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TI Designs – Precision: Verified Design

±50A Current Sensor using Closed-Loop Compensated Hall Element

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Circuit Description

This single-supply closed loop current transducer solution is designed to accurately measure dc, ac and pulsed currents to +/-50 A with galvanic isolation between the primary and secondary circuits. The linear range of the output is from 500 mV to 4.5 V.

Design Resources

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

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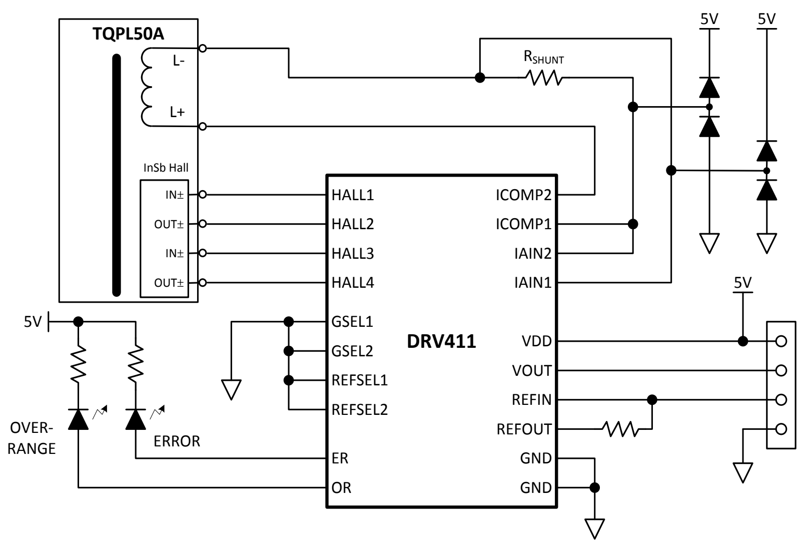

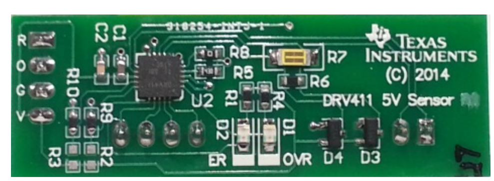

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1 Design Summary

The design requirements are as follows:

- Supply Voltage: 5 V
- Input: ±50 A
- Conversion Ratio 1:1000
- Output: 500 mV – 4.5 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

	Goal	Calculated	Measured
Error (%FSR)	± 0.2%	0.16%	±0.014%
Offset	± 7 mV	±5.12 mV	-5.6 mV

