

## ***‘NON-INTRUSIVE’ HALL-EFFECT CURRENT-SENSING TECHNIQUES PROVIDE SAFE, RELIABLE DETECTION and PROTECTION for POWER ELECTRONICS***

by Paul Emerald

### **Abstract**

As systems extend and expand the exploitation of the latest power semiconductors (IGBTs, MCTs, etc.) that manifest the very relentless advance in power output limits, a prerequisite (and parallel) demand for sensing these escalating current levels is (increasingly) very apparent. Hall-effect ICs provide ‘non-intrusive’ current sensing techniques and safe, isolated detection of high current levels without dissipating the sizable amounts of wasted power (and the resultant heating) associated with resistive current-sensing methods. Further, Hall-effect current sensing provides electrical isolation between the current-carrying conductor; hence, a safe environment for circuitry, operators, etc.

The proliferating current-sensing applications for Hall-effect sensors continue; become even more diverse; plus expand and grow as other designers endeavor to protect systems, create more reliable ‘bulletproof’ equipment, and reconcile any safety issues. The prime applications for cost-effective Hall-effect sensors for current sensing include:

- Current Imbalance
- Current Monitoring
- Operator/User Safety and Security
- Overcurrent Detection/System Protection
- System Diagnosis and Fault Detection
- Test and Measurement

### **Background and Introduction**

The discovery of the Hall-effect originated back in 1879; however, any meaningful application of this Edwin H. Hall finding awaited semiconductor integration that first occurred in the late 1960s. Subsequently, further advances (particularly those of the 1990s) have evolved further, more fully functional integration plus an expanding series of application-specific Hall sensor types. Yet the relentless progress of magnetic sensor electronics continues to proliferate an increasing demand for low-cost, reliable, and ‘non-contact’ Hall-effect circuitry for sensing/detecting motion, direction, position, and measuring/monitoring current.

Hall-effect sensor ICs (especially the ratiometric linear types) are superb devices for ‘open-loop’ current-sensing designs.

However, there are limits to the operational range, accuracy and precision, frequency response, etc. that may be realized. Because many prospective users are ignorant of and/or oblivious to either the benefits or shortcomings of current-sensing techniques using Hall-effect ICs, this paper endeavors to provide a comprehensive discussion of the essential, basic techniques of ‘non-intrusive’ current sensing with silicon Hall-effect devices (HEDs) now available.

Most Hall-effect current-sensing requirements do not develop adequate magnetic fields without the use of a slotted toroid to concentrate (and focus) the induced flux field. Low-to-modest currents ( $\approx 15$  amperes) require winding sufficient turns on the slotted toroid (core) to induce usable flux strength and develop a suitable signal voltage. A higher current level ( $>15$  to 20 amperes) induces field intensities that allow passing the current-carrying conductor straight through the center of the toroid (no turns necessary at these higher currents).

Designs requiring a broad (or continuous) current range mandate utilizing linear Hall-effect sensor ICs. However, overcurrent protection and/or fault detection designs can be accommodated by digital HEDs. Examples and particulars of the essentials of current-sensing techniques, device parameters, temperature stability, and other relevant concerns of Hall-effect current sensing are covered in this treatise on HEDs for sensing ac and dc currents.

### **Rival, Competing Technologies**

Although there are many current-sensing methods, only three are commonplace in low-cost, volume applications. The others are expensive laboratory systems, emerging technologies (magnetoresistive is an example), or seldom used. The commonly used techniques include: (1) resistive, (2) Hall-effect, and (3) current transformers.

Resistive sensing is very widely used, low-cost, and easily understood. However, the shortcomings are its insertion loss (heating and wasted power) and lack of isolation. Also, the series inductance of many power resistors constrains the frequency range with low-cost components; hence, resistive sensing is classed as either a dc or ac application per the

# 'NON-INTRUSIVE' HALL-EFFECT CURRENT-SENSING TECHNIQUES

categories in Table 1. Low inductance, high-power resistors for high frequency are more expensive, but allow operation beyond 500 kHz. Further, signal amplification is (usually) required with resistive current-sensing techniques (either a comparator or operational amplifier is needed).

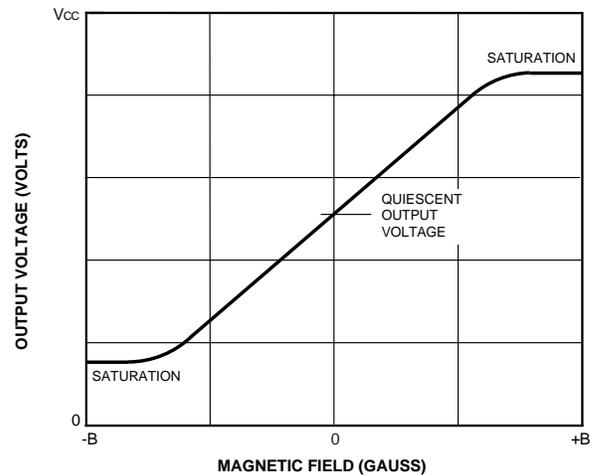
Hall-effect sensor ICs (open- and closed-loop) represent the next tier of commonplace solutions. Insertion loss (and related heating, etc.) are not an obstacle. However, frequency range, cost, dc offset, and external power represent the potential disadvantages of Hall-effect IC technology when compared to the resistive-sensing methods.

Current transformers close out the last low-cost technology, and (as the term transformer should imply) are only useful with alternating currents. Most low-cost current transformers are designed for narrow frequency ranges, are more expensive than resistive or Hall-effect, and cannot be used for dc currents. However, current transformers avoid insertion loss, offer electrical isolation, do not require external power, and exhibit no offset voltage at the zero (null) current level.

Because this treatise focuses upon Hall-effect ICs, understanding the elements of linear, ratiometric HEDs is imperative to open-loop current sensing.

## Linear Hall-Effect Sensor ICs

As the term implies, linear Hall sensors develop an output signal that is proportional to the applied magnetic field. Normally, in any current-sensing application, this flux field is focused by a 'slotted' toriod to develop an adequate field intensity, and this magnetic field is induced by current flowing in a conductor. A 'classical' transfer curve for a ratiometric linear is illustrated in Figure 1. Note that, at each extreme of its range, the output saturates.



Dwg. PRE-507

Figure 1: Linear Hall Sensor Transfer Curve

Table 1: Commonplace, Inexpensive Current-Sensing Techniques

Widely Used Sensors	Insertion Loss	Circuit Isolation	External Power	Frequency Range	Offset (Zero I)	Accuracy (Est. *)	Rel. Cost
Resistive dc	Yes	None	None	<100 kHz	None	>99%	Lowest
ac	Yes	None	None	>500 kHz	None	>99%	Low
Hall-Effect Open-Loop	None	Yes	Yes	≥20 kHz†	Yes	90-95%	Med
Closed-Loop	None	Yes	Yes	≥150 kHz	None	>95%	High
Current Transformers	Yes (ac)	Yes	None	Constant‡	None	>95%§	Highest

\* (Estimated): accuracy and precision very dependent upon design implementation.

† 20 kHz to 25 kHz represents (typical) usable frequency limit.

‡ Current transformers (usually) designed for limited frequency range.

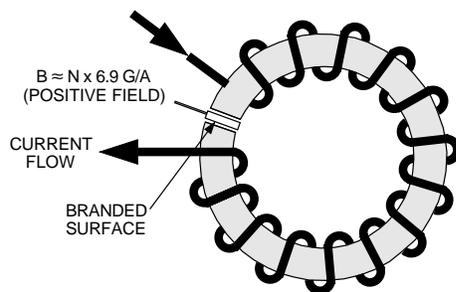
§ Accuracy very contingent upon component and cost factors.

# 'NON-INTRUSIVE' HALL-EFFECT CURRENT-SENSING TECHNIQUES

Most recent linear Hall ICs provide a ratiometric output voltage. The quiescent (i.e., null) voltage is (nominally) 50% of the applied, stable supply. This quiescent output voltage signal equates to no applied magnetic field and, for current sensing, is equivalent to zero current flow. A south polarity field induces a positive voltage transition (toward  $V_{CC}$ ), and a north polarity field results in a transition toward ground (0 V). Output saturation voltages are (typically) 0.3 V (high/sourcing) and 0.2 V (low/sinking) and are measured at  $\pm 1$  mA.

Each linear Hall-effect IC integrates a sensitive Hall element (also called a 'plate'), a low-noise (bipolar) amplifier, and sink/source output stage. Any systems problems associated with low-level signals and noise are minimized by the monolithic integration of magnetic sensor, amplifier, output, and allied signal processing circuitry.

Existing very stable, linear HEDs exploit dynamic quadrature offset cancellation circuitry and utilize electronic switching to change the current path in the sensor element. Switching the current paths, from  $0^\circ$  to  $90^\circ$ , at a high repetition rate offers a new answer to the (intrinsic) dc offset that has long plagued linear sensor operation and stability.



