# TI Designs
# *On-board Charger Load Feedback Sub-system*

## Design Overview

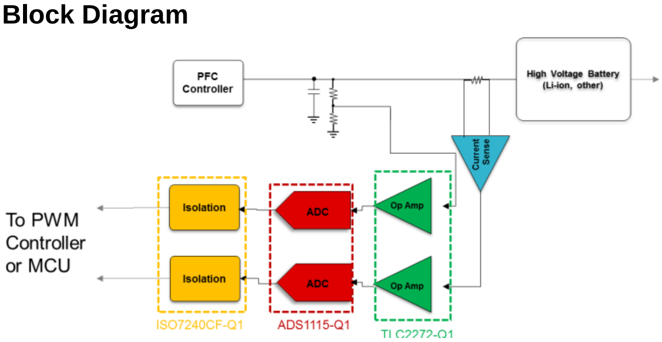
This TI Design uses Texas Instruments current shunt amplifiers, operational amplifiers (Op-Amp), ADCs, and digital isolators to provide current and voltage measurements for an on-board charger system in a hybrid-electric/electric vehicle (HEV/EV). The measured current and voltage can be used as control signals for battery charging optimization.

The design is capable of measuring high-side current at up to 400-V common-mode voltage, while being isolated from the AC portion of the charging circuit to reduce noise.

## Design Resources

| | |
|---|---|
| TIDA-00456 | Design Folder |
| INA138-Q1 | Product Folder |
| TLC2272A-Q1 | Product Folder |
| ADS1115-Q1 | Product Folder |
| ISO7241C-Q1 | Product Folder |

## Block Diagram



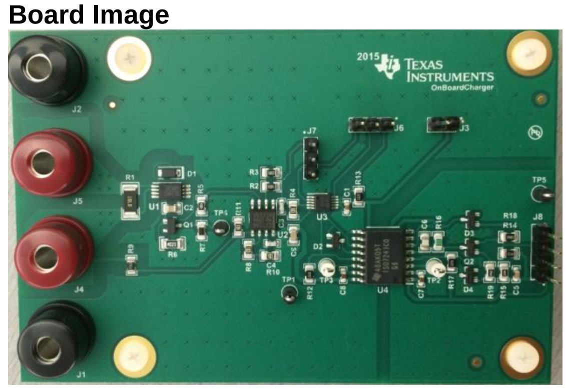

## Design Features

- High side current monitoring, up to 400-V common mode, enables short to ground protection
- Less than 5% current measurement error for the charging current range 1-A to 10-A
- Less than 10 µS over current detection
- Up to 400-V voltage monitoring with less than 5% error
- Less than 10uS voltage step detection
- 4000-$V_{peak}$ safety isolation

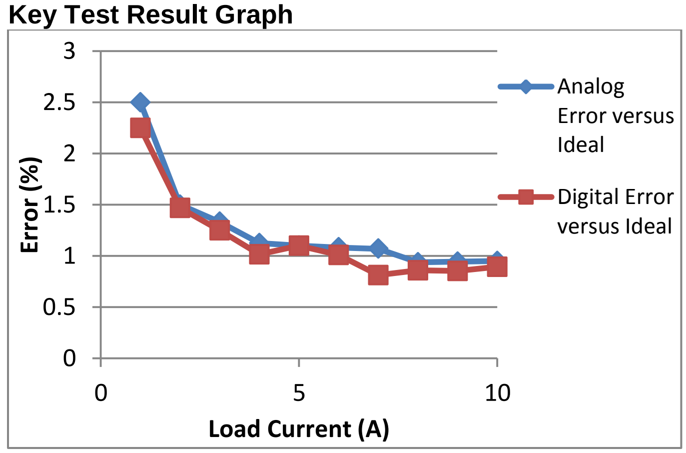
## Featured Applications

- On-board charger for HEV/EV hybrid vehicles
- PFC power factor corrector for industrial applications
- 160 to 400-V DC/DC converter

## Board Image



## Key Test Result Graph



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## 1 Key System Specifications

**Table 1: Key System Specifications**

| PARAMETER | SPECIFICATION | DETAILS |
|---|---|---|
| Input voltage | 160 to 400-V | 2.2 |
| Load current | 1-A to 10-A | 2.1 |
| Isolation | 4000-$V_{peak}$ | 2.4 |
| Current sensing gain | 100-mV/A | 4.1 |
| Voltage measurement | 0.0101 V/V | 4.2 |
| Interface | I2C 5-V TTL compatible | 2.3 |
| Available Measured signals | Analog and digital | 4.3 |
| Measurement Error | +/- 5% max | 6.1 |
| Operating temperature | -40ºC to 125ºC | |



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## 2 System Description

The number of hybrid electric vehicles and electric vehicles (HEV/EV) on the road is growing quickly. While high efficiency and independence from gasoline are attractive to drivers, these vehicles have unique design requirements that need to be met. The heart of the HEV/EV vehicle is the battery pack. These battery packs can store anywhere from 160-V to 400-V, about 10 to 30 times as much as the gasoline car.

To charge these massive battery packs, owners must plug their cars into an AC power source. An AC/DC converter on the car must be used to regulate the battery charging voltage, and it must do so safely since the battery pack can draw up to 10-A of current while charging. This is done by galvanically isolating the battery side from the AC power source. Isolation means that there is no physical connection between the two sides. Grounds are separated, and all signals must pass through an isolation barrier. A transformer is used to couple the power output and digital isolators are used to pass through digital signals.

High power AC/DC converters create switching noise, which can interfere with the feedback signals needed to control the switching mechanism. To achieve higher tolerances and lower electromagnetic interference, current and voltage feedback signals can be measured on the battery pack side of the isolation barrier.

The AC/DC converter pulse width modulation controller can be analog, such as a PWM controller, or digital, such as an MCU or micro-controller. The feedback signals should be analog in case of a PWM controller and digital in case of an MCU or micro-controller.

This reference design is based on a circuit using automotive grade TI devices for measuring the output voltage and load current in an AC/DC converter. The circuit is designed for high precision and minimum noise across a wide voltage and current range. The immediate application is for HEV/EV battery pack chargers, also called “on board chargers”, up to 400-V and 10-A. Figure 1 shows the entire on board charger system. To the left of the isolation barrier is the AC/DC converter and controller; to the right is the load and feedback signals. The blue blocks show the elements of this TI Design.

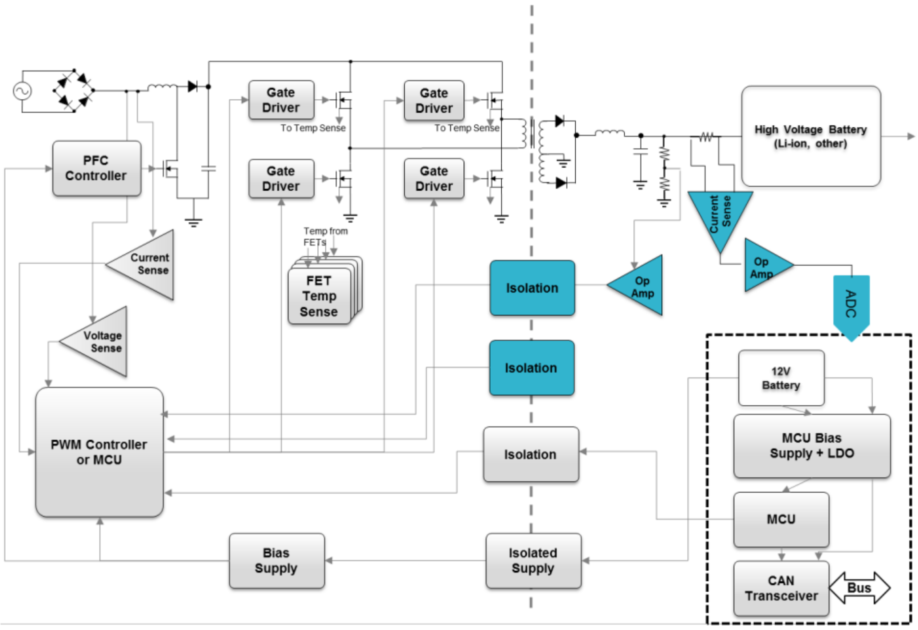


**Figure 1: Complete Analog On-Board Charger System**



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Current is measured on the high side by a simple circuit using the INA138-Q1. The INA138-Q1 delivers output current proportional to the sensed load current. The device common mode voltage is 40V but it can be much higher by floating the ground pin and buffering its output current with high voltage PNP transistor. Voltage is measured by a voltage divider and buffered using the TLC2272A-Q1 that has low offset voltage and 2.2 MHz of unity gain bandwidth.

Both current and voltage are converted from analog to digital by using an analog to digital converter (ADC) such as the ADS1115-Q1. The ADC must communicate back to the PWM controller or MCU on the AC/DC converter side, meaning that the digital signals of the I2C bus must pass the isolation barrier. Safety is achieved by isolating these digital signals with a digital isolator, the ISO7241C-Q1.

## 2.1 Current Measurement

In a charging system, load measurement is a key for charging optimization with high accuracy. Low side measurements can provide the accuracy but are not capable of detecting short to ground. High side measurements can achieve the accuracy and can detect short to ground; however, the high common mode voltage, up to 400-V, puts constraints on the design. With a few additional components around the current shunt, 400-V common mode voltage can be achieved with both accuracy and short to ground features.

The current shunt must be a current output (trans-conductance amplifier). The INA138-Q1 is the best candidate to achieve this function with minimal passive components. A pull down resistor on the INA138-Q1 output develops a voltage proportional to the sensed current; however, increasing the gain will decrease the bandwidth and increase the response time.

For maintaining adequate gain and response time, the output of the INA138-Q1 is cascaded to an op amp which boosts the gain without impacting the bandwidth. The op amp scales the voltage to the full scale input range of the ADC.

## 2.2 Voltage measurement

Measuring the 400V battery voltage requires a high impedance resistive voltage divider and a low output impedance buffer for conditioning the signal. The voltage divider ratio is on the order of 0.01 if the electronics circuit supply voltage is 5-V. To maintain the desired accuracy, a low offset, low input capacitance, and high impedance op amp is required.

Two op amps or a two channel op amp is needed to satisfy the current and voltage measurement requirements. The general purpose op amp TLC2272A-Q1 has two channels and meets the requirements for the voltage measurement feedback path. In addition, its bandwidth is 2.2 MHz which allows for a fast response time.

## 2.3 Analog to Digital Conversion

An ADC is necessary to convert the analog signals into digital. The digital signal is then sent to the microcontroller as feedback for the charging system. For the on-board charger application, two ADC channels are necessary, one for voltage and one for current.

The ADS1115-Q1 is a 16 bit ADC with two differential channels or four single-ended channels. Its integrated oscillator and reference simplifies the design and reduces external components. It has an I2C interface for communication with the microcontroller and can achieve the high accuracy required from the system. It also has an input voltage range from 2-V to 5.5-V, meaning that it can work in the 5-V system.



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The conversion rate is a maximum of 860 samples per second, meaning that a conversion occurs every 1.2µs. This helps achieve the less than 10 µs response time requirement.

### 2.4 4000-$V_{peak}$ Digital Isolation

Isolation is needed between the battery and the AC/DC power converter for safety and to remove switching noise from the battery side. High power isolation is achieved by using a transformer. For complete isolation, the control circuit needs to be isolated as well. In this design, the control circuit utilizes an I2C communication bus. A digital isolator is necessary to achieve this requirement.

The I2C bus requires two lines, but to use a digital isolator, an extra isolation channel is necessary for the SDA line since data is bidirectional. The ISO7241C-Q1 is a 4000-$V_{peak}$ quad-channel digital isolator with three channels going one direction and the fourth channel going in the opposite direction. If a fourth channel is needed in the system, either the ISO7241C-Q1 or the ISO7242C-Q1 could be used depending on the direction of the fourth channel. The ISO7242C-Q1 has two channels in each direction.

