

TI Designs: TIDA-01467

使用磁通门传感器的迹线上三相电流感应参考设计



说明

该参考设计展示了一款三相电流传感器，该传感器通过测量载流导体（如 PCB 迹线）生成的磁场来测量电流。传感器放置在载流 PCB 迹线附近，以测量通过迹线的电流。

电流感应设计适用于需要进行基本电源监控的工业应用。

通过使用磁通门技术，该设计可以覆盖高达每相 5A 的三相电流测量，同时实现高分辨率。

资源

TIDA-01467
DRV425

设计文件夹
产品文件夹



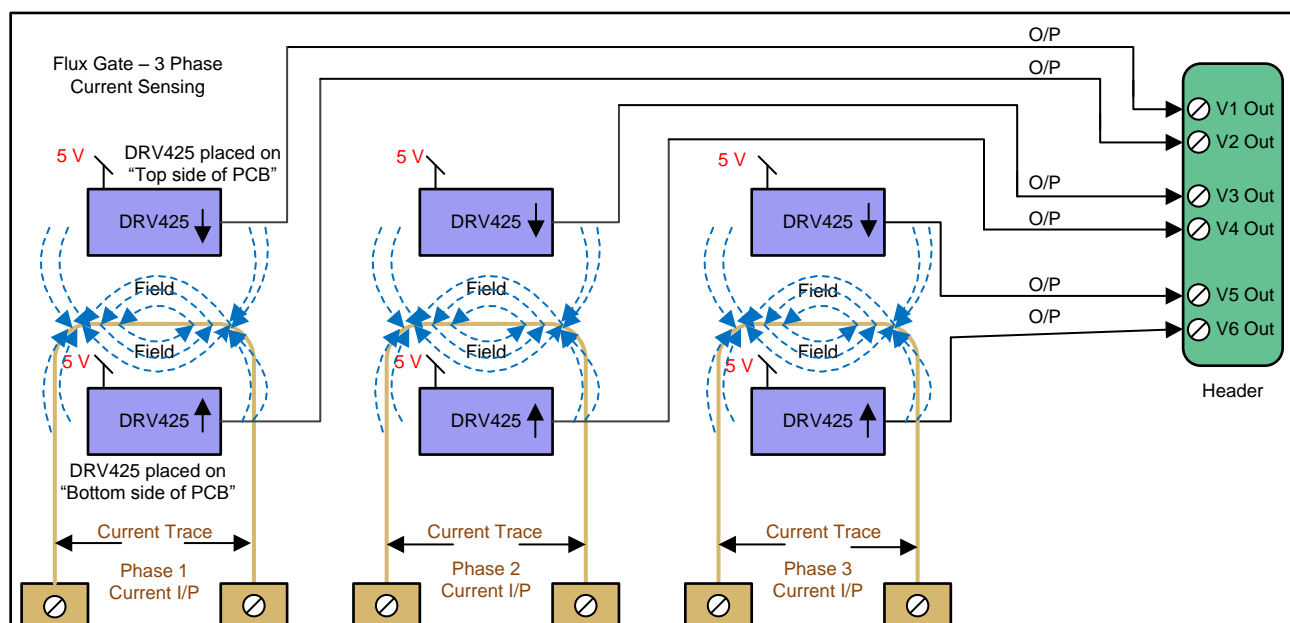
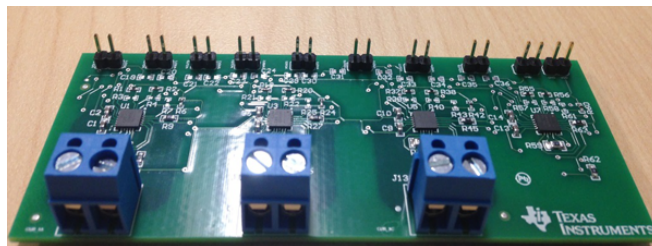
咨询我们的 E2E 专家

特性

- 使用磁通门传感器进行三相电流测量
- 经过校准的电流测量精度： $\leq \pm 1\%$
- 迹线（PCB 迹线）上的电流感应
- 电流测量范围：500mA 至 5A
- 线性输出电压
- 高达 $\pm 2\text{mT}$ （最大值）的可调传感器范围
- 电源电压范围：3.0 至 5.5V
- 小外形尺寸：4 英寸 \times 1.5 英寸

