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TI Designs – Precision: Verified Design

±100 A Closed-Loop Current Sensor Reference Design using Bi-Polar Supplies

TEXAS INSTRUMENTS

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Design Resources

Archive	All Design files
TINA-TI™	SPICE Simulator
DRV411	Product Folder
OPA237	Product Folder
TPS79850	Product Folder

Circuit Description

This dual-supply closed loop current sensor solution is designed to accurately measure dc, ac and pulsed currents to ±100 A with galvanic isolation between the primary and secondary circuits. The linear range of the output is ±2.5 V using a supply voltage of ±6 V to ±15 V.

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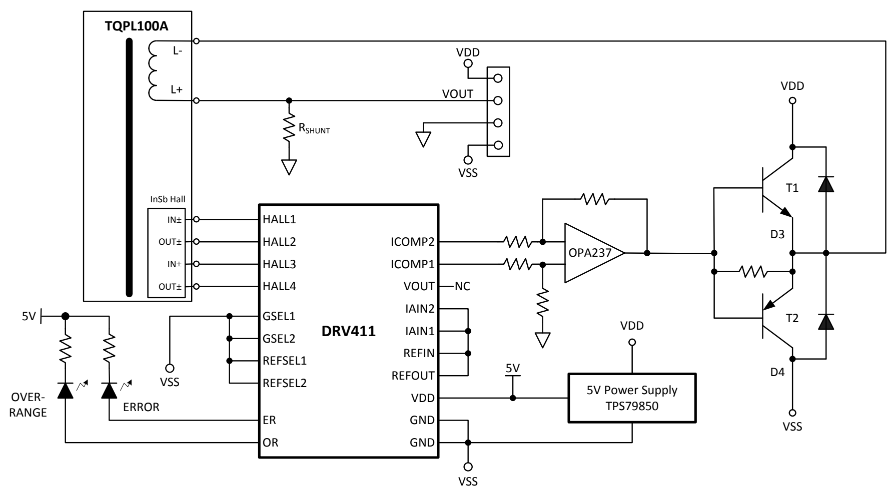

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1 Design Summary

The design requirements are as follows:

- Supply Voltage: ±6 V to ±15 V
- Input: ±100 A
- Conversion Ratio 1:2000
- Output: -2.5 V – +2.5 V
- Maximum Shunt Voltage: 2.5 V

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

	Goal	Calculated	Measured
Error (%FSR)	±0.2%	0.14%	±0.07%
Offset	±7 mV	±7.14 mV	3.4 mV

