Designing with High Performance Hermetic Analog Isolation Amplifiers

White Paper

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Abstract

Today, optocouplers are a ubiquitous electronic component, found in almost any piece of electrical equipment and in most industry segments. Since their introduction over twenty five years ago, optically coupled isolators, also known as optocouplers, photocouplers, or optoisolators, have proven to be an indispensable component for galvanic insulation and for ground loop noise rejection, or other EMI induced noise interference isolation. These optocouplers in their most basic form consist of just an LED emitter on the input side, and a bipolar photo-detector on the output side, separated by a high dielectric strength insulation film placed between the two and enclosed in a small package.

Initially, these optocouplers were primarily used in digital applications. They had a reputation for being notoriously non-linear in their input-output response, and required ingenious design techniques to "make" them work in linear applications. Less known perhaps is that linear optocouplers are now also available. Qualities such as small size, high reliability, and low power that make optocouplers so popular with the digital designers also makes them a favorite component with analog designers.

Avago Technologies' HCPL-7851 hermetic analog isolation amplifier is available for analog current or voltage sensing applications. This analog isolation amplifier is designed to replace the traditional methods of current measurements such as Closed or Open Loop Hall Effect devices or current transformers. In this paper, linear hermetic optocouplers such as the HCPL-7851, HCPL-785K, or the HCPL-7850 are presented. We also compare and contrast the performance of these hermetic linear amplifiers with competitive technologies, such as the Hall Effect devices and current transformers.

Optically Isolated Hermetic Analog Isolation Amplifier

The HCPL-7851 family of hermetic analog isolation amplifiers is designed to perform linear current sensing or voltage sensing up to a minimum guaranteed bandwidth of 40 kHz. A proprietary internal shielding process is designed to allow a high common mode noise rejection (CMR) of 5 kV/μs at a common mode voltage of 1 kV. The maximum non-linearity of 0.8% is guaranteed over the full Mil-Std operating temperature range of -55° to 125°C, and over the full-scale input dynamic range of ±200mV. The total power dissipated by the analog amplifier is quite low. The input side and the output side consume no more than 15.5 mA of quiescent bias current, respectively. This low power requirement allows bootstrapping techniques to be employed for supplying isolated power.

All of these isolated analog amplifiers are based on sigma-delta (ΣΔ) analog-to-digital converters which are optically coupled to integrated output digital-to-analog converters. The analog isolation amplifiers have very high common mode transient rejection capability (CMR), which is often necessary in modern fast switching motor control electronics. They also provide high isolation voltages through optical transmission of the signal, from the input to the output. The voltage is sensed by the isolation amplifier inputs over a low value external shunt resistor connected in parallel with the input pins. The analog linearity is guaranteed over the maximum input range of ±200 mV. The output voltage of the isolation amplifier is the analog output voltage proportional to the input voltage.

The block diagram of the isolation amplifier is shown in Figure 1.

