±100A Bus Bar Current Sensor using Open-Loop Fluxgate Sensors Reference Design

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Circuit Description

This 5 V single-supply open-loop current sensing solution is designed to accurately measure dc, ac and pulsed currents in bus bar applications. Featuring a sensitivity of 18.9 mV/A, the nominal input range of the solution is ±100 A.
1 Design Summary

The design requirements are as follows:

- Supply Voltage: 5 V
- Nominal Input: ±100 A
- Reference Voltage: 2.5 V
- Output Range: 2.5 V ± 2.0 V
- Maximum Shunt Voltage: 500 mV

The design goals and performance are summarized in Table 1. Figure 1 depicts the measured transfer function of the design.

Table 1. Comparison of Design Goals, Calculations, and Measured Performance

<table>
<thead>
<tr>
<th>Goal</th>
<th>Calculated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (mV/A)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Total Unadjusted Error (%FSR)</td>
<td>± 0.150%</td>
<td>±0.098%</td>
</tr>
<tr>
<td>Calibrated Error (%FSR)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 1: Measured Transfer Function
2 Theory of Operation

Traditional bus bar 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 bus bar.

When a hole is drilled into the center of the bus bar, 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 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.

![Figure 2: DRV425 Based Bus Bar Current Measurement](image)

Figure 3 shows the distribution of the magnetic fields inside the hole drilled through the bus bar. With a bus bar measuring 1 inch wide by ¼ inch thick, simulations show that the magnetic field seen by the DRV425 devices is approximately 546µT at 100A.

![Figure 3: DRV425 Based Bus Bar Current Measurement](image)
The output voltage from the bus bar configuration is proportional to the current flowing in the bus bar. The output voltage ($V_{OUT}$) is defined in Equation 1.

$$V_{OUT} = B \times G \times R_{SHUNT} \times G_{AMP}$$  \hspace{1cm} (1)

Where the terms are:
- $V_{OUT}$: DRV425 differential output voltage,
- $B$: magnetic field to be measured,
- $G$: gain of the fluxgate sensor,
- $R_{SHUNT}$: shunt resistor, and
- $G_{AMP}$: gain of the sense amplifier.

### 2.1 Sources of Output Error

The physical construction of the circuit and the component tolerances will introduce error in the transfer function of the bus bar sensor. Several sources of errors are discussed in the following sections.

#### 2.1.1 Fluxgate Sensor Offset Voltage

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.

#### 2.1.2 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 $V_{REF}$.

#### 2.1.3 Shunt Resistor

The shunt or sense resistor will have a direct impact on the overall gain of the design. This design was tailored to support ± 100 A, because of limitations on the available current source in our lab. Reducing the size of the shunt resistor will allow a much higher current range to be measured. The schematic shown in Appendix A.1 uses a 10 ohm shunt which yields an output voltage of 2.5 ± 325 mV at ± 100 A bus bar current. By extrapolation, bus bar current up to ± 600 A are possible with this hardware.
3 Component Selection

3.1 Integrated Fluxgate Sensor, Signal Conditioning, Coil Driver and Sense amplifier

The DRV425 was chosen to minimize the component count and error sources. This IC has an integrated fluxgate sensor, a compensation coil driver and a precision differential amplifier for the output stage.

The H-Bridge driver stage can provide up to 250 mA to the compensation coil and the differential amplifier stage provides a gain of 4 V/V to the shunt resistor voltage.

![Diagram of DRV425 with integrated fluxgate sensor](image)

Figure 4: Open Loop System Using DRV425 with Integrated Fluxgate Sensor

3.2 Shunt Resistor Selection

A shunt resistor is placed in series with the internal compensation coil current to provide a voltage to the output differential sense amplifier stage. Selection of an appropriate shunt resistor is dependent on the amount of current flowing through the compensation coil as well as the gain of the difference amplifier.

The gain of the difference amplifier in the DRV425 is 4 V/V. With a design target of ±500 mV voltage across the shunt ($V_{shunt}$) for ±100 A of bus bar current, the value of $R_{shunt}$ is calculated in Equation 2.

$$R_{shunt(max)} = \frac{V_{OUT(max)}}{B \times G \times G_{AMP}} = \frac{2000mV}{546 \mu T \times 12.2 \times 4} = 75.1\Omega$$

(2)
3.2.1 Output Voltage

The output voltage of the difference amplifier will be directly proportional to the magnetic field generated by bus bar current and it will be biased at the reference voltage ($V_{REF}$). With ±100 A of bus bar current, the output voltage ($V_{out}$) with respect to the reference voltage ($V_{REF}$) can be calculated using Equation 3.

$$V_{out(max)} - V_{REF} = V_{shunt} \cdot G_{DA} = 500mV \cdot 4 = 2.00V$$  \hspace{1cm} (3)

Where $G_{AMP}$ is the voltage gain of the difference amplifier in the output stage of the DRV425.