## 3 Block Diagram

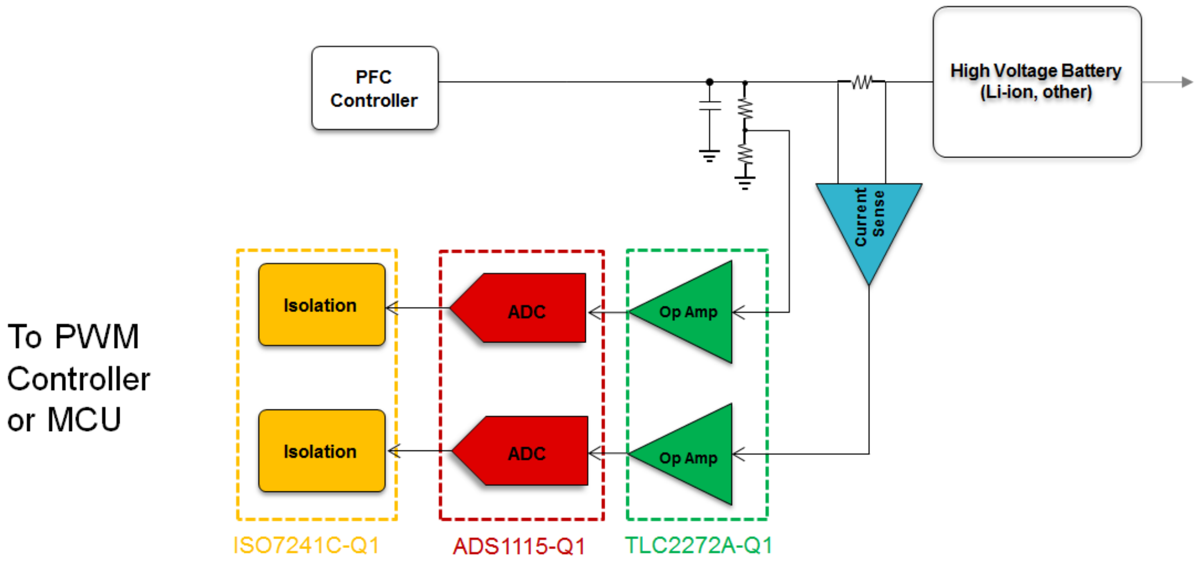


**Figure 2: On-Board Charger Load Feedback Subsystem**

### 3.1 Highlighted Products

The On-Board Charger Load Feedback Reference Design features the following devices:

- INA138-Q1: Automotive 36-V High-Side Current Output Current Shunt Monitor
- TLC2272A-Q1: Automotive Catalog Advanced LinCMOS™ Rail-to-Rail Operational Amplifier
- ADS1115-Q1: Automotive 16-Bit ADC with Integrated MUX, PGA, Comparator, Oscillator, and Reference
- ISO7241C-Q1: Automotive Catalog Quad, 4/0, 25 Mbps, Digital Isolator, Selectable Failsafe

For more information on each of these devices, see their respective product folders at ti.com.



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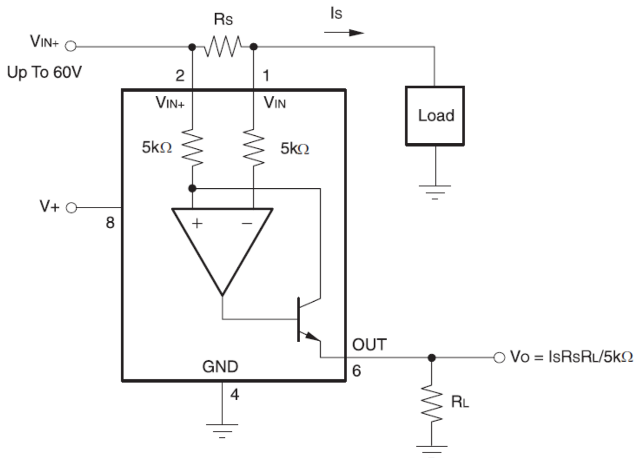
### 3.1.1 INA138-Q1

The INA138-Q1 is a high-side, unipolar, current shunt monitor. Wide input common-mode voltage range, low quiescent current, and tiny packaging enable uses in a variety of applications.

Input common-mode and power-supply voltages are independent and can range from 2.7-V to 36-V for the INA138-Q1. Quiescent current is only 25 µA, which permits connecting the power supply to either side of the current-measurement shunt with minimal error.

The device converts a differential input voltage to a current output. The current is converted back to a voltage with an external load resistor that sets any gain from 1 to over 100. Although designed for current shunt measurement, the circuit invites creating applications in measurement and level shifting.

The INA138-Q1 is available in TSSOP-8 and is specified for the -40°C to 125°C temperature range.




Features:

- **Qualified For Automotive Applications**
- ESD Protection Exceeds 2000-V Per MIL-STD-883, Method 3015; Exceeds 200-V Using Machine Model (C = 200 pF, R = 0)
- **Complete Unipolar High-Side Current-Measurement Circuit**
- **Wide Supply And Common-Mode Range: 2.7-V to 36-V**
- **Independent Supply and Input Common-Mode Voltages**
- **Single Resistor Gain Set**
- **Low Quiescent Current (25-µA Typical)**
- Wide Temperature Range: –40°C to 125°C



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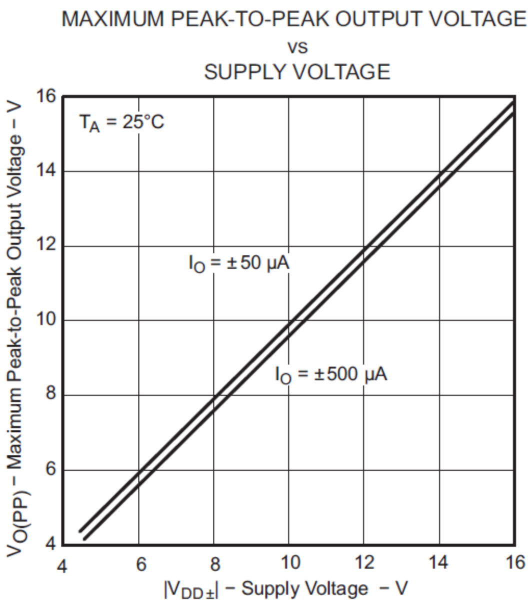
### 3.1.2 TLC2272A-Q1

The TLC2272A-Q1 is a dual operational amplifier from Texas Instruments. The device exhibits rail-to-rail output performance for increased dynamic range in single or split-supply applications. The TLC2272A-Q1 offers 2MHz of bandwidth and 3 V/µs of slew rate for higher speed applications. This device offers comparable AC performance while having better noise, input offset voltage, and power dissipation than existing CMOS operational amplifiers. The TLC2272A-Q1 has a noise voltage of 9 nV/√Hz.

The TLC2272A-Q1, exhibiting high input impedance and low noise, is excellent for small-signal conditional for high-impedance sources, such as piezoelectric transducers. In addition, the rail-to-rail output feature, with single- or split-supplies, makes this device a great choice when interfacing with analog-to-digital converters (ADCs). For precision applications, then TLC2272A-Q1 is available with a maximum input offset voltage of 950-µV. This device is fully characterized at 5-V and ±5-V.

The TLC2272A-Q1 offers increased output dynamic range lower noise voltage, and lower input offset voltage. This enhance feature set allows the device to be used in a wider range of applications.




Features:

- **Qualified for Automotive Applications**
- **Output Swing Includes Both Supply Rails**
- Low Noise . . . 9 nV/√Hz Typ at f = 1 kHz
- **Low Input Bias Current . . . 1-pA Typ**
- Fully Specified for Both **Single-Supply** and Split-Supply Operation
- Common-Mode Input Voltage Range Includes Negative Rail
- **High-Gain Bandwidth . . . 2.2 MHz Typ**
- High Slew Rate . . . 3.6 V/µs Typ
- **Low Input Offset Voltage . . . 950-µV Max at TA = 25°C**
- **Low common-mode input capacitance . . . 8pF Typ**
- –40°C to 125°C Operating Range



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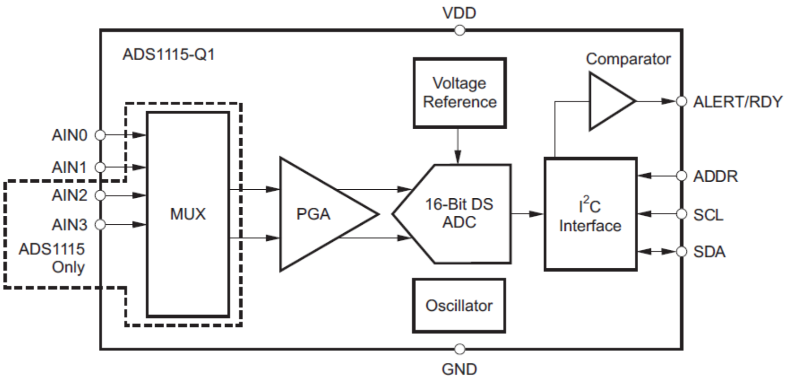
### 3.1.3 ADS1115-Q1

The ADS1115-Q1 device is a precision analog-to-digital converter (ADCs) with 16 bits of resolution offered in a VSSOP-10 package. The ADS1115-Q1 is designed with precision, power, and ease of implementation in mind. The ADS1115-Q1 features an onboard reference and oscillator. Data are transferred via an I$^2$C-compatible serial interface; four I$^2$C slave addresses can be selected. The ADS1115-Q1 operates from a single power supply ranging from 2-V to 5.5-V.

The ADS1115-Q1 can perform conversions at rates up to 860 samples per second (SPS). An onboard PGA is available on the ADS1115 that offers input ranges from the supply to as low as ±256-mV, allowing both large and small signals to be measured with high resolution. The ADS1115-Q1 also features an input multiplexer (MUX) that provides two differential inputs or four single-ended inputs.

The ADS1115-Q1 operates either in continuous conversion mode or a single-shot mode that automatically powers down after a conversion and greatly reduces current consumption during periods. The ADS1115-Q1 is specified from -40°C to 125°C.

**ADS1115-Q1 Block Diagram**




Features:

- **Wide Supply Range: 2-V to 5.5-V**
- Low Current Consumption:
  - Continuous Mode: Only 150-µA
  - Single-Shot Mode: Auto Shut-Down
- Programmable Data Rate: 8 SPS **to 860 SPS**
- **Internal Low-Drift Voltage Reference**
- **Internal Oscillator**
- Internal PGA
- I2C Interface: Pin-Selectable Addresses
- **Four Single-Ended or Two Differential Inputs**
- Programmable Comparator



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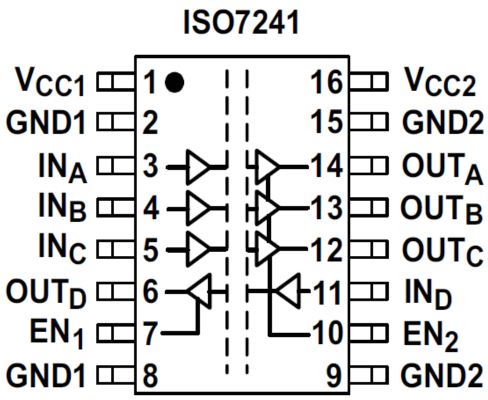
### 3.1.4 ISO7241C-Q1

The ISO7241C-Q1 is a quad-channel digital isolator with multiple channel configurations and output enable functions. These devices have logic input and output buffers separated by TI's silicon dioxide ($SiO_2$) isolation barrier. Used in conjunction with isolated power supplies, these devices block high voltage, isolate grounds, and prevent noise currents from entering the local ground and interfering with or damaging sensitive circuitry.

