Isolation Amplifiers and Hall-Effect Device For Motor Control Current Sensing Applications

Application Note 5121

Introduction

A current sensor is an essential component in a motor control system. Recent progress in sensor technology has improved the accuracy and reliability of current sensors, while reducing their cost. Many sensors are now available that integrate the sensor and signal-conditioning circuitry into a single package.

The three most popular isolated current sensors that can be used to feedback current information to a micro-controller or digital signal processor in motor control applications are:

- Isolation amplifier with shunt
- Hall-effect current sensor
- Current-sensing transformer

This paper will focus on isolation amplifiers and Hall-effect current sensors, and present a comparison of the characteristics of these two current sensing technologies.

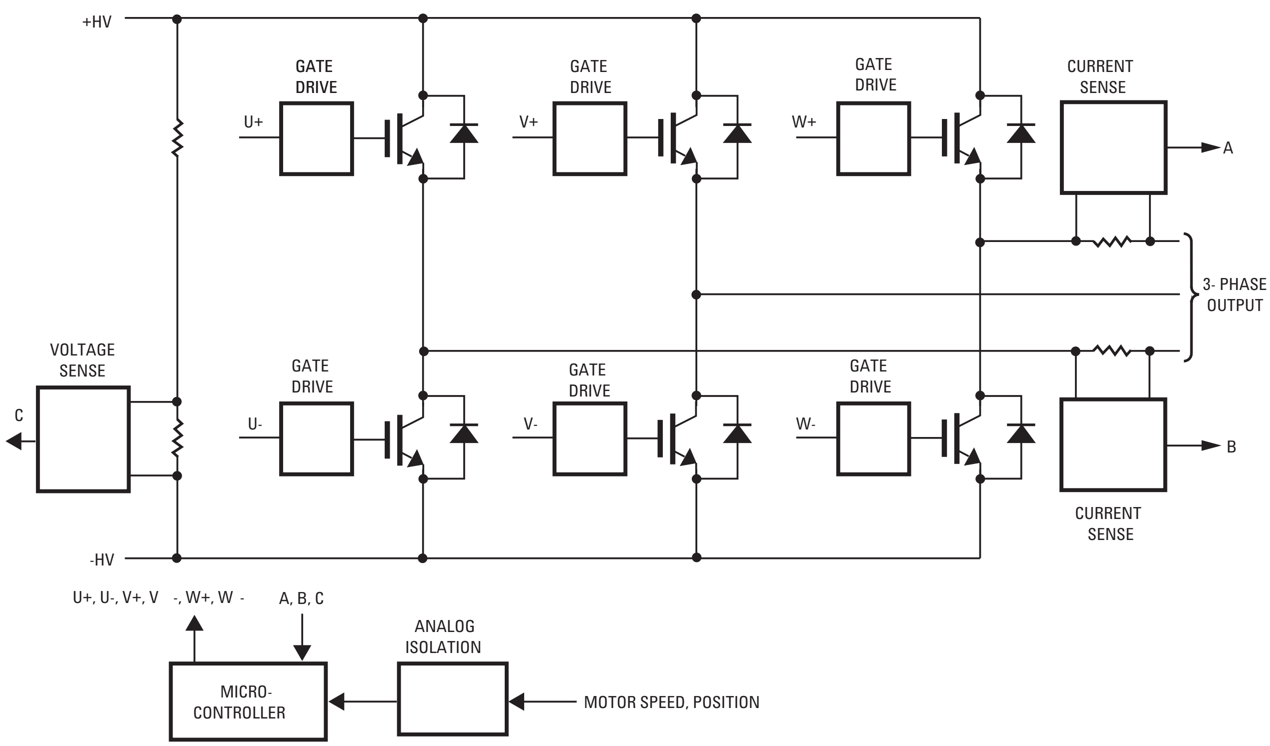

Figure 1. Typical Motor Block Diagram

Isolation Amplifiers

Shunt–based current sensors are prevalent current sensing solutions because they provide an accurate measurement at a low cost. The voltage drop across a known low-value resistor connected in series with the load is monitored in order to determine the current flowing through the load.

One of the more difficult problems of curre nt shunt sensing circuit design is to either galvanically isolate or dynamically level shift a precision analog signal in an extremely noisy environment such as that found in the motor phase current. The difficulty in galvanically isolating or level shifting arises from the large common-mode voltage, the large variability of the common mode, and the transients that are generated by the switching of the inverter transistor (IGBT). These very large transients (equal in amplitude to the DC supply voltage) can exhibit extremely fast rates of rise (greater than 10 kV/μs), making it extremely difficult to sense the current flowing through each of the motor phases.

