Accuracy of Hall-Effect Current Measurement Transducers in Automotive Battery Management Applications using Current Integration

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Abstract:

This paper presents the basic technology of open-loop Hall-effect transducers for use in automotive battery management applications. A description of the measurement errors inherent in this technology is presented, along with an analysis of the behavior of these errors when the transducers are used in current-integration for battery management applications of internal-combustion engines or hybrid-electric vehicles (HEV's). Current-profile cycles are introduced, and results are presented that compare the characteristic error values of a transducer with the errors achieved when integrating current over time and using a predefined current-profile cycle. Conclusions are drawn as to the relevance of a transducer's real-world performance, instead of the benchmark performance values traditionally used for selection of the most appropriate transducer for a given application.

Keywords: current, measurement, transducer, accuracy, sensor, duty cycle, coulometry, battery management, automotive, Hall-effect, open-loop.

1 Introduction

The automotive industry today is facing increased pressure from both government and non-government organizations, as well as from the buying public to improve it's performance in energy efficiency and reduction of air pollutants. Arguably the hottest subject facing the industry today is how to reduce emissions of CO_2, blamed for its adverse contribution to global warming. Numerous and sometimes divergent solutions are being proposed by the major car manufacturers to achieve a reduction in CO_2 emissions, while maintaining the comfort and convenience that drivers expect from today's cars. Most, if not all of these solutions require a better understanding and control of the electric currents generated and consumed by the different systems of the automobile, whether it be for charging/discharging batteries or managing the consumption and production of electric current to feed the increasing number of electric devices in automobiles today. Between the electric, the hybrid and the internal-combustion vehicles with smart technologies, there is undoubtedly an increased need to monitor and manage electric currents, their consumption and availability. To this end, car batteries are becoming the center point (and arguably the weak link) of the systems in new vehicles designed to reduce their emissions of pollutants, and the battery current measurement a critical and increasingly sophisticated junction between the battery and the rest of the system. In this paper we will look at how a standard current-measuring transducer with average offset and drift characteristics used in a battery-management application can provide a high-level of accuracy when used for current-integration.

2 Technologies of Current Sensing Transducers

Different technologies exist for measuring electric currents passing through a battery cable. Among them exist resistive technologies, using what is commonly called a "shunt", and Hall-effect technologies which capture the magnetic fields around charge-carrying bars or cables. Hall-effect technologies can, in turn be applied in closed-loop or in open-loop transducers.

Each of the these technologies has certain advantages and disadvantages relative to the other. These can relate to cost, accuracy, efficiency, and energy consumption, among others.

Resistive, or "Shunt"-based current transducers, for example, have the advantage of generally being less expensive to produce than Hall-effect transducers. However, their higher consumption of energy, and the associated losses pose problems in certain applications critical to heat and/or parasitic losses. They also "cut" the battery cable by having to be installed in-line with the current flow, causing noise or distortion.

Closed-loop Hall-effect transducers provide perhaps the highest performance of the three solutions mentioned. They are based on the same principle as **open-loop Hall-effect** solutions, but take it a step beyond. Closed-loop systems have renowned accuracy and speed in measuring currents of all amplitudes, from milliamps to kilo amps. They offer the advantage of being placed externally to the signal cable (not adding noise or cutting the cable), and do not generate any resistive losses in the systems. Resistive losses (or heat) can be a big concern when measuring high currents. By design, they can withstand very high levels of current in the primary cable without suffering permanent damage. Open-loop Hall-effect transducers offer the same advantage of isolation from the current-bearing cable as closed-loop transducers, and likewise do not generate any losses in the system being measured. They are, however, generally less accurate, and slower than closed-loop systems, and will reach magnetic saturation at currents above their designed range. Two big advantages of open-loop Hall-effect solutions are their low-energy consumption and their low cost.

All in all, the choice of technology, whether it be resistive, open-loop or closed-loop Hall-effect, or some other type, will largely depend on the particular constraints of the application. In this paper we will concentrate on open-loop Hall-effect transducers.