应用

- 电能质量分析仪



Copyright © 2017, Texas Instruments Incorporated



该 TI 参考设计末尾的重要声明表述了授权使用、知识产权问题和其他重要的免责声明和信息。

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 公式 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 公式 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

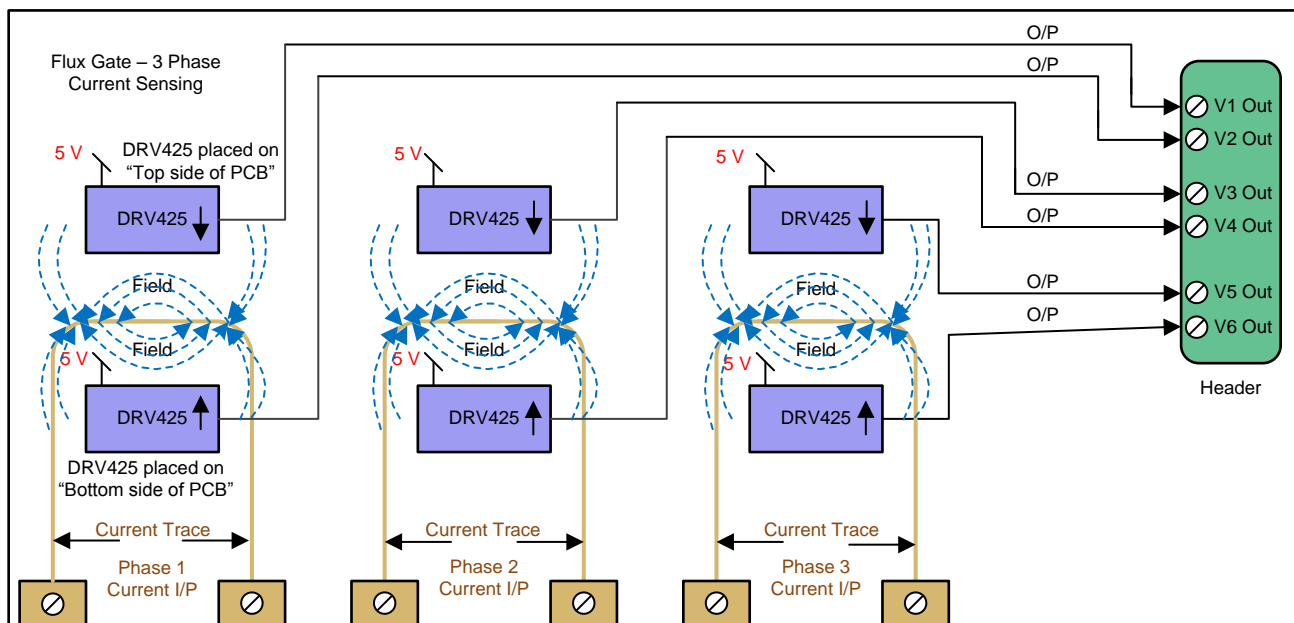
| PARAMETER | SPECIFICATIONS |
|---------------------------------|---------------------------|
| Number of phases | Three phase currents |
| Accuracy | ≤ ±1% |
| Current sensor | Flux gate magnetic sensor |
| Current inputs | ≤ 5-A AC |
| Magnetic field range | ±2 mT (max) |
| Supply voltage, V _{DD} | 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



Copyright © 2017, Texas Instruments Incorporated

图 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.

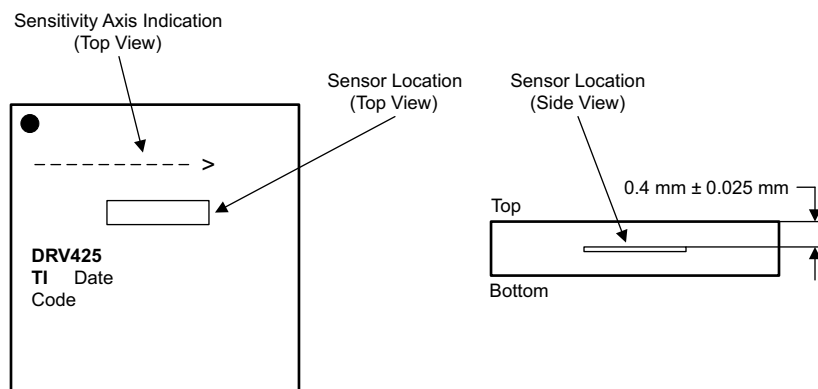
2.3.2 Fluxgate Sensor

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 图 2. 图 2 also shows the location of the sensor inside the package.



