TI Designs: TIDA-01467
フラックスゲート･センサを使用する、トレース上の三相電流センシングのリファレンス･デザイン

TEXAS INSTRUMENTS

概要

このリファレンス･デザインでは、PCBトレースなど電流を搬送する導体により生成される磁場を測定し、電流を測定する、三相電流センサを紹介します。これらのセンサは電流を搬送するPCBトレースの近くに配置され、トレースを通過する電流を測定します。

この電流センシング設計は、基本的な電力監視を必要とする産業用アプリケーションでの使用に好適です。

磁気フラックスゲート･テクノロジを使用することで、このデザインは位相ごとに最大5Aの三相電流を、高い精度で測定できます。

リソース

TIDA-01467	デザイン･フォルダ
DRV425	プロダクト･フォルダ

TI E2E™ Community

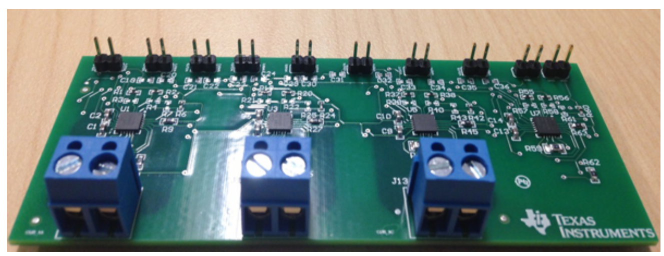
E2Eエキスパートに質問

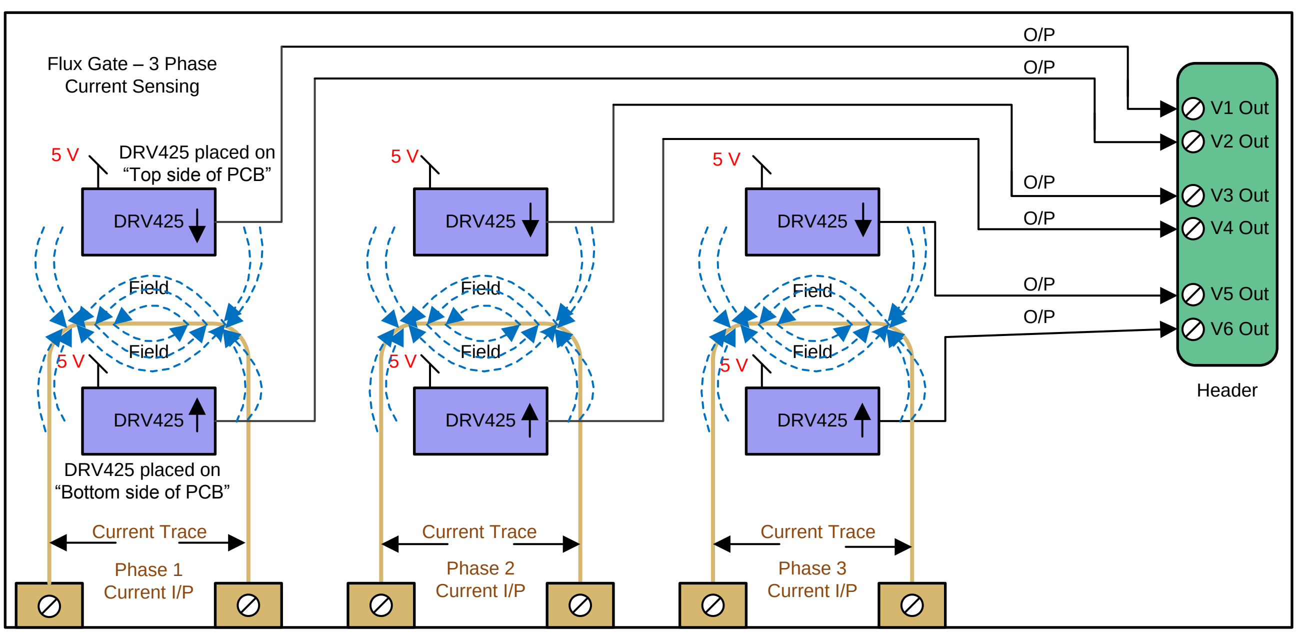
特長

- 磁気フラックスゲート･センサによる三相電流測定
- 較正された電流測定精度: ≤ ±1%
- トレース上(PCBトレース)の電流センシング
- 電流測定範囲: 500mA～5A
- リニア出力電圧
- センサ範囲を最大±2mTまで変更可能(最大値)
- 電源電圧範囲: 3.0～5.5V
- 小型フォーム･ファクタ: 4in×1.5in

アプリケーション

- 電力品質解析





1 System Description

Current is one of the most common signals sensed to evaluate and analyze the quality of power. Several methods are available to sense current, such as shunt resistor, current transformer, Rogowski coil, Hall effect sensors, and fluxgate sensors.