The ISO7241C-Q1 has all four channels in the same direction. It also has TTL input threshold and a noise-filter at the input that prevents transient pulses from being passed to the output of the device. The ISO7241C-Q1 has an input disable function on pin 7, and a selectable high or low failsafe-output function with the CTRL pin (pin 10). The failsafe-output is a logic-high when a logic-high is placed on the CTRL pin or when it is left unconnected. If a logic-low signal is applied to the CTRL pin, the failsafe-output becomes a logic-low output state. This device input disable function prevents data from being passed across the isolation barrier to the output. When the inputs are disabled, the outputs are set by the CTRL pins.

This device may be powered from either 3.3-V or 5-V supplies on either side in any 3.3-V/3.3-V, 5-V/5-V, 5-V 3.3-V, or 3.3-V/ 5-V combination. Note that the signal input pins are 5-V tolerant regardless of the voltage supply level being used.

The ISO7241C-Q1 is characterized for operation over the ambient temperature range of -40°C to 125°C.




Features:

- **Qualified for Automotive Applications**
- Selectable Failsafe Output
- 25 and 150-Mbps Signaling Rate Options
  - **Low Channel-to-Channel Output Skew; 1 ns Max**
  - Low Pulse-Width Distortion (PWD); 2 ns Max
  - **Low Jitter Content; 1 ns Typ at 150 Mbps**
- Typical 25-Year Life at Rated Working Voltage
- **4000-Vpeak Isolation, 560-Vpeak VIORM**
  - **UL 1577 , IEC 60747-5-2 (VDE 0884, Rev 2), IEC 61010-1, IEC 60950-1 and CSA Approved**
- 4 kV ESD Protection
- **Operate With 3.3-V or 5-V Supplies**
- **High Electromagnetic Immunity**
- –40°C to 125°C Operating Range



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# 4 System Design Theory

## 4.1 Current Monitoring

The INA138-Q1 output current can be buffered with a high voltage bipolar PNP transistor for common mode voltages up to 400-V. Figure 3Figure 3: Schematic of INA138-Q1 in a High Common Mode Voltage Application shows the circuit for high common mode voltage current sensing. VOUT is connected to the op amp input to boost the gain by 2.

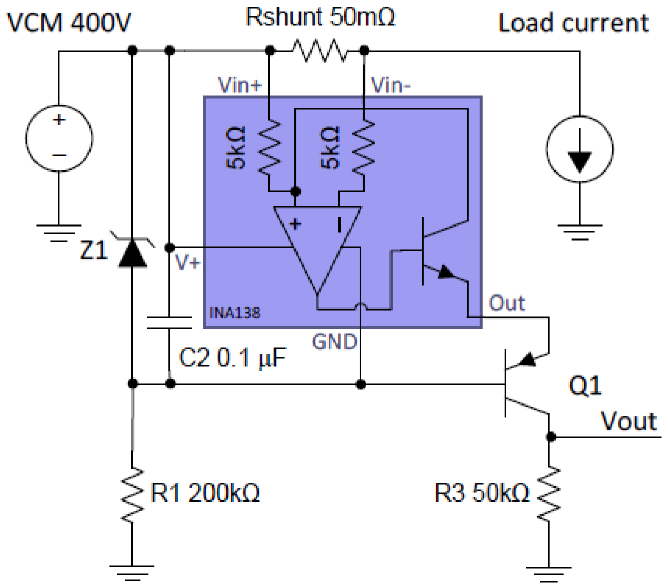


**Figure 3: Schematic of INA138-Q1 in a High Common Mode Voltage Application**

The ideal output equation is shown below. In the equation, $g_m$ is the transconductance gain of the current shunt monitor, $R_L$ is the pull-down resistor (R3 in Figure 3), $R_S$ is the shunt resistor, and $I_S$ is the load current.

$$VOUT = g_m * R_L * R_S * I_S$$

$$VOUT = 200\left(\frac{\mu A}{V}\right) * 50k\Omega * 10m\Omega * I_S$$

$$VOUT(V) = 0.1\left(\frac{V}{A}\right) * Is(A)$$

The INA138-Q1 gain can be increased with the pull down resistor; however, this also decreases the bandwidth. With a pull-down resistor of 50kΩ, the device bandwidth is 100 kHz which gives a response time of 3.5µS. For increasing the current measurement gain and without impacting the bandwidth, an op amp with a gain of 2 is cascaded with the INA138-Q1. This sets the overall current measurement gain to

$$VOUT(V) = 0.2\left(\frac{V}{A}\right) * Is(A)$$

For more details about how to use the INA138-Q1, refer to TIDA-00332, which is a reference design that discusses how to use the INA138-Q1 in a high common mode voltage application.



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## 4.2 Voltage Monitoring

The battery voltage must first be scaled down through a resistive divider to the full scale range of the ADC. Then a buffer is used to drive the ADC. Figure 4 shows the circuit used to condition the battery voltage signal.

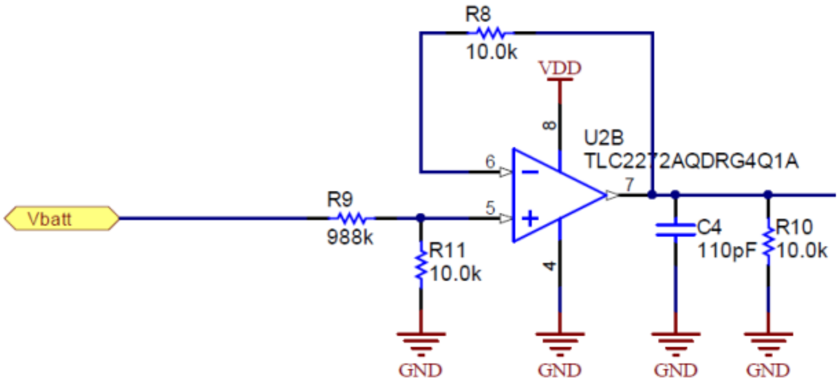


**Figure 4: Battery Voltage Measurement Circuit**

The full scale input range of the ADC is 4.096-V, so this circuit was designed so that at 400-V, the ADC input would be 4.0V. This requires scaling down the voltage by a factor of 100.

$$VIN = V_{BATT} * \frac{R11}{R9 + R11}$$
$$VIN = V_{BATT} * \frac{10k}{988k + 10k}$$
$$VIN = 0.01 * V_{BATT}$$

## 4.3 Control signals

The measured current and voltage signals are available in both analog and digital forms. This design assumes that a digital control mechanism is used; however, analog signals can be used as feedback if an analog PWM controller is used.

The ADS1115-Q1 can be configured for two differential or four single-ended inputs. In this application, the ADC is configured for two single-ended inputs.

The full scale input voltage of the ADS1115-Q1 changes depending on the programmable gain amplifier (PGA) setting, as shown in Table 2. For this design, the input range of 4.096-V is used, meaning that the PGA should be set to a gain of 1. If the maximum input signal amplitude is lower, then a different PGA setting can be selected.

**Table 2: ADS1115-Q1 Full Scale Range for PGA Settings**

| PGA Setting | Full-Scale Range (V) |
|---|---|
| 2/3 | ±6.144 |
| 1 | ±4.096 |
| 2 | ±2.048 |
| 4 | ±1.024 |
| 8 | ±0.512 |
| 16 | ±0.256 |



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The ADS1115-Q1 communicates over an I2C bus. It is capable of operating down to 2-V; however, for this design, 5-V rails are used, meaning that the I2C interface operates at 5-V TTL levels.

## 4.4 Isolation

Three of the four isolation channels on the ISO7241C-Q1 are used for I2C. Two channels are needed for SDA and one for SCL. Digital isolators are designed with unidirectional communication in mind, so configuring an isolator for a bidirectional digital line requires extra external components.

Figure 5 shows the external circuitry required for bidirectional communication through a digital isolator. The SDA line is split into two separate receive and transmit paths. The two Shottky diodes convert the push-pull outputs of the ISO7241C-Q1 into open-collector outputs. Transistor Q1 serves as a comparator that stops the transmitting signal from feeding back through the other channel. Application note SLYT403 explains this circuit in detail.

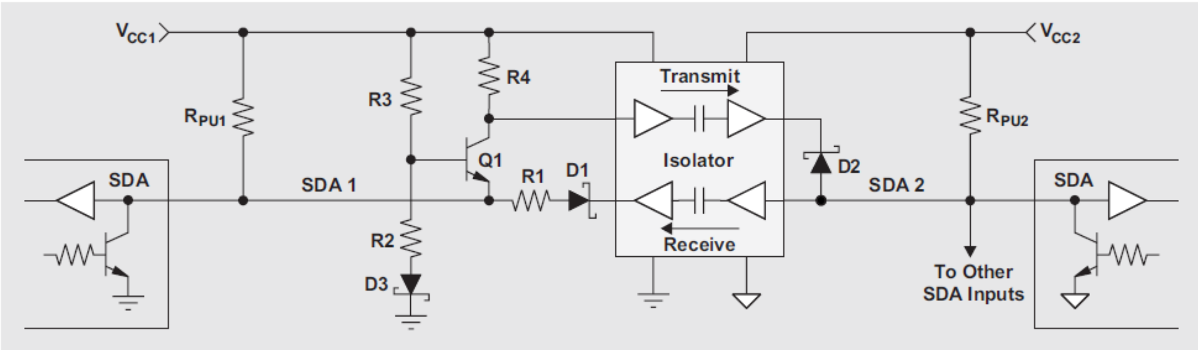


**Figure 5: Bidirectional Communication with Digital Isolator**

The SCL line is unidirectional, so it does not require extra components beyond the pull-up resistor.

The ISO7241C-Q1 can operate in 5-V or 3.3-V environments. It can also serve as a level translator with one side biased to 5-V and the other to 3.3-V.



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## 5 Test Setup

Refer to Figure 6 for a diagram of the test set-up.

**Equipment:**

- Two isolated power supplies set to 5-V
- One high voltage power source, up to 400-V
- 1 to 10-A electronic load that is 400-V tolerant or use a dummy load
- 2 digital multimeters
- 2 channel oscilloscope
- I2C controller

**Set-Up**

- Primary supply voltage VDD = 5-V, apply across J3, pins 1 and 2
- Secondary supply voltage VDD_Mstr = 5-V, apply across J8, pins 1 and 4
- High voltage 160 to 400-VDC applied between J4 and J1 connector (positive on J4)
- Load current 0 to 10-A pulled from J5 and J2

**Analog signals:**

- The charging current analog output is measured at pin 1 of connector J7
- The battery voltage analog output is measured at pin 3 of connector J7

**Digital signals:**

- Communicate with ADS1115-Q1 by connecting I2C controller to J8.
    - Pin 2: SCL
    - Pin 3: SDA
    - Pin 4: GND

