White Paper

Sensing Elements for Current Measurements

Introduction

The fundamentals to translating the analog world into the digital domain reduces to a handful of basic parameters. Voltage, current and frequency are electrical parameters that describe most of the analog world. Current measurements are used to monitor many different parameters, with one of them being power to a load.

There are many choices of sensing elements to measure current to a load, and the choices of current sensing elements can be sorted by applications, as well as the magnitude of the current measured. This in-depth write up discusses three different types of current sensing elements.

- First, we'll focus on evaluating current measurements using a shunt (sense) resistor. We'll explain how to choose a sense resistor and discuss the inaccuracies associated with the sensing element and extraneous parameters that compromise the overall measurement.
- Then, we'll evaluate a direct current resistance (DCR) sensing architecture that allows for lossless current sense in some power applications. We'll explain how to design a DCR circuit for power applications, analyze the drawbacks of the architecture and provide a way to improve the current measurement technique through calibration.
- Finally, we'll cover measuring current by way of a Hall Effect sensor, explain how a Hall Effect sensor works and discuss the drawbacks of the technology and recent improvements in the technology.

Element 1: Shunt Resistor

Shunt resistors are the most versatile and cost effective means to measure current. A shunt resistor cost ranges from a few pennies to several dollars—its price is differentiated by value, temperature coefficient, power rating and size. Shunt resistors commonly increase in cost for lower temperature coefficient (TC) and for higher power rating, while offering precision features in a small package size.

Figure 1. Picture of a Shunt (Sense) Resistor

With the knowledge of Ohm's law and the magnitude of the current to be measured, a shunt resistor can be designed into many applications. The simplicity of the design in process makes a resistor a versatile current sensing element.

In choosing a sense resistor value, the full scale voltage drop across the sense resistor and the maximum expected current measured for the application has to be known.

When possible, the voltage across the sense resistor should be kept to a minimum to lower the power dissipated by the sensing element. Low power dissipated by the sense resistor limits the heating of the resistor. A small temperature change to the sensor resistor results in a smaller resistance change versus all current sensing values. The stability and accuracy of the sense resistor versus all currents improves with a constant value shunt resistor.

For most current sensing applications, the minimum and maximum measurable currents are known. The designer chooses the allowable voltage drop across the shunt resistor. For this discussion, assume the current measured is bidirectional. The max shunt voltage is chosen as ±80mV. Assume the max measured current is ±100A. The shunt (sense) resistor value is calculated using

Equation 1.

$$R_{sense} = \frac{V_{shunt\_max}}{Imeas_{Max}}$$

Equation 1. Using Ohm's Law to Calculate the Shunt Resistor Value

For this example, the shunt resistor, R_{sense}, is calculated to equal 0.8mΩ. Table 1 is a list of other calculated shunt resistor values for a series of full scale current values.

Table 1. Shunt Resistor Values and Minimum Power Rating for Several Full Scale Currents

Imeas_Max	R_{shunt}/P_{rating} Vshunt_max = 80mV
100µA	800Ω/8µW
1mA	80Ω/80µW
10mA	8Ω/800µW
100mA	800mΩ/8mW
500mA	160mΩ/40mW
1A	80mΩ/80mW
5A	16mΩ/400mW
10A	8mΩ/800mW
50A	1.6mΩ/4W
100A	0.8mΩ/8mW
500A	0.16mΩ/40W

The minimum power rating for the sense resistor is calculated in Equation 2.

$$P_{res\_rating} = V_{shunt\_max} \cdot Imeas_{Max}$$

Equation 2. The Minimum Power Rating Calculation of the Sense Resistor

The minimum power rating of sense resistor is calculated as 8W for the example. A general rule of thumb is to multiply the power rating calculated using Equation 2 by 2. This allows the sense resistor to survive an event when the current passing through the shunt resistor is greater than the measurable maximum current. The higher the ratio between the power rating of the chosen sense resistor and the calculated power rating of the system, the less the resistor heats up in high current applications.

The temperature coefficient (TC) of the sense resistor directly degrades the current measurement accuracy. The surrounding temperature of the sense resistor and the power dissipated by the resistor results in a sense resistor value change. The change in resistor temperature with respect to the amount of current that flows through the resistor is directly proportional to the ratio of the power rating of the resistor versus the power being dissipated. A change in sense resistor temperature results in a change in sense resistor value resulting in a change in measurement accuracy for the system. The change in a resistor value due to a temperature rise is calculated using Equation 3.

$$\Delta R_{sense} = R_{sense} \cdot Rsense_{TC} \cdot \Delta Temperature$$

Equation 3. The Equation to Calculate the Resistance Change When Temperature Changes

ΔTemperature is the change in temperature in Celsius. $Rsense_{TC}$ is the temperature coefficient rating for a sense resistor. R_{sense} is the resistance value of the sense resistor at the initial temperature.

The change in the sensing element resistance is directly proportional to the current passing through resistor. The package size of the sense resistor determines the sensing element ability to counter temperature rise due to the power being dissipated by the resistor. The thermal resistance of the sensing elements package, Θ_{ja}, should be considered when choosing a sensing resistor. Θ_{ja} is the primary thermal resistive parameter to consider in determining the temperature rise in a resistor. Θ_{ja} is the thermal resistance between the resistor and the temperature outside the resistor. Table 2 lists the thermal resistances of common surface mount packages.

