TI Designs: TIPD205

±100-A Busbar Current Sensor Reference Design Using Open-Loop Fluxgate Sensors

Description

This complete, busbar assembly reference design offers a non-invasive (isolated and lossless) current measurement solution up to ±100 A. This assembly includes a busbar with a circular cutout, insert, printed-circuit board (PCB), isolated standoffs, terminal blocks, and interface cable assembly to enable high-current measurement right out of the box.

Resources

TIPD205	Design Folder
DRV425	Product Folder
OPA320	Product Folder

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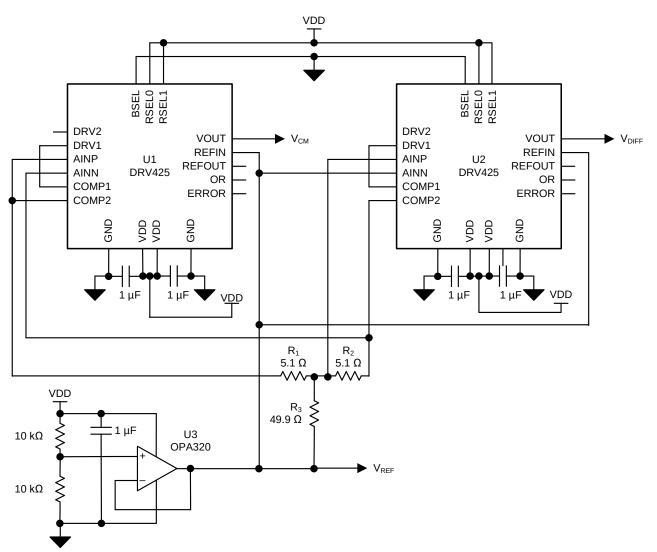
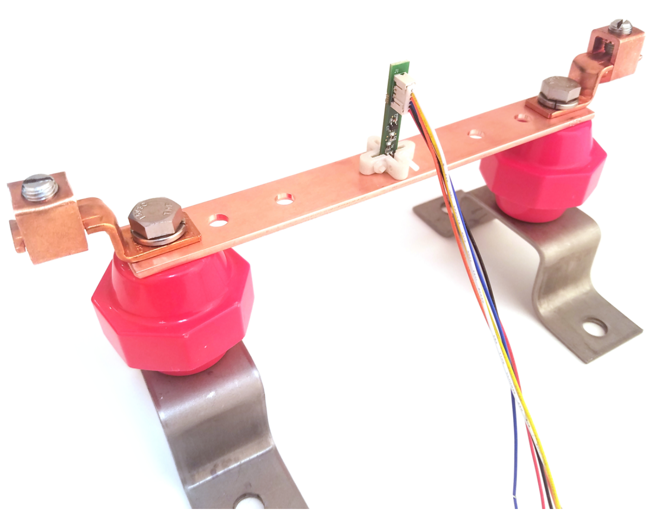
Features

- Current Range up to 100 A
- Non-Invasive (Isolated and Lossless) Measurement
- Complete Assembly
- Open-Loop Current Sensor
- Accurately Measure DC and AC Currents

Applications

- Battery Management System (BMS)
- AC Drive Control Module
- Servo Drive Control Module
- Brushless DC Motor Drives
- Surge Protection Device





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1 System Description

A variety of methods are available for measuring current. One method is to measure the magnetic field generated by the current source, which creates an isolation between the current and the measurement system. This method eliminates some of the concerns normally associated with a typical current shunt monitor by removing the shunt resistor, which can causes unwanted power loss. This method also eliminates high-voltage concerns due to isolating through the magnetic field. This reference design provides instruction for measuring current through a busbar by measuring the magnetic field generated using two DRV425 devices. Using the DRV425 fluxgate sensor to measure the magnetic field has the benefit of low drift and low noise, which are often larger when using typical Hall effect sensors. This reference design provides two PCB orientations that can be used to measure the current. The TIPD205 design allows for quick evaluation of both PCB orientations(horizontal and vertical). See *Bus Bar Theory of Operation* (SLOA237) for further detailed information regarding busbar operation. This busbar measures ±100 A using a 5-V supply. This design is scalable to measure higher or lower current.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS
Current range	±100 A
Supply voltage	5.0 V
Magnetic field orientation	Horizontal and vertical

