Shunt Resistor Selection for High-Accuracy, Optically Isolated Sigma-Delta Modulator Current-Sensing Solution

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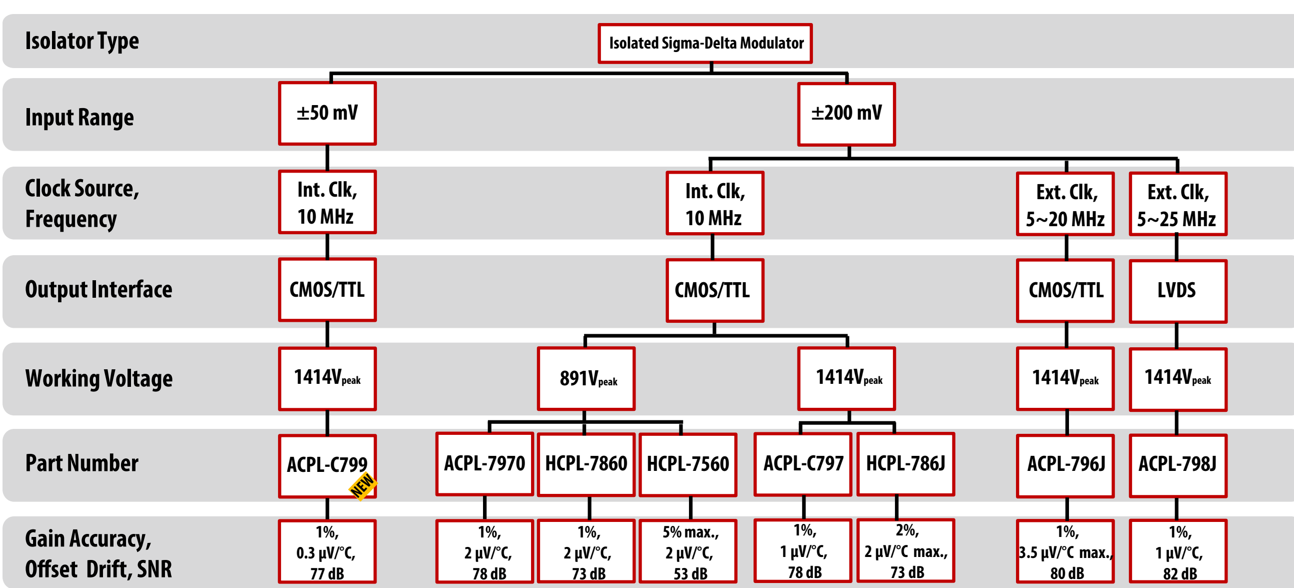
Abstract

As modern factory automation (including servo motors, industrial robots, and computer numerical control [CNC] machines) trends toward higher precision, power, speed, multi-axis, and multi-direction, the requirement for accurate sensing of motor phase current has become ever more demanding. Traditionally, current sensing is performed by a current transformer (CT) or Hall Effect Sensor (HES), but these solutions are bulky, expensive, and less accurate over operating temperatures. A smaller, low-cost solution can be easily realized by connecting a shunt resistor directly to the sigma-delta modulator. Phase current flows through a shunt resistor with the resistance value selected such that the maximum current range corresponds to an optimum recommended low-input voltage range of the sigma-delta modulator. At this low voltage, power dissipation loss across the shunt resistor is minimized.

Broadcom Optically Isolated Sigma-Delta Modulator

Broadcom offers a wide selection of isolated sigma-delta modulators with various small-form, standard surface-mount packages suitable for volume production. Combined with superior optical coupling isolation technology, Broadcom sigma-delta modulators deliver high noise margins and excellent immunity against isolation-mode transients. Boasting a minimum distance through insulation (DTI) of 0.5 mm, these sigma-delta modulators provide reliable double protection and a high working voltage suitable for fail-safe designs. This proven isolation performance is superior to magnetic or capacitive-based isolators, where DTI is only a third of 0.1 mm. Additionally, since signals are optically transmitted through the isolation barrier, Broadcom's sigma-delta modulators are immune to external magnetic fields and absent of hysteresis effect remanence when the external magnetic field is removed. Figure 1 shows the sigma delta product tree.

