Designing with High Performance Hermetic Analog Isolation Amplifier, HCPL-7851

By Jamshed Namdar Khan
Optocoupler Applications Engineer
Avago Technologies

Abstract

Optocouplers today are a ubiquitous electronic component, found in almost any electrical equipment or in any industry segment. Since they were first introduced 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 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 to be 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. Same qualities such as small size, high reliability, and low power that makes optocouplers so popular with the digital designers, also makes them a favorite component with analog designers.

The HCPL-7851 Hermetic analog isolation amplifier is now 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 available from Avago Technologies, such as the HCPL-7851, HCPL-785K, or the HCPL-7850 will be presented. We will also compare and contrast the performance of these Hermetic linear amplifiers with competitive technologies such as the Hall Effect devices and the current transformers.

Optically Isolated Hermetic Analog Isolation Amplifier

The HCPL-7851 family of Hermetic Analog isolation amplifiers are designed to perform linear current sensing or voltage sensing at 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 at 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 ($\Sigma\Delta$) analog-to-digital converters which are optically coupled to an 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, in addition to providing 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 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 an analog output voltage proportional to the input voltage.

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

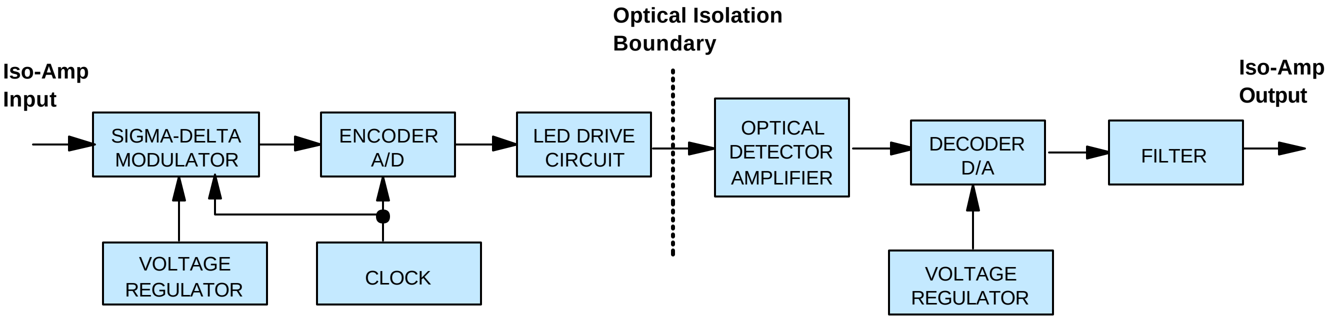

Figure 1. A Block Diagram of the Optically Isolated Analog Isolation Amplifier

In operation, the sigma-delta modulator converts the analog input signal into high-speed serial bit stream. The time average 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 analog signal, which is filtered to obtain the final output signal. Figure (2) shows a typical application circuit.

