# Isolated Open Loop Current Sensing Using Hall Effect Technology in an Optimized Magnetic Circuit

Richard Dickinson & Shaun Milano

Allegro MicroSystems, Inc.
162 Pembroke Rd.
Concord NH, 03301 USA
Tel: 001 (603) 228-5533
Fax: 001 (603) 224-2466

## Abstract:

With the expected arrival of a 42V parallel bus power supply aboard automobiles and new energy efficiency standards being imposed on most household appliances, there is a growing need for current sensing as a means of monitoring and controlling power consumption.

There are three rival technologies that are typically used for measuring current: sense resistors, Hall effect sensors and current transformers. Each have attributes that differentiate them on a cost versus performance scale. Galvanic isolation, ease of implementation, robustness and low cost are a few attributes that users demand when choosing a current sensor.

Galvanic isolation is needed to protect the sensing device from potentially damaging high power signals (over-current spikes) and to minimize the power dissipated (and heat generated) by sense resistors. Because Hall effect sensors measure the magnetic field strength in close proximity to the current conductor, they can be separated by a few millimeters from the current signal, providing several kilovolts of isolation. Other open loop Hall effect current sensor designs internalize the current carrying conductor, allowing the user to optimize the current sensor package's size and thermal characteristics.

While closed loop sensing can provide excellent accuracy, size and cost prohibit the use of these types of transducers in many applications. Open loop sensors usually have a more limited range of linearity and cannot compensate for offset and residual field errors. However, magnetic circuits and the linear Hall effect IC can be designed to reduce these types of errors without the external control circuitry that is typically required by closed loop systems.

This paper will explore magnetic circuit design, IC circuit designs, and integrated packaging techniques that attempt to minimize the errors associated with open circuit designs in order to achieve a sensor with accuracy equivalent to that of sense resistors, but without the isolation tradeoff.

## Introduction

Applications requiring current sensing are becoming ubiquitous, from battery management systems aboard automobiles to dc motor controllers within household appliances. While sense resistors may have previously represented the state of the art in current sensing, the need for safe, isolated detection of electrical current has spurred the development of non-intrusive current sensing methods and devices. Among a handful of alternative current-sensing methods, Hall-Effect sensors may be implemented in high volume with relatively low cost for many of these applications.

## Current Sensing Technology Overview

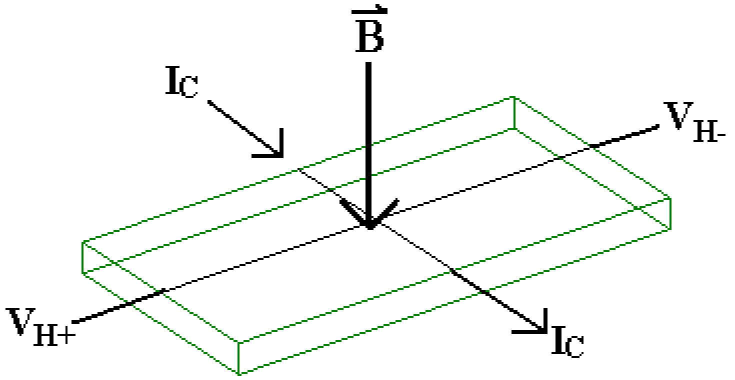
There are three technologies that are typically used for measuring current: sense resistors, current transformers and Hall effect sensors.

Sense resistors are simply a resistor placed in series with the load. By ohms law, the voltage drop across the device is proportional to the current. For low currents, these provide very accurate measurement given the resistance value has a tight tolerance. Although sense resistors with high performance thermal packages have been developed for larger currents, they still result in insertion loss. In addition, they do not provide a measurement isolated from transient voltage potentials on the load. Sense resistors also require other circuitry such as instrumentation amplifiers to generate a distinguishable signal.

Current transformers are relatively simple to implement and are passive devices that do not require driving circuitry to operate. The primary current (AC) will generate a magnetic field that is coupled into a secondary coil by Faraday's Law. The magnitude of the secondary current is proportional to the number of turns in the coil, which is typically as high as >1000. The secondary current is then sensed through a sense resistor to convert the output into a voltage.