This design uses a 5V source and a fixed 2.5V reference so the total output voltage swing will be $V_{REF} \pm 2.00V$.

3.3 Reference Buffer Selection

The OPA320 was chosen as a buffer for the reference voltage because of its very low offset voltage and low quiescent current. The small SC-70 package was utilized due to size constraints on the printed circuit board.
4 Calculated Performance

4.1 Uncalibrated Error

The major sources of error associated with the selected components are listed in Table 2.

Table 2. Typical Error Contributions

<table>
<thead>
<tr>
<th>Specification</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRV425 Fluxgate Sensor Offset (µT)</td>
<td>2</td>
</tr>
<tr>
<td>DRV425 Differential Amplifier Offset1 (µV)</td>
<td>±10</td>
</tr>
<tr>
<td>DRV425 Differential Amplifier Gain Error (%FS)</td>
<td>0.02</td>
</tr>
<tr>
<td>DRV425 Differential Amplifier Linearity (ppm)</td>
<td>12</td>
</tr>
<tr>
<td>Shunt Tolerance2 (%)</td>
<td>0.03</td>
</tr>
</tbody>
</table>

These errors can be translated to equivalent bus bar current values as shown in Equations 4 – 8.

\[
\text{FluxgateOffset}(A) = \frac{\text{FluxgateError}(T)}{\text{BusBarMagneticGain}(T/A)} = \frac{1\mu T}{5.46 \mu T/A} = 183mA
\] (4)

\[
\text{DiffAmpOffset}(A) = \frac{\text{DiffAmpOffset}(V)}{\text{ModuleSensitivity}(V/A)} = \frac{10\mu V}{20mV/A} = 0.50mA
\] (5)

\[
\text{GainError}(A) = \frac{\text{GainError}(\%FS)}{100} \times I_{\text{MAX}} = \frac{0.02}{100} (200A) = 4mA
\] (6)

\[
\text{LinearityError}(A) = \frac{\text{Linearity}(ppm)}{10^6} \times I_{\text{MAX}} = \frac{12}{10^6} (200A) = 2.4mA
\] (7)

\[
\text{ShuntToleranceError}(A) = \frac{\text{ShuntTolerance}(\%)}{100} \times I_{\text{MAX}} = \frac{0.033}{100} (200A) = 66mA
\] (8)

1 Referred to the output.
2 Assuming 0.1% with ± 3 sigma distribution.
Table 3 lists the errors referred to the full-scale bus bar current of 100 A.

<table>
<thead>
<tr>
<th>Error Cause</th>
<th>Typical Error (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRV425 Fluxgate Sensor Offset</td>
<td>183</td>
</tr>
<tr>
<td>DRV425 Differential Amplifier Offset</td>
<td>0.5</td>
</tr>
<tr>
<td>DRV425 Differential Amplifier Gain Error</td>
<td>4</td>
</tr>
<tr>
<td>DRV425 Differential Amplifier Linearity</td>
<td>2.4</td>
</tr>
<tr>
<td>Shunt Tolerance</td>
<td>66</td>
</tr>
</tbody>
</table>

Once expressed in amperes of equivalent bus bar current, one can take the root of the sum of the squared terms (RSS) to obtain a probable estimate for the total output error of the system.

$$\text{Error}(mA) = \sqrt{183^2 + 0.50^2 + 4^2 + 2.4^2 + 66^2} = 194.59 mA$$  \hspace{1cm} (9)

The full-scale error is then calculated using Equation 10.

$$\text{Error}(\%FS) = \frac{\text{Error}(A)}{I_{MAX}(A)} = \frac{0.195}{200} = 0.098\%$$  \hspace{1cm} (10)

Note that the expected error is dominated by the shunt tolerance.

### 4.2 Temperature Drift

Measurements across temperature were not performed for this design. However, the DRV425 datasheet provides measurement results for the DRV425 used in open-loop sensing applications. Below are calculations pertaining to this design for the shunt drift, differential amplifier offset drift and differential amplifier gain drift when temperature increases from 27°C to 85°C.

$$\text{DiffA}_{\text{OffsetDrift}} = \frac{(\text{DiffAmpOffsetDrift})(\Delta T)}{\text{Sensitivity}} = \frac{0.4\mu V/°C(85 - 27)°C}{20\text{mV/A}} = 1.16 mA$$  \hspace{1cm} (11)

$$\text{DiffA}_{\text{GainDrift}} = \frac{\text{DiffAmpGainDrift}(\text{ppm/}°C)(\Delta T)}{10^6} I_{MAX} = \frac{1\text{ppm/}°C(58°C)}{10^6} = 0.00116 mA = 11.6mA$$  \hspace{1cm} (12)

$$\text{Shunt}_{\text{Drift}} = \frac{\text{TempCoef}(\text{ppm/}°C)(\Delta T)}{10^6} I_{MAX} = \frac{25\text{ppm/}°C(58°C)}{10^6} = 0.0029 mA = 290mA$$  \hspace{1cm} (13)

The DRV425 datasheet provides more details on the temperature drift specifications of the device.
5 PCB Design

The PCB schematic and bill of materials can be found in the Appendix.