This reference design showcases a three-phase current sensor for current measurements using fluxgate technology integrated in the DRV425. Fluxgate sensors are magnetic field based, where the measured magnetic field (B) is proportional to the current (I) and inversely proportional to the distance (r) from the current carrying conductor (Ampere's Law) as shown in 式 1:

$$B = \mu_0 I / 2\pi r \quad (1)$$

The integrated fluxgate sensor in the DRV425 senses the magnetic field generated by a current-carrying conductor such as a PCB trace and outputs an analog signal that is proportional to the sensed magnetic field. As per 式 1, current is proportional to the magnetic field, and as the current increases, the surrounding magnetic field increases, leading to the output from the sensor increasing as well. Similarly with decrease in current, the surrounding magnetic field and sensor output decrease.

The fluxgate sensors are highly sensitive and are susceptible to stray magnetic fields or common-mode field interferences such as the earth's magnetic field, which affects the accuracy of measured outputs. To eliminate the common-mode field interferences, this reference design implements a differential approach by using two DRV425 devices per phase placed near a PCB trace. The current-carrying PCB trace is placed on the first inner layer of the PCB, with one DRV425 placed on the top layer of the PCB and a second DRV425 placed on the bottom layer of the PCB. The outputs of the two sensors are measured differentially, eliminating common-mode field interferences. In addition, this reference design provides flexibility to measure the output of each sensor independently to estimate if any common-mode field is present.

1.1 Key System Specifications

表 1. Key System Specifications

PARAMETER	SPECIFICATIONS
Number of phases	Three phase currents
Accuracy	≤ ±1%
Current sensor	Flux gate magnetic sensor
Current inputs	≤ 5-A AC
Magnetic field range	±2 mT (max)
Supply voltage, V_{DD}	3 to 5 V
Operating temperature	–40°C to 125°C
Form factor	4" × 1.5"

2 System Overview

The system is designed for three-phase current measurements of up to 5 A. The current sensing is achieved by using the DRV425, which senses the magnetic field generated by a current carrying conductor such as a PCB trace. The output of the DRV425 is an analog signal proportional to the sensed magnetic field. The analog output of the DRV425 can be processed by a 12- to 24-bit analog-to-digital converter (ADC).

To measure the current per phase, this reference design uses two DRV425 devices. One DRV425 is placed on the top side of the PCB and a second DRV425 is placed on the bottom side of the PCB, with a current-carrying PCB trace placed on the first inner layer of the PCB.