Table 2. Thermal Resistance of Surface Mount Resistors Referenced from Vishay Application Notes 28844 and 60122

Resistor Size	Thermal Resistance, Θ_{ja} (ΔC/W)
0406	30
2512	25
1206	32
0805	38
0603	63
0402	90

Table 2 validates the intuitive conclusion that there is a greater temperature rise in smaller packages resulting in a larger resistance changes.

A 0.8mΩ sense resistor with 50A through it dissipates 2W. The resistance change is calculated using Equation 4.

$$\Delta \text{Temperature} = \theta_{ja} \cdot I^2 \cdot R_{sense}$$

Equation 4. Relates the Current Flow through a Sense Resistor to the Temperature Change of a Resistor

In Equation 4, $I^2 * R_{sense}$ is the power dissipated by the shunt resistor. θ_{ja} is the thermal resistance of the sense resistor chosen. Assuming a 2512 is the sense resistor's package, the change in temperature of the resistor is calculated as 50C. Assume the $R_{sense_{TC}}$ is 100ppm/C. The change in resistance, using Equation 3, is calculated as 4µΩ. 4µΩ does not seem like a sizable change in resistance. To interpret the number a different way, compare the resistance change to the overall resistance value. 50A of current changes the resistor by 0.5% from nominal, resulting in a 0.5% current measurement error due to the change in shunt resistance.

Figure 2 plots current measurement error due to resistor self-heating. Smaller packages have less material to prevent the resistor from self-heating, and therefore have lower power dissipation limits. A method of increasing the power rating of a resistor while preserving a small footprint is to choose a wide package. The thermal resistance of a 0406 package roughly equals the thermal resistance of a 1206 package.
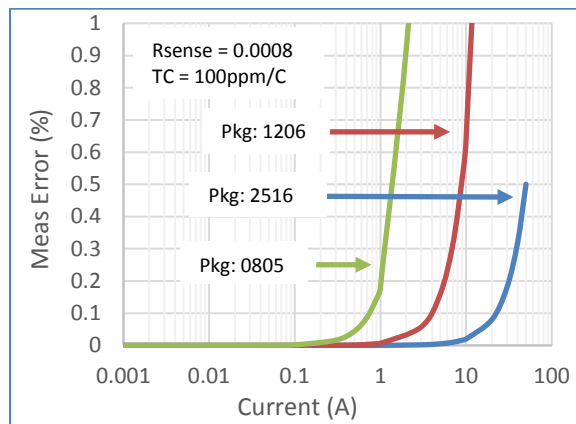

Figure 2. A Plot of Current Measurement Error Caused by Resistor Self-Heating

It is often hard to readily purchase shunt resistor values for a desired current. Either the value of the shunt resistor does not exist or the power rating of the shunt resistor is too low. A means of circumventing the problem is to use two or more shunt resistors in parallel to set the desired current measurement range.

Assume that a 0.8mΩ shunt resistor with an 8W power rating is not readily available. Assume the power ratings and the shunt resistor values available for design are 1mΩ/4W, 2mΩ/4W and 4mΩ/4W.

Let's use a 1mΩ and a 4mΩ resistor in parallel to create the shunt resistor value of 0.8mΩ. Figure 3 shows an illustration of the shunt resistors in parallel.
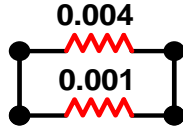
Figure 3. A Simplified Schematic Illustrating the Use of Two Shunt Resistors to Create a Desired Shunt Value

The power to each shunt resistor should be calculated before calling a solution complete. The power to each shunt resistor is calculated using Equation 5.

$$P_{shuntRes} = \frac{V_{shunt\_max}^{2}}{R_{sense}}$$

Equation 5. Power Equation through a Resistor

The power dissipated by the 1mΩ resistor is 6.4W. 1.6W is dissipated by the 4mΩ resistor. 1.6W exceeds the rating limit of 1W for the 1mΩ sense resistor. Another approach would is use three shunt resistors in parallel as illustrated in Figure 4.
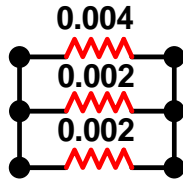
Figure 4. Increasing the Number of Shunt Resistors in Parallel to Create a Shunt Resistor Value Reduces the Power Dissipated by Each Shunt Resistor

Using Equation 5, the power dissipated to each shunt resistor yields 3.2W for the each 2mΩ shunt resistor and 1.6W for the 4mΩ shunt resistor. All shunt resistors are within the specified power ratings.

Layout
The layout of a current measuring system is equally important as choosing the correct sense resistor and the correct analog converter. Poor layout techniques could result in severed traces, signal path oscillations, magnetic contamination which all contribute to poor system performance.