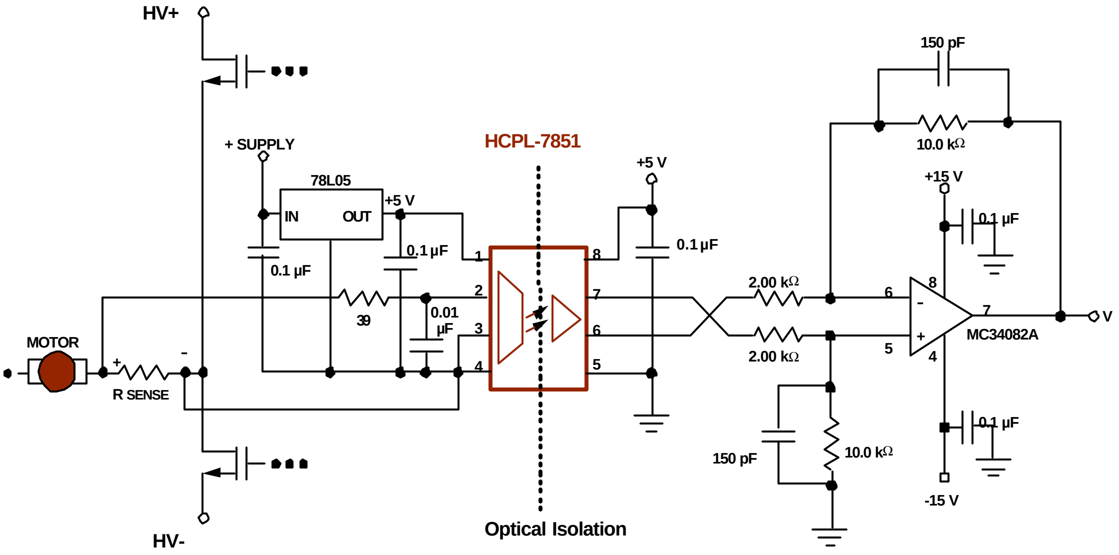

Figure 2. Typical Application Circuit Using the HCPL-7851 Iso-Amp for Current Sensing

The input is sensed across a precision, low resistance, low inductance, and low temperature coefficient shunt resistor. Low pass filter at the input (39 Ω resistor and 0.01 µ F capacitor) rejects high frequency noise components and is an anti-aliasing filter. 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 micro controller. The differential amplifier's bandwidth can be adjusted by the R-C filter in the feedback path; and adjusting this bandwidth to a minimum level also helps to reject and to minimize the noise at the output if necessary. Table (1) gives some comparative performance information between Avago Technologies Optical Isolation Amplifiers and Hall effect devices).

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
SD **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

Above comparison 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 smaller form factor, and are auto-insertible and surface mountable. These significant advantages allow the optically isolated analog amplifiers to be very competitive in low cost, reliable, accurate, and efficient motor designs.

Typical Application Circuits

The HCPL-7851 is designed for current sensing applications such as measuring bus currents, ac phase currents, and voltage sensing of the bus voltages, temperature sensing (voltage from 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) had shown the HCPL-7851 in a motor phase current sensing topology. In Figure (3) we show how a suitable voltage divider to step the voltage down at the input (such that the sensing voltage is below ±200 mV) allows one to measure the dc bus voltage or counter emf of brushless dc motors.

In this case, the constraint is that the value of R1 should be kept below 1kohm, such that input impedance of the HCPL-7851 (280 kohm) and input current (1 uA 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, as the voltage divider resistor will perform the same low pass filter function.

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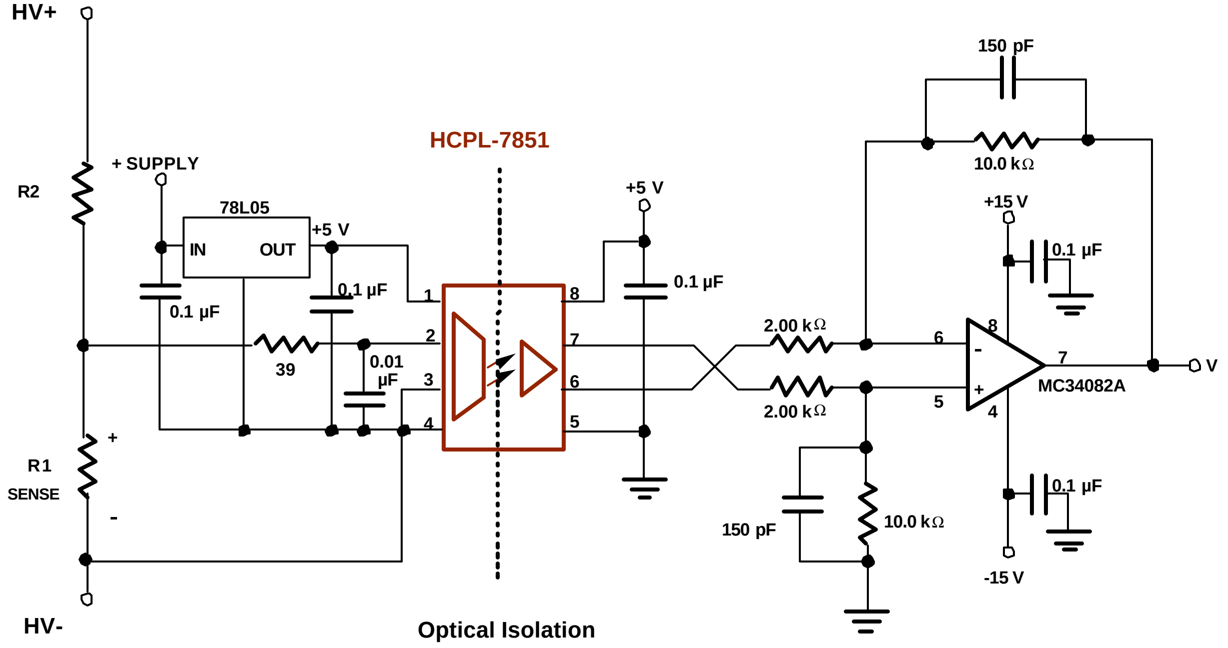

