

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

表 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/μs (typ), 70 kV/μs (min)	
Output	0 V to 5 V	
Operating temperature	-40°C to +125°C	

2 System Overview

2.1 Block Diagram

图 1. TIDA-020018 Block Diagram

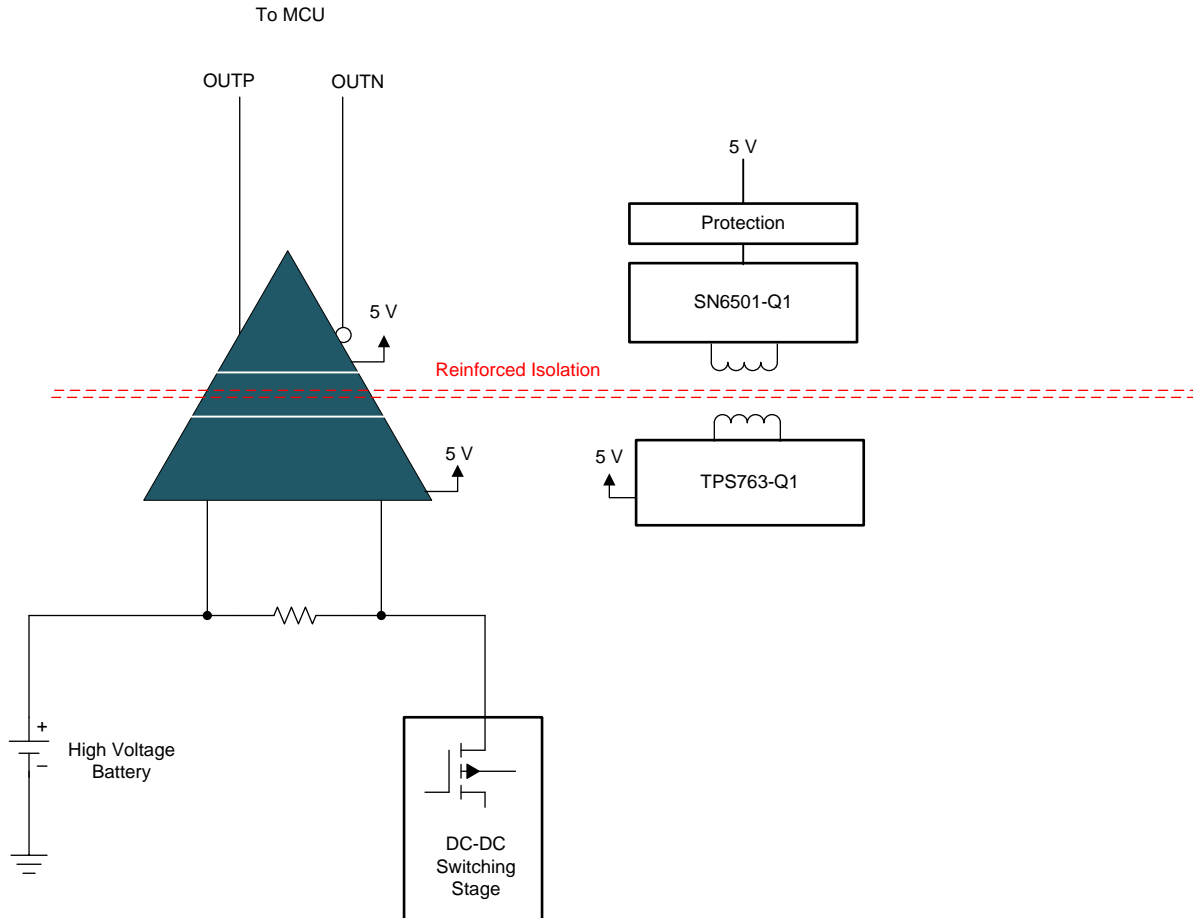


图 1 shows the block diagram of the TIDA-020018.

SHUNT: 图 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 descretes.

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 ± 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 μ 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 μ V maximum), low noise (7.5 nV/ $\sqrt{\text{Hz}}$), quiescent current of 950 μ 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.

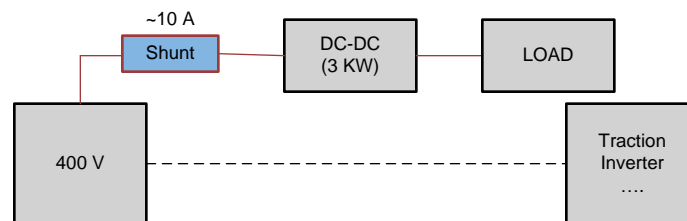
2.4.1 Selection of Shunt Resistor

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.