**Figure 2: Current Sensing with Gapped Toroid**

Sample-and-hold circuitry and a low-pass filter are exploited to properly 'recondition' the internal dynamic signals of these innovative linear HEDs.

Linear Hall-effect ICs can detect small changes in flux intensity, and are (generally) more useful than digital Hall ICs for current sensing. Linear HEDs are often capacitively coupled to op amps, or dc connected to comparators, to attain system design objectives. Also, microcontrollers ( $\mu$ Cs) and microprocessors ( $\mu$ Pcs) are being exploited to detect small signal changes from linear Hall ICs, and are very suitable (with proper software) of sensing/measuring either ac or dc currents.

## Inducing a Magnetic Field

As mentioned, Hall-effect current sensing usually necessitates the use of a slotted toroid (made of ferrous materials). The toroid both concentrates and focuses an induced magnetic field toward the location of the Hall-effect element within the IC package. Figure 2 typifies a classic example of 'non-intrusive' current sensing exploiting a slotted toroid. The conductor current flows through the turns wound upon the toroid, and the induced flux field is concentrated on the sensor in the gap (or slot) in the toroid. Usually, this gap is made to closely match the Hall IC package thickness (approx. 0.060" or 1.52 mm), and this provides optimal magnetic coupling. The current flow (with this 'tight' magnetic coupling) induces a flux intensity per the formula

$$B \text{ (gauss)} \approx N \text{ (turns)} \times 6.9 \text{ gauss/ampere}$$

Note — 6.9 gauss/ampere is updated from the earlier 6 G/A.

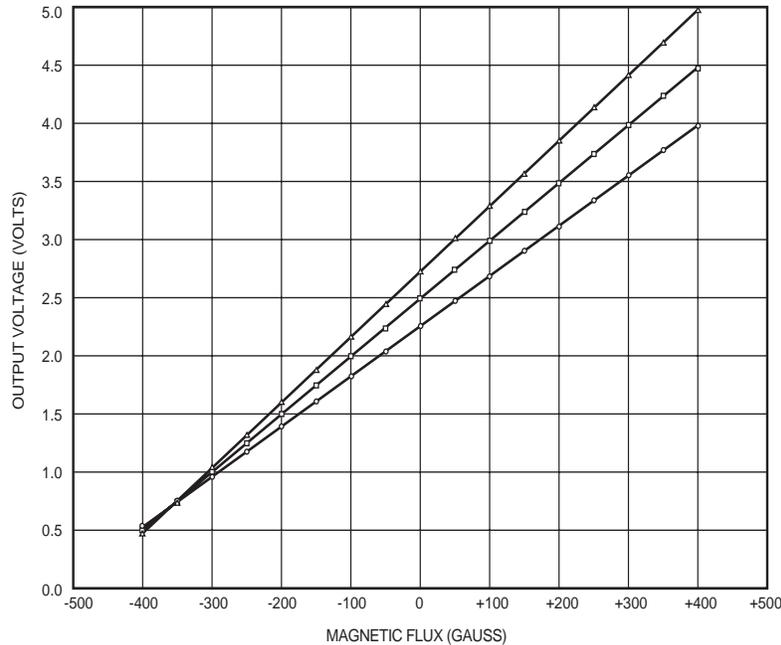
Widening the (gap) slot reduces the flux coupling and can increase the upper current limit, which is predicated upon the Hall sensor sensitivity (more to follow). However, decoupling the induced field to extend the maximum current limit may affect linearity, usable range, etc. This 'loose' coupling is under evaluation, but not yet complete; hence, no new formulas for magnetic flux and conductor current (and larger gaps) have been documented.

## 'Calibrated' Ratiometric Linear HEDs

The two newest linear Hall sensors, with dynamic dc offset cancellation, provide a cornerstone for a discourse on linear ratiometric HEDs and current sensing. The A3515 plot (Figure 3) and related data (Table 2) record the vital characteristics of the most sensitive linear HED; its counterpart, the A3516, properties are in Figure 4 and Table 3.

Presently, though seldom sold, 'calibrated' linear Hall-effect ICs are superb circuits for setting up and measuring system magnetic parameters, and represent an excellent entry to the performance, characteristics, and limitations of ratiometric ICs.

# 'NON-INTRUSIVE' HALL-EFFECT CURRENT-SENSING TECHNIQUES



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**Figure 3: Linear, Ratiometric Hall-Effect Sensor Characteristics (A3515 Output)**

**Table 2: Linear, Ratiometric Hall-Effect Sensor Characteristics Measurement Data (A3515)**

	Measured Over $\pm 250$ Gauss				
	$V_{CC}$ (Volts)	$V_{OQ}$ (Volts)	Sensitivity (mV/G)	Non-Linearity (%)	Symmetry (%)
○	4.500	2.217	4.350	$\leq 0.1$	99.9
□	5.000	2.463	5.014	$\leq 0.2$	99.9
△	5.500	2.710	5.704	$\leq 0.1$	99.7

## Sensor Sensitivity

The elemental distinction between the A3515 and A3516 is magnetic sensitivity. The nominal data for the two specific sensors depicted in Figures 3 and 4 is listed in Tables 2 and 3. Sensitivity is specified in millivolts per gauss (mV/G). Three voltages are listed; however, most designs utilize fixed, low-cost 5 V regulator ICs for stability. The nominal sensitivity (and usable range) of the two linear HEDs is as follows

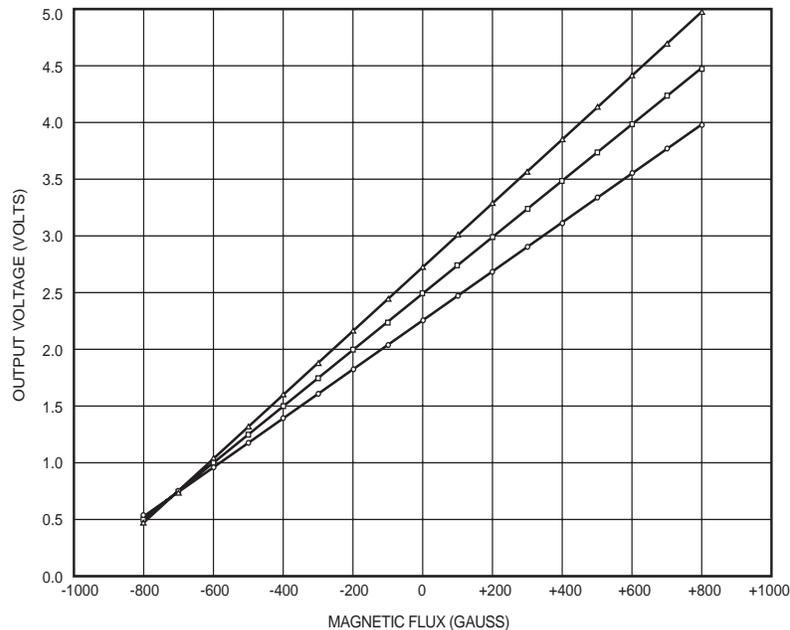
( $V_{CC} = 5$  V):

- A3515: Sensitivity: 5.0 mV/G  
Range:  $\geq \pm 400$  G ( $\geq \pm 2.0$  V)
- A3516: Sensitivity: 2.5 mV/G  
Range:  $\geq \pm 800$  G ( $\geq \pm 2.0$  V)

## Linearity and Symmetry

From these plots (Figures 3 and 4) it is apparent that neither linearity nor symmetry (the deviation in the slope from the quiescent (or null) voltage) is a vital design consequence as neither surpasses 0.3 % for the A3515. The plots record  $\pm 400$  G for the A3515, and  $\pm 800$  G for the A3516, and output voltage swings of  $\geq \pm 2.0$  V for both types.

# ‘NON-INTRUSIVE’ HALL-EFFECT CURRENT-SENSING TECHNIQUES



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**Figure 4: Linear, Ratiometric Hall-Effect Sensor Characteristics (A3516 Output)**

**Table 3: Linear, Ratiometric Hall-Effect Sensor Measurement Data (A3516)**

V <sub>CC</sub> (Volts)	Measured Over ±500 Gauss				
	V <sub>OQ</sub> (Volts)	Sensitivity (mV/G)	Non-Linearity (%)	Symmetry (%)	
○ 4.500	2.232	2.149	≤ 0.1	99.9	
□ 5.000	2.475	2.481	≤ 0.1	99.6	
△ 5.500	2.723	2.820	≤ 0.1	99.9	

### Linear Current Range(s)

The practical current limit (maximum with ‘tight’ coupling) is derived using the range and flux per turn in the prior formula per the approximation:

$$\text{A3515: } \geq \pm 400 \text{ G} \div 6.9 \text{ G/A} \approx \pm 58 \text{ A}$$

$$\text{A3516: } \geq \pm 800 \text{ G} \div 6.9 \text{ G/A} \approx \pm 116 \text{ A}$$

Per a prior mention, current values beyond ≈115 amperes mandate reducing the magnetic coupling, shunting higher current levels (i.e., pass a portion of the total through the toroid), or other methods that effectively ‘desensitize’ the circuitry. There are many, growing and expanding applications for ‘non-intrusive’ current sensing, especially at high currents (>100 A). An ultra-low value resistor (<1 milliohm) dissipates considerable power and heating at these currents, and the ‘non-inductive’ resistors needed raise costs. I<sup>2</sup>R losses cannot be

avoided; a sense resistor of 500 μΩ and 200 A produces 20 watts. Obviously, this is a situation that a designer would prefer to avoid. However, low-cost options are scarce (or non-existent).