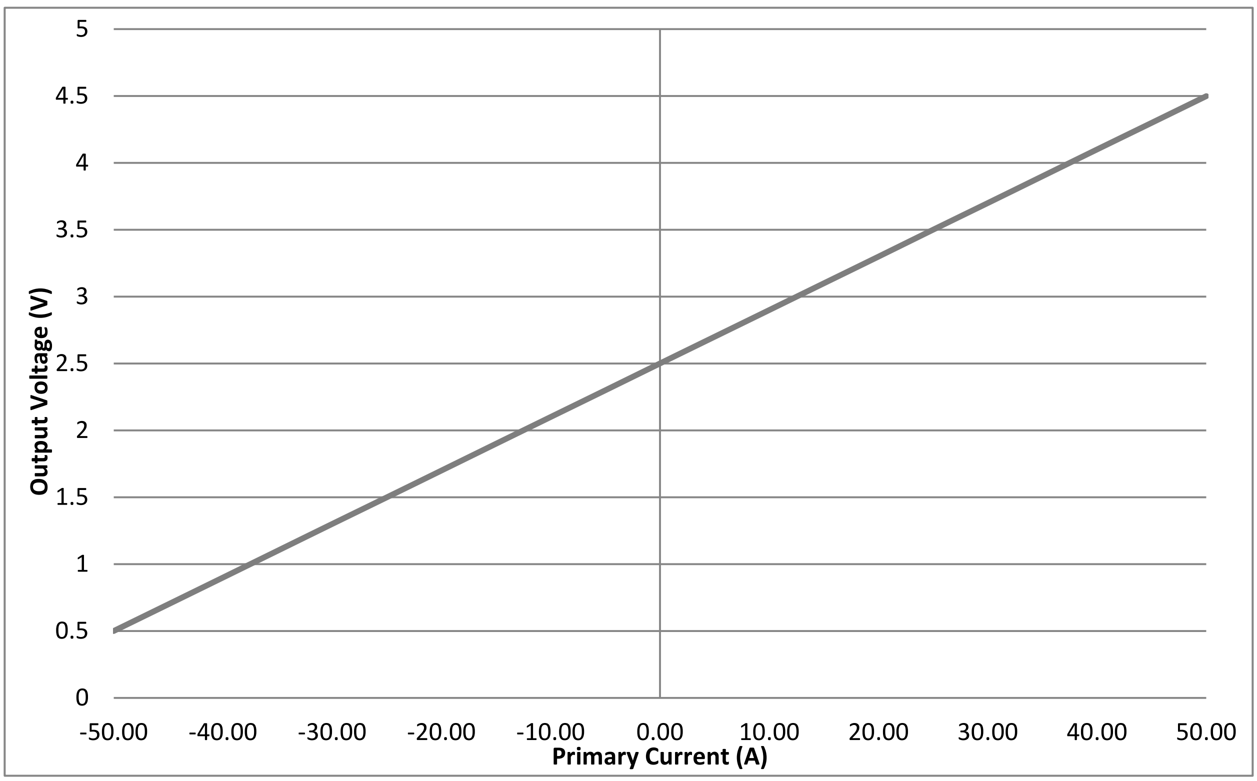

Figure 1: Measured Transfer Function

2 Theory of Operation

Closed loop current transducers use a ferro-magnetic 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 sense element and passed on to a signal conditioning stage for filtering and amplification. The coil driver stage provides current to the compensation coil which creates an opposing magnetic field that cancels the effect of the primary current. The compensation current passes through a shunt resistor which provides a differential voltage to a precision sense amplifier. The amplifier gains the shunt voltage and drives the output stage of the transducer. The resulting voltage output is proportional to the current flowing through the primary winding as shown in the transfer function defined in Equation 1.

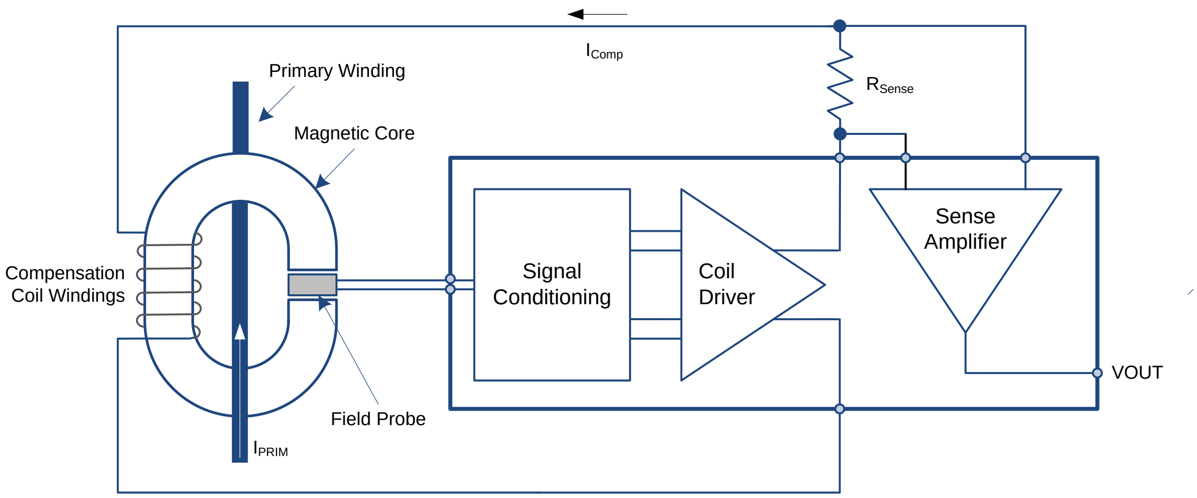

Figure 2: Closed Loop Sensor Block Diagram

$$VOUT = I_{PRIM} * \left(\frac{N_P}{N_s}\right) * R_{SENSE} * Gain \qquad (1)$$

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 transducer. Several sources of errors are discussed in the following sections.

