Selecting the Right Sense Resistor for Motor Control with Reinforced Isolation

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Introduction

The use of current sense resistors is part of a trend in motor control system design that benefits from adopting new digital isolation technologies. These technologies offer higher reliability levels to designers based on the introduction of the component level standard IEC 60747-17, which specifies the performance, test, and certification requirements for capacitive and magnetically coupled isolators. Digital isolation offers other benefits such as faster loop responses, allowing for integrated overcurrent protection, as well as narrower dead times. This enables smoother output voltages that, in turn, provide better control of torque. This article presents a summary of the differences in standards between traditional optocoupler-based technologies and inductive and capacitive technologies for reinforced isolation. It also provides an overview of a system using digital control of a motor drive that incorporates current sense resistors for sensing winding current. The article will also offer recommendations for selecting the best current sense resistor for this application.

Update on Standards for Isolation as Applied to Motor Drives

Designers of motor drives are most likely aware of the need to comply with international standards for isolation. Isolation is necessary for a number of reasons:

- It prevents electrical noise from the ground connection of a high power circuit being induced onto a low power signal line.
- It provides electrical safety for end users by preventing dangerous voltages and currents from transferring to a benign, low voltage environment.

The IEC 61010-1 Edition 3 standard specifies that the system-level designer must be aware of the distances between conductors, through air (clearance) and over surfaces (creepage). It also stipulates they must know the separation between conductors and metallic parts in potting, moulding compounds, and thin film insulation. A designer should ensure that the chosen components guarantee a certain level of safety if they are being used on systems compliant to IEC61010-1. According to the standard IEC 60747-17, the reinforced isolation is tested using the industry accepted time dependent dielectric breakdown (TDDB) analysis, which then helps to extrapolate the device's lifespan and continuous working voltage (VIORM).

While IEC 60747-17 (DIN V VDE V 0884-11) was adopted to specifically define insulation using inductive and capacitive technologies, the well established IEC 60747-5-5 standard was used to define the insulation using optocoupler technologies. However, IEC 60747-5-5 does not specify the TDDB analysis to determine the continuous working voltage or lifetime. It relies on the partial discharge voltage test to establish the working voltage, but does not define the working lifetime of the device. Hence, inductive and capacitive technologies have a minimum rated lifetime of 37.5 years, while there is no definition for optocoupler-based isolators.

Table 1 summarizes the key differences between optocoupler and non optocoupler-based standards. The conclusion is that nonoptocoupler-based standards will gain more acceptance over time as they offer greater security to design engineers and longer operating lifespans.

Table 1. Key Differences Between Optocoupler and Nonoptocoupler-Based Isolation

Specification	IEC 60747-17		IEC 60747-5-5
	Basic Isolation	Reinforced Isolation	Reinforced Only
Partial Discharge Test	1.5 × VIORM	1.875 × VIORM	1.875 × VIORM
Working Voltage (VIORM)	Based on TDDB* analysis	Based on TDDB* analysis	Based on PD** test
Minimum Rated Lifetime	26 Years	37.5 years	Not defined
Failure Rate over Lifetime	1000 ppm	1 ppm	Not defined

*Time dependent dielectric breakdown.
**Partial discharge.