2 System Overview

2.1 Block Diagram

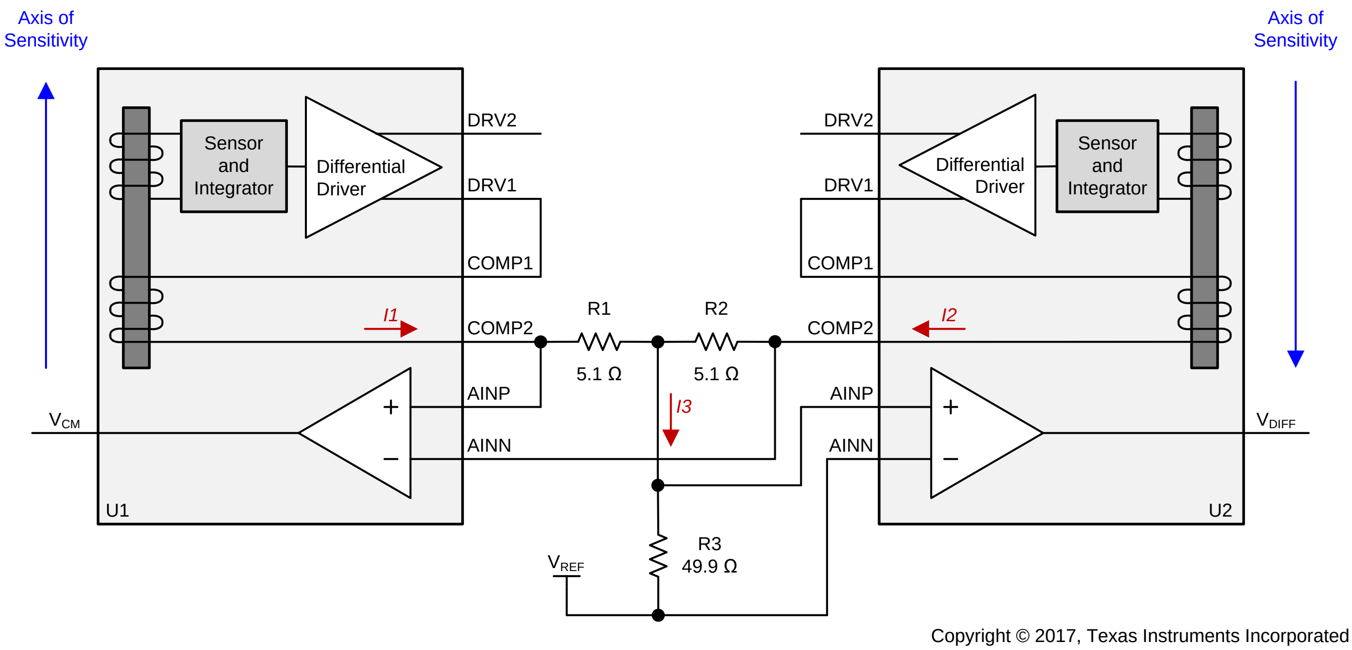

Figure 1. TIPD205 Block Diagram

2.2 Highlighted Products

2.2.1 DRV425

The DRV425 is designed for single-axis magnetic field sensing and enables electrically-isolated, high-sensitivity, and precise DC- and AC-field measurements. The device provides a proprietary, integrated fluxgate sensor (IFG) with an internal compensation coil to support a high-accuracy sensing range of ±2 mT with a measurement bandwidth of up to 47 kHz. The low offset, offset drift, and noise of the sensor, combined with the precise gain, low gain drift, and very-low nonlinearity provided by the internal compensation coil result in unrivaled precision for magnetic field measurement. The output of the DRV425 is an analog signal which is proportional to the sensed magnetic field. The DRV425 offers a complete set of features, including an internal difference amplifier, on-chip precision reference, and diagnostic functions to minimize component count and system-level cost. The DRV425 is available in a thermally-enhanced, non-magnetic, thin WQFN package with a PowerPAD™ integrated circuit package for optimized heat dissipation. The device is specified for operation over the extended industrial temperature range of –40°C to +125°C.

2.2.2 OPA320

The OPA320 amplifier in a buffer configuration drives the reference pin along with the output current from the DRV pins of the DRV425 pairs. The OPA320 is selected as the buffer for the reference voltage because of its very-low offset voltage, low quiescent current, low input bias current, and low noise. Use the small SOT-23 package to enable the size constraint of the PCB.

