Application Report
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Designing With the DRV421: Control Loop Stability

Martijn Snoeij and Tom Hendrick *Precision Analog - Energy Solutions Products*

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 discusses how to ensure that the system control loop is stable under all conditions, how to select the proper gain setting on DRV421 for stable operation, and what properties the magnetic core should have to ensure stable operation.

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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 compensation coil wound on a ferro-magnetic core which acts as a field concentrator. A magnetic sensor (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 compensation 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 is also passed through a shunt resistor (R_{SHUNT}) 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 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.

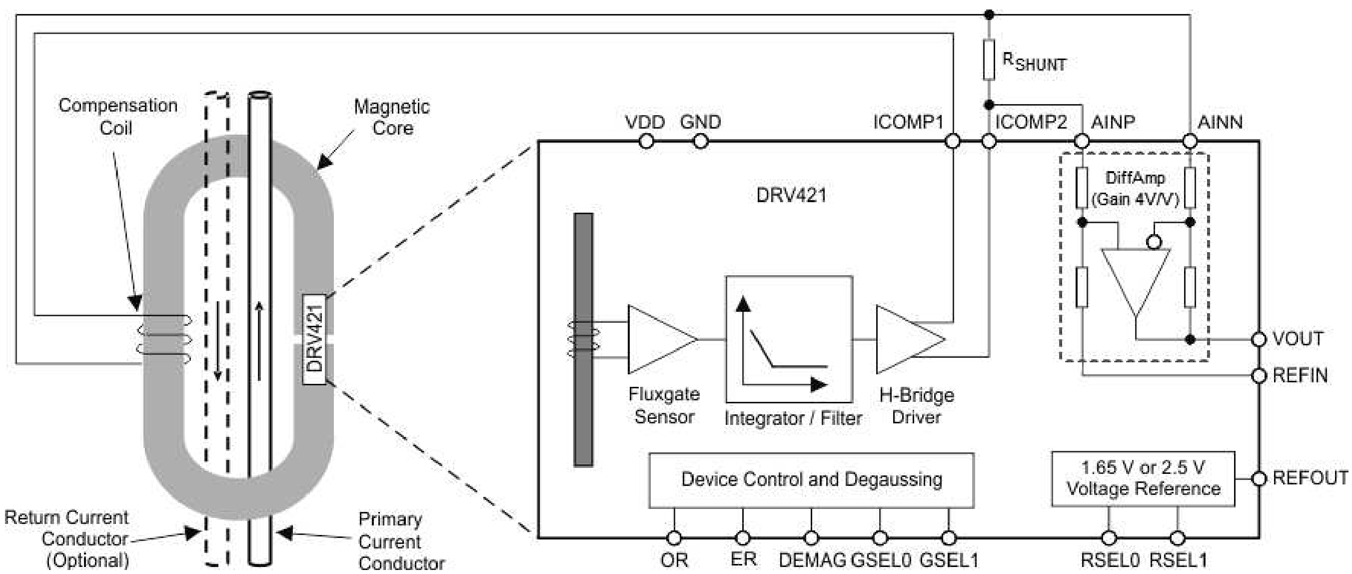

Figure 1. Closed-Loop Current Sensor Module

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

2 Control Loop Stability in Normal Operation

2.1 DRV421 Control Loop Block Diagram

A block diagram of the current sensing control loop around DRV421 and a magnetic core is depicted in Figure 2.