2.1.1 Hall Effect Sensor

In closed loop transducers, the Hall voltage is amplified and the amplifiers current output flows through the compensation coil wound around the magnetic core. This generates magnetism with amplitude that is the same 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. Offset of a typical indium antimonide (InSb) Hall element is typically ±7 mV.

2.1.2 Sense Amplifier and Internal Reference

The 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. There can be an additional error form the internal reference which biases the sense amplifier output. This 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 transducer. Using a good quality sense resistor properly sized to reduce the effects of self-heating will directly impact the circuit performance.

3 Component Selection

3.1 Hall Signal Conditioning, Coil Driver and Sense amplifier

To minimize the component count and error sources, the DRV411 was chosen to provide a complete solution to drive the hall element, the compensation coil and to provide a precision differential amplifier for the output stage.

The DRV411 employs a current spinning technique to drive the Hall element. This technique effectively removes the offset and temperature drift errors inherent in the Hall element. An H-Bridge driver stage can provide up to 250 mA to the compensation coil. The differential amplifier stage provides gain of 4 V/V to the shunt resistor.

3.2 Sensor Selection

The sensor has two components; a compensation coil and a Hall element. A typical compensation winding found in a 50 A current transducer has 1000 turns (N_s). With 1 turn through the primary (N_p) carrying 50 A (I_p), the resulting current conversion ratio is 1:1000. The resulting secondary current (I_s) is 50 mA as shown in Equation 3.

$$I_s = \frac{I_p * N_P}{N_s} = \frac{50A*1}{1000} = 50mA \quad (3)$$

In precision current transducers, the field probe is often a linear hall device. The TQPL50A from Topstek is a passive sensor which houses a 1000 turn compensation coil and an indium antimonide (InSb) Hall effect device. For the TQPL50A passive sensor, the resistance of the secondary winding is typically 11 Ω at 25° C.

3.3 Shunt Resistor Selection

A shunt resistor placed in series with the compensation winding current path is needed 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 secondary coil as well as the gain of the difference amplifier.

The gain of the difference amplifier in the DRV411 is 4 V/V. With a design target of ±2V output for ±50A of primary current, the maximum voltage across the shunt (V_{shunt}) will be ±500 mV. The maximum value of R_{shunt} is calculated in Equation 4.

$$R_{shunt(\max)} = \frac{V_{shunt(\max)}}{I_{s(\max)}} = \frac{500mV}{50mA} = 10\Omega \qquad (4)$$

3.3.1 Output Voltage

The output voltage from the difference amplifier will be directly proportional to the primary current plus the common mode output voltage (V_{cm}). With ±50 A of primary current, the output voltage (V_{out}) can be calculated using Equation 5.

$$V_{out(\max)} = \pm V_{shunt} \times G = \pm 500mV \times 4 = \pm 2.0V \qquad (5)$$

The output common mode output voltage of the DRV411 is based on the reference voltage. This design uses a 5V source and fixed 2.5V reference so the total output voltage swing will be from 0.5 V to 4.5V.

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
Gain Error DRV411 (%FS)	0.02
Linearity DRV411 (ppm)	12
Reference Error (mV)	±5
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 6 – 10.

$$\text{Offset Error(V)} = \text{InputOffset} * 4\text{V/V} = 120\mu V \qquad (6)$$

$$\text{GainError(V)} = \frac{\text{GainError(\%FS)}}{100} * 4\text{V} = 800\mu V \qquad (7)$$

$$\text{Linearity(V)} = \frac{\text{Linearity(ppm)}}{1000000} * 4\text{V} = 48\mu V \qquad (8)$$

$$\text{Reference Error (V)} = \pm 5\,\text{mV} \qquad (9)$$

$$\text{ShuntTolerance(V)} = \frac{\text{ShuntTolerance(\%)}}{100} * 4\text{V} = 4mV \qquad (10)$$

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

Table 3. Typical Error Values

Specification	Typical (mV)
Offset DRV411	0.120
Gain Error DRV411	0.800
Linearity DRV411	0.048
Reference Error	5
Shunt Tolerance	4