Copyright © 2017, Texas Instruments Incorporated

图 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 公式 2 with referring to ANSI/IPC-2221 standard.

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

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 节 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 图 3.

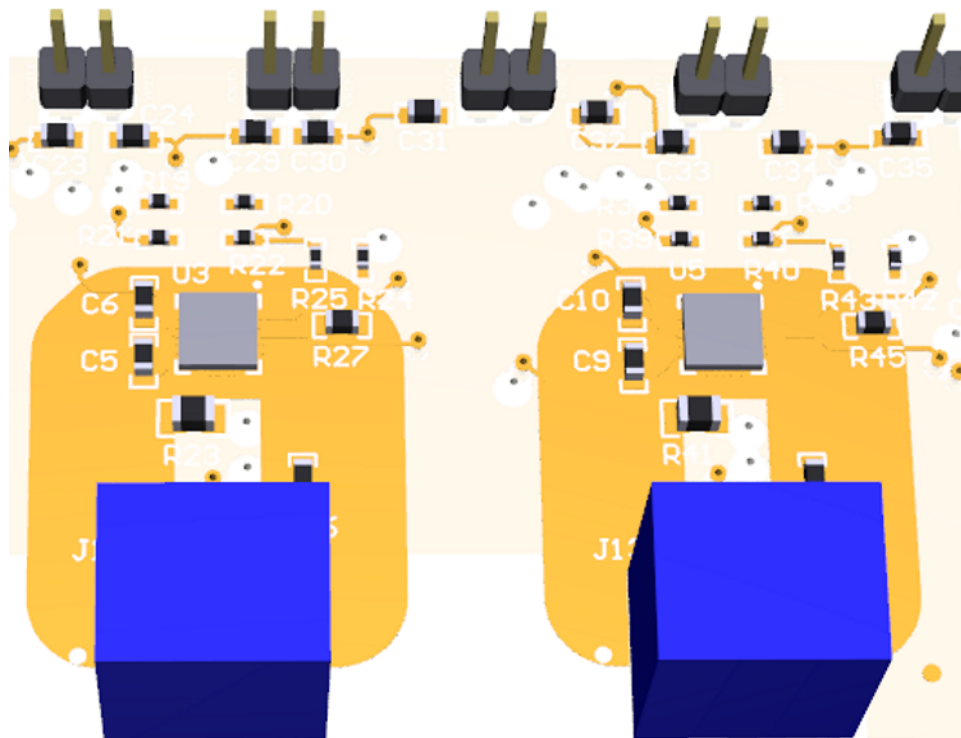


图 3. PCB Current Trace

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 .