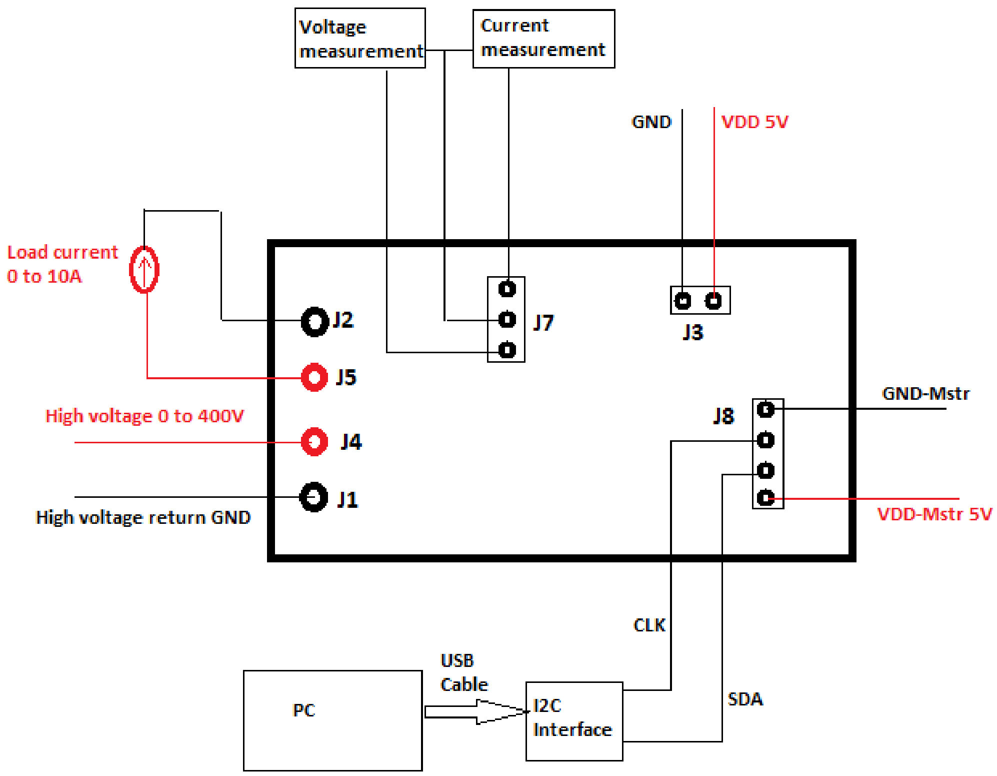


**Figure 6: Test Set-up for TIDA-00456**



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## 6 Test Data

Analog and digital data was collected according to the test setup. The analog data was measured with voltage meters connected to the outputs of the TLC2272A-Q1. The digital data was collected from the ADS1115-Q1 over the I2C bus. The numerical value shown in the "Digital Data" column is the average of the collected samples. The "Digital Ideal" values in the table were calculated with the following equation, where VIN is from the "Analog Ideal" column:

$$ADC\ Code = V_{IN} * \frac{2^{15}}{4.096}$$

The "Analog Error" column shows the error only in the analog signal path. The "Digital Error" column shows the total system error. The error equation is as follows:

$$Error(\%) = \frac{Ideal\ value - Measured\ value}{Ideal\ value} * 100$$

The ideal vs actual data shows a maximum error of only 2.5% for all test cases. At 0-A load current, the error is not calculated because it is only the device offset and mathematically cannot be calculated because the denominator is zero.



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## 6.1 Load current data collection

**Table 3: Analog and Digital Data vs. Load Current from 0 to 10A at 160V Battery Voltage**

| Load current (A) | Analog data (V) | Analog ideal (V) | Digital data | Digital Ideal | Analog Error versus Ideal (%) | Digital Error versus Ideal (%) |
|---|---|---|---|---|---|---|
| **0** | 0.006 | 0 | 7 | 0 | NA | NA |
| **1** | 0.195 | 0.2 | 1564 | 1600 | 2.5 | 2.25 |
| **2** | 0.394 | 0.4 | 3153 | 3200 | 1.5 | 1.46875 |
| **3** | 0.592 | 0.6 | 4740 | 4800 | 1.3333333 | 1.25 |
| **4** | 0.791 | 0.8 | 6335 | 6400 | 1.125 | 1.015625 |
| **5** | 0.989 | 1 | 7912 | 8000 | 1.1 | 1.1 |
| **6** | 1.187 | 1.2 | 9503 | 9600 | 1.0833333 | 1.010417 |
| **7** | 1.385 | 1.4 | 11109 | 11200 | 1.0714286 | 0.8125 |
| **8** | 1.585 | 1.6 | 12690 | 12800 | 0.9375 | 0.859375 |
| **9** | 1.783 | 1.8 | 14277 | 14400 | 0.9444444 | 0.854167 |
| **10** | 1.981 | 2 | 15857 | 16000 | 0.95 | 0.89375 |

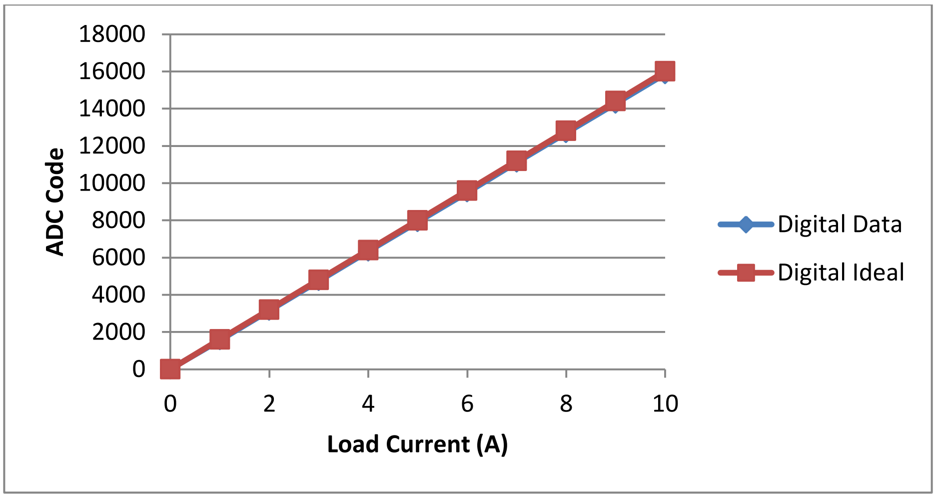


**Figure 7: Digital Data and Digital Ideal versus Load Current, Battery Voltage = 160V**

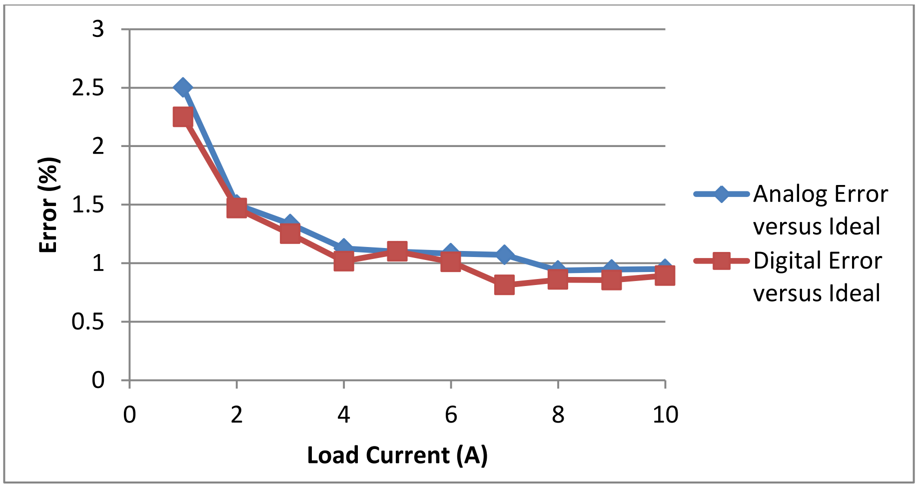


**Figure 8: Analog and Digital Error vs Load Current, Battery Voltage = 160V**



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**Table 4: Analog and Digital Data vs. Load Current from 0 to 10A at 400V Battery Voltage**

| Load current (A) | Analog data (V) | Analog ideal (V) | Digital data | Digital Ideal | Analog Error versus Ideal (%) | Digital Error versus Ideal (%) |
|---|---|---|---|---|---|---|
| **0** | 0.009 | 0 | 42 | 0 | | |
| **1** | 0.195 | 0.2 | 1566 | 1600 | 2.5 | 2.125 |
| **2** | 0.394 | 0.4 | 3162 | 3200 | 1.5 | 1.1875 |
| **3** | 0.593 | 0.6 | 4763 | 4800 | 1.1666667 | 0.770833 |
| **4** | 0.791 | 0.8 | 6354 | 6400 | 1.125 | 0.71875 |
| **5** | 0.99 | 1 | 7923 | 8000 | 1 | 0.9625 |
| **6** | 1.19 | 1.2 | 9521 | 9600 | 0.8333333 | 0.822917 |
| **7** | 1.388 | 1.4 | 11129 | 11200 | 0.8571429 | 0.633929 |
| **8** | 1.585 | 1.6 | 12706 | 12800 | 0.9375 | 0.734375 |
| **9** | 1.785 | 1.8 | 14300 | 14400 | 0.8333333 | 0.694444 |
| **10** | 1.985 | 2 | 15874 | 16000 | 0.75 | 0.7875 |

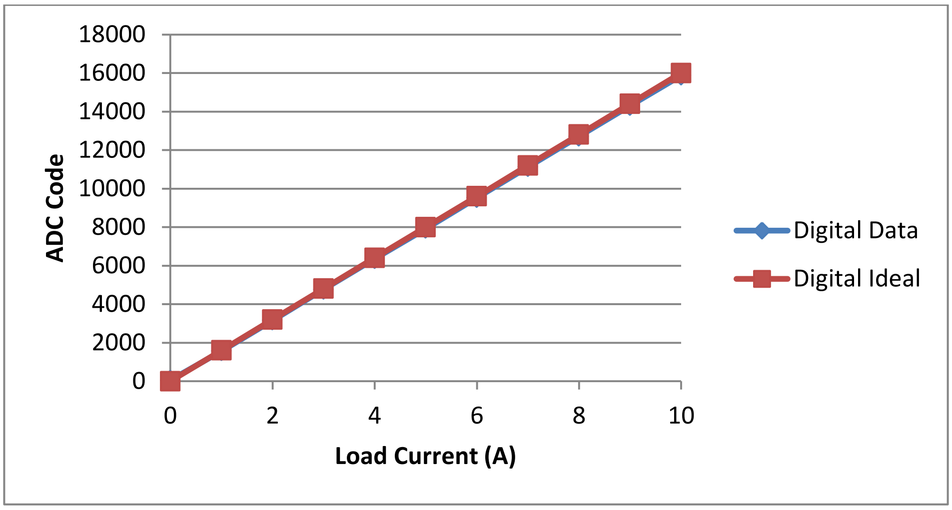


**Figure 9: Digital Data and Digital Ideal versus Load Current, Battery Voltage = 400V**

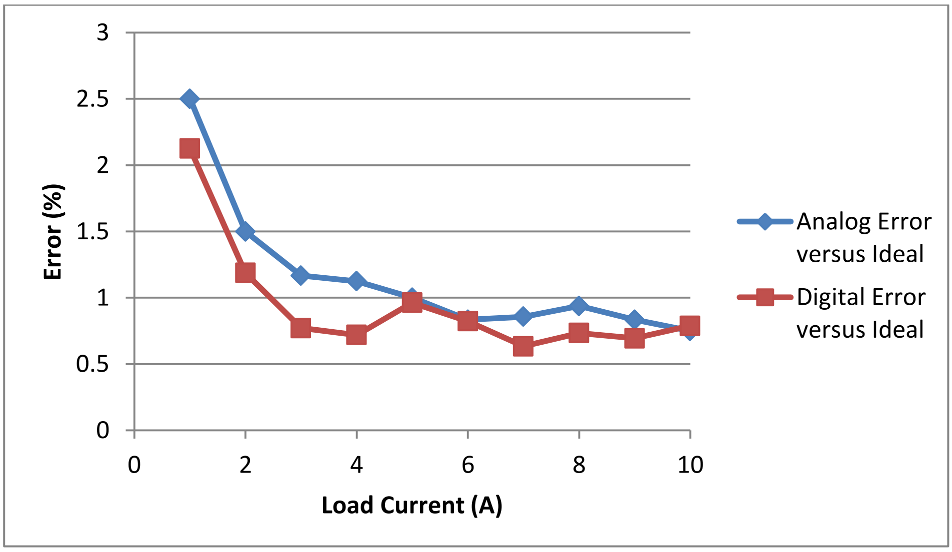


**Figure 10: Analog and Digital Error vs Load Current, Battery Voltage = 400V**



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## 6.2 Voltage data collection