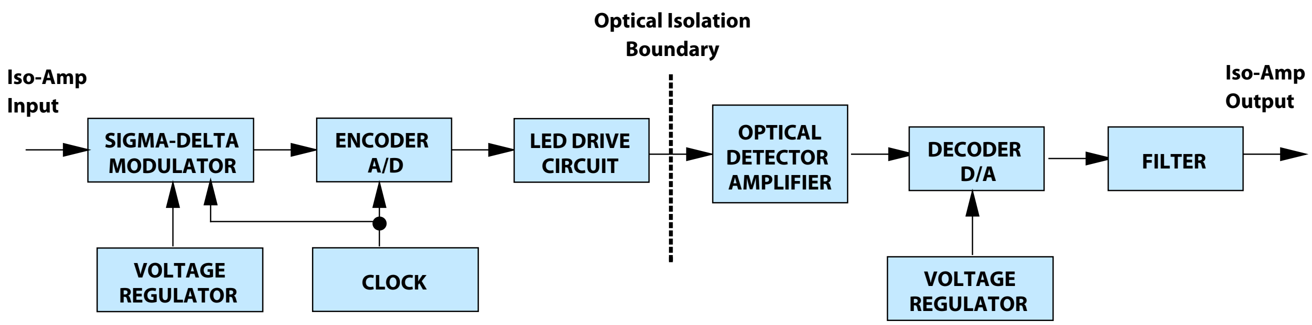

Figure 1. A Block Diagram of the Optically Isolated Analog Isolation Amplifier

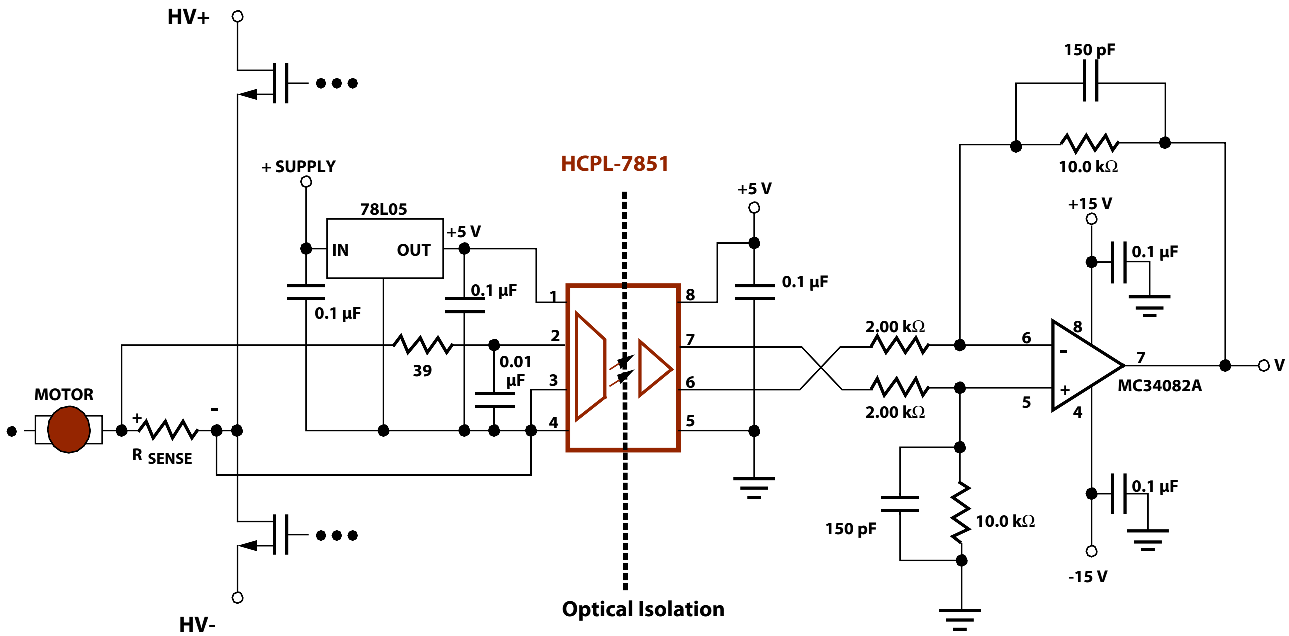

Figure 2. Typical Application Circuit Using the HCPL-7851 Iso-Amp for Current Sensing

The input is sampled at a high rate through a chopper stabilized differential amplifier that is a part of the ΣΔ amplifier. The input sensing at a very high rate is accomplished by a sampling rate typically between 6 to 10 MHz. This high speed sensing guarantees that the Nyquist criterion is always met when sensing the input at high frequency signals.

In operation, the ΣΔ modulator converts the analog input signal into a high-speed serial bit stream. The average time of this bit stream is directly proportional to the input signal. This stream of digital data is encoded and optically transferred to the detector circuit. The detected signal is decoded and converted back into an analog signal, which is then filtered to obtain the final output signal. Figure 2 shows a typical application circuit.

The input is sensed across a precise, low resistance, low inductance, and low temperature co-efficient external shunt resistor. A low pass filter at the input (39Ω resistor and 0.01 µF capacitor) rejects high frequency noise components and is an anti-aliasing filter. The post differential amplifier converts the differential output signal of the isolation amplifier to a ground referenced voltage compatible with an A/D converter at the microcontroller. The differential amplifier's bandwidth can be adjusted by the R-C filter in the feedback path. Adjusting this bandwidth to a minimum level also helps to reject and minimize the noise at the output, if necessary. Table 1 gives some comparative performance information between Avago Technologies' optical isolation amplifiers and the Hall Effect devices.

The comparison below indicates that the isolation amplifiers outperform both the Open and Closed Loop Hall Effect devices in terms of offset drifts, gain drifts, common mode rejection, and price. In addition, optoisolators have a smaller form factor, and can be auto-inserted and surface mounted. These significant advantages allow the optically isolated analog amplifiers to be very competitive in low cost, reliable, accurate, and efficient motor designs.