### Linear, Ratiometric Hall-Effect ICs

The latest linear HEDs incorporating the dynamic quadrature dc offset cancellation are illustrated in Figure 5. The Hall element is a ‘single-plate’, and designated by its symbol (X). Sensor current is switched from a 0° orientation (downward) to a 90° path (across the Hall plate) at ≈170 kHz. This precludes most of the earlier offset related factors (dc imbalances due to resistive gradients, geometrical dissimilarities, piezoresistive effects, etc.). A low-pass filter and a sample-and-hold circuit are employed to recondition the signal fed to the linear, ratiometric Hall sensor output.



# ‘NON-INTRUSIVE’ HALL-EFFECT CURRENT-SENSING TECHNIQUES

## Distinctive Linear HED Parameters

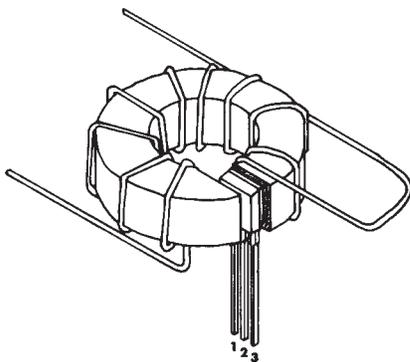
Various, numerous linear-HED characteristics are of concern in current-sensing applications, and brief descriptions of these follow. Subsequently, many of these characteristics and parameters will be embodied in a focus on accuracy, temperature effects, linearity, symmetry, etc.

### Voltage Output

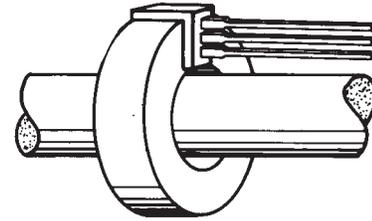
As mentioned, the ratiometric, linear Hall sensors provide an output voltage that is proportional to the applied magnetic field induced by current as illustrated in Figure 2. The output is specified to sink and source  $\pm 1$  mA at guaranteed limits. Per Figures 2, 3, and 4, the usable range is  $\geq \pm 2.0$  V with a 5 V supply. Also previously mentioned, the quiescent output voltage is 1/2 the supply when no magnetic field is present (or current induced). A stable, well-regulated supply is very necessary for proper operation, otherwise the output voltage will fluctuate and follow any variations in supply.

### Circuit Loading with Hall-Effect Sensors

The linear HEDs present no load to the conductor being sensed. A ‘no-disconnect’, ‘non-intrusive’ technique is based upon forming a ‘toriod’ around the conductor being sensed. Rather than pass the wire through the toroid (Figures 6A & 6B), a soft iron piece is formed around the conducting wire. This permits sensing currents without the need for disconnecting any conductors in the power system (‘no-disconnect’ formed toriod in Figure 6C).

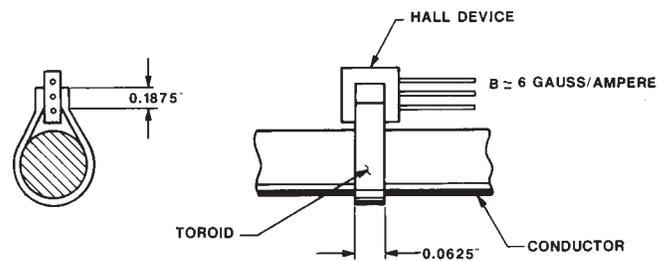


**Figure 6A: Toroidal Current Sensor (<15 A)**



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**Figure 6B: Toroidal Current Sensor (>15 A)**



Dwg. No. 13,166

**Figure 6C: ‘No-Disconnect’ Current Sensor**

### Tolerance to Current Overloads

As mentioned, a conductor current that exceeds the range of the linear Hall IC forces the output into a non-linear, saturated condition. Excessive current does not impair or damage the sensor IC. However, extreme, sustained overcurrent could be a fire or safety hazard if the conductor overheats and creates a dangerous situation.

### Response Time of Hall-Effect Current Sensors

A review of some of the current sensors utilizing Hall-effect-based techniques and toriods reveals a rather broad range of sensor response times. A majority of these (those including amplifiers) fall within a range of  $\approx 7 \mu\text{s}$  to  $\approx 15 \mu\text{s}$ , though others are below and above these limits. Testing is (normally) specified with  $di/dt = 100 \text{ A}/\mu\text{s}$ ; and the specified linear current ranges vary from rather low (<5 A) to the extreme (>20,000 A). Obviously, the 20 kA variety are expensive and do not exploit any low-cost toriod techniques.

# 'NON-INTRUSIVE' HALL-EFFECT CURRENT-SENSING TECHNIQUES

## Hall-Effect Sensor Bandwidth

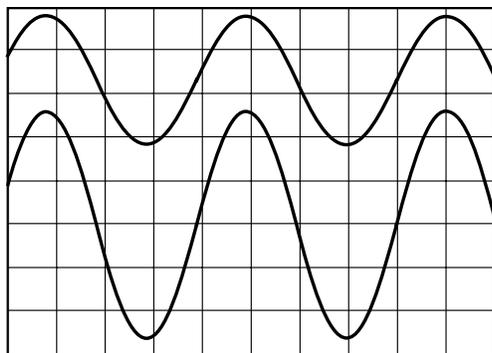
Today, the usable bandwidth of most linear Hall ICs is  $\geq 20$  kHz. Signal voltage changes little up to this frequency. However, noticeable phase shift becomes distinct at somewhat lower frequencies. Some variation is apparent amongst different ICs and vendors, but the rolloff is quite steep beyond  $\approx 20$  kHz. Although the cutoff frequency for the -3 dB rolloff of all linear HEDs is inconsistent, 20 kHz to 25 kHz is a valid approximation.

Representative oscilloscope plots show the effects of frequency on the Hall sensor signal. From dc to 500 Hz (Figure 7) no discernible phase shift materializes. The top signal is the HED voltage, and the lower trace is the winding (coil) current.

The phase shift becomes quite noticeable with a 10 kHz input rate (Figure 8), and very apparent at 20 kHz (Figure 9). Note — testing performed with 20 turns on a gapped toriod; and the voltage scales of the three plots are not identical. Other intermediate-frequency plots exhibit similar phase shifts, but were not included due to space limits.

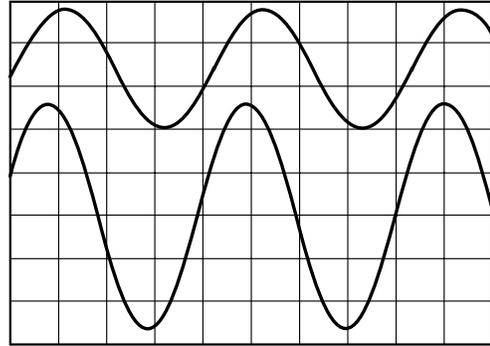
Also, it should be mentioned that this bandwidth limitation is correlated with the linear sensor. The magnetics (and induced coupling) is definitely not a restricting factor to bandwidth within this range of operating frequencies.

Obviously, with such bandwidth limitations, Hall sensors cannot sense high-power PWM circuitry exploiting power MOSFETs or IGBTs at normal, inaudible operating frequencies ( $>20$  kHz), but a linear HED is viable for dc and 'mains' power.



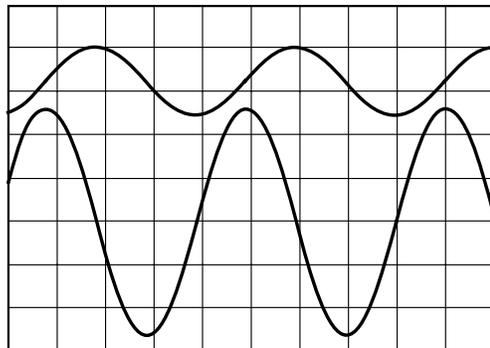
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Figure 7:  $V_{OUT}$  (Upper) vs  $I_{IN}$  (Lower) at 500 Hz



Dwg. WH-018-8

Figure 8:  $V_{OUT}$  (Upper) vs  $I_{IN}$  (Lower) at 10 kHz



Dwg. WH-018-9

Figure 9:  $V_{OUT}$  (Upper) vs  $I_{IN}$  (Lower) at 20 kHz

## Linear HED Response to Application of Power

Increasingly, systems designers confront stringent power 'budgets', and seek techniques to conserve current and power. Battery-powered and battery 'backup' designs are particular concerns, and any method capable of curtailing power is scrutinized.