2.3 System Design Theory

Traditional busbar current measurement techniques use closed-loop current modules to accurately measure and control current. While these modules are accurate, they usually require a large magnetic core and often dissipate several watts of power. An alternative approach is to use two DRV425 devices connected for a differential measurement, mounted on a printed circuit board which is then placed into a hole drilled in the center of the busbar. When a hole is drilled into the center of the busbar, the current is split into two equal parts that generate magnetic field gradients with opposite directions inside the hole. The opposing fields cancel each other out in the center of the hole. The high sensitivity and linearity of the DRV425 devices positioned equidistant from the center of the hole allow small opposing fields to be sensed and current to be measured with a high degree of accuracy.

The busbar design has two different orientations available for evaluation. The two PCB orientations are very similar and the most significant reason to chose one version over the other is due to stray magnetic fields. Neighboring currents typically cause these stray fields, which can either be in the vertical or horizontal axis. Adding these stray fields to the desired field being measured can cause a situation that saturates the DRV425 devices. The user must use a perpendicular (or normal) orientation for the DRV425 axis of sensitivity in relation to these stray fields to avoid saturation.

This system is designed for current measurements up to 100 A by measuring the magnetic field generated by the current through the busbar. See *Bus Bar Theory of Operation* (SLOA237) for a more detailed explanation on the system design theory.

2.3.1 Busbar Design

The measured current and the amount of temperature from which the busbar can increase from the ambient temperature determine the busbar dimensions. The bar has a cutout which increases the power dissipated through the busbar and must be taken into account for the temperature rise. The design of the bar enables a very-low temperature rise when 100 A passes through it. All the dimensions and the type of cutout affect the magnetic field monitored by the DRV425 devices. Use the DRV425 Bus Bar Application Magnetic Field Calculator to calculate the dimensions required for the current measurement. Figure 2 shows a screenshot from the calculator used in the design. A design must attempt to get the highest magnetic field to improve the signal-to-noise (desired field-to-stray field) performance. The highest field is limited by the DRV425 saturation of 2 mT.

Figure 2. DRV425 Busbar Application Magnetic Field Calculator for Vertical and Horizontal Design

2.3.2 Circuit Design

The circuit must produce an output that represents the current through the busbar and reduces any stray magnetic fields. Achieve this output by measuring the difference in magnetic fields from the two DRV425 devices. The circuit provides an output that represents the magnetic field produced by the current being measured and the common magnetic field. The designer is not required to use the output of the V_{CM} (common magnetic field); however, this output can be useful to determine if the DRV425 devices are close to saturation. *Bus Bar Theory of Operation* provides a circuit analysis for this circuit with multiple examples on the expectations and the DRV425 limitations. Rshunt determines the gain of the circuit and the user can adjust this for the desired gain. The TIPD205 reference design has an Rhsunt of 49.9 Ω (see Figure 2).

2.3.3 Insert Design

The insert to place the PCB is designed to place both versions of the PCB into the busbar. The insert is polarized and the holes for the nylon screws only align if the user has correctly placed the PCB inside the insert. The purpose of the provided nylon screws is to secure the PCB to the insert and limit the movement of the PCB board. Nylon screws are non-magnetic and do not disturb the magnetic flux. The alignment is structured such that the DRV425 devices are equidistant from the center depending on the PCB orientation. The insert also has alignment pins that match up with the busbar to prevent users from incorrectly placing it. The material is selected for cost and ease of use and is not designed for high-temperature applications; however, the designer can change the material to meet a variety of requirements. Measuring the current through the magnetic flux automatically creates an isolation barrier between the current and the measurement system. The insert provides separation from the PCB to the busbar, which creates a limited physical isolation. This design of the insert is not intended for significant isolation but instead to visually determine the location of the DRV425 devices relative to the busbar and to allow the flexibility of using both orientations. The insert limits the voltage isolation with a clearance and creepage of 1.524 mm (60 mils). Increase the clearance and creepage by redesigning the insert to meet isolation requirements.

2.3.4 Error Sources

The designer must account for some of the error sources. Calibrate some of these errors out of the system by simply measuring the known currents like 0 A and 100 A against the accuracy required. Use these two values to calculate the offset and gain of the system and obtain a low measurement error.

