

## TI Designs: TIDA-020018

# Automotive shunt-based isolated current sensor reference design for DC/DC and OBC applications



## Description

This design describes high-side primary current sensing for DC/DC and onboard charger (OBC) applications. Although an isolated shunt approach has advantages such as high accuracy, linearity, and robustness, the shunt still experiences higher power dissipations because of the larger input range of isolated amplifiers. This reference design helps solve the problem with a lower input range isolated amplifier, resulting in lower power dissipations. All advantages of the shunt at the cost of lower power dissipation can be achieved.

## Resources

<a href="#">TIDA-020018</a>	Design Folder
<a href="#">AMC1302-Q1</a>	Product Folder
<a href="#">SN6501-Q1</a>	Product Folder
<a href="#">TPS763-Q1</a>	Product Folder
<a href="#">OPA376-Q1</a>	Product Folder
<a href="#">LM4132-Q1</a>	Product Folder

## Features

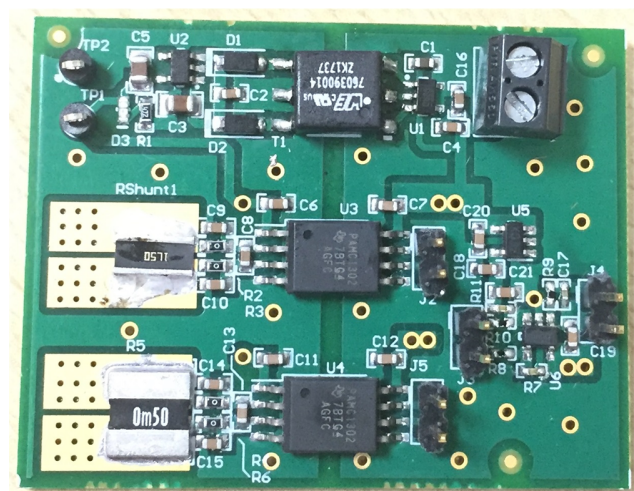
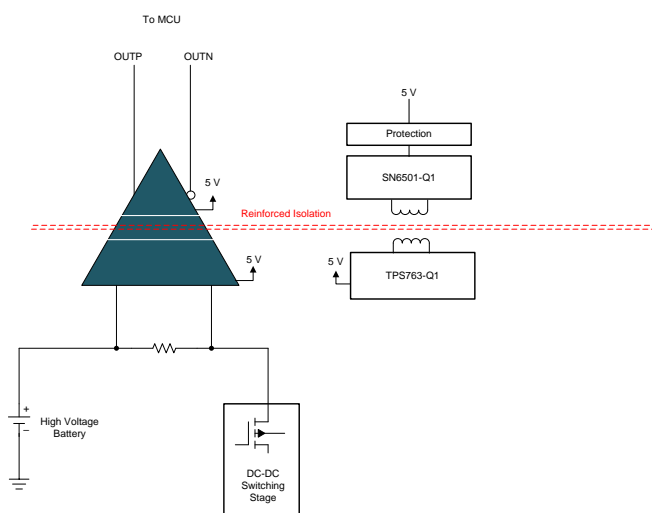
- Lower input range of +/-50 mV facilitates lower power dissipations on the shunt
- 3-us Latency (fast response) with the isolated amplifier
- High-side current sense circuit with CMTI of 140 kV/ $\mu$ s (typical), 70 kV/ $\mu$ s (minimum)
- Un-librated accuracy of less than 1% across a temperature range of -40°C to 125°C (AMC output)
- Interfaces directly with differential- or single-ended ADC
- Fully tested for DC/DC and OBC applications

## Applications

- [DC/DC converter](#)
- [Onboard charger](#)



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## 1 System Description

DC/DC converters and onboard chargers (OBC) need high-side current sensing on the high voltage battery side for accurate monitoring of charging and discharging currents and for control loop operations. To measure high-side current on a high-voltage battery (400 V, 600 V, 800 V) there must be an isolation presence because of higher common-mode voltages. In general, isolation is provided through magnetic isolation or reinforced isolation. Instead of using expensive magnetics, LEM modules, and getting severe non-linearities because of the temperature effects on the magnet, a shunt approach has several advantages such as high linearity, high accuracy, robustness, and so forth. However, the shunt presents issues with higher power dissipations. Higher power dissipations are due to the larger values of the shunt resistor. Larger values of the shunt resistor were required because of the limit of the front-end stages of the isolated amplifier portfolio in the market. This design addresses the problem with lower input range analog front-end isolated amplifiers. With the lower input voltage front-ends, it is possible to get the lower shunt values, resulting in lower power dissipation. This design shows the isolated-shunt-based approach for DC/DC and OBC applications for current sensing.

The power levels of conventional DC/DC converters in automotive applications is 3 KW, and they need about 10 A at full operational mode. Similarly, OBC converters operate at 6.6 KW, and current of approximately 32 A flows. The input range of isolated amplifier chosen is 50 mV, meaning shunt values are designed in such a way that there is 5 mOhm for the DC/DC application and 1.5 mOhm for the OBC application. This implies lower power dissipation.

The AC or DC current flows through the shunt, resulting in a linear voltage drop across the shunt which appears on the front-end terminals of the isolated amplifier. which is amplified and converted into single ended stage and given to the ADC for further signal processing.

In DC/DC converters and onboard chargers, analog and digital control loop must determine faults at a faster rate in charging and discharging states. Lower delay at the isolation barrier helps the control loop to react at a faster rate on several kind of faults. The AMC1302-Q1 provides a less than 3-us delay.

### 1.1 Key System Specifications

**Table 1. Key System Specifications**

PARAMETER	SPECIFICATIONS	DETAILS
Sensor type	Shunt	
Parameter measured	Current	
Current type	DC	
DC bus voltage	400 V	
Calibrated accuracy	< 1% absolute	
Common-mode transient immunity	140 kV/ $\mu$ s (typ), 70 kV/ $\mu$ s (min)	
Output	0 V to 5 V	
Operating temperature	-40°C to +125°C	