Figure 3. Typical Application Circuit Using the HCPL-7851 Iso-Amp for Voltage Sensing

The actual output of the HCPL-7851 analog Isolation amplifier at the 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. In addition, the post amplifier helps to establish a desired gain, and by selecting an appropriate low bandwidth of the differential amplifier it also helps to filter high frequency chopper noise.

The noise-shaping characteristics of the sigma-delta modulator results 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 Fgure (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 so selecting the resistor and capacitor values places the two poles 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.

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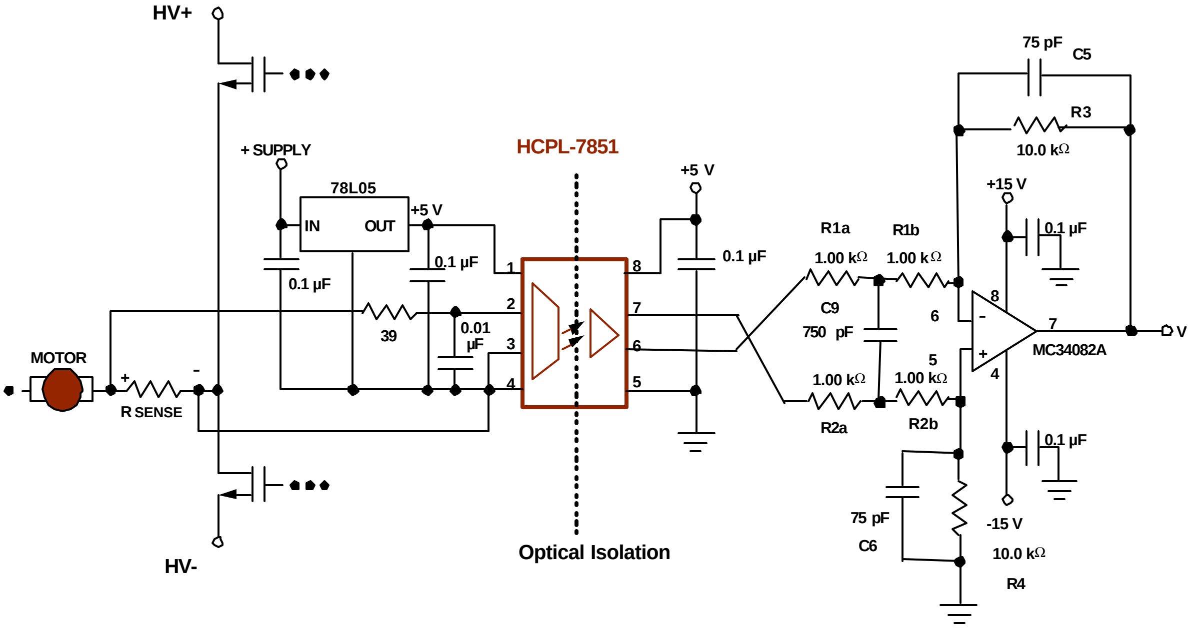

Figure 4. Post-Amplifier Circuit with second-Order Filter Response

The post-amplifier circuit can also be easily modified to allow for single supply operation. Figure (5) shows a schematic for a post-amplifier for use in 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.

