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Contactless and Precise AC-Current Sensing Using a Hall Sensor

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Design Resources

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Design Features

This reference design for contactless and precise AC-current sensing using a Hall sensor subsystem enables AC current measurements while maintaining the insulation around the wire.

- Contactless Proximity Current Sensing for AC, 3-Phase Input Currents
- Maximum Measured Error Less than 5% from 1-A to 10-A RMS
- Flux Concentrator as Described in This Design Improves the Magnetic Flux Density by a Factor of 6 (15 dB)
- Only Single-Point Gain Correction at Maximum Current Range — Second-Order Curve Fit Implemented In Firmware
- Maximum Current that Can Be Sensed Can Be Adapted by Changing Flux Concentrator Design

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- Building Automation
- Circuit Breakers
- Electrical Panels
- Control Panel

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System Description

This reference design for contactless and precise AC-current sensing using a Hall Sensor subsystem provides a solution knowing how much AC current is flowing through a wire without any physical intervention. In some cases during a system debug, determining whether or not an AC current is flowing through the wire is required. The reference design for a contactless AC-current sensing sub-system helps the user to do the following:

• Indicate overcurrent alarm conditions
• Determine the load characteristics by monitoring the sourced current
• Indicate alarm conditions when no current is flowing through the monitored wire
• Monitor all three phases of power for debug, data logging or both

The key subsystem challenge during the design process was determining the AC-current flow in a contactless manner. This challenge implies that the plastic insulation around the AC wire is intact yet the user can still determine the AC current flow.

In such a case, one option to determine the AC current flow is to find the magnetic flux around the AC current wire. This method has one challenge that the user must overcome. Even with a high AC current of 10-A flowing through a wire, the magnetic flux generated at the surface is still low, such as 4 Gauss for an 18 gauge wire.

To overcome these challenges, a flux concentrator has been implemented in this subsystem design as shown in Figure 8. The goal of the addition of the flux concentrator, which is non-contact, is to concentrate the flux around the AC current-carrying wire, rather than letting it escape in air, and then direct that flux to a Hall Sensor. Concentrating the magnetic flux using a flux concentrator was improved by more than 15 dB (see Section 3). When this improvement is achieved, then a Hall Sensor and analog output can be used to indicate the strength of the AC current proportional to the Hall Sensor output voltage.

Key Requirements for the Flux Concentrator Design (see Section 3)

• High permeability material
• A design that ensure that the AC current wire is surrounded by this material
• Flexible design so that the ends of the clip can touch the Hall Sensor

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### Key System Specifications

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<td>Contactless Hall Sensor based, with flux concentrator concentrating the flux</td>
<td>See Section 3.3, Section 3.4, and Section 3.5</td>
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<tr>
<td>Current sensing range</td>
<td>In this design implementation, 500-mA to 10-A AC RMS, however, the maximum current range is dependent on the flux concentrator</td>
<td>See Section 3.4, Section 5.2, and Section 5.3</td>
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<td>Flux concentrator material</td>
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<td>See Section 3.5</td>
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<td>Input operating voltage</td>
<td>USB powered or 12-V to 24-V DC powered</td>
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<td>Operating temperature</td>
<td>–40 to 85°C</td>
<td></td>
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<td>Negligible</td>
<td></td>
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<td>Operating maximum current with this existing flux concentrator design</td>
<td>Approximately 13-A AC RMS</td>
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<td></td>
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<td>Output</td>
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1 System Description
Key Requirements for the Hall Sensor
• Use of a through hole package because it provides more flexibility in conjunction with flux concentrator
• An analog output that indicates magnetic-flux concentration
TI’s DRV5053 device met the above requirements and was selected for this design (see Section 3).

Key Requirements for the Microcontroller
• ADC input channels
• Enough memory and resources to perform lookup-table functionality as well as linear interpolation
TI’s MSP430F5529 device met the above requirements (see Section 3).

1.1 DRV5053
The DRV5053 device is a chopper-stabilized Hall IC that offers a magnetic sensing solution with superior sensitivity stability over temperature and integrated protection features. The 0- to 2-V analog output responds linearly to the applied magnetic flux density and distinguishes the polarity of magnetic flux direction. A wide operating voltage range from 2.5 to 38 V with reverse polarity protection up to –22 V makes the device suitable for a wide range of industrial and consumer applications.
Internal protection functions are provided for reverse supply conditions, load dump, and output short circuit or over current.

1.2 MSP430F5529
The Texas Instruments MSP430™ family of ultralow-power microcontrollers (MCU) consists of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with extensive low-power modes, is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in 3.5 μs (typical).
The MSP430F5529, MSP430F5527, MSP430F5525, and MSP430F5521 devices are microcontroller configurations with integrated USB and PHY supporting USB 2.0, four 16-bit timers, a high-performance 12-bit analog-to-digital converter (ADC), two universal serial communication interfaces (USCI), hardware multiplier, DMA, real-time clock module with alarm capabilities, and 63 I/O pins. The MSP430F5528, MSP430F5526, MSP430F5524, and MSP430F5522 include all of these peripherals but have 47 I/O pins.
The MSP430F5519, MSP430F5517, and MSP430F5515 devices are microcontroller configurations with integrated USB and PHY supporting USB 2.0, four 16-bit timers, two universal serial communication interfaces (USCI), hardware multiplier, DMA, real time clock module with alarm capabilities, and 63 I/O pins. The MSP430F5514 and MSP430FF5513 include all of these peripherals but have 47 I/O pins.
Typical applications include analog and digital sensor systems, data loggers, and others that require connectivity to various USB hosts.

