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

Application Note 5121

Introduction

Current Sensor is an essential component in a motor control system. Recent progresses in sensor technology have improved the accuracy and reliability of sensors, while reducing the 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 microcontroller or digital signal processor in motor control applications are:

- Isolation amplifier and shunt resistor
- Hall effect current sensor
- Current-sensing transformer

This paper will focus on Isolation amplifier and shunt resistor and Hall effect current sensor, and present a comparison of these two different current sensing technologies.

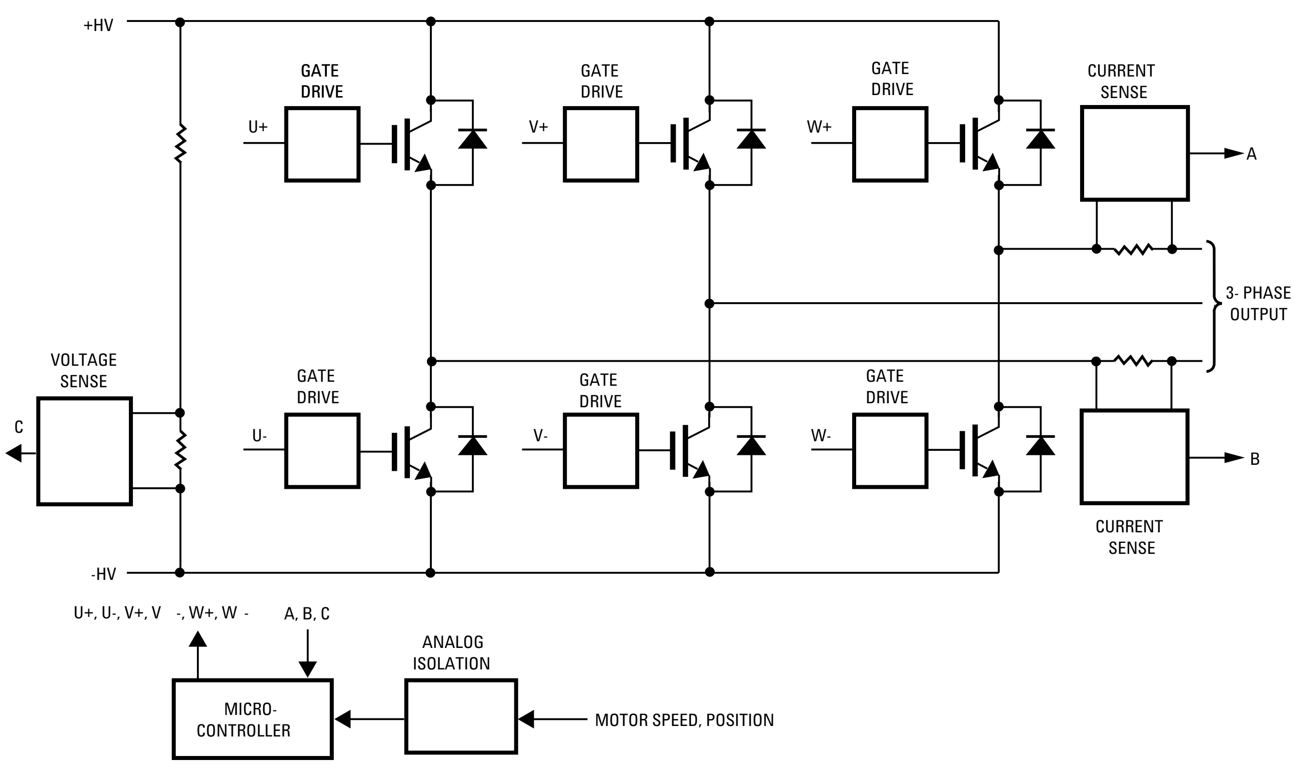

Figure 1. Typical Motor Block Diagram.

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Isolation Amplifier and Shunt Resistor

Shunt resistors are prevalent current sensors because they provide an accurate measurement at a low cost. The voltage drop across a known low value resistor is monitored in order to determine the current flowing through the load.

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

Sigma-Delta (Σ–Δ) modulation isolation amplifier from Agilent Technologies is one way of galvanically isolating the shunt resistor current sensing signal from the load current, while maintaining excellent gain and offset accuracy. It exhibits outstanding stability over both time and temperature, as well as excellent common mode transient noise rejection (CMR). Isolation amplifiers manufactured by Agilent Technologies is not affected by external magnetic field; and it does not exhibit residual magnetization effects that can affect offset compare with Hall effect current sensor. It 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 range 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 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 efficient filter out.