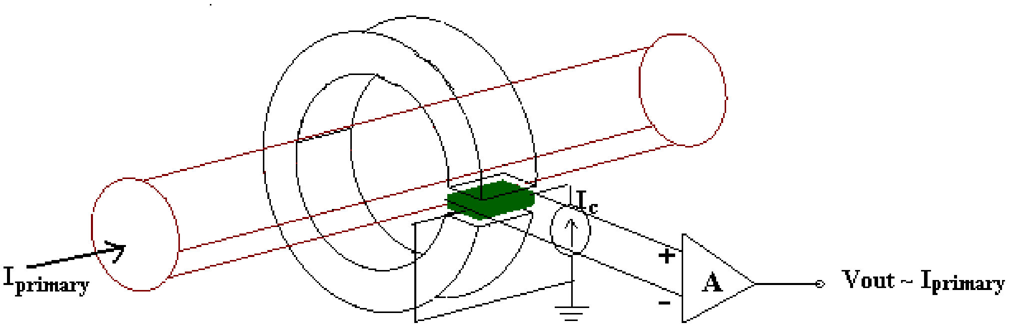
There are two techniques for sensing current using Hall effect devices. According to the Hall effect, a magnetic field passing through a semiconductor resistor will generate a differential voltage proportional to the field (figure 1).

**Figure 1: Representation of the Hall effect and its electrical parameters**



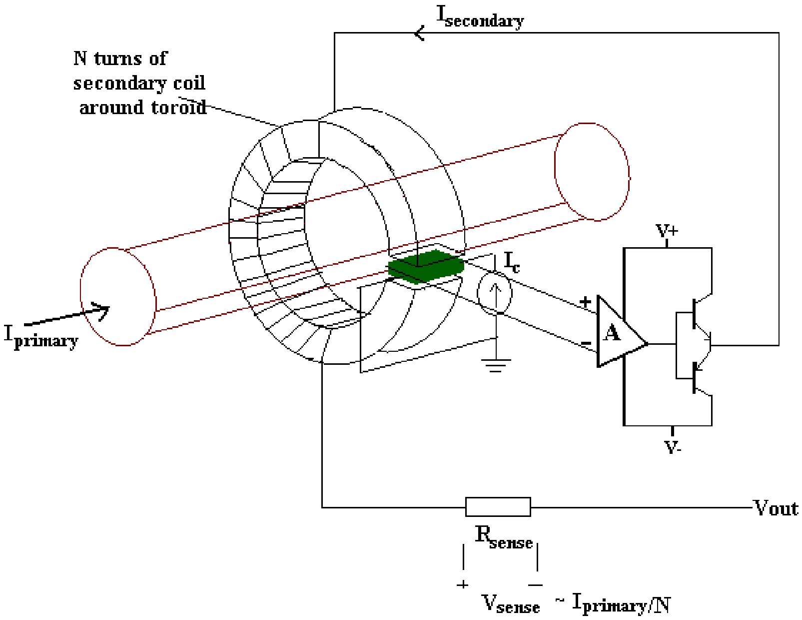
Concentric magnetic field lines are generated around a current carrying conductor. Approximating the primary current conductor as infinitely long, the magnetic field strength may be defined $B = \mu_0 I/2pr$, where $\mu_0$ is the permeability of free space, I is the current and r is the distance from the center of the current conductor. In order to induce a larger signal out of the Hall element; the current conductor may be wrapped around a slotted ferrous toroid N number of times, such that $B = \mu_0 NI/ 2pr$. In an open loop topology, the Hall element output is simply amplified and the output is read as a voltage that represents the measured current through a scaling factor as depicted in figure 2.

**Figure 2: Basic Topology of Open Loop Hall Effect Current Sensor**



In a closed loop topology, the output of the Hall element drives a secondary coil that will generate a magnetic field to cancel the primary current field. The secondary current, scaled proportional to the primary current by the secondary coil ratio, can then be measured as voltage across a sense resistor.

**Figure 3: Basic Topology of Closed Loop Hall Effect Current Sensor**



By keeping the resultant field at zero, the errors associated with offset drift, sensitivity drift and saturation of the magnetic core will also be effectively canceled. Closed-loop Hall effect current sensors also provide the fastest response times. However, with a secondary coil that may be needed to drive up to several milli-amps of current, power consumption is much higher in closed loop Hall effect devices than open loop topologies. The closed loop configuration also limits the magnitude of the current that can be sensed since the device may only drive a finite amount of compensation current. Figure 4 provides a simple comparison of different current sensing techniques.

