Application Report
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Designing with the DRV421: Closed Loop Current Sensor Specifications

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ABSTRACT

The DRV421 is a signal-conditioning integrated circuit for use in closed-loop magnetic current sensor modules. The DRV421 is designed with an internal fluxgate sensor to provide superior performance and simplify system design. The DRV421 contains all the necessary excitation and signal-conditioning circuitry to drive the current-sensing feedback loop. This application note presents key specification considerations for designing a closed-loop current sensor with the DRV421.

Contents

List of Figures

List of Tables

1 Introduction

Closed-loop current transducers measure currents over wide frequency ranges, including dc currents. Their measurement range is dependent on the ratio of primary current conductor windings (N_P) to the number of secondary or compensation coil windings (N_S) and the value of a shunt resistor (R_{SHUNT}) placed in series with the compensation coil. These types of closed-loop modules offer a contact-free current-sensing method, as well as excellent galvanic isolation combined with high resolution, accuracy, and reliability.

At dc and in low-frequency ranges, the magnetic field induced from the current in the primary winding (I_{PRIM}) is compensated by a current driven through a secondary compensation coil wound on a ferro-magnetic core which acts as a field concentrator. A magnetic sensor (an integrated fluxgate) located within a gap in the magnetic core detects the magnetic flux created by current flowing through the primary winding. This probe delivers a feedback signal to the signal-conditioning circuitry block which, in turn, drives a current (I_{SEC}) through the compensation coil. The secondary current creates a flux equal in magnitude but in the opposite direction to the flux created by the primary, bringing the magnetic flux back to zero.

The compensation current flows through a shunt resistor creating a voltage drop which is passed to a differential amplifier. The differential amplifier provides a gain of 4 V/V which is delivered to the DRV421 output stage. The resulting output voltage of the sensor is proportional to the current flowing through the primary winding as shown in the transfer function defined in Equation 1. Figure 1 shows the principle of a closed-loop current sensor using the DRV421.

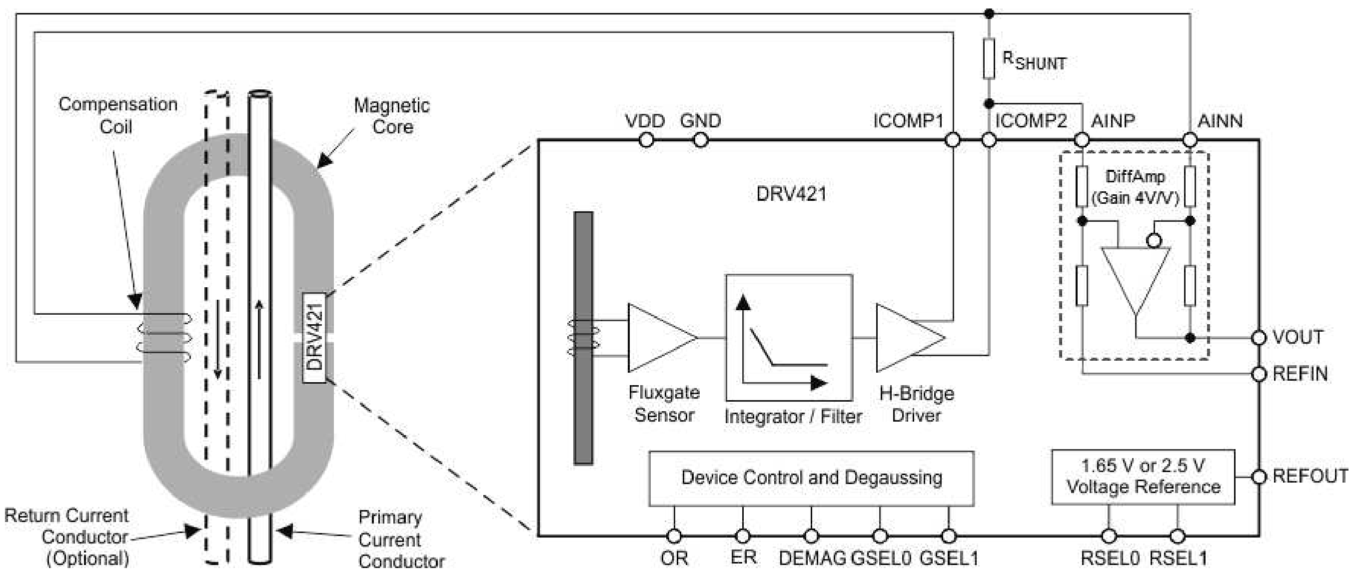

Figure 1. Closed-Loop Current Sensor Module

$$VOUT = I_{PRIM} \times \left(\frac{N_P}{N_s} \right) \times R_{SHUNT} \times Gain \quad (1)$$