The offset is mostly dominated by the reference error. 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 9.

$$Error(mV) = \sqrt{.12^2 + .80^2 + .048^2 + 5^2 + 4^2} = 6.45 \quad (11)$$

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

$$Error(\%FS) = \frac{Error(V)}{Vout(FS)} * 100 = \frac{0.00645}{4} * 100 = 0.16\% \quad (12)$$

5 PCB Design

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

5.1 PCB Layout

The two-layer printed circuit board (PCB) used in this design measures 1.875” x 0.650” as shown in Figures 2A and 2B. The DRV411 and supporting circuitry occupies the top-copper layer. The bottom-copper layer contains a solid ground plane which provides a low-impedance path for return currents. U1 (the TPQL50A module) and J1 are mounted from the bottom side.

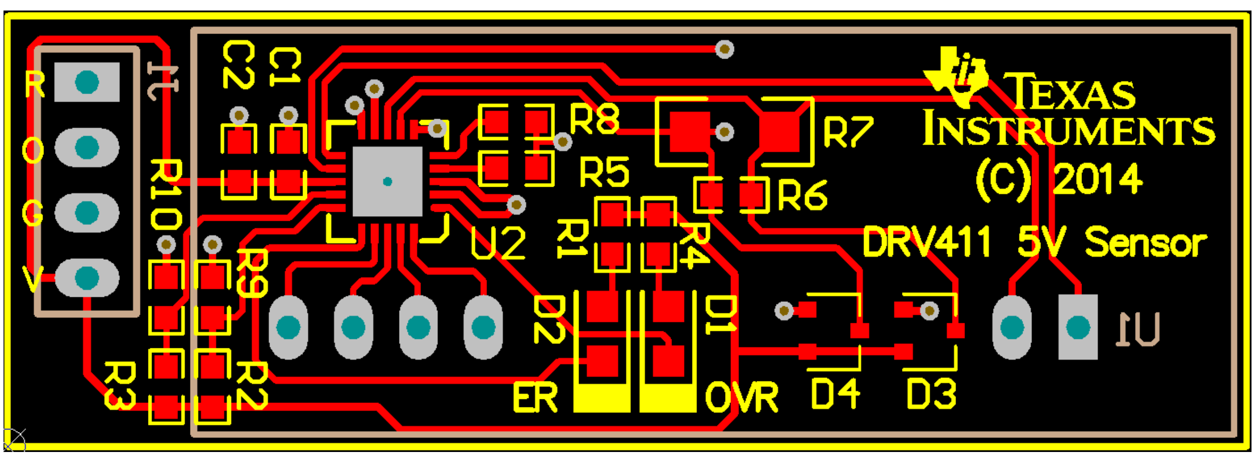

Figure 3A: PWB Top Layer

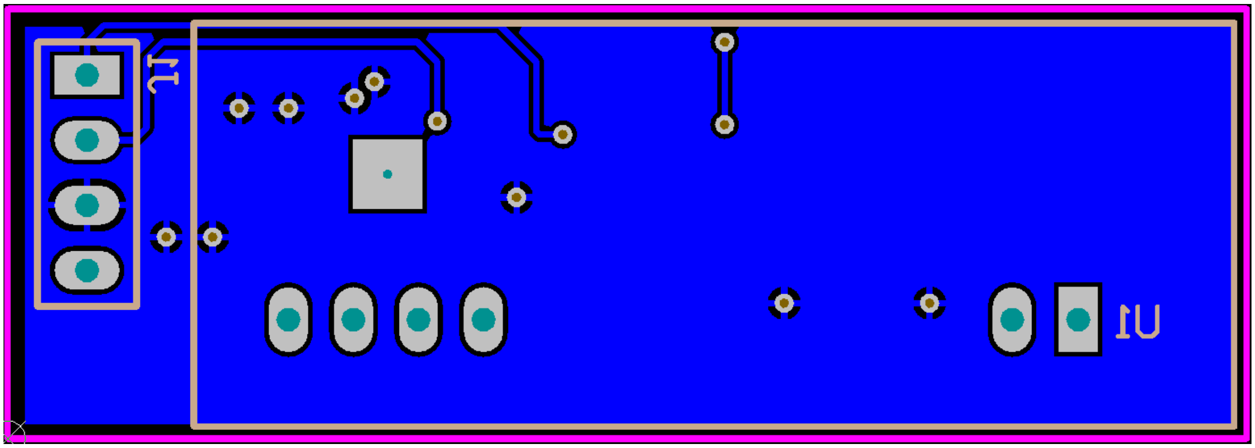

Figure 3B: PWB Bottom Layer

6 Verification & Measured Performance

A fixed 5V power supply provided power to the transducer circuit. Primary current was provided through a 100 A DC source across the entire input range of ±50 A. Figure 3 shows the printed wiring board with the sensor and primary winding.

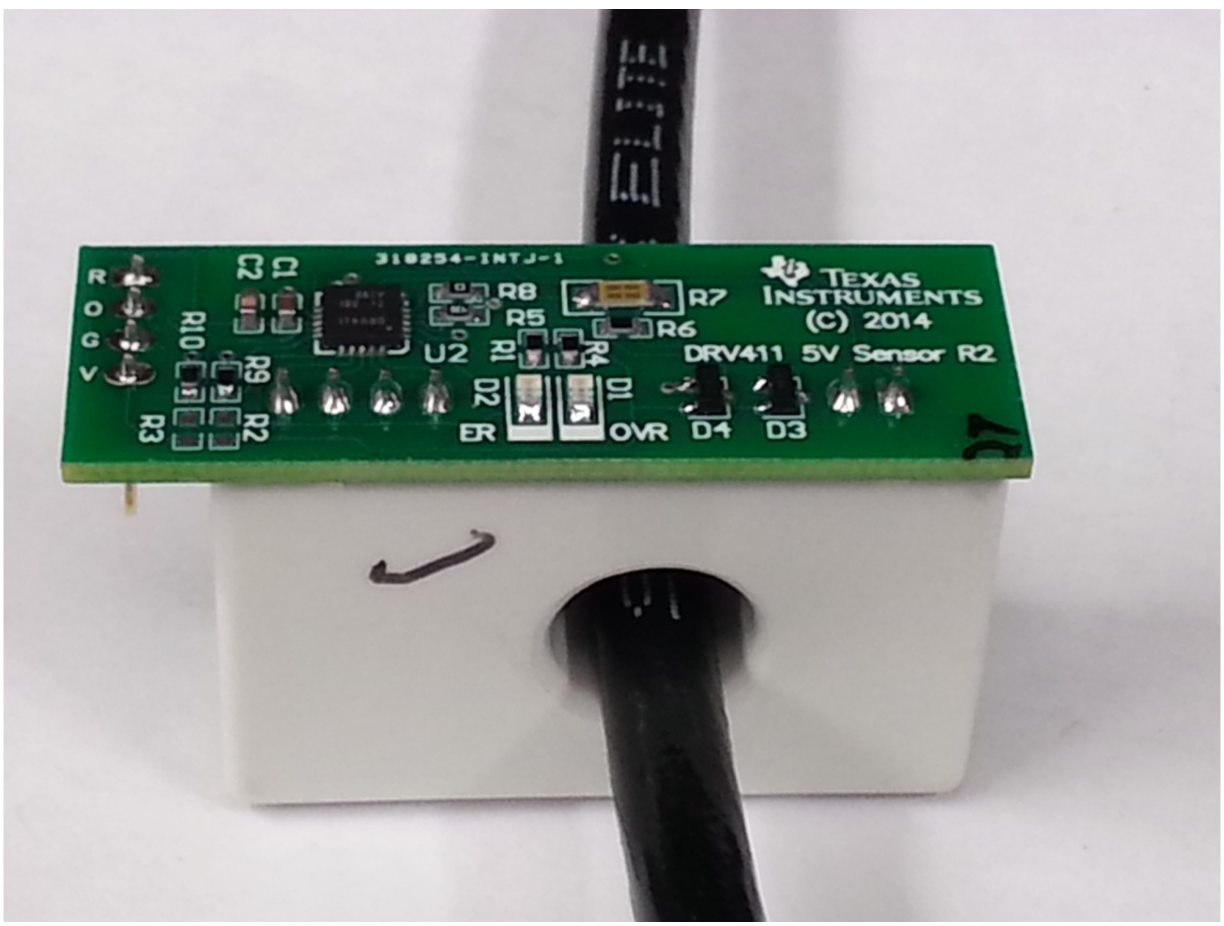

Figure 4: Primary Winding, Sensor and PWB

6.1 Transfer Function

The output voltage was measured at 5A increments across the full range of current sensing (±50 A). The measured dc transfer function is shown in Figure 4.

