Error at 0.5 L

APPLIED CURRENT (A)	ERROR POWER (%)								ERROR CURRENT σ (%)
	REPEAT 1	REPEAT 2	REPEAT 3	REPEAT 4	REPEAT 5	REPEAT 6	REPEAT 7	REPEAT 8	
1	–0.208	–0.213	–0.160	–0.043	–0.138	–0.063	–0.053	–0.139	0.068
5	–0.178	–0.203	–0.167	–0.086	–0.130	–0.073	–0.077	–0.139	0.049
20	–0.090	–0.106	–0.107	–0.062	–0.048	–0.085	–0.085	–0.167	0.036
50	–0.104	–0.149	–0.116	–0.057	–0.073	–0.133	–0.114	–0.160	0.035
90	–0.065	–0.142	–0.114	–0.054	–0.043	–0.071	–0.108	–0.161	0.043

7.5 Output Response Waveforms of Rogowski Coil Integrator

The output response waveforms of the Rogowski coil integrator are captured for a 20-A input current. Cursor 'a' is set at an additional 5% margin for the expected peak amplitude and start of the waveform. Cursor 'b' is set at the expected peak amplitude and where the waveform peak amplitude starts staying within the margin.

Figure 28 settles within ±5% of the final measured value of < 200 ms. Figure 29 settles within ±5% of the final measured value of < 30 ms.