2.3.4.1 Physical Construction

The physical construction of the busbar, placement of the sensors, as well as the sensor separation causes errors. The silicon placement (sensor location) in the package of the DRV425 has a tolerance of 0.025 mm in all directions, which only accounts for some of the error because of the sensor separation (see Figure 3). The majority of the error regarding the separation of the two DRV425 sensors is due to the assembly and manufacturing of the PCB. Sensor separation that varies from the intended distance produces a gain error and the user can simulate this using the DRV425 Bus Bar Application Magnetic Field Calculator by changing the sensor spacing input field and comparing the output values. A 1% error in placement typically equates to an approximate 1% error in gain error, but this varies depending on the dimensions of the busbar. This gain error is consistent and the user can calibrate for this.

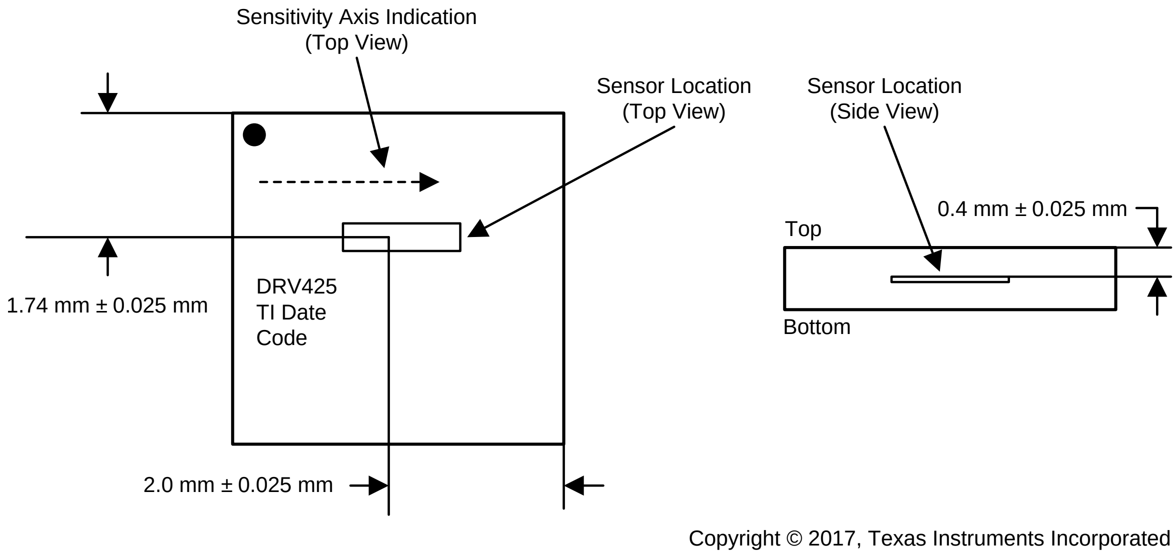

Figure 3. Sensor Location Inside DRV425

2.3.4.2 Fluxgate Sensor Offset

The DRV425 is an open-loop magnetic field sensor; however, the internal closed-loop nature of the device compensates for any nonlinearities of the fluxgate sensor. A small offset error of the fluxgate remains which can impact system performance. The typical offset error of the DRV425 is 2 µT. For this design, the full-scale value for one DRV425 device in vertical orientation is 470.7 µT and the offset error calculates to a 0.43% error of full scale. Calibrate this error by measuring the output voltage with zero current.

2.3.4.3 Sense Amplifier and External Reference

The sense amplifier offset voltage (V_{OS}) is another source of offset error. The magnitude of offset error at the output equals the product of the amplifier gain and input-referred offset voltage along with the offset voltage from the fluxgate sensor. The reference is derived from a resistor divider on the supply voltage and is buffered before being sent to the sense amplifier. Many implementations use a difference amplifier to sense the voltage across R_{SENSE}, in those cases the exact voltage reference level does not play a role in the system error because the reference voltage is used for the reference input of the difference amplifier and the transducer output is measured as V_{OUT} with respect to V_{REF}.