## 2 System Overview

### 2.1 Block Diagram

Figure 1. TIDA-020018 Block Diagram

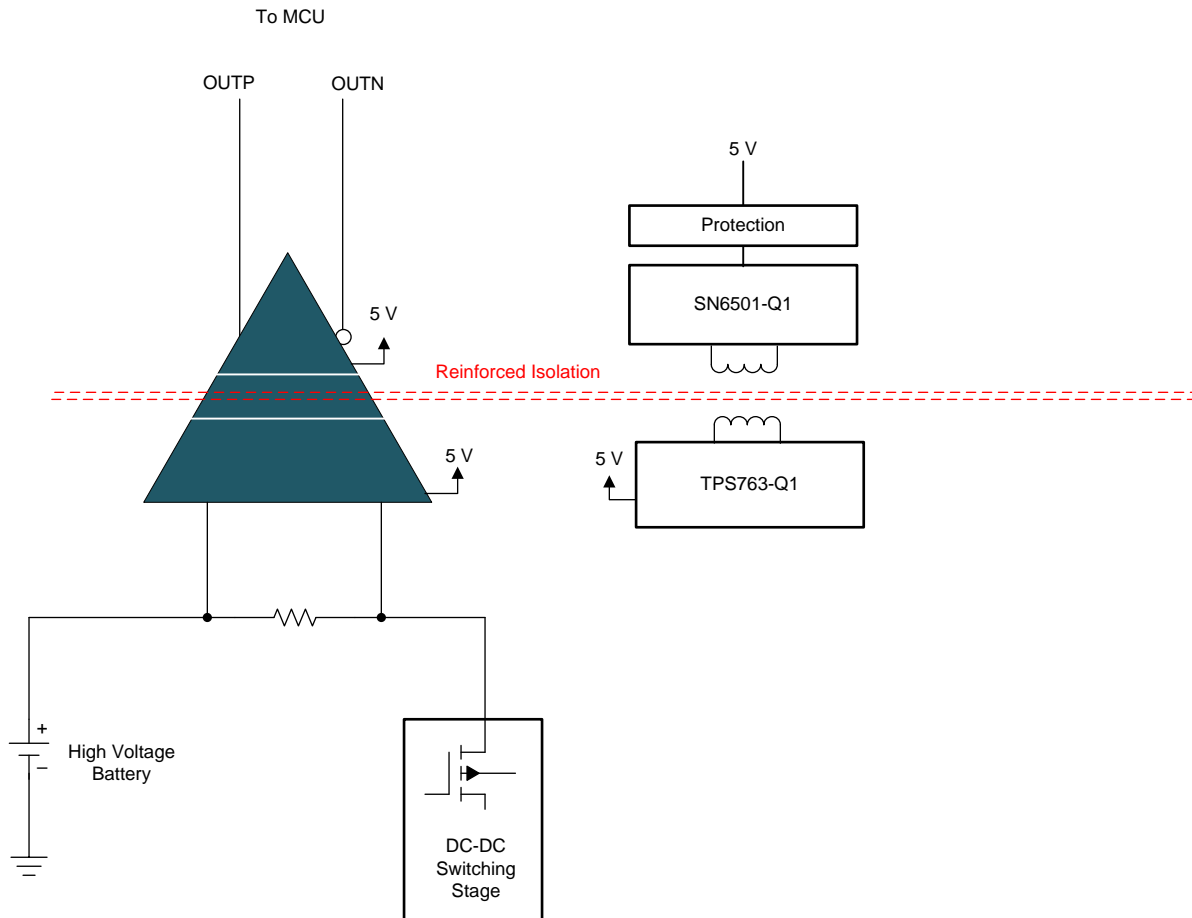


Figure 1 shows the block diagram of the TIDA-020018.

**SHUNT:** Figure 1 shows that the shunt is connected in between the high-voltage battery and the DC/DC switching stage. Uni-directional current flows through the shunt from battery to the DC/DC converter.

**AMC1302-Q1:** This is an isolated amplifier with +/-50-mV input range. This device amplifies the voltage drop across the shunt and provides the signal isolation.

**Protection:** Input power supply protection is implemented using some discretes.

**SN6501-Q1-Q1:** This is a transformer driver with isolated power of 5 V generated from the source.

**TPS763-Q1:** High CMRR/PSRR low dropout (LDO) does not have an affect from any power supply noise.

### 2.2 Design Considerations

This design is mainly used for evaluating the performance of an isolated shunt-based current sensor for DC/DC and OBC applications. It is a subsystem in a high-voltage to low-voltage DC/DC converter OBC end equipments. The design inserts in between the high-voltage side battery and DC/DC converter switching stage. This design operates on 12 V and is isolated current sense. Output of the design goes to the ADC, or microcontroller, stage on the DC/DC converter main board for determining the faults, charging, and discharging currents.

## 2.3 Highlighted Products

### 2.3.1 AMC1302-Q1

The AMC1302 is a precision isolated amplifier with a capacitive isolation barrier that has high immunity to magnetic interference. Conventional isolated amplifiers in the market have the larger input range which makes the selection of shunt value higher, implying higher power dissipations. TI's AMC1302-Q1 with the  $\pm 50$ -mV input voltage range allows significant reduction of the power dissipation through the shunt.

The input stage of the AMC1302 is optimized for direct connection to shunt resistors. Additionally, the low high-side supply current and voltage of the AMC1302 allow use of low-cost isolated power-supply solutions. The integrated input commonmode overvoltage and missing high-side supply voltage detection features of the AMC1302 simplify system-level diagnostics.

### 2.3.2 TPS763-Q1

The TPS763-Q1 is a low-dropout (LDO) voltage regulator that operates on low-power and has miniaturized packaging. Lower cost, 60 db of PSRR, and less than 2  $\mu$ A of quiescent current makes this device suitable for the current application.

### 2.3.3 OPA376-Q1

This op amp is used for converting isolated amplifier differential signal to single-ended version.

This features rail-to-rail output, low offset (25  $\mu$ V maximum), low noise (7.5 nV/ $\sqrt{\text{Hz}}$ ), quiescent current of 950  $\mu$ A (maximum), and a 5.5-MHz bandwidth make this part very attractive for the current application. The OPA376-Q1 (single version) is available in MicroSIZE SC70-5, SOT23-5, and SOIC-8 packages.

### 2.3.4 LM4132-Q1

The LM4132 family of precision voltage references performance is comparable to the best laser-trimmed bipolar references but in cost-effective CMOS technology. Unlike other LDO references, the LM4132 can deliver up to 20 mA and does not require an output capacitor or buffer amplifier. These advantages, along with the SOT-23 packaging, are important for space-critical applications. The LM4132 gives 2.5 V at a very high accuracy of 0.05% with a specified temperature coefficient of 10 ppm/ $^{\circ}\text{C}$  or less.

### 2.3.5 SN6501-Q1

The SN6501-Q1 device is a monolithic oscillator and power-driver designed for small form factor, isolated power supplies in isolated interface applications. The device drives a low-profile, center-tapped transformer primary from a 3.3- or 5- V DC power supply, has a 350-mA output drive, thermal shutdown and soft start features, and switches at 410 kHz. The secondary can be wound to provide any isolated voltage based on the transformer turns ratio.

## 2.4 System Design Theory

Current information is vital in DC/DC and OBC applications. This information is useful in electrical vehicles. This design is aimed at sensing the current on primary side, or hot side, of the high-voltage battery side. Although this design is made for DC/DC or OBC applications, it can also be used in several other applications.