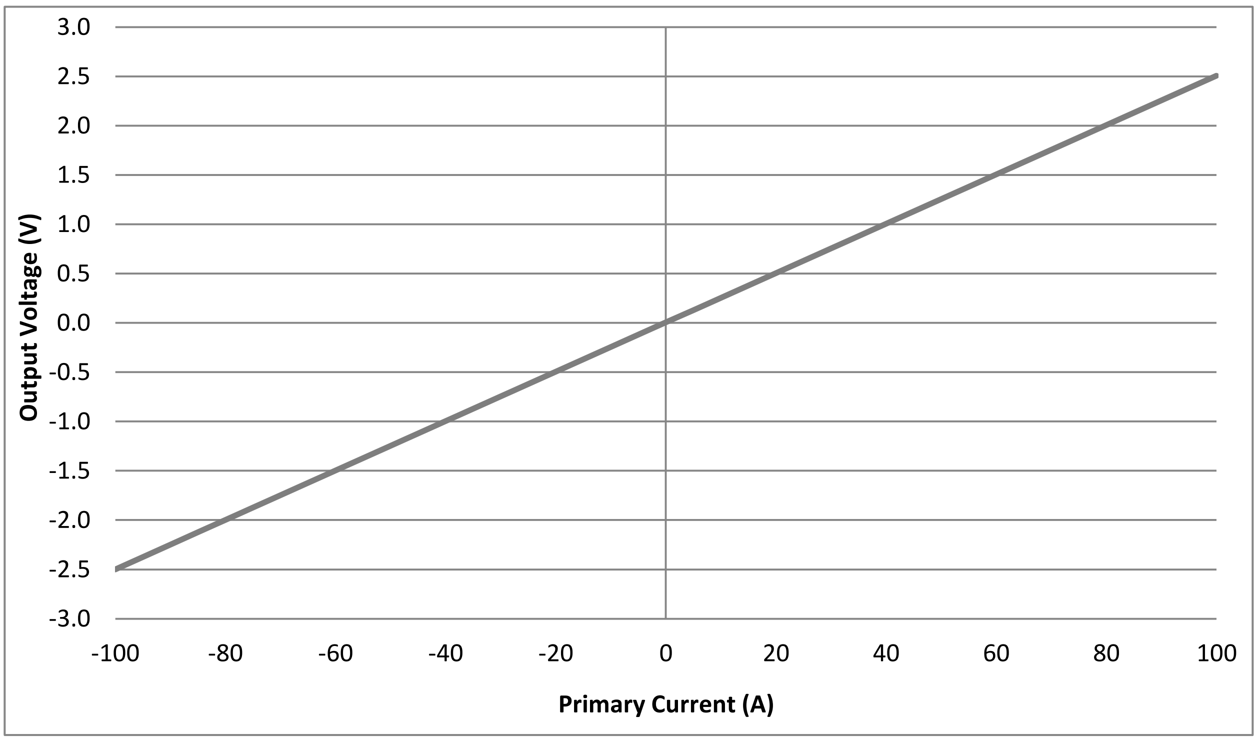

Figure 1: Measured Transfer Function

2 Theory of Operation

Closed-loop current sensors use a Ferromagnetic core with a sensing element or field probe inserted into a gap in the core. The core picks up the magnetic field created by the current flowing through the primary winding. Changes in the magnetic field are measured by the sensing element and passed on to a signal-conditioning stage for filtering and amplification. The external drive stage provides current to the compensation coil, which creates an opposing magnetic field that cancels the effect of the primary current. The resulting voltage output is proportional to the current flowing through the primary winding as shown in the transfer function defined in Equation 1.

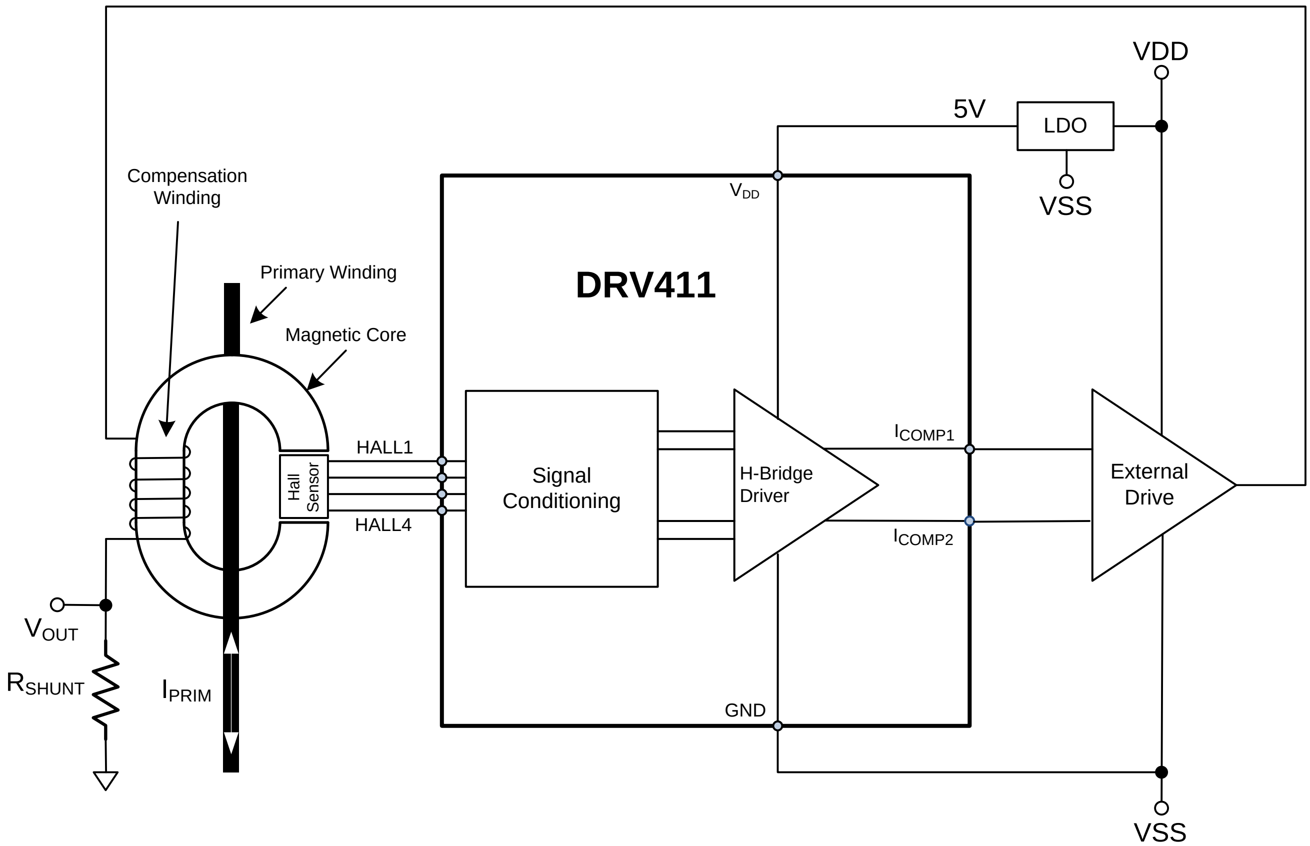

Figure 2: Closed-Loop Sensor Block Diagram

$$V_{OUT} = I_{PRIM} \times \left(\frac{N_P}{N_S}\right) \times R_{SHUNT} \quad (1)$$