图 2. Placement of Shunt in DC/DC Converter



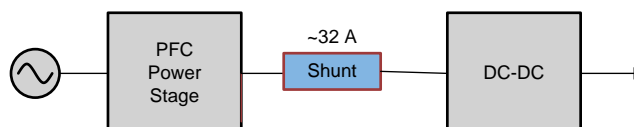
$$R = 50 \text{ mV} / 10 \text{ A} = 5 \text{ m}\Omega$$

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

R: shunt resistor value, P: power dissipation

Shunt resistor calculation for OBC (onboard charger): 图 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.

图 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

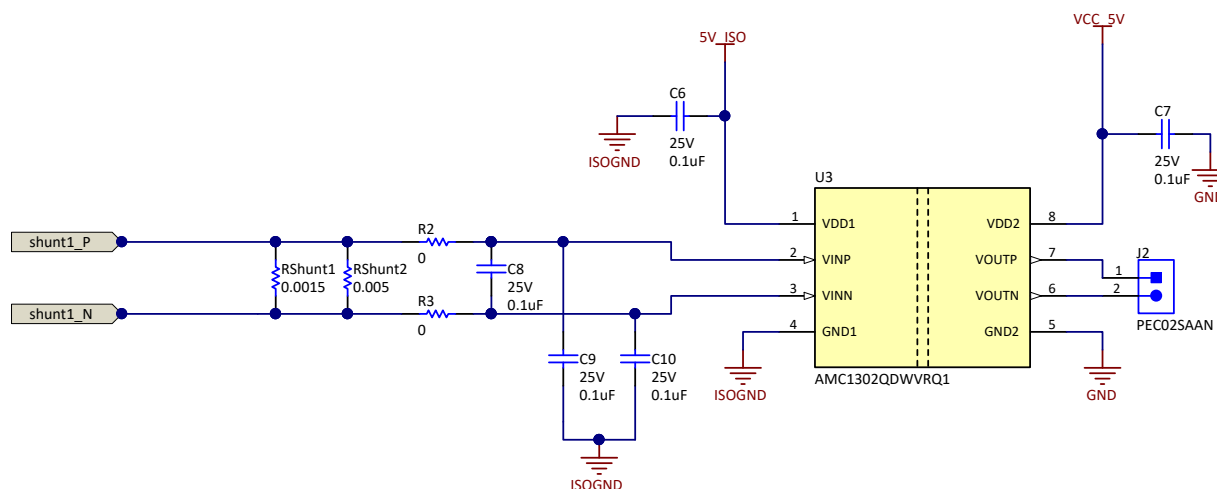
This design uses the AMC1302-Q1 to provide reinforced isolation between the high-voltage and low-voltage sides. The AMC1302-Q1 provides a fixed gain of 41 along with level shifting the output. The high-voltage side is to be powered by 5 V while the low-voltage side can be powered either by 5 V or 3.3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

图 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 $\pm 2.05\text{-V}$ output swing is mapped to approximately 0 V to 5 V. This mapping is accomplished by the differential amplifier stage that 图 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 $\pm 2.05\text{-V}$ 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 (**Vor**) 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.

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

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

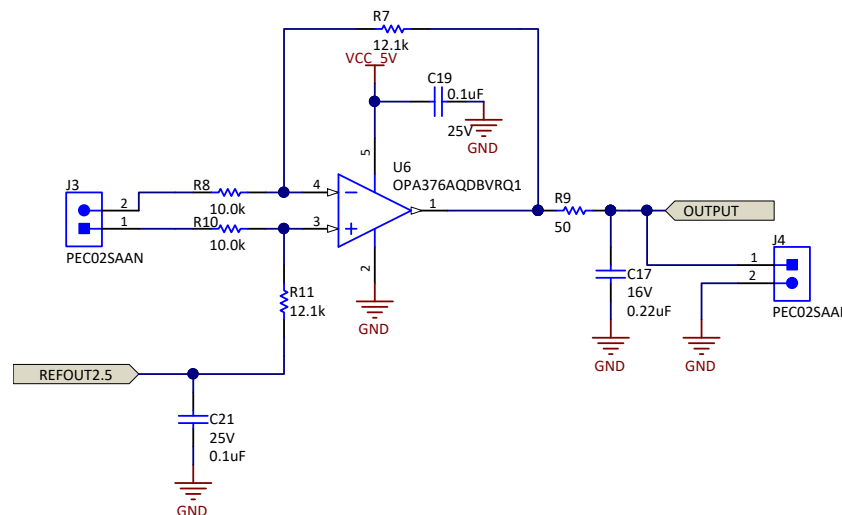
$$R7/R8 = 1.2$$

$$R11/R10 = 1.2$$

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

In this scenario, VISO_OUT is the output of the AMC1301 device, as 图 5 shows, and VOUT is the final output of the level shifter. 图 5 shows the schematic of the level shifter. With all the values inserted, 图 5 shows the differential amplifier to the single-ended stage schematic.