2 Closed-Loop Current Sensor Specifications

The required core properties will be dependent on the system level specifications as well as the loop stability requirements of the current sensor module. This application note will focus on the contributions of the core versus the DRV421 on the overall system parameters. For details on loop stability calculations, please refer to *Designing with the DRV421: Control Loop Stability* (SLOA224).

2.1 DRV421 Specifications vs Magnetic Core Properties

Several DRV421 specifications, such as offset, offset drift, and noise, are given in magnetic units (Tesla). This may puzzle a module designer who is interested in specifications in terms of primary current. The relation between applied primary current and the magnetic field it produces when no feedback is applied defines the Magnetic core gain (G). A typical core design will have a gain of about 500 µT/A; overall, it ranges from 200–1000 µT/A. Using the magnetic core gain, it is possible to relate the magnetic specifications of the DRV421 to current measurement specifications. Table 1 provides a relationship of system-level performance parameters impacted by the DRV421 and the magnetic core.

Table 1. Closed-Loop Current Sensor Specifications

Parameter	Performance Determined by	
	Core	DRV421
Offset and Offset Drift	No	Yes
Offset after Overload	Yes	No
Noise	No	Yes
Linearity Error	No	Yes
Gain Error	Yes	No
Measurement Range	Yes	Yes
Neighboring Fields/Current Rejection Ratio (NBRR)	Yes	No
Bandwidth Gain and Flatness	Yes	No
Common-mode Current Rejection (CMIRR)[1]	Yes	No
Overall Accuracy	Yes	Yes

(1) For fault current sensors

2.1.1 Offset and Offset Drift over Temperature

Offset and offset drift over temperature is defined as the closed-loop current sensor output voltage for zero primary current input, zero ambient field/neighboring current, and zero common-mode current (for fault current sensing).

The three primary contributors to this offset and offset drift are the core magnetization (that is, core remanence), the fluxgate offset and the differential amplifier offset. Mechanical stress or current overloads can cause core magnetization producing a magnetic field that is measured by the fluxgate sensor. The DRV421 can remove this offset by providing a demagnetization function which can be activated during the power up sequence of the sensor. The power up demagnetization function also removes the initial offset of the fluxgate. After demagnetization, the only sources of offset and offset drift remaining is in the fluxgate drift; typically 20 nT/°C; and the differential amplifier offset and offset drift. For the typical core gain of 500 µT/A, the fluxgate offset drift would be equivalent to 40 µA/°C of primary current. The contribution of the differential amplifiers offset and offset drift depends on the shunt resistance. For a 10Ω shunt, the offset contribution would be 100 µV/(4*10) or 2.5 µA secondary current, assuming 1000 turns on the secondary this equates to 2.5 mA of primary current. The differential amplifiers offset drift would be equivalent to 2 µV/(4*10) or 50 nA/°C of secondary current or 50 µA/°C of primary current drift.

2.1.2 Offset and Overload

During an overload condition, such as a short circuit situation, the DRV421 cannot deliver enough compensation current to keep the magnetic field in the core at zero. As a result, a large field is built up, which can saturate and magnetize the core. After the overload condition subsides, the magnetized core causes an offset. The amount of offset depends on the remanence of the core material and the core geometry. Triggering a demagnetization cycle (by toggling the 'DEMAG' pin) will recover the original offset performance of the core. Note, ensure the primary current is zero before attempting to demagnetize the core.

2.1.3 Noise

The noise contribution of the magnetic core and secondary coil are negligible. The two main sources of noise are from the differential amplifier and the fluxgate found inside the DRV421. The differential amplifier noise is specified as 170 nV / $\sqrt{Hz}$ at the output or 42.5 nV / $\sqrt{Hz}$ at its input. The fluxgate noise (1.5 nT / $\sqrt{Hz}$) is amplified by the shunt resistor, so its contribution depends on the value of the shunt, the magnetic core gain, and the number of secondary windings on the core.