Table 1. Comparison of Isolation Amplifiers versus Hall Effect Devices

Sensor Type	Nominal Current Measured A(rms)	Uncalibrated Accuracy (25°C)	Calibrated Accuracy (25°C)	Uncalibrated Accuracy Over Temp	Bandwidth	Solution Cost
ΣΔ Iso-Amp HCPL-7851	Up to 25 A	4.6 %	0.2 %	7 %	100 kHz (typical)	Less Expensive
Hall-Effect (Open Loop)	Up to 25 A	4.2 %	1.2 %	16 %	25 kHz	Less Expensive
Hall-Effect (Closed Loop)	Up to 25 A	1.1 %	0.6 %	3 %	150 kHz	More Expensive

Typical Application Circuits

The HCPL-7851 is designed for current sensing applications such as measuring bus currents, AC phase currents, voltage sensing of the bus voltages, temperature sensing (voltage from the temperature sensor of the heat sink of the IGBT or IPM), or counter electromotive voltage of the motor (for brushless DC motors only). Figure 2 shows the HCPL-7851 in a motor phase current sensing topology. Figure 3 shows how a suitable voltage divider can be used to measure the DC bus voltage or counter emf of brushless motors by stepping the voltage down at the input so that the sensing voltage is below ±200 mV.

In this case, the constraint is that the value of R1 should be kept below 1kohm, such that the input impedance of the HCPL-7851 (280 kohm) and input current (1 µA typical) do not introduce offsets and inaccuracies in the measurement. An input bypass capacitor of 0.01 µF is still required, although the 39 ohm resistor can be omitted, and the voltage divider resistor performs the same low pass filter function.

The actual output of the HCPL-7851 analog isolation amplifier at output pins 6 and 7 is a differential output. The prime purpose of the post amplifier circuit (differential amplifier at the output of the HCPL-7851) is to transform the differential output of the HCPL-7851 to a ground referenced output signal. The post amplifier also helps to establish a desired gain, and by selecting an appropriate low bandwidth of the differential amplifier, it helps to filter high frequency chopper noise.

The noise-shaping characteristics of the ΣΔ modulator result in an output noise spectrum that is flat up to about 40 kHz, where it breaks up at 12 dB per octave. The internal filter begins to roll off the noise spectrum at about 200kHz with a steep drop just below 1 MHz.

As mentioned earlier, reducing the bandwidth of the post amplifier circuit reduces the amount of output noise. Due to the increasing noise behavior above 40 kHz, a second order filter response can be much more effective at filtering noise than a first order filter. Minimizing the post amplifier bandwidth will minimize the output noise. The typical application circuits shown in Figures 2 and 3 exhibit a first order low pass filter characteristic. By adding two additional resistors and a capacitor (R1a, R2a, C9) as shown in Figure 4, a second order filter response can be obtained. Capacitor C9 should be chosen so that the product of R1a and C9 is equal to the product of R3 and C5. By selecting the resistor and capacitor values, the two poles are placed at exactly the same frequency. The practical impact of two poles implies that the gain roll-off will be -40 dB/decade for the second order filter versus -20 dB/decade for the first order low pass filter.