3 Basic Principles of Hall-Effect Transducers

The goal of a Hall-effect transducer is to provide an output signal (usually voltage) proportional to the current passing through a bar or cable. It does this by capturing the magnetic field generated by the passing primary current, and directing it to a Hall-effect cell (Figure 3-1). This cell generates a voltage potential proportional to the magnetic field passing through it. The cell is embedded on an ASIC, and this ASIC processes the cell output and sends it to an output terminal. In this way, we can obtain information about the current passing through a bar or cable without actually interfering with the primary signal, but by getting "free" information from the magnetic field that the current generates. The non-contact specificity of Hall-effect transducers makes them very interesting in high-current or high-power applications where losses from an alternative resistive "shunt" transducers can be very significant, or very costly.

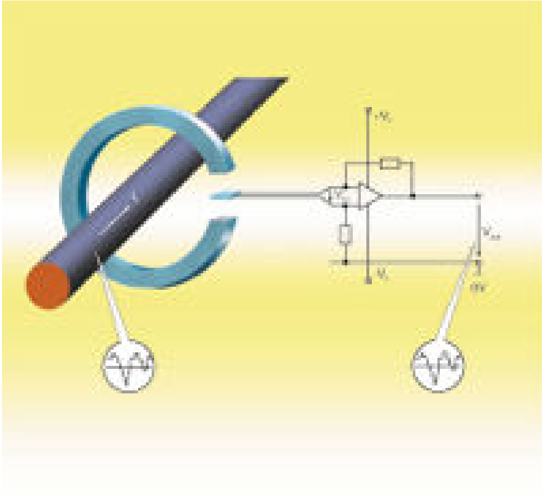

Figure 3-1: Open-Loop Hall-Effect Principle

There are three basic components to a Hall-effect transducer:

- The magnetic core
- The electronics with the Hall-effect sensor
- The housing

A closed-loop Hall-effect transducer adds a metal coil to this list of components (Figure 3-2).

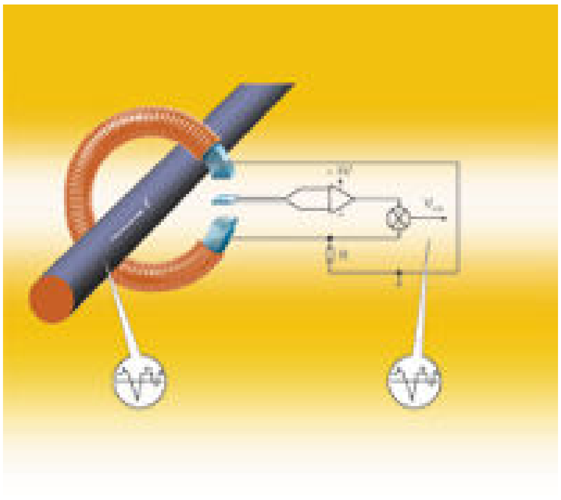

Figure 3-2: Closed-loop Hall Effect Principle

The role of the **magnetic core**, composed usually of sheaths of silicon-iron (FeSi) or nickel-iron alloys (FeNi) of varying concentrations is to direct the magnetic field generated by the primary carrier's current onto the surface of the Hall-effect sensor. The Hall-effect sensor and associated electronics, which are more and more often integrated in an **ASIC,** output a voltage potential proportional to the magnetic field flux. They convert the voltage potential output from the Hall-effect sensor into a legible signal at the output terminals of the transducer by amplifying it, and sometimes converting the signal into a pulse-width-modulated (PWM) signal or other specific protocol of communication such as local-interconnect-network protocol (LIN). These electronics can also convert the Hall cell output into a digital signal and perform additional functions such as filtering the output signal and "correcting" it from some sources of error, as per the parameters programmed into its memory during the transducer's production calibration phase. These sources of error are discussed in section 4 below.

The **housing** of the transducer serves to hold the magnetic core and the electronics together in place, to protect the assembly, and to electrically and physically isolate the primary current cable or bar from the input and output conductors of the electronics or ASIC. High-voltage primary currents could otherwise short the transducer's supply voltage and/or output signal connections.