2.1 Potential Sources of Output Error

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

2.1.1 Hall Effect Sensor

In closed-loop sensors, the Hall sensor voltage is amplified causing a current to flow through the compensation coil wound around the magnetic core. This action generates magnetism with amplitude that is the same magnitude but in the opposite direction to that of the primary current conductor, compensating the flux in the core to zero. The nonlinearity and temperature dependence of the Hall element are therefore compensated, but the offset remains. The offset of a quality indium antimonide (InSb) Hall element is typically ±7 mV.

2.1.2 External Drive Amplifier

The external drive amplifier's offset voltage (V_{OS}) will be a contributing source of offset error in this design. The magnitude of offset error at the output will equal the product of the amplifier's gain and offset voltage along with the offset voltage from the Hall element. Ideally, the offset error is linear across the entire input range and appears as a vertical shift (up or down) in the transfer function. This vertical shift can be calibrated out at the expense of dynamic range.

2.1.3 Shunt Resistor

The shunt or sense resistor will have an impact on the overall gain of the sensor. To improve the circuit performance, use a good-quality sense resistor properly power sized to reduce the effects of self-heating.

3 Component Selection

3.1 Hall Signal Conditioning

The DRV411 is used in this design to drive the hall element and provide an output voltage that is proportional to the input current to an external bi-polar drive stage. The DRV411 employs a current spinning technique that effectively removes the offset and temperature drift errors inherent in the Hall element. The H-Bridge driver stage of the DRV411 is connected to an OPA237, which is powered from ±6V to ±15V. The differential amplifier stage provides gain of 4 V/V to a matched pair of bipolar junction transistors that drive the compensation coil.

3.2 5V LDO Selection

The TPS79850-Q1 low-dropout (LDO) linear regulator was chosen for this reference design because of its wide input voltage range, low-dropout voltage, and low quiescent current. The current consumption of the DRV411 is typically 12 mA. With a sensor power supply range of ±6 V to ±18 V (MAX), the TPS79850-Q1 can easily provide the power required by the DRV411. In the DGN package, the power dissipated (P_{DISS}) is defined in Equation 2:

$$I_{OUT(MAX)} \times (V_{IN(MAX)} - V_{OUT}) + I_{GND} \times (V_{IN(MAX)}) \quad (2)$$

Where:

$I_{OUT(MAX)} = 13$ mA
$V_{IN(MAX)} = 36$ V
$V_{OUT} = 5$V
I_{GND} at ($I_{OUT} = 13$ mA, $V_{IN} = 36$V) = 1 mA

Therefore:

$$P_{DISS} = 13mA \times (36V - 5V) + 1mA \times (36V) = 0.0364W \quad (3)$$

The junction temperature rise above ambient will be approximately equal to the following:
0.0364 W × 60° C/W or 2.18° C.

3.3 Sensor Selection

The passive sensor in this design has two components: a compensation coil and a Hall element. A typical compensation winding found in a 100-A current sensor has 2000 turns (N_s). With one turn through the primary (N_p) carrying 100 A (I_p), the resulting current conversion ratio is 1:2000. The resulting secondary current (I_s) is 50 mA as shown in Equation 4.

$$I_S = \frac{I_p \times N_P}{N_S} = \frac{100A \times 1}{2000} = 50mA \quad (4)$$

In precision current sensors, the field probe is often a linear hall device. The TQPL100A from Topstek is a passive sensor that houses a 2000-turn compensation coil and an indium antimonide (InSb) Hall Effect device.

3.4 Shunt Resistor Selection

A shunt resistor placed in series with the compensation winding current path is needed to provide a voltage to the output of the sensor. Selection of an appropriate shunt resistor is dependent on the amount of current flowing through the secondary coil.

With a design target of ±2.5 V output for ±100A of primary current, the maximum voltage across the shunt (V_{shunt}) will be ±2500 mV. The maximum value of R_{shunt} is calculated in Equation 5.

$$R_{shunt(max)} = \frac{V_{shunt(max)}}{I_{s(max)}} = \frac{2500mV}{50mA} = 50\Omega \quad (5)$$

3.4.1 Output Voltage

The output voltage from the sensor will be directly proportional to the primary current. With ±100 A of primary current, the output voltage (V_{out}) can be calculated using Equation 6.

$$V_{out(max)} = \pm V_{shunt} = R_{SHUNT} \times I_S = 50\Omega \times \pm 50mA = \pm 2.5V \quad (6)$$

3.5 Compensation Coil Drive Stage

The compensation coil drive stage is comprised of an OPA237 and a pair of matched bi-polar junction transistors. The OPA237 was chosen for this application because of its low cost, wide supply range, and low output offset voltage specification of 250 µV typical.