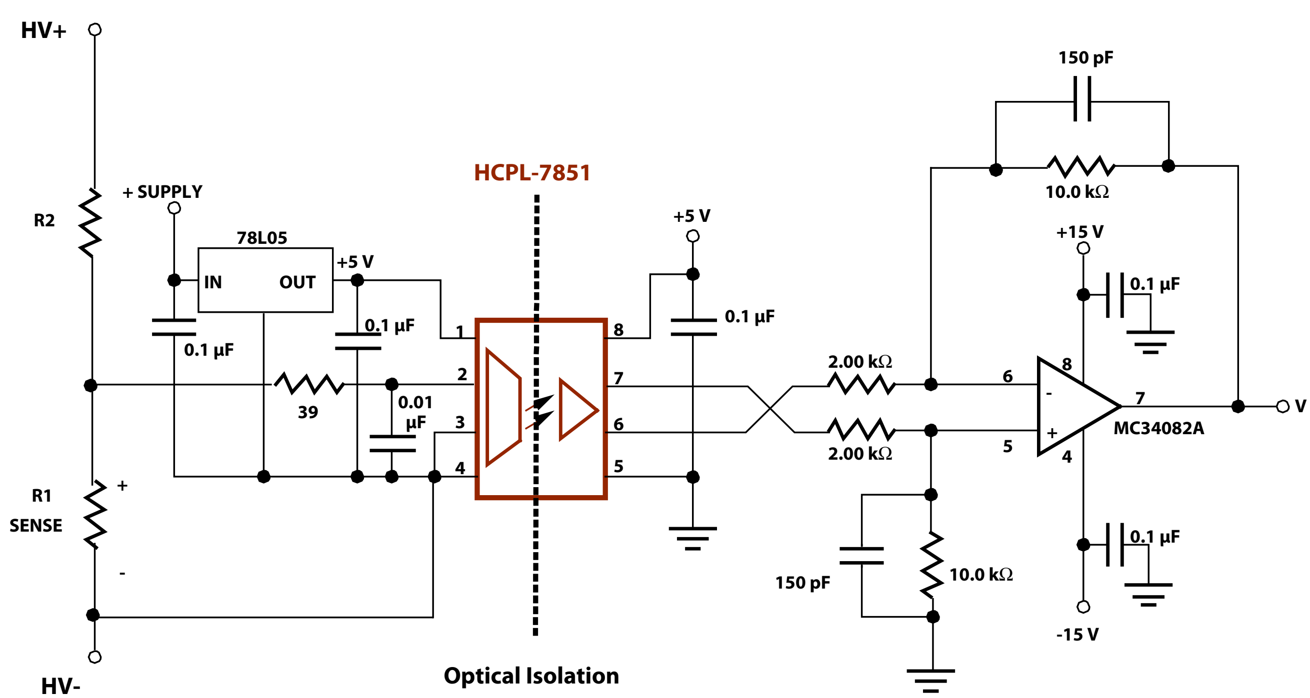

Figure 3. Typical Application Circuit Using the HCPL-7851 Iso-Amp for Voltage Sensing

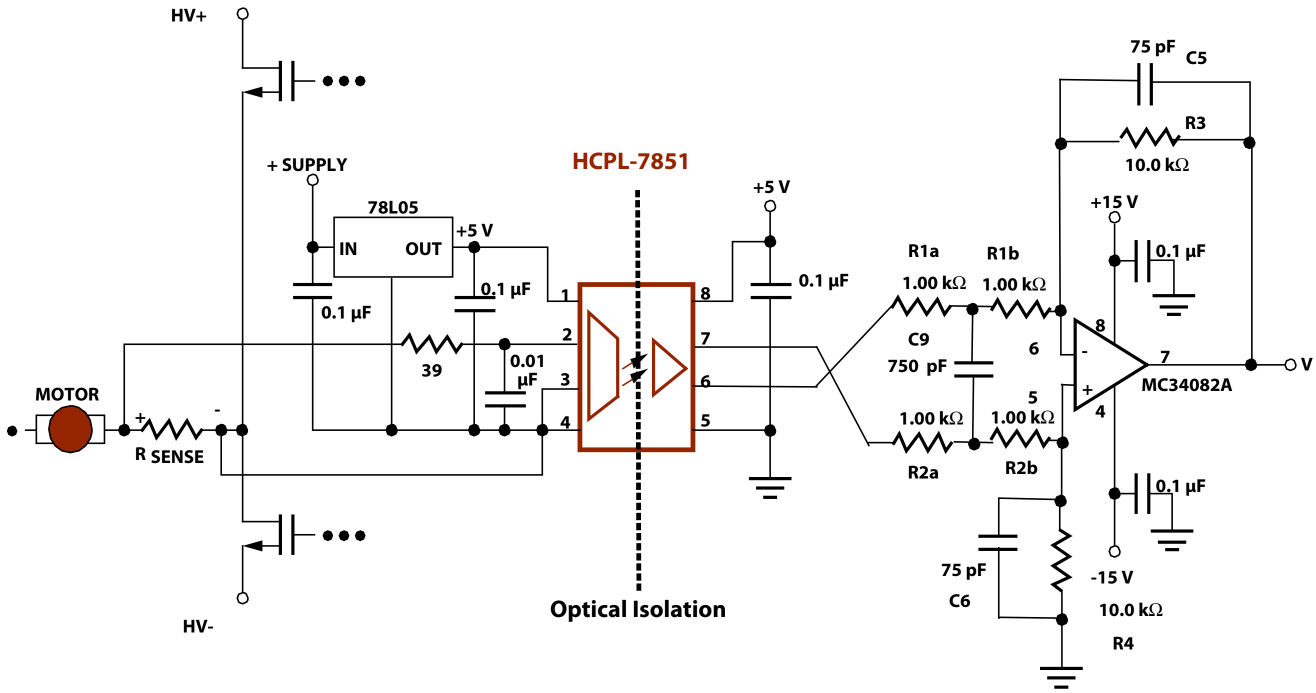

Figure 4. Post-Amplifier Circuit with Second-Order Filter Response

The post-amplifier circuit can also be easily modified to allow for a single supply operation. Figure 5 shows a schematic for a post-amplifier used in a 5V single supply application. One additional resistor (R4a) is needed and the gain is decreased to allow circuit operation over the full input voltage range. Adding the resistor shifts the output reference voltage from zero to one-half the supply voltage.