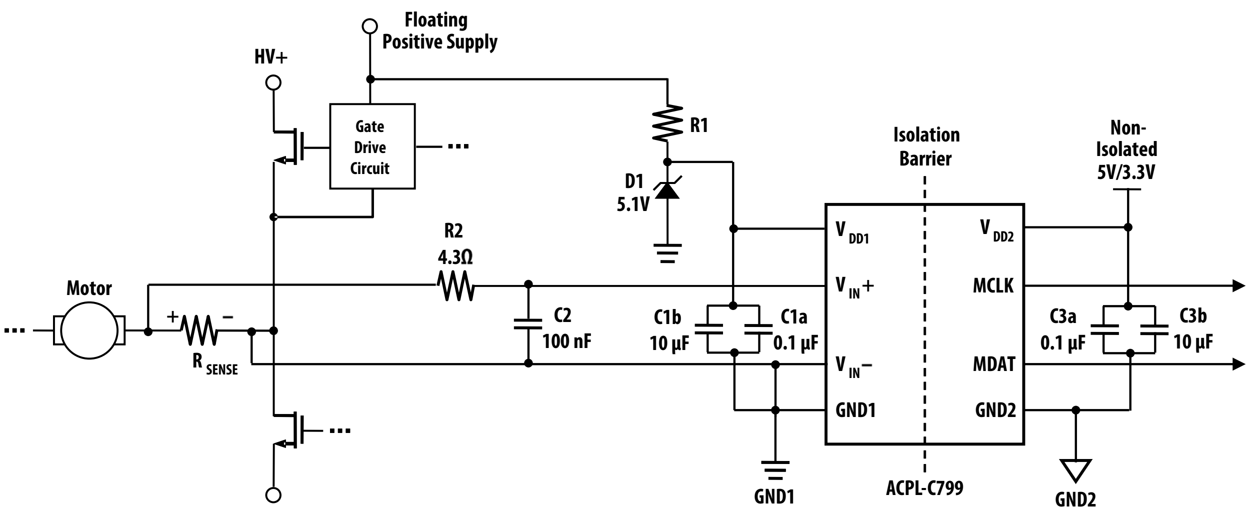
Figure 1 Broadcom Isolated Sigma-Delta Modulator Product Tree



ACPL-C799 ±50 mV Input Internally Clocked Sigma-Delta Modulator

The Broadcom ACPL-C799 is the Industry's first ±50 mV input optically isolated sigma-delta modulator. The new device features a low-differential input range of ±50 mV, allowing designers to reduce power dissipation across a current-sensing shunt resistor in servo drive and motor applications. Figure 2 shows a typical application circuit using the ACPL-C799 in a motor phase current-sensing mode.

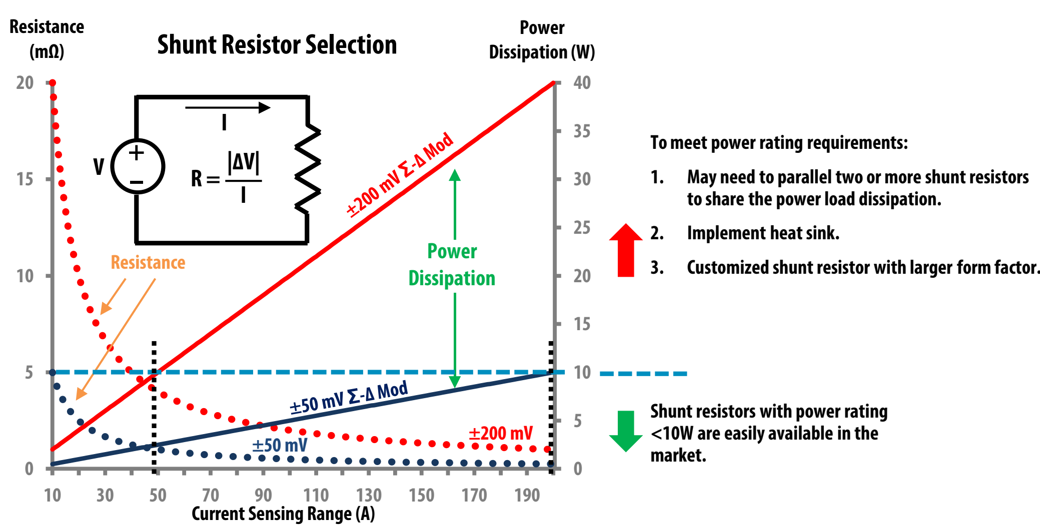
Figure 2 Typical Application Circuit Using ACPL-C799 in Motor-Phase Current Sensing Mode