As an example, consider a closed-loop sensor where the core gain is 500 µT/A, there are 1000 turns on the secondary coil and a 10-Ω shunt resistor is used in front of the differential amplifier found in the DRV421. The fluxgate noise is specified as 1.5 nT / $\sqrt{Hz}$. When referred to the primary current, this is equal to 1.5 nT / 500 µT/A or 3 µA / $\sqrt{Hz}$. Referred to the secondary, this is equal to 3 µA / 1000 turns or 3 nA / $\sqrt{Hz}$. The voltage noise from the fluxgate as seen across the shunt is therefore 3 nA × 10 Ω or 30 nV / $\sqrt{Hz}$. The total noise contribution is therefore 30 nV / $\sqrt{Hz}$ (fluxgate) + 42.5 nV / $\sqrt{Hz}$ (differential amp) or 52 nV / $\sqrt{Hz}$. From this example, it can be shown that the differential amplifier noise dominates with low value shunt resistors while the fluxgate noise dominates with higher shunt resistor values.

2.1.4 Linearity Error

The main sources of error in open loop sensors are related to the core and sensor non-linearities. In closed-loop sensors, these non-linearities are virtually eliminated because of the large loop gain which accurately drives the magnetic field in the core and sensor to zero. The DRV421 features a DC gain of 250 V / µT. With a maximum ±5-V output swing, the input field only changes by 10 V / 250 V / µT or 40 nT. Lab experiments on a variety of cores typically show that linearity is well below 0.1%.

2.1.5 Gain Error

Closed-loop sensor gain is generally determined by the primary to secondary winding turns ratio. The main error source is limited magnetic coupling between primary current and compensation coil, and thus relates to magnetic core properties. Higher core permeability (core material properties) and a larger core cross-section can reduce gain errors. A change in the primary conductor position can also influence gain errors. Fixing the position of the primary conductor via mechanical packaging can reduce gain error variations.

2.1.6 Measurement Range

In closed-loop current sensors, the measurement range is determined by the amount of current which can be driven into the secondary or compensation coil. This current limit is determined by the maximum current the driver stage can deliver, or by the secondary winding resistance combined with the current shunt resistance and the maximum driver output voltage. The DRV421 can deliver up to 250 mA and provides a minimum of 4.2 Vpp into a 20-Ω load when powered from a 5-V rail.

2.1.7 Neighboring Current Rejection Ratio

Neighboring Current Rejection Ratio (NBRR) is the closed-loop sensors ability to reject external magnetic fields. The source of an external magnetic field can be from other conductors in close proximity to the sensor, nearby equipment such as motors or relays, or even the earth's magnetic field. There are no industrial standards governing NBRR and there are a number of contributing factors involved such as the field direction, distance to neighboring currents, magnitude of neighboring currents, and so forth, NBRR is particularly critical in fault current sensing applications where very small signals (< 30 mA in some cases) are being monitored in the presence of large disturbing fields. NBRR is solely related to core design; the permeability, thickness and gap configuration will impact the core's ability to reject external magnetic fields. It is important to note that in practical lab environments, there are always external magnetic fields present, unless the magnetic core is placed in a zero gauss chamber. For instance, the earth magnetic field can add measurement offset. Although the using the degauss function will remove such offset, a change in field due to a movement/rotation of the magnetic core will lead to a change in earth magnetic field and thus an offset shift.

2.1.8 Bandwidth and Gain Flatness

Closed-loop current sensors have two signal paths which enable them to measure both DC and AC current signals. At DC and low frequencies (that is, less than 100 Hz), the active loop with the fluxgate dominates. At higher frequencies, the sensor acts like a current transformer.