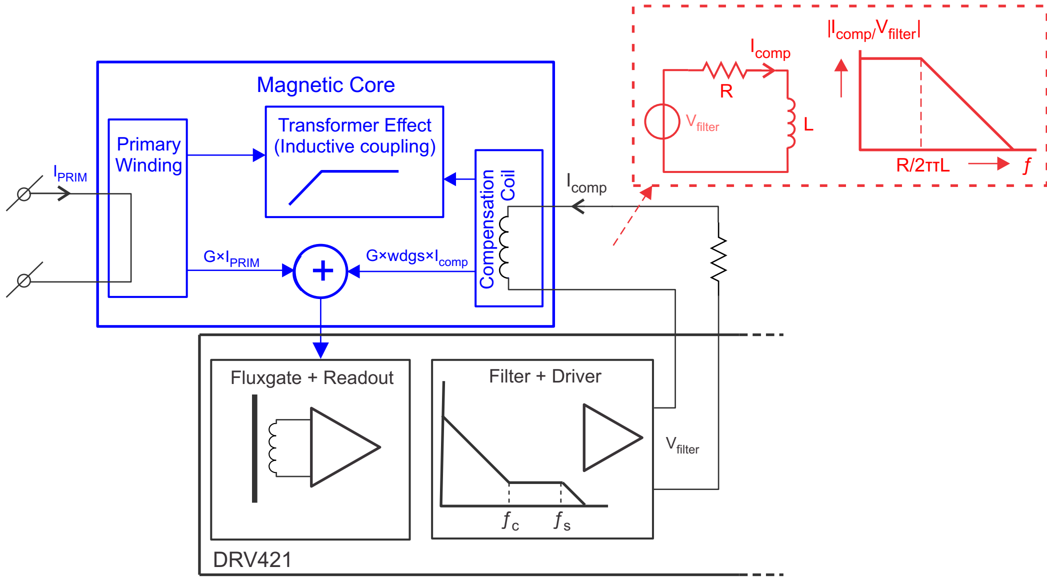

Figure 2. Current-Sensing Control Loop Comprising DRV421 and Magnetic Core

As can be seen in Figure 2 the loop comprises both the DRV421 and the magnetic core, and therefore, stable operation depends on properties of both these elements. First, there are a number of variables in the loop that are to first order constant with frequency. The magnetic core gain, defined as how much magnetic field a given amount of current through the compensation coil produces, is a factor in the overall loop gain. Similarly, the number of compensation coil windings influences the loop gain. Furthermore, in order to assess the stability of the loop, the gain vs frequency (and thus, any poles and zeroes) of each block in the loop needs to be determined. Starting with DRV421, the output of the fluxgate is fed to an analog filter that serves as an integrator at low frequencies, and has a flat-band region between frequencies f_c and f_s, as shown in Figure 3. The corner frequency f_c, as well as the flat band gain of the filter, depend on GSEL1/0 pin logic levels (see data sheet) and enable a stable compensation loop for a wide range of magnetic cores, as will be explained later. Frequency f_s is at approximately 250 kHz, and reflects the fact that both the sensor and the filter are sampled.

The output of the filter is applied across the magnetic core's compensation coil. This applied voltage results in a current through the compensation coil that generates a magnetic field. This voltage/current conversion forms a second pole in the control loop, which is determined by the series connection of the resistance and inductance connected to the compensation driver. The corner frequency is therefore determined by:

$$f_{tf} = \frac{R}{2\pi L} \tag{2}$$

Here, the resistance R comprises both the shunt resistor as well as the ohmic resistance of the compensation coil, while L is the inductance of the compensation coil. It can be shown that this corner frequency f_{tf} also equals the corner frequency from which the magnetic core starts to operate as a current transformer.

2.2 Control Loop Bode Diagram

By combining the frequency transfer of the DRV421 filter and the magnetic core, a complete Bode diagram of the control loop can be obtained, as shown in Figure 3.

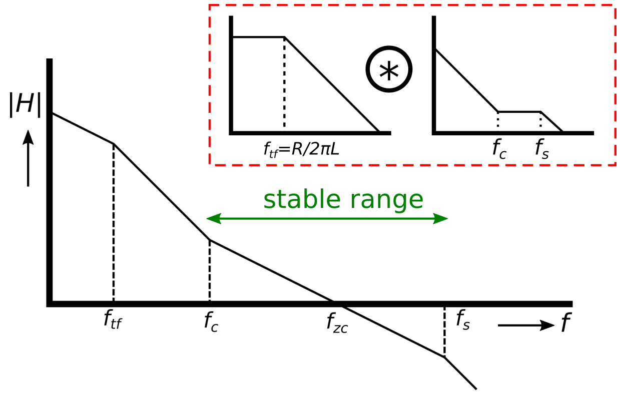

Figure 3. Bode Diagram of the Current-Sensing Loop

From control theory, it is well known that a 20 db/decade roll-off is needed at the zero crossing frequency f_{zc} of the loop in order to ensure stability. In this case, f_{zc} must therefore be somewhere between the filter corner frequency f_c and sampling frequency f_s. Since f_c is 1.9 kHz or 3.8 kHz, and f_s is about 250 kHz, this zero crossing can fall inside relatively large frequency span of nearly 2 decades. Therefore, even without adjusting the gain settings of DRV421, the control loop will usually be stable. Nonetheless, it is a good design target for f_{zc} to be close to 20 kHz. This allows about a 10x variation in crossing frequency in both directions, and ensures maximum robustness against tolerances in both the DRV421 and the magnetic core.