1.3 LP2985–33
The LP2985 family of fixed-output, low-dropout regulators offers exceptional, cost-effective performance for both portable and nonportable applications. Available in voltages of 1.8 V, 2.5 V, 2.8 V, 2.9 V, 3 V, 3.1 V, 3.3 V, 5 V, and 10 V, the family has an output tolerance of 1% for the A version (1.5% for the non-A version) and is capable of delivering 150-ma continuous load current. Standard regulator features, such as overcurrent and overtemperature protection, are included.
The LP2985 device has a host of features that makes the regulator an ideal candidate for a variety of portable applications. These features include the following:
• Low dropout: A PNP pass element allows a typical dropout of 280 mV at 150-ma load current and 7 mV at 1-ma load.
• Low quiescent current: The use of a vertical PNP process allows for quiescent currents that are considerably lower than those associated with traditional lateral PNP regulators
• Low dropout: A PNP pass element allows a typical dropout of 280 mV at 150-ma load current and 7 mV at 1-ma load.
• Low quiescent current: The use of a vertical PNP process allows for quiescent currents that are considerably lower than those associated with traditional lateral PNP regulators.

• Shutdown: A shutdown feature is available, allowing the regulator to consume only 0.01 μA when the ON/OFF pin is pulled low.

• Low-ESR-capacitor friendly: The regulator is stable with low-ESR capacitors, allowing the use of small, inexpensive, ceramic capacitors in cost-sensitive applications.

• Low noise: A BYPASS pin allows for low-noise operation, with a typical output noise of 30 μVRMS, with the use of a 10-nF bypass capacitor.

• Small packaging: For the most space-constrained needs, the regulator is available in the SOT–23 package.

1.4 TPS7A1633

The TPS7A16 family of ultralow power, low-dropout (LDO) voltage regulators offers the benefits of ultralow quiescent current, high input voltage, and miniaturized, high thermal-performance packaging. The TPS7A16 family of devices is designed for continuous or sporadic (power backup) battery-powered applications where ultra-low quiescent current is critical to extending system battery life. The TPS7A16 family offers an enable pin (EN) compatible with standard CMOS logic and an integrated open drain active-high power good output (PG) with a user programmable delay. These pins are intended for use in microcontroller-based, battery powered applications where power-rail sequencing is required. In addition, the TPS7A16 is ideal for generating a low-voltage supply from multicell solutions ranging from high cell-count power-tool packs to automotive applications; not only can this device supply a well-regulated voltage rail, but it can also withstand and maintain regulation during voltage transients. These features translate to simpler and more cost-effective, electrical surge-protection circuitry.

1.5 TMP103

The TMP103 device is a digital-output temperature sensor in a four-ball wafer chip-scale package (WCSP). The TMP103 device is capable of reading temperatures to a resolution of 1°C. The TMP103 device features a two-wire interface that is compatible with both I²C and SMBus interfaces. In addition, the interface supports multiple device access (MDA) commands that allow the master to communicate with multiple devices on the bus simultaneously, eliminating the need to send individual commands to each TMP103 device on the bus. Up to eight TMP103 devices can be tied together in parallel and easily read by the host. The TMP103 device is especially ideal for space-constrained, power-sensitive applications with multiple temperature measurement zones that must be monitored. The TMP103 device is specified for operation over a temperature range of –40°C to 125°C.

1.6 TPD3E001

The TPD3E001 is a low-capacitance ±15-kV ESD-protection diode array designed to protect sensitive electronics attached to communication lines. Each channel consists of a pair of diodes that steer ESD current pulses to VCC or GND. The TPD3E001 device protects against ESD pulses up to ±15-kV human-body model (HBM), ±8-kV contact discharge, and ±15-kV air-gap discharge, as specified in IEC 61000–4–2. This device has a 1.5-pF capacitance per channel, making it ideal for use in high-speed data IO interfaces.

The TPD3E001 device is a triple-ESD structure designed for USB On-the-Go (OTG) and video applications.

The TPD3E001 device is available in DRL, DRY, and thin QFN packages and is specified for –40°C to 85°C operation.
2 Block Diagram

Figure 1. Contactless and Precise AC Current Sensing Using Hall Sensor Block Diagram

2.1 Highlighted Products

The reference design for contactless and precise AC-current sensing using a Hall Sensor features the following devices:

- **DRV5053**
  - 2.5-V to 38-V analog-bipolar, hall-effect sensor
- **MSP430F5529**
  - 16-bit ultralow power microcontroller, 128-kB flash, 8-kB RAM, USB, 12-bit ADC, 2 USCl's, 32-bit HW MPY
- **LP2985–33**
  - Single output LDO, 150 mA, fixed (3.3 V), 1.5% tolerance, low quiescent current, low noise
- **TPS7A1633**
  - 60-V, 5-μA I_Q, low-dropout 100-mA linear regulator with enable and power good
- **TMP103**
  - Digital temperature sensor with $i^2$C and SMBUS expanded interface
- **TPD3E001**
  - Low-capacitance 3-channel ±15KV ESD-protection array for high-speed data interfaces

For more information on each of these devices, see the respective product folders at www.ti.com or the resources listed in Section 7.
The DRV5053 features are as follows:

- Linear output Hall Sensor
- Superior temperature stability
  - Sensitivity ±10% over temperature
- High sensitivity options:
  - –11 mV/mT (OA)
  - –23 mV/mT (PA)
  - –45 mV/mT (RA)
  - –90 mV/mT (VA)
  - +23 mV/mT (CA)
  - +45 mV/mT (EA)
- Supports a wide voltage range
  - 2.5 to 38 V
  - No external regulator required
- Wide operating temperature range
  - \( T_A = -40 \) to 125°C (Q)
- Amplified output stage
  - 2.3-mA sink, 300 µA source
- Output voltage: 0.2 ~ 1.8 V
The MSP430F5529 features are as follows:

- Low supply-voltage range: 3.6 V down to 1.8 V
- Ultralow-power consumption
  - Active mode (AM): all system clocks active 290 µA/MHz at 8 MHz, 3, flash program execution (Typical) 150 µA/MHz at 8 MHz, 3, RAM program execution (typical)
  - Standby mode (LPM3): real-time clock with crystal, watchdog, and supply supervisor operational, full RAM retention, Fast Wake-Up: 1.9 µA at 2.2 V, 2.1 µA at 3 (typical) low-power oscillator (VLO), general-purpose counter, watchdog, and supply supervisor operational, full RAM retention, fast wake up: 1.4 µA at 3 (typical)
  - Off mode (LPM4): full RAM retention, supply supervisor operational, fast wake up: 1.1 µA at 3 V (typical)
  - Shutdown mode (LPM4.5): 0.18 µA at 3 (Typical)
- Wake up from standby mode in 3.5 µs (typical)
- 16-bit RISC architecture, extended memory, up to 25-MHz system clock
- Flexible power management system
– Fully integrated LDO with programmable regulated core supply voltage
– Supply voltage supervision, monitoring, and brownout

• Unified clock system
  – FLL control loop for frequency stabilization
  – Low-power low-frequency internal clock source (VLO)
  – Low-frequency trimmed internal reference source (REFO)
  – 32-kHz watch crystals (XT1)
  – High-frequency crystals up to 32 MHz (XT2)
• 16-bit timer TA0, Timer_A with five capture and compare registers
• 16-bit timer TA1, Timer_A with three capture and compare Registers
• 16-bit timer TA2, Timer_A with three capture and compare Registers
• 16-bit timer TB0, Timer_B with seven capture and compare shadow registers
• Two universal serial communication interfaces
  – USCI_A0 and USCI_A1 each support:
    • Enhanced UART supports auto-baudrate detection
    • IrDA encoder and decoder
    • Synchronous SPI
  – USCI_B0 and USCI_B1 each support:
    • I²C
    • Synchronous SPI
• Full-speed universal serial bus (USB)
  – Integrated USB-PHY
  – Integrated 3.3-V and 1.8-V USB power system
  – Integrated USB-PLL
  – Eight input and eight output endpoints
• 12-Bit analog-to-digital converter (ADC) (MSP430F552x only) with internal reference, sample-and-hold, and autoscan feature
• Comparator
• Hardware multiplier supports 32-bit operations
• Serial onboard programming, no external programming voltage needed
• Three-channel internal DMA
• Basic timer with real-time clock feature
• See the data sheet for a list of devices in this device family, SLAS590
• For complete module descriptions, see the MSP430x5xx and MSP430x6xx Family User’s Guide, SLAU208
The LP295 features are as follows:

- Output tolerance of
  - 1% (A grade)
  - 1.5% (standard grade)
- Ultralow dropout, typically
  - 280 mV at full load of 150 mA
  - 7 mV at 1 mA
- Wide $V_{IN}$ range: 16 V maximum
- Low $I_d$: 850 µA at full load at 150 mA
- Shutdown current: 0.01 µA typical
- Low noise: 30 µ$V_{RMS}$ with 10-nF bypass capacitor
- Stable with low-ESR capacitors, including ceramic
- Overcurrent and thermal protection
- High peak-current capability
- ESD protection exceeds JESD 22
  - 2000-V human-body model (A114-A)
  - 200-V machine model (A115-A)
The TPS7A1633 features are as follows:
- Wide input voltage range: 3 to 60 V
- Ultralow quiescent current: 5 µA
- Quiescent current at shutdown: 1 µA
- Output current: 100 mA
- Low dropout voltage: 60 mV at 20 mA
- Accuracy: 2%
- Available in:
  - Fixed output voltage: 3.3 V, 5 V
  - Adjustable version from 1.2 to 18.5 V
- Power good with programmable delay
- Current-limit and thermal shutdown protections
- Stable with ceramic output capacitors: ≥ 2.2 µF
- Packages: high thermal performance MSOP–8 and SON–8 PowerPAD™
- Operating temperature range: –40°C to 125°C
The TMP103 features are as follows:

- **Multiple device access (MDA):**
  - Global read and write operations
- **I^2C- and SMBus™-compatible interface**
- **Resolution:** 8 bits
- **Accuracy:** ±1°C typical (–10°C to 100°C)
- **Low quiescent current:**
  - 3-μA active $I_Q$ current at 0.25Hz
  - 1-μA shutdown current
- **Supply range:** 1.4 to 3.6 V
- **Digital output**
- **Package:** 4-Ball WCSP (DSBGA)
The TPD3E001 features are as follows:

- 3-Channel ESD clamp array to enhance system-level ESD protection
- Exceeds IEC61000–4–2 (level–4) ESD protection requirements
  - ±8-kV IEC 61000–4–2 contact discharge
  - ±15-kV IEC 61000–4–2 air-gap discharge
- ±15-kV human-body model (HBM)
- 5.5-A peak pulse current (8/20-μs Pulse)
- Low 1.5-pF input-output capacitance
- Low 1-nA (max) leakage current
- 0.9- to 5.5-V supply-voltage range
- Space saving DRY, DRL, and DRS package options
- Alternate 2-, 4-, and 6-channel options available: TPD2E001, TPD4E001, and TPD6E001
3 System Design Theory

3.1 Magnetic Field

The magnetic field lines around a long wire carrying an electric current form concentric circles around the wire. The direction of the magnetic field is perpendicular to the wire and the direction of the current flow follows the right-hand rule. When the user wraps their right hand around the wire with their fingers curling in the direction of the magnetic field, the direction of the pointing thumb is the direction of the current flow. The magnetic field of an infinitely-long straight wire can be obtained by applying Ampere’s law. The expression for the magnetic field is shown in Equation 1.

\[
B = \frac{\mu \times I}{2 \times \pi \times R}
\]

where
- \(B\) = magnetic field
- \(I\) = current in Amperes
- \(R\) = radial distance in m
- \(\mu\) = permeability in free space: \(4\pi \times 10^{-7}\, \text{T.m/A}\)

As shown in Equation 1, the magnetic energy generated by a current-carrying wire is low even at 10 A for an 18-AWG wire. The magnetic field is only 4 Gauss.

3.2 Permeability

Permeability is the degree of magnetization the material gains as a response to that field. Permeability occurs when a magnetic field is applied to a material.

Using the information in Section 3.1 and this section, concentrating the magnetic flux from the AC current-carrying wire is desirable such that a wider dynamic-range response can be obtained from the Hall Sensor output that is indicative of the AC current.

3.3 Flux Concentrator

Multiple ferrite cores were shaped in a form as shown in Figure 8. The purpose of this form is to force the AC current-carrying wire through the opening in the flux concentrator such that the flux concentrator surrounds the AC current-carrying wire. Then, as the flux concentrator tapers it can direct the magnetic flux through the through-hole package on the Hall Sensor DRV5053 device.

![Figure 8. Flux Concentrator Concept](image)
3.4 **AC Current Magnetic Flux With and Without Flux Concentrator**

This section shows the improvement received by using a flux concentrator versus not using a flux concentrator. The results were generated using the following steps:

- Use a space heater for a resistive load. Feed the current from the cord of the heater (AC line) through the flux concentrator as shown in Figure 8.
- Use a space heater for a lower setting (the equivalent of 6.8-A was measured on the power meter) and as shown in Figure 9. The Hall Effect sensor measured 272 mV\(_{\text{pp}}\).
- To confirm if the flux concentrator had an effect, use the same current and remove the flux concentrator. Place the hall effect sensor next to the cord. Figure 10 shows the results. The peak-to-peak (pp) amplitude was measured at only 46 mV.

The results confirmed that a first attempt at designing a flux concentrator resulted in an improved magnetic flux of approximately 15 dB. This result can translate into a more accurate response for the Hall Sensor DRV5053 device over a wide dynamic range of AC currents.
3.5 Flux Concentrator Design

A detailed CAD drawing was generated such that a flux concentrator can be manufactured to given tolerances as shown in Figure 11 and Figure 12. The flux concentrator was designed using 1010 CRS material.

![Figure 11. Flux Concentrator Drawing](image1)

Dimensions are in Inches.

![Figure 12. Flux Concentrator Solder Pads for PCB](image2)

Dimensions are in Inches.

3.6 Low-Pass Filter on DRV5053 Analog Outputs

The output bandwidth of the DRV5053 device is 20 kHz. The AC current under measurement is 60 Hz. A low-pass filter was included on the DRV5053 outputs so that the cutoff frequency is 225 Hz. The intent of the low-pass filter is to filter the high frequency noise from the analog output lines of DRV5053 device above 3 to 4 times the frequency of interest, which, in this case, is 60 Hz.

![Figure 13. Low-Pass Filter on DRV5053 Analog Outputs](image3)
The design guidelines for the analog layout were followed for the DRV5053 analog output. As shown in Figure 14, the analog output line was surrounded by ground pours with via stitching such that the noise from any surrounding circuitry or other source can be isolated from the analog output lines.

The low-pass filter was placed closer to the MSP430 ADC input pins.

The Hall Sensor was placed directly underneath the flux concentrator and away from the power and EP section as shown in Figure 15.
3.8 MSP430 ADC Resources

The MSP430F5529 device has an internal 12-bit successive approximation (SAR) analog-to-digital converter (ADC). The internal ADC samples the DRV5053 device on each channel. Use to calculate the ADC count value based on the actual voltage signal from the DRV5053 device.

\[
\text{ADC count} = \frac{(3.3 \, \text{V} \times \text{sample})}{4095}
\]

The external reference voltage of the ADC is set to 3.3 V as shown in Figure 13. The value 4095 is used because the internal ADC has 12-bits of accuracy, \(2^{12} = 4096\).