图 5. Differential Amplifier Stage



2.4.4 Power Supply Section

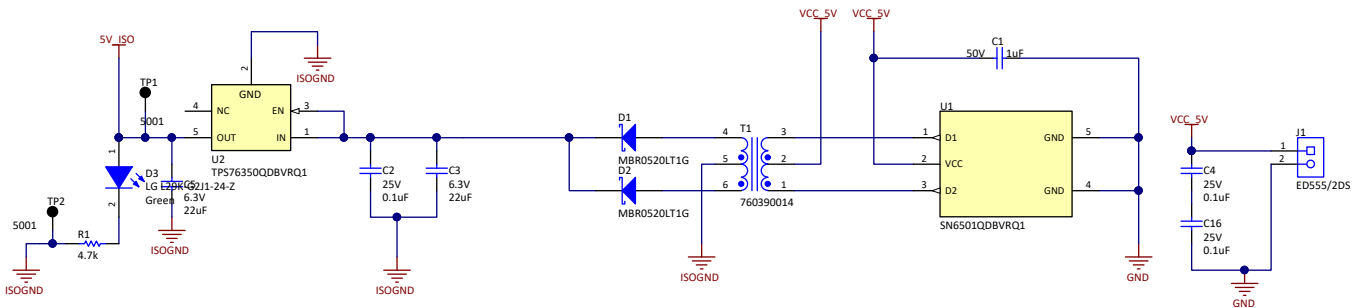
The AMC1302-Q1 requires an isolated power supply for powering its input section. The SN6501-Q1 is used as a switching device to generate a 5-V isolated output and drives the transformer.

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 μ s to 150 V μ s with typical footprints of 10 mm \times 12 mm. 图 6 shows the isolated power supply schematic.

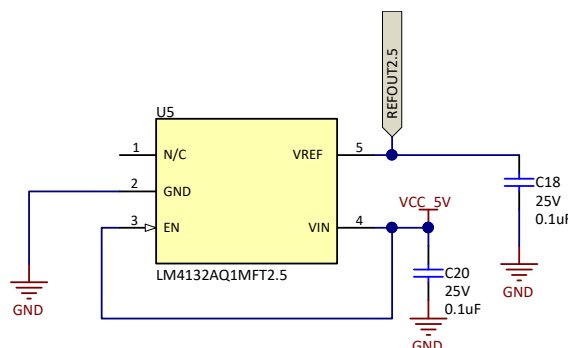
图 6. Isolated Power Supply Schematic



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.

图 7. Reference Circuit Schematic



The IC is supplied with a 5-V power supply. The output is 2.5 V. Place 0.1- μ F noise decoupling capacitors close to the IC pins for a clean power input and output rails. 图 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

图 8 和 图 9 显示测试设置安排，用于响应时间和精度随温度变化的计算。DC 输入电压由 Keithley™ 2650 源表提供。设计的精度在输入电压范围从 -50 mV 到 50 mV 的范围内，每 1 mV 计算一次。

类似的测试是在 AC 输入电压和电流下进行的，其中设计在输入范围从 1 mVRMS 到 17 mVRMS 且以 1-mV 为步长的条件下进行测试。

为了测试设计在 -40°C 到 125°C 的温度范围内，电路板被放入温度试验箱中，并进行了类似的测试。图 8 显示了在 -40°C 到 125°C 温度范围内的测试设置。