Choose a 3.3-KW DC/DC and 6-KW OBC. The maximum current a DC/DC of 3.3 KW can draw is 10 A and an OBC of 6.6 KW can draw as much as 32 A. The analog front end (for example, the isolated amplifier AMC1302-Q1) accepts 50 mV on its differential input terminals.

This following sections detail the design procedure for each circuit section.

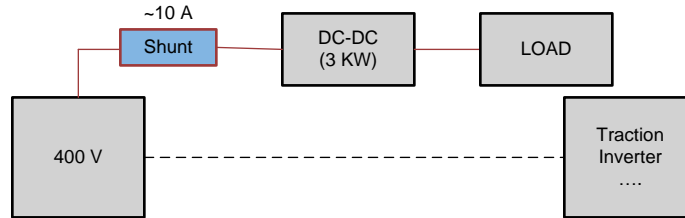
### 2.4.1 Selection of Shunt Resistor

The shunt resistor must provide 50-mV drop across the AMC1302-Q1 input terminals, as AMC1302-Q1 supports 50-mV input. Based on the amount of current flow through that particular value of the shunt has to be chosen.

32-A of current is flowing through the shunt when operating for the OBC application, and 10-A current is flowing through it when operating for the DC/DC application. Based on this, shunt values are chosen in such a way that 5 mOhms for DC/DC and 50 mOhms for OBC current sensing. In either case, it matches with 50-mV analog front-end of the isolated amplifier, meaning in DC/DC with a shunt chosen of 5 mΩ, it gives off **0.5 W of power dissipation**, and similarly in OBC applications with 1.5 mΩ it gives **1.6 W of power dissipation**. In either case, the amount of power it dissipates is much lower compared to the conventional larger input voltage terminals. The following sections describe the shunt resistor calculations.

**Shunt resistor calculation for DC/DC:** shows the DC/DC converter flow path and placement of shunt along the series connection between the 400-V battery and DC/DC converter.

**Figure 2. Placement of Shunt in DC/DC Converter**



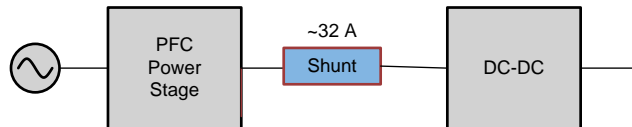
$$R = 50 \text{ mV} / 10 \text{ A} = 5 \text{ m}\Omega$$

$$P = 0.5 \text{ W}$$

R: shunt resistor value, P: power dissipation

**Shunt resistor calculation for OBC (onboard charger):** Figure 3 shows the onboard charger flow path and placement of the shunt along the series connection between the PFC power stage and the DC/DC converter.

**Figure 3. Placement of Shunt in Onboard Charger**



$$R = 50 \text{ mV} / 32 \text{ A} = 1.5 \text{ m}\Omega$$

$$P = 1.6 \text{ W}$$

R: shunt resistor value, P: power dissipation

These shunts are connected in kelvin configuration with the front-end isolated amplifier. Other important parameters include the resistance tolerance, the temperature coefficient of resistance, low thermal EMF, and low inductance.

## 2.4.2 Isolation Amplifier

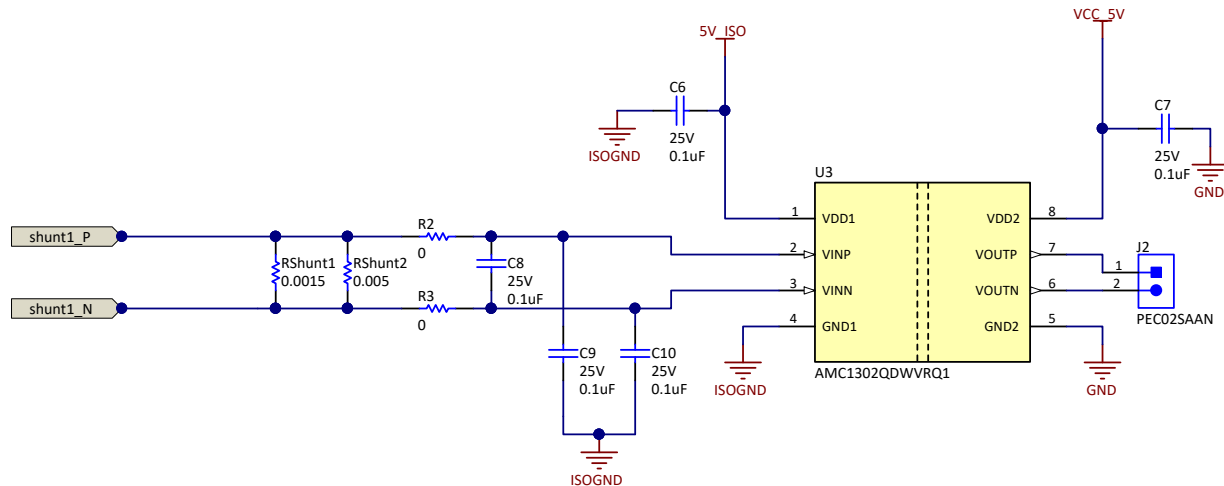
This design uses the AMC1302-Q1 to provide reinforced isolation between the high-voltage and low-voltage sides. The AMC1302-Q1 provides a fixed gain of 41 along with level shifting the output. The high-voltage side is to be powered by 5 V while the low-voltage side can be powered either by 5 V or 3.3 V depending on the level shift of the output required. This design uses 5 V to power the high-voltage side and 5 V to power the low-voltage side.

The shunt is kelvin-connected to the AMC1302-Q1. The AMC1302-Q1 is an isolated amplifier. This 50-mV device is amplified at a gain factor of 41, which results in output voltage levels of -2.05 V to +2.05 V on the differential output stage of an isolated amplifier. This means that it amounts to a peak-to-peak voltage of 4.10 V on the output terminals of the AMC1302-Q1. Figure 4 shows the isolated amplifier schematic.

The isolated amplifier is fast enough to take actions on faults at a very fast rate. The main feature of the AMC1302 is a 3-μs delay which gives the faster response times.

R shunt 1 and R shunt 2 are connected based on the input current requirements. The RC filter is inserted between the shunts and AMC input to eliminate the EMI noise. Values of the RC filter need to be adjusted based on the environment chosen.

**Figure 4. Isolated Amplifier Schematic**



### 2.4.3 Differential- to Single-Ended Conversion

To use the complete dynamic input range of a 5-V ADC, the  $\pm 2.05$ -V output swing is mapped to approximately 0 V to 5 V. This mapping is accomplished by the differential amplifier stage that [Figure 5](#) shows. The OPA376-Q1 operational amplifier (op amp) was chosen for this stage mainly because of its low offset and high CMRR.