Trace Width
Matching the current carrying density of a copper trace with the maximum current that passes through is critical in the performance of the system. Neglecting the current carrying capability of a trace results in a large temperature rise in the trace, and a loss in system efficiency due to the increase in resistance of the copper trace. In extreme cases, the copper trace could be severed because the trace could not pass the current. The current carrying capability of a trace is calculated using Equation 6.

$$Trace_{width} = \frac{\left(\dfrac{Imax}{k \cdot \Delta T^{0.44}} \right)^{\frac{1}{0.725}}}{Trace_{Thickness}}$$

Equation 6. The Minimum PCB Trace Width for Currents That Pass Through the Trace

I_{max} is the largest current expected to pass through the trace. ΔT is the allowable temperature rise in Celsius when the maximum current passes through the trace. $Trace_{Thickness}$ is the thickness of the trace specified to the PCB fabricator in mils. A typical thickness for general current carrying applications (<100mA) is 0.5oz copper or 0.7mils. For larger currents, the trace thickness should be greater than 1.0oz or 1.4mils. A balance between thickness, width and cost needs to be achieved for each design. The coefficient k in Equation 6 changes depending on the trace location. For external traces, the value of k equals 0.048 while for internal traces the value of k reduces to 0.024. The k values and Equation 6 are stated per the ANSI IPC-2221(A) standards.

Trace Routing

It is always advised to make the distance between voltage source, sense resistor and load as close as possible. The longer the trace length between components will result in voltage drops between components. The additional resistance reduces the efficiency of a system.

The bulk resistance, ρ, of copper is 0.67µΩ/in or 1.7µΩ/cm at +25°C. The resistance of trace can be calculated from Equation 7.

$$R_{trace} = \rho \cdot \frac{Trace_{length}}{Trace_{width} \cdot Trace_{thickness}}$$

## Equation 7. Trace Resistance Calculation

Figure 5 illustrates each dimension of a trace.
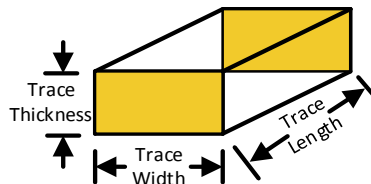
Figure 5. Illustration of the Trace Dimensions for a Strip Line Trace

For example, assume a trace has 2oz of copper or 2.8mil thickness, a width of 100mil and a length of 0.5in. Using Equation 7, the resistance of the trace is approximately 2mΩ. Assume 1A of current is passing through the trace. A 2mV voltage drop results from trace routing.

Current flowing through a conductor takes the path of least resistance. When routing a trace, avoid orthogonal connections for current bearing traces.
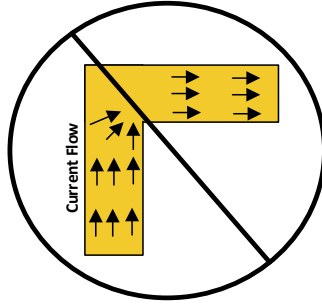
Figure 6. Avoid Routing Orthogonal Connections for Traces That Have High Magnitude through Currents

Orthogonal routing for high current flow traces could result in current crowding, localized heating of the trace and a change in trace resistance.
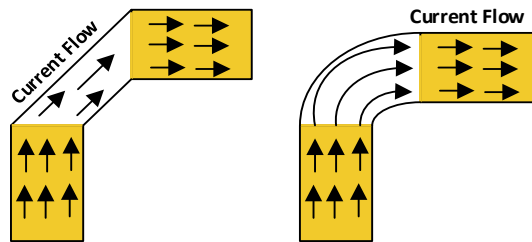
Figure 7. Use Arcs and 45 Degree Traces to Safely Route Traces with Large Current Flows

The utilization of either arcs or 45 degree traces in routing large current flow traces will maintain uniform current flow throughout the trace.   Figure 7 illustrates the routing technique.

Connecting Sense Traces to the Current Sense Resistor

Ideally, a four terminal current sense resistor would be used as the sensing element. Four terminal sensor resistors can be hard to find for specific values and sizes. Often a two terminal sense resistor is designed into the application.

Sense lines are high impedance by definition. The connection point of a high impedance line reflects the voltage at the intersection of a current bearing trace and a high impedance trace.

The high impedance trace should connect at the intersection where the sense resistor meets the landing pad on the PCB. The best place to make a current sense line connection is on the inner side of the sense resistor footprint. The illustration of the connection is shown in Figure 8. Most of the current flow is at the outer edge of the footprint. The current ceases at the point the sense resistor connects to the landing pad. Assume the sense resistor connects at the middle of the each landing pad. This leaves the inner half of the each landing pad with little current flow. With little current flow, the inner half of each landing pad is classified as high impedance and perfect for a sense connection.
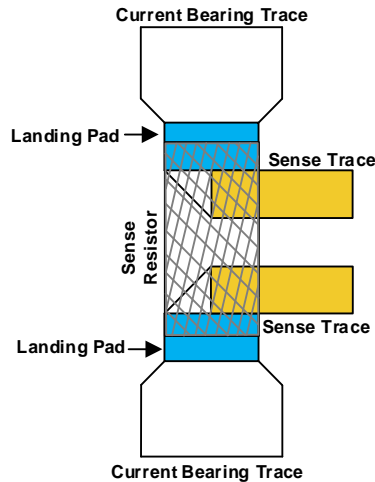
Figure 8. Connecting the Sense Lines to a Current Sense Resistor

Current sense resistors are often smaller than the width of the traces that connect to the footprint. The trace connecting to the footprint is tapered at a 45 degree angle to control the uniformity of the current flow.