图 8. TIDA-020018 测试设置

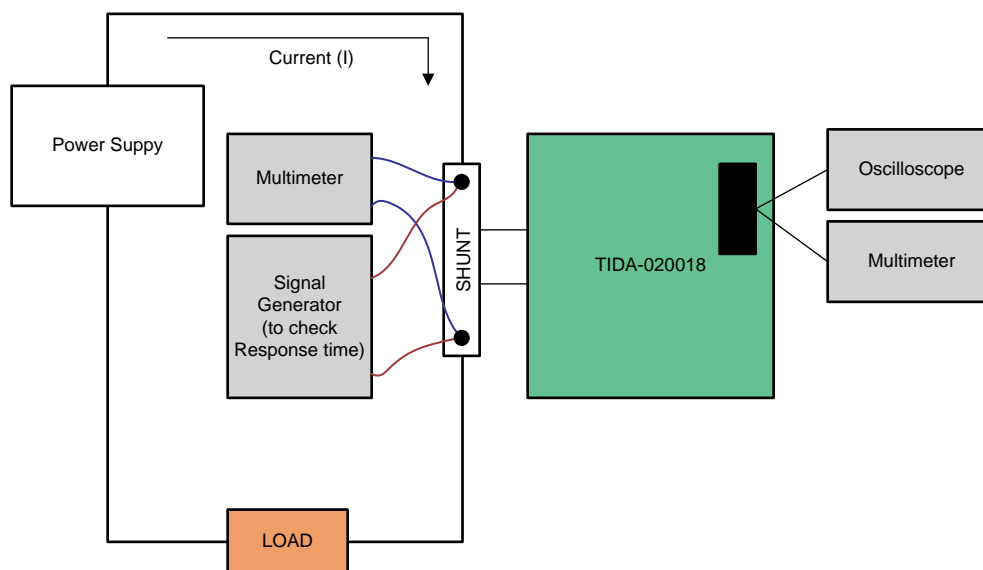
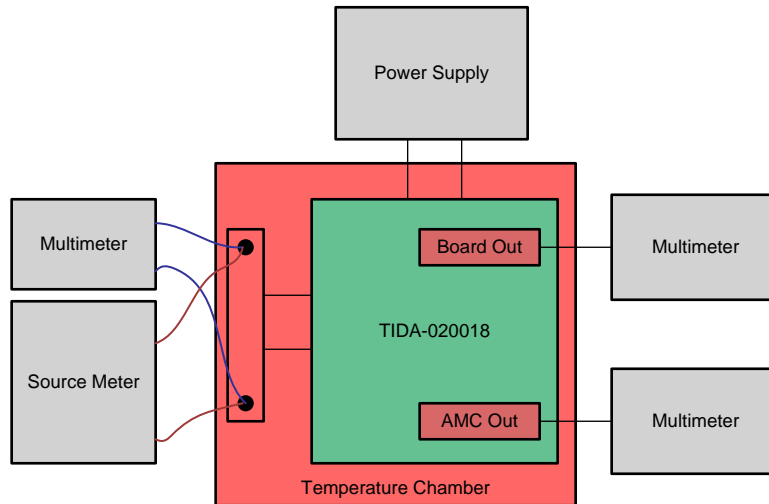


图 9. Test Setup for Accuracy Calculations



3.2.2 Test Results

3.2.2.1 Power Supply

图 10 和 图 11 显示在板上生成的 $\pm 2.5\text{-V}$ 隔离电源，用于偏置前端增益阶段和 AMC1301 设备的高电压侧。图 10 和 图 11 显示 5-V 和 2.5-V 电源的电源轨。