The OPA237 is configured as a difference amplifier with a gain of 4 V/V similar to the configuration of the difference amplifier found inside the DRV411.

4 Calculated Performance

The errors from the selected components are listed in Table 2.

Table 2. Typical Error Contributions

Specification	Typical
Input Offset DRV411 (µV)	±30
Diff Amp Gain Error (%FS)	0.1
OPA237 Offset Error (µV)	250
Shunt Tolerance (%)	0.1

These errors can be referred to the output and compared to the full-scale output voltage to determine the total error as shown in Equations 7 – 10.

$$V_{os\_DRV411}\,(V) = \text{InputOffset} \times 4V/V = \pm 120\mu V \quad (7)$$

$$GE_{DA}(V) = \frac{\text{GainError}(\%FS)}{100} \times 5V = \pm 5mV \quad (8)$$

$$V_{OS\_OPA237}\,(V) = \text{Offset} \times 4V/V = \pm 1mV \quad (9)$$

$$R_{SH\_TOL}(V) = \frac{\text{ShuntTolerance}(\%)}{100} \times 5V = \pm 5mV \quad (10)$$

Table 3 lists the errors referred to the full-scale output voltage.

Table 3. Typical Error Values

Specification	Typical (mV)
Offset DRV411	0.120
Diff Amp Gain Error	5
OPA237 Offset Error	1
Shunt Tolerance	5

Taking the root of the sum of the squared terms (RSS) provides a probable estimate for the total output error for the system as shown in Equation 11.

$$\text{Error(mV)} = \sqrt{0.12^2 + 5^2 + 1^2 + 5^2} = 7.14 \tag{11}$$

The full-scale error is then calculated using Equation 12.

$$\text{Error(\%FS)} = \frac{\text{Error(V)}}{\text{Vout(FS)}} \times 100 = \frac{0.00714}{5} \times 100 = 0.14\% \tag{12}$$

5 PCB Design

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

5.1 PCB Layout

The two-layer printed circuit board (PCB) used in this design measures 1.875” x 0.725” as shown in Figures 3A and 3B. The DRV411 and supporting circuitry occupies the top-copper layer. The bottom-copper layer contains a solid-ground plane that provides a low-impedance path for return currents. U1 (the TPQL100A module) and J1 are mounted from the bottom side.