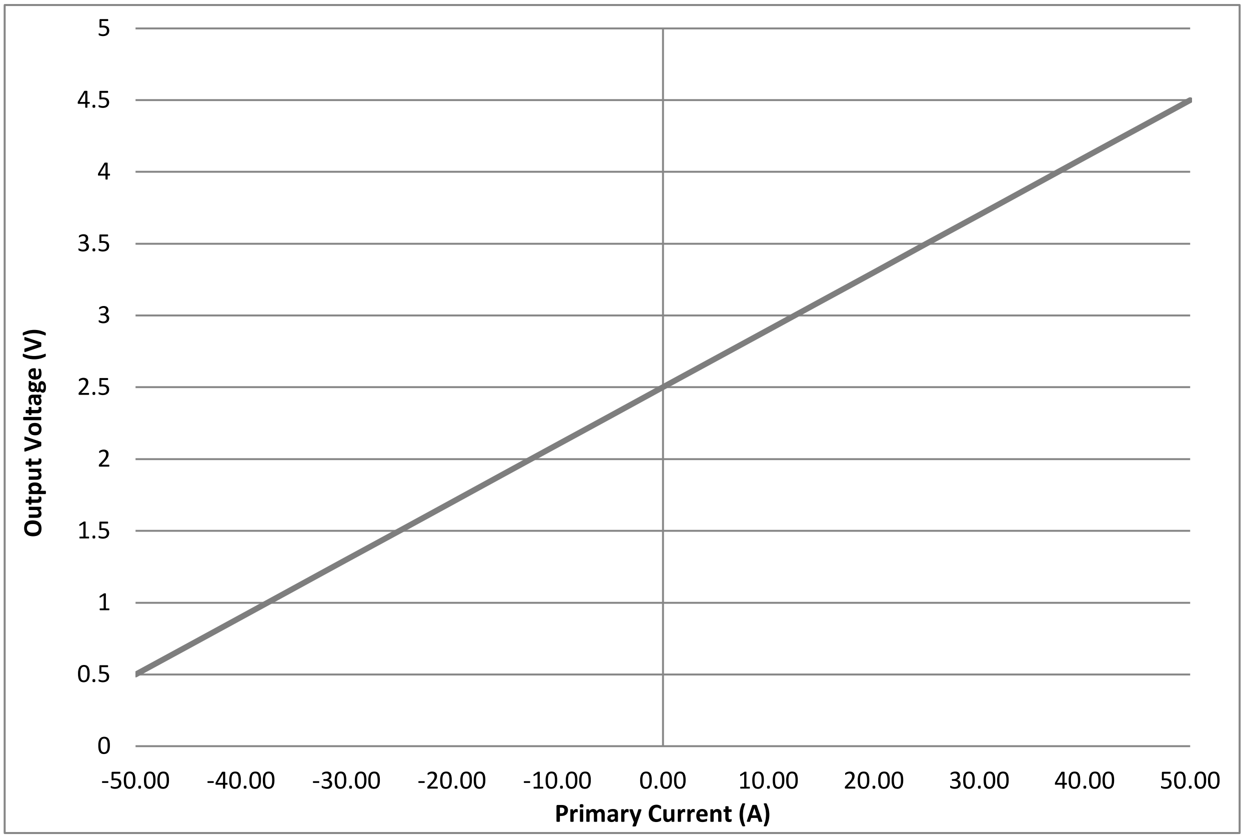

Figure 5: DC Transfer Function (Vout vs. Ip)

6.2 Full-Scale Error Analysis

The full-scale error (%FSR) of the output is calculated using Equation 2.

$$\text{Full-Scale Error (\%FSR)} = 100 \times \frac{V_{OUT\_MEASURED} - V_{OUT\_IDEAL}}{V_{OUT\_IDEAL\_MAX} - V_{OUT\_IDEAL\_MIN}} \qquad (12)$$

The circuit's full-scale range error is plotted over the ±50A input range in Figure 5.