This latest addition to Broadcom's market-leading optically isolated current-sensing portfolio enables higher efficiency through shunt resistor size reduction while delivering improved performance with unparalleled robustness. Compared to previous generation products with an input range of ±200 mV, the ACPL-C799 enables the use of a smaller shunt resistor with one-quarter the value, thereby eliminating 75% of the shunt resistor's power losses. Despite the reduced input voltage range, the device delivers superb SNR, ENOB, and offset drift performance, enabling high-precision motor control in space-constrained, high-temperature environments.

Normally, shunt resistors exhibit a continuous power rating of less than 10W. Figure 3 shows that with a lower input voltage of ±50 mV, this allows ACPL-C799 to sense higher current ranges up to 200A in conjunction with low-cost, easily available shunt resistors.

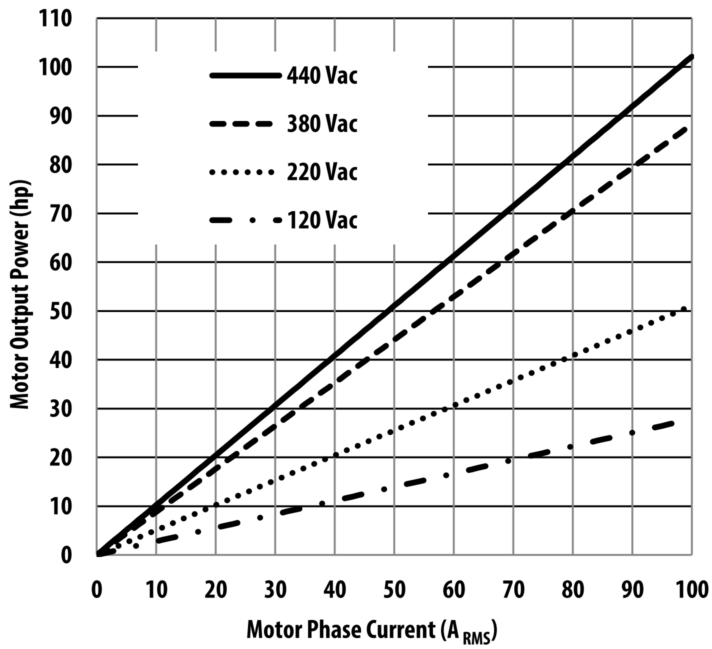
Figure 3 Shunt Resistor Values and Power Rating Requirement vs. Current-Sensing Range



Shunt Resistor Selection

The current-sensing shunt resistor should have low resistance to minimize power dissipation, low inductance to minimize di/dt-induced voltage spikes that could adversely affect operation, and reasonable tolerance to maintain overall circuit accuracy. Choosing a particular value for the shunt is usually a compromise between minimizing power dissipation and maximizing accuracy. Smaller shunt resistances decrease power dissipation, while larger shunt resistances can improve circuit accuracy by utilizing the full input range of the isolated modulator.

Figure 4 Motor Output Horsepower vs. Motor Phase Current and Supply



Determining Shunt Resistor Values

The first step in selecting a shunt is to determine how much current the shunt will be sensing. The graph in Figure 4 shows the RMS current in each phase of a three-phase induction motor as a function of average motor output power (in horsepower) and motor drive supply voltage. The maximum value of the shunt is determined by the current being measured and the maximum recommended input voltage of the isolated modulator. The maximum shunt resistance can be calculated by taking the maximum recommended input voltage and dividing it by the peak current that the shunt should see during normal operation.