**Figure 4: Summary of current sensing techniques and attribute comparison**[i]

| **Current-sensing Technique** | **Accuracy** | **Galvanic Isolation** | **Power dissipation**[1] | **Relative Cost**[2] | **Typical current ranges** |
|---|---|---|---|---|---|
| Sense resistor | >95% | None | High | Low | <20A, DC-100kHz |
| Transformer | ~95 | Yes | Moderate | Med. | Up to 1000A, AC |
| Open loop Hall effect sensor | 90-95% | Yes | Low | Med. | Up to 1000A, DC-20kHz |
| Closed loop Hall effect sensor | >95% | Yes | Moderate-High | High | <500A, DC-150kHz |

## Design Considerations for Open Loop Hall Effect Current Sensors

The measurable current range, the output linearity and measurement accuracy are attributes that influence the design of a current sensor package. The linearity and accuracy are determined through the magnetic circuit that couples the primary current to the magnetic field sensed by the Hall element. Offsets and inaccuracy introduced in the magnetic circuit can often be minimized in the linear Hall effect IC design.

The measurable current range often dictates the size of an open loop current sensor. For current levels less than100A, a reduced package size can be achieved by internalizing the primary conductor. Combining the Hall effect sensor, flux concentrator and primary conductor into a single assembly for PCB installation opens up applications that previously relied on sense resistors. For current levels of100A and higher, any discontinuity in the bus-bar could present reliability risks. Therefore, rather than soldering or welding on a current sensor, end users desire a package that can be clamped/installed around the conductor. If the primary conductor is internalized into the package the design objective is to minimize the insertion losses. Any power dissipated through the primary conductor will generate heat in close proximity to the Hall effect IC and will be seen as a temperature coefficient. Figure 5 provides an example of a proposed 100A full-scale current sensor package integrating the primary conductor.

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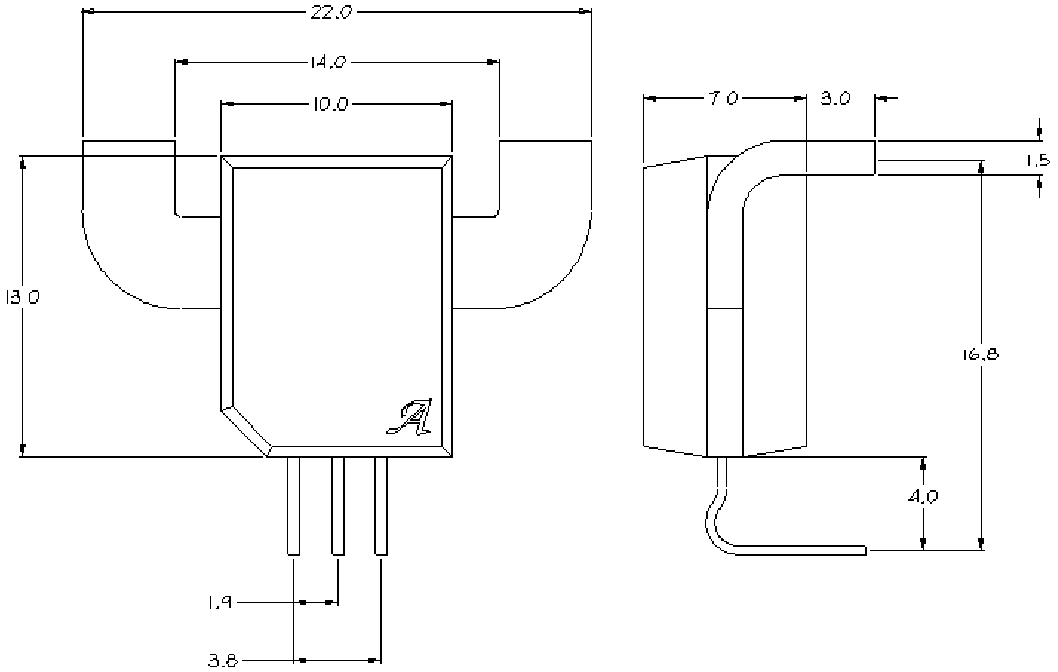
[1] Including power loss through primary current carrying conductor & power consumed by device

[2] Estimated, including cost of auxillary circuitry needed to implement device in operating environment

**Figure 5: Open loop Hall effect current sensor integrating primary conductor**

Open loop Hall effect current sensor package under development at Allegro Microsystems, Inc.