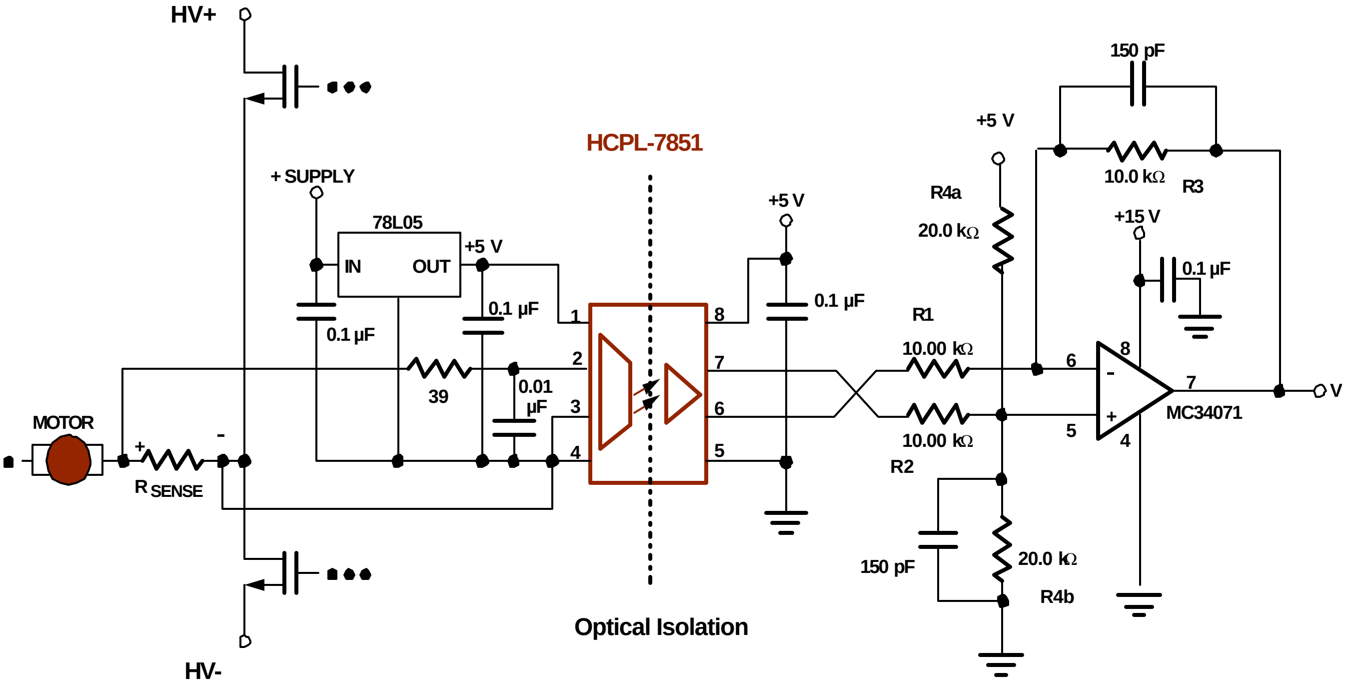

Figure 5. Single Supply Post Amplifier Circuit for HCPL-7851

Different Methods of Current Measurement

After the inverter gate driver requirements, second big challenge in motor control applications is how to measure motor phase current, bus currents, and other analog parameters like temperature or voltage. And 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 are employed that incorporate some type of isolation technique. These three methods are:

(1) Current transformers
(2) Hall Effect current Sensors
(3) Optically Isolated Analog Sensors

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

The current 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 in the secondary. 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).