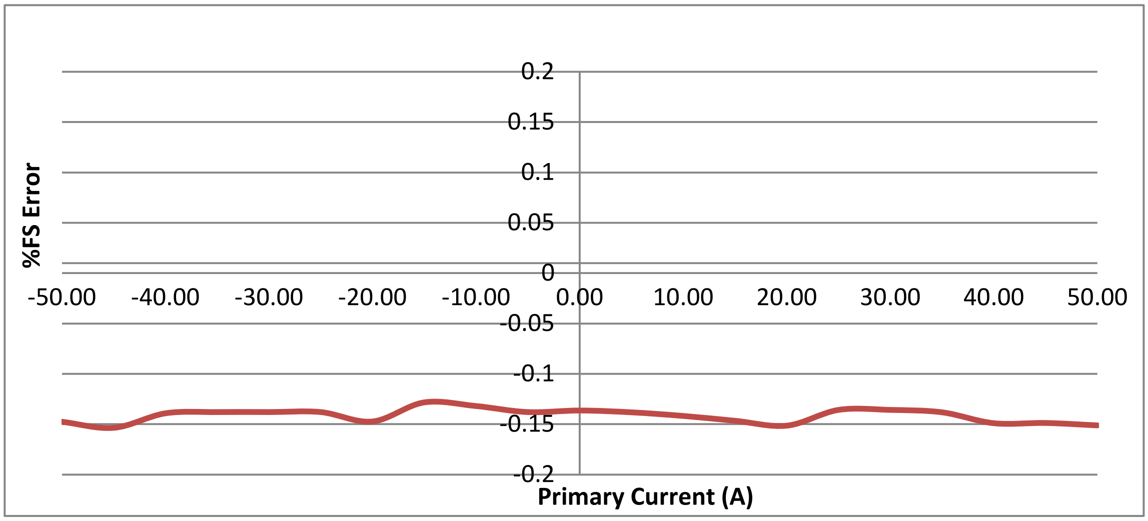

Figure 6: Full-Scale Error vs. Input Current

6.3 Table of Measured Results

The following table provides raw data for several measurement points.

Table 2. Measurement Data

I Primary (A)	Vout (V)	% FSR Error
50	4.495	-0.151
25	3.494	-0.135
0	2.494	-0.136
-25	1.494	-0.138
-50	0.494	-0.147

The final error is dominated by the offset error of the reference voltage and can be greatly improved by applying an offset calibration term.

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.

Larger currents can be measured with the DRV411 by choosing a different turn's ratio on the compensation coil.

Appendix A.