2.1 Block Diagram

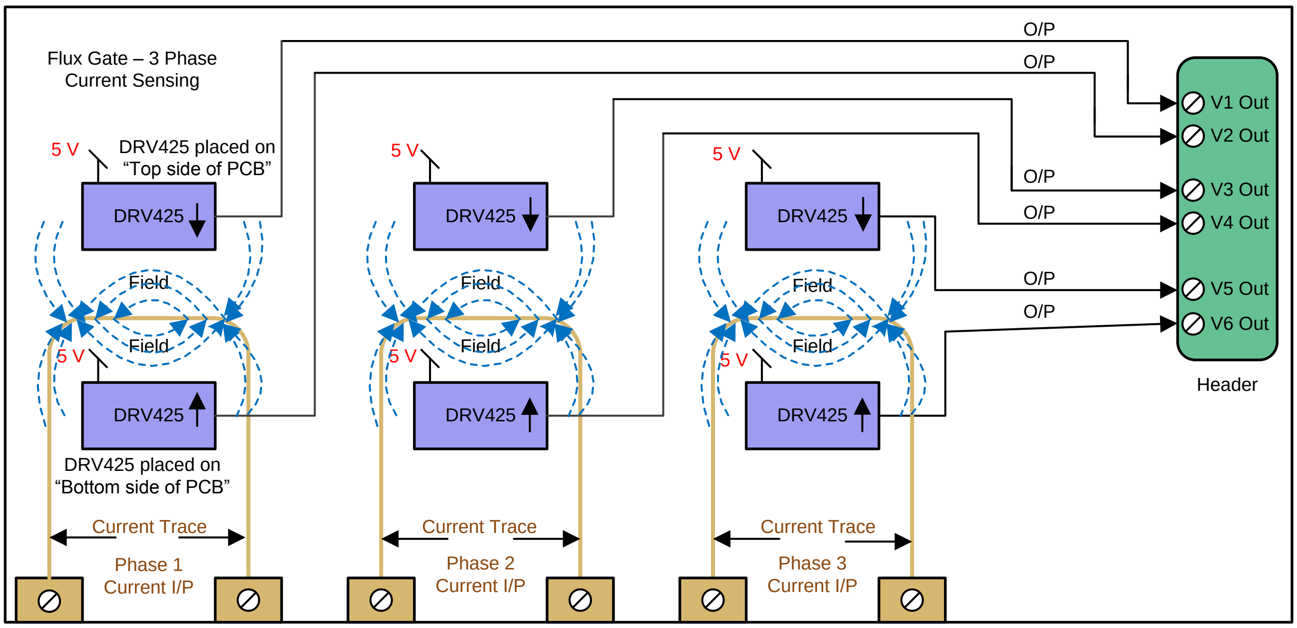


図 1. Block Diagram

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 the unique and 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 magnetic field measurement precision. The output of the DRV425 is an analog signal 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™ for optimized heat dissipation, and is specified for operation over the extended industrial temperature range of –40°C to 125°C.

2.3 System Design Theory

The system is designed for three-phase current measurements up to 5 A by measuring the magnetic fields generated by a current-carrying conductor such as a PCB trace. The maximum measured current is dependent on the thickness of the PCB trace. For this reference design, the PCB trace thickness is designed to support currents up to 5 A.

The sensor used in this current sensing design is the DRV425, which provides the unique and proprietary IFG with an internal compensation coil to support a high-accuracy sensing range of ±2 mT.

2.3.1 Magnetic Sensors

A magnetic field is one of the most important physical quantities that is used in various technical areas. In industry applications, the current flowing in an electric circuit generates a magnetic field proportional to the current. Thus, by sensing the magnetic field distribution it is possible to measure the current. Based on magnetic field strengths and measurement range, magnetic field sensors can be classified as low- (< 1 mT) or high-field (> 1 mT) sensors. An example of low-field sensors is fluxgate technology.

2.3.2 Fluxgate Sensor

Fluxgate sensors offer significantly higher sensitivity, lower drift, lower noise, and high linearity and enable up to 1000 times better accuracy in measurement. The sensor detects the magnetic field vectors in its axis and is a widely used device. Fluxgates are affordable, rugged, reliable, and compact with advancements in technology leading to integrating the complete sensor solutions in devices.

The DRV425 sensor used in this reference design consists of a magnetic fluxgate sensor with the necessary sensor conditioning and compensation coil to internally close the control loop. The fluxgate sensor is repeatedly driven in and out of saturation and supports hysteresis-free operation with excellent accuracy. The internal compensation coil assures stable gain and high linearity.

The magnetic field (B) is detected by the internal fluxgate sensor in the DRV425. The device integrates the sensor output to assure high-loop gain. The integrator output connects to the built-in differential driver that drives an opposing compensation current through the internal compensation coil. The compensation coil generates an opposite magnetic field that brings the original magnetic field at the sensor back to zero.

The DRV425 measures magnetic fields only in its axis of sensitivity. This axis of sensitivity is in the x-axis when looking at a top view with pin 1 in the upper left corner. The orientation and the sensitivity axis of the fluxgate sensor is indicated by a dashed line on the top of the package, as shown in 図 2. 図 2 also shows the location of the sensor inside the package.

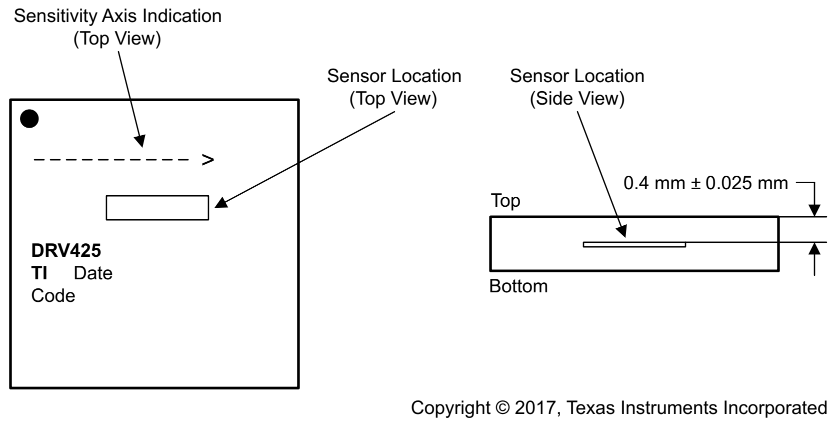


図 2. Magnetic Sensitivity Direction of Integrated Fluxgate Sensor

2.3.3 Over-the-Trace PCB Design for Current Sensing

The design considerations for PCB trace and the design steps are as follows:

- Determine thickness of the trace.
- Calculate the width of PCB trace based on placement of trace on the internal or external layer of the PCB. The trace width is calculated by 式 2 with referring to ANSI/IPC-2221 standard.

$$I = K * (\triangle T^{0.44}) * (A^{0.725}) \quad (2)$$

where:

- I = maximum current in amps
- ΔT = temperature rise in °C
- A = cross-sectional area in mils
- K = constant such that:
  - K = 0.024 for internal layers
  - K = 0.048 for external layers
- Determine the distance of the trace from the fluxgate sensor.
- Calculate the magnetic field intensity of the trace on the sensor (see 2.3.4).

Multiple currents are measured on the board. The sensor placed over the trace senses the magnetic fields generated by the trace and may also senses the magnetic field of the adjacent trace if the fields are large enough. To reduce cross talk placement and proximity of PCB trace is critical. In this design the trace is placed on the board as shown in 図 3.

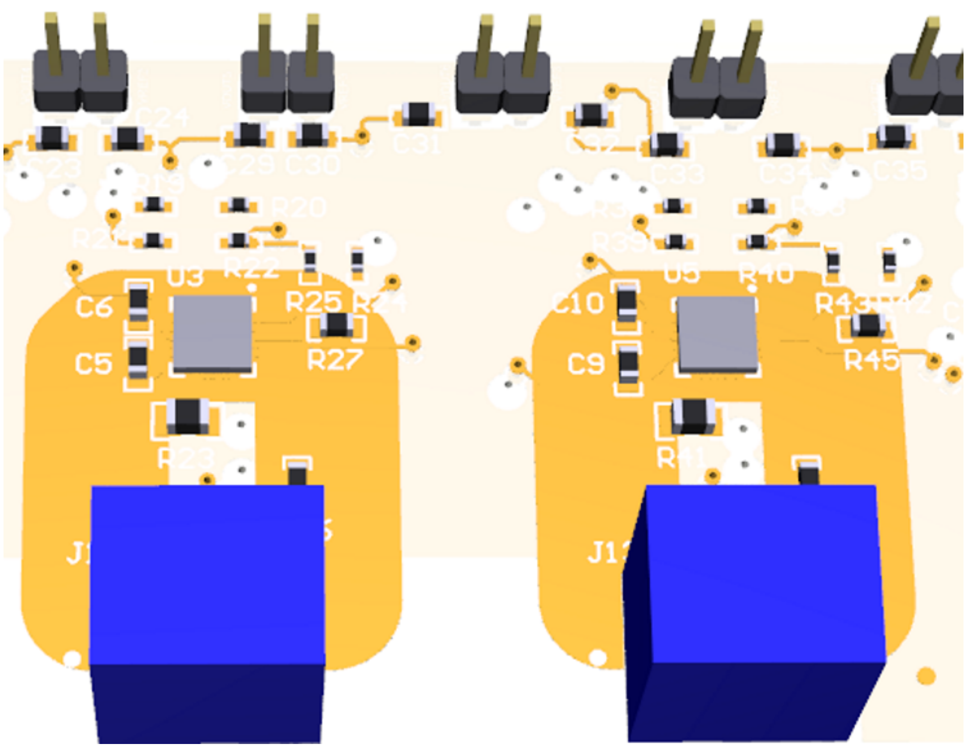


図 3. PCB Current Trace

2.3.4 Magnetic Field Simulation

Many tools are available that can simulate the magnetic fields for a system design. For simulating the magnetic fields, FEMM simulation tool was used. This section shows how to use the FEMM tool to calculate the magnetic fields.

The FEMM tool uses the finite element method for solving 2D planar and axisymmetric problems in low-frequency magnetics. The finite element method is a numerical method to calculate solutions for partial differential equations by breaking the problem down into large number regions, each with a simple geometry (such as triangles). The benefit of breaking the problem down into a small number of elements is a difficult problem to solve can be transformed into a relatively easy problem to solve.