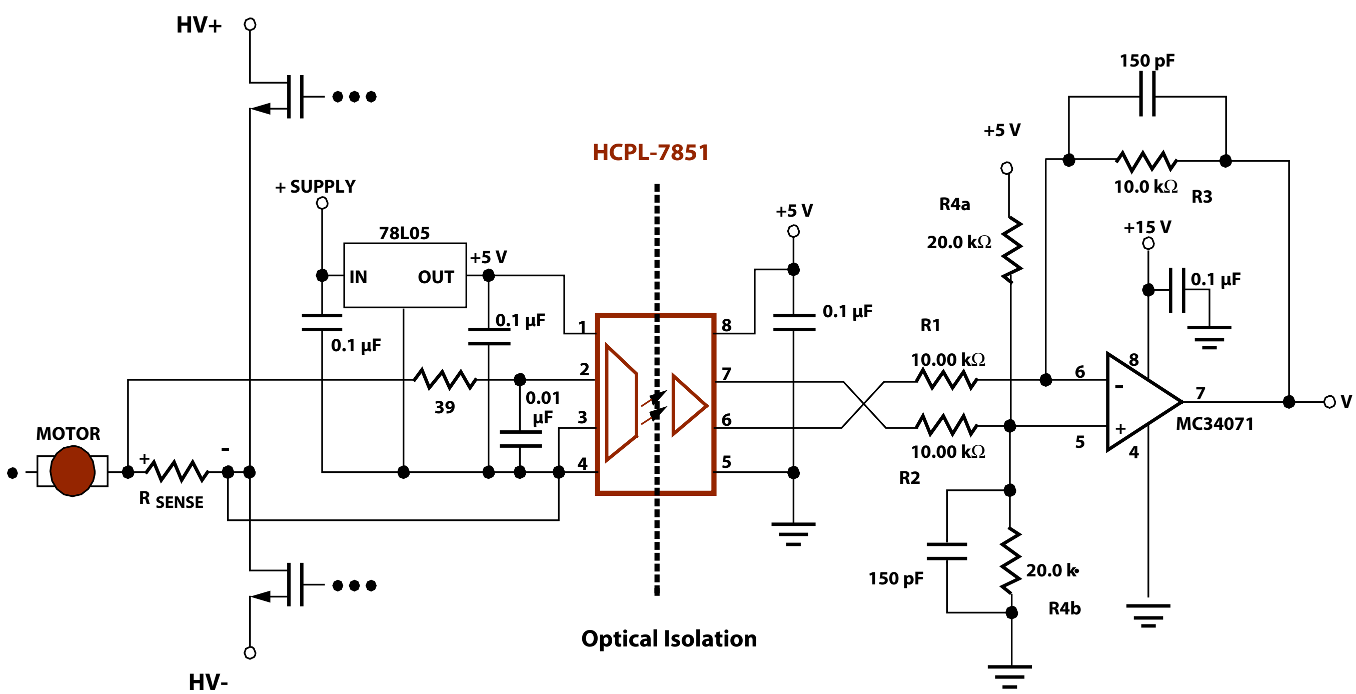

Figure 5. Single Supply Post Amplifier Circuit for HCPL-7851

Different Methods of Current Measurement

Besides meeting the inverter gate driver requirements, the next big challenge in motor control applications is how to measure motor phase current, bus currents, and other analog parameters like temperature or voltage. Typically, all these measurements need to be made through some type of safe isolation barrier. At the present time there are three main methods that incorporate some type of isolation technique.

1. Current transformers
2. Hall Effect current sensors
3. Optically isolated analog sensors

Each of the above methods offers some advantages and disadvantages. A designer will pick the solution that best reduces overall cost, optimizes performance and reliability, minimizes board space, and meets the accuracy and linearity requirements.

At present, the transformer current sensing method is based on the simple fact that, for a given current flow in a conductor, a proportional magnetic field is generated according to Ampere's law. The primary winding in the transformer couples this magnetic field in the secondary winding of the transformer, causing a proportional current to flow in the secondary winding. Depending upon the ratio of turns, a precise secondary current representation is generated. This current can be appropriately sensed through common op-amp linear amplification techniques. An example of this method of current measurement is shown in Figure 6.