A.1 Electrical Schematic

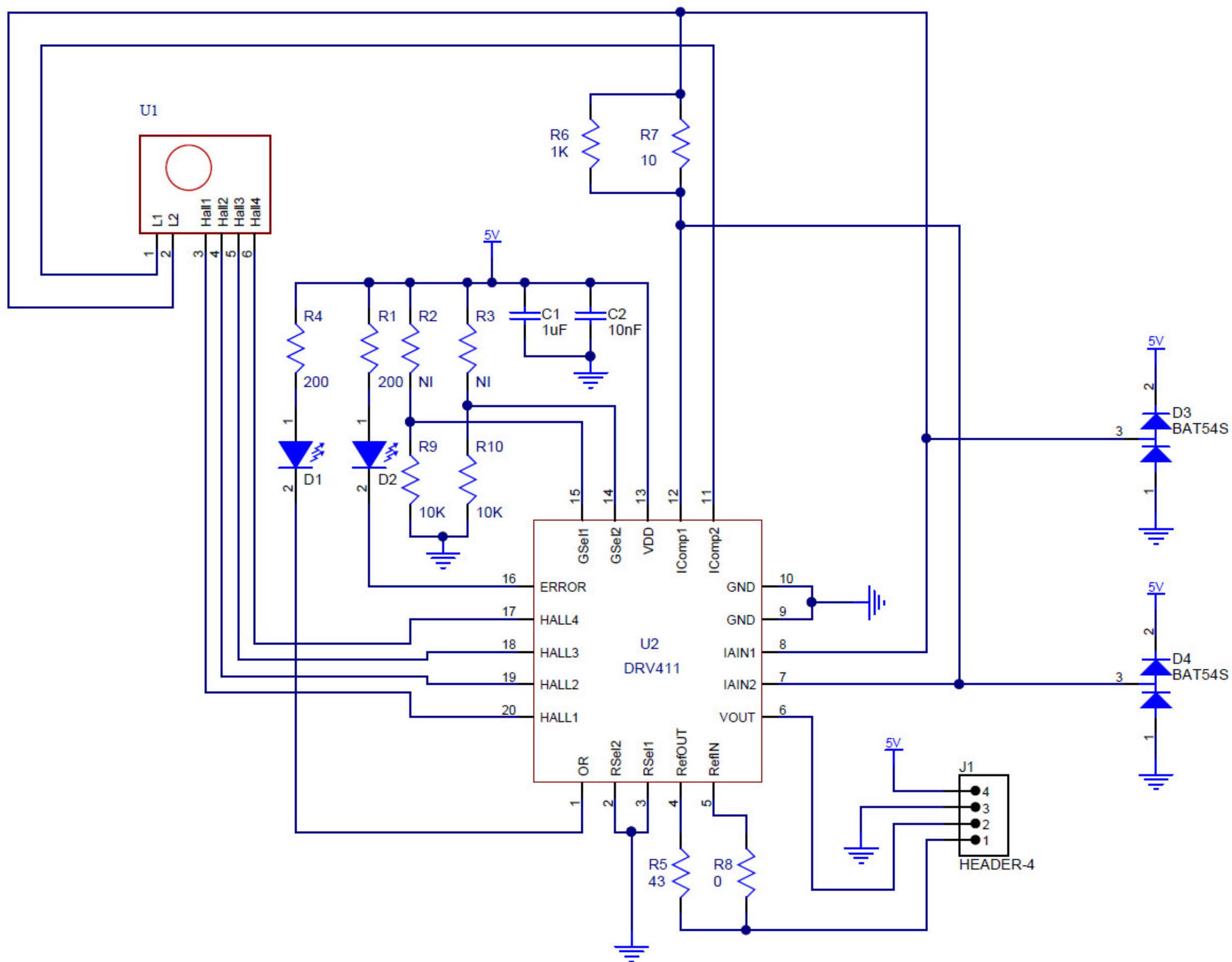

Figure A-1: Electrical Schematic

A.2 Bill of Materials

Item #	Qty	Designator	Description	Manufacturer	Part Number
1	1	N/A	Printed Wiring Board	Texas Instruments	TBD
2	1	C1	1.0uF, 0603, Ceramic, X7R, 10V, 10%	Kemet	C0603C105K8RACTU
3	1	C2	0.1uF, 0603, Ceramic, X7R, 10V, 10%	Kemet	C0603C104K8RACTU
4	2	D1 D2	Yellow LED	Lite-On	LTST-C170KSKT
5	2	D3 D4	BAT54S, Dual Schottkey	Vishay	BAT54S-E3-08
6	2	R1 R4	200 ohm, 0603, 5%, .1W Resistor	Yageo America	RC0603JR-07200RL
7	3	R6 R9 R10	10K ohm, 0603, 5%, .1W Resistor	Yageo America	RC0603JR-0710KL
8	1	R5	43 ohm, 0603, 5%, .1W Resistor	Yageo America	RC0603JR-0743RL
9	1	R7	10 ohm, 1206, 0.1%, 1W Resistor	Vishay	PHP01206E10R0BST5
10	1	R8	0 ohm, 0603, 5%, .1W Resistor	Yageo America	RC0603JR-070RL
11	0	R2 R3	Not Installed		
13	1	J1	4-pin, Single Row verticle mount male header	Samtec	TSW-104-06-T-S
14	1	U1	50 A Passive Current Sensor	Topstek	TQPL50A
15	1	U2	Sensor Signal Conditioning IC	Texas Instruments	DRV411AIRGP

Figure A-2: Bill of Materials