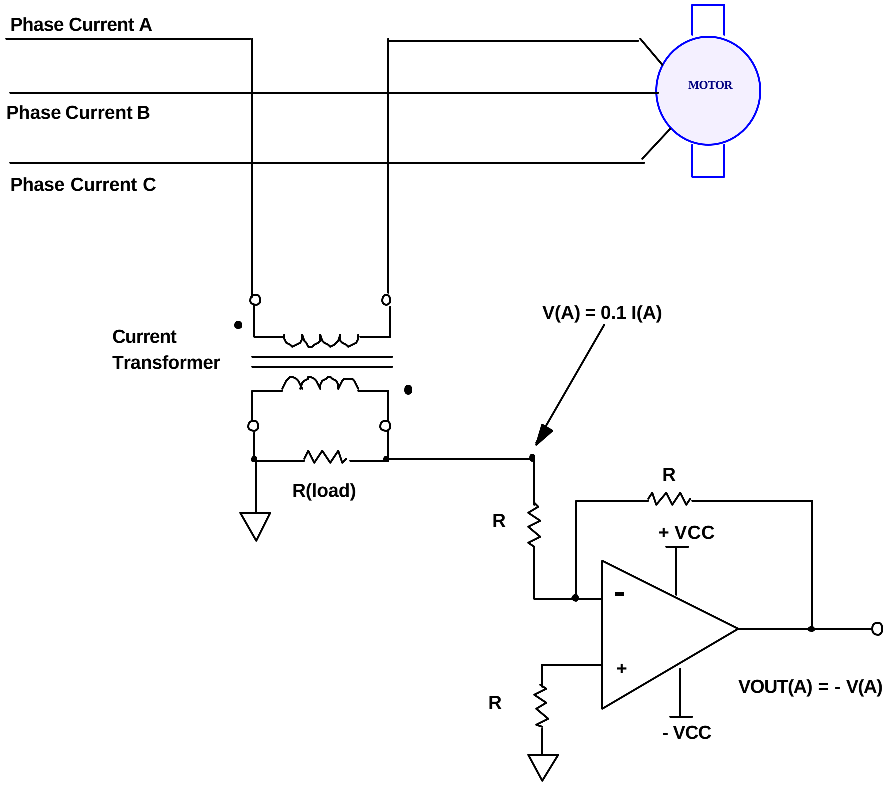

Figure 6. Using Current Transformers to Measure Motor Phase Currents

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

For analog sensing of high currents, for instance in monitoring the phase currents of a motor, one of the major competitive technologies, although an old one, facing Avago Technologies modern state of the art optically isolated Analog Isolation Amplifiers, are the Open and Closed Loop Hall Effect Transducers. 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, and will drift towards one side of the conductor and thus will generate a transverse Hall potential difference between two side 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, and is perpendicular to both the magnetic field and the direction of the current flow.

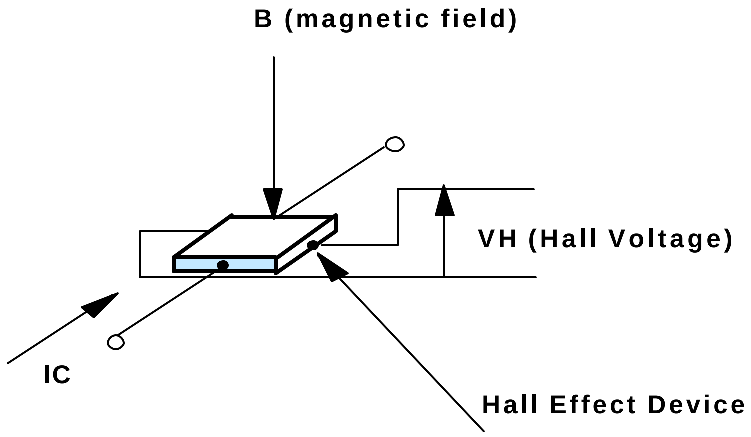

Figure 7. The Hall Effect Principle

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, and senses the magnetic field that is generated by this conductor. The magnetic field generated by a conductor 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 in any physical contact with any high voltage potential. Based on this isolation capability alone Hall Effect devices have a potential to compete with Avago Technologies current / voltage sensing analog isolation optoisolators. 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

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 which the semiconductor Hall element senses to produce a proportional voltage. Open loop transducers provide an output voltage proportional to the magnetic field. Thus, magnetic core hysteresis (i.e. Zero Offsets) is one of the problems associated with open loop Hall effect Transducers. Closed loop transducers, on the other hand, operate by generating a current that is fed back 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 thus are less sensitive to hyteresis. The closed Loop sensors are more accurate and linear, and consequently more costly than the open loop sensors.