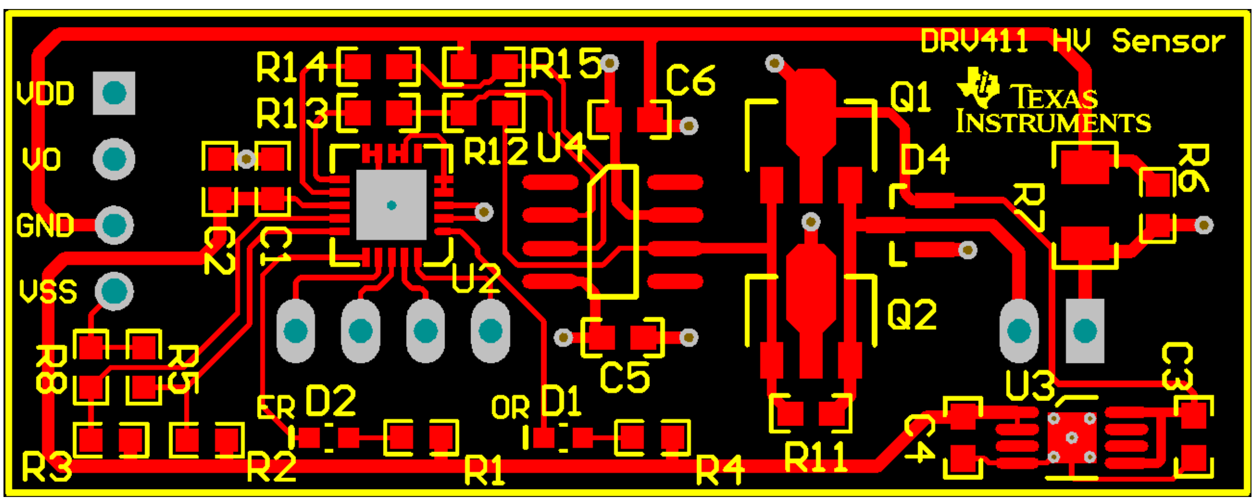

Figure 3A: PWB Top Layer

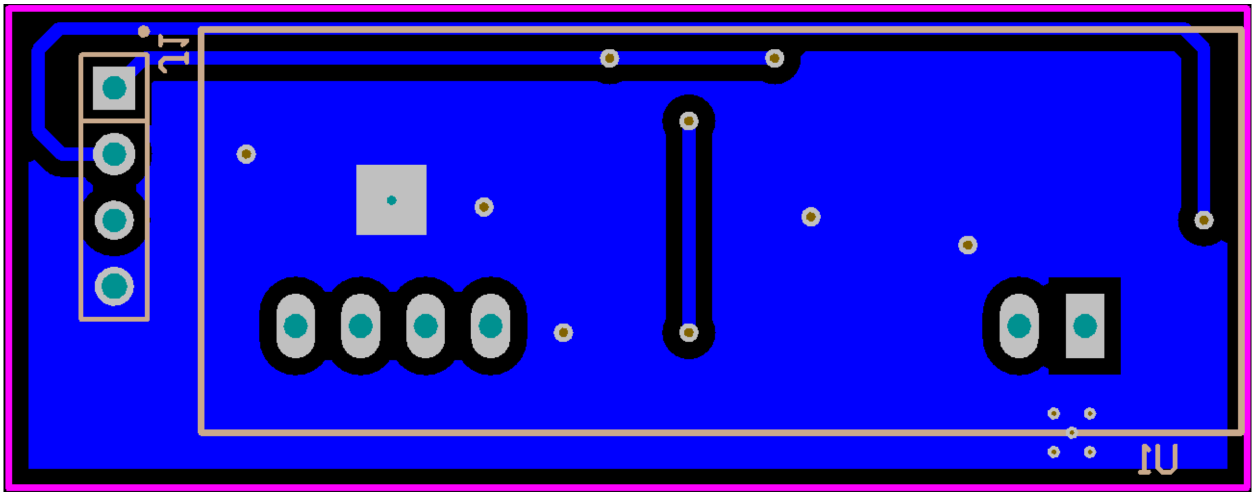

Figure 3B: PWB Bottom Layer

6 Verification & Measured Performance

A fixed ±15-V power supply provides power to the sensor circuit. Primary current is provided from a 250-A DC source across the entire input range of ±100 A. Figure 4 shows the printed wiring board with the sensor and primary winding.

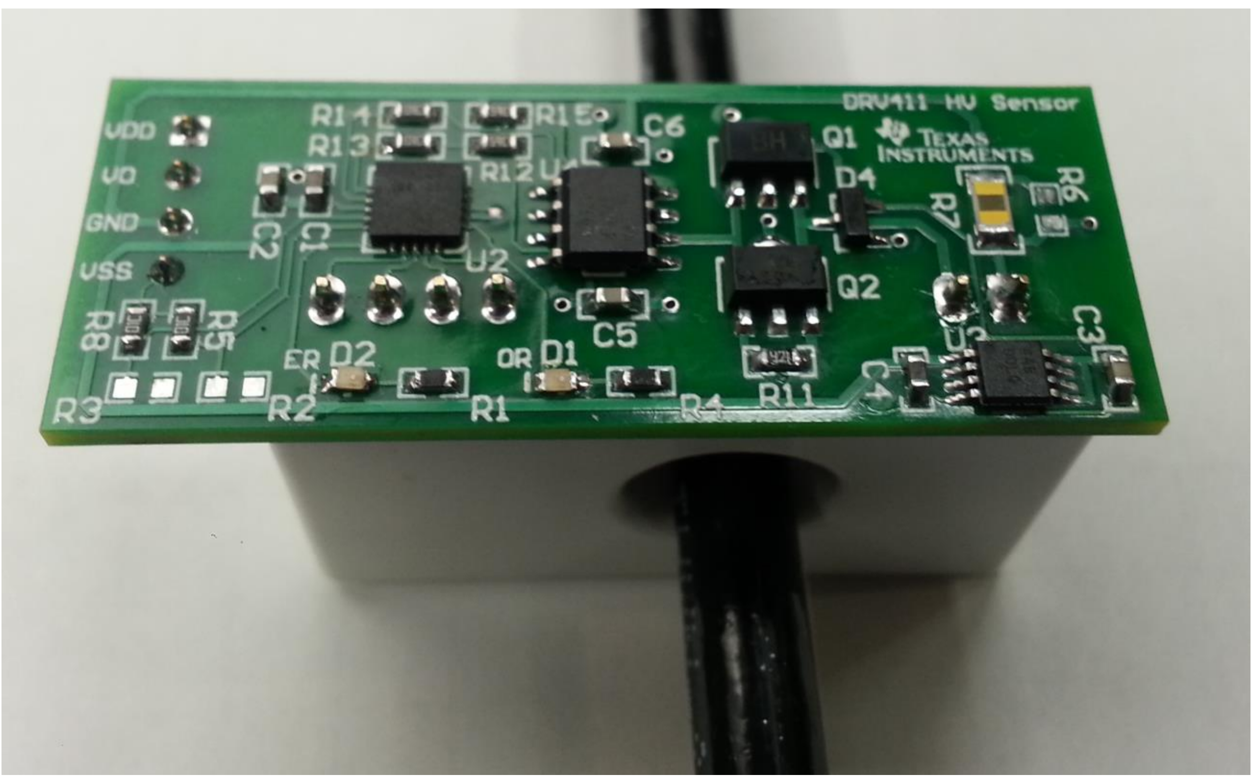

Figure 4: Primary Winding, Sensor and PWB

6.1 Transfer Function

The output voltage was measured at 5-A increments across the full range of current sensing (±100 A). The measured DC transfer function is shown in Figure 5.