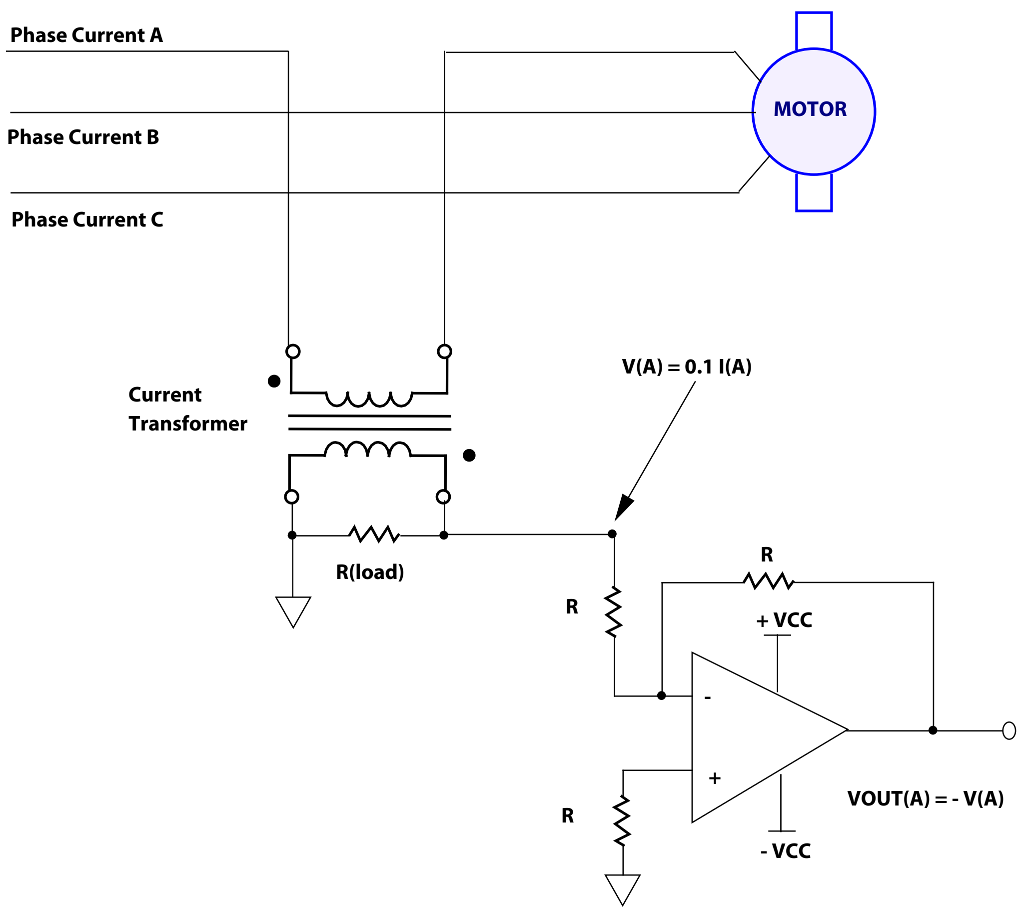

Figure 6. Using Current Transformers to Measure Motor Phase Currents

The key advantages of using current transformers are that they provide reasonable linearity for measuring current, provide safety insulation, and are quite reliable. In addition, transformers generate a proportional current that intrinsically provides higher noise immunity compared to voltage measurements. The disadvantages are that the transformers can only measure high frequency AC currents, may induce measurement errors at lower frequencies, and couple in stray magnetic field errors. The size of the transformers is also typically large.

Hall Effect transducers are based on the Hall Effect, which was discovered in 1879 by Edward H. Hall. This law states that electrons in a conductor experience force in the presence of magnetic fields, drift towards one side of the conductor and generate a transverse Hall potential difference between two sides of the conductor. This Hall voltage can be used to linearly monitor the motor phase currents instead of the analog optoisolators techniques.

The Hall effect, Figure 7, states that when a magnetic field (B) is applied to metal or a semiconductor carrying a current (IC) that is perpendicular to the applied field, a potential (VH) will appear across the Hall specimen which is perpendicular to both the magnetic field and the direction of the current flow.

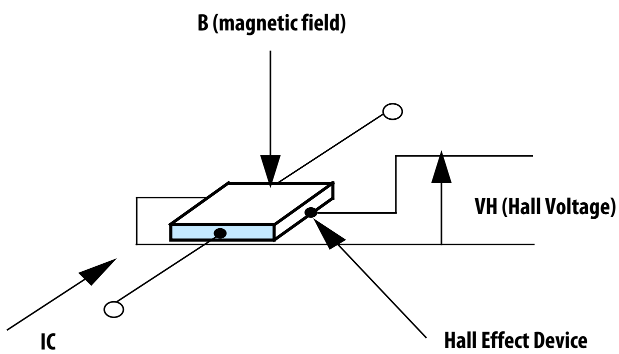

Figure 7. The Hall Effect Principle

This relationship which forms the basis for the Hall Effect devices can be stated as:

$$V_H = K \times I_C \times B$$

where K is a constant of proportionality and depends on the physical properties of the Hall specimen.