2.3.4.4 Shunt Resistor

The shunt or sense resistor has a direct impact on the overall gain of the design. This design supports ±100 A. Reducing the size of the shunt resistor allows the designer to measure a higher current range. The schematic, which is available in *Schematics*, uses a 49.9-Ω shunt which yields an output voltage of 2.5 ±2.2923 V in the vertical orientation and 2.5 ±1.9143 V in the horizontal orientation at ±100-A busbar current.

3 Getting Started Hardware

3.1 Hardware

Secure the terminal block to the busbar and isolation standoffs. When assembling the hardware, all high-current connections must be tight and secure, as any loose connections create a high-resistance path. When dealing with high currents, a small increase in resistance creates an increase in power dissipation and temperature. With time the copper can build an oxide layer and create a higher resistance path between the terminal blocks and the busbar, which the user can eliminate by scraping off the oxide with an abrasive material, adding NO OX-ID-A, using an electrical contact grease that prevents formation of oxides, or any combination thereof.

Decide which orientation to use and place the board inside the insert. J1 is the connector for the vertical orientation and J2 is the connector for the horizontal orientation. Another way to determine the orientation of the PCB section is by noting that the vertical version of the DRV425 devices are aligned and the horizontal version of the DRV425 devices are offset. Figure 4 shows the PCB inserted in both orientations.

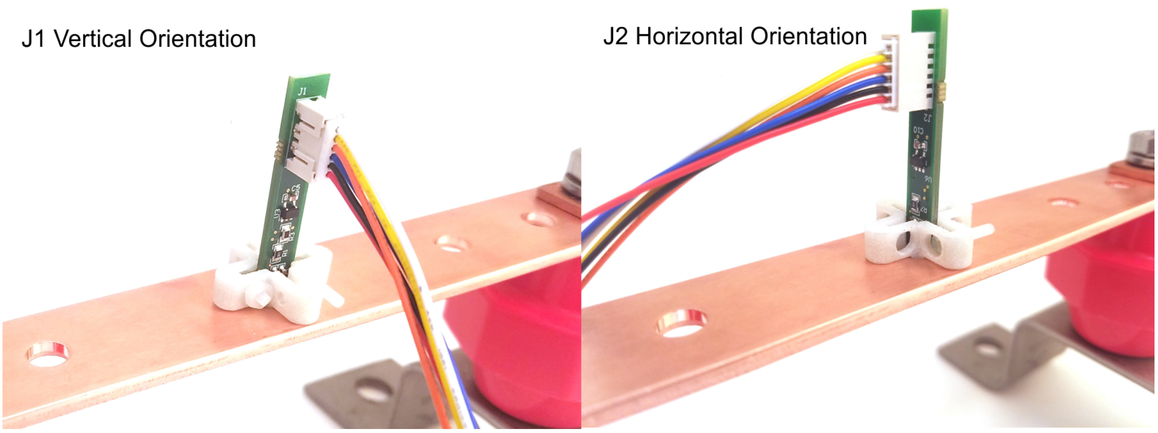

Figure 4. PCB Orientation

Secure the PCB board to the insert with the nylon bolts and nuts. Figure 5 shows a magnified photo of the nylon bolts and shows the bolt going through the larger hole of the insert and making contact with the PCB to secure it. Attach high-current cables (not provided) to the busbar using the terminal blocks.

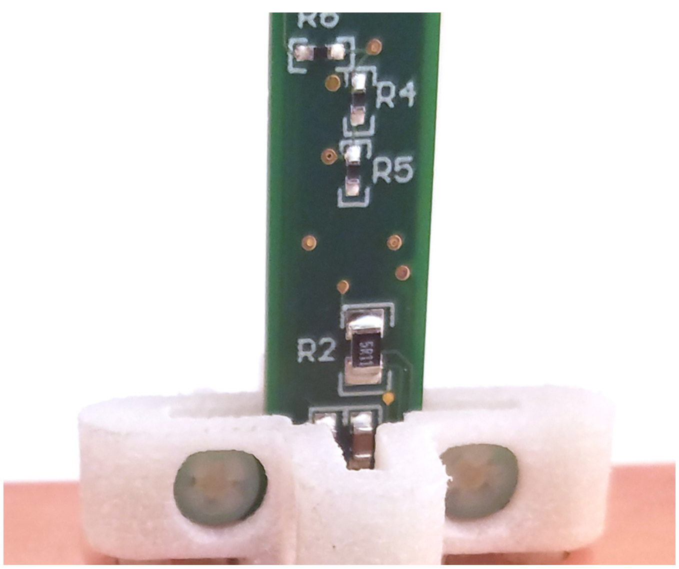

Figure 5. Zoomed-In Photo of Nylon Bolts Securing PCB

Place the connector on the board to J1 or J2 and connect the power supply and measurement instruments based on Table 2.