Differential output is given to the operational amplifier where it is converted into single-ended output to give it to the ADC for digital processing.

The OPA376 output voltage swing is limited up to 40 mV from the rails typically. Considering the mismatch in resistor values, the output voltage is designed to be limited to a little over 80 mV from the rails.

The  $\pm 2.05$ -V input to the differential amplifier is to be mapped to 0 V to 5 V and the input of 0 V is mapped to 2.5 V (VREF). Thus, the ratio of resistors required to achieve this shift is calculated using the following equations.

V output required ( **V<sub>or</sub>** ) is required for the OPA376-Q1: [op amp supply]-[op amp rail to rail swing].

40 mV is the offset from one rail so the rail-to-rail offset is 80 mV.

$$V_{or} = 5 \text{ V} - 80 \text{ mV} = 4.92 \text{ V}$$

$$\text{Op amp gain required} = 4.92 \text{ V} / 4.10 \text{ V} = 1.2 \text{ V/V}$$

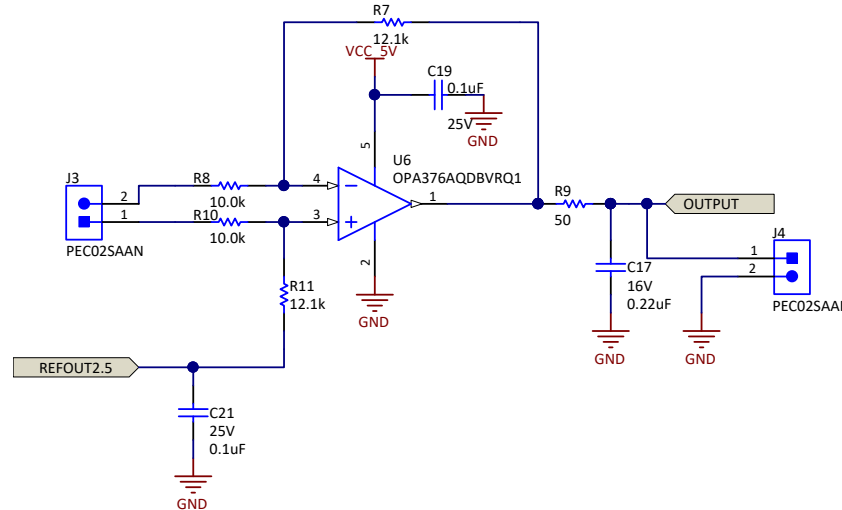
$$R7/R8 = 1.2$$

$$R11/R10 = 1.2$$

$$R7, R11 = 12\text{K}, R8, R10 = 10\text{K}$$

In this scenario, VISO\_OUT is the output of the AMC1301 device, as [Figure 5](#) shows, and VOUT is the final output of the level shifter. [Figure 5](#) shows the schematic of the level shifter. With all the values inserted, [Figure 5](#) shows the differential amplifier to the single-ended stage schematic.

Figure 5. Differential Amplifier Stage



### 2.4.4 Power Supply Section

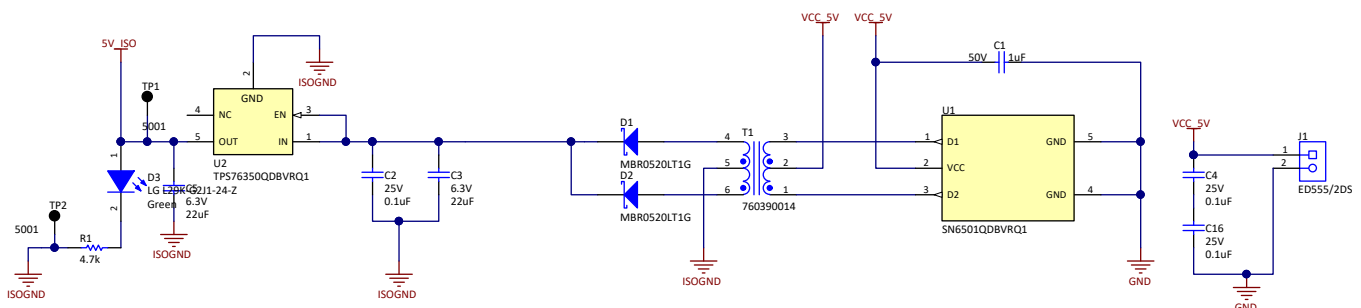
The AMC1302-Q1 requires an isolated power supply for powering its input section. The SN6501-Q1 is used as a switching device to generate a 5-V isolated output and drives the transformer.

The SN6501-Q1 is a monolithic oscillator and power-driver, specifically designed for isolated power supplies in isolated interface applications with a small form factor. The device drives a low-profile, center-tapped transformer primary from a 3.3- or 5-V DC power supply. The SN6501-Q1 consists of an oscillator followed by a gate drive circuit that provides the complementary output signals to drive the ground referenced N-channel power switches. The internal logic ensures break-before-make action between the two switches. The SN6501-Q1 features a push-pull driver for small transformers and a single 3.3- or 5-V supply.

While selecting the transformer, preventing the transformer from saturation is important. To achieve this protection, the V-t product of the transformer must be greater than the maximum V-t product applied by the SN6501-Q1 device. The maximum voltage delivered by the SN6501-Q1 device is the nominal converter input plus 10%. The maximum time this voltage is applied to the primary is half the period of the lowest frequency at the specified input voltage. Therefore, the minimum V-t product of the transformer is determined using the following equation.

Common  $V \times t$  values for low-power, center-tapped transformers range from 22 V  $\mu$ s to 150 V  $\mu$ s with typical footprints of 10 mm  $\times$  12 mm. Figure 6 shows the isolated power supply schematic.

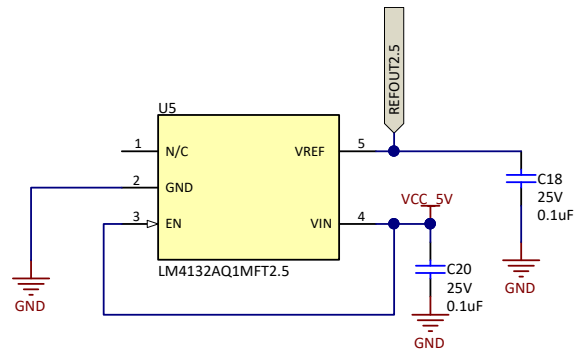
Figure 6. Isolated Power Supply Schematic



### 2.4.5 Reference Detection

In this application, a unipolar power supply must be used to sense a bipolar signal. This sensing requires level shifting of the signal to the midpoint of the power supply rail. A voltage reference is used to bias the signal-conditioning stage output to the middle of the ADC dynamic range. The LM4132-Q1 integrated circuit (IC) provides 2.5 V.