3.8.1 Firmware Description

The three main clocks, ACLK, SMCLK, and MCLK, are referenced off of the external 24-MHz crystal. The ACLK clock oscillates at 3 MHz, the SMCLK clock oscillates at 6 MHz, and the MCLK clock oscillates at 24 MHz. An open-source TI library, IQMath, calculates the RMS value for the user in a time-efficient matter. To download the IQMath library, go to www.ti.com/tool/msp430-iqmathlib.

A calibration sequence runs on startup and requires 2 s of data to find the average noise. The average noise value is removed from each sample before adding it to the total run time.

When the ADC is configured with the respective buffers and a sampling rate of approximately 5940 samples per second, the calibration is complete. The main loop waits until the sample buffer completes a full second of data (5940 samples). The ADC triggers an interrupt when a sample can be read. At this time, the sample is squared and added to a running total. After 5940 samples are taken, the running total is copied to another buffer. The previous total is cleared and the ADC is ready to receive new data. While waiting for more ADC interrupts, RMS calculations can occur with the new buffer as shown in Equation 2.

\[
\text{RMS} = \sqrt{\frac{1}{n} \sum x^2}
\]

Because the sum of squares are already calculated with the running total, only the divide and square root must be calculated. Peak-to-peak values are stored during the sampling stage of ADC interrupt-service routine and are updated every second along with the calculated RMS and current values.
4 Hardware Overview

4.1 USB Power

To set up the USB power, follow these steps:

• Install jumper J1 and J3.
• Ensure that the J4 jumper is installed between pins 1 and 2.

The default of the firmware is set to a value so that the threshold for the RMS-voltage readout from the analog output of the DRV5053 device is 15 mV. This default value means that as long as the noise on the lines is below 15 mV, the design will read 0 A of current.

• Pass current-carrying wire under test through the opening in the flux concentrator as shown in Figure 21.
• Ensure that the plastic insulation on the AC wire is intact.

The MSP430 firmware performs a running average of the sample size. The sample frequency is approximately 5940 samples per second. The display is updated about every second after the RMS calculations are complete.

See Figure 17 for the display readout description.

4.2 24-V DC Power Source

To set up the 24-V DC power source, follow these steps:

• Install jumper J1 and J3.
• Ensure that the J4 jumper is installed between pins 2 and 3.
• See Section 4.1 for the remaining steps.
5 Test Data

5.1 Maximum Measured Error

Figure 18. Power Source

A Kikusui PCR1000M power source was used to source the variable AC currents. The AC voltage was kept low for safety reasons and to ensure that the power across resistor loads was kept low.

Figure 19. Power Meter

A Voltek PM1000+ power meter was made available if needed. However, for this test, the use of a current probe was needed for data logging purposes. The corresponding AC peak-to-peak, RMS readings, and the Hall voltage output was recorded across different settings.

Figure 20. Hardware Description
A Clarostat decade box was used as a resistive load across different AC input-current settings.

![AC current-carrying wire under test – inside the flux concentrator opening](image)

**Figure 21. Complete Setup**

![AC Current Probe Measurement and Hall Sensor Output Voltage](image)

**Figure 22. AC Current Probe Measurement and Hall Sensor Output Voltage**

Measurements of the Hall Sensor output voltage were taken across different AC current settings as shown in Figure 22. Table 1 lists the RMS and pp values for the AC input current and the Hall Sensor output voltage for each measurement.
As listed in Table 1, for this particular set of data collection, a maximum current of 10 A was used (limited by the test equipment). The maximum current measured was not limited by the Hall Sensor capability (see Section 5.2).

To calibrate the Hall Sensor across different systems, a single-point gain calibration is proposed.

In this setup, the gain calibration of 10 A was used across board 5 and board 7 for gain correction with board 6 as the baseline. Figure 23 shows a second-order polynomial.

\[
y = -0.0000554x^2 + 0.0583711x + 0.0712513, \quad R^2 = 0.9997402
\]

**Figure 23. Hall Sensor Output Response Across Different Boards and Curve Fit**
### Table 2. Measured Error of Board 5 After Gain Calibration and Curve Fit Equation of Board 6 as Reference

<table>
<thead>
<tr>
<th>BOARD 5</th>
<th>HALL SENSOR MEASUREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAIN CORRECTED HALL SENSOR OUTPUT VOLTAGE (mV)</td>
<td>REFERENCE CURRENT FLOWING IN WIRE RMS (A)</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>3.22</td>
<td>0.2</td>
</tr>
<tr>
<td>7.55</td>
<td>0.49</td>
</tr>
<tr>
<td>11.78</td>
<td>0.75</td>
</tr>
<tr>
<td>15.95</td>
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<td>33.32</td>
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<tr>
<td>51.76</td>
<td>2.98</td>
</tr>
<tr>
<td>73.12</td>
<td>4.01</td>
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<tr>
<td>93.98</td>
<td>4.96</td>
</tr>
<tr>
<td>138.99</td>
<td>6.98</td>
</tr>
<tr>
<td>211.86</td>
<td>10</td>
</tr>
</tbody>
</table>

As shown in Table 2, the measured error on board 5 is only 2.17% from 1 A to 10 A with board 6 curve fit equation and after gain calibration.