In closed-loop systems, an additional **copper coil**, wound around the magnetic core serves to compensate the field generated by the primary with an equal and opposite field. Instead of providing an output voltage that is proportional to the primary's magnetic field, closed-loop systems provide an output that is proportional to the current required to induce a magnetic field of equal and opposite magnitude to the primary current's field. A major advantage of this method is that the closed-loop transducer coils always oscillate around 0 teslas, and thereby avoid magnetic saturation of the coil, even at very high current inputs. They operate in the most linear range of the transducer, giving the highest accuracy and the quickest reaction time possible. On the downside, they cost more to produce, have a higher content of increasingly expensive materials, and consume more energy than open-loop systems because the secondary coil needs to be fed the compensating current. The higher the measured current, the higher the transducer's energy consumption. Especially for these two reasons automotive applications rely primarily on the open-loop variety, sacrificing accuracy and reaction time for low cost and low energy consumption.

4 Sources of Error in Hall-Effect Transducers

Before understanding how we can obtain high accuracy results using open-loop Hall-effect transducers to measure car battery currents over time, we must discuss the different sources of error inherent to open-loop Hall-effect transducer designs.

There are four (4) types of errors that determine the measurement accuracy of an open-loop Hall-effect transducer. These errors emanate from the mechanical properties of the materials, such as the magnetic core in the transducer, by the resolution of the ASIC, and by the behavior of these two at different temperature ranges.

The four types of errors are:

- Electric offset
- Magnetic offset
- Sensitivity or gain
- Linearity

All the above errors can, in turn be influenced by the temperature range in which they operate. Industrial transducers are usually rated to operate in the range of -40° C to +85° C. Automotive environments are generally harsher, and sometimes require transducers capable of operating in an extended temperature range, from -40° C to +125° C.

4.1 Electric offset error

The electric offset of a Hall-effect transducer is constant for all current ranges at a given temperature. As a matter of speaking, it is the error of the zero-point of the transducer. If it were not for the magnetic offset which we address in section 4.2 below, the electric offset would be equal to the transducer output value at an input of zero (0) current. It is an error caused by several sources, including the tolerances of production and the maximum digital resolution of the ASIC, or LSB (least significant bit) which has the "zero" position programmed during the production calibration phase. If the "zero" position happens to fall between two digital values, the choice of either value as the zero point will introduce an error equal to the difference between the chosen zero point (the chosen bit) and the actual zero point.

Electric offset is also significantly affected by temperature. The ASIC is the element of the transducer most affected by it. The different expansion and contraction coefficients of the ASIC components play a role in affecting the output signal from it. Temperature behaviors will generally be constant for a particular ASIC or transducer over it's lifetime, but may vary from ASIC to ASIC, or from one ASIC production batch to another. It is therefore very difficult to remove or compensate in high-volume production components (Figure 4-1).