An isolation amplifier using sigma-delta (Σ–Δ) modulation from Avago Technologies is one way of galvanically isolating the shunt resistor current sensing signal from the load current, while maintaining excellent gain and offset accuracy. The Avago isolation amplifier exhibits outstanding stability over both time and temperature, combined with excellent common-mode transient noise rejection (CMR). Isolation amplifiers manufactured by Avago Technologies are not affected by external magnetic fields, and do not exhibit residual magnetization effects that can affect offset (a characteristic of Hall-effect current sensors). The Avago isolation amplifier is also easily mounted on a printed circuit board (PCB) and is very flexible for designers to use, allowing the same circuit and layout to be used to sense different current ranges simply by substituting different current-sensing resistors. These features make isolation amplifiers an excellent choice for sensing current in many different applications.

The advantage of using a Σ–Δ converter for analog-to-digital conversion is two-fold:

1. The conversion accuracy is achieved mainly by virtue of the high sampling rate, and is not very dependent upon IC process device matching.
2. The Σ–Δ modulator shapes amplifier noise to allow it to be more efficiently filtered out.

Understanding Isolation Amplifier Parameters

Isolation amplifier specifications which are key for motor drive current sensing applications are:

Input-Referred Offset Voltage – this is the input required to obtain a 0 V output.

All isolation amplifiers require a small voltage between their inverting and non-inverting inputs to balance mismatches due to unavoidable process variations. The required voltage is known as the input offset voltage and is abbreviated V_{OS}.

Avago Technologies data sheets show another parameter related to V_{OS}: the average temperature coefficient of the input offset voltage. The average temperature coefficient of the input offset voltage, $|\Delta V_{OS}/\Delta T_A|$, specifies the expected input offset drift over temperature, in units of μV/° C. V_{OS} is measured at the temperature extremes of the part, and $|\Delta V_{OS}/T_A|$ is computed as $\Delta V_{OS}/\Delta°$ C.

Gain Tolerance – this is important especially in multiple-phase drives, where accurate gain tolerance is required to ensure that precise phase-to-phase accuracy is maintained. For isolated modulators such as the Avago HCPL-7860/786J/7560, the important specification is the reference tolerance of the D/A converter, V_{REF}.

Avago Technologies data sheets show another parameter related to G: the average temperature coefficient of gain. The average temperature coefficient of G, $|\Delta G/\Delta T_A|$, specifies the expected gain drift over temperature in units of V/V/° C. G is measured at the temperature extremes of the part, and $|\Delta G/\Delta T_A|$ is computed as $\Delta G/\Delta°$ C. For isolated modulators such as the HCPL-7860/786J/7560, it will be $|\Delta V_{REF}/\Delta T_A|$, with units of ppm/° C.

Nonlinearity – this gives an indication of the device's accuracy over the input current range, and represents the deviation of the device output voltage from the expected voltage expressed as a percentage of the full-scale output range. A smaller percentage is better, being closer to perfectly linear.

Avago Technologies data sheets show another parameter related to NL: the average temperature coefficient of nonlinearity. The average temperature coefficient of nonlinearity, $|\Delta NL/\Delta T_A|$, specifies the expected nonlinearity over temperature. Its units are %/° C. NL is measured at the temperature extremes of the part, and $|\Delta NL/\Delta T_A|$ is computed as $\Delta\%/\Delta°$ C.

Common-Mode Rejection (CMR) – in electronic motor drives, there are large voltage transients generated by the switching of the inverter transistors. These very large transients (at least equal in amplitude to the DC rail voltage) can exhibit extremely fast rates of rise (as high as 10 kV/μs), making it difficult to sense the current flowing through each of the motor phases.

Propagation Delay and Bandwidth – device speed should be fast enough to ensure that the input signal is accurately represented and system stability is not compromised.

The device should also be fast enough to protect against short circuit situations.

Accuracy of the Isolation Amplifier

The typical isolation amplifier has an overall accuracy of a few percent. There are a number of error terms that combine to create this error, both at nominal room temperature (+25° C) and across the temperature range.