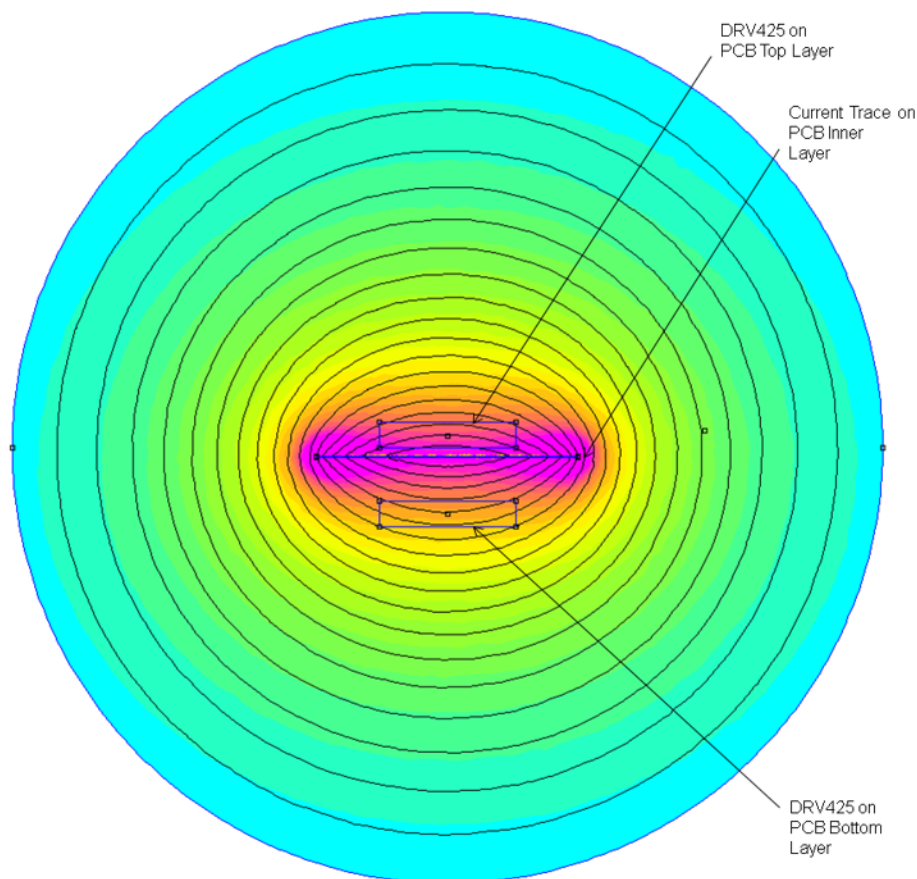


图 4. FEMM 4.2 Magnetic Simulation

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

图 5 displays the strength of magnetic flux density.

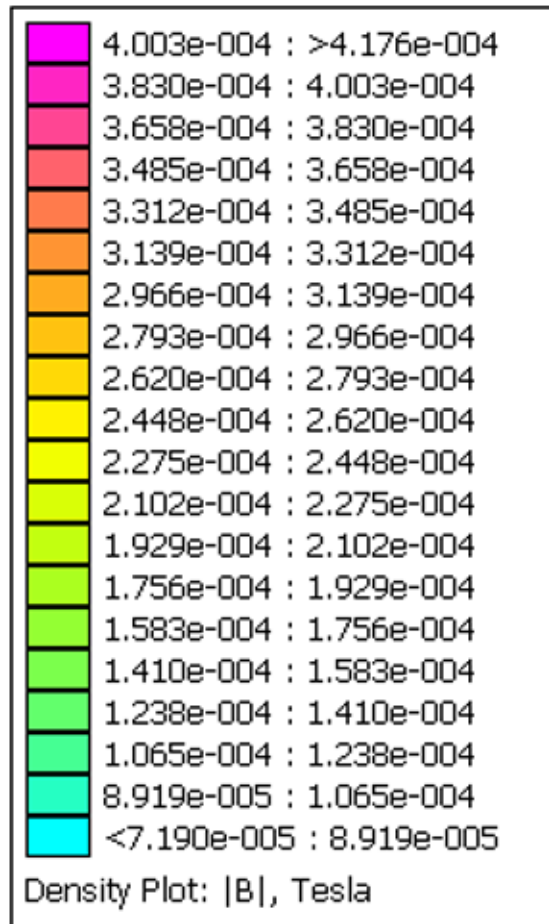


图 5. FEMM 4.2 Density Plot Table

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.

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

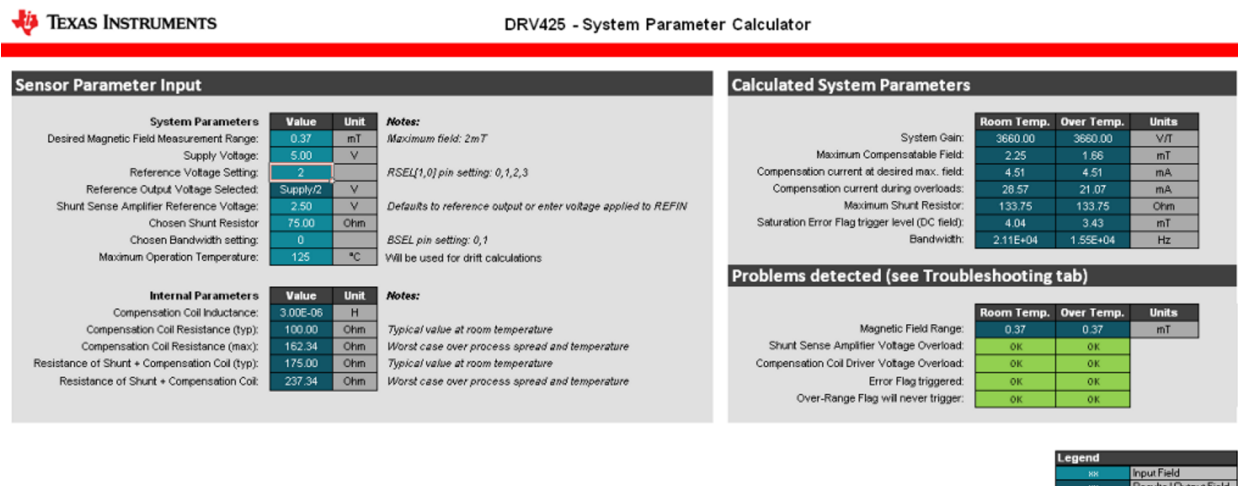


图 6. DRV425 System Parameters for TIDA-01467

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 图 7.