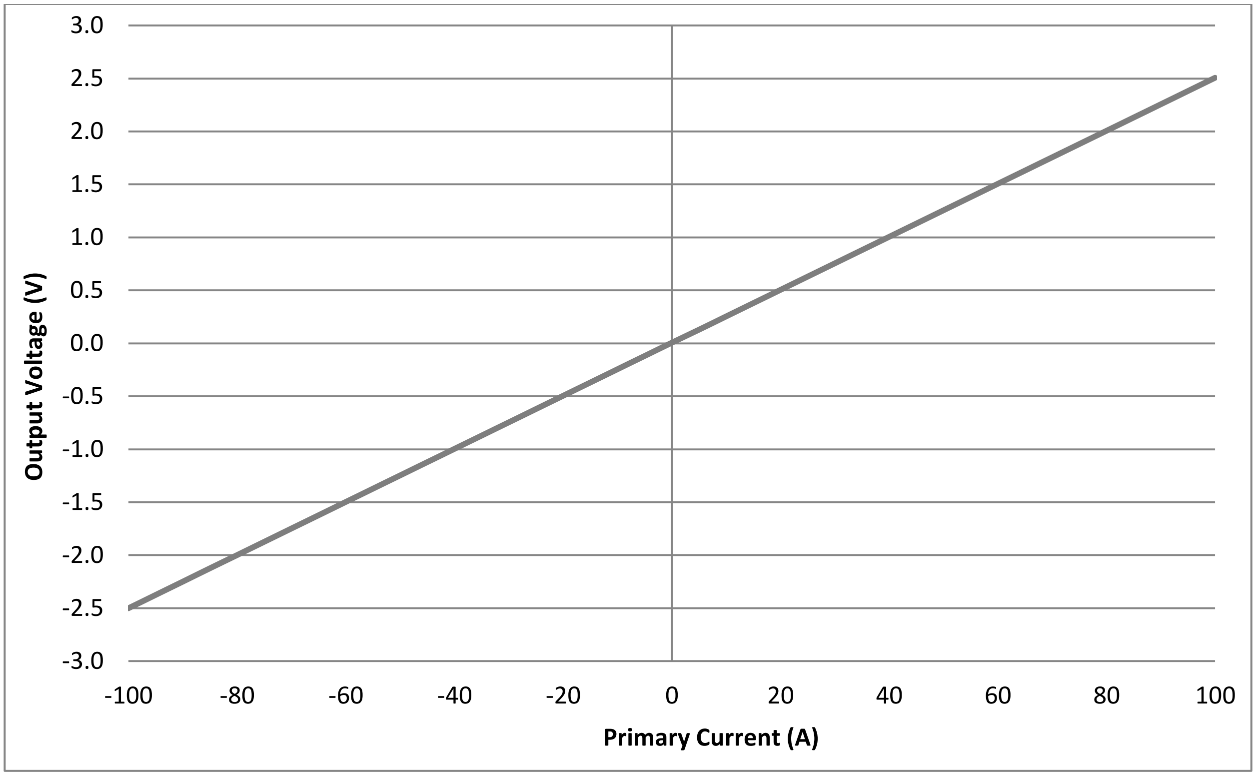

Figure 5: DC Transfer Function (V_{OUT} vs. Ip)

6.2 Full-Scale Error Analysis

The full-scale error (%FSR) of the output is calculated using Equation 13.

$$\text{Full-Scale Error (\%FSR)} = 100 \times \frac{V_{OUT\_MEASURED} - V_{OUT\_IDEAL}}{V_{OUT\_IDEAL\_MAX} - V_{OUT\_IDEAL\_MIN}} \quad (13)$$

The circuit's full-scale range error is plotted over the ±100-A input range in Figure 6.