The accuracy is limited by the combination of:

- DC offset at zero current
- Gain error
- Linearity
- Limitations in bandwidth

Temperature changes also create drift in:

- DC offset
- Gain
- Linearity

HCPL-7860 Isolation Modulator and Shunt Resistor Performance

Error due to reference voltage	1%
Error due to non-linearity	0.01%
Error due to shunt resistor	1%
Error at 25° C	2.01%
For operating ambient up to 85° C	
Error due to offset voltage temperature drift	0.75%
Error due to reference voltage temperature drift	0.36%
Error due to non-linearity temperature drift	0.14%
Error due to shunt resistor temperature drift	0.3%
Error due to temperature drift	1.55%
Total uncalibrated error over temperature range	3.56%
Total calibrated* error over temperature range	2.56%

* The heading "calibrated error" refers to error of the gain tolerance or reference voltage (ΔGain or V_{ref}) and/or offset voltage (V_{OS})of the device is calibrated out.

HCPL-7800A Isolation Amplifier and Shunt Resistor Performance

Error due to offset voltage	0.5%
Error due to gain tolerance	1%
Error due to non-linearity	0.0037%
Error due to shunt resistor	1%
Error at 25° C	2.50037%
For operating ambient up to 85° C	
Error due to offset voltage temperature drift	0.75%
Error due to gain temperature drift	0.19%
Error due to non-linearity temperature drift	0.35%
Error due to shunt resistor temperature drift	0.3%
Error due to temperature drift	1.59%
Total uncalibrated error over temperature range	3.60%
Total calibrated* error over temperature range	2.01%

* The heading "calibrated error" refers to error of the gain tolerance or reference voltage (ΔGain or V_{ref}) and/or offset voltage (V_{OS})of the device is calibrated out.

HCPL-7510 Isolation Amplifier and Shunt Resistor Performance

Error due to offset voltage	0.25%
Error due to V_{ref}*	1%
Error due to gain tolerance	3%
Error due to non-linearity	0.06%
Error due to shunt resistor	1%
Error at 25° C	5.31%
assume V_{ref} has 1% tolerance.	
For operating ambient up to 85° C	
Error due to offset voltage temperature drift	1.5%
Error due to gain temperature drift	1.8%
Error due to non-linearity temperature drift	0.55%
Error due to shunt resistor temperature drift	0.3%
Error due to temperature drift	4.15%
Total uncalibrated error over temperature range	9.46%
Total calibrated* error over temperature range	6.21%

* The heading "calibrated error" refers to error of the gain tolerance or reference voltage (ΔGain or V_{ref}) and/or offset voltage (V_{OS})of the device is calibrated out.

Other Consideration for the Isolation Amplifier Application Circuit

A recommended application circuit is shown in Figure 2. In this circuit a floating power supply (which in many applications could be the same supply that is used to drive the high-side power transistor) is regulated to 5 V using a simple zener diode D1; the value of resistor R4 should be chosen to supply sufficient current from the floating supply. The voltage from the current sensing resistor or shunt (Rsense) is applied to the input of the HCPL-7860 (also applicable to other isolation amplifiers) through an RC anti-aliasing filter (R2 and C2). Although the application circuit is relatively simple, a few recommendations should be followed to ensure optimal performance.