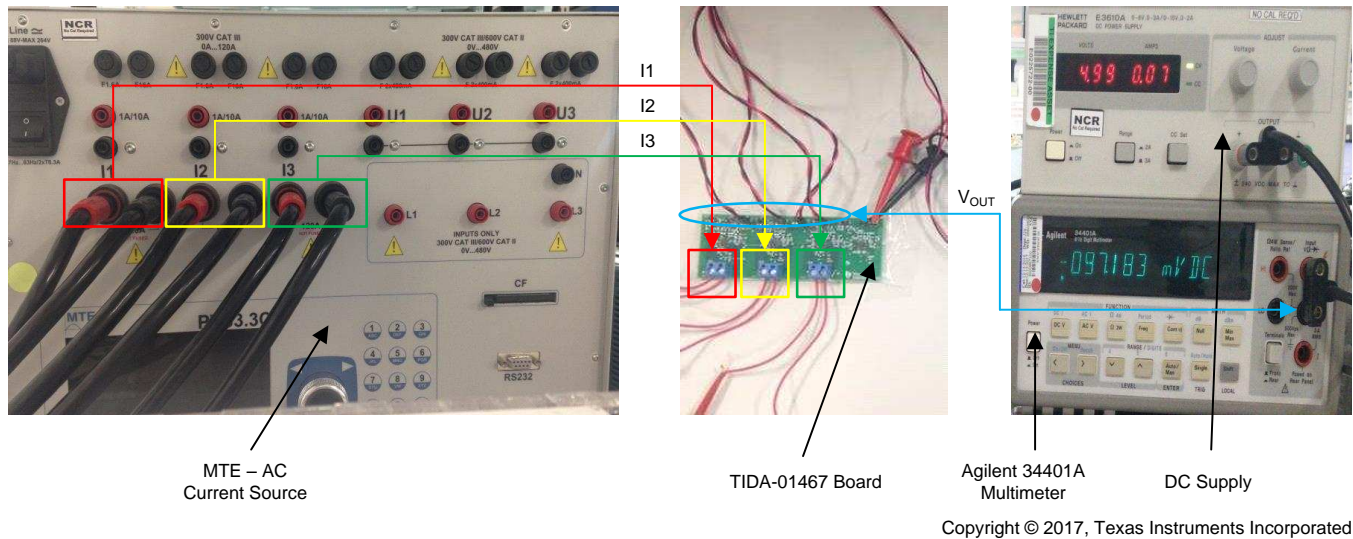


图 7. Test Setup

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.

图 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 公式 3.

$$\text{Factor} = \Delta \text{Voltage} / \Delta \text{Current} = (V5A - V0.5A) / (5A - 0.5A) \quad (3)$$

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

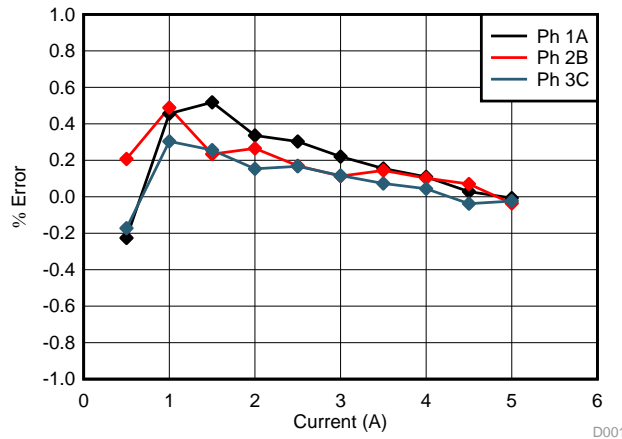


图 8. Measurement Error versus Current

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 图 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. |