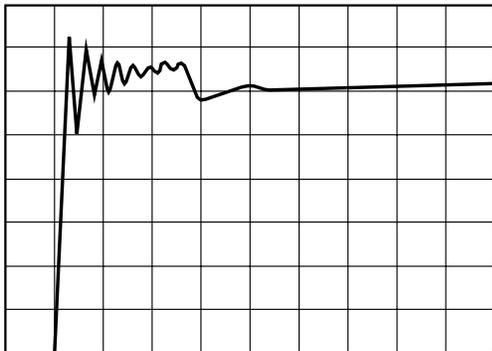
A recurring technique is to (periodically) activate the sensor by switching the power supply ON for brief intervals, and then OFF for longer periods. Average power is related to duty cycle. Thus, for low duty-cycle applications, the power consumed can be decreased substantially. Fixed-voltage IC regulators (with an ENABLE input) are one very viable circuit technique to switch the HED supply and reduce average power.

# 'NON-INTRUSIVE' HALL-EFFECT CURRENT-SENSING TECHNIQUES

Clearly, the time required for a linear Hall IC to provide a stable, usable signal is very important, and two different linear HEDs were evaluated to ascertain their power-up response characteristics. The devices exhibit dissimilar properties, and the oscilloscope plots portray their dynamic operation upon applying power to the linears. These plots include a 5% window to compare the settling of the signals as the voltage attains its final value.

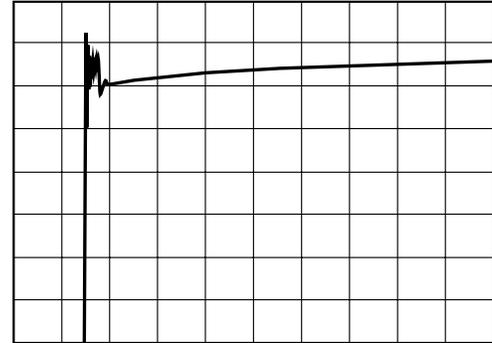
The latest linear HEDs (with dynamic quadrature offset cancellation) have a slower response than an earlier generation that exploits the orthogonal Hall element. The previous series (A3506, etc.) settles to above 95% of final voltage in less than 1  $\mu\text{s}$  (per Figure 10), and takes approximately 15  $\mu\text{s}$  (per Figure 11) to reach its final value. The very obvious tradeoff: speed vs accuracy and resolution of the signal voltage at power-up.

The newest devices (A3515 and A3516) exhibit a slower response ( $\approx 25 \mu\text{s}$  to  $\geq 95\%$ , and  $\approx 40 \mu\text{s}$  for a final, stable voltage level). These plots reveal basic tradeoffs in performance vs response speed, and the latent potential for conserving power.



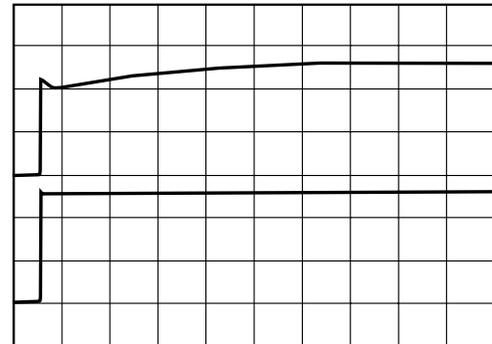
Dwg. WH-018-10

**Figure 10: A3506 Power-Up (0.2  $\mu\text{s}/\text{Div.}$ )**



Dwg. WH-018-11

**Figure 11: A3506 Power-Up (2.0  $\mu\text{s}/\text{Div.}$ )**



Dwg. WH-018-12

**Figure 12: A3515 Power-Up (5.0  $\mu\text{s}/\text{Div.}$ )**

## Linear Hall Sensor/Toroid Hysteresis

Tests executed at  $\pm 6 \text{ A}$ , which induce a substantial output voltage signal swing, reveal that any error involving hysteresis is rather minor ( $\approx 1\%$  for the combination of linear HED (A3516) and gapped toriod. Inherently, linear Hall sensors exhibit no hysteresis. However, different slotted toroids (and varied magnetic materials) may possess differing hysteretic properties.

The actual measured voltage differentials ranged from  $\approx 16 \text{ mV}$  to  $\approx 22 \text{ mV}$  with  $\geq 2.1 \text{ V}$  changes. Hysteresis is a minor concern when using ferrite cores, but other ferrous cores (such as powdered iron) may exhibit different characteristics.

Thus, a complete, thorough evaluation of specific toroids and the associated linear sensor IC would be a very prudent (and recommended) suggestion.

# **‘NON-INTRUSIVE’ HALL-EFFECT CURRENT-SENSING TECHNIQUES**

## Core (Toroid) Saturation

Normally, the saturation of a core should not be an issue. A current-sensor design that employs sufficient turns to drive the output voltage of the HED to nearly full scale (at the maximum design current) first induces saturation of the sensor IC. For optimum accuracy, the number of turns used should induce output voltage transitions that (just) fall short of saturating the sensor (more on this).

## Zero Crossover

With a linear Hall-effect sensor, zero crossover corresponds to a zero magnetic field (no induced flux field as  $B = 0$  with 0 A). The HED output voltage with a zero magnetic field equates to 1/2 supply (i.e., the quiescent output voltage).

## Wide-Band Output Noise of Linear HEDs

The wide-band noise of these linear Hall ICs is inconsequential, and its value linked to the sensor chosen. The testing specifications for the recent, stable linear Hall IC series are:

$$B = 0, BW = 10 \text{ Hz to } 10 \text{ kHz}, I_{\text{OUT}} \leq 1 \text{ mA}$$

Typical equivalent input noise voltage ( $V_n$ ) values for the two series of linears are:

A3506, A3507, A3508:	125 $\mu\text{V}$
A3515, A3516:	400 $\mu\text{V}$

Given that the lowest sensitivity of these HEDs is 2.5 mV/G, plus that accurate measurement is not feasible at very low flux strengths (more on this later), the consequences of wide-band noise is (typically) a very minor consideration. Other factors (particularly quiescent output voltage drift with temperature) are much more significant.

## The System Temperature

A crucial constituent to consider, the temperature range must be well understood, properly specified (without inordinate margins), and controlling this very vital design element greatly aids the ability to realize reasonable accuracy. Note — open-loop designs cannot (easily) resolve small variations in current. A core hysteresis of  $\approx 1\%$  precludes this without contemplating the other (and more acute) effects of temperature upon a linear HED output parameters and their relationship to performance.

## Quiescent Output Voltage (DC Offset)

Essentially, the dc offset of a ratiometric, linear Hall IC relates to its deviation from the nominal quiescent output voltage (i.e., 1/2 supply). Lacking a system calibration or individual ‘look-

up’ table, this dc parameter very tangibly affects accuracy of any current-sensing system utilizing linear Hall ICs. By referring back to both Figures 3 and 4, and Tables 2 and 3, the significance of dc offset ( $V_{\text{OQ}}$ , or quiescent output voltage) is very plain.

The latest ratiometric Hall-effect sensors specify the dc quiescent output voltage limits as 1/2 supply  $\pm 0.2 \text{ V}^\circ$ . The quiescent output voltage drift over the HED operating-temperature range corresponds to  $\pm 10$  gauss with the newest linear Hall ICs.

A significant facet of the static quiescent voltage is its tolerance limits. Present specifications list  $\pm 0.2 \text{ V}^*$  from the nominal, and this translates into a  $\pm 8\%$  maximum error without any temperature-induced effects (A3515/3516). Obviously, this latent error factor poses a formidable constraint, and must be given serious deliberation if accurate voltages are prerequisite to system performance.

DC compensation for the quiescent output voltage is feasible by regulating the supply to achieve the 2.5 V nominal, but this also influences sensitivity and any interrelated offsets are likely to prove intolerable in production. Per Figures 3 and 4, boosting the supply offsets a low quiescent output voltage, and reducing the supply compensates for a high quiescent voltage. However, such offsets adversely influence sensitivity and counteract the positive aspects of ‘nulling’ the quiescent voltage.