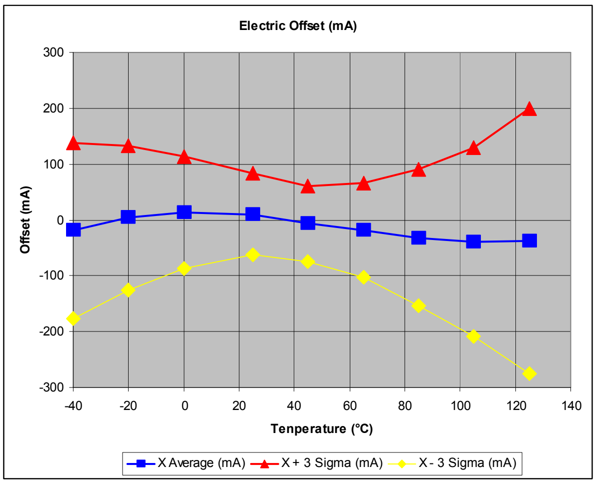

Figure 4-1 : Electric Offset Variation in Temperaturture

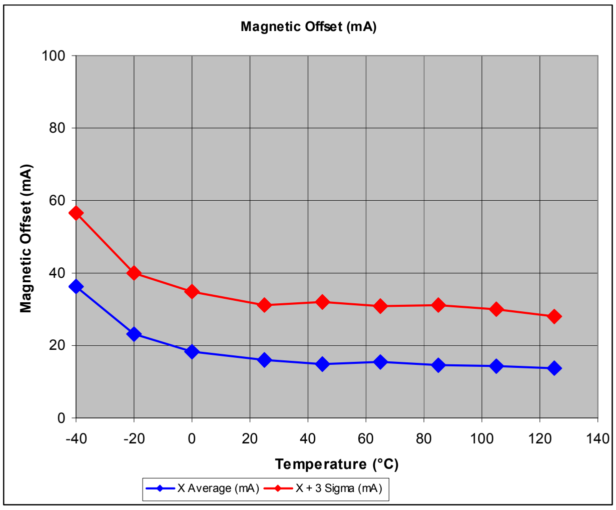

Figure 4-3 : Magnetic Offset Variation in Temperatature

4.2 Magnetic offset error

Magnetic offset in Hall-effect transducers is a measurement shift caused by the residual flux (or remanence, B_R) of the magnetic core in the transducer. It's value is dependent on the previous core magnetization and is highest after the coil has been magnetized to full saturation or beyond. It can be characterized as the hysteresis in the transducer's response. A given input current, I_P will produce different output values depending on whether I_P was higher or lower moments before the reading. Though impractical in many applications, magnetic offsets can be removed or minimized before making a measurement with the transducer by feeding a degauss cycle (Figure 4-2) to demagnetize the transducer's coil.

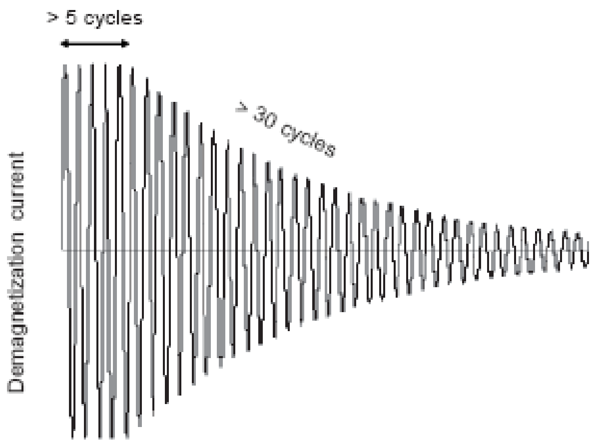

Figure 4-2: Degauss Cycle Current

4.3 Sensitivity or gain error

Sensitivity or gain error is generated by tolerances in the air gap between the Hall cell and the magnetic core brought on by the expansion and contraction of the core with temperature changes, and/or by mechanical stresses on the ASIC itself. These mechanical stresses can be generated by the ASIC's packaging, or by temperature and humidity changes. Much effort is being put into finding ways of reducing the vulnerability of the ASIC to these environmental stresses. Like with the electric offset, the resolution of the digital system, or LSB will also contribute to the gain error.

In a plot of V_{OUT} vs. I_P the gain error is equivalent to the error in slope of the response curve. Contrary to the electric offset, which is constant over all current ranges at a given temperature, the sensitivity error is proportional to the primary current, I_P. Gain error is also significantly affected, like the electric offset error, by temperature, as shown in Figure 4-4 below.