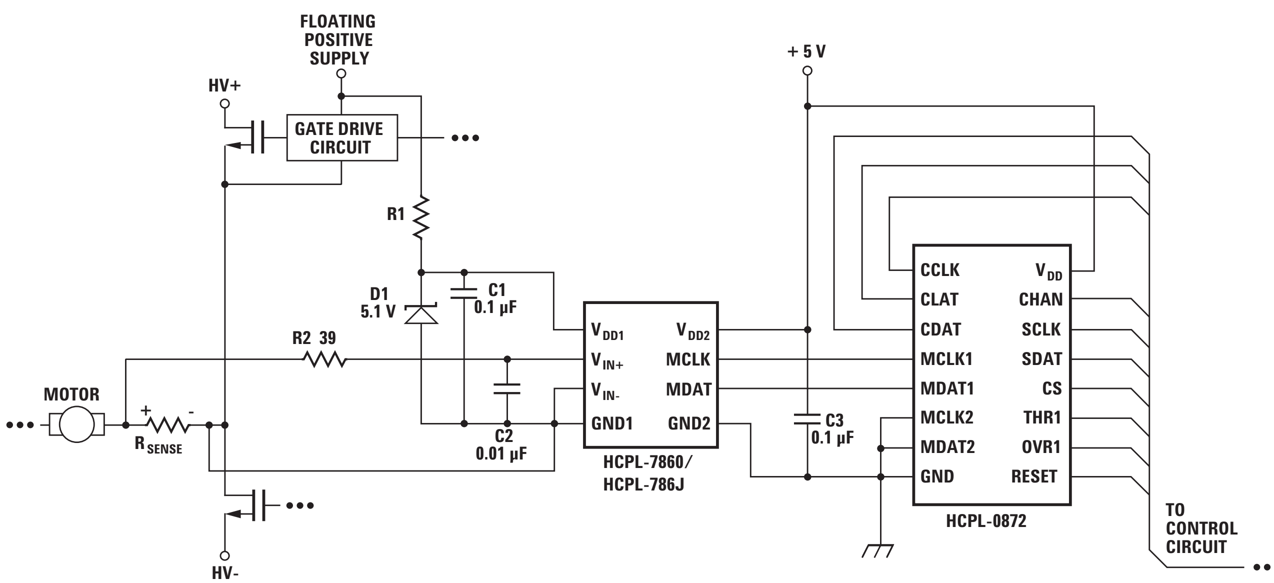

Figure 2. Recommended application for the HCPL-7860

Supplies and Bypassing

The power supply for the isolation amplifier is most often obtained from the same supply used to power the power transistor gate drive circuit. If a dedicated supply is required, in many cases it is possible to add an additional winding to an existing transformer. Otherwise, some sort of simple isolated supply can be used, such as a line-powered transformer or a high-frequency DC-DC converter.

An inexpensive three-terminal regulator such as the 78L05 can be used to reduce the gate-drive power supply voltage to 5 V. To help attenuate high frequency power supply noise or ripple, a resistor or inductor can be used in series with the input of the regulator to form a low-pass filter with the regulator's input bypass capacitor.

The 0.1 μF bypass capacitors (C1 and C3) shown in Figure 2 should be located as close as possible to the input and output power-supply pins of the isolation amplifier. The bypass capacitors are required because of the high-speed digital nature of the signals inside the isolation amplifier. A 0.01 μF bypass capacitor (C2) is also recommended at the input pin(s) due to the switched-capacitor nature of the input circuit. The input bypass capacitor forms part of the anti-aliasing filter, which is recommended to prevent high frequency noise from aliasing down to lower frequencies and interfering with the input signal. The input filter also performs an important reliability function – it reduces transient spikes from ESD events flowing through the current-sensing resistor.

PC Board Layout

The design of the PCB should follow good layout practices, such as keeping bypass capacitors close to the supply pins, keeping output signals away from input signals, and the use of ground and power planes. In addition, the layout of the PCB can also affect the isolation transient immunity (CMR) of the isolated modulator, due primarily to stray capacitive coupling between the input and the output circuits. To obtain optimal CMR performance, the layout of the PC board should minimize any stray coupling by maintaining the maximum possible distance between the input and output sides of the circuit and ensuring that any ground or power plane on the PC board does not pass directly below or extend much beyond the body of the isolated modulator.

Shunt Resistor Selection

The criteria for selecting current shunt resistors requires the evaluation of several tradeoffs, including:

- Increasing R_{SENSE} increases the V_{SENSE} voltage, which makes the voltage offset (V_{OS}) and input bias current offset (I_{OS}) amplifier errors less significant.
- A large R_{SENSE} value causes an increased voltage drop and a reduction in the power efficiency due to the I^2 x R loss of the resistor.
- A large R_{SENSE} value will cause a voltage offset to the load in a low-side measurement that may impact the EMI characteristics and noise sensitivity of the system.
- Special-purpose, low inductance resistors are required if the current has a high-frequency content.
- The power rating of R_{SENSE} must be evaluated because the I^2 x R power dissipation can produce self-heating and a change in the nominal resistance of the shunt.

In order to maximize accuracy of current measurement with isolation amplifiers, it is important to choose a shunt resistor with good tolerance, low lead inductance, and low temperature coefficient. Many resistor manufacturers, such as those listed in the Appendix, offer such resistors.

Choosing a particular value for the current sense resistor is usually a compromise between minimizing power dissipation and maximizing accuracy. Smaller values decrease power dissipation, while a higher resistance can improve accuracy by utilizing the full input range of the isolation amplifier.

Two-terminal current-sense resistors are useful for lower-cost applications, using the HCPL-7840, HCPL-7510, HCPL-7520, HCPL-788J and HCPL-7560. Four-terminal current-sense resistors provide two contacts for current to flow and two sense contacts for measuring voltage by making a Kelvin connection from the sense terminal to the isolation amplifier input.