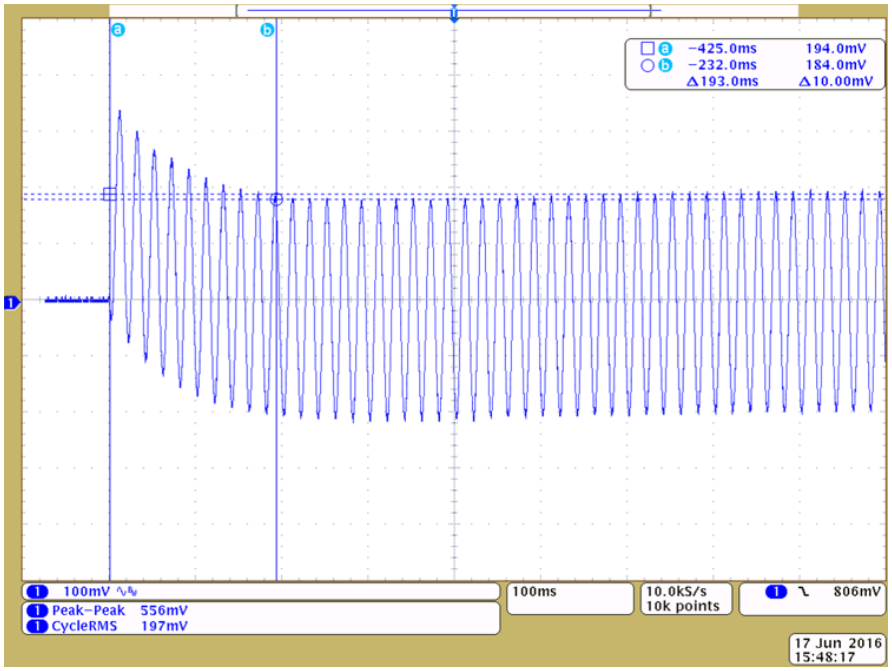


Figure 28. Integrator Output Waveform for Precision Measurement

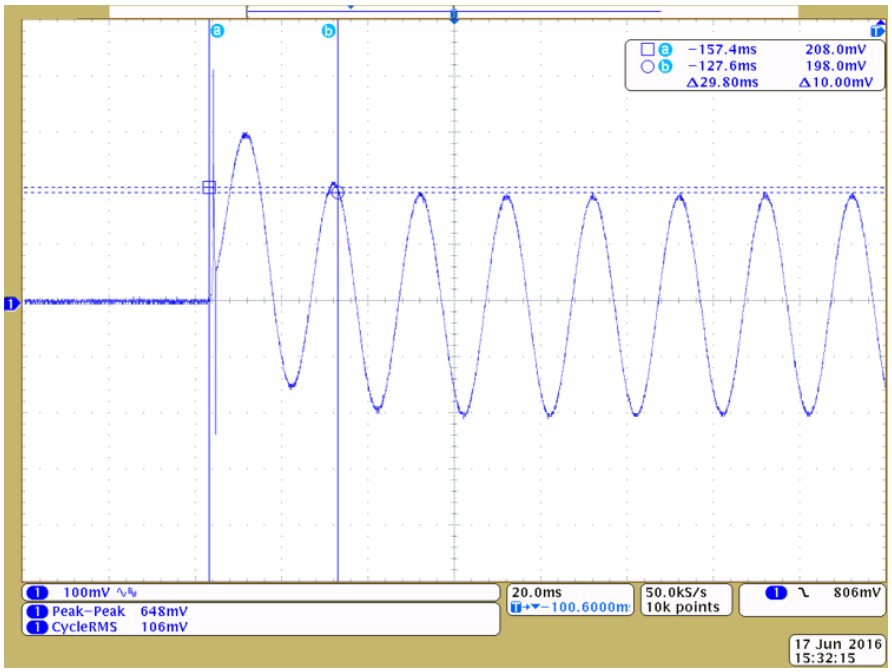


Figure 29. Integrator Output Waveform for Fast Settling

7.6 Temperature Drift Test

This test is to test the TIDA-00777 board performance over temperature from –10°C to 60°C. Current and power error is computed in PPM/°C for delta of 35°C at 25°C ambient temperature.

7.6.1 Precision Measurement

Table 30. Summary of Current and Power Measurement Accuracy Drift in PPM for 35°C Temperature Difference

APPLIED CURRENT (A)	POWER FACTOR	ERROR AT 25°C		ERROR AT 60°C		Δ ERROR (FOR 35°C)			
		CURRENT (%)	POWER (%)	CURRENT (%)	POWER (%)	CURRENT (%)	POWER (%)	CURRENT (PPM/°C)	POWER (PPM/°C)
0.5	UPF	–0.03	–0.14	–0.40	–0.47	–0.37	–0.33	–106.2	–95.2
1.0	UPF	–0.04	–0.09	–0.39	–0.44	–0.35	–0.35	–99.8	–99.5
5.0	UPF	–0.04	–0.06	–0.37	–0.38	–0.33	–0.32	–93.9	–91.2
20.0	UPF	0.03	0.02	–0.29	–0.32	–0.32	–0.34	–90.4	–95.8
50.0	UPF	0	–0.02	–0.33	–0.36	–0.33	–0.34	–95.2	–97.9
90.0	UPF	0.01	–0.01	–0.32	–0.36	–0.33	–0.35	–95.5	–100.9
0.5	0.5 L	–0.07	–0.37	–0.39	–0.73	–0.31	–0.36	–89.8	–102.9
1.0	0.5 L	–0.04	–0.21	–0.33	–0.47	–0.29	–0.26	–83.5	–73.0
5.0	0.5 L	–0.02	–0.20	–0.35	–0.52	–0.33	–0.32	–95.4	–90.9
20.0	0.5 L	0.05	–0.14	–0.31	–0.42	–0.35	–0.27	–101.0	–78.3
50.0	0.5 L	0.01	–0.13	–0.34	–0.41	–0.34	–0.28	–97.9	–80.1
90.0	0.5 L	0.01	–0.13	–0.32	–0.39	–0.34	–0.26	–96.6	–74.0

Table 31. Summary of Current and Power Measurement Accuracy Drift in PPM for –35°C Temperature Difference