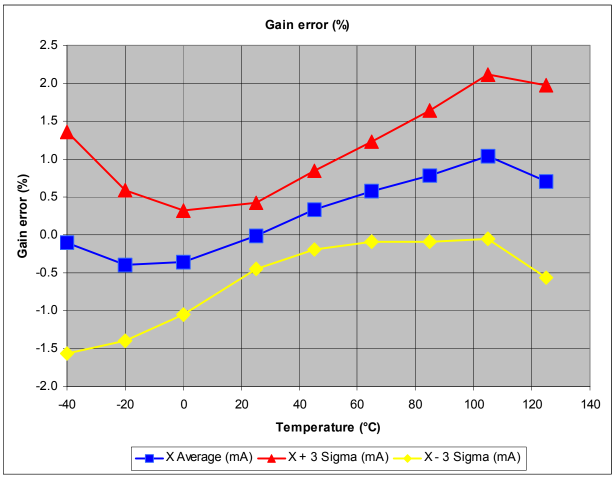

Figure 4-4 : Gain Error Variation in Temperature

4.4 Linearity error

Linearity of the transducer is the "straightness" of the response curve over the operating range. Linearity error is caused by saturation of the magnetic core, the magnetic offset mentioned in section 4.2 above, and by the ASIC design. To avoid the occurrence of linearity errors due to the saturation of the core, we can choose a transducer type whose magnetic core will not reach saturation levels while operating in the desired current range for the specified application. The transducer will henceforth be operating in the "linear" portion of the response curve. Since magnetic offset is treated as a separate error characteristic, we will generally not include it's impact when talking about linearity error. In this way, when we speak of linearity error, we will generally be talking only about the ASIC's contribution to this error. A good ASIC design can help minimize errors of linearity.

5 Global Error of Current Transducers

When a particular transducer is put on the market, there is usually a data sheet that is made available with the technical description of the transducer's characteristics and behavior. In this data sheet appear the results of lab testing performed by the manufacturer, which include the individual error values calculated for the specific transducer. In this way, it becomes possible to know, for example, the electric offset error characteristic of a transducer, it's magnetic offset error, and overall linearity over a given temperature range. Data sheets for different transducers can also then be compared for their respective error behaviors, and on this basis a choice can be made of the best transducer for a given application.

More than the specific electric, magnetic, and gain errors, engineers will be most interested in the overall or global error behavior of a transducer. In this way, the global transducer error can most easily be added to the error of the complete system, of which the transducer is a part. The easiest way to compute a global transducer error is to simply add the different errors from the data sheet, obtaining a total maximum error for the transducer. For example, the data sheet for a particular transducer can state an offset error of +/- 300 mA from -10°C to 65°C, or +/- 500 mA from -40°C to +125°C. The gain error can be stated as +/- 2.5% from -10°C to 65°C, and +/- 4.0% from -40°C to +125°C. A linearity error of +/- 1.0% can be given for the whole operating range. With this information, we might decide that our particular application requires the transducer to operate in an extended temperature range up to +125°C, and that therefore the corresponding error values must be taken. If the application requires a maximum current measurement range of +/- 25 A, we will calculate the overall error to be:

= 0.5 A + 4% of 25A + 1% of 25 A

= 1.75 A of error at 25 A, or 7%

Based on this result of 7% error, we will decide whether the performance of the transducer is sufficient for the application in question. Oftentimes, since the transducer error must be added to other errors in the system, it will be determined that the transducer performance is insufficient for the particular application, and a higher-performance and often higher-cost transducer will be sought.

Fortunately or unfortunately, the calculation above is overly simplistic and does not represent the real behavior of the transducer when used to integrate current values over time. Though each of the elements of error in the data sheet are correctly stated as being the measured result from the laboratory, the sum of the elements does not correctly represent the behavior of the transducer in dynamic operation. In operation, errors interact and will in some cases add up, and in other cases subtract from each other. It is impossible for the transducer's overall error to ever be the arithmetic sum of the different error elements, as calculated previously. This is an important consideration to keep in mind when choosing the transducer design for a given system application in order to avoid choosing a solution with higher performance, and usually higher cost than necessary.

6 Current profile cycle

To understand the actual performance of a current transducer in current integration, a current profile or cycle over a particular time frame must be defined. This current profile simulates the charging and discharging cycles that the car battery might experience, and therefore that the transducer might measure in a normal cycle of operation outside the laboratory (Figure 6-1).