Because the sensitivity specifications for the newest linears encompass a  $\pm 10\%$  tolerance without any temperature effects, ‘nulling’ the quiescent output voltage (to 2.5 V) to escape a  $\pm 8\%$  error in the quiescent output voltage seems rather absurd.

The dc drift of the earlier linears equated to  $\pm 20$  gauss for the ‘premium’ type, and ranged to  $\pm 50$  gauss for a ‘limited’ temperature unit. Also, the ranges of tolerances for quiescent output voltage of prior ICs was broader (or very much broader) than the newest ICs with offset cancellation.

This impedes the capacity to design an accurate, precise linear sensing system that operates over a broad temperature range. Designs necessitating tight current-sensing tolerances must confront and reconcile any concerns linked to quiescent output voltage (value and drift), and these are discussed in greater detail under accuracy of linear HEDs.

Applying the drift relationships mentioned above, the maximum quiescent output voltage drift error can be closely approximated. These calculations are based upon the (nominal) linear sensitivities:

\* Refer to addendum.

# ‘NON-INTRUSIVE’ HALL-EFFECT CURRENT-SENSING TECHNIQUES

- A3515:  $\pm 10 \text{ G} \times 5.0 \text{ mV/G} \approx \pm 50 \text{ mV}$
- A3516:  $\pm 10 \text{ G} \times 2.5 \text{ mV/G} \approx \pm 25 \text{ mV}$
- A3506:  $\pm 20 \text{ G} \times 2.5 \text{ mV/G} \approx \pm 50 \text{ mV}$
- A3507:  $\pm 35 \text{ G} \times 2.5 \text{ mV/G} \approx \pm 87 \text{ mV}$
- A3508:  $\pm 50 \text{ G} \times 2.5 \text{ mV/G} \approx \pm 125 \text{ mV}$

Essentially, the list establishes the A3516 as the favored linear when the quiescent voltage drift is an important criteria, and maximum sensitivity is not the primary consideration. In current-sensing applications this entails twice the number of turns (vs. A3515) to attain the same voltage swing.

Over a full-scale voltage swing ( $\geq \pm 2.0 \text{ V}$ ) the maximum error with the A3516 is  $\leq \pm 1.3\%$  but, consistently, quiescent voltage drift is  $< \pm 3 \text{ G}$  ( $\approx \pm 7.5 \text{ mV}$  with the A3516). This error factor is dependent upon temperature; hence, sufficient turns should be employed to drive the output near full-scale. This minimizes the overall effect of temperature-related quiescent output voltage drift. Therefore, operation near full-range is absolutely advised as the  $\Delta V_{OQ}$  error percentage is lower.

### Temperature Influence upon Sensor Sensitivity

The nominal sensitivities (and ranges) of both of the new linears was mentioned previously. However, the circuit tolerances were unspecified. The ICs have different nominal sensitivities; however, the temperature-related maximum shifts are identical. Reiterating sensitivity and range, plus adding the tolerances, produces the following Hall-effect IC parameters and device temperature shifts:

- A3515: Sensitivity .....  $5.0 \text{ mV/G}, \pm 10\%$   
 $\Delta$ Sensitivity( $\Delta T$ ) at  $T_A = \text{Max}$   
 $-2.5\%$  (min),  $+2.5\%$  (typ),  $+7.5\%$  (max)  
 $\Delta$ Sensitivity( $\Delta T$ ) at  $T_A = \text{Min}$   
 $-9.0\%$  (min),  $-1.3\%$  (typ),  $+1.0\%$  (max)  
Magnetic Range .....  $\geq \pm 400 \text{ G} (\geq \pm 2.0 \text{ V})$
- A3516: Sensitivity .....  $2.5 \text{ mV/G}, \pm 10\%$   
 $\Delta$ Sensitivity( $\Delta T$ ) at  $T_A = \text{Max}$   
 $-2.5\%$  (min),  $+2.5\%$  (typ),  $+7.5\%$  (max)  
 $\Delta$ Sensitivity( $\Delta T$ ) at  $T_A = \text{Min}$   
 $-9.0\%$  (min),  $-1.3\%$  (typ),  $+1.0\%$  (max)  
Magnetic Range .....  $\geq \pm 800 \text{ G} (\geq \pm 2.0 \text{ V})$

### Temperature Ranges:

- $T_A$  (min) .....  $-40^\circ\text{C}$
- $T_A$  (max) .....  $+85^\circ\text{C}$  or  $+125^\circ\text{C}$

Essentially, the attainable accuracy of open-loop linear HEDs involves dc offset and sensitivity.

### Accuracy of Open-Loop Linear Hall Sensors

In any classic mystery, at this juncture the ‘plot’ thickens. Because precise, exacting measurement demands are increasing, a concise explanation of the interrelated elements associated with attaining ‘accuracy’ and dependability is next. Accuracy, repeatability, cost, etc. are very interrelated.

Though parametric maximums can be defined, the cumulative impact on accuracy is quite nebulous. Also, it is improbable that all worst-case errors occur coincidentally. Increasingly, cost-sensitive designs are based upon typical specifications, and this may precipitate a small (although tolerable) failure rate that cannot (easily) be decreased.

Pinpointing the absolute accuracy of ‘open-loop’ current sensing is beyond this treatise. However, reviewing the essential factors supports analysis.

- Hysteresis, hys .....  $\approx \pm 1\%$
- Output Quiescent Voltage,  $V_{OQ}$  .....  $\pm 8\%*$   
(A3515 or A3516 .....  $2.5 \text{ V} \pm 0.2 \text{ V}$ )
- Output Quiescent Voltage Drift,  $\Delta V_{OQ}$  .....  $\pm 10 \text{ G}$   
(A3515 .....  $\leq \pm 50 \text{ mV}$ )  
(A3516 .....  $\leq \pm 25 \text{ mV}$ )
- Sensitivity,  $T_A = \text{Max}$  .....  $\pm 10\%$   
(A3515 .....  $5.0 \text{ mV/G}$ )  
(A3516 .....  $2.5 \text{ mV/G}$ )
- $\Delta$ Sensitivity,  
 $T_A = \text{Max}$  .....  $-2.5\%$  to  $+7.5\%$   
 $T_A = \text{Min}$  .....  $-9.0\%$  to  $+1.0\%$
- Positive/Negative Linearity .....  $\approx 99.7\%$
- Symmetry .....  $\approx 99.7\%$
- Wide-Band Noise,  $e_n$  .....  $400 \mu\text{V}$

Clearly, some of these elements are very crucial to attaining accurate current sensing, while others are rather inconsequential. Fundamentally, errors correlated to hysteresis, linearity, symmetry, and wide-band noise become quite insignificant. The factors linked to quiescent voltage and sensitivity are (absolutely) essential to any implementation of an accurate and precise current sensing design.

Errors linked to quiescent output voltage drift are range dependent and device related. The  $\pm 10 \text{ G}$  (typically  $< \pm 5 \text{ G}$ ) shift correlates to a potential error of 50% with a 10 gauss applied magnetic field. However, the  $\pm 10 \text{ G}$  drift represents less than 1.5% with a field strength  $> 667 \text{ G}$ . Thus, the quiescent voltage error factor is ‘non-linear’ and is (substantially) diminished with large output-voltage swings of the A3516 linear HED.

\* Refer to addendum.

# 'NON-INTRUSIVE' HALL-EFFECT CURRENT-SENSING TECHNIQUES

The quiescent output-voltage tolerance is listed as a percentage ( $\leq \pm 8\%$ )\*. This is predicated upon a nominal ratiometric ( $1/2$  supply = 2.5 V), and the specified limits of  $\leq \pm 0.2$  V\*. Because the majority of linear Hall sensors are much closer to nominal ( $\leq \pm 0.1$  V), the  $\pm 8\%$  tolerance represents a very 'worst-case' quiescent output-voltage scenario.

The sensitivity parameters also pose considerable error potential. However, these listings equate to a worst-case analysis. Further, the relationships between sensitivity and the effects of temperature are not (as yet) completely specified. Whether a consistent correlation between devices near either limit of sensitivity and temperature-induced shifts exists is not specified. The temperature-related effects might be nil, or miniscule (temperature cancels any cumulative deviations), or cumulative (temperature further exacerbates the tolerances).

Based upon the published parameters and limits, open-loop current-sensing designs cannot readily expect to attain results below  $\approx \pm 10\%$  to  $\pm 15\%$ . However, after reviewing recent plots based upon test data (A3515/16), the prospect for boosting the measurement accuracy (absolutely) improves.

Two plots (Figures 13 and 15) delineate  $V_{OQ}$  vs temperature. The  $+25^\circ\text{C}$  data registers an A3515 minimum of 2.468 V; a maximum of 2.512 V; the A3516 spans from a minimum of 2.464 V to a maximum of 2.501 V. This is much tighter than specified. The  $-3$  sigma limits for the ICs are: 2.457 V (A3515), and 2.462 V (A3516). The  $+3$  sigma data limits are 2.520 V (A3515) and 2.509 V (A3516), and these voltages convert to well within the published  $\pm 8\%$  tolerances\* for the quiescent output voltage of these linears.