In addition to the tradeoff between insertion losses and size for a given current range, there is also a relationship between the flux concentrator and the measurable current range. The magnetic field sensed by the Hall effect transducer is proportional to the product of the primary current and a gain factor related to a flux concentrator. In order to keep a magnetic circuit in its linear region for a given current, the dimensions of the flux concentrator and its effective magnetic path length, must be appropriately scaled. A typical design rule is to use a toroid with a cross sectional area that is twice as large as the area seen in the gap where the sensing element sits. Choosing a magnetic flux concentrator material with the appropriate effective permeability can be determined as a function of the primary current range,

$$\mu_e = Bl_e/0.4pNI$$

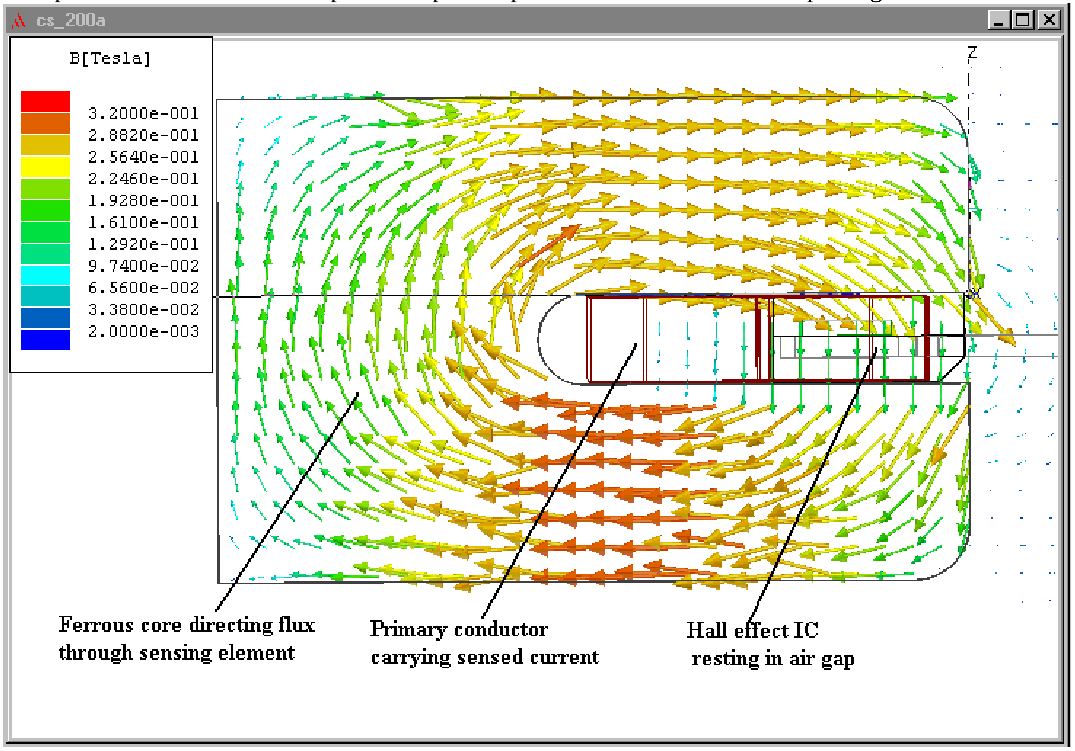
where N is the number of turns (typically 1), $l_e$ is the effective path length and I is the full scale current. The effective path length is

$$l_g = l_e(1/\mu_e - 1/\mu_I)(0.397)$$

As the primary current range increases, it is often necessary to increase the air gap size to ensure a linear output. A material commonly used as a flux concentrator is powdered iron, having magnetic permeability 2000 to 5000 times greater than air. Figure 6 provides a diagram of an open loop Hall effect sensor package, with a ferrous core concentrating flux onto a Hall effect IC.