**Figure 7. Reference Circuit Schematic**



The IC is supplied with a 5-V power supply. The output is 2.5 V. Place 0.1-µF noise decoupling capacitors close to the IC pins for a clean power input and output rails. [Figure 7](#) shows the reference circuit schematic.



## **3 Hardware, Software, Testing Requirements, and Test Results**

### **3.1 Required Hardware and Software**

#### **3.1.1 Hardware**

The following list shows the hardware used in this design.

- Dual power supply
- 6½ digital multimeter
- Function generator
- Oscilloscope
- Temperature chamber

## 3.2 Testing and Results

The tests were conducted with DC input voltage, AC input voltage, and current input. The frequency of AC input used for conducting the tests was 50 Hz. The values of voltages were measured after every stage using a 6½ digital multimeter (DMM) from Agilent™ with the aid of averaging functionality.

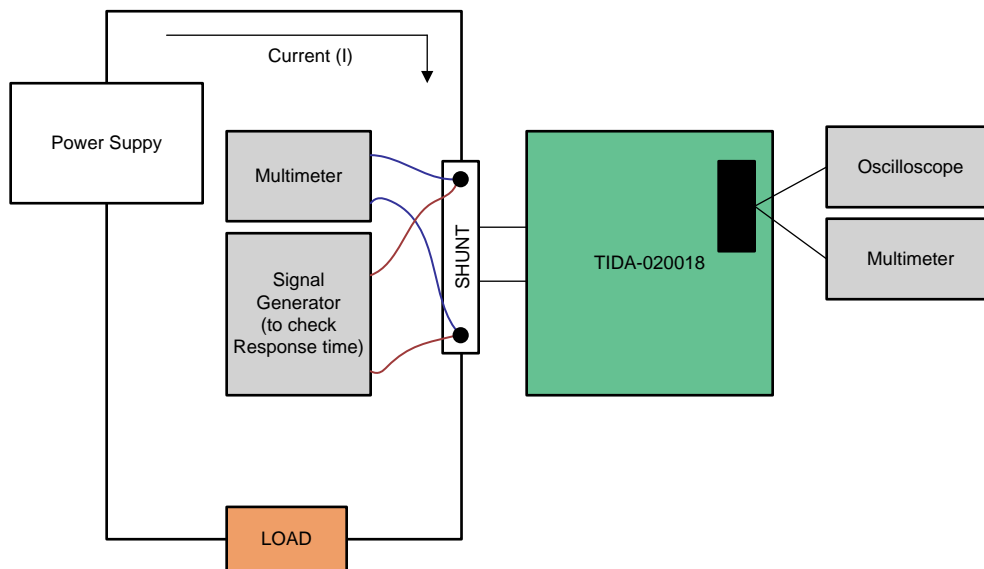
### 3.2.1 Test Setup

Figure 8 and Figure 9 show the test setup arrangements for response times and accuracy versus temperature calculations. The DC input voltage was supplied by a Keithley™ 2650 source meter. The accuracy of the design was calculated for every 1 mV in the input voltage over a range of –50 mV to 50 mV.

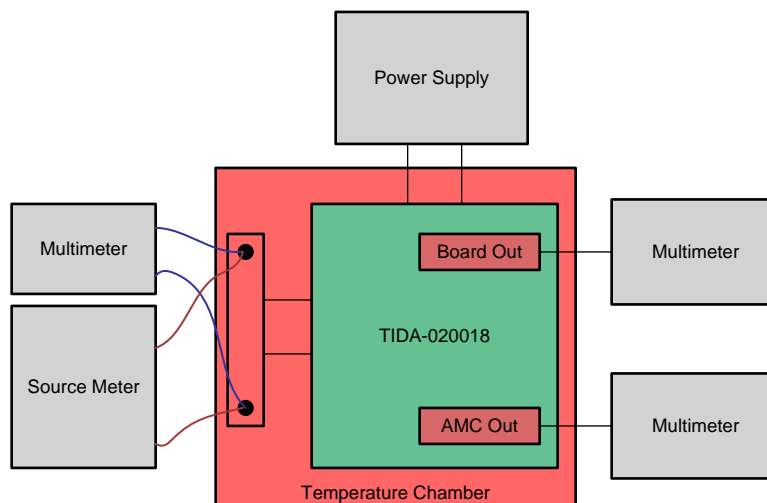
A similar test was conducted with AC input voltage and current wherein the design was tested for an input ranging from 1 mVRMS to 17 mVRMS with 1-mV steps.

For testing the design over the temperature range of –40°C to 125°C, the board was kept inside the temperature chamber and similar tests were conducted. Figure 8 shows the setup for testing across the temperature range of –40°C to 125°C.

**Figure 8. TIDA-020018 Test Setup**



**Figure 9. Test Setup for Accuracy Calculations**



### 3.2.2 Test Results

#### 3.2.2.1 Power Supply

Figure 10 and Figure 11 show the  $\pm 2.5$ -V isolated power supplies generated onboard to bias the front-end gain stage and high-voltage side of the AMC1301 device. Figure 10 and Figure 11 show the power supply rails of the 5-V and 2.5-V supply.