In FEMM, for every element, a basic condition is defined. The basic conditions are material property, boundary condition, and circuit. The basic function details are inserted into a partial differential equation and equations are solved numerically. For more details of the tool, see the documentation available on www.femm.info/wiki/HomePage.

To run a FEMM 4.2 simulation, follow these recommendations:

- Define the dimensions of DRV425 sensors (see the DRV425 datasheet for the dimensions).
- Place DRV425 sensors on top and bottom sides of PCB. The thickness of PCB is 1.63 mm and varies depending on capabilities of PCB manufacturer.
- Define the dimensions of current carrying trace placed on inner layer of PCB block. The trace has a width of 7.62 mm and height of 0.03556 mm.
- Define the dimension of the surrounding area, such as air. A circular area can be defined in the same direction the user wants to calculate the magnetic field.
- Set the properties of defined areas such as current carrying trace, the DRV425, and air.
- For current carrying trace, the circuits property defines the current in amps and the material property is defined by copper.
- Run the simulation and view the results.
- To view the top and bottom magnetic field results of the DRV425, press the Tab key and input the x and y coordinates for each DRV425 device. The distance of the top DRV425 from the current trace is 0.64 mm and the bottom DRV425 is 1.65 mm. The result obtained for the top DRV425 is 368 µT and the bottom DRV425 is 306 µT.

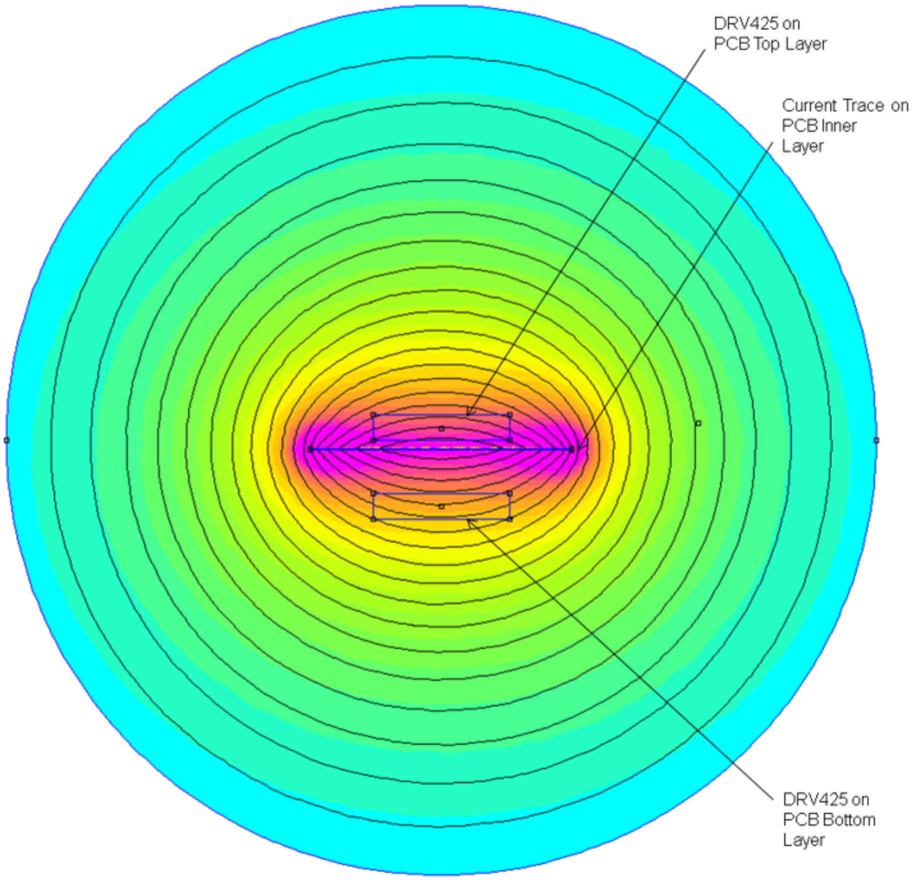


図 4. FEMM 4.2 Magnetic Simulation

The results are shown in 図 4. The thin lines indicate the magnetic flux lines. Higher the density of magnetic flux lines, higher the magnetic flux density.

図 5 displays the strength of magnetic flux density.