Magnetic Interference

The magnetic field generated from a trace is directly proportional to the current passing through the trace and the distance from the trace the field is being measured at. Figure 9 illustrates the direction the magnetic field flows versus current flow.

$$B = \frac{\mu_o \cdot I}{2 \cdot \pi \cdot r}$$

Figure 9. The Conductor on the Left Shows the Magnetic Field Flowing in a Clockwise Direction for Currents Flowing into the Page; Current Flowing Out of the Page Has a Counter Clockwise Magnetic Flow

The equation in Figure 9 determines the magnetic field, B, the trace generates in relation to the current passing through the trace, I, and the distance the magnetic field is being measured from the conductor, r. The permeability of air, μ_o, is $4\pi * 10^{-7}$ H/m.

When routing high current traces, avoid routing high impedance traces in parallel with high current bearing traces. A means of limiting the magnetic interference from high current traces is to closely route the paths connected to and from the sense resistor. The magnetic field cancels outside the two traces and adds between the two traces. Figure 10 illustrates a magnetic field insensitive layout.

If possible, do not cross traces with high current. If a trace crossing cannot be avoided, cross the trace in an orthogonal manor and the furthest layer from the current bearing trace. The inference from the current bearing trace will be limited.
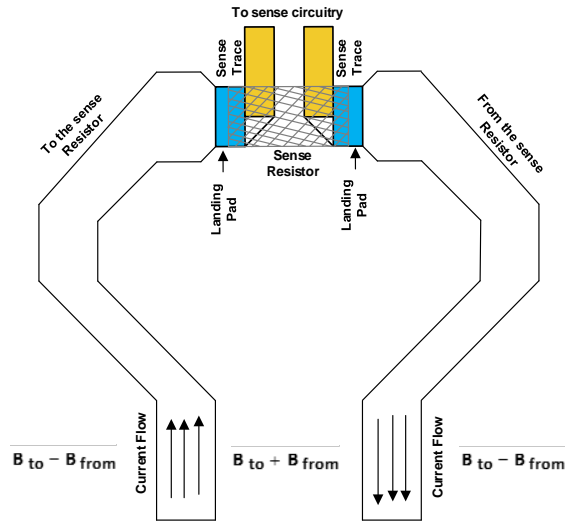
Figure 10. Closely Routed Traces That Connect to the Sense Resistor Reduces the Magnetic Interference Sourced from the Current Flowing through the Traces

Shunt Resistor Summary

Using a sense resistor to measure current is straight forward as long as proper care is taken with respect to layout and in choosing a sense resistor. The power rating and temperature coefficient parameters of a sense resistor are critical for designing a high accuracy current measurement system. With the knowledge of Ohm's law, sense resistors are easy to design with. A drawback of the technology is that a sense resistor consumes power which eats into voltage headroom and lowers the efficiency of some applications.

Element 2: Direct Current Resistance

DCR circuits are commonly used in low supply voltage applications where the voltage drop of a sense resistor is a significant percentage of the supply voltage being sourced to the load. A low supply voltage is often defined as any regulated voltage lower than 1.5V.
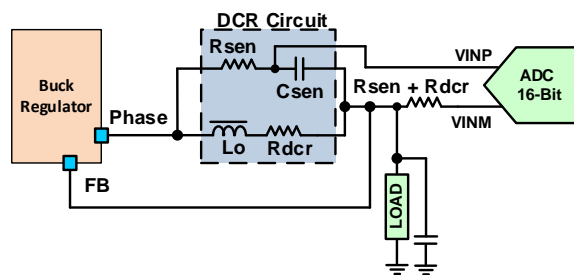
Figure 11. A Simple Schematic of a DCR Circuit

A DCR sense circuit is an alternative to a sense resistor. The DCR circuit utilizes the parasitic resistance of an inductor to measure the current to the load. A DCR circuit remotely measures the current through an energy storing inductor of a switching regulator circuit. The lack of components in series with the regulator to the load makes the circuit lossless.

A properly matched DCR circuit has an effective impedance with respect to the ADC that equates to the resistance within the inductor. Figure 11 is a simple schematic of a DCR circuit. Before deriving the transfer function between the inductor current and voltage at the input of the ADC, let's review the definition of an inductor and capacitor in the Laplacian domain.

$$X_c(f) = \frac{1}{j \cdot \omega(f) \cdot C} \qquad\qquad X_L(f) = j \cdot \omega(f) \cdot L$$

Equation 8. The Admittance and Reactance Equations for a Capacitor and Inductor, Respectively

X_c is the impedance of a capacitor related to the frequency and X_L is the impedance of an inductor related to frequency. ω equals to 2πf. f is the switching frequency dictated by the regulator. Using Ohm's law, the voltage across the DCR circuit in terms of the current flowing through the inductor is defined by Equation 9.

$$V_{dcr}(f) = \left(R_{dcr} + j \cdot \omega(f) \cdot L\right) \cdot I_L$$

Equation 9. The Voltage Equation Measured Across the DCR Circuit

In Equation 9, R_{dcr} is the parasitic resistance of the inductor. The voltage drop across the inductor (Lo) and resistor (R_{dcr}) is the same as the voltage drop across the resistor (Rsen) and capacitor (Csen). Equation 10 defines the voltage across the capacitor (Vcsen) in terms of the inductor current (I_L).