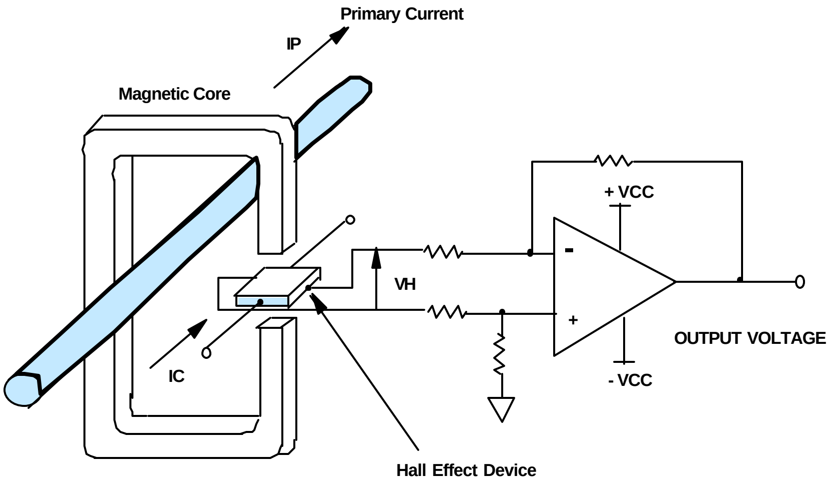

Figure 8. Open Loop Hall Effect Transducer

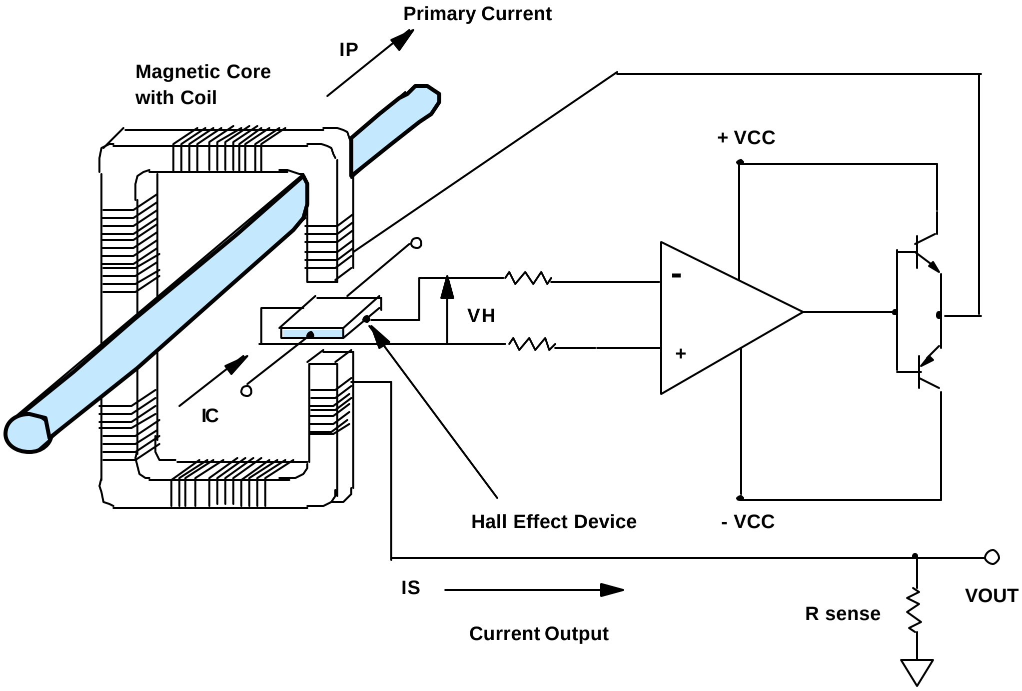

Figure 9. Closed Loop Hall Effect Transducer

Advantages of Hall effect devices are that they can measure both AC and DC currents, while providing galvanic isolation. Major disadvantage of Hall Effect 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 are equally important in decision making are response time/speed, bandwidth, temperature sensitivity, and linearity. Based on these parameters, optoisolators provide much better linearity, optoisolators are faster than open loop transducers, but perhaps equivalent or slower to 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 will depend 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. Thus, overall analog isolation amplifiers provide a more advantageous, precise, linear, and reliable solution than either open or closed loop Hall Effect transducers.

Conclusion

In this article we have shown that Avago Technologies provides Hermetic analog isolation amplifier family of products such as 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 applications. 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 temperature of the IGBT or MOSFET. In addition, we have considered competitive methods of measuring currents such as the Hall Effect devices and the current transformers. Based on performance criteria such as linearity, offsets, 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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