Data for the A3515 provides the following:

$V_{OQ}$	$-40^\circ\text{C}$	$+25^\circ\text{C}$	$+85^\circ\text{C}$	$+150^\circ\text{C}$
$-3 \sigma$	2.448	2.457	2.463	2.472
min	2.461	2.468	2.473	2.481
mean	2.487	2.489	2.493	2.501
max	2.517	2.512	2.520	2.530
$+3 \sigma$	2.525	2.520	2.523	2.531

in volts with  $V_{CC} = 5$  V and

$V_{OQ}$	$-40^\circ\text{C}$	$+25^\circ\text{C}$	$+85^\circ\text{C}$	$+150^\circ\text{C}$
$-3 \sigma$	-4.04	0.00	-1.15	-1.54
min	-2.90	0.00	-0.60	-0.60
mean	-0.59	0.00	0.74	2.38
max	2.60	0.00	2.40	5.50
$+3 \sigma$	2.86	0.00	2.63	6.31

as a percentage drift from  $+25^\circ\text{C}$ .

\* Refer to addendum.

Data on the A3516 discloses similar properties:

$V_{OQ}$	$-40^\circ\text{C}$	$+25^\circ\text{C}$	$+85^\circ\text{C}$	$+150^\circ\text{C}$
$-3 \sigma$	2.454	2.462	2.462	2.466
min	2.458	2.464	2.467	2.472
mean	2.484	2.485	2.483	2.485
max	2.503	2.501	2.498	2.499
$+3 \sigma$	2.514	2.509	2.504	2.504

in volts with  $V_{CC} = 5$  V and

$V_{OQ}$	$-40^\circ\text{C}$	$+25^\circ\text{C}$	$+85^\circ\text{C}$	$+150^\circ\text{C}$
$-3 \sigma$	-3.97	0.00	-3.36	-5.13
min	-3.60	0.00	-1.60	-2.90
mean	0.12	0.00	-0.14	0.56
max	3.20	0.00	3.08	5.70
$+3 \sigma$	4.22	0.00	3.60	6.25

as a percentage drift from  $+25^\circ\text{C}$ .

The data and plots of  $\Delta V_{OQ}$  vs temperature also record better performance than the specified limit of  $\pm 10\%$  (earlier listed in millivolts). Figures 14 and 16 show the  $V_{OQ}$  drift is well within range, and the drift is very small in any narrow temperature band about  $+25^\circ\text{C}$ . Clearly, temperature range affects the output voltage shift tolerances.

Because these plots and data entail characteristics that fall within certain HED specifications, some earnest deliberation on the achievable accuracy is absolutely advised (particularly if the temperature range is limited). Fundamentally, the effects of temperature are the foremost consideration in any endeavor to attain single-digit ( $< 10\%$ ) precision without calibration and/or compensation methods.

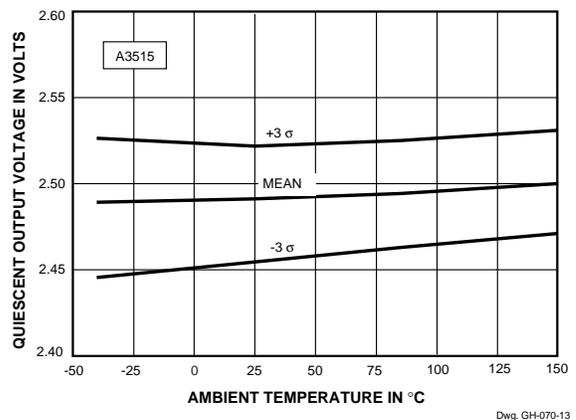


Figure 13:  $V_{OQ}$  vs Temperature (A3515)

# ‘NON-INTRUSIVE’ HALL-EFFECT CURRENT-SENSING TECHNIQUES

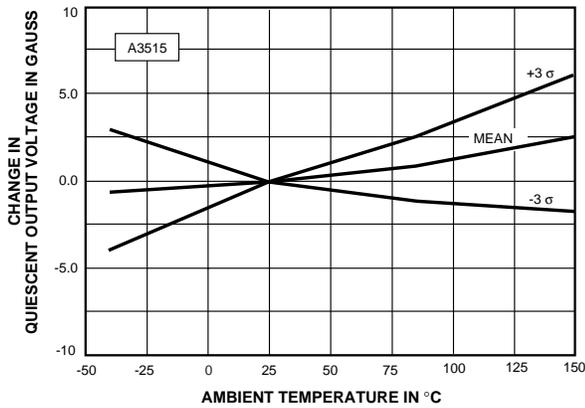


Figure 14:  $\Delta V_{OQ}$  vs Temperature (A3515)

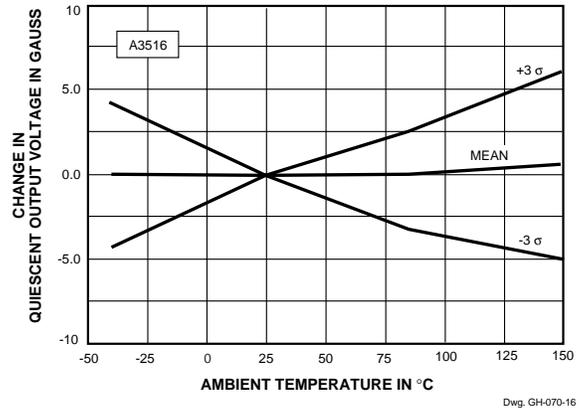


Figure 16:  $\Delta V_{OQ}$  vs Temperature (A3516)

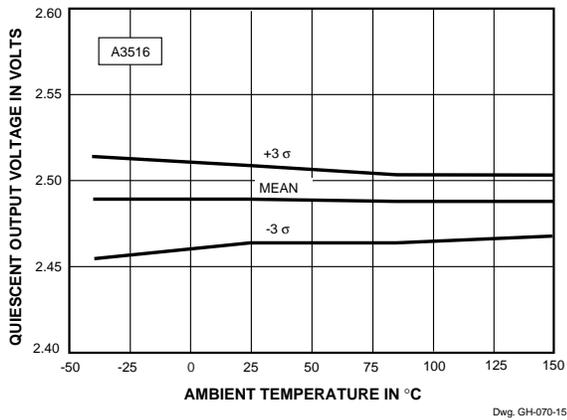


Figure 15:  $V_{OQ}$  vs Temperature (A3516)

### Effects of Sensitivity upon Accuracy

The plots and data for sensitivity confirm that the new linear HEDs are within published limits, and delineate another (albeit secondary) constituent in the resolution of accuracy. The device sensitivity and its interrelated variation over temperature are conservative, albeit without extreme test margins. Figures 17 through 20 depict the sensitivity data, and the A3515 test data provides the following:

Sensitivity	-40°C	+25°C	+85°C	+150°C
-3 $\sigma$	4.408	4.683	4.795	4.842
min	4.454	4.793	4.930	4.927
mean	4.761	4.988	5.109	5.121
max	5.181	5.316	5.392	5.359
+3 $\sigma$	5.113	5.293	5.423	5.400

in mV/G and

Sensitivity	-40°C	+25°C	+85°C	+150°C
-3 $\sigma$	-7.6	0.0	-0.1	-0.7
min	-7.1	0.0	-0.9	-1.0
mean	-4.7	0.0	2.3	2.5
max	-2.5	0.0	3.7	4.4
+3 $\sigma$	-1.9	0.0	4.6	5.8

as a percentage drift from +25 C.

Data on the A3516 reveals similar properties:

Sensitivity	-40°C	+25°C	+85°C	+150°C
-3 $\sigma$	2.174	2.313	2.393	2.410
min	2.263	2.401	2.465	2.476
mean	2.340	2.457	2.530	2.528
max	2.586	2.700	2.758	2.728
+3 $\sigma$	2.506	2.600	2.667	2.646

in mV/G and

# 'NON-INTRUSIVE' HALL-EFFECT CURRENT-SENSING TECHNIQUES

Sensitivity	-40°C	+25°C	+85°C	+150°C
-3 $\sigma$	-7.1	0.0	1.1	-0.1
min	-6.8	0.0	2.0	0.9
mean	-5.0	0.0	2.7	2.6
max	-4.0	0.0	3.7	4.3
+3 $\sigma$	-2.9	0.0	4.2	5.3

as a percentage drift from +25°C.

Clearly, neither data nor plots reflect the overall distribution of the ratiometric linear Hall sensors. This insight into accuracy is intended to advise of a basic necessity to reconcile the attainable limits of precise current sensing with HEDs, but it does not imply any definite constraint. Ultimately, the application of innovative, thoughtful circuit-design techniques determines the essential limits of open-loop Hall-effect current sensing.