$$V_c(F) = \left[\frac{\left(j \cdot \omega(f) \cdot L + R_{dcr}\right)}{1 + j \cdot \omega(f) \cdot C_{sen} \cdot R_{sen}}\right] \cdot I_L = R_{dcr} \cdot \left[\frac{\left[1 + \frac{(j \cdot w(f) \cdot L)}{R_{dcr}}\right]}{1 + j \cdot \omega(f) \cdot C_{sen} \cdot R_{sen}}\right] \cdot I_L$$

Equation 10. The Voltage Equation for the Sense Capacitor

The relationship between the inductor load current (I_L) and the voltage across capacitor simplifies if the component selection in Equation 11 is true.

$$\frac{L}{R_{dcr}} = C_{sen} \cdot R_{sen}$$

Equation 11. The Mathematical Relation That Enables the DCR to Work

If Equation 11 holds true, the numerator and denominator of the fraction in Equation 10 cancels reducing the voltage across the sense capacitor to the equation represented in Equation 12.

$$V_c = R_{dcr} \cdot I_L$$

Equation 12. The Equation for the Voltage across the Capacitor When Equation 11 Holds True

Most inductor datasheets specify the average value of the R_{dcr} for the inductor. R_{dcr} values are usually sub 1mΩ with a tolerance averaging 10%. Common chip capacitor tolerances average to 10%.

Inductors are constructed out of metal. Metal has a high temperature coefficient. The temperature drift of the inductor value and the parasitic resistance (R_{dcr}) could cause the DCR circuit to be un-balanced. The change in the inductor value and parasitic resistance could be a result of either self-heating due to current passing through the inductor or environmental temperature rise. Copper has a resistive change of 3.9mΩ/C. The change in inductor wire temperature directly impacts the value of R_{dcr}. To counter the temperature

variance, a temperature sensor could be used to monitor the temperature of the inductor. The DCR can be compensated with knowledge change in inductor resistance.

In Figure 11, there is a resistor in series with the 16-bit ADC, which could be an ISL28023 digital power monitor, negative shunt terminal (VINM) with the value of R_{sen} + R_{dcr}. The resistor's purpose is to counter the effects of offset bias current from creating a voltage offset at the input of the ADC.

Assume the circuit in Figure 11 is an ISL85415 buck regulator with a switching frequency of 900kHz. The inductor value is 22µH inductor with a ±20% tolerance. The inductor and the bypass caps complete the buck regulator circuit such that voltage to the load is stable. The R_{dcr} is inherent to the inductor. The values of the R_{dcr} for this example is 0.185Ω typical and 0.213Ω maximum. That is roughly a ±13% variance from inductor to inductor. The value of R_{sen} for the DCR circuit is chosen as 11.8kΩ. Using Equation 11, the capacitance value of the DCR circuit, C_{sen}, equals to 10nF. Assume the tolerance of the capacitor is ±10%.

Inductor and capacitor values are not tightly controlled. If a DCR circuit is designed into a system without any additional tuning circuits built in, how do the tolerances of the sense capacitor and inductor effect the current measurement error?
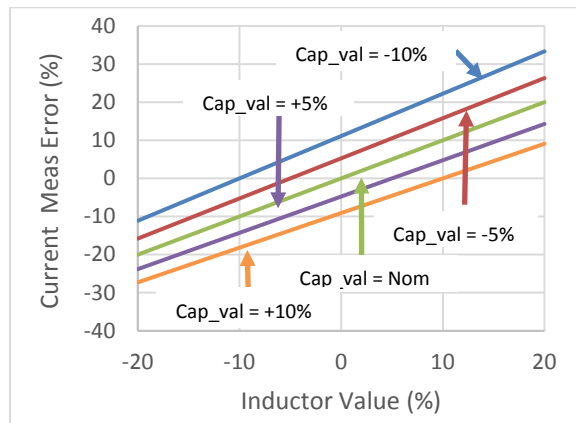
Figure 12. Capacitor and Inductor Tolerances and Their Effects on the Current Measurement

Designing a DCR circuit without tuning capabilities can result in a current measurement error of up to 35% due to the variance of the inductor and capacitor within the DCR circuit. Figure 12 plots measurement error versus different inductor and capacitor tolerance values. The measurement errors could increase to approximately 50% when including the R_{dcr} variation.

A simple trimming circuit utilizing a non-volatile digital potentiometers (DCP) drastically improves the current measurement accuracy.
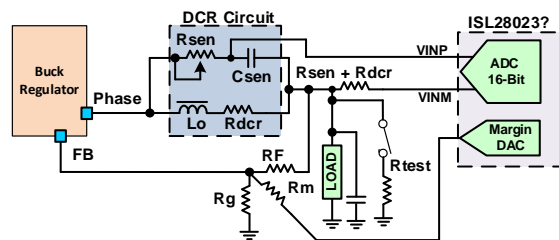
Figure 13. The Current Measurement Can Be Improved By Using A DCP to Tune the Circuit

A factory calibration technique to improve the current measurement performance is to apply a known current load in addition to the nominal current load sourced by the regulator. The DCP is trimmed while monitoring the voltage across the sense capacitor (C_{sen}).