### Table 3. Measured Error of Board 7 After Gain Calibration and Curve Fit Equation of Board 6 as Reference

<table>
<thead>
<tr>
<th>BOARD 7</th>
<th>HALL SENSOR MEASUREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAIN CORRECTED HALL SENSOR OUTPUT VOLTAGE (mV)</td>
<td>REFERENCE CURRENT FLOWING IN WIRE RMS (A)</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>3.26</td>
<td>0.2</td>
</tr>
<tr>
<td>7.82</td>
<td>0.49</td>
</tr>
<tr>
<td>12.15</td>
<td>0.75</td>
</tr>
<tr>
<td>16.31</td>
<td>1</td>
</tr>
<tr>
<td>33.4</td>
<td>2</td>
</tr>
<tr>
<td>52.61</td>
<td>2.98</td>
</tr>
<tr>
<td>72.94</td>
<td>4.01</td>
</tr>
<tr>
<td>94.27</td>
<td>4.96</td>
</tr>
<tr>
<td>139.06</td>
<td>6.98</td>
</tr>
<tr>
<td>211.44</td>
<td>10</td>
</tr>
</tbody>
</table>

As shown in Table 3, the measured error on board 7 is only 2.2% from 1 A to 10 A using board 6 curve fit equation and after gain calibration.

The equation used to calculate current from the RMS value was adjusted to allow for current measurement down to 0.5 A.

In this setup, measurements were taken from 0.5 A to 10 A using board 7. Figure 24 shows a second-order polynomial fit.
As listed in Table 4, the measured error on board 7 is within 5% of the actual AC current through the wire from 1 A to 10 A.
5.2 Maximum Current Range

To ensure that the Hall Sensor output is not saturated, putting the maximum current specification that the system can sense based on the overall sensitivity specification of the Hall Sensor is important.

For the DRV5053 device the sensitivity is from –140 mV/mT to –35 mV/mT based on the device data sheet.

To ensure that the output is not saturated at the maximum current across the device range, use the known B field versus output voltage of the Hall Sensor data that was collected on a unit (referred here as calibrated unit) as listed in Table 5.

<table>
<thead>
<tr>
<th>MAGNETIC FIELD (B) MEASURED</th>
<th>HALL SENSOR OUTPUT VOLTAGE</th>
<th>SENSITIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0 mT</td>
<td>1.003 V</td>
<td>–86.7 mV/mT</td>
</tr>
<tr>
<td>+0.55 mT</td>
<td>1.05 V</td>
<td>–80 mV/mT</td>
</tr>
<tr>
<td>+1.15 mT</td>
<td>1.102 V</td>
<td>–80.6 mV/mT</td>
</tr>
<tr>
<td>+1.75 mT</td>
<td>1.15 V</td>
<td>–85.2 mV/mT</td>
</tr>
<tr>
<td>+2.37 mT</td>
<td>1.2 V</td>
<td>–80.9 mV/mT</td>
</tr>
<tr>
<td>+2.98 mT</td>
<td>1.252 V</td>
<td>–83.3 mV/mT</td>
</tr>
<tr>
<td>+4.5 mT</td>
<td>1.375 V</td>
<td>–81 mV/mT</td>
</tr>
<tr>
<td>+6 mT</td>
<td>1.5 V</td>
<td>–83.3 mV/mT</td>
</tr>
<tr>
<td>+7.53 mT</td>
<td>1.624 V</td>
<td>–81 mV/mT</td>
</tr>
<tr>
<td>+9.03 mT</td>
<td>1.749 V</td>
<td>–83.3 mV/mT</td>
</tr>
</tbody>
</table>

This particular unit was then soldered on board 7 and, with the same setup (see Section 5.1), data was collected across different known currents as listed in Table 6.

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>BOARD 7 WITH CALIBRATED UNIT SOLDERED</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>CURRENT FLOWING IN WIRE</td>
</tr>
<tr>
<td></td>
<td>pp (A)</td>
</tr>
<tr>
<td>Room</td>
<td>1.5</td>
</tr>
<tr>
<td>Room</td>
<td>3.04</td>
</tr>
<tr>
<td>Room</td>
<td>6.08</td>
</tr>
<tr>
<td>Room</td>
<td>9.4</td>
</tr>
<tr>
<td>Room</td>
<td>12.5</td>
</tr>
<tr>
<td>Room</td>
<td>15.2</td>
</tr>
<tr>
<td>Room</td>
<td>21.8</td>
</tr>
<tr>
<td>Room</td>
<td>30.4</td>
</tr>
</tbody>
</table>

As listed in Table 6, the pp range for the 10-A range is 582 mV. As listed in Table 5, this value corresponds to approximately +7 mT in the mT range.

Assuming the worst case with a device that has sensitivity of –140 mV/mT, then the overall mT range is approximately +10 mT, assuming a total $V_{OUT}$ range of 1.4 V for the Hall Sensor (assuming a $V_{OUT}$ common mode of 1.1 V and maximum pp of 1.8 V).

Therefore, in a worst-case scenario with a device sensitivity of –140 mV/mT, the maximum current that can be sensed with this existing flux concentrator design is approximately 14 A before saturation.

However, the flux concentrator design can easily be changed (either the material or design) to increase the maximum current range if desired.
5.3 Minimum Current Range

The minimum current of the system is determined by the noise of the Hall Sensor output under quiescent conditions. As previously stated, a low-pass filter is included in this design to ensure that the high frequencies can be filtered off. The peak-to-peak noise that was measured on the Hall Sensor output with no current flowing in the wire was 1.73 mV\textsubscript{RMS} as shown in Figure 25. As listed in Table 1, the minimum current-limit of 1.5 times the quiescent noise with no field ensures that no false triggers are generated and that reliable current measurements occur at the low end of the range.

\[ 1.5 \times 1.73 = 2.6\text{-}mV_{\text{RMS}} \]

Based on the second-order curve fit shown in Figure 23, the corresponding minimum current is 220 mA. However, as described in Section 5.1, the accuracy at the low-end of the current is low.