Example

A motor has a maximum RMS current of $70A_{RMS}$ and can experience up to 50% overload during normal operation. Using the ACPL-C799 for current sensing, the shunt resistor value is calculated to be 0.5 mΩ. The maximum average power dissipation in the shunt can also be determined by multiplying the shunt resistance by the square of the maximum RMS current, which is about 2.45W. The following list shows the detailed calculations.

- ACPL-C799 recommended linear input range: ±50 mV
- ACPL-C799 recommended full-scale range (FSR): ±80 mV
- Maximum RMS current through the motor: $70A_{RMS}$
- Peak current: 100A
- Overload during normal operating condition: 50%

Determining shunt resistor value:

- Calculated shunt resistor value (50 mV/100A)—0.5 mΩ
- Shunt resistor power dissipation ($70A_{RMS} \times 70A_{RMS} \times 0.5$ mΩ)—2.45W
- Sigma-delta modulator input during overload condition (100A × 50% × 0.5 mΩ)—±75 mV (within the ACPL-C799 FSR)

If the power dissipation in the shunt is too high, the resistance of the shunt can be decreased below the maximum value to decrease power dissipation. The minimum value of the shunt is limited by the precision and accuracy requirements of the design. As the shunt value is reduced, the output voltage across the shunt is also reduced, which means that the offset and noise (both fixed) become a larger percentage of the signal amplitude. The selected value of the shunt should fall somewhere between the minimum and maximum values, depending on the particular requirements of a specific design.

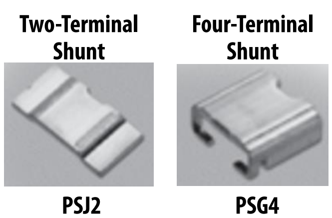
Shunt Resistor Temperature Coefficient Consideration

When sensing currents are large enough to cause significant heating of the shunt, the temperature coefficient (tempco) of the shunt can introduce nonlinearity due to the signal-dependent temperature rise of the shunt. The effect increases as the shunt-to-ambient thermal resistance increases. This effect can be minimized either by reducing the thermal resistance of the shunt or by using a shunt with a lower tempco. Lowering the thermal resistance can be accomplished by repositioning the shunt on the PCB, by using larger PCB traces to carry away more heat, or by using a heat sink.

Two-Terminal vs. Four-Terminal Shunt Resistor

For a two-terminal shunt, as the value of shunt resistance decreases, the resistance of the leads becomes a significant percentage of the total shunt resistance. This has two primary effects on shunt accuracy. First, the effective resistance of the shunt can become dependent on factors such as how long the leads are, how they are bent, how far they are inserted into the board, and how far solder wicks up the lead during assembly. Secondly, the leads are typically made from a material such as copper, which has a much higher tempco than the material from which the resistive element itself is made, resulting in a higher tempco for the shunt overall. Both of these effects are eliminated when a four-terminal shunt is used. A four-terminal shunt has two additional terminals that are Kelvin-connected directly across the resistive element itself; these two terminals are used to monitor the voltage across the resistive element while the other two terminals are used to carry the load current. Because of the Kelvin connection, any voltage drops across the leads carrying the load current should have no impact on the measured voltage. Figure 5 shows an example of two-terminal and four-terminal shunt resistors.

Figure 5 Two-Terminal and Four-Terminal Shunt Resistor Examples[2]



Several two-terminal and four-terminal SMT shunt resistors suitable for sensing currents in motor drives up to 70 A_{RMS} (71 hp or 53 kW) are shown as examples in Table 1.