**Figure 10. 5-V Supply**

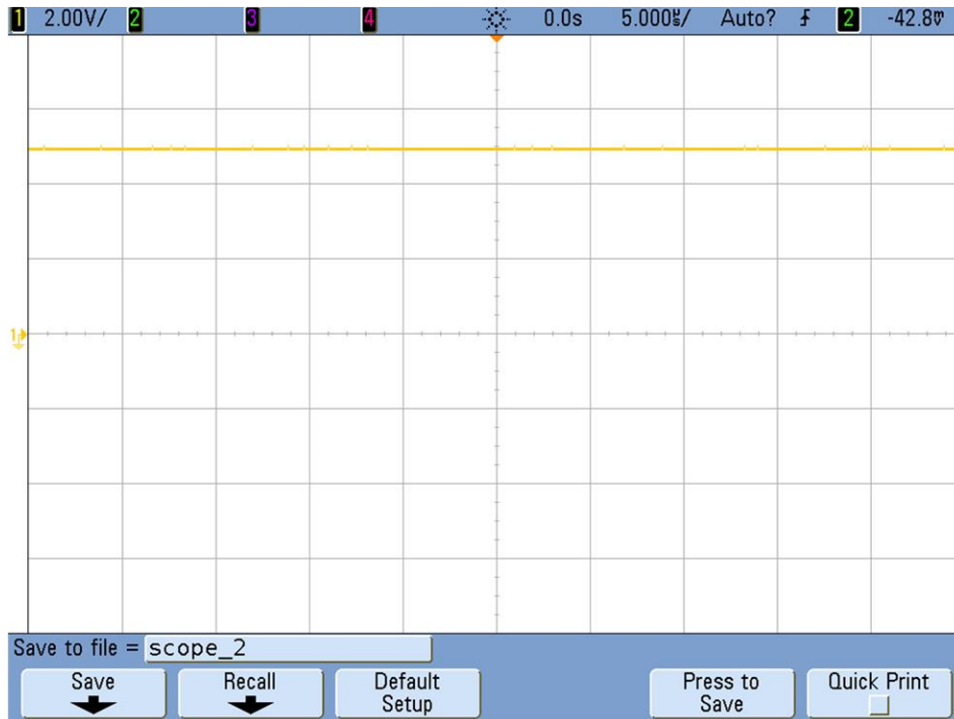


Figure 11. 2.5-V Supply

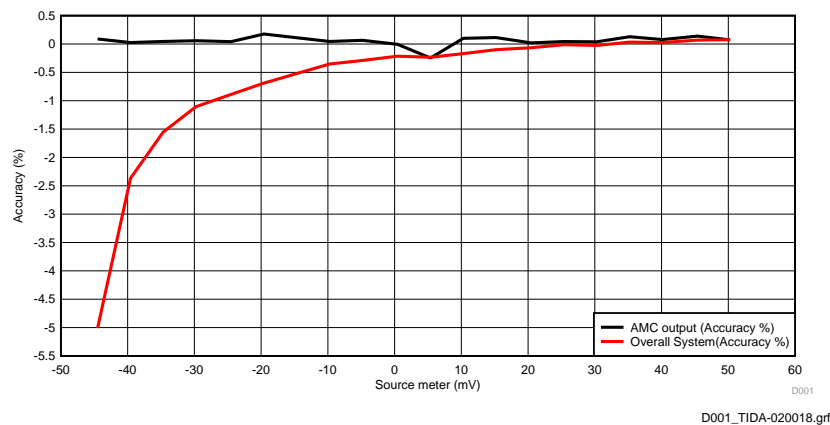


### 3.2.2.2 Accuracy Results

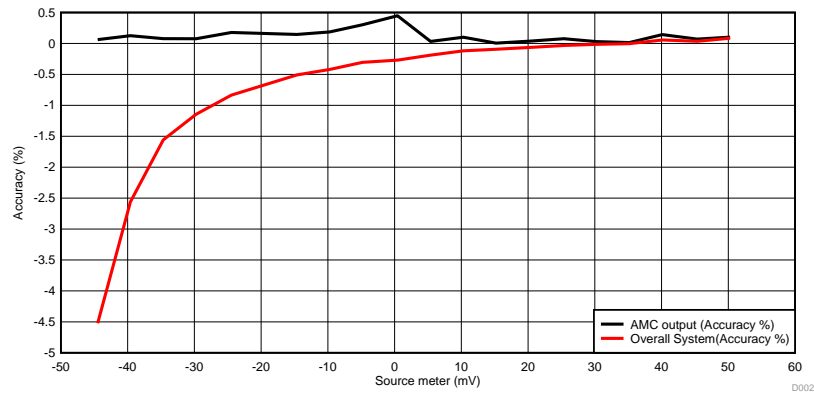
This section provides the accuracy graphs obtained for this design.

Figure 12 to Figure 16 show the accuracy for AMC output voltage and overall system output voltage for the source meter voltages ranging from -50 mV to +50 mV. The 50-mV range corresponds to 10 A in DC/DC and 32 A in OBC.

Figure 12. Accuracy of AMC Output and Overall System Output at -20°C

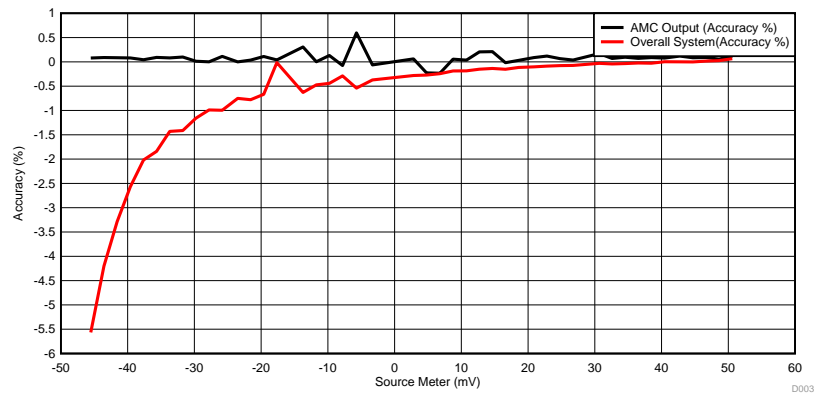


**Figure 13. Accuracy of AMC Output and Overall System Output at 0°C**



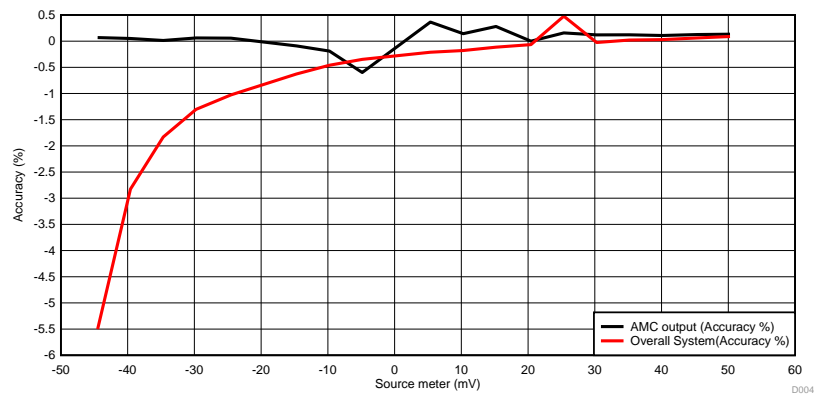
D002\_TIDA-020018.grf

**Figure 14. Accuracy of AMC Output and Overall System Output at 25°C**



D003\_TIDA-020018.grf

**Figure 15. Accuracy of AMC Output and Overall System Output at 75°C**



D004\_TIDA-020018.grf

**Figure 16. Accuracy of AMC Output and Overall System Output at 120°C**

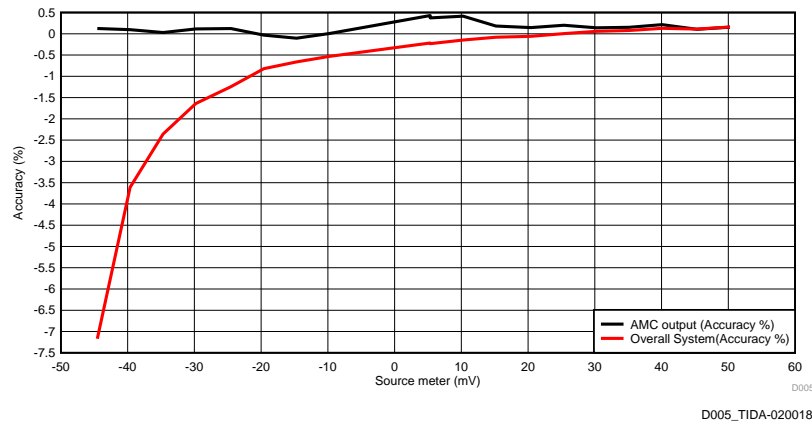


Figure 17 shows the accuracy for AMC output voltage at various temperature ranges.