In many production applications, the circuits are tested for functionality. A common test is to margin the power supplies by ±10% from the nominal supply value to ensure functionality and proper current draw by the load. R_m combined with the feedback circuitry of the regulator enables the voltage to the load to be margined. Without margining, the regulated voltage to the load is represented by Equation 13.

$$V_{out} = V_{ref} \cdot \left(1 + \frac{R_f}{R_g} \right)$$

Equation 13. The Regulated Output Equation to the Load (Without Margining)

V_{ref} is the reference voltage determined by the voltage regulator. R_f and R_g are the gain resistors that are multipliers to the reference voltage. For example, let's use the ISL85415 as the buck regulator. The ISL85415 has a reference voltage of 0.6V. The desired regulated voltage is 1.0V. R_f is arbitrarily chosen as 100kΩ. When choosing a feedback resistor, the value should not be too low in value. A higher value feedback resistor prevents unnecessary power dissipation in the feedback circuit. The feedback resistor value should not be too high either; this may result in noise or even oscillation at the regulated voltage node. Using Equation 13, R_g is calculated to be 150kΩ for a 1.0V regulated voltage.

A ±10% margin voltage equates to a 1.1V and 0.9V regulated voltage to the load. To achieve a voltage change of 0.1V at the load, a margining DAC and resistor, R_m, are added to the circuit. This is illustrated in Figure 13. Equation 14 describes the regulation voltage in terms of the margin DAC and resistor, R_m.

$$V_{out} = V_{ref} \cdot \left(1 + \frac{R_f}{R_g} \right) + \frac{R_f}{R_m} \cdot \left(V_{ref} - V_{mdac} \right)$$

Equation 14. The Regulated Output Equation to the Load (With Margining)

V_{ref}, R_f and R_g are previously defined. V_{mdac} is the margin DAC voltage. R_m is the margining resistor. Let's assume the regulated voltage is 1.1V when the margin DAC equals 1.0V. Using Equation 14, R_m equals 600kΩ. Using Equation 14 again, the margin DAC voltage, V_{mdac}, equals 1.2V for a regulated voltage of 1.1V. To save board space, the ISL28023 has a margin DAC with common margining voltage ranges integrated into the chip's functionality.

The circuit in Figure 13 has a switch and an R_{test} resistor in parallel to the load. The purpose of the R_{test} resistor is to add a known current to the existing load to allow for DCR inaccuracies to be trimmed out. In an ideal system, the voltage measurement would report out both magnitude and phase. The R_{sen} trims the DCR circuit until the phase equals 0 degrees. A phase of 0 degrees results in a tuned DCR circuit described in Equation 11.

The current measurement reading is purely resistive as described in Equation 12. The current measurement could still have a measurement error of up to ±13%. The current measurement error is directly due to the variation in the DCR resistance, R_{DCR}. The DCR resistance is calculated by changing the load current by a set amount and measuring the change in the voltage across the sense capacitor. The voltage change measured divided by the change in current equates to the R_{dcr} value.

A voltage measurement made from an ADC reports out the magnitude of the measurement. The phase is unknown without additional measurements and circuitry. Without knowing the phase of the measurement,

the DCR circuit is calculated by trimming R_{sen} such that the system resistance equals the R_{dcr} nominal. This is described in Equation 15.

$$\frac{dV_c}{dI_L} = \left[\frac{R_{dcr}\cdot\left[1 + \dfrac{(j\cdot\omega(f)\cdot L)}{R_{dcr}}\right]}{1 + j\cdot\omega(f)\cdot C_{sen}\cdot R_{sen}}\right] = R_{dcr}(Nom)$$

Equation 15. System Resistance of the DCR Circuit

The procedure for measuring the system resistance is to measure the voltage change across the sense capacitor, C_{sen}, when R_{test} is connected and not connected. The value of R_{test} should be chosen such that the current change is measureable. Changing the current by 10% of the nominal current is a good current change to design for. If the current change is too high with respect to the nominal current, the resistance of R_{dcr} will change due to the additional current heating the DCR resistor. A current change too low will result in an unreadable current change.

Suppose the load draws 100mA nominally from the buck regulator. The output voltage is set to 1.1V and the R_{test} resistor value is 100Ω. When the switch that is connected to R_{test} is enabled, the current sourced by the regulator increases by 11mA. Measure the difference in V_c voltage between the test load connected to the circuit and not connected to the circuit. The difference between the two measurements equals dV_c in Equation 15. Dividing the dV_c/dI_L equals the sense resistance. Adjust R_{sen} and repeat the two measurements until the resistance value equals $R_{dcr}(nom)$. In this case, the $R_{dcr}(nom)$ equals 0.185Ω.

The R_{dcr} value varies by ±13%. Since the voltage measured is a magnitude, there isn't a way to calibrate R_{dcr} directly. Trimming the R_{sen} resistor to an effective resistance of 0.185Ω may result in an unbalanced DCR circuit if the actual R_{dcr} value does not equal 0.185Ω. An unbalanced circuit results in an imaginary component when solving for the effective resistance in Equation 10.

An unbalanced DCR circuit results that has an effective resistance dependent on frequency. How much does a 13% R_{dcr} resistance variance contribute to the effective resistance value of the DCR circuit?