With a four-terminal current-sense resistor the voltage that is sensed is the voltage appearing across the body of the resistor (and not across the higher-inductance resistor leads). Furthermore, four-terminal current-sense resistors typically have very low temperature-coefficient and thermal resistance. Therefore four-terminal current-sense resistors are especially useful for higher-accuracy applications.

Hall-Effect Current Sensors

Hall-effect current sensors measure current flowing in a wire by measuring the magnetic field created by that current with a Hall-effect IC and producing a preoperational output voltage (known as the Hall voltage). Hall-effect current sensors are widely used because they provide a measurement without adding components in series with the load. Several vendors offer devices that combine the magnetic sensor and conditioning circuit in a single package. These IC sensors typically produce an analog output voltage that can be input directly into a microcontroller's ADC.

Hall-effect current sensors can be classified as open-loop and closed-loop. Open-loop Hall-effect current sensors consist of a core to magnify the magnetic field created by the sensed current, and a Hall-effect IC, which detects the magnetic field and produces a voltage linearly proportional to the sensed current. Like all devices using ferromagnetic material, open-loop Hall-effect current sensors have a hysteresis characteristic, which contributes significantly to offset error.

Closed-loop Hall-effect current sensors integrate additional circuitry and a secondary winding nulling the flux and significantly improving the measurement accuracy of the sensor. They are, however, substantially more expensive than open-loop sensors, and have a comparatively high current consumption, since the power supply must provide compensation and bias current.

In general, the comparatively large profile and footprint of both open-loop and closed-loop Hall-effect current sensors poses a challenge for incorporation on high-density circuit boards. Their larger profile also means that auto-insertion may be difficult or impossible with standard pick-and-place machines.

Accuracy of Hall-effect Current Sensors

The typical Hall-effect current sensor has an overall accuracy of a few percent. There are a number of error terms that combine to create this error, at nominal temperature (+25° C) and across the temperature range.

The accuracy is limited by the combination of:

- DC offset at zero current
- Tolerance of the measuring resistor, RIM (for closed-loop Hall-effect current sensors)
- Gain error
- Linearity
- Bandwidth limitation

Temperature changes also create drift in:

- DC offset
- Gain
- Drift of measuring resistor, R_{IM} (for closed-loop Hall-effect current sensors)
- Linearity

Open-Loop Hall Effect Current Sensor Typical Performance

Error due to offset voltage	1%
Error due to primary current accuracy	1%
Error due to linearity	1%
Error at 25° C	3%
For operating ambient up to 85° C	
Error due to offset voltage temperature drift	2%
Error due to gain temperature drift	6%
Error due to temperature drift	8%
Total uncalibrated error over temperature range	11%
Total calibrated* error over temperature range	10%

* The heading "calibrated error" refers to error of the gain tolerance or reference voltage (ΔGain or V_{ref}) and/or offset voltage (V_{OS})of the device is calibrated out.

Closed-Loop Hall Effect Current Sensor Typical Performance

Error due to offset voltage	1%
Error due to tolerance of R_{IM}	0.5%
Error due to number of secondary turns	0.1%
Error due to non-linearity	0.1%
Error at 25° C	1.7%
For operating ambient up to 85° C	
Error due to R_{IM} temperature drift	0.3%
Error due to offset voltage temperature drift	2%
Error due to temperature drift	2.3%
Total uncalibrated error over temperature range	4%
Total calibrated* error over temperature range	3%

* The heading "calibrated error" refers to error of the gain tolerance or reference voltage (ΔGain or V_{ref}) and/or offset voltage (V_{OS})of the device is calibrated out.

Comparison of Isolation Amplifiers and Shunt Resistor and Hall Effect Current Sensors with Nominal Measured Current of 25 A_{RMS}

	High Performance Solution			Generic Application Solution	
Sensors	**HCPL-7860**	**HCPL-7800A**	**Closed-Loop Hall Effect**	**HCPL-7510**	**Open-Loop Hall Effect**
Accuracy @25° C	2.0%	2.5%	1.7%	5.3%	3.0%
Temperature drift Error	1.6%	1.6%	2.3%	4.2%	8.0%
Uncalibrated accuracy over temperature range	3.6%	3.6%	4.0%	9.5%	11.0%
Calibrated accuracy over temperature range	2.6%	2.0%	3.0%	6.2%	10.0%
Bandwidth	18 kHz*	50 kHz	150 kHz	50 kHz	50 kHz
Power budget	Low	Low	≈ 1 - 2 Watts	Low	≈ 0.5 Watts
Solution cost	Medium	Medium	High	Low	Low

*12 bits resolution

The table above lists some characteristics of isolation amplifiers compared with closed-loop and open-loop Hall-effect current sensors. Generally, Σ–Δ modulated isolation amplifiers and open-loop Hall-effect current sensors are comparably priced. Closed-loop Hall-effect current sensors are relatively more expensive due primarily to the additional core winding and the flux-nulling servo-amplifier.