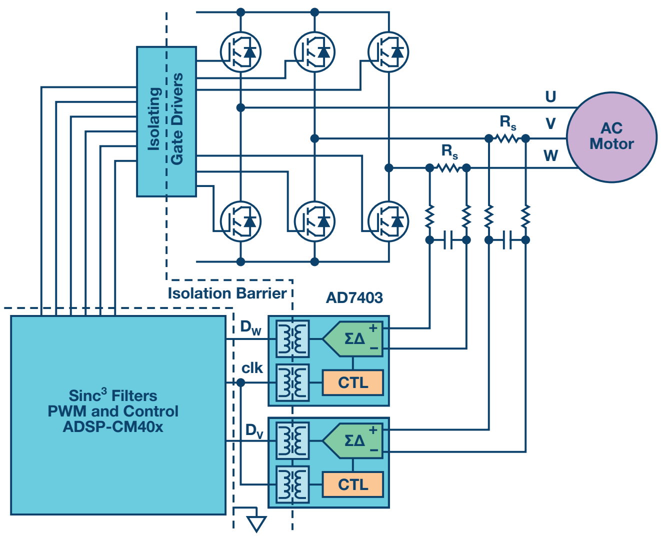


Figure 1. Block diagram of three phase motor drive with digital isolation and sense resistors.

Typical System with Reinforced Isolation Using Sense Resistors

Figure 1 shows a typical three phase permanent magnet motor drive using sense resistors for measuring the winding current and with feedback through the Analog Devices' AD7403 isolated Σ-Δ modulator and a sinc³ filter. The AD7403 uses a single second-order modulator digitizing circuit that converts the analog signal from the sense resistor into an isolated single-bit pulse stream, which scales according to the full scale input voltage range. The sinc³ filter then extracts the average value of the current, while eliminating noise created by inverter switching. It can store a 16-bit integer representing the current in memory and, at the same time, it can compare the number with a reference representing current limits and send an alert via a separate pin during overload conditions. The use of shorter filters for overload monitoring, in parallel with the measurement filter, allows alert latencies to be reduced.

The AD7403 has reinforced isolation allowing the current sense resistor voltage to be measured directly by the modulator with no extra components apart from a simple, discrete, low-pass filter, comprising of a resistor and capacitor. The specified maximum operating voltage of the modulator is ±250 mV, which requires that the resistance value of the current sense resistor to be less than 250 mV/I_{MAX}.

Considerations in Selecting the Right Sense Resistor

Resistance Drift with Temperature

Given that the output of the AD7403 is a 16-bit number, the potential accuracy of the current measurement is limited not by the ADC conversion, but by the voltage reading itself. The drift of the resistance with temperature will vary depending on the material used in the resistor element, as well as the power rating and the actual physical size of the component.

Resistive elements made up of special alloys of nickel, copper, and manganese have parabolic resistance drift curves, as shown in Figure 2. These alloys are the most accurate materials used for current sensing applications. Figure 2 also shows the upper and lower limits of resistance drift of a Bourns model CSS4J-4026R resistor, corresponding to a temperature coefficient of 50 ppm/°C. This gap is caused by the copper terminals of the resistor, which increase drift due to the high TCR of copper (4000 ppm/°C). The Bourns model CST0612 series is a 1 W, 4-terminal resistor made from a special alloy. It measures 3.2 mm × 1.65 mm, has a TCR of ±100 ppm/°C, and the difference in TCR between Bourns model CST0612 and model CSS4J-4026R can be explained by the proportion of copper, with respect to the resistive element. The additional copper with its low thermal resistance helps the component absorb the high power without overheating. This example demonstrates the trade-off between the size of the component, the power rating, and the drift in the resistance value over temperature.

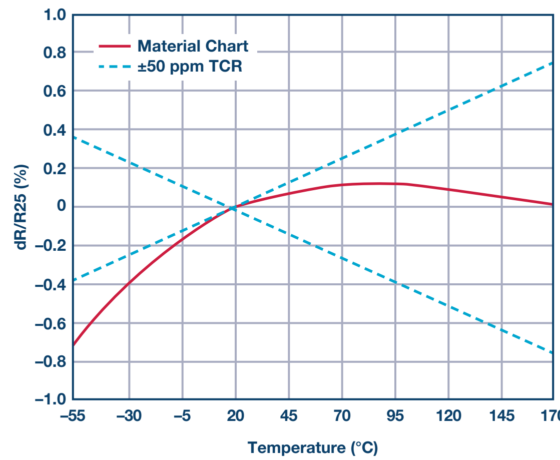


Figure 2. Parabolic TCR curve of Bourns model CSS4J-4026R current sense resistor.