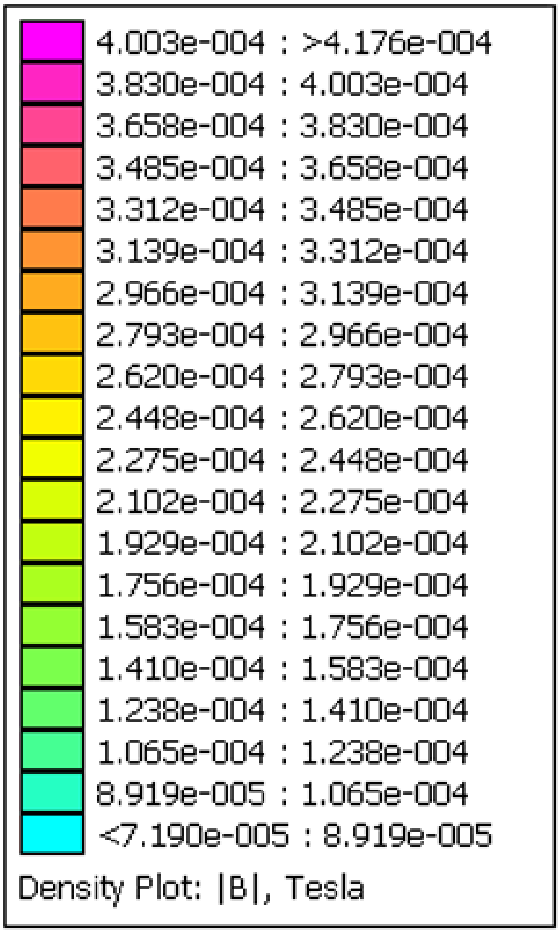


図 5. FEMM 4.2 Density Plot Table

2.3.5 Design Procedure

The following design procedure is used to design the solution based on the DRV425:

表 2. DRV425 Design Parameters

DESIGN PARAMETER	EXAMPLE VALUE
Magnetic field range	VDD = 5 V: ±2 mT (max) VDD = 3.3 V: ±1.3 mT (max)
Supply voltage, V_{DD}	3.0 to 5.5 V
Reference voltage, V_{REFIN}	Range: GND to VDD If an internal reference is used: 2.5 V, 1.65 V, or VDD / 2
Shunt resistor, R_{SHUNT}	Depends on the desired magnetic field range, reference, and supply voltage; for more details, see the DRV425 System Parameter Calculator.

- Select the proper supply voltage (V_{DD}) to support the desired magnetic field range (see 表 2 for reference).
- Select the proper reference voltage (V_{REFIN}) to support the desired magnetic field range and to match the input voltage specifications of the desired ADC.
- Use the DRV425 System Parameter Calculator (RangeCalculator tab) to select the proper shunt resistor value of R_{SHUNT}.
- The sensitivity drift performance of a DRV425-based linear position sensor is dominated by the temperature coefficient of the external shunt resistor. Select a low-drift shunt resistor for best sensor performance.
- Use the DRV425 System Parameter Calculator (see the Problems Detected Table in the DRV425 System Parameters tab) to verify the system response.

The high sensitivity of the DRV425 may require shielding of the sensing area to avoid influence of undesired magnetic field sources (such as earth magnetic field). Alternatively, an additional DRV425 is used to perform difference measurement to cancel the influence of a static magnetic field source.

図 6 shows the parameters selected for the TIDA-01467 design.