APPLIED CURRENT (A)	POWER FACTOR	ERROR AT 25°C		ERROR AT –10°C		Δ ERROR (FOR –35°C)			
		CURRENT (%)	POWER (%)	CURRENT (%)	POWER (%)	CURRENT (%)	POWER (%)	CURRENT (PPM/°C)	POWER (PPM/°C)
0.5	UPF	–0.03	–0.14	0.03	–0.07	0.07	0.07	19.4	18.9
1.0	UPF	–0.04	–0.09	0.10	0.06	0.15	0.15	41.9	43.2
5.0	UPF	–0.04	–0.06	0.16	0.15	0.20	0.20	56.6	57.9
20.0	UPF	0.03	0.02	0.24	0.22	0.21	0.20	61.1	58.0
50.0	UPF	0	–0.02	0.21	0.19	0.21	0.21	59.3	61.1
90.0	UPF	0.01	–0.01	0.21	0.19	0.20	0.20	57.5	56.7
0.5	0.5 L	–0.07	–0.37	0.14	–0.40	0.21	–0.03	60.5	–8.4
1.0	0.5 L	–0.04	–0.21	0.17	–0.11	0.21	0.10	59.2	27.3
5.0	0.5 L	–0.02	–0.20	0.17	–0.04	0.19	0.17	54.1	47.3
20.0	0.5 L	0.05	–0.14	0.24	0.06	0.20	0.21	56.6	59.4
50.0	0.5 L	0.01	–0.13	0.21	0.04	0.20	0.17	57.1	49.0
90.0	0.5 L	0.01	–0.13	0.22	0.06	0.20	0.20	57.9	56.6

7.6.1.1 Measurement Data

Table 32. 25°C Data

APPLIED CURRENT (A)	POWER FACTOR (UPF or 0.5 L)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.5	UPF	0.500	–0.03	115.0	114.8	–0.14
1.0	UPF	1.000	–0.04	230.0	229.8	–0.09
5.0	UPF	4.998	–0.04	1150.0	1149.4	–0.06
20.0	UPF	20.005	0.03	4600.0	4600.9	0.02
50.0	UPF	50.000	0	11500.0	11497.5	–0.02
90.0	UPF	90.010	0.01	20700.0	20697.8	–0.01
0.5	0.5 L	0.500	–0.07	57.5	57.3	–0.37
1.0	0.5 L	1.000	–0.04	115.0	114.8	–0.21
5.0	0.5 L	4.999	–0.02	575.0	573.8	–0.20
20.0	0.5 L	20.009	0.05	2300.0	2296.7	–0.14
50.0	0.5 L	50.004	0.01	5750.0	5742.6	–0.13
90.0	0.5 L	90.013	0.01	10350.0	10336.1	–0.13

Table 33. –10°C Data

APPLIED CURRENT (A)	POWER FACTOR (UPF or 0.5 L)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.5	UPF	0.500	0.03	115.0	114.9	–0.07
1.0	UPF	1.001	0.10	230.0	230.1	0.06
5.0	UPF	5.008	0.16	1150.0	1151.7	0.15
20.0	UPF	20.048	0.24	4600.0	4610.2	0.22
50.0	UPF	50.104	0.21	11500.0	11522.1	0.19
90.0	UPF	90.191	0.21	20700.0	20738.9	0.19
0.5	0.5 L	0.501	0.14	57.5	57.3	–0.40
1.0	0.5 L	1.002	0.17	115.0	114.9	–0.11
5.0	0.5 L	5.008	0.17	575.0	574.8	–0.04
20.0	0.5 L	20.049	0.24	2300.0	2301.5	0.06
50.0	0.5 L	50.104	0.21	5750.0	5752.4	0.04
90.0	0.5 L	90.195	0.22	10350.0	10356.6	0.06

Table 34. 60°C Data

APPLIED CURRENT (A)	POWER FACTOR (UPF or 0.5 L)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.5	UPF	0.498	–0.40	115.0	114.5	–0.47
1.0	UPF	0.996	–0.39	230.0	229.0	–0.44
5.0	UPF	4.982	–0.37	1150.0	1145.7	–0.38
20.0	UPF	19.942	–0.29	4600.0	4585.5	–0.32
50.0	UPF	49.834	–0.33	11500.0	11458.1	–0.36
90.0	UPF	89.709	–0.32	20700.0	20624.7	–0.36
0.5	0.5 L	0.498	–0.39	57.5	57.1	–0.73
1.0	0.5 L	0.997	–0.33	115.0	114.5	–0.47
5.0	0.5 L	4.982	–0.35	575.0	572.0	–0.52
20.0	0.5 L	19.938	–0.31	2300.0	2290.4	–0.42
50.0	0.5 L	49.832	–0.34	5750.0	5726.4	–0.41
90.0	0.5 L	89.709	–0.32	10350.0	10309.3	–0.39