**Figure 6: Open loop Hall effect current sensor magnetic circuit topology**

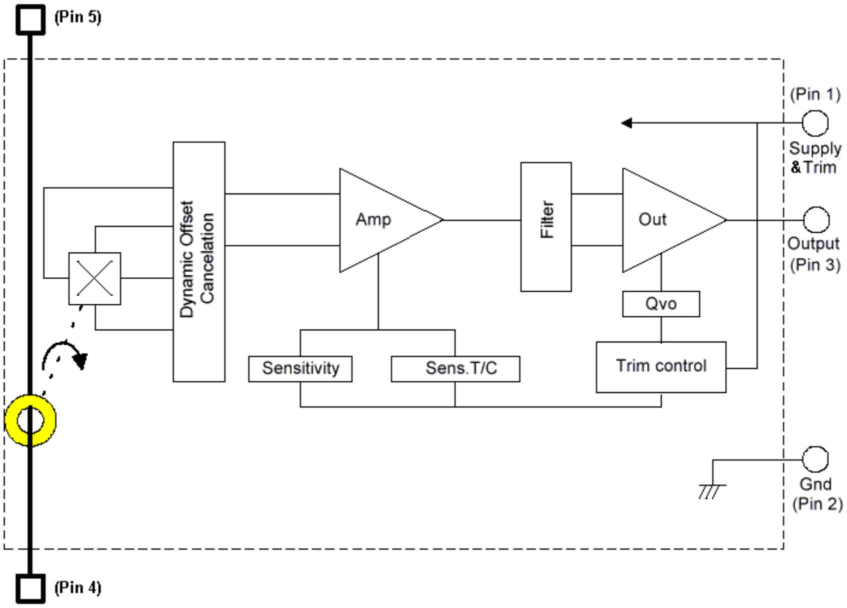
Computer simulation screen capture of open loop Hall effect current sensor package



Another property of the magnetic flux concentrator that affects the linearity of the open loop output is hysteresis. In addition to having high permeability, ferromagnetic materials tend to retain some magnetic induction after an applied field is removed. This leads to inaccuracy at low current levels. In order to minimize this error, it is best to use materials with low magnetic remenance, $B_r$ and low magnetic coercivity, $H_c$. Soft ferrites and round loop NiFe alloys provide the closest balance between high permeability and low hysteresis. Another way to minimize hysteresis-offset error is to scale the toroid such that the entire core will not saturate until current levels well beyond the intended full- scale current.

The voltage generated on the Hall element is filtered and amplified into an output voltage proportional to the sensed primary current. Techniques such as chopper stabilization, (alternating the Vcc and sense terminals on the Hall element) help to minimize offset voltages and zero current error. Factory trimming of resistors within the IC adjusts the gain so that the linear region of the amplifier matches the linear region of the magnetic circuit. The block diagram in Figure 7 summarizes the functionality provided by a typical linear Hall effect sensor.