There are two types of Hall Effect transducers commercially available at this time—Open Loop Hall Effect devices (Figure 8) and Closed Loop Hall Effect devices (Figure 9). The Hall Effect transducers are round circular devices that can be placed around the wires that are conducting the motor phase currents or any other currents that need to be monitored. These transducers sense the magnetic field generated by this conductor. This magnetic field is proportional to the current flowing through it and forms the basis for linear Hall measurements.

A Hall Effect device has a magnetic field sensor that produces a voltage proportional to the sensed magnetic field. It is evident from this that the Hall Effect Transducer provides isolation capability, as the sensing is conducted through the magnetic field, without the sensor coming into any physical contact with any high voltage potential. A decision to use either the Hall Effect devices or optoisolators will be dependent on competitive performance criteria like:

- Isolation Voltage Capability
- Linearity
- Zero Offset
- Response Time / Speed
- Bandwidth
- Temperature Rating
- Hysteresis
- Noise Immunity / Common Mode Rejection
- Insertion Loss
- Cost

The Hall Element in the Hall Effect transducers is usually a semiconductor device that generates a voltage due to the deflection of electrons in the presence of the magnetic filed of a current carrying conductor. The transducer has a magnetic core to concentrate the magnetic field sensed by the semiconductor Hall element, producing a proportional voltage. Open Loop transducers provide an output voltage proportional to the magnetic field. Magnetic core hysteresis (i.e., zero offsets) is one of the problems associated with the Open Loop Hall Effect transducers. Closed Loop transducers operate by generating a current that is fed through a feedback winding to cancel the flux in the original magnetic field. This current is the output of the Closed Loop transducer and is proportional to the current that is being monitored by the transducer. The Closed Loop sensors have zero magnetic flux in the core and are less sensitive to hyteresis. The Closed Loop sensors are more accurate and linear, and, consequently, more costly than the Open Loop sensors.

An advantage of Hall Effect devices is that they can measure both AC and DC currents, while providing galvanic isolation. A major disadvantage of these devices is that they have zero current offsets (output signal for zero current flow). Key advantages of the optoisolator-based solution are determined on high performance, high common mode noise immunity (CMR), small package profile and foot-print area, zero current offsets and very low over temperature drifts.

Other parameters that are not listed, but that are equally important in the decision-making process, are the response time/speed, bandwidth, temperature sensitivity and linearity. Based on these parameters, optoisolators provide much better linearity. Optoisolators are faster than Open Loop transducers, and equivalent to or slower