![Figure 25. Hall Sensor Output With No current Flowing](image-url)
5.4 Temperature Data

![Figure 26. Input Referred Noise vs Ambient Temperature](image)

As shown in Figure 26, a variation of approximately 3.4% occurs from –40°C to 125°C. If the system requires better accuracy over temperature, the on-board temperature sensor, TMP103, can be used to compensate for the variation of temperature versus input-referred noise as shown in Figure 27.

![Figure 27. On-Board Temperature Sensor for temperature Compensation](image)

5.5 Life-Time Stress Data (HTOL)

No measurable shift was observed during life time stress of the DRV5053 device.

6 Design Files

6.1 Schematics

The schematics are presented in the following order:
1. MSP430, Hall Sensor (see Figure 28)
2. Power Section, Display (see Figure 29)
Contactless and Precise AC-Current Sensing Using a Hall Sensor

Figure 28. Schematic Section – MSP430, Hall Sensor
Vin Connectors & EMI Protection

Figure 29. Power Section, Display

Contactless and Precise AC-Current Sensing Using a Hall Sensor

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### Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA–00218](https://www.ti.com). Table tbd shows the BOM for the Contactless and Precise AC Current Sensing using Hall Sensor Reference Design.

#### Table 7. BOM

<table>
<thead>
<tr>
<th>DESIGNATOR</th>
<th>QUANTITY</th>
<th>VALUE</th>
<th>DESCRIPTION</th>
<th>PACKAGE REFERENCE</th>
<th>PART NUMBER</th>
<th>MANUFACTURER</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPCB1</td>
<td>1</td>
<td></td>
<td>Printed Circuit Board</td>
<td></td>
<td>ISE4016</td>
<td>Any</td>
</tr>
<tr>
<td>C1</td>
<td>1</td>
<td>4.7µF</td>
<td>CAP, CERM, 4.7µF, 10V, ±10%, X5R, 0805</td>
<td>0805</td>
<td>0805ZD475KAT2A</td>
<td>AVX</td>
</tr>
<tr>
<td>C2, C24, C25, C26, C27, C28, C29, C30, C31, C32, C33</td>
<td>11</td>
<td>1µF</td>
<td>CAP, CERM, 1µF, 16V, ±10%, X7R, 0603</td>
<td>0603</td>
<td>C1608X7R1C105K</td>
<td>TDK</td>
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<td>C3</td>
<td>1</td>
<td>2.2µF</td>
<td>CAP, CERM, 2.2µF, 10V, ±10%, X5R, 0805</td>
<td>0805</td>
<td>C0805C225K8PACTU</td>
<td>Kemet</td>
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<tr>
<td>C4</td>
<td>1</td>
<td>0.01 µF</td>
<td>CAP, CERM, 0.01 µF, 16V, ±10%, X7R, 0402</td>
<td>0402</td>
<td>GRM155R71C103KA01D</td>
<td>Murata</td>
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<tr>
<td>C5</td>
<td>1</td>
<td>22µF</td>
<td>CAP ALUM 22UF 10V 20% SMD</td>
<td>E55</td>
<td>EEE–1AA220WR</td>
<td>Panasonic - ECG</td>
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<td>C6, C8, C19</td>
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<td>2200pF</td>
<td>CAP, CERM, 2200pF, 100V, ±5%, X7R, 0603</td>
<td>0603</td>
<td>06031C222JAT2A</td>
<td>AVX</td>
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<tr>
<td>C7, C9</td>
<td>2</td>
<td>18pF</td>
<td>CAP, CERM, 18pF, 50V, ±5%, C0G/NP0, 0603</td>
<td>0603</td>
<td>0603A180JAT2A</td>
<td>AVX</td>
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<td>C10, C12, C13</td>
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<td>0.22µF</td>
<td>CAP, CERM, 0.22µF, 10V, ±10%, X5R, 0402</td>
<td>0402</td>
<td>GRM155R61A224KE19D</td>
<td>Murata</td>
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<td>0.47µF</td>
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<td>Kemet</td>
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<td>10µF</td>
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<td>Kemet</td>
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<td>0603C104JAT2A</td>
<td>AVX</td>
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<td>Murata</td>
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<td>C1210C102KGRACTU</td>
<td>Kemet</td>
</tr>
<tr>
<td>C21</td>
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<td>0402</td>
<td>GCM155R71H103KAA55D</td>
<td>Murata</td>
</tr>
<tr>
<td>C22, C23</td>
<td>2</td>
<td>10µF</td>
<td>CAP, CERM, 10µF, 10V, ±10%, X7R, 1210</td>
<td>1210</td>
<td>GRM32ER71H106KA12L</td>
<td>Murata</td>
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<tr>
<td>D1, D2, D3, D4, D5, D8</td>
<td>6</td>
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<td>DPY0002A</td>
<td>TPD1E10B06DPYR</td>
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<td>J1, J3</td>
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<td>Header 2x1</td>
<td>90120–0122</td>
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<td>Header, 3 PIN, 100mil, Tin</td>
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<td>BSS138</td>
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<td>CRCW0603200RJNEA</td>
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<td>EUJ–2GE0R00X</td>
<td>Panasonic</td>
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<td>R10, R11, R12, R13</td>
<td>4</td>
<td>1.50k</td>
<td>RES, 1.50 k, 1%, 0.063 W, 0402</td>
<td>0402</td>
<td>CRCW04021K50FKED</td>
<td>Vishay-Dale</td>
</tr>
<tr>
<td>R14, R15</td>
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<td>3.16k</td>
<td>RES, 3.16k ohm, 1%, 0.1W, 0603</td>
<td>0603</td>
<td>CRCW06033K16FKEA</td>
<td>Vishay-Dale</td>
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<td>Switch, Tactile, SPST-NO, 0.05A, 12V, SMT</td>
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<td>TE Connectivity</td>
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<td>SH-J1, SH-J2</td>
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<td>1x2</td>
<td>Shunt, 2mm, Gold plated, Black</td>
<td>2mm Shunt, Closed Top</td>
<td>2SN-BK-G</td>
<td>Samtec</td>
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<td>TP1, TP2, TP3</td>
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<td>5000</td>
<td>Keystone</td>
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<td>1</td>
<td>Orange</td>
<td>Test Point, Miniature, Orange, TH</td>
<td>Orange Miniature Testpoint</td>
<td>5003</td>
<td>Keystone</td>
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<td>Yellow</td>
<td>Test Point, Miniature, Yellow, TH</td>
<td>Yellow Miniature Testpoint</td>
<td>5004</td>
<td>Keystone</td>
</tr>
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<td>U1</td>
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<td></td>
<td>Micropower 150 mA Low-Noise Ultra Low-Dropout Regulator, 5-pin SOT–23, Pb-Free</td>
<td>MF05A</td>
<td>LP2985AIM5–3.3/NOPB</td>
<td>National Semiconductor</td>
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<tr>
<td>U2</td>
<td>1</td>
<td></td>
<td>Low-Capacitance +/- 15 V ESD-Protection Array for High-Speed Data Interfaces, 3 Channels, –40 to +85 °C, 5-pin SOT (DRL), Green (RoHS &amp; no Sb/Br)</td>
<td>DRL0005A</td>
<td>TPD3E001DRLR</td>
<td>Texas Instruments</td>
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<td>U3</td>
<td>1</td>
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<td>Mixed Signal MicroController, PN0080A</td>
<td>PN0080A</td>
<td>MSP430F5529IPN</td>
<td>Texas Instruments</td>
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<td>U4, U5, U6, U7</td>
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<td>Analog Linear Hall –80 mV/mt–40 to 125°C, LPG0003A</td>
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6.3 Layer Plots