Table 2. Connection Table

COLOR	I/O	NAME	DESCRIPTION
Red	Input	VDD	Input power 5 V
Black	Input	GND	Ground
Blue	Output	Vout	Output voltage referenced to V_{REF}
Orange	Output	Vref	Voltage reference VDD/2
Yellow	Output	VCM	Common field output
White	Output	Alert	Diagnostic flag active low

4 Testing and Results

The test setup consists of the TIPD205 assembly (busbar, standoffs, insert, vertical and horizontal PCB boards, and terminal blocks), two DC supplies, two 3458A digital multimeters (DMM), a programmable load, and a 500-µΩ shunt resistor. One of the DC supplies must be able to provide a current higher than 100 A with the full circuit load. To control the current through the busbar, a programmable load (Kikusui PLZ1205W) was used to control the current and to be able to sweep it from 0 A to 100 A. An accurate, 500-µΩ shunt resistor was used to obtain an accurate measurement. Figure 6 shows a block diagram with all the required connections for the measurements. Note that the alert pin and the VCM pins have not been used in this setup. The function of the alert pin is to help determine if either of the DRV425 devices are saturated. The function of the VCM pin is to determine if the setup has a high external stray field, which is not an issue in this setup.

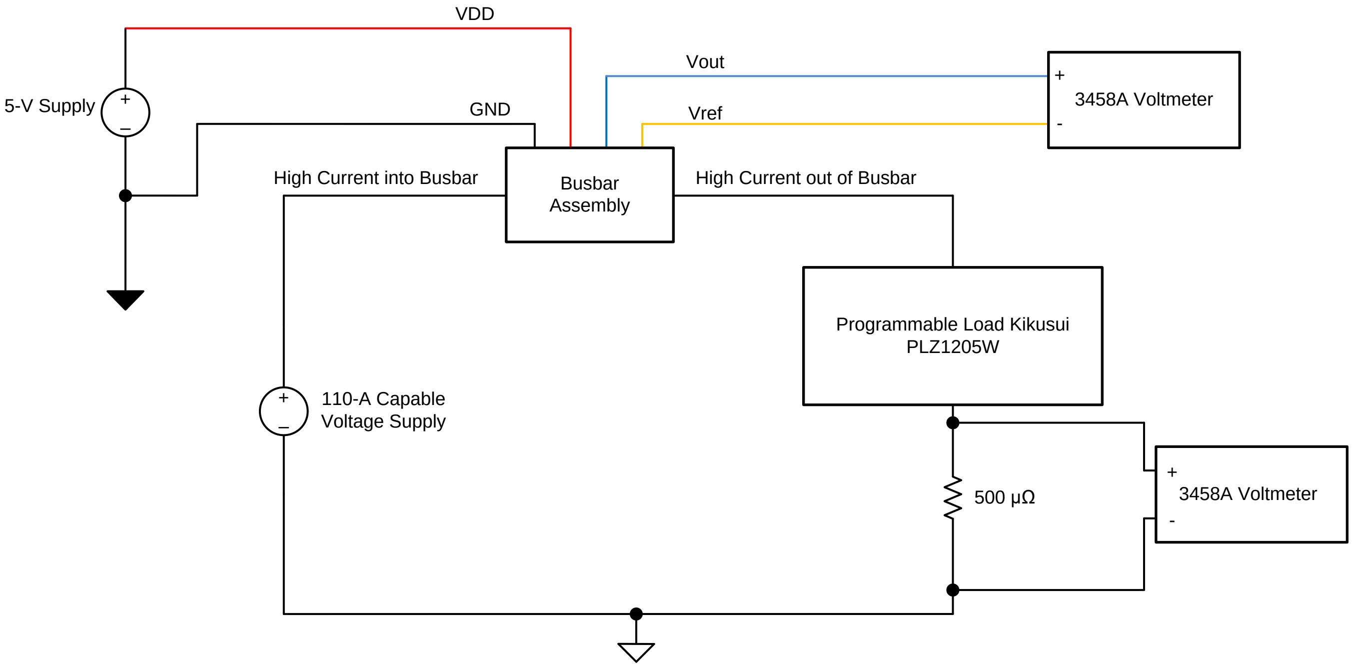

Figure 6. Test Setup Diagram

The TIPD205 setup was used for both orientations and produced the following transfer curves in Figure 7 and Figure 8.