## Calibration and Compensation

Current-sensing designs endeavoring to realize an open-loop accuracy below  $\pm 10\%$  should consider alternatives. Implementing 'hardware' calibration and/or compensation represents a costly, complex option, and (for most designs) should be ignored.

Whereas it is very feasible to establish trip points by using a comparator (or multiple comparators) calibrating, or compensating, for temperature and quiescent voltage to realize a full range of linear operation is a formidable task. The comparators can provide discrete current signals (overcurrent, normal operation, etc.) with useful accuracy, but cannot (easily) distinguish small current changes.

Increasingly, software is the solution to extending the accuracy of HED current sensing. Typically, this involves microcontrollers,  $\mu$ Ps, or computers, and a software calibration/compensation scheme.

Because the linearity, symmetry, and ratiometry of linear HEDs is  $\approx 100\%$ , these error factors can (largely) be disregarded. The temperature range is a definite factor if the system requires a wide operating range. However, a benign environment with a narrow temperature span alleviates design difficulties. The use of software (and a  $\mu$ C/ $\mu$ P) to exploit a look-up table necessitates measuring and storing sufficient data points to implement an acceptable (and individual) calibration technique for each current sensor. This (usually) involves the following calibration/compensation steps:

- Measuring and storing  $V_{OQ}$  (the null current),
- Measuring and storing (specific) current points,
- Computing sensitivity from  $V_{OQ}$  and data, and
- Measuring/storing temperature drift (if needed).

Determining the current level involves employing the 'look-up' data to calculate the current value via using the stored  $V_{OQ}$  and sensitivity data.

Measure  $V_{OUT}$  and calculate current value

Measure system temperature and compensate for its drift effects (if a system requirement).

In essence, the 'look-up' table corresponds to the 'calibrated' linear HEDs already mentioned. This software/look-up table method can easily achieve  $< \pm 10\%$  accuracy, and its ultimate limit (perhaps  $\approx \pm 1\%$ ) is probably constrained by factors linked to software development, the requisite calibration and compensation (including equipment), and the associated costs and time of increased accuracy.

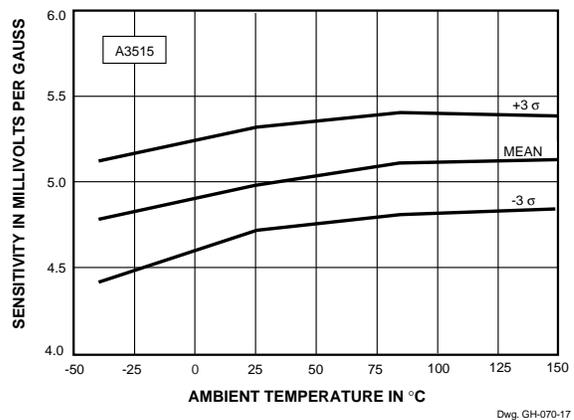


Figure 17: Sensitivity vs Temperature (A3515)

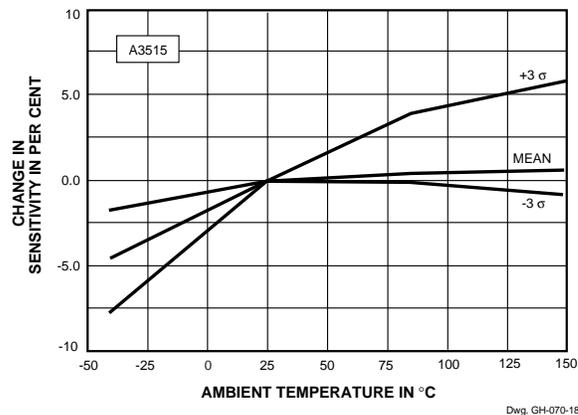
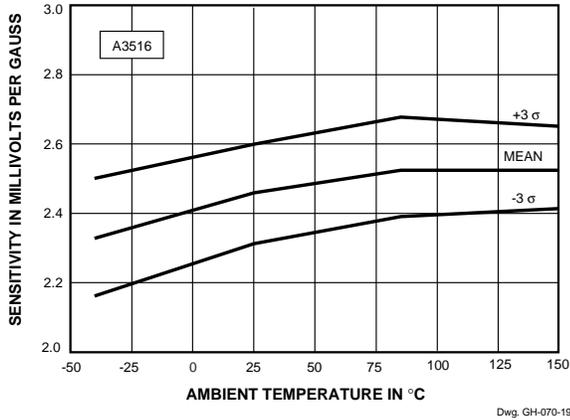
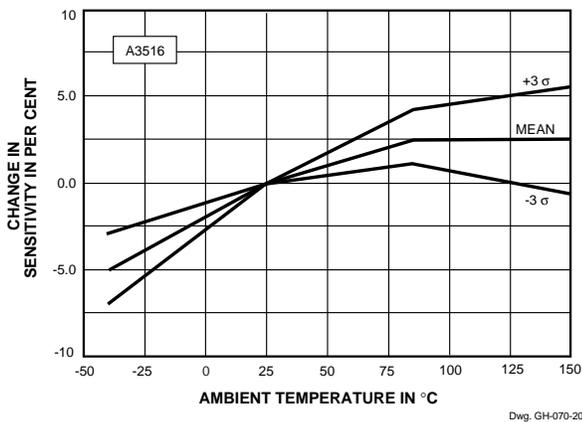


Figure 18:  $\Delta$ Sensitivity vs Temperature (A3515)

# ‘NON-INTRUSIVE’ HALL-EFFECT CURRENT-SENSING TECHNIQUES



**Figure 19: Sensitivity vs Temperature (A3516)**



**Figure 20: ΔSensitivity vs Temperature (A3516)**

Obviously, the data-storage demands non-volatile memory for the parametric measurements, and an individual, initial calibration program. A look-up table compensates for the variations in quiescent voltage, sensitivity, and temperature effects. The latent errors associated with these constituents to system accuracy can be minimized by a software calibration and compensation technique. Although this may appear to be complicated and costly, the other solutions are liable to be more complex and more expensive than using a low-cost 8-bit  $\mu$ C.

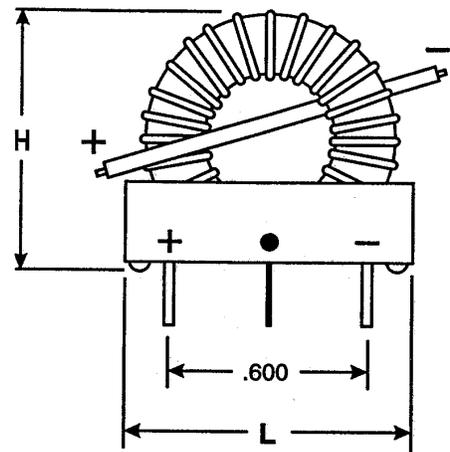
### Sorting of Hall-Effect Sensors

Although this approach could tighten device output parameters; presently, only linears with published datasheet limits are available for sale. Some ‘value-added’ sorting is provided by

others, but this procedure and service is neither common nor inexpensive. Despite this, specific customers have elected to solve formidable design issues by outside testing, sorting, and selecting linear HEDs to specific, tightened device limits. Clearly, any improvement in availability of presorted HED ICs is a definite advantage to current-sensing designs, and the availability of ‘sorted’ HEDs may change.

### Size and Form of Sensor Assembly

Because various sizes of toroids with slots expressly cut to fit a HED package are available (Eastern Components, Inc.), a typical size cannot be identified. Figure 21 illustrates one basic configuration that is provided in six different current ranges (peak current ratings sensed are: 1 A, 3 A, 5 A, 8 A, 10 A, and 100 A). The length, height, and width vary somewhat, and the largest version measures 0.950" long, 1.025" high, and 0.500" wide; all versions are PCB through-hole form.



**Figure 21: Hall IC Current-Sensing Assembly**

### Cost of a Current-Sensing ‘Sub-System’

Identifying the costs associated with a linear Hall IC-based current sensor is virtually as difficult as the various issues involved with system accuracy. The costs of the indispensable components (linear HED and slotted toroid) can readily be determined, and the prices of the complete assembly depicted in Figure 21 start at  $\approx$ \$8.00 (1000 quantity).