**Figure 17. Accuracy of AMC Output at Various Temperatures**

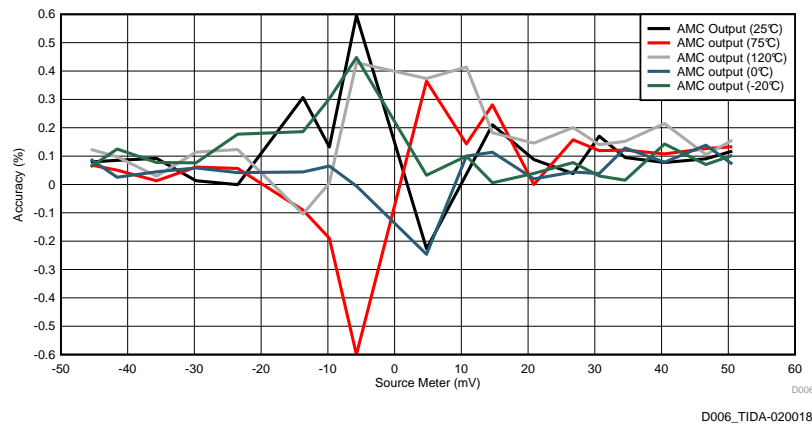
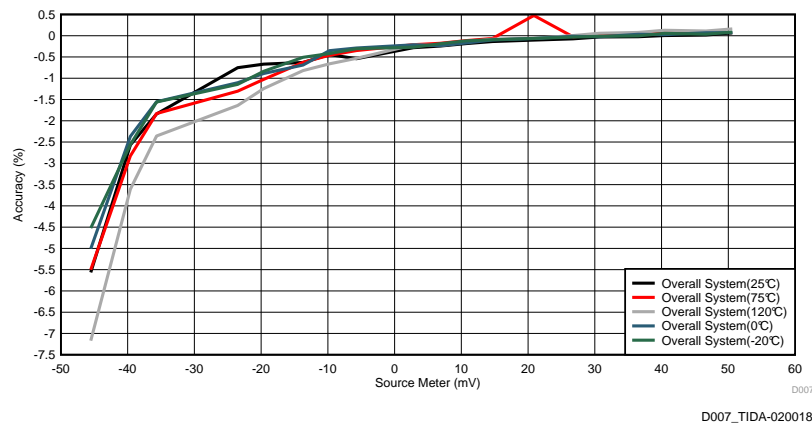


Figure 18 shows the accuracy of overall system with the source meter voltages ranging from -50 mV to +50 mV.

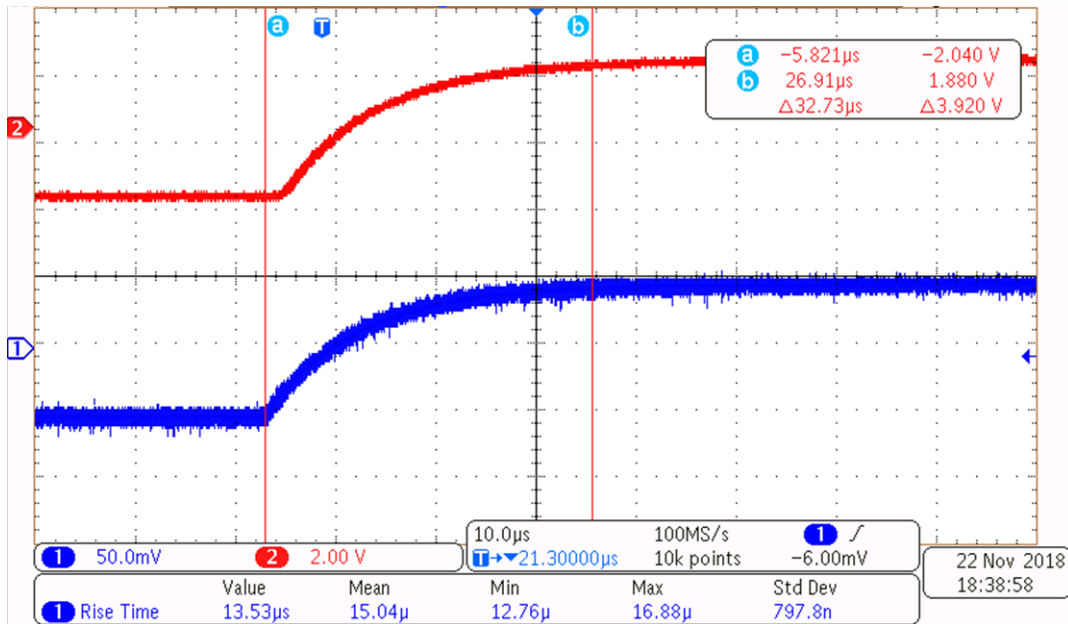
**Figure 18. Accuracy of Overall System Output at Various Temperature Ranges**



### 3.2.2.3 Time Response

This section shows the response of the design to a step input of 50 mV. Figure 19 and Figure 20 show the total rise time of the input and output.

Figure 19. AMC1302 Input Rise Time



The measured rise time of the step input is 13.53 μs, and the corresponding rise time of output is 27.73 μs. Figure 19 shows the rise time of only the AMC1200 when a step input of 50 mV is fed to it.