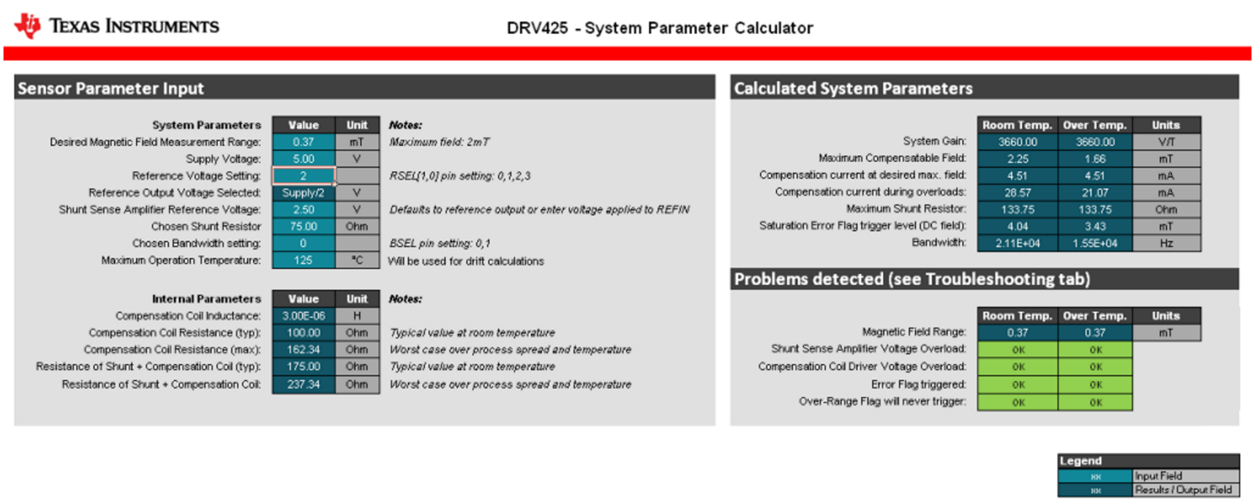


図 6. DRV425 System Parameters for TIDA-01467

3 Hardware, Testing Requirements, and Test Results

3.1 Required Hardware

The hardware is populated with headers and terminal blocks to support three-phase current inputs and capture of output signals. The details of the header or terminal blocks are listed in 表 3.

表 3. TIDA-01467 Header Description

HEADER or TERMINAL BLOCK	FUNCTION
J1	Differential output of sensor U1
J2	Differential output of sensor U2
J3	Differential output of sensor U3
J4	Differential output of sensor U4
J5	Differential output of Sensor U5
J6	Differential output of sensor U6
J9	J9-Pin1 VDD input (3 to 5 V) J9-Pin2 GND
J10	Header for GND
J11	Current input terminal block
J12	Current input terminal block
J13	Current input terminal block

3.2 Testing and Results

3.2.1 Test Setup

The test setup consists of the reference design board, MTE AC current source, DC power supply and 6½ digital multimeter (DMM), as shown in 図 7.

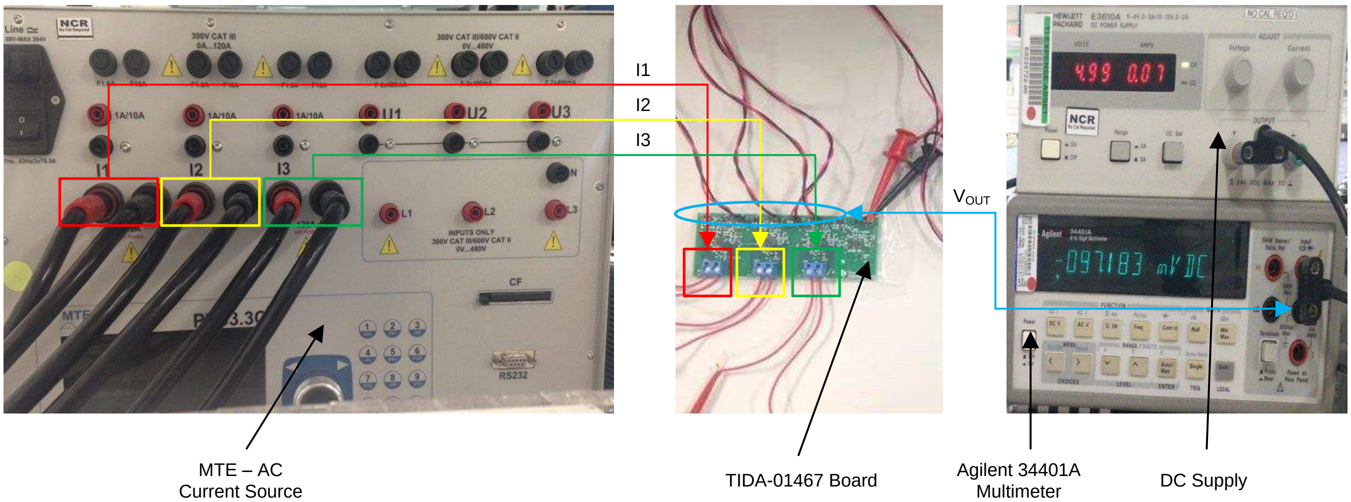


図 7. Test Setup

Follow these steps to perform the tests:

1. Connect a 5-V DC power supply to Jumper J9 of the design board to provide power to the board.
2. Connect the AC current inputs I1, I2, and I3 from the MTE current source to connectors J11, J12, and J13 of the design board.
3. Connect the differential outputs of each sensor at jumpers J1, J2, J3, J4, J5, and J6 of the design board to the 6½ DMM and measure the output voltage.