# **‘NON-INTRUSIVE’ HALL-EFFECT CURRENT-SENSING TECHNIQUES**

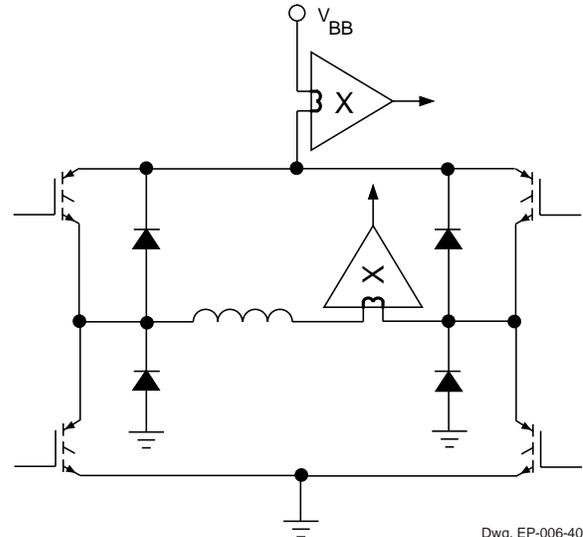
Slotted ferrite cores (usually) cost <\$1.00 (even in modest quantities), and the linear Hall-effect sensor costs range from <\$2.50 to <\$3.25 (1k pieces). This price span reflects the various Hall-sensor types and the different temperature ranges. Obviously, unit costs diminish in higher volumes, and the combined sensor/toroid cost could easily fall (well) below \$3.00 for volume production. A conversion from ferrite cores to powdered iron toroids with a ‘cast’ gap can meaningfully reduce overall cost. Rather than ferrites with an \$0.80 to \$0.85 cost, powdered-iron cores are estimated to be ≈\$0.20 to \$0.25 in similar quantities.

However, other factors such as engineering time, software programming, assembly labor, etc. vary (considerably) based upon each individual design requirement. Clearly, every system temperature, resolution, and accuracy are prerequisites that affect the system cost. The outlays of developing and implementing a high-resolution, very precise design with a wide temperature range are greatly different than sensing only excessive current. An overcurrent fault detection application may allow a very broad tolerance (perhaps  $\pm 20\%$ ), and this would not warrant any of the software ‘look-up’, stringent device and temperature evaluation that a precise, full temperature design mandates.

Therefore, only the essential components (and the assembly of Figure 21) can be identified. Costs associated with software creation, system design engineering, etc. are (well) outside the realm of utilizing linear Hall ICs for current sensing.

## **Protecting High-Power Electronics**

An classical example of current-sensing detection and protection for high-power IGBTs is shown in Figure 22. This diagram can relate to a single-phase of an adjustable speed drive (ASD) for an ac induction motor or other power circuitry that requires a full-bridge or triple half-bridge drive (for example, a 3-phase PM brushless dc motor). Such a configuration can detect excessive current in the supply rail (upper current sensor). This can result from shorting the power rail to ground, or a shorted output combined with a corresponding IGBT that is activated. Any combination of either a shorted lower or upper output with an ON output in the opposite portion of the same ‘leg’ can result in an (unsafe) overcurrent fault in the system.



**Figure 22: ‘Full-Bridge’ with Current Sensors**

Alternatively, the linear sensor in series with the winding (center sensor) provides detection from shorted loads, and also monitors the actual coil current. Current sensors in both locations should preclude fire and safety hazards (and protect any personnel); and high-speed ‘shut-down’ circuitry can prevent damage to the power outputs (if the overcurrent results from an external fault such as improper equipment servicing). Clearly, overall circuit response speed (shutdown time) is critical to protecting the system and providing safety.

## **Summary and Perspective**

The applications for linear Hall-effect sensors in open-loop current sensing continue to evolve and expand. Presently, the devices available are far superior to any earlier linears, and advancements in design, processing, packaging, testing, etc. are incessant and relentless. As mentioned, present-day HEDs have tolerances and temperature drifts that pose formidable challenges to those intending to design, develop, and implement systems that demand dependable, single-digit accuracy over a wide range of system operating temperatures.

Expect further progress in HED performance and temperature stability, more functional integration, and other developments that make linear HEDs more viable for higher resolution current sensing.

# **'NON-INTRUSIVE' HALL-EFFECT CURRENT-SENSING TECHNIQUES**

Future linears may allow programming the sensor after HED packaging. This would permit users to tune the gain (sensitivity), calibrate the output quiescent voltage ( $V_{OQ}$ ), and compensate for the issues of temperature variations. Clearly, this involves an innovative, more complex technique in the circuit design and testing. However, the opportunities for applying such Hall sensors expand exponentially.

Hall-effect sensors have undergone revolutionary changes since their integration in the late 1960s. With further advancements and improvements, the applications for new linear HEDs are expected to expand and multiply to satisfy the many emerging needs of future power electronics systems.

## **Acknowledgement**

The symbol for a linear Hall-effect current sensor was created by Raymond Dewey of Allegro MicroSystems. Presently, no standard or accepted schematic symbol exists for current sensors utilizing Hall-effect technology.

## **References**

Course: P. Emerald, "Open-Loop Current Sensing for Power Conversion and Motion System Applications" in Principles of Current Sensing, PCIM Power Electronics Institute, Chapter six, PowerSystems World '97; Baltimore, MD; plus various contributors of the chapters comprising this one-day professional advancement course.

Workshop: P. Emerald and Joe Gilbert "Integrated Hall-Effect Sensors for Motion Control and Positioning Applications", PowerSystems World '95, Long Beach, CA.

## **ADDENDUM**

Since this paper was written (December 1997), and presented, a change to the specifications for the A3515 and A3516 ratiometric, linear Hall-effect sensors was made. In April 1998, the new, and tightened, limits for quiescent output voltage were changed from the original  $2.5\text{ V} \pm 0.2\text{ V}$  to  $2.5\text{ V} \pm 0.075\text{ V}$ . In addition to this upgrade in the quiescent output voltage limits, the effective linear current range can be extended by widening the toroid gap (i.e., slot) to 'desensitize' the magnetic coupling.

Per the page 10 section headed **Quiescent Output Voltage (DC Offset)**, originally, the specifications listed the ratiometric output as (nominally) 2.5 V. The limits were 2.3 V (min) and 2.7 V (max) with  $V_{CC} = 5\text{ V}$  over the device operating temperature range. This improvement affects the achievable accuracy of systems applying the ratiometric, linear Hall-effect sensors (refer to the page 11 section that is headed **Accuracy of Open-Loop Linear Hall Sensors**).

As mentioned, this paper shows the following output quiescent voltage limits:

$$V_{OQ} \dots\dots\dots 2.48\text{ V to }2.52\text{ V } (\pm 8\%)$$

The upgraded specification now shows this as:

$$V_{OQ} \dots\dots\dots 2.425\text{ V to }2.575\text{ V } (\pm 3\%)$$

This tightened specification significantly enhances the ability to realize more accurate measurements via utilizing these linear, ratiometric Hall-effect sensors. This means that single-digit accuracy is a reality for some designs (especially those with limited temperature fluctuations).

## **Linear Current Range(s)**

Per the original material (page 5) on **Linear Current Range**, with 'tight' magnetic coupling ( $\approx 60$  mil gap to match the sensor package) the ranges are unchanged:

$$\text{A3515: } \geq \pm 400\text{ G} \div 6.9\text{ G/A} \approx \pm 58\text{ A}$$

$$\text{A3516: } \geq \pm 800\text{ G} \div 6.9\text{ G/A} \approx \pm 116\text{ A}$$

'Desensitizing' the magnetic coupling can readily be realized via expanding (widening) the slot in the toroid. The first endeavor to desensitize the magnetic coupling involved increasing the slot to 120 mils ( $\approx$  twice the package body), and this reduced the flux coupling and increased the upper current limit as follows:

$$\text{A3516: } \geq \pm 800\text{ G} \div 3.85\text{ G/A} \approx \pm 210\text{ A}$$

Testing revealed that placement of the sensor had no effect upon the magnetic coupling. Centering the 'calibrated' linear Hall-effect sensor resulted in the same output signal as position-

# ***'NON-INTRUSIVE' HALL-EFFECT CURRENT-SENSING TECHNIQUES***

## **ADDENDUM (cont'd)**

ing the sensor against either face of the slot. Because many users endeavor to attain higher current ranges, another evaluation ensued (after new ferrite toroids were obtained from Eastern Components, Inc.).

The next extension of the current range limit was undertaken with toroids gapped at 250 mils (e.g., one-quarter inch and more than 4x the package thickness dimension). This (very) 'desensitized' magnetic coupling increased the maximum current limit per the following calculation:

$$A3516: \quad \geq \pm 800 \text{ G} \div 1.7 \text{ G/A} \approx \pm 470 \text{ A}$$

Further evaluations are intended as toroids gapped with differing dimensions become available. This should offer a more complete, albeit overlapping, set of current ranges with an upper limit (as yet) unknown. Also, other toroid materials (powdered iron in particular) are to be evaluated.

### **Summary**

The tightened quiescent output voltage tolerance offers better accuracy for the ratiometric, linear HEDs, and widening the toroid slot increases the maximum current limitation of these devices.

This paper was presented at the International Appliance Technical Conference, Ohio State University, May 6, 1998.  
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