**Table 5: Analog and Digital Data vs. Load Current from 0 to 10A at 400V Battery Voltage**

| Battery Voltage (V) | Analog data (V) | Analog ideal (V) | Digital data | Digital Ideal | Analog Error versus Ideal (%) | Digital Error versus Ideal (%) |
|---|---|---|---|---|---|---|
| **160** | 1.624 | 1.623 | 13012 | 12984 | | |
| **180** | 1.827 | 1.825 | 14637 | 14600 | -0.109589041 | -0.253424658 |
| **200** | 2.03 | 2.028 | 16240 | 16224 | -0.098619329 | -0.098619329 |
| **220** | 2.233 | 2.231 | 17925 | 17848 | -0.089645899 | -0.431420887 |
| **240** | 2.436 | 2.434 | 19539 | 19472 | -0.082169269 | -0.344083813 |
| **260** | 2.639 | 2.637 | 21183 | 21096 | -0.075843762 | -0.412400455 |
| **280** | 2.842 | 2.84 | 22812 | 22720 | -0.070422535 | -0.404929577 |
| **300** | 3.044 | 3.042 | 24396 | 24336 | -0.06574622 | -0.246548323 |
| **320** | 3.248 | 3.245 | 26022 | 25960 | -0.092449923 | -0.238828968 |
| **340** | 3.451 | 3.448 | 27622 | 27584 | -0.087006961 | -0.137761021 |
| **360** | 3.654 | 3.651 | 29250 | 29208 | -0.082169269 | -0.14379622 |
| **380** | 3.856 | 3.854 | 30863 | 30832 | -0.051894136 | -0.100544888 |
| **400** | 4.06 | 4.057 | 32484 | 32456 | -0.073946266 | -0.086270643 |

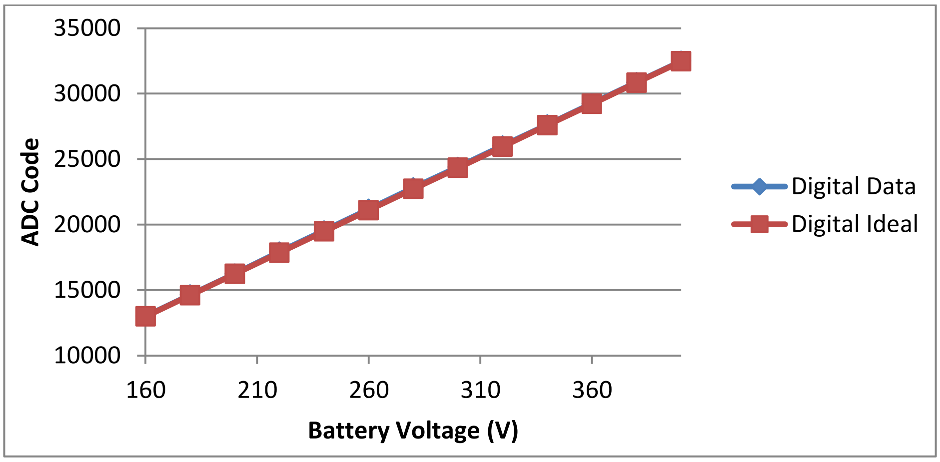


**Figure 11: Digital Data and Digital Ideal versus Battery Voltage**

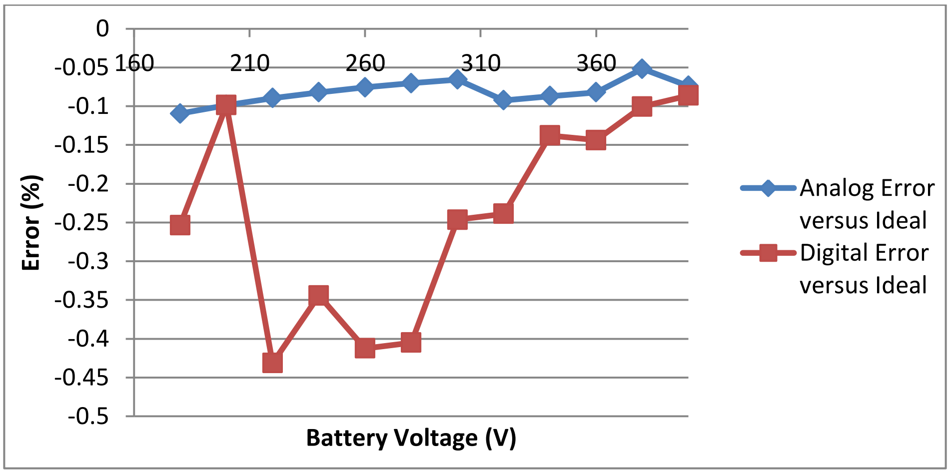


**Figure 12: Analog and Digital Error vs Battery Voltage**



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## 6.3 Load step response time

The goal is to achieve less than 10µS response time. Between the voltage and current measurements, the current measurement has the worst response time because it is limited by the bandwidth of the current shunt monitor; however, data shows that the current measurement response time is less than 2µS, which is within the design requirements.

In the figures below, scope channel 1 (yellow) is the current measurement output and channel 2 (blue) is the load current. Current scale is by 100. Figure 13 shows a load step response time of 1.84µs when jumping from 4-A to 6-A. Figure 14 shows a load step response time of 1.76µs when jumping from 6-A to 4-A.

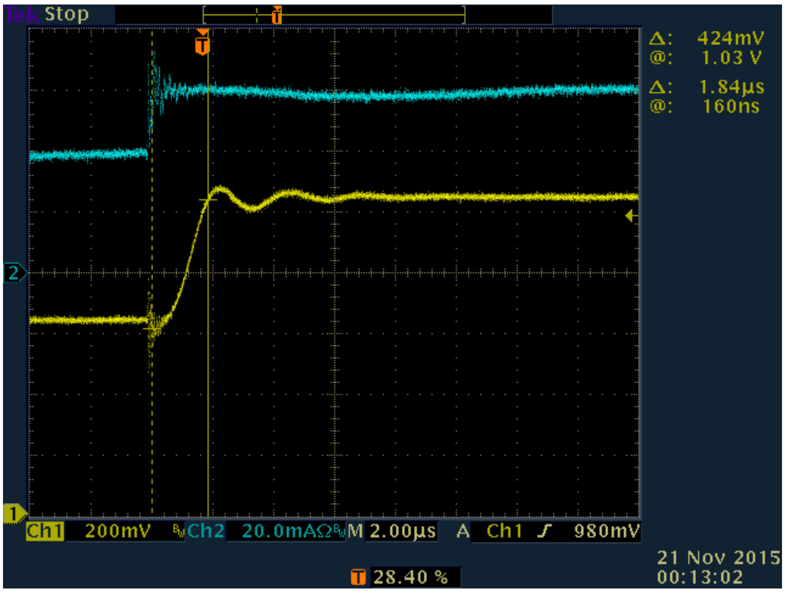


**Figure 13: 4A to 6A Load Step Response Time**

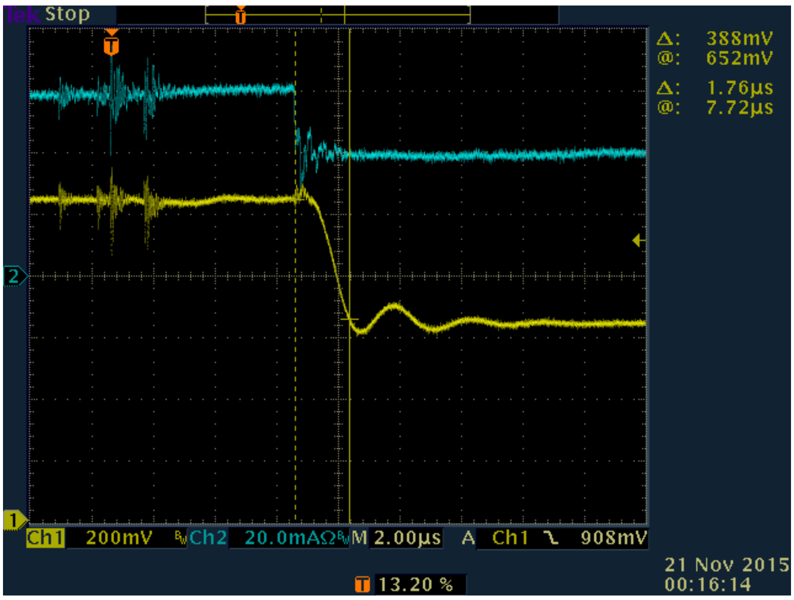


**Figure 14: 6A to 4A Load Step Response Time**



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# 7 Design Files

## 7.1 Schematics

To download the Schematics for each board, see the design files at http://www.ti.com/tool/TIDA-00456.

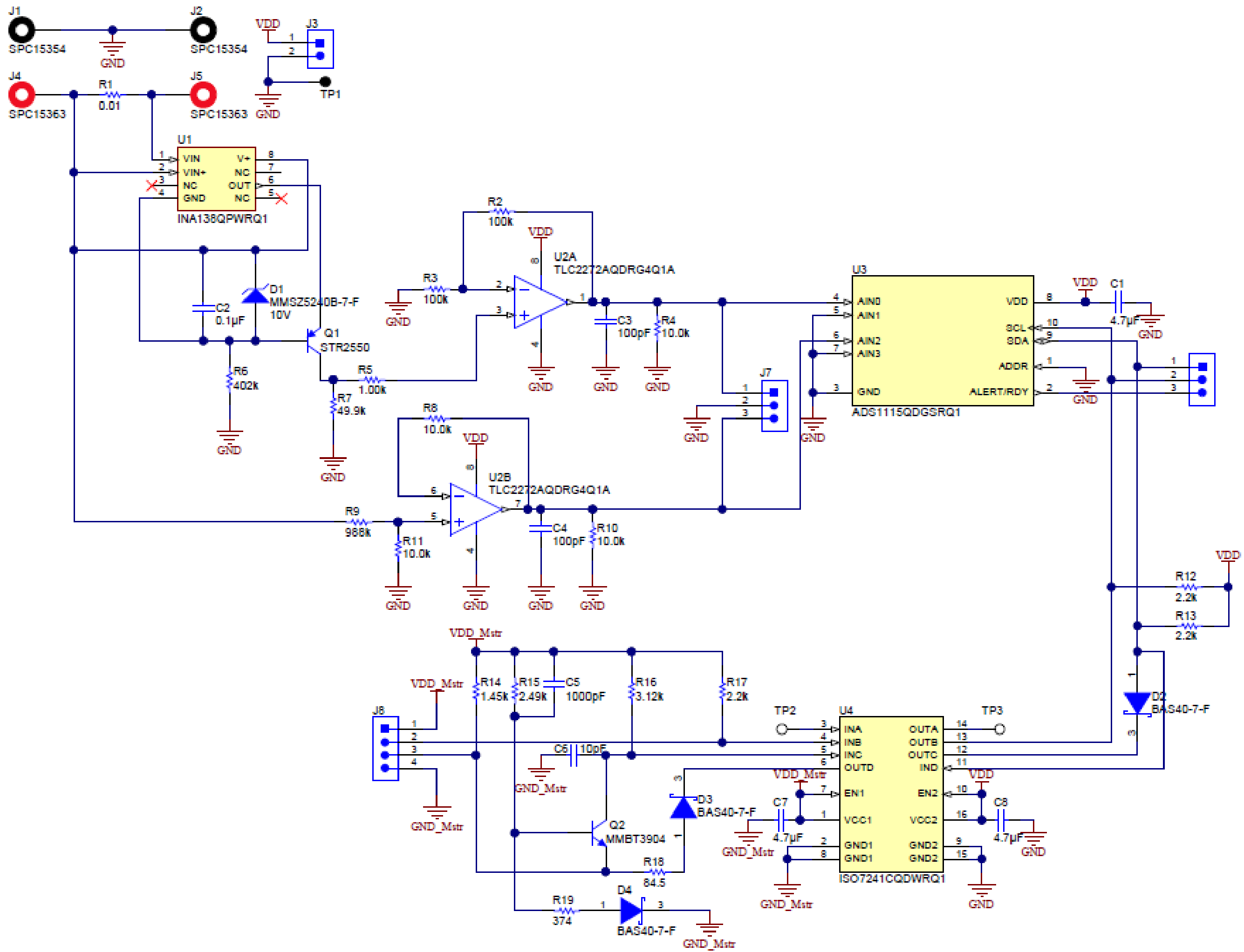

**Figure 15: Schematic of TIDA-00456**



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## 7.2 Bill of Materials

To download the Bill of Materials for each board, see the design files at http://www.ti.com/tool/TIDA-00456.