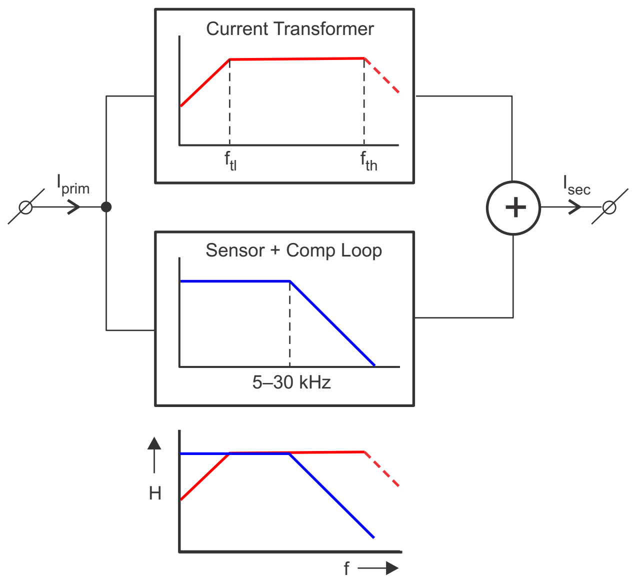

Figure 2. Closed-Loop Current Sensor Frequency Behavior

Overlap between the two paths is needed to ensure that there is a flat frequency response to ensure a smooth transition between sensor mode and transformer mode. The bandwidth of the overall system is determined by the transformer properties. The typical bandwidth of a closed-loop current sensor is 100–200 kHz, while the active loop bandwidth is typically 5–30 kHz. It should be noted that both the compensation coil inductance and the shunt resistance determine the current transformer corner frequency, f_{tl}. Therefore, increasing the shunt resistor to large values (> 500 ohm), for instance to measure small currents in fault current sensors, may lead to significant gain non-flatness.

2.1.9 Common-Mode Current Rejection (CMIRR)

Closed-loop current sensors that are used in fault detection applications are constructed with two primary conductors carrying current in opposite directions. Fault sensors need to measure small differential currents (that is, < 30 mA), while rejecting large common mode currents (that is, 50 A). In order to achieve this level of rejection, it is imperative that an equal and opposite current in the primary conductors results in equal and opposite magnetic fields on the fluxgate sensor.

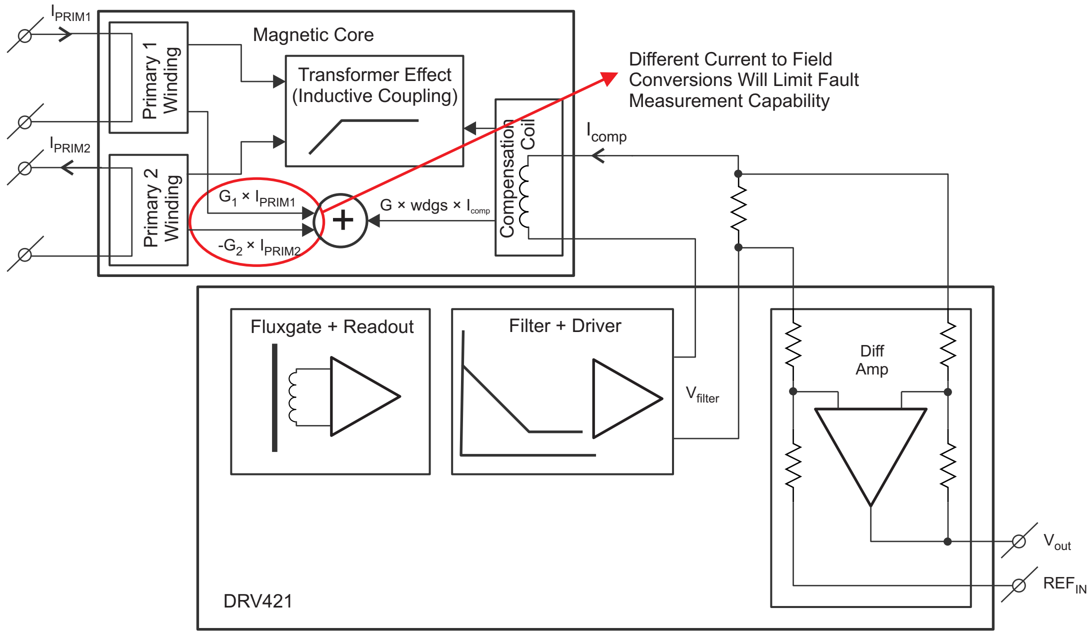

Figure 3. Common-Mode Current Rejection

Factors which influence the common-mode current rejection capabilities of the fault sensor include the core permeability and the position of the primary conductors. Asymmetrically placed conductors can cause an imbalance in the field seen by the sensor which can limit the abilities to measure fault currents accurately.

3 Summary

Closed-loop current sensor offset and offset drift, noise and linearity parameters are dependent on the DRV421. Parameters regarding gain and gain error, measurement range, the ability to reject external magnetic fields, and the overall sensor bandwidth are dependent primarily on the transformer core design.