Understanding Isolation Amplifier Parameters

Isolation amplifier specification 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}.

Agilent data sheets show another parameter related to V_{OS}; the average temperature coefficient of input offset voltage. The average temperature coefficient of input offset voltage, $|\Delta V_{OS}/\Delta T_A|$, specifies the expected input offset drift over temperature. Its units are 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 requires for ensuring that precise phase-to-phase accuracy is maintained. For the isolated modulator such as HCPL-7860/786J/7560, the important specification is reference tolerance of the D/A, V_{REF}.

Agilent's 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. Its units are 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 the isolated modulators such as HCPL-7860/786J/7560, it will be $|\Delta V_{REF}/\Delta T_A|$, with unit of ppm/°C.

Nonlinearity – this gives an indication of the device's accuracy over the input current range. It is the deviation of the device output voltage from the expected voltage expressed as a percentage of the full-scale output range. Smaller percentage is better (closer to perfectly linear).

Agilent 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 Δ%/Δ°C.

Common-Mode Rejection (CMR) – in electronic motor drives, there are large voltage transient 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 10kV/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 compromise. The device should also be fast enough to protect against short circuit.

Accuracy of 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, at nominal temperature (25°C) and across the temperature range.

The accuracy is limited by the combination of:

- DC offset at zero current
- Gain error
- Linearity
- Bandwidth limitation

Temperature changes also create drift in:

- DC offset
- Gain
- Linearity

Isolation Modulator HCPL-7860 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.

Isolation Amplifier HCPL-7800A 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.

Isolation Amplifier HCPL-7510 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 Isolation Amplifier and Shunt Resistor

Application Circuit

The recommended application circuit is shown in Figure 2. 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 existing 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.

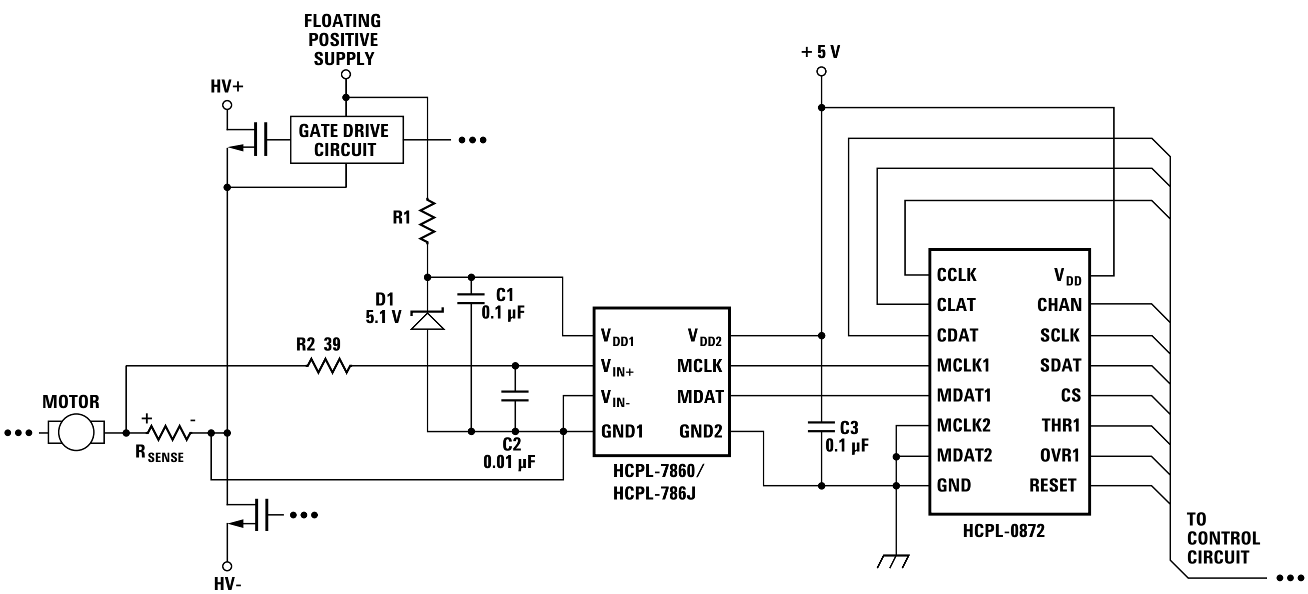

Figure 2. Recommended application for HCPL-7860

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 on 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.