At room temperature, Hall-effect (open-loop and closed loop) current sensors have better accuracy than the shunt isolation amplifier solution. However, a comparison of accuracy over temperature between Hall-effect current sensors and isolation amplifiers reveals a pronounced performance difference, since isolation amplifiers do not share the same sensitivity to temperature that affects Hall-effect current sensors.

With calibration, isolation amplifiers show a clear accuracy advantage. Hysteresis error of the Hall-effect current sensors is always present and cannot be removed with calibration.

Selection of Isolation Amplifiers

Avago Technologies offers the widest range of isolation amplifiers in the industry. These isolation amplifiers come with high bandwidth, high voltage isolation, best CMR performance, excellent gain and offset characteristics and high linearity. They are also available in a number of different output configurations to suit a variety of application needs.

Summary

Hall-effect (open-loop and closed-loop) current sensors have better accuracy than isolation amplifiers at room temperature. A comparison of accuracy over temperature between Hall-effect current sensors and isolation amplifiers reveals that isolation amplifiers do not share the same sensitivity to temperature that affects Hall-effect current sensors.

In summary, isolation amplifiers provide a cost-effective, low-noise solution for motor control current sensing. They have a smaller form factor, and are auto-insertable and surface-mountable providing flexibility for tighter PCB integration.

Avago Technologies Isolation Amplifiers

		Gain Tol	Non-Linearity	Prop Delay	CMR - V/μs@V_{CM}			V_{ISO}	V_{IORM}
		%	%	μs	CMR	V_{CM}		V_{RMS}	V
Part No.	Package	max	max	max	V/μs (min)	V	Output Configuration	min	peak
HCPL-7860	300 mil DIP	Isolated 12 bit A/D Converter with Isolated Modulator						3750	891
HCPL-7560	300 mil DIP	Isolated 8 bit A/D Converter with Isolated Modulator						3750	891*
HCPL-786J	SO16	Isolated 12 bit A/D Converter with Isolated Modulator						3750	891
HCPL-0872	SO16	Digital Interface IC for A/D Converter							
HCPL-7800A	300 mil DIP	1	0.2	9.9	10000	1000	Differential	3750	891
HCPL-7800	300 mil DIP	3	0.2	9.9	10000	1000	Differential	3750	891
HCPL-7840	300 mil DIP	5	0.2	9.9	10000	1000	Differential	3750	891*
HCPL-788J	SO16	5	0.4	20	10000	1000	Single-ended	3750	891
HCPL-7510	300 mil DIP	3	0.4	9.9	10000	1000	Single-ended	3750	891*
HCPL-7520	300 mil DIP	5	0.4	9.9	10000	1000	Single-ended	3750	891*

Notes: * - with IEC/EN/DIN EN 60747-5-2 Option 060

References

1. Avago Technologies HCPL-7800A/HCPL-7800 Isolation Amplifier Data Sheet, Avago Technologies Publication Number AV02-0410EN
2. Avago Technologies HCPL-7510 Isolated Linear Sensing IC Data Sheet, Avago Technologies Publication Number AV02-0951EN
3. Avago Technologies HCPL-7860/HCPL-786J Optically Isolated Sigma-Delta (Σ–Δ) Modulator Data Sheet, Avago Technologies Publication Number AV02-0409EN
4. Application Note 1078: Designing with Avago Technologies Isolation Amplifiers, Avago Technologies Publication Number 5965-5976E

Appendix

Shunt Resistor Manufacturers

Caddock Electronics, Inc.	http://www.caddock.com/
Vishay Dale	http://www.vishay.com/company/brands/dale/
TT electronics IRC	http://www.irctt.com/
Isotek Corporation	http://www.isotekcorp.com/
Iwaki Musen Kenkyusho	http://www.iwakimusen.co.jp/
Micron Electric Co., Ltd.	http://www.micron-e.co.jp/
Precision Resistor Company, Inc.	http://www.precisionresistor.com/
Riedon	http://www.riedon.com/

For product information and a complete list of distributors, please go to our web site: **www.avagotech.com**

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