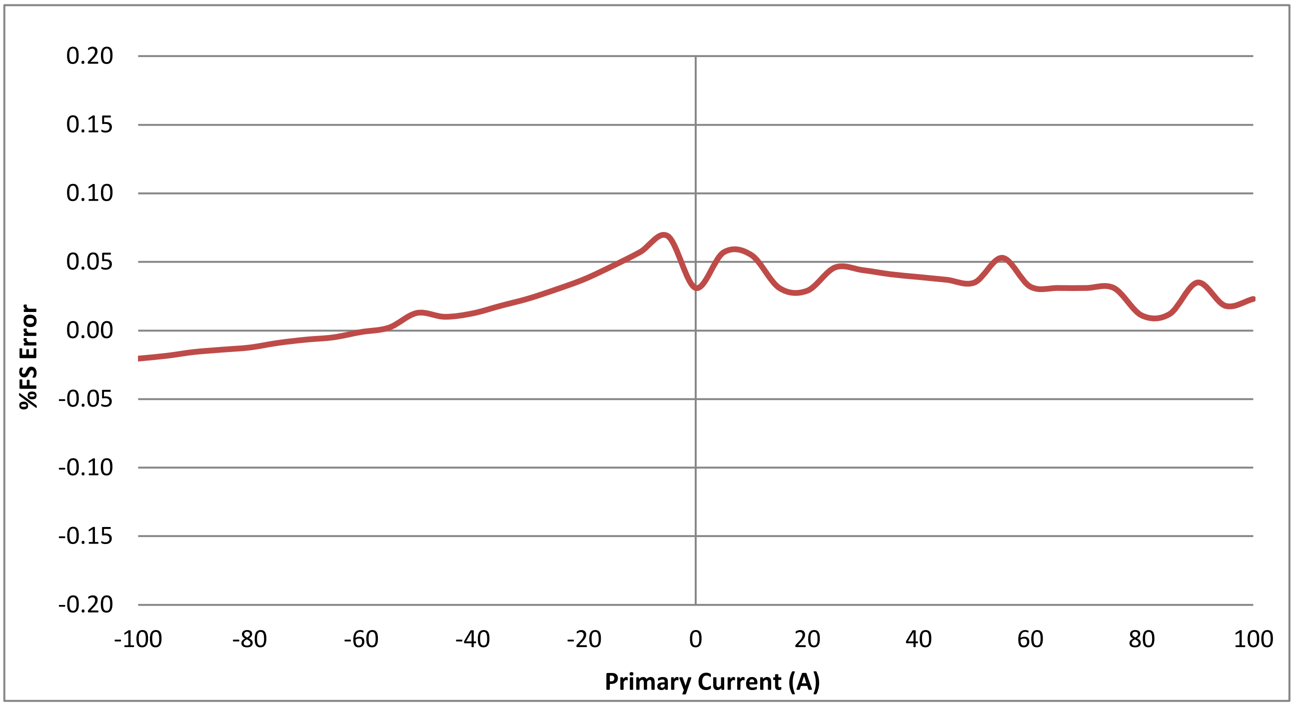

Figure 6: Full-Scale Error vs. Input Current

6.3 Table of Measured Results

The following table provides raw data for several measurement points.

Table 4. Measurement Data

I Primary (A)	V_{OUT} (V)	% FSR Error
100.03	2.502	0.023
75.05	1.878	0.031
50.05	1.253	0.035
25.02	0.628	0.046
0	0.002	0.031
-25.01	-0.624	0.030
-50.02	-1.249	0.013
-75.03	-1.876	-0.009
-100.03	-2.502	-0.020

7 Modifications

The reference board includes two LEDs as indicators for over range and error conditions. These components are not a critical need for the design and can be left off for cost savings. The printed wiring board could also be made in such a way that it is incorporated into the housing with the coil and Hall effect device.

The OPA237 package used in this design is the MSOP8. Single OPA237 devices are available in a SOT23-5 package, which would make the overall footprint of the sensor smaller. Tighter tolerance on the gain resistors around the OPA237 would also provide more accuracy to the sensor module.

The shunt resistor can be sized for the desired output voltage if the power limitations of the resistor are considered along with its thermal drift characteristics.

Appendix A.