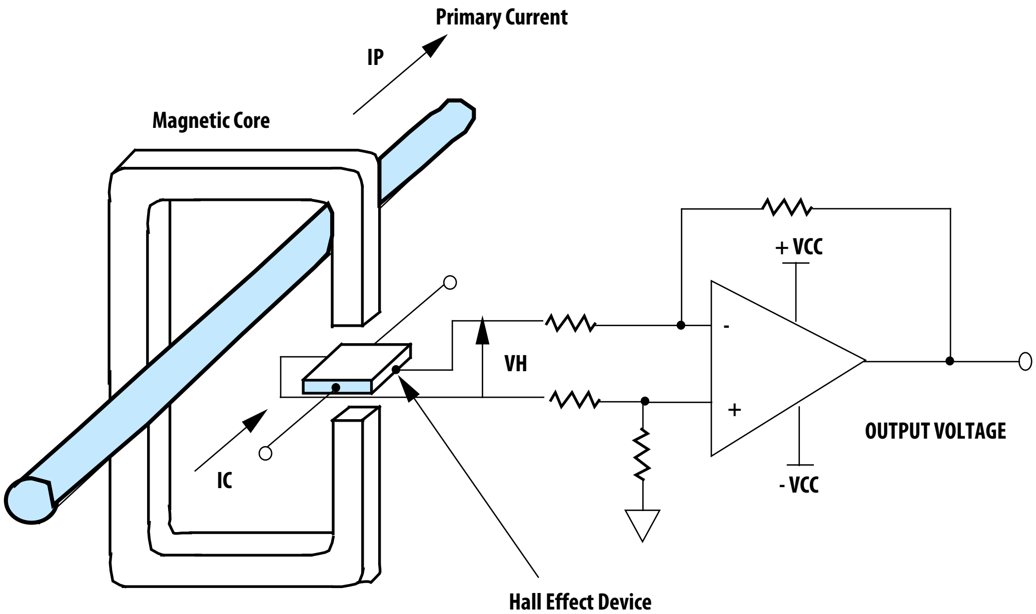

Figure 8. Open Loop Hall Effect Transducer

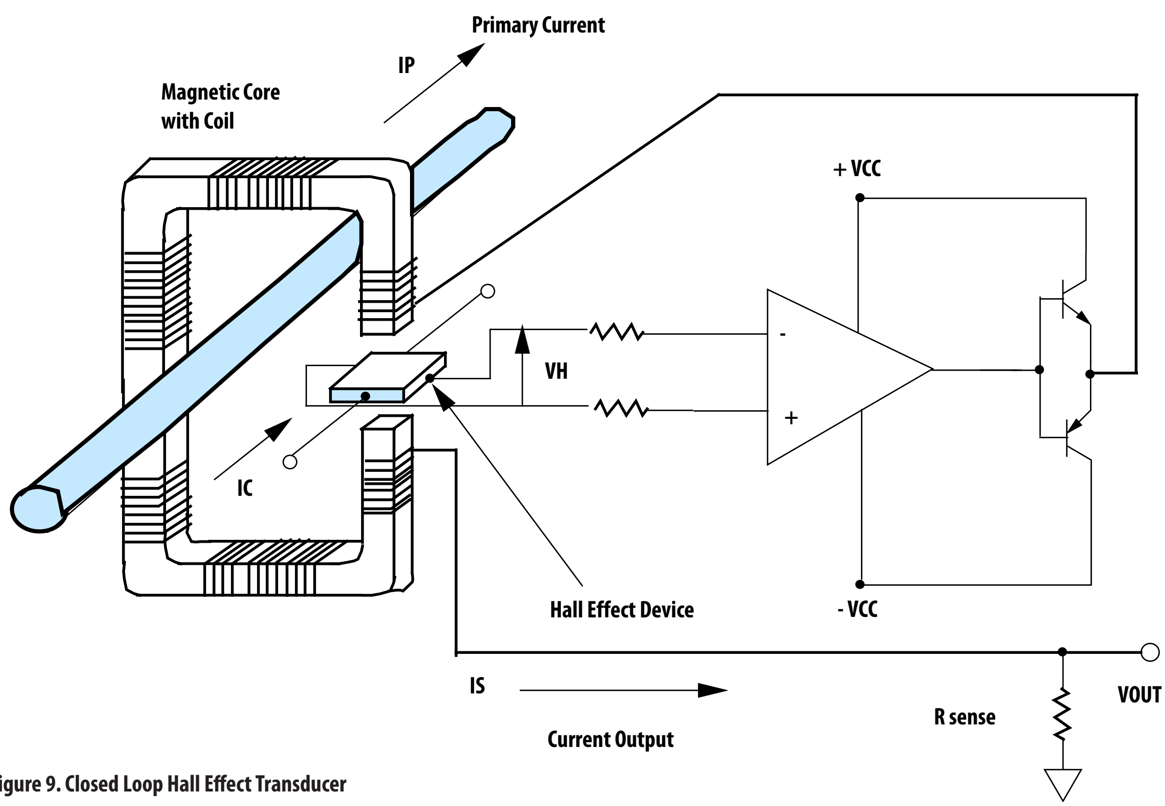

Figure 9. Closed Loop Hall Effect Transducer

than Closed Loop transducers. In terms of bandwidth, optoisolators have much higher bandwidth than Open Loop transducers, and are approximately equivalent or slower to the Closed Loop transducers. Temperature sensitivity for the isolation amplifiers depends on the temperature coefficient of an external shunt resistor, which is very low. Open and Closed Loop transducers have greater temperature sensitivity due to the magnetic core material and its associated hysteresis sensitivity. Overall, analog isolation amplifiers provide a more advantageous, precise, linear, and reliable solution than either the Open or Closed Loop Hall Effect transducers.

Conclusion

In this article we have shown that Avago Technologies provides a hermetic analog isolation amplifier family of products that includes the HCPL-7851, HCPL-785K, and the HCPL-7850. These devices are modern, state-of-the-art, reliable, sophisticated, and application specific analog optocouplers for various current or voltage sensing applications. The current sensing analog isolation amplifiers are particularly optimized for monitoring analog parameters in applications such as variable-speed motor control. In particular, these analog optocouplers are well suited and optimized to monitor DC bus voltages, AC motor phase currents, DC bus currents, and will also measure suitably converted heat sink temperatures of the IGBT or MOSFET. In addition, we have considered competitive methods of measuring currents, such as Hall Effect devices and current transformers. Based on performance criteria such as linearity, offsets and over temperature stability, we have shown that analog optoisolators are very competitive devices for current or voltage sensing analog applications. The analog optocouplers outperform competitive technologies for current or voltage measurements.

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