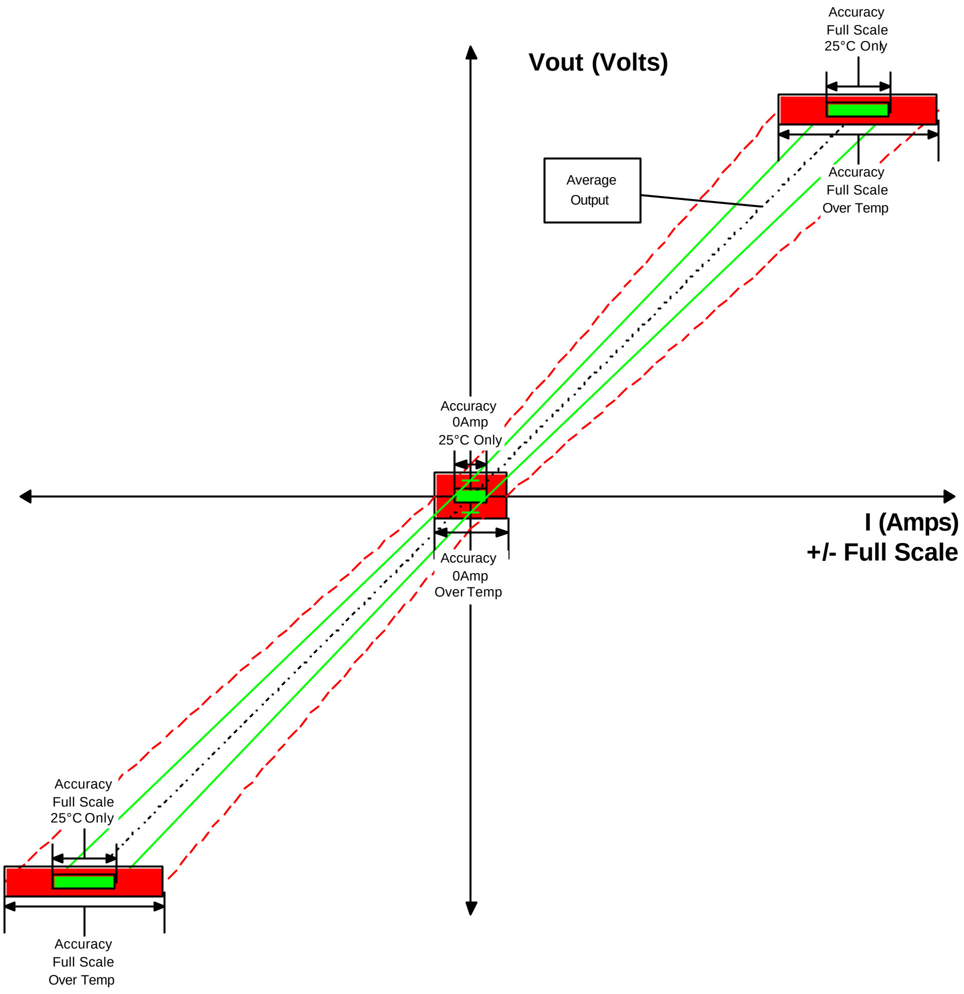
**Figure 7: Functionality of linear Hall effect sensor used in Allegro ACS750KCA-100 Current sensor**



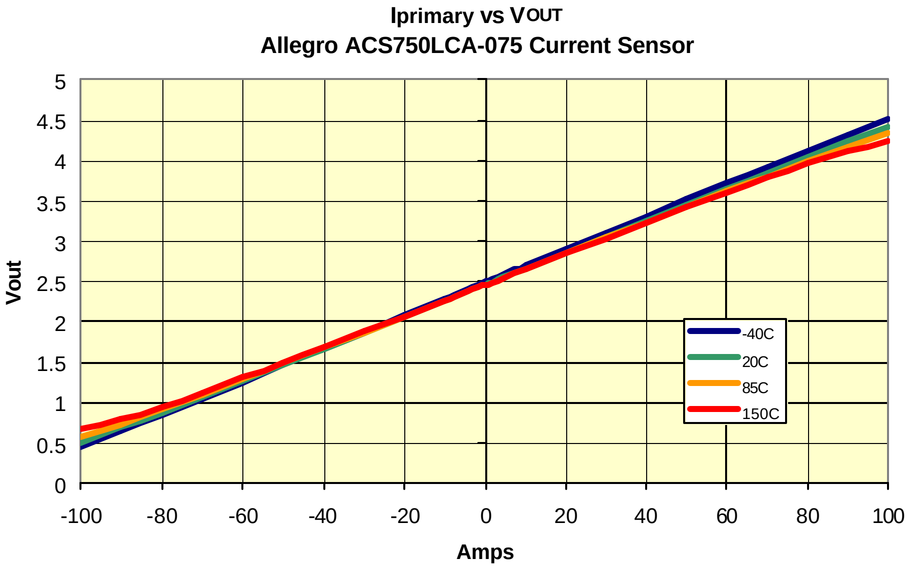
Unfortunately, the linear Hall effect sensor cannot compensate and remove all sources of error in an open loop current sensor. At zero amps, magnetic hysteresis and temperature drift of the quiescent voltage will act as a source of error. At full scale current, the non-linearity of the flux concentrator, the resolution of the sensitivity trim and temperature coefficient from the packaged device will also create inaccuracy. Transfer curves of Iprimary versus Vout are presented in figure 8.