3.2.2 Test Results

3.2.2.1 *Current Flow up to 5 A*

The accuracy error test is done across three phases with current flowing through the PCB current trace of each phase. The DRV425 detects the magnetic fields generated by the current in the trace and stray fields and outputs an analog signal proportional to sensed magnetic field. The output is measured in RMS voltage between VOUT and REFOUT signals of each DRV425 using a DMM. The accuracy test is done to measure the error in measuring the AC current inputs from 500 mA to 5 A.

注: Lower currents (< 0.5 mA) can be measured by modifying the current trace on the PCB layout. The recommendation is to run the current trace on both signal layer 1 and signal layer 2. This approach helps with obtaining a higher gain of magnetic field.

図 8 provides the accuracy error results for current inputs applied simultaneously across three phases after calibration.

Follow these steps to calibrate the measured data:

1. Measure the voltage (V0.5A) at a known non-zero current (0.5 A).
2. Measure the voltage (V5A) at a known non-zero current (5 A).
3. Obtain the calibration factor using 式 3.

$$Factor = \triangle Voltage / \triangle Current = (V5A - V0.5A)/(5A - 0.5A) \quad (3)$$

4. Apply the calibration factor and obtain the current measured.

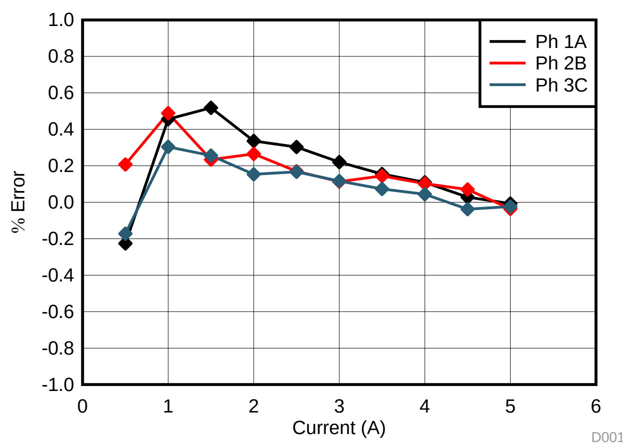


図 8. Measurement Error versus Current

3.2.2.2 Current Flow, Neighbor Current Stray Field

A neighbor current does not produce the same magnetic field at each DRV425 device because the distance from the neighboring current varies from each DRV425. The distance away from the source determines the magnetic field strength. To detect the effect of a neighbor current stray field, the tests listed in 表 4 are conducted. The distance of the DRV425 (center of DRV425 package) from a neighbor current PCB trace in this reference design is ≈ 660 mil. See 図 9 for stray field errors.

表 4. Neighbor Current Stray Field Tests

CURRENT INPUT (A)			NOTE
Ph 1A	Ph 2B	Ph 3C	
I1	0	0	Apply current across single-phase Ph 1A.
0	I2	0	Apply current across single-phase Ph 2B.
0	0	I3	Apply current across single-phase Ph 3C.

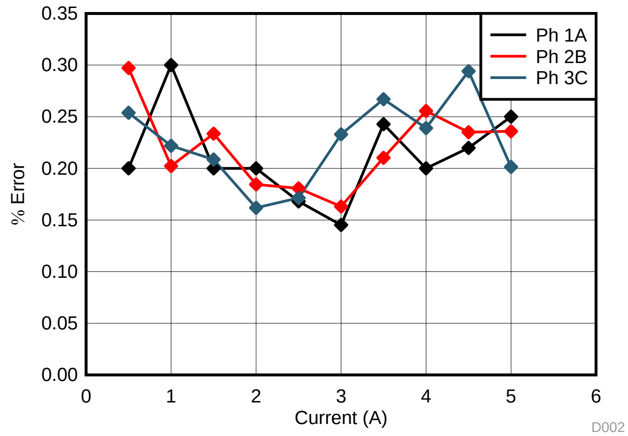


図 9. Stray Field Neighbor Current Error

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01467.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01467.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01467.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01467.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01467.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01467.

5 Related Documentation

1. Texas Instruments, *DRV425 Fluxgate Magnetic-Field Sensor*, DRV425 Datasheet (SBOS729)
2. Meeker, D.C., FEMM 4.2, Finite Element Method Magnetics (http://www.femm.info)
3. Texas Instruments, *DRV425EVM User's Guide* (SLOU410)
4. Texas Instruments, DRV425 System Parameter Calculator (SLOC331)
5. Advanced Circuits, 4PCB Trace Width Website Calculator (http://www.4pcb.com/trace-width-calculator.html)

5.1 商標

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