图 10. 5-V Supply

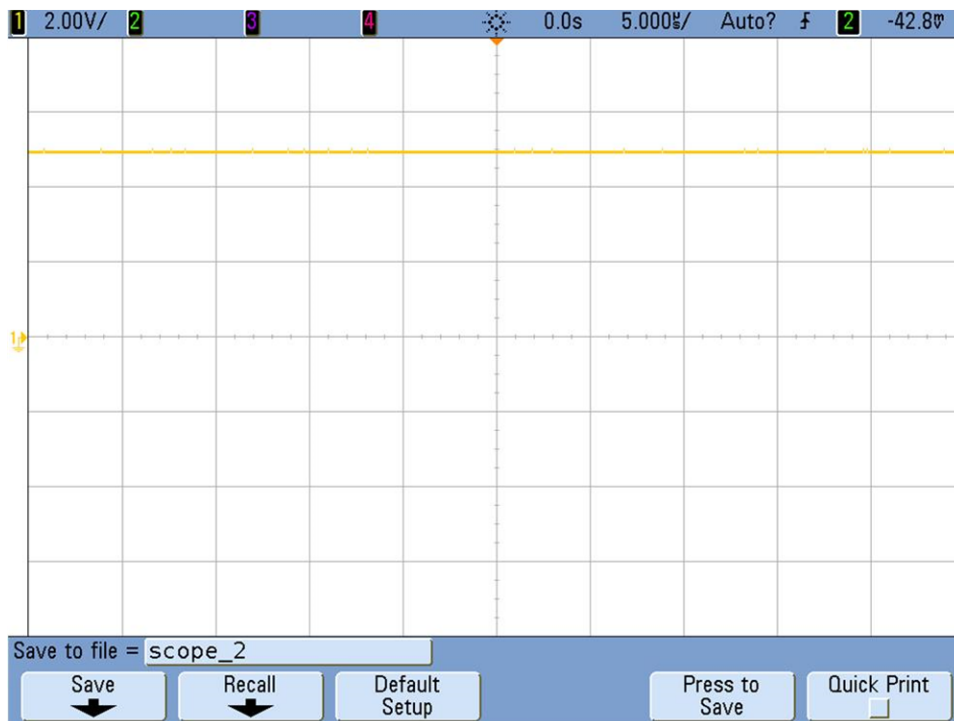


图 11. 2.5-V Supply

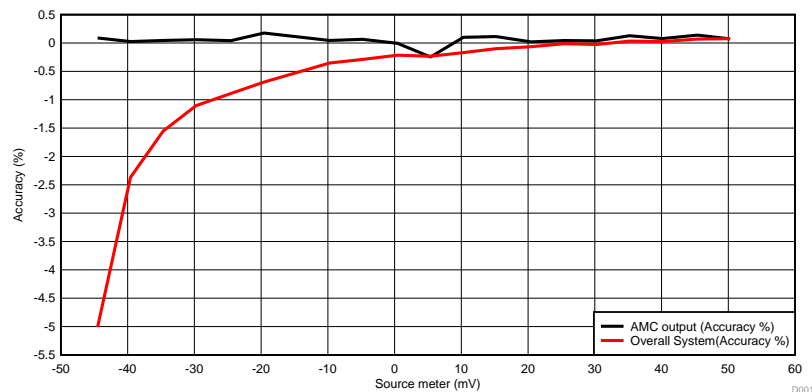


3.2.2.2 Accuracy Results

This section provides the accuracy graphs obtained for this design.

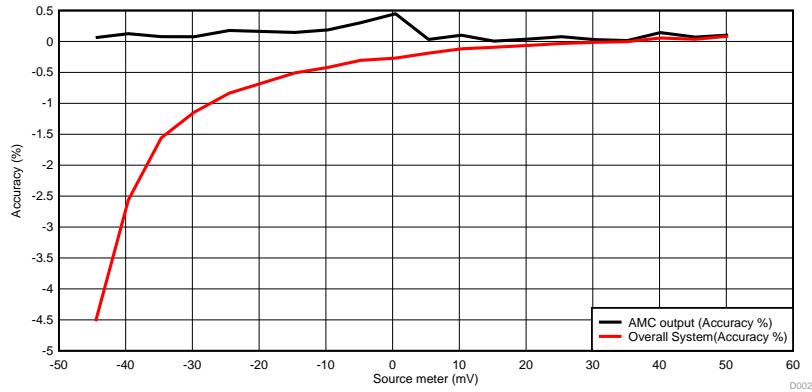
图 12 到 图 16 显示 AMC 输出电压和整体系统输出电压的精度，适用于源表电压范围从 -50 mV 到 +50 mV。50-mV 范围对应于 DC/DC 中的 10 A 和 OBC 中的 32 A。