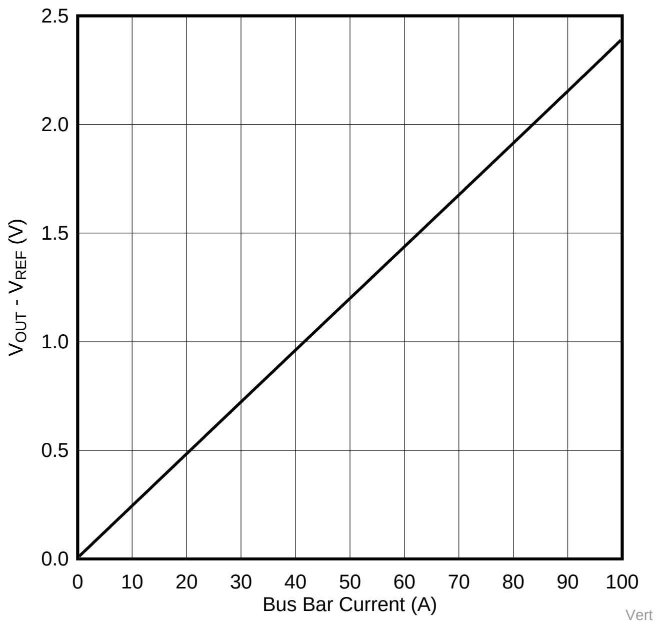

Figure 7. V_{OUT} versus Input Current for Vertical Orientation (J1)

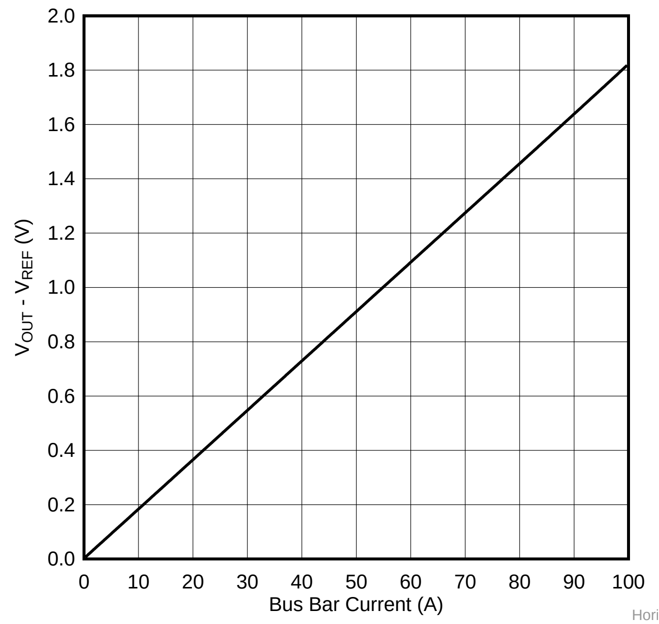

Figure 8. V_{OUT} versus Input Current for Horizontal Orientation (J2)

The gain and offset were calculated to increase accuracy. Calibrate the gain using Equation 1 for the vertical orientation and Equation 2 for the horizontal orientation. The offset is the measured V_{OUT} to V_{REF} when the current is 0 A.

$$\text{Gain}_{\text{Meas}} = \frac{(V_{OUT} - V_{REF})100\text{ A} - (V_{OUT} - V_{REF})0\text{ A}}{100 - 0} = \frac{2.396\text{ V} - (0.00606\text{ V})}{100} = \frac{23.9\text{ mV}}{\text{A}} \tag{1}$$

$$\text{Gain}_{\text{Meas}} = \frac{(V_{OUT} - V_{REF})100\text{ A} - (V_{OUT} - V_{REF})0\text{ A}}{100 - 0} = \frac{1.8232\text{ V} - (0.00258\text{ V})}{100} = \frac{18.21\text{ mV}}{\text{A}} \tag{2}$$

After completing these calculations, calculate the complete the full-scale error using Equation 3.

$$\text{Full} - \text{ScaleError}\ (\%) = \frac{I_{BUSBAR} - \dfrac{V_{OUT} - V_{REF}}{\text{Gain}_{\text{Meas}}}}{200\ (\text{A})} \tag{3}$$

Figure 9 and Figure 10 show the calculated full-scale error from 0 A to 100 A.