As mentioned prior, the buck regulator has a switching frequency of 900kHz. Solving Equation 10 for R_{dcr} equal to 0.213Ω yields a measured R_{dcr} value of $0.185 - 5.266*10^{-5}i$ for an inductor that is 20% low and a capacitor that is 10% high. R_{sen} value was for 8600Ω for this instant. The imaginary part of the resistance is 0.028% of the real value at a switching frequency of 900kHz. The effective resistance across C_{sen} is constant as long as the switching frequency is constant. Figure 14 graphs the frequency dependence between a mismatched DCR circuit and a matched DCR circuit.
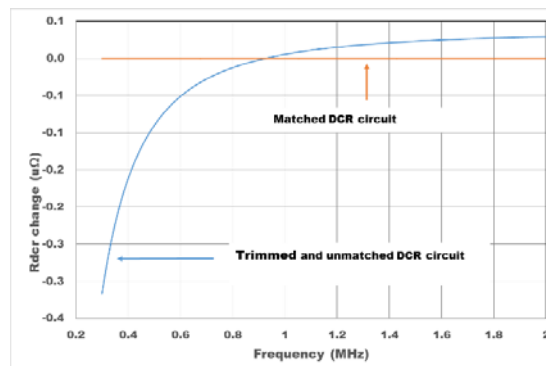

Figure 14. Graph of the Sense Resistance between a Matched and an Unmatched and Trimmed DCR Circuit

A trimmed DCR circuit with a +13% R_{dcr} value has a 0.4uΩ or 2.2ppm variance across the switching frequency range of the ISL85415. The change in resistance value is small versus switching frequency.

DCR Summary
A DCR circuit is a lossless circuit that requires little board space to construct. The circuit requires tuning for proper operations. Therefore, extra steps need to be taken at the manufacturing to guarantee proper operation of the circuit. The tolerances of the reactive components can cause large variances in the effective resistance between circuits. Inductors and capacitors have strong temperature coefficients which add to the inaccuracies of the circuit once it is tuned. Overall, the DCR circuit architecture is good for measuring gross currents while maintaining a lossless system for switching regulators.

Element 3: Hall Effect Sensor

A Hall Effect sensor measures the strength of a magnetic field from a nearby conductor in determining the magnitude of the current passing through a conductor. Hall Effect sensors that measure current are commonly found in lossless and very high current applications. A Hall Effect sensor remotely measures current passing through a conductor by measuring the magnitude of the magnetic field sourced from a trace. Systems in which employ Hall Effect sensors are considered lossless since the sensor remotely measures current. Applications above 200A may use Hall Effect sensors because the power dissipation from a sense resistor is large for high current applications. Figure 15 illustrates the basic concept of a Hall Effect current measuring application.
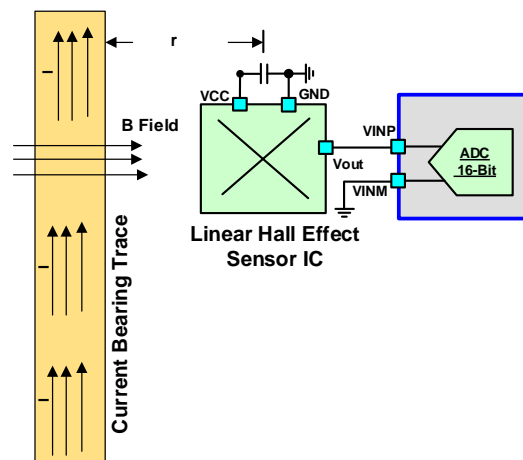

Figure 15. Hall Effect Sensor Example

The circuit in Figure 15 measures current through the trace by measuring the magnetic field, B, emitted from the current flowing through the trace. The B field is directly proportional to the magnitude and direction of the current flowing through the trace. The B field is perpendicular to the current flow. The direction of the B field with respect to current flow is illustrated in Figure 16.

CURRENT FLOW IN   CURRENT FLOW OUT
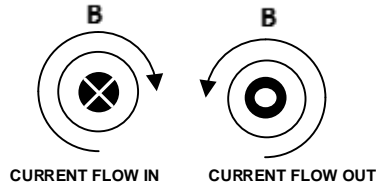
Figure 16. An Illustration of Current Flow with Respect to the Magnetic Field Direction

The mathematical relation between the magnitude of the current and the magnetic field is represented in Equation 16 for a wire. A strip line trace has a slightly different equation. For simplicity, this paper uses Equation 16 to discuss the relationship between current and magnetic fields.

$$B = \frac{\mu_0 \cdot I}{2 \cdot \pi \cdot r} \qquad OR \qquad I = \frac{2 \cdot \pi \cdot r \cdot B}{\mu_0}$$

Equation 16. The Mathematical Relationship between Current and Magnetic Field for a Wire

μ_0 is the permeability of the magnetic field. The permeability value, μ_0, of free space equals $4\pi*10^{-7}$ H/m. The value r is the distance in meters between the conductor and the linear Hall Effect sensor. The variable I is the current flowing in amps through the conductor. B is the magnetic field in Gauss.
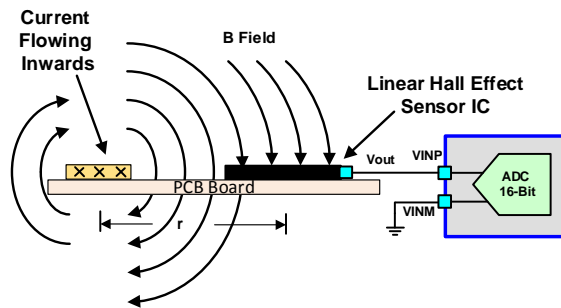
Figure 17. A Side Profile of the Circuit in Figure 15

From Equation 16, the strength of the magnetic field diminishes as the spacing between conductor and sensor increases. A linear Hall Effect sensor converts the magnetic field measured into either a current or a voltage. The gain of the sensor is reported as either mV/G or mA/G. Some manufactures report the gain in Teslas. A Tesla equals 10,000 Gauss.