Figure 20. AMC1302 Output Rise Time

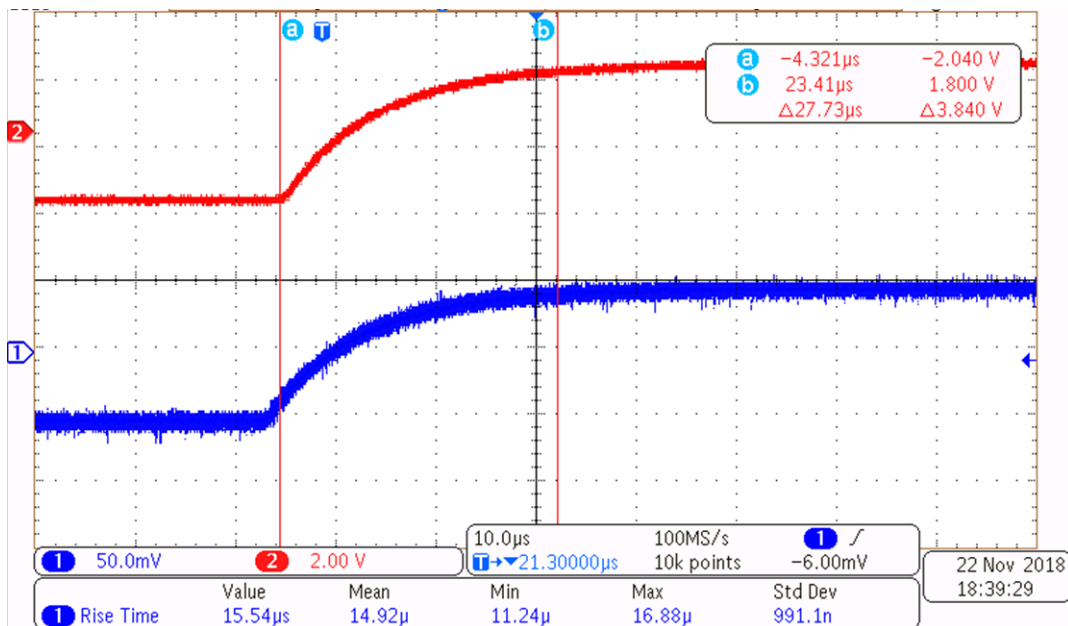


Figure 21 shows the propagation delay (AMC1302-Q1 input to AMC1302-Q1 output). It is clearly visible that there is a propagation delay of only 2.028 us.

Figure 21. AMC1302 Input, Output Latency

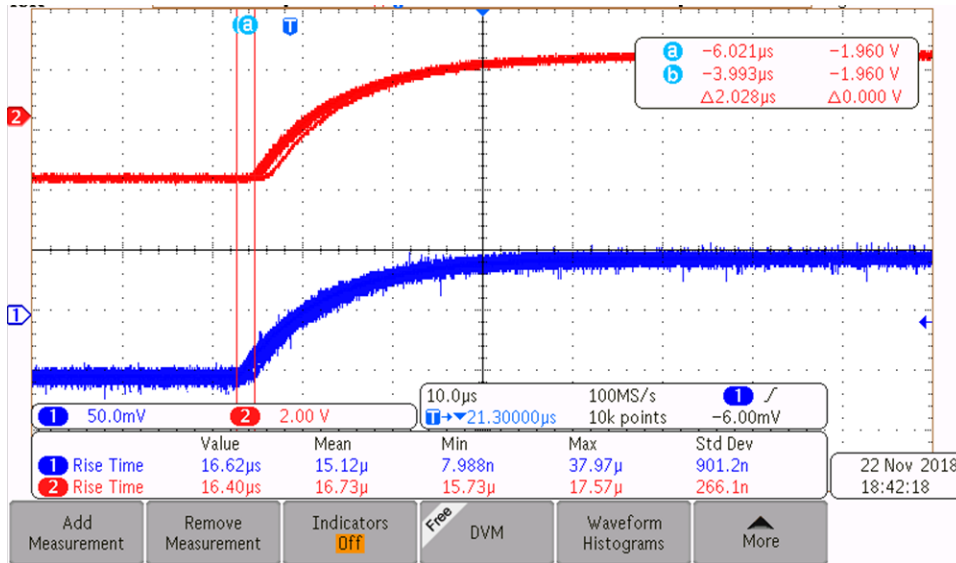
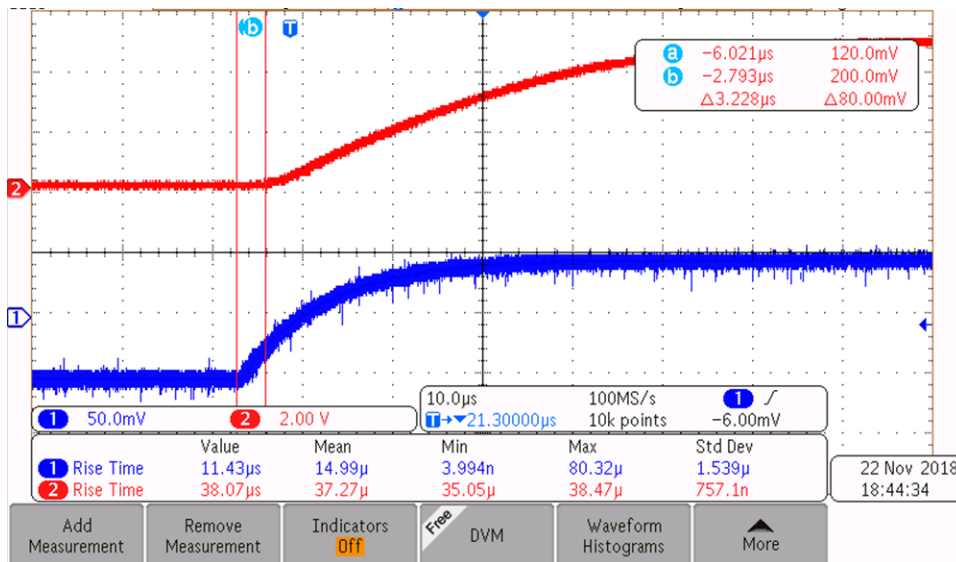


Figure 22 shows the propagation delay (AMC1302-Q1 input to board output). It is clearly visible that there is a propagation delay when considering the whole board is 3.228 us.

Figure 22. AMC1302 Versus Board Output Latency





## 4 Design Files

### 4.1 Schematics

To download the schematics, see the design files at [TIDA-020018](#).

### 4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-020018](#).

### 4.3 PCB Layout Recommendations

#### 4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-020018](#).

### 4.4 Altium Project

To download the Altium Designer® project files, see the design files at [TIDA-020018](#).

### 4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-020018](#).

### 4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-020018](#).

## 5 Related Documentation

1. Texas Instruments, [SN6501-Q1 Transformer driver for isolated power supplies data sheet](#)
2. Texas Instruments, [High-voltage isolation quality and reliability for AMC130x white paper](#)
3. Texas Instruments, [Interfacing a differential-output \(isolated\) amp to a single-ended input ADC application report](#)
4. Texas Instruments, [Understanding failure modes in isolators white paper](#)

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## 6 About the Author

**SANDEEP TALLADA** is a systems engineer at Texas Instruments. As a member of the Automotive Systems Engineering team, Sandeep focuses on HEV/EV, powertrain end-equipments and creating subsystem reference designs. He brings to this role experience in sensor systems technology. Sandeep earned his master of science in sensor systems technology from the University of Applied Sciences Karlsruhe, Germany.

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