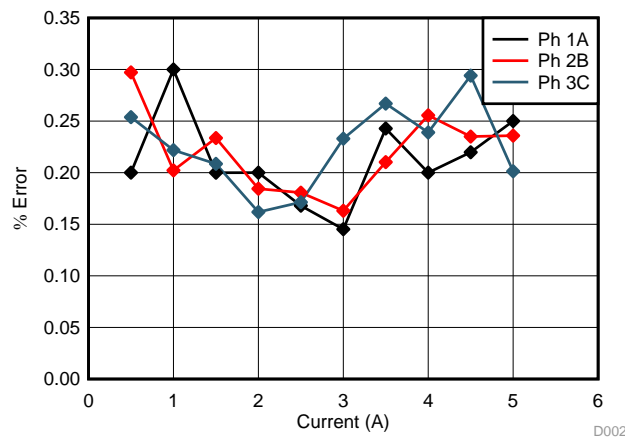


图 9. Stray Field Neighbor Current Error

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 商标

PowerPAD is a trademark of Texas Instruments.
All other trademarks are the property of their respective owners.

有关 TI 设计信息和资源的重要通知

德州仪器 (TI) 公司提供的技术、应用或其他设计建议、服务或信息，包括但不限于与评估模块有关的参考设计和材料（总称“TI 资源”），旨在帮助设计人员开发整合了 TI 产品的应用；如果您（个人，或如果是代表贵公司，则为贵公司）以任何方式下载、访问或使用了任何特定的 TI 资源，即表示贵方同意仅为该等目标，按照本通知的条款进行使用。

TI 所提供的 TI 资源，并未扩大或以其他方式修改 TI 对 TI 产品的公开适用的质保及质保免责声明；也未导致 TI 承担任何额外的义务或责任。TI 有权对其 TI 资源进行纠正、增强、改进和其他修改。

您理解并同意，在设计应用时应自行实施独立的分析、评价和判断，且应全权负责并确保应用的安全性，以及您的应用（包括应用中使用的 TI 产品）应符合所有适用的法律法规及其他相关要求。您就您的应用声明，您具备制订和实施下列保障措施所需的一切必要专业知识，能够 (1) 预见故障的危险后果，(2) 监视故障及其后果，以及 (3) 降低可能导致危险的故障几率并采取适当措施。您同意，在使用或分发包含 TI 产品的任何应用前，您将彻底测试该等应用和该等应用所用 TI 产品的功能。除特定 TI 资源的公开文档中明确列出的测试外，TI 未进行任何其他测试。

您只有在为开发包含该等 TI 资源所列 TI 产品的应用时，才被授权使用、复制和修改任何相关单项 TI 资源。但并未依据禁止反言原则或其他法律授予您任何 TI 知识产权的任何其他明示或默示的许可，也未授予您 TI 或第三方的任何技术或知识产权的许可，该等产权包括但不限于任何专利权、版权、屏蔽作品权或与使用 TI 产品或服务的任何整合、机器制作、流程相关的其他知识产权。涉及或参考了第三方产品或服务的信息不构成使用此类产品或服务的许可或与其相关的保证或认可。使用 TI 资源可能需要您向第三方获得对该等第三方专利或其他知识产权的许可。

TI 资源系“按原样”提供。TI 兹免除对 TI 资源及其使用作出所有其他明确或默示的保证或陈述，包括但不限于对准确性或完整性、产权保证、无屡发故障保证，以及适销性、适合特定用途和不侵犯任何第三方知识产权的任何默认保证。

TI 不负责任何申索，包括但不限于因组合产品所致或与之有关的申索，也不为您辩护或赔偿，即使该等产品组合已列于 TI 资源或其他地方。对因 TI 资源或其使用引起或与之有关的任何实际的、直接的、特殊的、附带的、间接的、惩罚性的、偶发的、从属或惩戒性损害赔偿，不管 TI 是否获悉可能会产生上述损害赔偿，TI 概不负责。

您同意向 TI 及其代表全额赔偿因您不遵守本通知条款和条件而引起的任何损害、费用、损失和/或责任。

本通知适用于 TI 资源。另有其他条款适用于某些类型的材料、TI 产品和服务的使用和采购。这些条款包括但不限于适用于 TI 的半导体产品 (<http://www.ti.com/sc/docs/stdterms.htm>)、[评估模块](#)和样品 (<http://www.ti.com/sc/docs/sampters.htm>) 的标准条款。

邮寄地址：上海市浦东新区世纪大道 1568 号中建大厦 32 楼，邮政编码：200122
Copyright © 2017 德州仪器半导体技术（上海）有限公司