The zero-crossing frequency f_{zc} is determined by both the filter gain of DRV421 in its flat-band region, as well as the amount of compensation current a given amount of voltage at the filter output is producing. The latter is determined by the compensation coil inductance, since its impedance dominates the load of the filter at higher frequencies. Therefore, a larger compensation coil inductance shifts the pole to lower frequencies and thus pushes the zero crossing down as well, as illustrated in Figure 4.

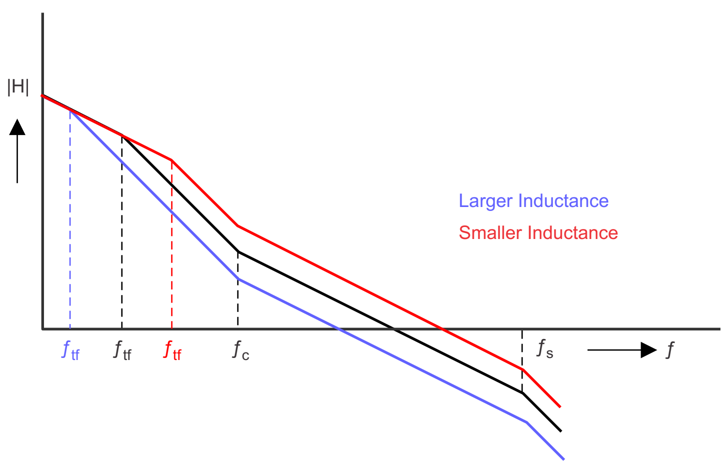

Figure 4. Effect of Inductance Change on Zero Crossing Frequency

In order to ensure stable operation for a wide range of compensation coil inductances and thus a wide range of magnetic cores, the change in the pole f_{tf} can be counteracted by adjusting flat-band gain of the filter using the gain select pins GSEL0 and GSEL1.

2.3 Recommended Filter Gain Settings

A key question is what filter gain setting is optimal for a given core design. In the previous sections, it was shown that the following magnetic core parameters are of importance:

- Magnetic core gain (magnetic field / primary transfer function, [uT/mA])
- Number of compensation coil windings (N_S)
- Compensation coil inductance

As mentioned in the previous sections, the magnetic core gain and number of compensation coil windings have a constant effect on loop gain over frequency, whereas the compensation coil inductance influences the loop properties at frequencies around the zero crossing. While the exact value of G_{CORE} will depend on the particular core design, the typical values range from 0.4mT/A to 1mT/A.

To properly select the gain it is useful to combine these 3 parameters into a gain factor, G_{MOD}, as follows:

$$G_{MOD} = \frac{G_{CORE} \times N_S}{L} \tag{3}$$

This gain factor should simply be understood as being a portion of the overall loop gain equation, with frequency dependencies removed, which is why we are using the coil inductance L instead of its impedance at a certain frequency. This provides a great simplification over a full gain equation that needs to include frequency-dependent factors. Both core gain and number of compensation windings increase the loop gain, while compensation coil inductance reduces it. Table 1 then relates the found core gain factor G_{MOD} to the optimal gain setting.

Table 1. DRV421 Loop Gain Filter Settings and Relation to Core Parameters

GSEL1	GSEL0	DRV421 Loop Filter Properties: Integrator Corner Frequency (kHz)	DRV421 Loop Filter Properties: Flat-Band Gain (V/mT)	Core Gain Factor G_{MOD} Range	Core Inductance Range for N_S = 1000, G_{core} = 0.6 mT/A
0	0	3.8	10	$3 < G_{MOD} < 12$	100 mH < L < 200 mH
0	1	3.8	50	$1 < G_{MOD} < 3$	200 mH < L < 600 mH *
1	0	1.9	35	$1 < G_{MOD} < 3$	200 mH < L < 600 mH
1	1	1.9	100	$0.3 < G_{MOD} < 1$	600 mH < L < 2 H

From Table 1, it can be noted that gain setting ‘01’ and ‘10’ overlap; the difference is mainly in the integrator corner frequency. For most normal sensors, setting ‘10’ is recommended. For fault current sensors however, ‘01’ can be better, as it features a higher integrator/flat-band cross-over frequency of 3.8 kHz. Due to the typically much lower current levels to be measured, fault current sensors will have a higher shunt resistor and thus a higher transformer pole frequency f_{tf}. This can cause problems, as it reduces the frequency overlap between the active compensation loop and the transformer effect. See also Designing with the DRV421: Closed-Loop Current Sensor Specifications (SLOA223). The larger integrator/flat-band cross over frequency counteracts this problem.