## Figure 8a: Typical $I_{primary}$ versus Linear Hall-Effect Transducer Output

Across full-scale and current operating conditions



## Figure 8b: Typical I<sub>primary</sub> versus Vout, Allegro ACS750LCA-075



The dynamic accuracy of a current sensor is another important attribute in applications in which the primary current is a transient signal. Although open loop Hall effect sensors are frequency limited compared to sense resistors and closed loop transducer topologies, there are design techniques that can improve their performance. As with many other performance traits, the composition of the flux concentrator is a relevant factor. According to Lenz' Law, dB/dt = µdI/dt, any change in magnetic field will induce eddy currents which produce magnetic fields opposite to the externally applied field. Any change in magnetic field will induce in the material, "a voltage that is in the opposite direction to the voltage producing the magnetizing current and the alternating magnetic field. The induced voltage will set up circular currents in the material which produce magnetic fields opposite to the original magnetic field."[ii] The power losses from eddy currents in a given material is expressed by

$$P_e = B_m^2 f^2 d^2/?$$

Where $B_m$ is the maximum magnetic induction, f is the frequency, d is the smallest dimension transverse to flux and ? is the material resistivity.

Since ferrites typically have high resistance, power losses are not a concern through the frequency range that open loop Hall effect current sensors operate. However, other core materials, such as steel alloys, are low resistance mediums may suffer significantly from eddy current losses. Fortunately, without significantly altering the magnetic reluctance, breaking a core into several thin layers (such that the value of d in the aforementioned equation approaches zero) can increase the transverse electrical resistance by an order of magnitude. For this reason, laminated cores are often used in current sensor packages requiring some degree of dynamic accuracy.

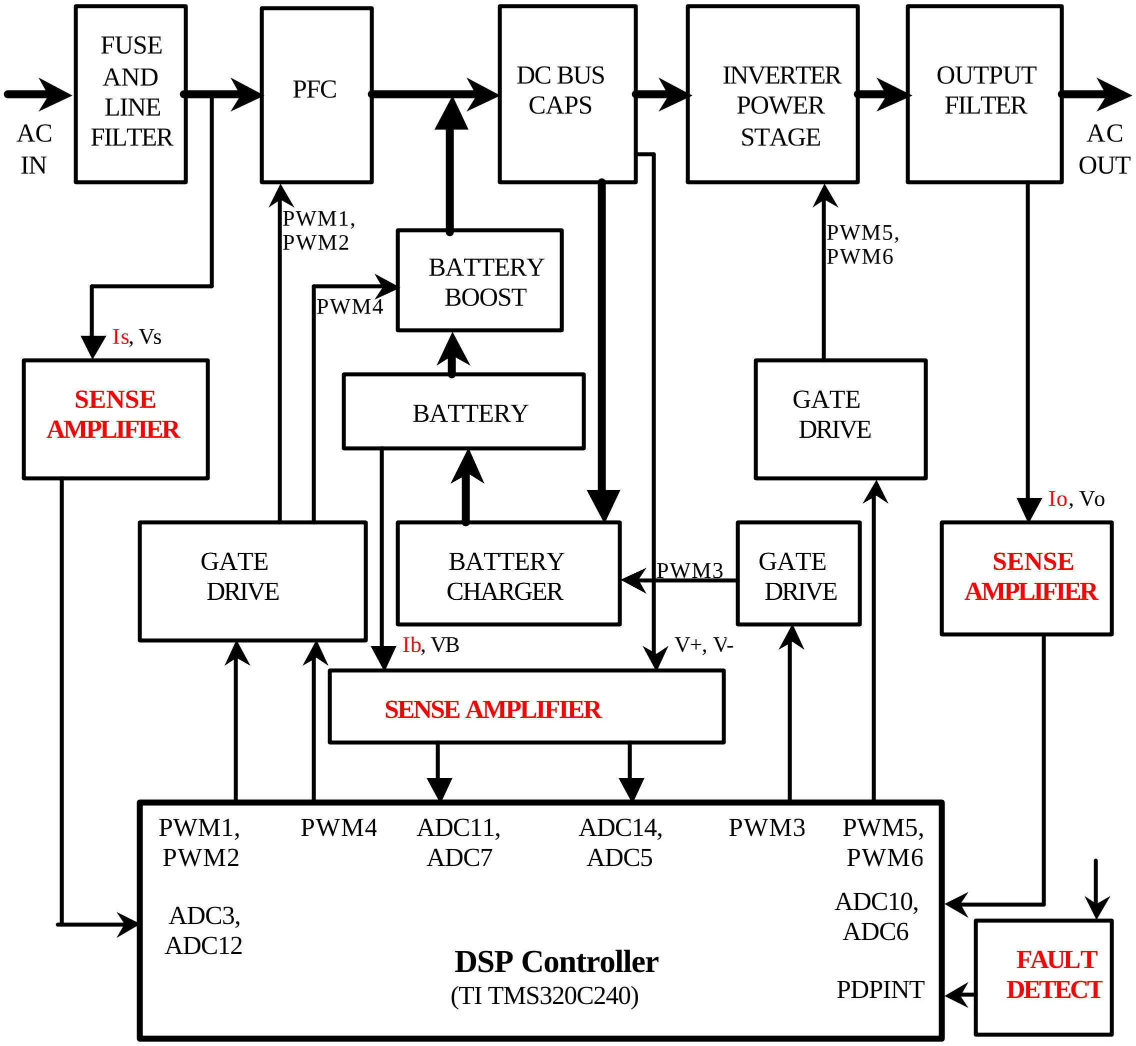
## Overview of Current Sensing Applications