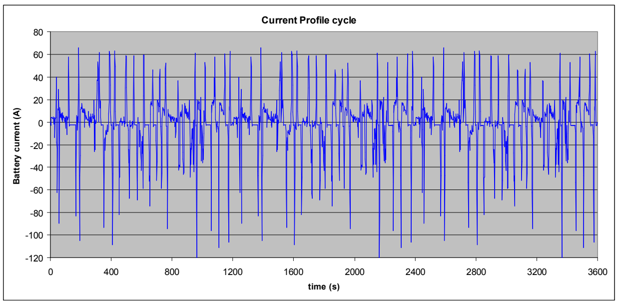

Figure 6-1 : Current Profile

7 Interaction of errors in a dynamic system

In HEV applications, for example, it is very important to have an accurate picture of the consumption and generation of electric current over time in order to optimize the various systems in the vehicle. To evaluate the systems' performance, a standard current profile cycle such as described in section 6 above is defined to allow different system configurations to be compared to a single benchmark.

When used in HEV or internal combustion engine applications, or applications where the current flows in both directions are about the same, (not the case of purely electric vehicles), the transducer errors will to a great extent cancel out, resulting in an error of integration that is much smaller than the transducer's benchmark performance values might indicate. This error can be so small as to become negligible in consideration of the overall system.

Our goal is to measure the error that the transducer will generate while integrating a charge/discharge cycle such as the one in Figure 6-1 above.

Of all the transducer errors mentioned above in section 4, the most important ones to keep in mind in current integration applications are linearity and electric offset. The gain error and magnetic offset will generally be small because of cancellations during the cycle integration.

Electric offset is the most important source of error in current-integration applications. This is simply because, no matter whether the primary current is positive or negative, the electric offset will always be of the same magnitude and sign (positive or negative). This means that over a cycle measurement of one hour, for example, the electric offset error contribution at the end of the cycle will be equal to the electric offset. It will not have been cancelled out by opposite-sign currents. It is therefore critical to choose a transducer with a low electric offset error, or have the ability to eliminate the error through other means, such as a system calibration.

Linearity is the second most important source of error because a strongly non-linear transducer response curve will cause the linearity errors to add up instead of cancel out in a balanced cycle of charging and discharging current. When linearity is good, whatever error is generated by the transducer during a positive current input will be cancelled by an error of equal magnitude but opposite sign when a negative current of equal magnitude is fed through the transducer.

Gain error and magnetic offset are less worrisome in a balanced current cycle since they will mostly be reduced to negligible levels. Gain error being a product of the transducer's gain error characteristic multiplied by the primary current, when the primary current is negative, an equal and opposite error will be generated by the transducer, and these will cancel out at the end of the integration.

Likewise for the magnetic offset, errors generated during a positive-sign current flows will be compensated and cancelled by negative-sign flows. Of course, since most operation cycles are not perfectly symmetric in terms of positive and negative current levels and durations, some magnetic offset and gain errors will remain. These will usually be negligible when compared to the total integrated current value.

Perhaps it becomes easier to understand when we look at Figure 7-1 below which represents the error in the transducer output measurement values (red dots) taken when the transducer was cycled through a current profile such as in Figure 6-1.

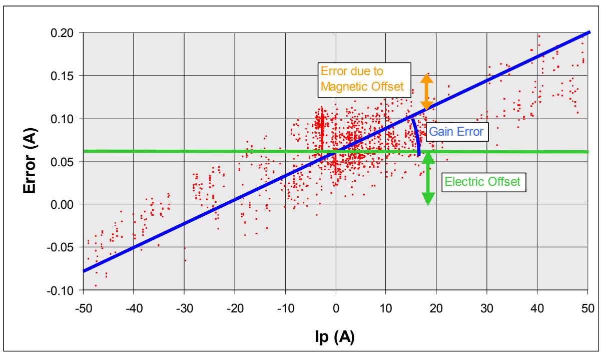

Figure 7-1: Transducer Output Error for Given Cycle

The error ε_j of a point *j* for any one measurement (any red dot in the above figure) can be defined as follows:

$$\varepsilon_j = \left(\varepsilon_{elec\_offset} + \varepsilon_{mag\_offset} + \varepsilon_{gain\_error}\right) \times \frac{t}{3600}$$

t represents the sampling rate of the transducer, in seconds, and the factor $\frac{t}{3600}$ enables the error to be expressed in A·h (amp hours).