**Table 6: Bill of Materials of TIDA-00456**

| Item # | Designator | Quantity | Value | Part Number | Manufacturer | Description | Package Reference |
|---|---|---|---|---|---|---|---|
| 1 | C1, C7, C8 | 3 | 4.7uF | GRM188R61A475ME15 | MuRata | CAP, CERM, 4.7 µF, 10 V, +/- 20%, X5R, 0603 | 0603 |
| 2 | C2 | 1 | 0.1uF | VJ1812Y104KXEAT5Z | Vishay-Vitramon | CAP, CERM, 0.1 µF, 500 V, +/- 10%, X7R, 1812 | 1812 |
| 3 | C3, C4 | 2 | 100pF | GRM033R71C101KA01D | MuRata | CAP, CERM, 100 pF, 16 V, +/- 10%, X7R, 0201 | 0201 |
| 4 | C5 | 1 | 1000pF | 885012206034 | Wurth Elektronik | CAP, CERM, 1000 pF, 16 V, +/- 10%, X7R, 0603 | 0603 |
| 5 | C6 | 1 | 10pF | C0805C100J5GACTU | Kemet | CAP, CERM, 10 pF, 50 V, +/- 5%, C0G/NP0, 0805 | 0805 |
| 6 | D1 | 1 | 10V | MMSZ5240B-7-F | Diodes Inc. | Diode, Zener, 10 V, 500 mW, SOD-123 | SOD-123 |
| 7 | D2, D3, D4 | 3 | 40V | BAS40-7-F | Diodes Inc. | Diode, Schottky, 40 V, 0.2 A, SOT-23 | SOT-23 |
| 8 | J1, J2 | 2 | | SPC15354 | Tenma | BANANA JACK, SOLDER LUG, BLACK, TH | Black Insulated Banana Jack |
| 9 | J3 | 1 | | TSW-102-07-G-S | Samtec | Header, 100mil, 2x1, Gold, TH | 2x1 Header |
| 10 | J4, J5 | 2 | | SPC15363 | Tenma | BANANA JACK, SOLDER LUG, RED, TH | Red Insulated Banana Jack |
| 11 | J6, J7 | 2 | | TSW-103-07-G-S | Samtec | Header, 100mil, 3x1, Gold, TH | 3x1 Header |
| 12 | J8 | 1 | | TSW-104-07-G-S | Samtec | Header, 100mil, 4x1, Gold, TH | 4x1 Header |
| 13 | Q1 | 1 | | STR2550 | Used in BOM report | Transistor, NPN, xxV, xA, [PackageReference] | Used in PnP output and some BOM reports |
| 14 | Q2 | 1 | | MMBT3904 | Used in BOM report | Transistor, NPN, xxV, xA, [PackageReference] | Used in PnP output and some BOM reports |
| 15 | R1 | 1 | 0.01 | PMR50HZPFU10L0 | Rohm | RES, 0.01, 1%, 1 W, 2010 | 2010 |
| 16 | R2, R3 | 2 | 100k | CRCW0805100KFKEA | Vishay-Dale | RES, 100 k, 1%, 0.125 W, 0805 | 0805 |
| 17 | R4, R8, R10, R11 | 4 | 10.0k | RT0805BRD0710KL | Yageo America | RES, 10.0 k, 0.1%, 0.125 W, 0805 | 0805 |
| 18 | R5 | 1 | 1.00k | ERJ-P06F1001V | Panasonic | RES, 1.00 k, 1%, 0.25 W, 0805 | 0805 |
| 19 | R6 | 1 | 402k | ERJ-8ENF4023V | Panasonic | RES, 402 k, 1%, 0.25 W, 1206 | 1206 |
| 20 | R7 | 1 | 49.9k | RG2012P-4992-B-T5 | Susumu Co Ltd | RES, 49.9 k, 0.1%, 0.125 W, 0805 | 0805 |
| 21 | R9 | 1 | 988k | RT0805BRD07988KL | Yageo America | RES, 988 k, 0.1%, 0.125 W, 0805 | 0805 |
| 22 | R12, R13, R17 | 3 | 2.2k | CRCW08052K20JNEA | Vishay-Dale | RES, 2.2 k, 5%, 0.125 W, 0805 | 0805 |
| 23 | R14 | 1 | 1.45k | RT0805BRD071K45L | Yageo America | RES, 1.45 k, 0.1%, 0.125 W, 0805 | 0805 |
| 24 | R15 | 1 | 2.49k | CRCW08052K49FKEA | Vishay-Dale | RES, 2.49 k, 1%, 0.125 W, 0805 | 0805 |



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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 25 | R16 | 1 | 3.12k | RT0805BRD073K12L | Yageo America | RES, 3.12 k, 0.1%, 0.125 W, 0805 | 0805 |
| 26 | R18 | 1 | 84.5 | CRCW080584R5FKEA | Vishay-Dale | RES, 84.5, 1%, 0.125 W, 0805 | 0805 |
| 27 | R19 | 1 | 374 | CRCW0805374RFKEA | Vishay-Dale | RES, 374, 1%, 0.125 W, 0805 | 0805 |
| 28 | TP1 | 1 | Black | 5001 | Keystone | Test Point, Miniature, Black, TH | Black Miniature Testpoint |
| 29 | TP2, TP3 | 2 | White | 5002 | Keystone | Test Point, Miniature, White, TH | White Miniature Testpoint |
| 30 | U1 | 1 | | INA138QPWRQ1 | Used in BOM report | | eg: 0603, used in PnP report |
| 31 | U2 | 1 | | TLC2272AQDRG4Q1A | Texas Instruments | Automotive Catalog Advanced LinCMOS(TM) Rail-to-Rail Operational Amplifier, 4.4 to 16 V, -40 to 125 degC, 8-pin SOIC (D0008A), Green (RoHS & no Sb/Br) | D0008A |
| 32 | U3 | 1 | | ADS1115QDGSRQ1 | Texas Instruments | Ultra-Small, Low-Power, 16-Bit Analog-to-Digital Converter with Internal Reference, DGS0010A | DGS0010A |
| 33 | U4 | 1 | | ISO7241CQDWRQ1 | Texas Instruments | 25 Mbps Automotive Catalog Quad Channels, 3 / 1, Digital Isolator, 3.3 V / 5 V, -40 to +125 degC, 16-pin SOIC (DW), Green (RoHS & no Sb/Br) | DW0016A |



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## 7.3 PCB Layout Recommendations

- A 2-layer board is enough for this design.
- Decoupling capacitors should be placed as close as possible to the devices' supply pins and ground pins
- Avoid ground loop for TLC2272A-Q1, ADC1115-Q1 and the primary side of ISO7241C-Q1.
- Avoid ground loop for ISO7241C-Q1 secondary side and its surrounding components.
- Connect the INA138-Q1 inputs directly to the sense resistor ends for avoiding voltage drop across the high current traces.
- Keep adequate spaces between the high voltage and low voltage nodes.



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### 7.3.1 Layout Prints

To download the Layout Prints for each board, see the design files at http://www.ti.com/tool/TIDA-00456.