Resistance Drift Calculation

Let us use Bourns part number CSS4J-4026R-L500F for calculating the resistance drift at full power and at an ambient temperature of 70°C. CSS4J-4026R-L500F is a 0.5 mΩ (±1%) sense resistor rated to 5 watts of power, at a maximum ambient temperature of 130°C. It derates from 100% power to 0 W at 170°C. The thermal resistance of the component therefore, is 8°C/W. At full power and an ambient temperature of 70°C, we can expect the surface temperature of the component to reach 110°C (70°C + 8 × 5°C). The drift in resistance at 110°C can be taken from Figure 3, which is +0.45% of the nominal value at 25°C. The absolute tolerance is ±1% and therefore, the accuracy of the current measurement will be a maximum of +1.45%.

Overloads

Motor drives will experience short circuits from time to time, and the current sense resistor must be able to handle short overloads without being damaged. Using the Bourns model CST0612 current sense resistor as an example, it is possible to calculate the mass of this component from the material data sheet on the Bourns website at 0.0132 g. Alternatively, it can be calculated from the dimensions, and the density of copper and alloys (8.4 g/cm³). The rate of rise in temperature can be calculated by the following:

$$\frac{dT}{dt} = \frac{P}{mC}$$

Where P is power (watts), m is the mass of the component (g), and C is the specific heat capacity of the metal alloy.

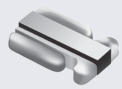
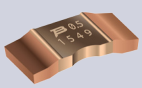
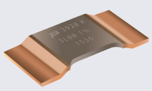
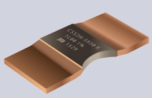
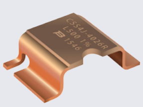
An overload of 50 A in a resistance of 1 mΩ, would create a 462°C per second temperature slew rate. Assuming a steady state temperature of 50°C, the width of the short circuit period cannot exceed 0.22 seconds. This can be extended by increasing the overall mass through copper plating on the circuit board.

A thicker, larger part such as model CSS4J-4026 with a mass of 0.371 g would have a temperature slew rate of 16.5°C per second, given the same overload. Assuming the component had a surface temperature of 100°C, it would handle the energy for up to four seconds before the surface temperature reached the maximum allowed value of 170°C.

Appropriate Resistance Value

The AD7403 has a full-scale input of ±250 mV from the resistor. The following matrix in Table 2 outlines the voltage drop at maximum current across Bourns high power, current sense resistor models. The designer can compensate for lower voltages by adjusting the scaling factor.

Table 2. Maximum Current and Voltage Drop Across Bourns Current Sense Resistor Models

Resistor Family	Image	Maximum Current (Lowest Resistance)	Voltage at Maximum Current
CST0612		44.7 A	22.3 mV
CSS2H-2512		140 A	42.4 mV
CSS2H-3920		245 A	49 mV
CSS2H-5930		126.5 A	63 mV
CSS4J-4026R		100 A	50 mV

Conclusion

According to IEC60747-17, the minimum lifetime of a digital isolator rated to reinforced isolation should be 37.5 years. While there is no such reference for more traditional optocoupler technologies, designers should feel more confident about working with digitally isolated systems in the future. Current sense resistors made using special alloys have low resistance drift over temperature and produce output voltages, which can be read with an adjustable scaling factor by an isolated Σ-Δ modulator, such as those using Analog Devices *i*Coupler® technology. The accuracy of the current measurement will depend on the temperature of the resistor, which in turn depends on the power as a proportion of the power rating, as well as the ambient temperature.

References

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O'Sullivan, Dara, Jens Sorensen, Aengus Murray. Application Note AN-1265, *Isolated Motor Control Feedback Using the ADSP-SM402F/ADSP-CM403F/ADSP-CM407F/ADSP-CM408F Sinc Filters and the AD7403*. Analog Devices, Inc., 2015.

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