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



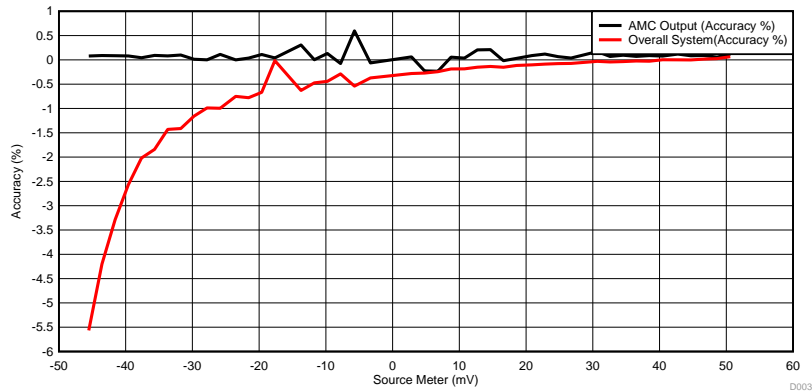
D001_TIDA-020018.grf

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



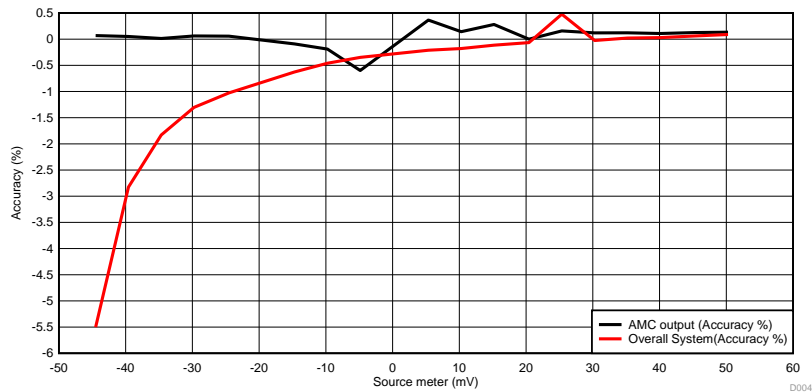
D002_TIDA-020018.grf

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



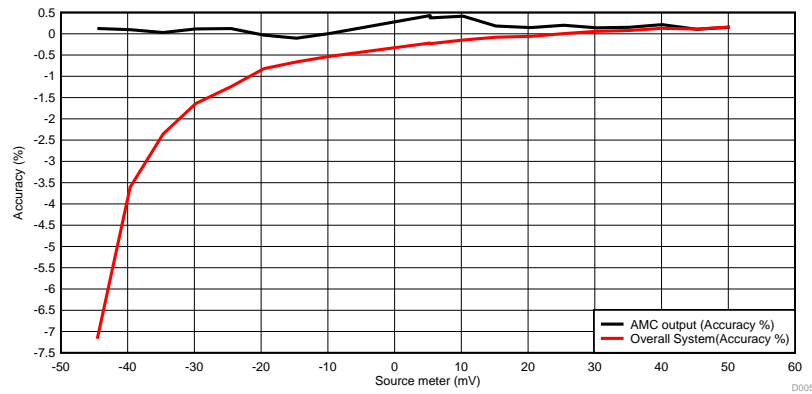
D003_TIDA-020018.grf

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



D004_TIDA-020018.grf

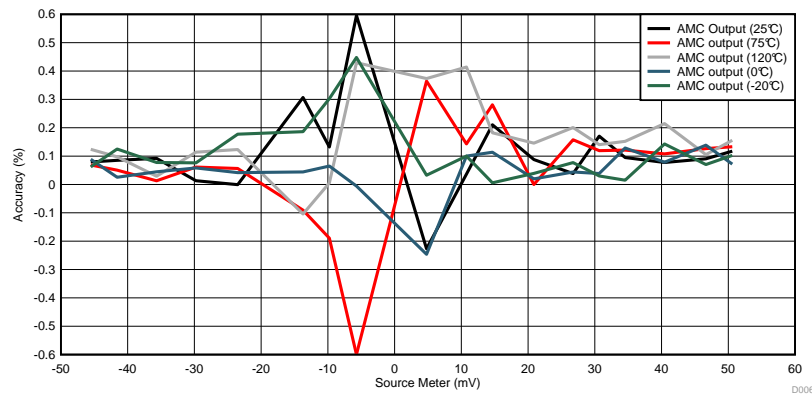
图 16. Accuracy of AMC Output and Overall System Output at 120°C



D005_TIDA-020018.grf

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

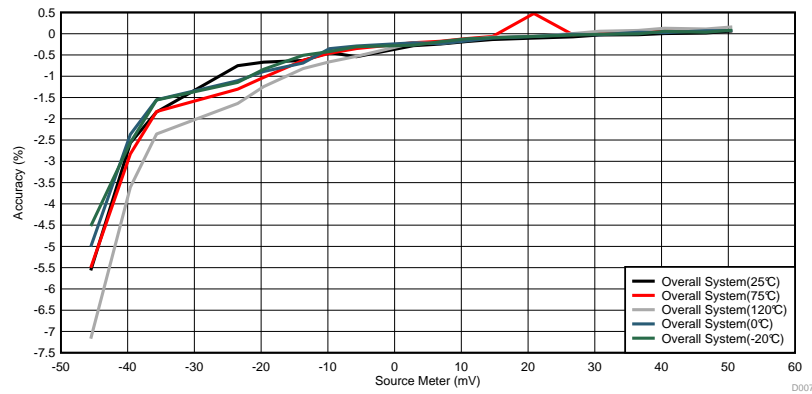
图 17. Accuracy of AMC Output at Various Temperatures