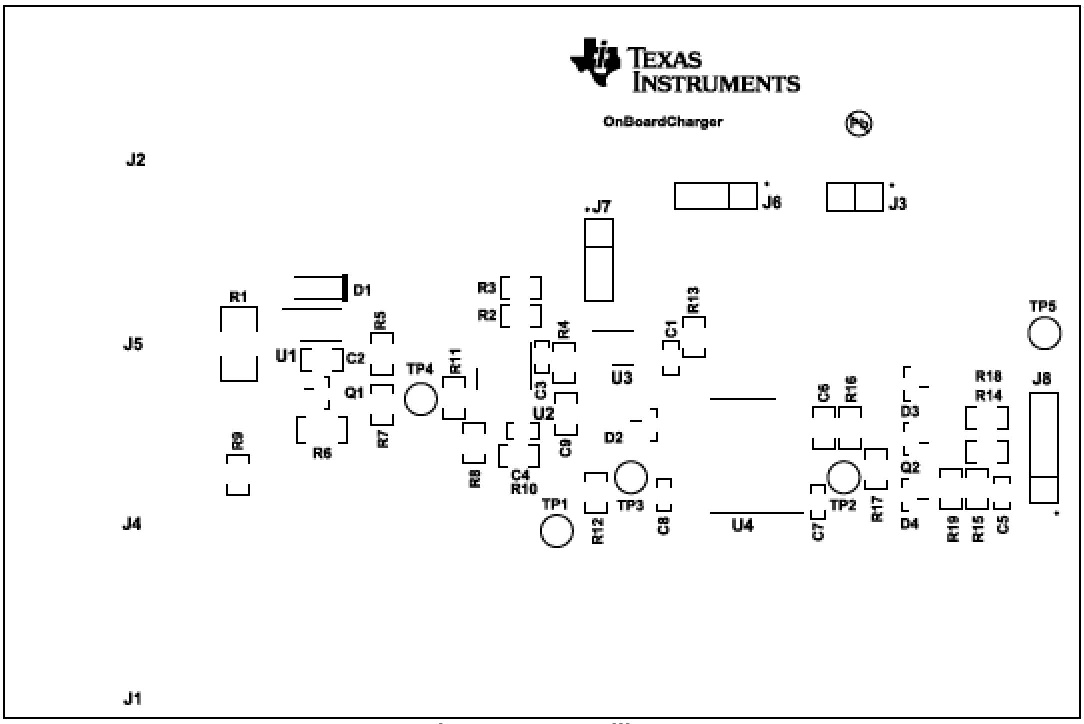

Figure 16: Top Silkscreen

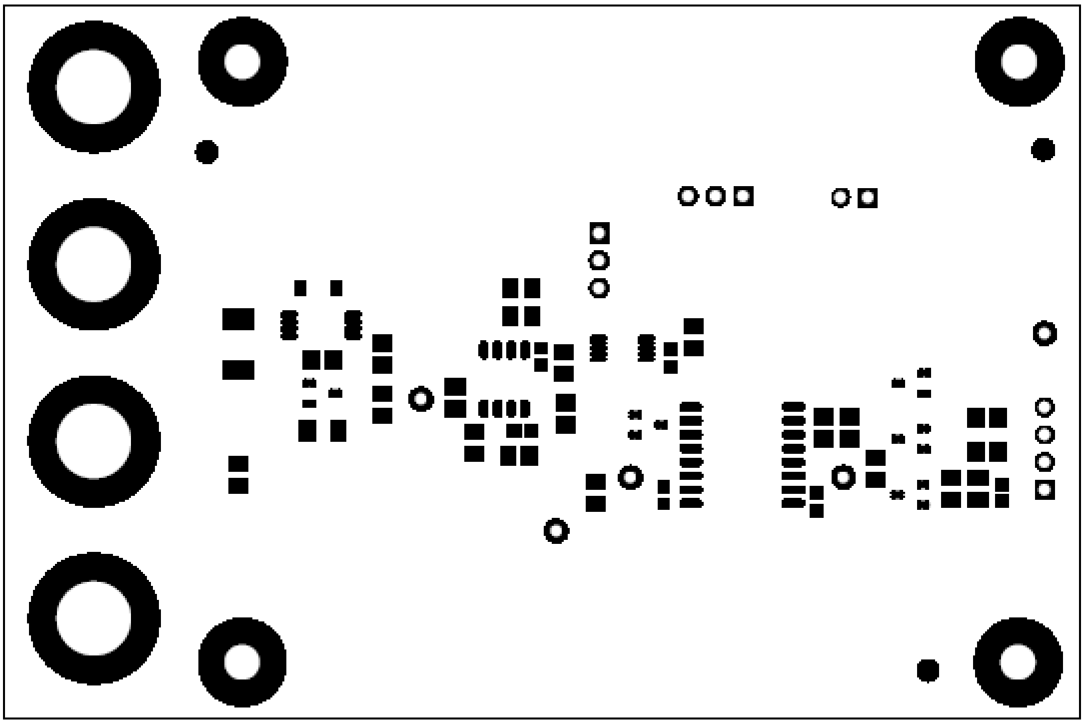
Figure 17: Top Solder Mask



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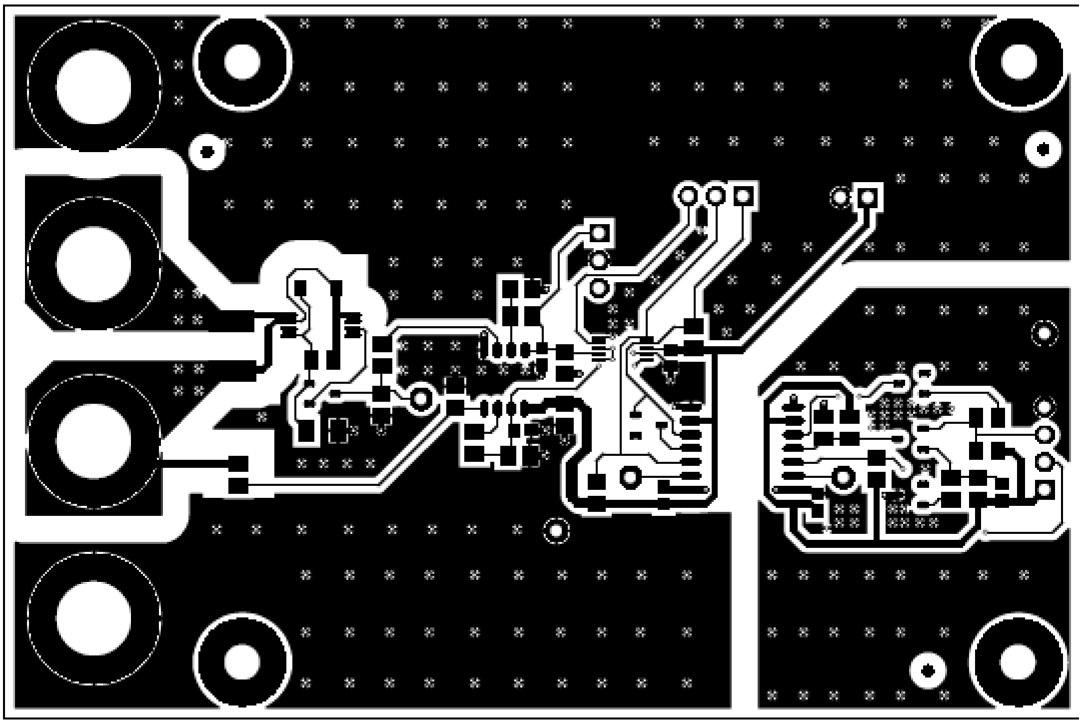

**Figure 18: Top Layer**

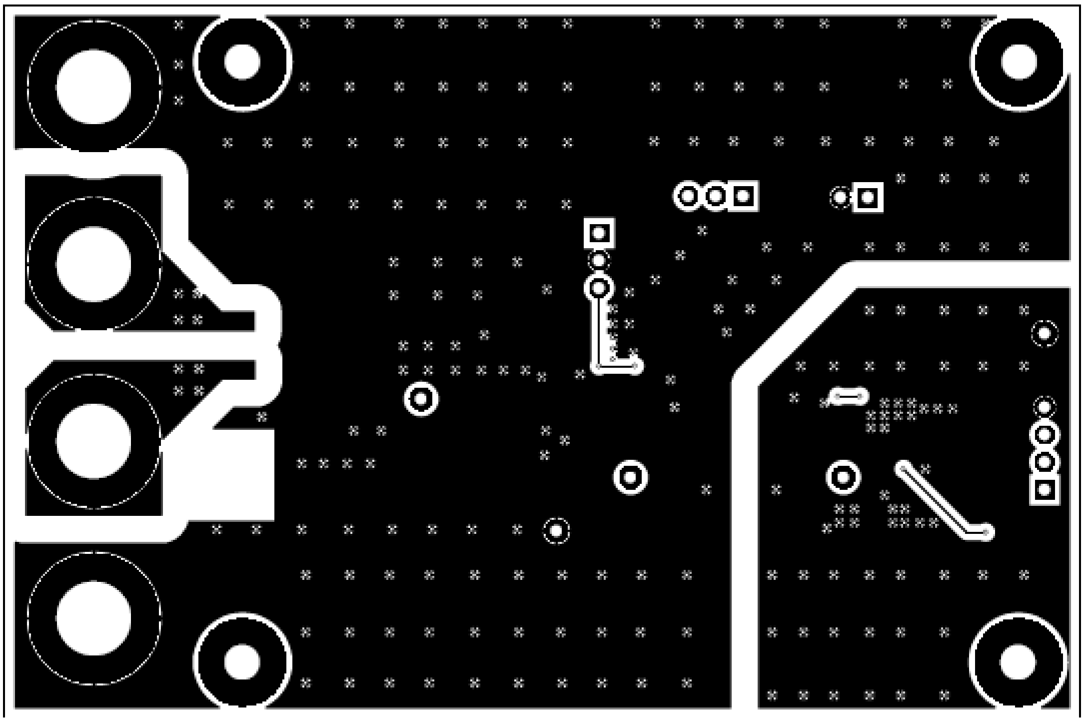

**Figure 19: Bottom Layer**



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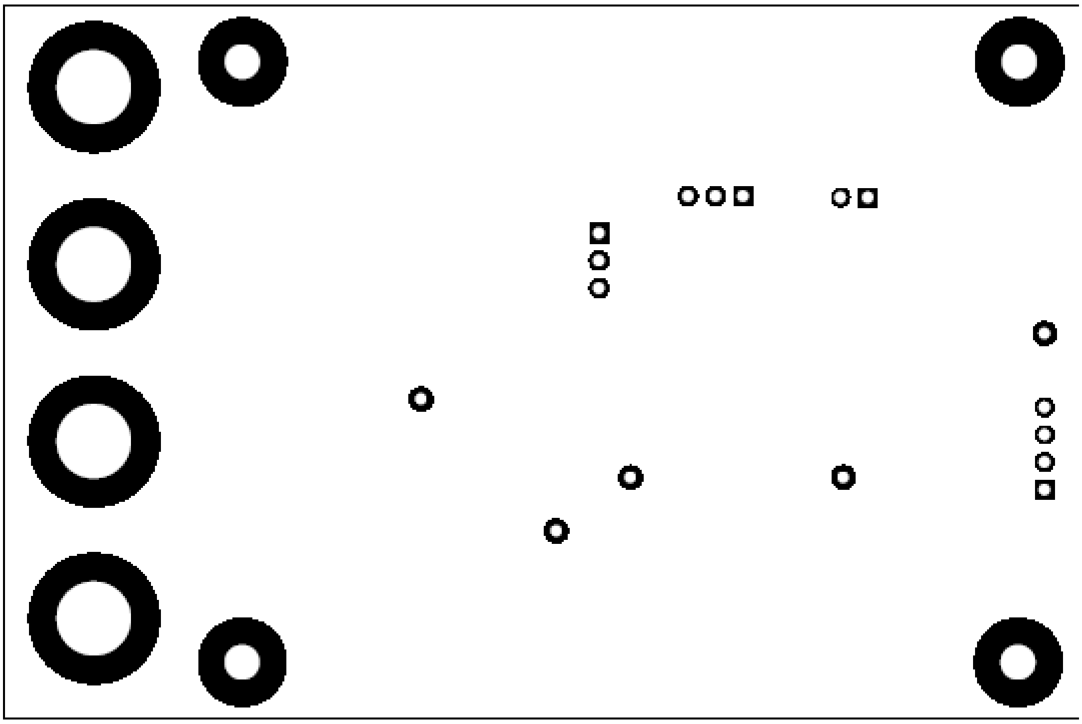

**Figure 20: Bottom Solder Mask**

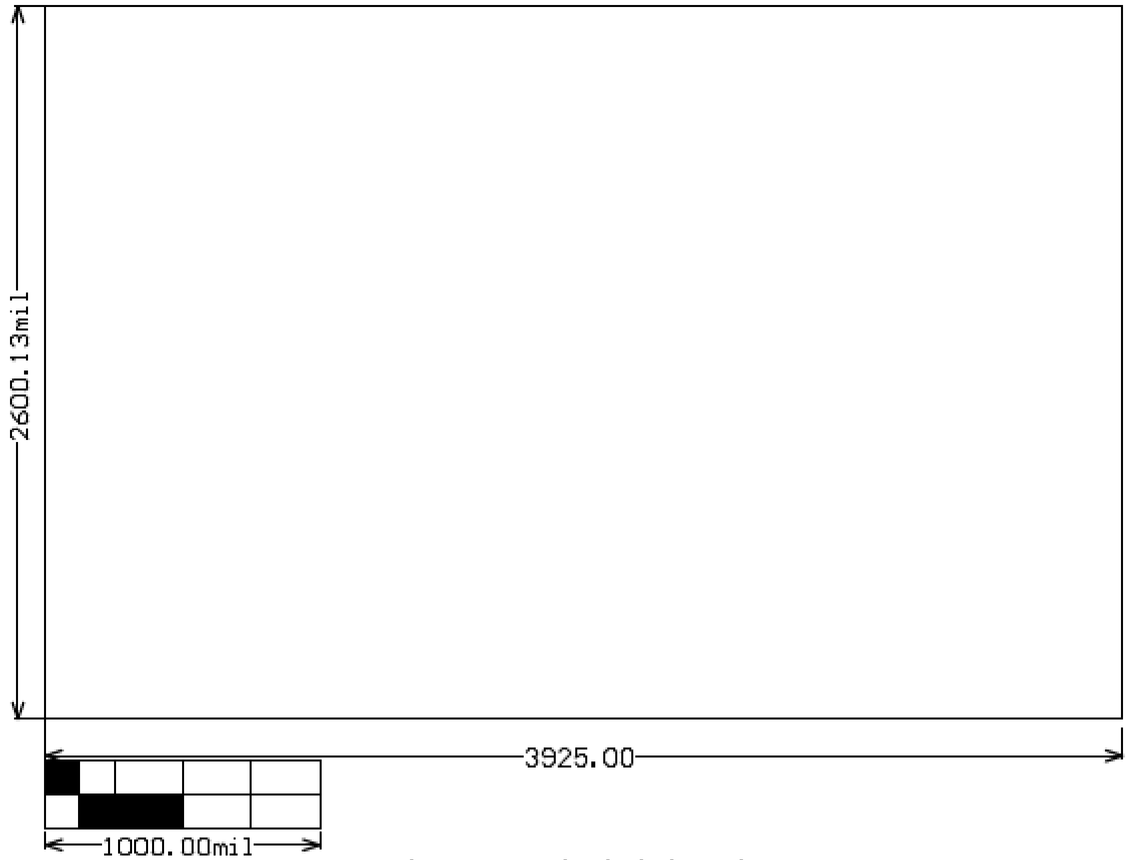


**Figure** 21**: Mechanical Dimensions**



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## 7.4 Altium Project

To download the Altium project files for each board, see the design files at http://www.ti.com/tool/TIDA-00456.