7.6.2 Fast Settling

Table 35. Summary of Current and Power Measurement Accuracy Drift in PPM for 35°C Temperature Difference

APPLIED CURRENT (A)	POWER FACTOR	ERROR AT 25°C		ERROR AT 60°C		Δ ERROR (FOR 35°C)			
		CURRENT (%)	POWER (%)	CURRENT (%)	POWER (%)	CURRENT (%)	POWER (%)	CURRENT (PPM/°C)	POWER (PPM/°C)
0.5	UPF	0.67	0.62	0.85	0.79	0.18	0.17	50.3	48.2
1.0	UPF	0.31	0.29	0.39	0.36	0.08	0.07	21.7	20.0
5.0	UPF	0	–0.02	–0.01	–0.01	0	0.01	–1.4	1.5
20.0	UPF	0	–0.01	–0.01	–0.03	–0.01	–0.02	–3.1	–5.8
50.0	UPF	–0.04	–0.06	–0.07	–0.10	–0.03	–0.05	–9.8	–12.9
90.0	UPF	–0.03	–0.05	–0.07	–0.10	–0.03	–0.05	–9.5	–15.0
0.5	0.5 L	0.45	1.31	0.60	1.64	0.14	0.32	40.8	92.4
1.0	0.5 L	0.21	0.60	0.25	0.80	0.04	0.20	10.6	57.1
5.0	0.5 L	0	–0.09	–0.03	–0.09	–0.03	0.01	–7.3	1.9
20.0	0.5 L	0.01	–0.16	–0.04	–0.14	–0.05	0.02	–14.1	6.0
50.0	0.5 L	–0.03	–0.17	–0.08	–0.16	–0.04	0.01	–12.1	3.1
90.0	0.5 L	–0.03	–0.19	–0.07	–0.15	–0.04	0.04	–11.6	11.3

Table 36. Summary of Current and Power Measurement Accuracy Drift in PPM for –35°C Temperature Difference

APPLIED CURRENT (A)	POWER FACTOR	ERROR AT 25°C		ERROR AT –10°C		Δ ERROR (FOR –35°C)			
		CURRENT (%)	POWER (%)	CURRENT (%)	POWER (%)	CURRENT (%)	POWER (%)	CURRENT (PPM/°C)	POWER (PPM/°C)
0.5	UPF	0.67	0.62	0.65	0.61	–0.02	–0.02	–5.2	–5.0
1.0	UPF	0.31	0.29	0.26	0.24	–0.06	–0.05	–15.7	–14.0
5.0	UPF	0	–0.02	-0.08	–0.09	–0.08	–0.08	–23.5	–22.1
20.0	UPF	0	–0.01	-0.08	–0.09	–0.08	–0.08	–22.0	–23.1
50.0	UPF	–0.04	–0.06	-0.13	–0.15	–0.10	–0.09	–27.5	–26.3
90.0	UPF	–0.03	–0.05	-0.13	–0.16	–0.10	–0.11	–28.8	–30.4
0.5	0.5 L	0.45	1.31	0.41	1.24	–0.04	–0.07	–12.3	–20.4
1.0	0.5 L	0.21	0.60	0.16	0.53	–0.05	–0.07	–14.6	–20.4
5.0	0.5 L	0	–0.09	-0.11	–0.19	–0.10	–0.10	–29.5	–27.6
20.0	0.5 L	0.01	–0.16	-0.09	–0.25	–0.10	–0.09	–29.0	–26.3
50.0	0.5 L	–0.03	–0.17	-0.13	–0.30	–0.10	–0.13	–28.3	–36.0
90.0	0.5 L	–0.03	–0.19	-0.13	–0.28	–0.10	–0.08	–28.8	–24.0