Table 1 Example of Two-Terminal and Four-Terminal Shunt Resistors for Motor Drives up to $70A_{RMS}$

Manufacturer/Shunt Resistor Part Number	Shunt Resistor Type	Shunt Resistance	Maximum RMS Current	Motor Power Range $120V_{AC}$ to $440V_{AC}$	
		mΩ	A	hp	kW
KOA—CSR series	Four-terminal	5	7	1.8 to 6.7	1.4 to 5
Isabellenhütte—BVS series	Two-terminal				
Vishay—WSL4026 series	Four-terminal	2	17	4 to 17	3 to 13
Isabellenhütte—BVE series	Two-terminal				
KOA—PSG4 series	Four-terminal	1	35	9 to 36	7 to 27
KOA—PSB series	Two-terminal				
Isabellenhütte—BVR series	Four-Terminal	0.5	70	19 to 72	14 to 54
KOA—PSJ2 series	Two-terminal				

A list of manufacturers that supply high-precision current sensing shunt resistors:

- Isabellenhuette Isotek
- KOA
- Micron Electric
- Powertron
- Precision Resistor
- TT Electronics
- Vishay

Shunt Resistor Power Derating Curves

As current flows through a shunt resistor, heat generally dissipates to ambient through three paths: conduction, convection, and IR radiation. Heat conducts to ambient from the terminals connected to the shunt resistor and it increases with the size of the terminals. Convection occurs through a natural transfer of heat to ambient and increases with the total surface area of the resistor. The third path is through IR radiation and, similar to convection, increases with the total surface area of the resistor. For SMT shunt resistors, 90% of the heat dissipates through conduction from the shunt resistor terminals mounted on the PCB. Hence, power derating curves measured based on the terminal temperature of shunt resistors is more accurate than ambient temperature near to the shunt resistors based on traditional JIS/IEC derating curve methodology. Implications include the following:

- Miniaturization of the SMT shunt resistor as the power rating requirement can be accurately determined
- Greater factor of safety when deciding design margins for power ratings
- Reduction in the number of resistors used in the case of paralleling two or more resistors to achieve higher power ratings

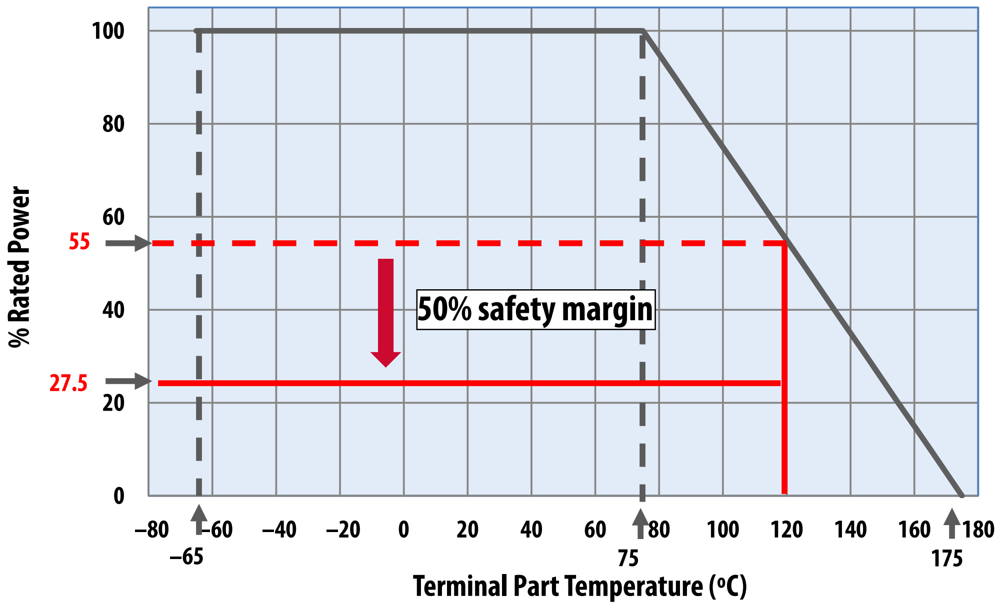
When considering whether a shunt resistor power rating is sufficient for high-temperature applications, examine the details of the temperature derating curve provided by the shunt resistor manufacturer for greater factors of design safety and margins.