5.1 PCB Layout

The four-layer printed circuit board (PCB) used in this design measures 38.3mm x 19.9mm as shown in Figures 5A and 5B. The DRV425 devices are mounted on a finger extension intended to be placed in the hole drilled through the bus bar.

Figure 5A: PCB Top Layer

Figure 5B: PCB Bottom Layer
6 Verification & Measured Performance

A 5 V power supply is provided to power to the bus bar circuit. The bus bar current was provided by a 100 A dc source whose output was swept in the range of ±100 A. Figure 5 shows the printed circuit board with the sensor, alignment plug and bus bar.

![Figure 6: DRV425 Board, Plug and Bus Bar](image)

6.1 Transfer Function

The transfer function is shown in Figure 7.

![Figure 7: Transfer Function](image)
6.2 Measured Uncalibrated Full-Scale Error

The full-scale error (%FSR) of the output is calculated using Equation 14.

\[
\text{Full - Scale Error} \ (\%\text{FSR}) = 100 \left( \frac{I_{\text{BUSBAR}} - V_{\text{OUT}} - V_{\text{REF}}}{20 \text{ mV} / \text{A}} \right) \frac{200\text{A}}{200\text{A}}
\]  \hspace{1cm} (14)

The uncalibrated full-scale range error is plotted over the ± 100A range in Figure 7. Note that the worse error observed is -0.120%.

Figure 7: Full-Scale Error vs. Bus Bar Current
6.3 Measured Sensitivity and Calibrated Full-Scale Error

The sensitivity of the bus bar circuit used can be obtained using an end-point straight line fit to the measured data. The slope of such line is calculated in Equation 15.

\[
\text{Sensit}_{\text{MEAS}} = \frac{(V_{\text{OUT}} - V_{\text{REF}})_{100A} - (V_{\text{OUT}} - V_{\text{REF}})_{-100A}}{100 - (-100)} = \frac{1.8997V - (-1.8948V)}{200} = 18.97mV/A \quad (15)
\]

A single point calibration was performed by removing the initial offset at 0 A from the output voltage. The calibrated full-scale range error is plotted over the ± 100 A range as shown in Figure 8. Note that the worse calibrated error observed is 0.049%.

![Figure 8: Calibrated Error vs. Bus Bar Current](image)
7 Modifications

Larger currents can be measured with the DRV425 by modifying the dimensions of the bus bar or the hole in which the DRV425 devices are placed in.

The current measurement range can also be modified by changing the value of the shunt resistor according to Equations 2 and 3. Using the 10 ohm resistor shown in the schematic in appendix A1, the projected current measurement levels would be ± 600A for the same output voltage levels described in this document. For systems that require a tighter uncalibrated error, choosing a shunt resistor with 0.05% tolerance can lower the corresponding error as shown in Equation 8.
A.1 Electrical Schematic

Figure A-1: Electrical Schematic
### A.2 Bill of Materials

#### Bill of Materials

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Value</th>
<th>Designator</th>
<th>Description</th>
<th>Manufacturer</th>
<th>PartNumber</th>
<th>Supplier Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>PCB</td>
<td>Printed Circuit Board</td>
<td>Any</td>
<td>TIPO205</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>R3</td>
<td>RES, 10kohm, 0.1%</td>
<td>Vishay Thin Film</td>
<td>PATT005E10R0BG</td>
<td>764-1050-2-ND</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>OPA320AIDV</td>
<td>IC, Precision, 20MHz, 0.95A, Low Noise, RIO, CMOS Op-Amp</td>
<td>TI</td>
<td>OPA320AIDBV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>PEC003DAUJ</td>
<td>Header, Male 2x3 pin. 100mil spacing</td>
<td>Qllens</td>
<td>PEC003DAAN</td>
<td>S2012E-02-ND</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>U1, U2</td>
<td>Flagpole Magnetic Field Sensor, RT-0020G</td>
<td>Texas Instruments</td>
<td>DRV4250JR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>10k</td>
<td>R4, R5</td>
<td>ROHM SEMICONDUCTORS</td>
<td>MCR01MRTF1002</td>
<td>RHM1002CDT-ND</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>5.1</td>
<td>R1, R2</td>
<td>RES, 5.1ohm, 1%</td>
<td>Panasonic</td>
<td>ERJFQFP516V</td>
<td>ERJ-FQP516V-ND</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>C1, C2, C3, C4, C5</td>
<td>CAP, CERD, 1uf, 25V, X7R, 10%, 0000</td>
<td>TDK</td>
<td>C1609X7R1E010K000A</td>
<td>445-9556-1-ND</td>
<td></td>
</tr>
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</table>

**Figure A-2: Bill of Materials**
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