7.6.2.1 Measurement Data

Table 37. 25°C Data

APPLIED CURRENT (A)	POWER FACTOR (UPF or 0.5 L)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.5	UPF	0.503	0.67	115.0	115.7	0.62
1.0	UPF	1.003	0.31	230.0	230.7	0.29
5.0	UPF	5.000	0	1150.0	1149.8	–0.02
20.0	UPF	19.999	0	4600.0	4599.4	–0.01
50.0	UPF	49.981	–0.04	11500.0	11493.6	–0.06
90.0	UPF	89.970	–0.03	20700.0	20689.9	–0.05
0.5	0.5 L	0.502	0.45	57.5	58.3	1.31
1.0	0.5 L	1.002	0.21	115.0	115.7	0.60
5.0	0.5 L	5.000	0	575.0	574.5	–0.09
20.0	0.5 L	20.003	0.01	2300.0	2296.3	–0.16
50.0	0.5 L	49.983	–0.03	5750.0	5740.2	–0.17
90.0	0.5 L	89.973	–0.03	10350.0	10330.1	–0.19

Table 38. –10°C Data

APPLIED CURRENT (A)	POWER FACTOR (UPF or 0.5 L)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.5	UPF	0.503	0.65	115.0	115.7	0.61
1.0	UPF	1.003	0.26	230.0	230.5	0.24
5.0	UPF	4.996	–0.08	1150.0	1148.9	–0.09
20.0	UPF	19.984	–0.08	4600.0	4595.7	–0.09
50.0	UPF	49.933	–0.13	11500.0	11483.0	–0.15
90.0	UPF	89.880	–0.13	20700.0	20667.9	–0.16
0.5	0.5 L	0.502	0.41	57.5	58.2	1.24
1.0	0.5 L	1.002	0.16	115.0	115.6	0.53
5.0	0.5 L	4.995	–0.11	575.0	573.9	–0.19
20.0	0.5 L	19.982	–0.09	2300.0	2294.2	–0.25
50.0	0.5 L	49.933	–0.13	5750.0	5732.9	–0.30
90.0	0.5 L	89.882	–0.13	10350.0	10321.4	–0.28

Table 39. 60°C Data

APPLIED CURRENT (A)	POWER FACTOR (UPF or 0.5 L)	MEASURED CURRENT (A)	ERROR CURRENT (%)	EXPECTED POWER (W)	MEASURED POWER (W)	ERROR POWER (%)
0.5	UPF	0.504	0.85	115.0	115.9	0.79
1.0	UPF	1.004	0.39	230.0	230.8	0.36
5.0	UPF	5.000	–0.01	1150.0	1149.9	–0.01
20.0	UPF	19.997	–0.01	4600.0	4598.4	–0.03
50.0	UPF	49.964	–0.07	11500.0	11488.4	–0.10
90.0	UPF	89.940	–0.07	20700.0	20679.0	–0.10
0.5	0.5 L	0.503	0.60	57.5	58.4	1.64
1.0	0.5 L	1.003	0.25	115.0	115.9	0.80
5.0	0.5 L	4.999	–0.03	575.0	574.5	–0.09
20.0	0.5 L	19.993	–0.04	2300.0	2296.8	–0.14
50.0	0.5 L	49.962	–0.08	5750.0	5740.8	–0.16
90.0	0.5 L	89.936	–0.07	10350.0	10334.2	–0.15

7.7 Summary of Test Results

Table 40. Test Result Summary

SERIAL NUMBER	PARAMETERS	RESULT
1	Power supply test	OK
2	Reference output	OK
3	Output at gain, integrator, and DC level shift stage (precision measurement)	OK
4	Output at integrator, gain, and DC level shift stage (fast settling)	OK
5	Accuracy, linearity, and phase error test at 50 and 60 Hz (precision measurement)	OK
6	Accuracy, linearity, and phase error test at 50 and 60 Hz (fast settling)	OK
7	Accuracy and linearity testing for 0- to 5-V range at 50 and 60 Hz (precision measurement)	OK
8	Accuracy and linearity testing for 0- to 5-V range at 50 and 60 Hz (precision measurement)	OK
97	Repeatability test (precision measurement)	OK, < ±0.2%
108	Repeatability test (fast settling)	OK, < ±0.2%
119	Accuracy drift with temperature (precision measurement)	OK, <150 PPM/°C
120	Accuracy drift with temperature (fast settling)	OK, <300 PPM/°C

8 Design Files

8.1 Schematics

To download the schematics, see the design files at TIDA-00777.