We can see from the graph that when integrating all the measured values over time, errors caused by a positive magnetic offset (values above the blue gain-error line) will on average be compensated by the negative magnetic offsets (values below the blue line). Similarly for the gain, errors from positive primary current compensate errors from negative primary current. This leads the magnetic offset and gain errors to be very small.

Electric offset, on the other hand, represented by the green horizontal line in Figure 7-1 will be constant for all primary current values. It's impact on the error of the current integration will be it's value. It's contribution to error is therefore considerable.

Linearity errors are not shown on this particular graph because the transducer used in the measurements has very good linearity in the chosen current range. Linearity errors were therefore assumed to be negligible. Nevertheless, if there were a significant linearity error, it would be represented as a blue line that would be curved or wavy instead of straight. One can see that in such a case, the symmetry between positive and negative primary currents would not be respected, and the various error values would not cancel out.

8 Presentation of Data

To confirm the argument that a standard open-loop Hall-effect current transducer with standard performance can provide very accurate results in current integration (or coulometry), several laboratory measurements were performed.

To demonstrate the above, current-integration measurements were performed using ten (10) standard automotive-grade LEM model DHAB S/34 transducers with dual magnetic cores (one core for measuring currents up to 50A, and the other core for measuring above 50A and up to 200A), and applying a particular current profile cycle lasting one hour (as in Figure 6-1). A reference measurement was concurrently made using laboratory-grade equipment, allowing for a comparison of the measurements and a determination of the accuracy of the DHAB transducers. Figure 8-1 shows the results.

	Sensor	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Reference current integration (mAh)	Low Range (mAh)	1186.55	1186.55	1186.55	1186.55	1186.55	1185.28	1185.28	1185.28	1185.28	1185.28
	High Range (mAh)	-1489.94	-1489.94	-1489.94	-1489.94	-1489.94	-1489.35	-1489.35	-1489.35	-1489.35	-1489.35
	Total (mAh)	-303.39	-303.39	-303.39	-303.39	-303.39	-304.07	-304.07	-304.07	-304.07	-304.07
DHAB current integration (mAh)	Low Range (mAh)	1186.18	1198.99	1173.26	1200.01	1198.38	1224.46	1173.36	1180.86	1159.99	1219.37
	High Range (mAh)	-1515.19	-1513.68	-1512.78	-1450.11	-1471.67	-1502.11	-1502.55	-1496.66	-1500.16	-1503.41
	Total (mAh)	-329.01	-314.69	-339.52	-250.10	-273.29	-277.66	-329.19	-315.80	-340.18	-284.04
Sensor error (mAh)	Low Range (mAh)	-0.37	12.44	-13.29	13.46	11.83	39.17	-11.92	-4.42	-25.29	34.09
	High Range (mAh)	-25.25	-23.74	-22.84	39.83	18.27	-12.76	-13.20	-7.31	-10.82	-14.07
	Total (mAh)	**-25.62**	**-11.30**	**-36.13**	**53.29**	**30.10**	**26.41**	**-25.12**	**-11.73**	**-36.11**	**20.03**

Figure 8-1 : DHAB S34 Transducer Current-Integration Error Measurements

In Figure 8-1 above we can observe that the error of current integration of the DHAB S34 in the selected one-hour profile cycle ranges from 11 to 54 mAh, depending on the transducer sample. This is quite a remarkable result, considering that the current cycle has peaks above +60 A and below -120 A, and that the average measured value in the cycle is around 16 A.

In contrast to the above values, Figure 8-2 shows an extract of the DHAB S/34 transducer data sheet, from which we can compute that the low-current channel (Channel 1) provides a maximum error of 3.9 % when the electric and magnetic offset errors, the gain and linearity errors are added together. By the same method the high-current channel (Channel 2) provides a maximum error of 4.2 %, or 8.5 A at 200 A. This performance is quite normal for an open-loop Hall-effect transducer of this kind, yet pales in comparison to the performance achieved when using the transducer in a coulometry, or current-integration application.