Application Example

- Maximum phase current: $70A_{RMS}$
- Shunt resistor value: 0.5 mΩ, ACPL-C799 (±50 mV input)
- Shunt Resistor Power Rating: 10W (KOA PSJ2)
- Ambient temperature of the board: 100°C
- Terminal temperature of the surface mount resistor: 120°C
- Actual power load: 2.5 W

Required margin of safety below rating—according to the designer's internal guidelines: 50%

Figure 6 Temperature-Power Derating Curve of the KOA PSJ2 Shunt Resistor[2]



According to Figure 6:

Required rated power (2.5W/27.5%) = 9.1W (within the PSJ2 power rating)

Overloading condition = 50% of peak current

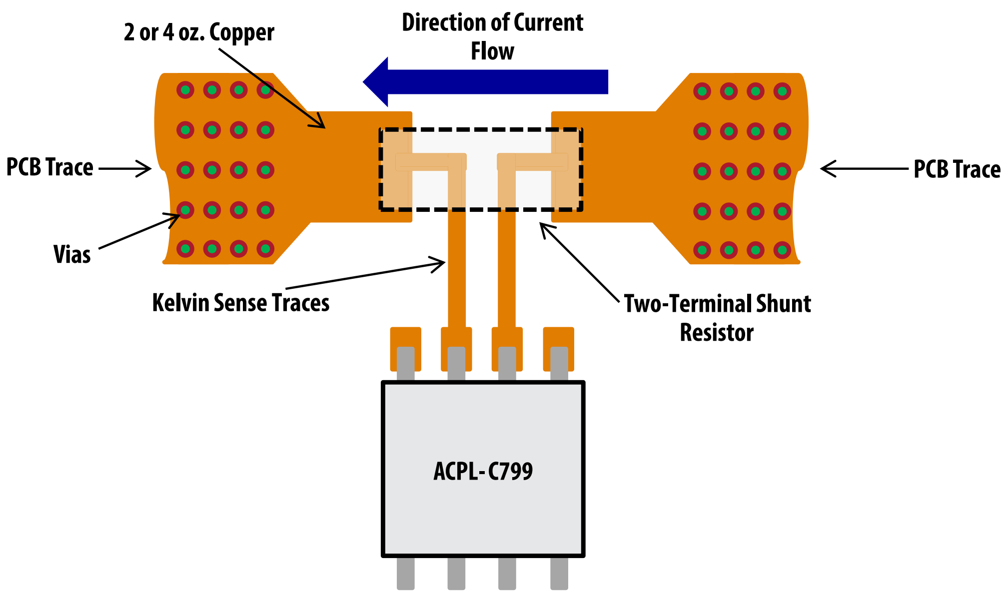
Power-load surge = (70A_{RMS} x 1.414 x 1.5)2 x 0.5 mΩ = 11.25W (PSJ2 can take 30W at 5 seconds of surge)

PCB Layout and Design Considerations

When laying out a PCB for the shunts, a couple of points should be kept in mind.

- Bring the Kelvin connections to the shunt together under the body of the shunt and then run them very close to each other to the input of the isolated modulator; this minimizes the loop area of the connection and reduces the possibility of stray magnetic fields from interfering with the measured signal. If the shunt is not located on the same PCB as the isolated modulator circuit, a tightly twisted pair of wires can accomplish the same result.
- Use multiple layers of the PCB to increase current-carrying capacity. Numerous plated-through vias should surround each non-Kelvin terminal of the shunt to help distribute the current between the layers of the PCB. The PCB should use 2 or 4 oz. copper for the layers, resulting in a current-carrying capacity in excess of 20A. Fairly large current-carrying traces on the PCB can also improve the shunt's power dissipation capability by acting as a heat sink. Liberal use of vias where the load current enters and exits the PCB is also recommended. Figure 7 shows a PCB layout design consideration for a two-terminal shunt resistor.

Figure 7 PCB Layout Design Consideration of a Two-Terminal Shunt Resistor



References

1. Avago Technologies, *ACPL-C799 Optically Isolated ±50 mV Sigma-Delta Modulator Data Sheet*, pub-005830, August 26, 2016.
2. KOA Speer Electronics Inc., *Introduction of the Derating Curves Based on the Terminal Part Temperature*, Technical Note, April 12, 2014.
3. Avago Technologies, *Optoisolation and Optical Sensor Products Selection Guide*, AV00-0254EN_042916, April 29, 2016.

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