Open-loop Hall effect current sensors are most appropriate for applications in which galvanic isolation is absolutely necessary. Battery management circuits running directly off of automobile batteries is one instance when isolating the primary current from the supply powering the sensing device is needed.

Monitoring electrical current flow is an excellent method of gauging the performance of motor-driven devices (such as fans, pumps, and chillers) controlled by a building automation system (BAS). The torque supplied by a shunt motor is proportional to the armature current, in which $T = k? I_{a.}$ The speed of a dc motor can also be monitored and controlled through the current driving it, in which $S = [Va – (IR)]/ k?$ . Solid-state current switches can be used to provide a contact closure to show that a motor is running, but many times it is helpful to be able to accurately measure current as a diagnostic tool. The power consumption through an appliance can provide insight into any component degradation or failure. For example, lower than normal current flow may indicate problems such as a broken coupling on a pump, a broken or loose belt on a fan, a dirty strainer on a pump application, or a dirty filter. A higher than normal current flow may indicate bad or worn bearings, or belts that misaligned on motor loads. A monitored current can also be used to determine the percent loading of a chiller.[iii]

Uninterruptible Power Supplies (UPS) are appliances that require current sensing applications. Figure 9 provides a block diagram for one-type of UPS configuration, an on-line or inverter-preferred topology that provides a regulated sinusoidal output under any line condition.[iv] Regardless of the configuration, all UPS devices require fault protection and current level measurement as inputs to their control circuitry.

**Figure 9: Block diagram of UPS highlighting current sensing applications within system**[v]



## Conclusion

The number of applications requiring current sensing is continuing to expand. Depending on the demands of an application such as the primary current range, the desired steady state and dynamic accuracy and cost pressures, a number of different techniques for sensing current are available. By providing galvanic isolation and a relatively low cost solution, open loop Hall effect sensors are well positioned to meet the needs of many of these applications.

## Sources consulted

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[i] Paul Emerald, "'Non-Intrusive' Hall-Effect Current-Sensing Techniques Provide Safe, Reliable Detection and Protection for Power Electronics," Allegro Microsystems, Inc. Technical Paper STP 98-1, page 2.

[ii] Alex Goldman, Handbook of Modern Ferromagnetic materials , Boston: Kluwer Academic Publishers, 1999, 59.

[iii] "Using Current Monitoring for Load Analysis," Kele Technical Reference PM6, accessed 062802, http://www.kele.com/Tech/Monitor/Power/TRefPM6.html.

[iv] Shamin Choudhury, "Implementing Triple Conversion Single Phase On-line UPS using TMS320C240," Texas Instruments Application Report, 6-30-1999, page 2, accessed 062702, http://wwws.ti.com/sc/psheets/spra589a/spra589a.pdf

[v] Diagram adapted and modified from Figure 2 of Shamin Choudbury's Texas Instruments Application Report "Implementing Triple Conversion Single Phase On-line UPS using TMS320C240."