Accuracy :

Channel 1 :

PARAMETER	Symbol	Unit	Specification Min	Specification Typical	Specification Max	Conditions
ELECTRICAL DATA						
Electrical offset current	$I_{OE\ channel1}$	mA		±50		@ T_A = 25°C
Magnetic offset current	$I_{OM\ channel1}$	mA		±50		@ T_A = 25°C
Global offset current	$I_{O\ channel1}$	mA		±100		@ T_A = 25°C
			-200		200	@ - 10°C < T° < 55°C
			-350		350	@ - 40°C < T° < 125°C
Sensitivity error	ε_G	%		±0.5		@ T_A = 25°C
			-2		2	@ - 10°C < T° < 55°C
			-3		3	@ - 40°C < T° < 125°C
Linearity error	ε_L	%		±0.5		of full range
Temperature coefficient of V_{OE}	TCV_{OE}	mV/°C	-0.14	± 0.05	0.14	@ - 40°C < T° < 125°C
Temperature coefficient of G	TCG	%/°C	-0.02	± 0.01	0.02	@ - 40°C < T° < 125°C

Channel 2 :

PARAMETER	Symbol	Unit	Specification Min	Specification Typical	Specification Max	Conditions
ELECTRICAL DATA						
Electrical offset current	$I_{OE\ channel2}$	A		±0.2		@ T_A = 25°C
Magnetic offset current	$I_{OM\ channel2}$	A		±1.5		@ T_A = 25°C
Global offset current	$I_{O\ channel2}$	A		±1.7		@ T_A = 25°C
			-2.5		2.5	@ - 10°C < T° < 65°C
			-3		3	@ - 40°C < T° < 125°C
Sensitivity error	ε_G	%		±0.5		@ T_A = 25°C
			-2		2	@ - 10°C < T° < 55°C
			-3		3	@ - 40°C < T° < 125°C
Linearity error	ε_L	%	-1		1	of full range
Temperature coefficient of V_{OE}	TCV_{OE}	mV/°C	-0.14	± 0.05	0.14	@ - 40°C < T° < 125°C
Temperature coefficient of G	TCG	%/°C	-0.02	± 0.01	0.02	@ - 40°C < T° < 125°C

Figure 8-2 : LEM DHAB S/34 Transducer Accuracy

9 Conclusion

A standard current-measuring transducer with average performance characteristics is able to provide very high-level of accuracy when used in current-integration applications. This high level of performance can be achieved because magnetic offset and gain errors are cancelled when a transducer with good linearity is used with a fairly well balanced current profile cycle that is typical in HEV or internal-combustion vehicle applications with battery management systems. The realization of this behavior allows the focus of attention to be on the quality of the measurement results, and not on the benchmark performance characteristics of the transducer being considered. Furthermore, it allows an optimized-cost solution to be determined quickly by understanding the real-world performance of a particular transducer, instead of it's laboratory benchmark values. This is why for the past several years now, the world's top car manufacturers have been using open-loop Hall-effect transducers in their battery management systems. A logical follow-up to this analysis would be to define the real-world performance specifications that allow for a quick understanding of a transducer's real-world performance, and an expedited comparison among different transducer models or types. Simulation tools are being developed to speed up the process of determining a transducer's performance when applied to a specified current cycle, thereby doing away with the guesswork involved in choosing a transducer solely on the basis of its gross error characteristics. A description of one such simulation tool is being presented at the end of this week at the 9th International Power Supply Conference and Exhibition in Nice, France.

10 Acknowledgement

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11 Glossary

Coulomb: Unit of measure of energy. Equivalent to the quantity of electricity passing through a conductive wire with a current of 1 Ampere during 1 second (1 A·s)

Primary current: the electric current from the battery or other device that is being measured.

ASIC: Application-Specific Integrated Circuit. A chip designed to perform a specific task.