D006_TIDA-020018.grf

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

图 18. Accuracy of Overall System Output at Various Temperature Ranges

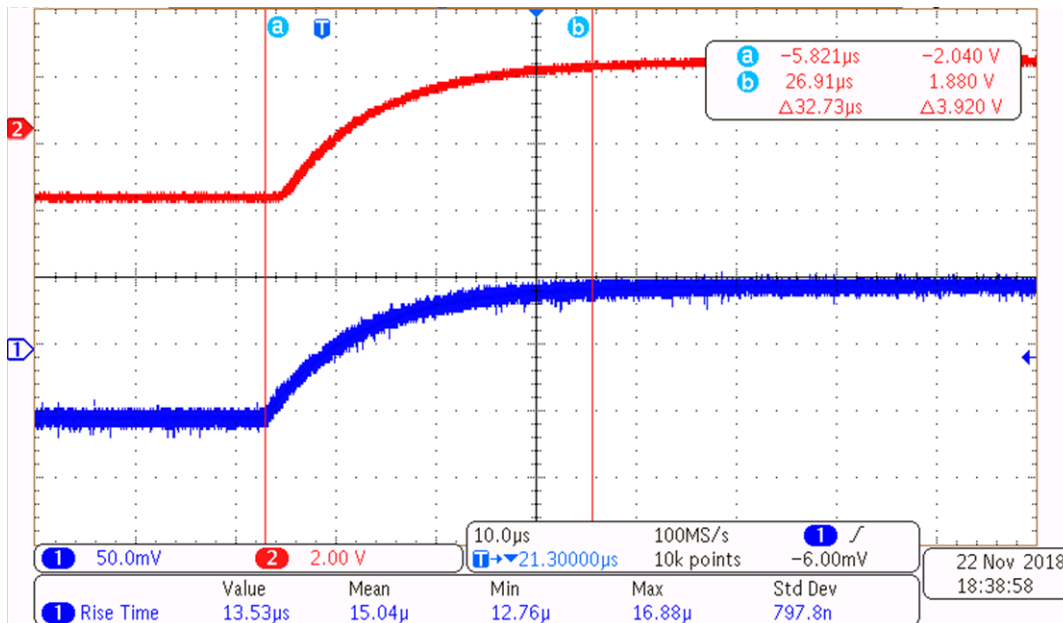


D007_TIDA-020018.grf

3.2.2.3 Time Response

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

图 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. 图 19 shows the rise time of only the AMC1200 when a step input of 50 mV is fed to it.

图 20. AMC1302 Output Rise Time

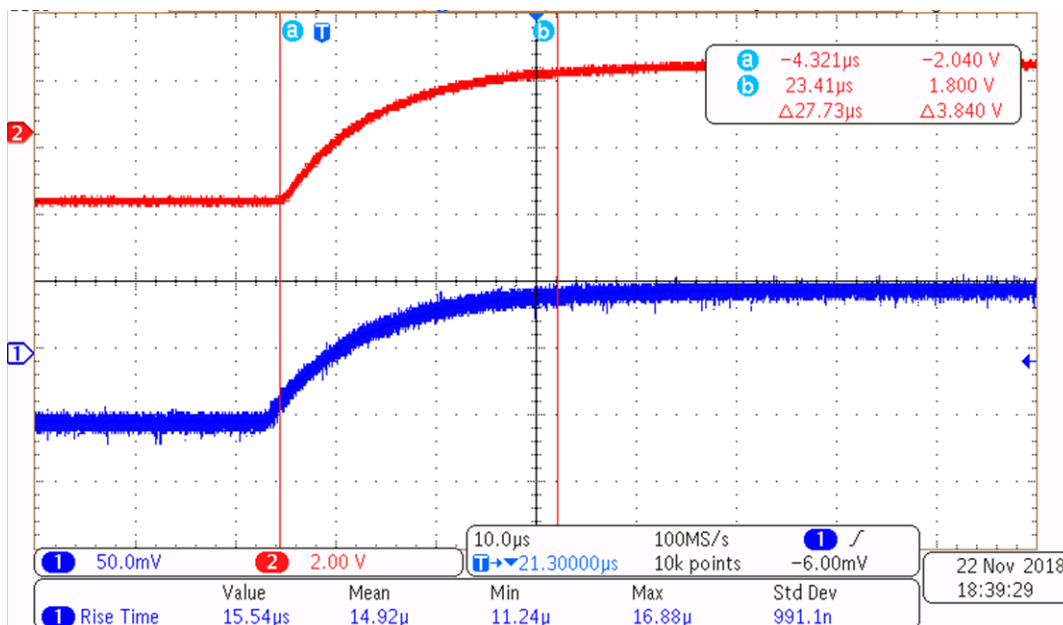


图 21 shows the propagation delay (AMC1302-Q1 input to AMC1302-Q1 output). It is clearly visible that there is a propagation delay of only 2.028 us.