As mentioned above, an inexpensive 78L05 three-terminal regulator 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.

As shown in Figure 2, 0.1 µF bypass capacitors (C1 and C3) 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 also 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 printed circuit board (PCB) should follow good layout practices, such as keeping bypass capacitors close to the supply pins, keeping output signals away from input signals, the use of ground and power planes, etc. 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 wider than the body of the isolated modulator.

Shunt Resistor Selection.

The selection criteria of a shunt current resistor requires the evaluation of several trade-offs, 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 a voltage loss 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 offer such resistors. A list of such resistor manufacturers is at the appendix.

Choosing a particular value for the current resistor us usually a compromise between minimizing power dissipation and maximizing accuracy. Smaller current-sense resistor decrease power dissipation, while a larger current-sense 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 lead.) 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 application.

Hall Effect Current Sensor

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 produces an output voltage (known as Hall voltage). Hall effect current sensors are widely used because they provide a non-intrusive measurement. 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 the microcontroller's ADC.

Generally, Hall effect current sensors can be classified into 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 ferromagnetic material, open-loop Hall effect current sensors have hysteresis error, which contributes significantly to offset error. Closed-loop Hall effect current sensors integrate additional circuitries and a secondary winding nulling the flux and improve the accuracy of current sensors significantly but more costly.

In general, the comparative large profile and footprint of both open-loop and closed-loop Hall effect current sensors poses a challenge for incorporation onto high density circuit boards. The larger profile also means that auto-insertion is difficult or impossible with standard pick-and-place machine.

The main disadvantages of Hall effect current sensors are that they are of larger profile that auto-insertion is difficult or impossible with standard pick-and-place machine and their accuracy varies with temperature.

The limitation of the closed-loop Hall effect current sensors are the high current consumption from the secondary supply (which must provide the compensation and bias current)

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 measuring resistor, R_{IM} (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

Table above lists some characteristics of the 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 prices. Closed-loop Hall Effect current sensors are relatively more expensive. The higher cost of close-loop Hall effect current sensor is due to 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 isolation amplifiers. A comparison of over-temperature accuracy between Hall effect current sensor and isolation amplifiers reveals a pronounces performance difference. This is because 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 on Hall effect current sensors is always present and cannot be calibrated.

Selection of Isolation Amplifiers

Agilent 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 characteristic and high linearity. These isolation amplifiers also have different output configurations suit different application needs.

Summary

From the investigation, Hall effect (open-loop and closed-loop) current sensors have better accuracy than isolation amplifiers at room temperature. A comparison of over-temperature accuracy between Hall effect current sensor and isolation amplifiers reveals a pronounced performance difference. This is because 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.

		Gain Tol	Non-Linearity	Prop Delay	CMR - V/µs@VCM			VISO	VIORM
		%	%	µs	CMR	VCM		VRMS	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. "Agilent HCPL-7800A/HCPL-7800 Isolation Amplifier Data Sheet", Agilent Technologies Publication Number 5989-2161EN (2/05)
2. "Agilent HCPL-7510 Isolated Linear Sensing IC Data Sheet", Agilent Technologies Publication Number 5989-2162EN (2/05)
3. "Agilent HCPL-7860/HCPL-786J Optically Isolated Sigma-Delta (Σ–Δ) Modulator Data Sheet", Agilent Technologies Publication Number 5989-2166EN (12/04)
4. "Application Note 1078 -Designing with Agilent Technologies Isolation Amplifiers", Agilent Technologies Publication Number 5965-5976E (11/99)

Appendix

Shunt Resistor Manufacturers

Caddock	http://www.caddock.com/
Dale	http://www.vishay.com/company/brands/dale/
IRC	http://www.irctt.com/
Isotek	http://www.isotekcorp.com/
Iwaki Musen Kenkyusho	http://www.iwakimusen.co.jp/
Micron Electric	http://www.micron-e.co.jp/
Precision Resistor	http://www.precisionresistor.com/
Riedon	http://www.riedon.com/

www.agilent.com/
semiconductors

For product information and a complete list of distributors, please go to our web site.

Data subject to change.

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