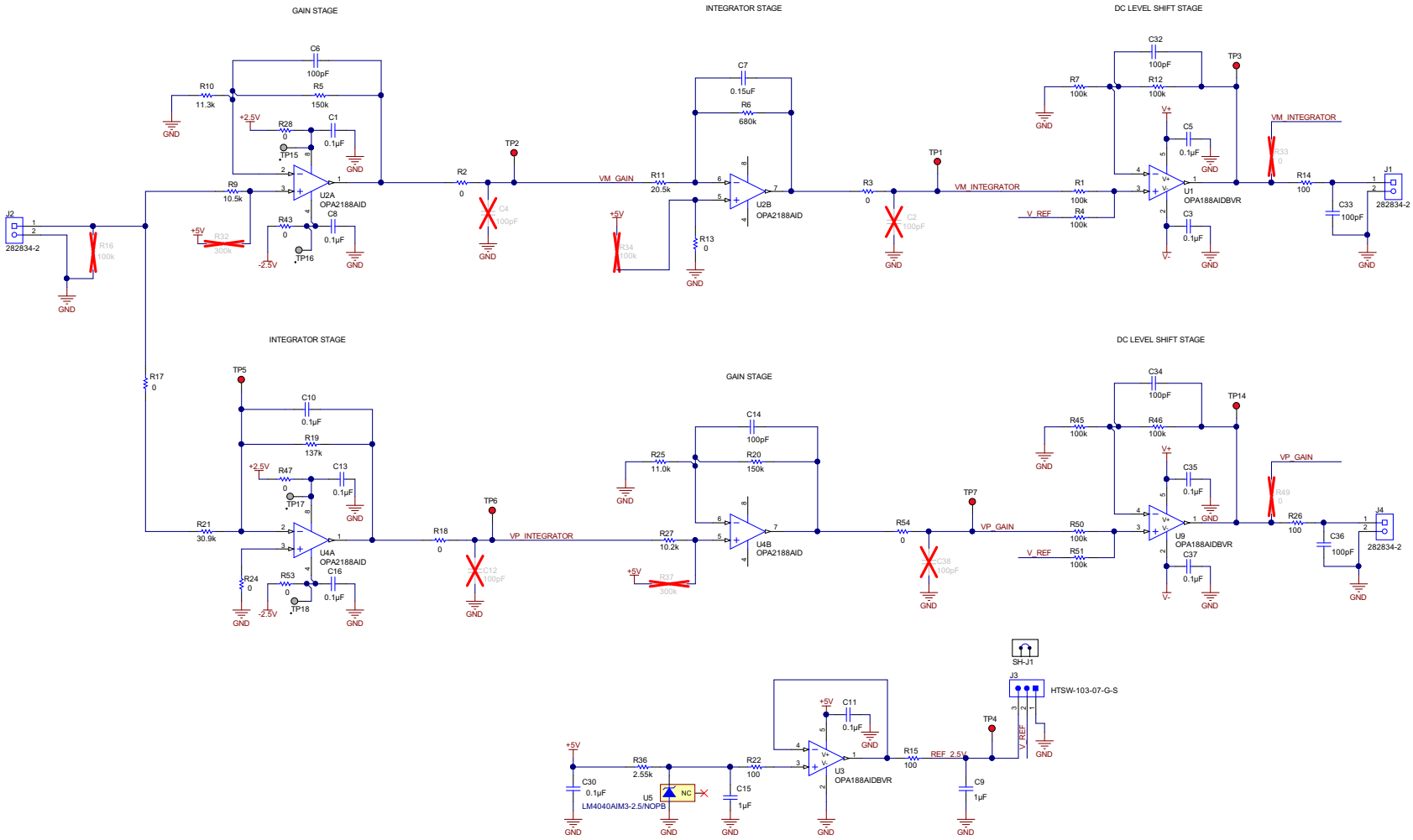


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Figure 30. Signal Conditioning