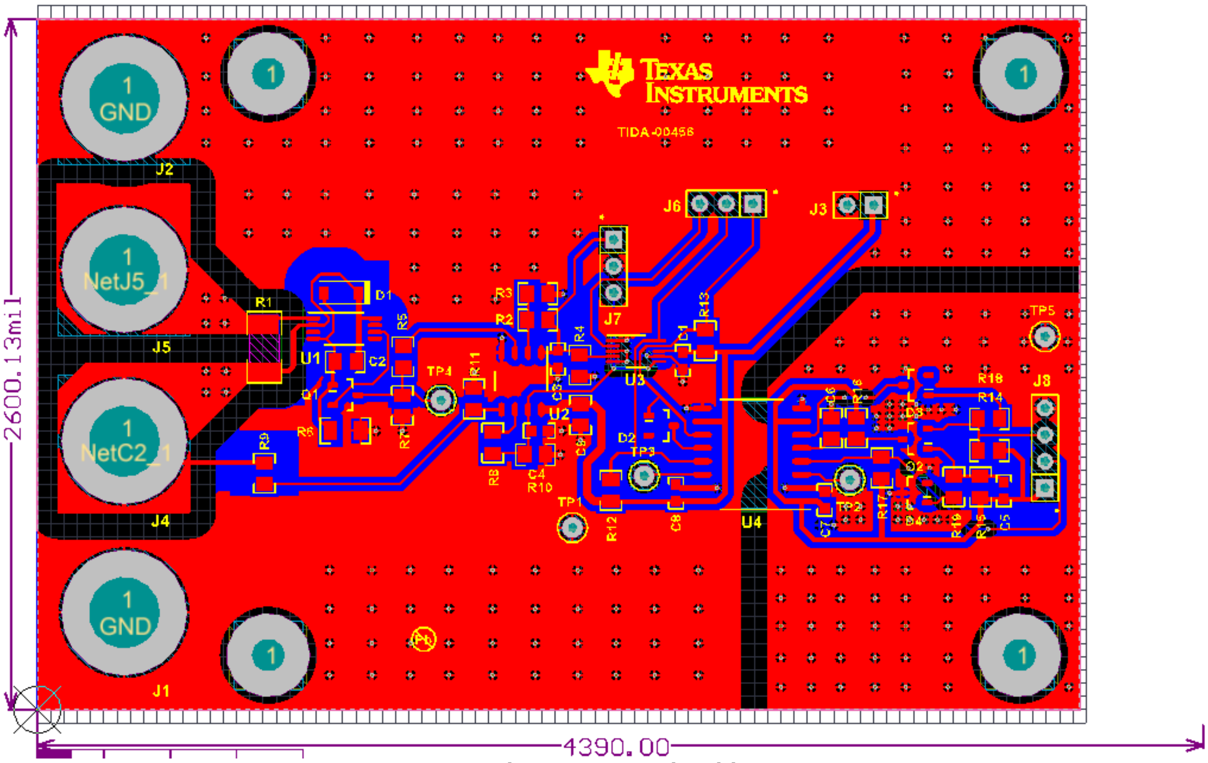


**Figure 22: PCB in Altium**



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## 7.5 Gerber files

To download the Gerber files for each board, see the design files at http://www.ti.com/tool/TIDA-00456.

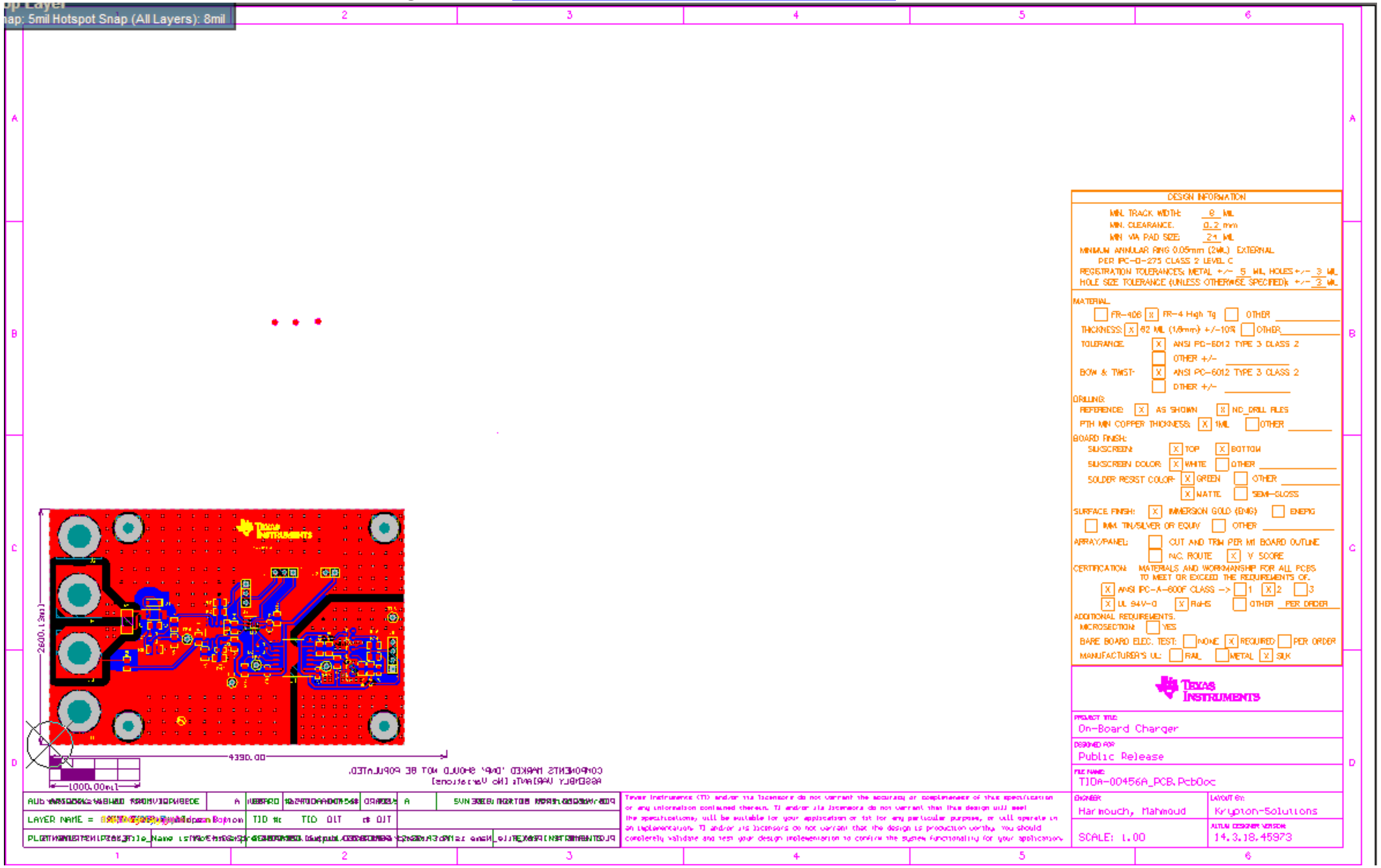


**Figure 23: Altium Project**



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## 7.6 Assembly Drawings

To download the Assembly Drawings for each board, see the design files at http://www.ti.com/tool/TIDA-00456.

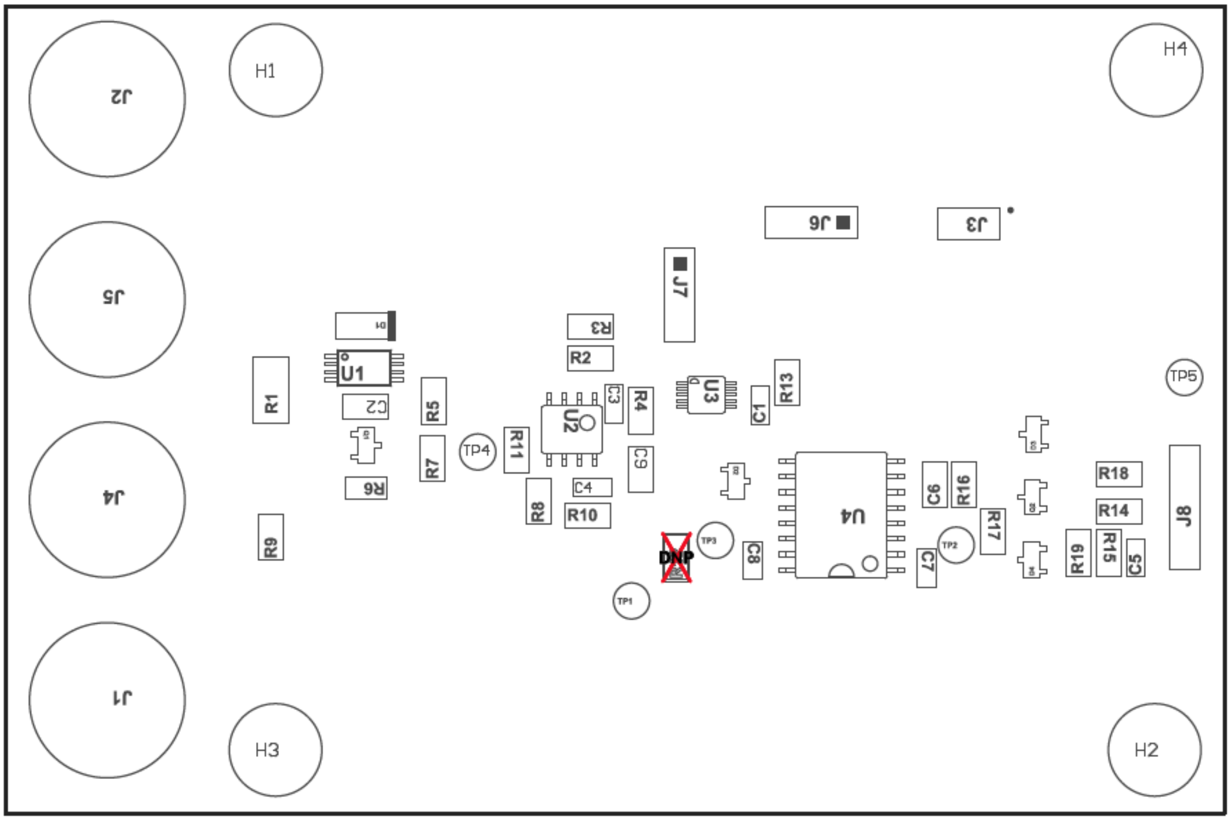


**Figure 24: Assembly Drawing**



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## 8 References

1. Texas Instruments TI Design, High Voltage 12 V – 400 V DC Current Sense Reference Design, TIDA-00332
2. Texas Instruments Application Report, Designing an Isolated I2C Bus Interface by Using Digital Isolators, SLYT403
3. Texas Instruments E2E Community, http://e2e.ti.com/

## 9 Terminology

- HEV/EV: Hybrid Electric Vehicle and/or Electric Vehicle
- On-board charger: The AC/DC converter that charges the high voltage battery pack in an HEV/EV.

## 10 About the Author

**Mahmoud Harmouch** is an applications engineer at Texas Instruments MSA catalog, where he is responsible for developing reference design solutions for the automotive segment. Mahmoud brings to this role his extensive experience in analog and power electronics expertise. Mahmoud earned his Master of Science in Electrical Engineering (MSEE) from Lyon University in France.

**Clancy Soehren** is an Applications Engineer at Texas Instruments, where she is responsible for automotive amplifiers and data converters. Clancy earned her Master of Electrical and Computer Engineering (MECE) from Rose-Hulman Institute of Technology in Terre Haute, IN.

**Akeem Whitehead** is an Applications Engineer at Texas Instruments, where he serves as a technical expert for the company's sales staff and customers, with an emphasis on ultrasonic sensor technology. Akeem received his BSEET from Texas A&M University in 2013. Akeem has developed evaluation modules, reference designs, graphical user interfaces, embedded processor firmware, training modules, and video tutorials since joining TI in 2013.



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