A.1 Electrical Schematic

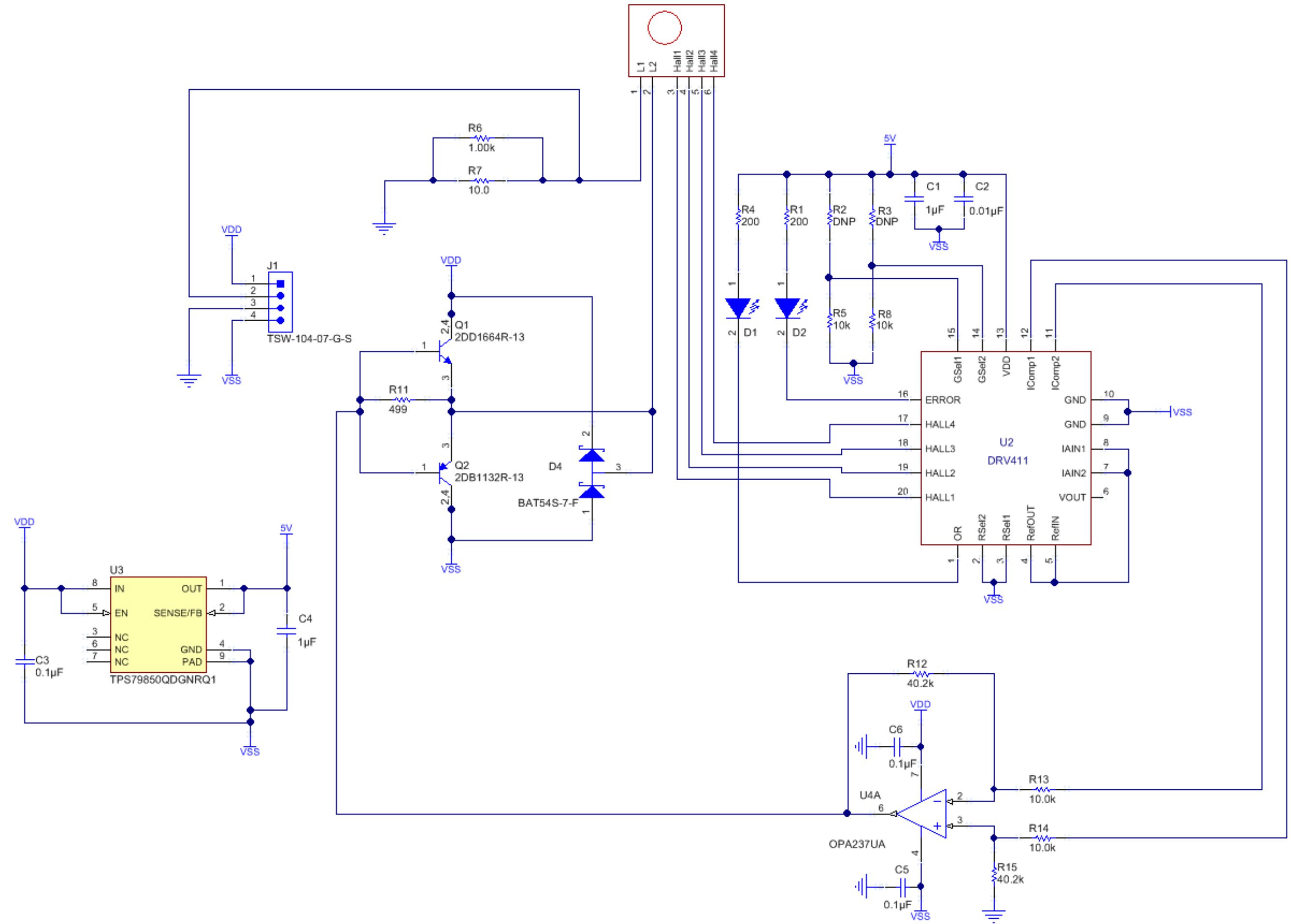

Figure A-1: Electrical Schematic

A.2 Bill of Materials

Item #	Qty	Designator	Description	Manufacturer	Part Number
1	1	N/A	Printed Wiring Board	Texas Instruments	N/A
2	2	C1 C4	1.0uF, 0603, Ceramic, X7R, 10V, 10%	Kemet	C0603C105K8RACTU
3	4	C2 C3 C5 C6	0.1uF, 0603, Ceramic, X7R, 50V, 10%	Kemet	C0603C104K5RACTU
4	2	D1 D2	Yellow LED	Lite-On	LTST-C191KSKT
5	1	D4	BAT54S, Dual Schottkey	Vishay	BAT54S-E3-08
6	1	Q1	NPN	Diodes Inc	BCX56TA
7	1	Q2	PNP	Diodes Inc	BCX53TA
8	2	R1 R4	200 ohm, 0603, 5%, .1W Resistor	Yageo America	RC0603JR-07200RL
9	2	R5 R8	10K ohm, 0603, 1%, .1W Resistor	Yageo America	RC0603FR-0710KL
10	2	R13 R14	10K ohm, 0603, 0.1%, .1W Resistor	Yageo America	RT0603BRD0710KL
11	1	R7	49.9 ohm, 1206, 0.1%, 1W Resistor	Vishay	PHP01206E49R9BST5
12	1	R11	470 ohm, 0603, 5%, .1W Resistor	Yageo America	RC0603JR-07470RL
13	2	R12 R15	40.2K ohm, 0603, 0.1%, .1W Resistor	Yageo America	RT0603BRD0740K2L
15	1	J1	4-pin, Single Row vertical mount male header	Samtec	TSW-104-14-T-S
16	1	U1	100 A Passive Current Sensor	Topstek	TQPL50A
17	1	U2	DRV411	Texas Instruments	DRV411AIRGPT
18	1	U3	TPS78950Q	Texas Instruments	TPS79850QDGNRQ1
19	1	U4	OPA237	Texas Instruments	OPA237UA

Figure A-2: Bill of Materials

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