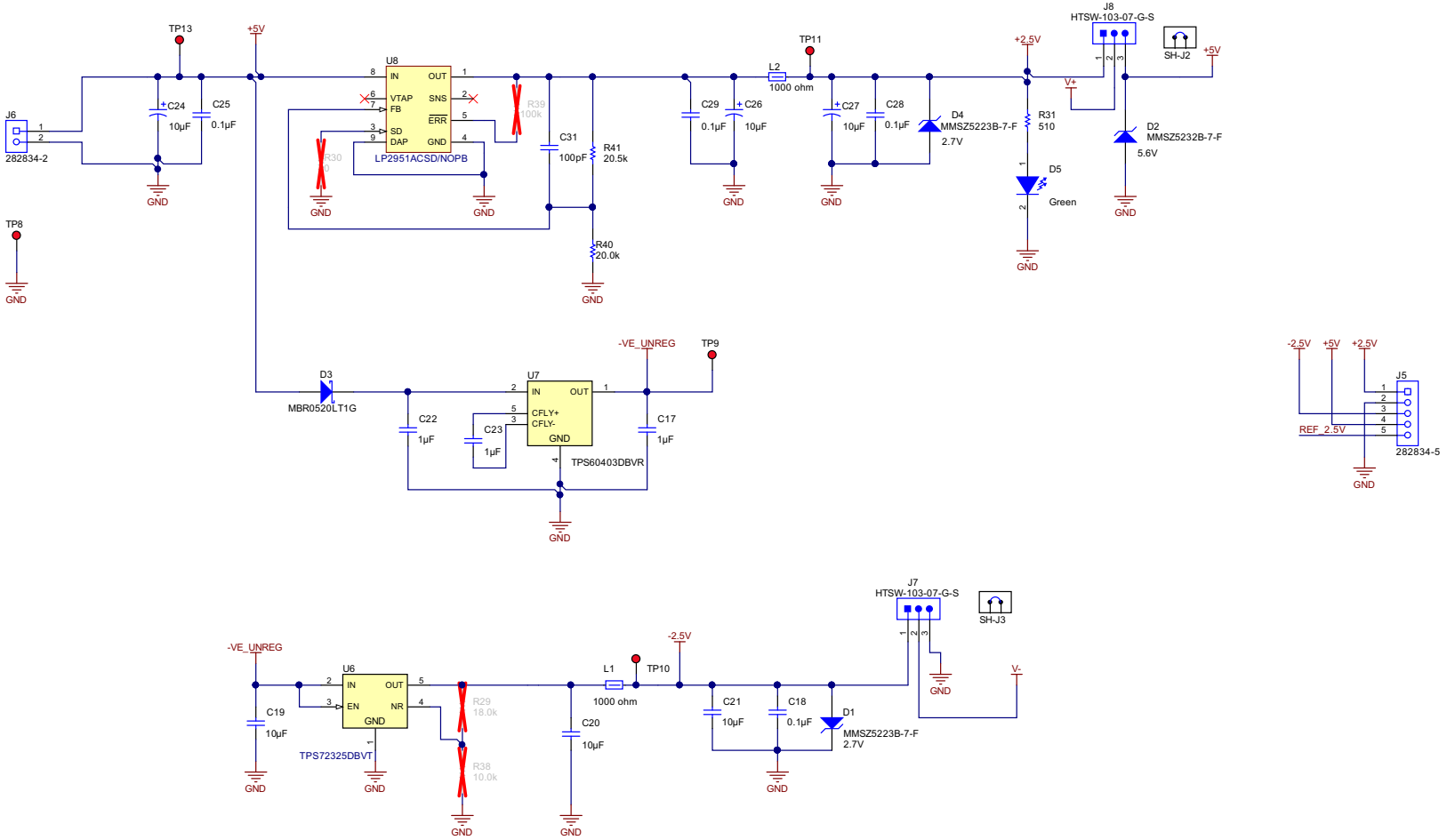

Figure 31. Power Supply

8.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00777.

8.3 Layout Prints

To download the layer plots, see the design files at TIDA-00777.

8.4 Altium Project

To download the Altium project files, see the design files at TIDA-00777.

8.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00777.

8.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00777.

9 References

1. Texas Instruments, *Noise Analysis in Operational Amplifier Circuits*, Application Report (SLVA043)
2. Texas Instruments, WEBENCH® Design Center (http://www.ti.com/webench)

10 About the Authors

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Revision A History

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

Changes from Original (July 2016) to A Revision	Page
• Changed from preview page	1

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