To download the layer plots, see the design files at **TIDA-00218**.

![Figure 30. Layer Plot 1](image1)

![Figure 31. Layer Plot 2](image2)

![Figure 32. Layer Plot 3](image3)
Figure 39. Layer Plot 10
6.4 Altium Project

To download the Altium project files, see the design files at TIDA-00218.

Figure 40. All Layers

Figure 41. Top Layer

Figure 42. Ground Layer

Figure 43. Power Layer
Figure 44. Bottom Layer
6.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00218.
6.6 Assembly Drawings

These assemblies are ESD sensitive. ESD precautions shall be observed.
These assemblies must be clean and free from flux and all contaminants. Use of no clean flux is not acceptable.
These assemblies must comply with workmanship standards IPC-A-610 Class 2, unless otherwise specified.

Figure 46. Assembly Drawing 1
Figure 47. Assembly Drawing 2
6.7 **Software Files**

To download the software files, see the design files at TIDA–00218

7 **References**

- DRV5053 Analog-Bipolar Hall Effect Sensor, SLIS153
- LP2985–33, 150-mA LOW-NOISE LOW-DROPOUT REGULATOR WITH SHUTDOWN, SLVS522
- Magnetic Field of Current, Magnetic Field of Current
- MSP430F5529, MIXED SIGNAL MICROCONTROLLER, SLAS590
- TMP103, Low-Power, Digital Temperature Sensor with Two-Wire Interface in WCSP, SBOS545
- TPD3E001, LOW-CAPACITANCE 3-CHANNEL ±15-kV ESD-PROTECTION ARRAY FOR HIGH-SPEED DATA INTERFACES, SLLS683
- TPS7A1633, 60-V, 5-μA \(I_o\) 100-mA, Low-Dropout Voltage Regulator with Enable and Power-Good, SBVS171
About the Author

AJINDER PAL SINGH is a Systems Architect at Texas Instruments, where he is responsible for developing reference design solutions for the industrial segment. Ajinder brings to this role his extensive experience in high-speed digital, low-noise analog and RF system-level design expertise. Ajinder earned his Master of Science in Electrical Engineering (MSEE) from Texas Tech University in Lubbock, TX. Ajinder is a member of the Institute of Electrical and Electronics Engineers (IEEE).

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### Revision History

<table>
<thead>
<tr>
<th>Changes from Original (October 2014) to A Revision</th>
<th>Page</th>
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<tr>
<td>• Added &quot;Control Panel&quot; to Featured Applications</td>
<td>1</td>
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<tr>
<td>• Updated device status to production data</td>
<td>6</td>
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NOTE: Page numbers for previous revisions may differ from page numbers in the current version.
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