To aid the designer in choosing the right gain settings, as well as evaluate the needed shunt resistance for a desired current measurement range, please refer to the Designing with the DRV421: System Parameter Calculator (SLOA225) application note and its associated Microsoft® Excel® spreadsheet. BothTable 1 and the Excel spreadsheet should be understood as an initial gain setting recommendation, based on a first-order model of the magnetic core. Second order magnetic effects can play a significant role in actual loop stability as outlined in the next section.

2.4 Second-Order Magnetic Effects

An important assumption in the previous section that was implicitly made is that both the compensation coil inductance and the magnetic core gain remain constant with frequency. However, there are several magnetic effects that can lead to significant deviations. Most importantly, in magnetic cores that have a significant conductivity (such as mu metal cores), significant eddy currents occur. These can affect both the core gain and the compensation coil inductance significantly, leading to different outcomes than predicted in Table 1. Other effects can include the proximity effect in the coil winding, leading to an increase in ohmic resistance, and magnetic hysteresis.

Some simulations and measurements have suggested that mu-metal based cores need a lower gain setting than predicted by Table 1, although at the same time the eddy current losses actually help to make the loop more stable. In contrast, ferrite cores, due to their low conductivity, more closely follow the predicted gain settings due to their superior high-frequency properties.

Due to the second order effects, experimental verification by checking the response of the loop to a current step is always strongly recommended, as outlined in the DRV421 data sheet (SBOS704). An example of such a current step is shown in Figure 5 for the case of a magnetic core with 300mH inductance and 1000 compensation coil windings. For this core, an optimum gain setting of GSEL[1:0] = 10 was found. If the ICOMP1 and ICOMP2 pins show significant ringing, a different gain setting or change to the core design is needed. In case multiple gain settings yield stable results, the lowest gain setting is preferred.

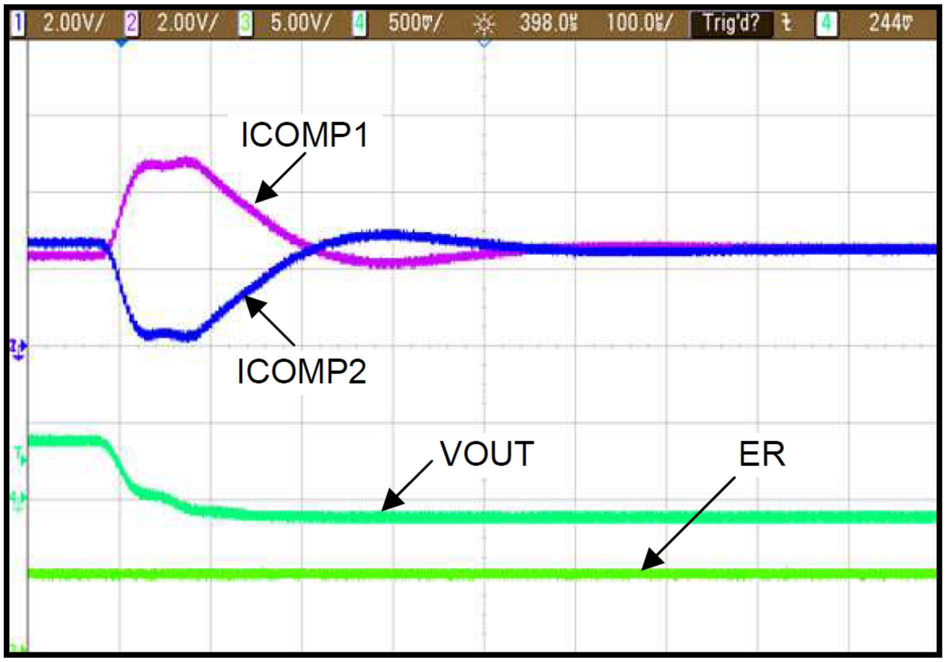

Figure 5. Settling of ICOMP1 and ICOMP2 with GSEL[1:0] = 10

3 Summary

The stability of the control-loop in a closed-loop current sensor depends on both the magnetic core and DRV421 properties. In order to enable the use of a wide range of magnetic cores, DRV421 features 4 different gain settings. In order to determine the correct gain settings for a particular magnetic core, an initial setting can be calculated from the magnetic core gain, the number of windings, and the compensation coil inductance. Due to second-order magnetic effects, however, experimental verification of the correct setting using step responses are highly recommended.

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Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265