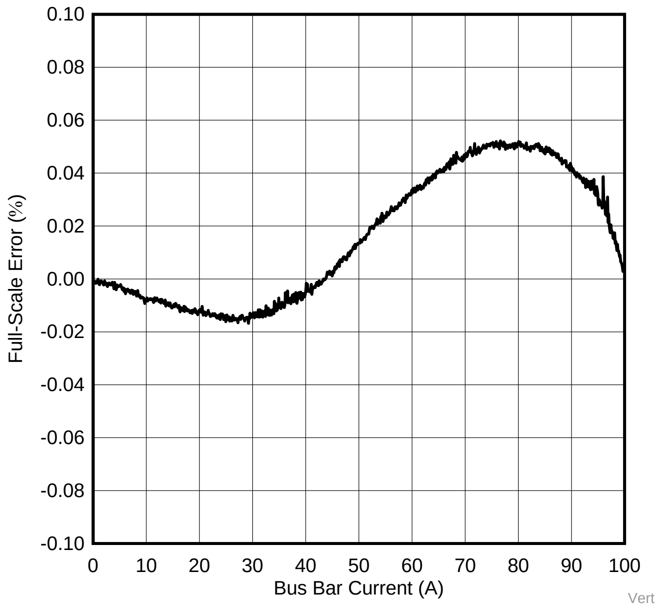

Figure 9. Full-Scale Error versus Current Vertical Orientation (J1)

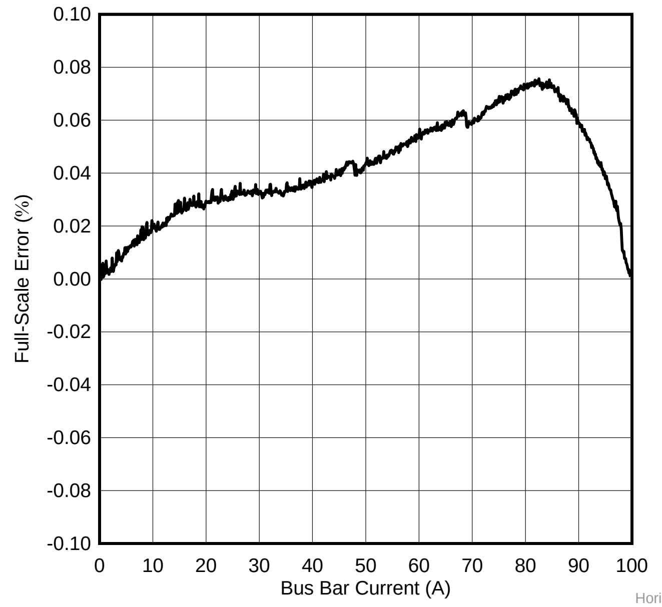

Figure 10. Full-Scale Error versus Current Horizontal Orientation (J2)

5 Design Files

5.1 Schematics

To download the schematics, see the design files at TIPD205.

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIPD205.

5.3 Altium Project

To download the Altium project files, see the design files at TIPD205.

5.4 Gerber Files

To download the Gerber files, see the design files at TIPD205.

5.5 Assembly Drawings

To download the assembly drawings, see the design files at TIPD205.

6 Related Documentation

1. Texas Instruments, *Bus Bar Theory of Operation*, Application Report (SLOA237)
2. Texas Instruments, *Design Considerations for Dual DRV425 Bus Bar Application*, TI TechNote (SBOA185)

6.1 Trademarks

PowerPAD is a trademark of Texas Instruments.
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7 About the Author

JAVIER CONTRERAS is an Applications Engineer at Texas Instruments.

TOM HENDRICK is a Senior Applications Engineer at Texas Instruments.

Revision History

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

Changes from Original (October 2015) to A Revision **Page**