Suppose a 200A current flows through a trace that is 0.03m from the center of the trace to the center of the of Hall Effect chip. What is the expected magnetic field at the center of the sensor? If the sensor has a gain of 5mV/G, what is the output voltage of the sensor?

Using the simplified relationship in Equation 16, the magnetic field is 13.33G. The output from the sensor is calculated to be equal to 66.67mV.

Linear Hall Effect sensors are active circuits that draw between 3mA to 10mA of current. The noise levels of the sensor averages around 25mV or 5G. In applications that either have low currents or large trace to

sensor spacing, the linear Hall Effect is not a good choice due to the noise level of the sensor, as well as the current draw from the sensor.

The environment in which the current bearing trace and the sensor are subjected to is important for measuring weak magnetic fields. A linear Hall Effect sensors measure the total available magnetic field at the set location. Current bearing traces routed near the sensor will change the magnetic field at the sensor and ultimately change the accuracy of the measurement. The sensor will also measure changes in the environmental magnetic fields. A change in the environmental magnetic field could be caused by a switching motor or any device that radiates energy.

A magnetic shield that encapsulates the current bearing trace and the Hall Effect sensor is a means to controlling the magnetic field in the sensor's environment. Figure 18 illustrates a metal case enclosing the trace and sensor. The enclosure is known as a Faraday cage.
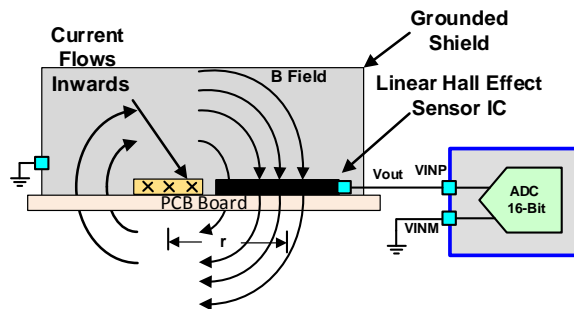
Figure 18. Shielding the Conductor and the Sensor Will Improve Low Magnetic Field Measurements

The shield in Figure 18 should be grounded since ground is usually the most stable and lowest impedance to which most circuits are referenced.

Recently, Hall Effect sensors that integrate the current conduction path, provide environmental shielding and temperature compensation circuitry in a single package have been released to market. The integration of the current conduction path simplifies the gain calculation between the current flowing through the conductor and the output voltage. The single chip solution simplifies the layout and the design of a Hall Effect sensor measuring application because a user does not have to worry about the conductor to sensor spacing and the environment the sensor is in. Figure 19 is a simplified circuit of the integrated solution.
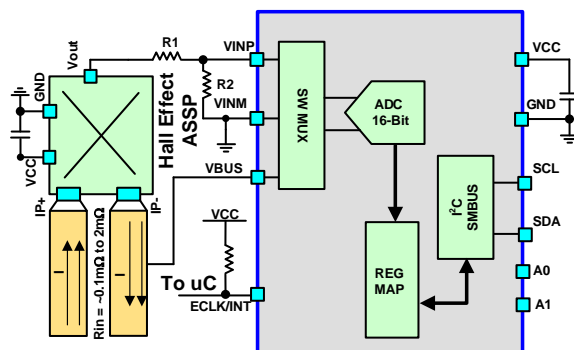
Figure 19. A Simplified Circuit Diagram of a Hall Effect Sensor That Integrates the Current Conduction Path

The integrated conduction path (IP+, IP-) has a resistance ranging from 0.1mΩ to 2mΩ. The current sense in Figure 19 is not a lossless system because of the loss associated with integrated conduction path.

Hall Effect Sensor Summary
Hall Effect technology has improved recently allowing for easier design-ins, better accuracy and better noise immunity. While there have been advancements, the strength of the technology resides with high current applications. A Hall Effect sensor dissipates less power than a shunt resistor.

Conclusion

In this in-depth paper about evaluating current sensing elements, it was learned that no one sensor is the choice solution for all applications. Shunt resistors are the most widely used current sensing element due to the simplicity of the design, precision of the measurement and cost of the solution. Direct Current Resistance (DCR) sensing is useful in switching regulator applications with low regulation voltages because current is measured remotely. Finally, Hall Effect sensors are suitable for high current applications where the power dissipation of a shunt resistor is greater than a Hall Effect solution.

For every positive about a sensing element, there is a drawback. Shunt resistors dissipate power resulting in power efficiency reductions. The voltage drop associated with current flowing through the shunt resistor consumes valuable voltage headroom in low voltage applications. A DCR sensing circuit specialty is to sense current remotely in switching power applications. A DCR circuitry is dependent on matching of a capacitor and an inductor. Both components have loose tolerances and high temperature coefficients. A Hall Effect sensor is susceptible to environment noise and design challenges. Advancements have been made in the technology but measurement accuracy is still a limitation.

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