图 21. AMC1302 Input, Output Latency

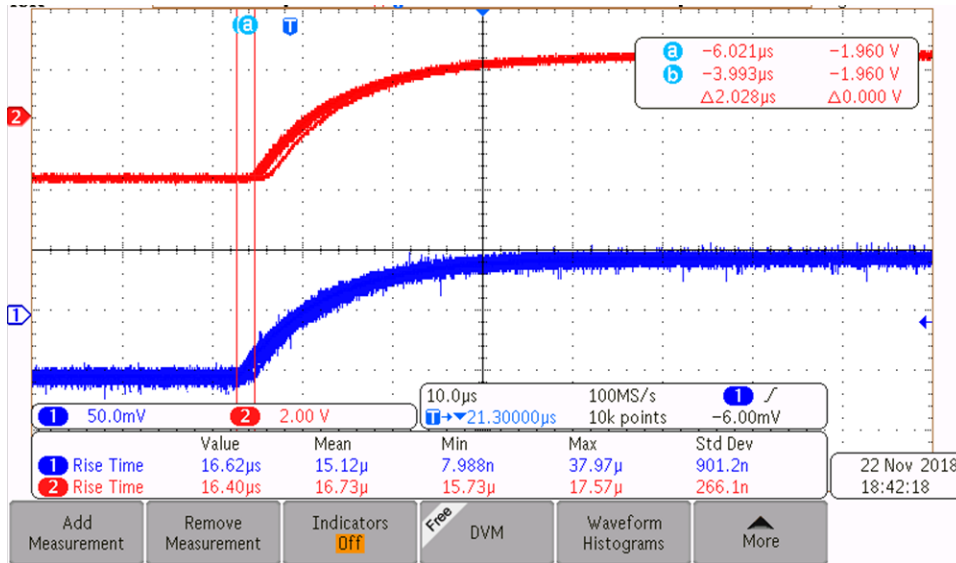
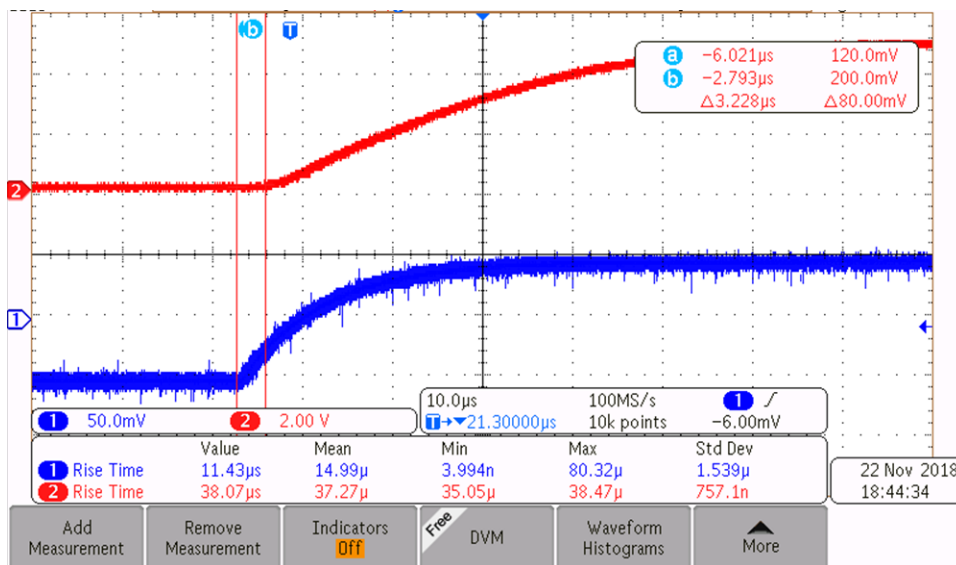


图 22 显示了传播延迟 (AMC1302-Q1 输入到板输出)。很明显，当考虑整个板子时，传播延迟是 3.228 us。

图 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](#)

5.1 商标

E2E is a trademark of Texas Instruments.

Agilent is a trademark of Agilent Technologies, Inc.

Altium Designer is a registered trademark of Altium LLC or its affiliated companies.

Keithley is a trademark of Keithley Instruments, LLC.

All other trademarks are the property of their respective owners.

5.2 Third-Party Products Disclaimer

TI'S PUBLICATION OF INFORMATION REGARDING THIRD-PARTY PRODUCTS OR SERVICES DOES NOT CONSTITUTE AN ENDORSEMENT REGARDING THE SUITABILITY OF SUCH PRODUCTS OR SERVICES OR A WARRANTY, REPRESENTATION OR ENDORSEMENT OF SUCH PRODUCTS OR SERVICES, EITHER ALONE OR IN COMBINATION WITH ANY TI PRODUCT OR SERVICE.

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.

重要声明和免责声明

TI“按原样”提供技术和可靠性数据（包括数据表）、设计资源（包括参考设计）、应用或其他设计建议、网络工具、安全信息和其他资源，不保证没有瑕疵且不做任何明示或暗示的担保，包括但不限于对适销性、某特定用途方面的适用性或不侵犯任何第三方知识产权的暗示担保。

这些资源可供使用 TI 产品进行设计的熟练开发人员使用。您将自行承担以下全部责任：(1) 针对您的应用选择合适的 TI 产品，(2) 设计、验证并测试您的应用，(3) 确保您的应用满足相应标准以及任何其他功能安全、信息安全、监管或其他要求。

这些资源如有变更，恕不另行通知。TI 授权您仅可将这些资源用于研发本资源所述的 TI 产品的应用。严禁对这些资源进行其他复制或展示。您无权使用任何其他 TI 知识产权或任何第三方知识产权。您应全额赔偿因在这些资源的使用中对 TI 及其代表造成的任何索赔、损害、成本、损失和债务，TI 对此概不负责。

TI 提供的产品受 [TI 的销售条款](#) 或 [ti.com](#) 上其他适用条款/TI 产品随附的其他适用条款的约束。TI 提供这些资源并不会扩展或以其他方式更改 TI 针对 TI 产品发布的适用的担保或担保免责声明。

TI 反对并拒绝您可能提出的任何其他或不同的条款。

邮寄地址：Texas Instruments, Post Office Box 655303, Dallas, Texas 75265

Copyright © 2022，德州仪器 (TI) 公司