Chapter 7

Current-Sensing Techniques

While Hall-effect sensors are most frequently used to detect the proximity, position, or speed of mechanical targets, they are also useful for sensing electrical current. This is done indirectly, by measuring the magnetic field associated with current flow. Before getting into magnetic current sensing, let's talk about the more commonly used technique of resistive current sensing.

7.1 Resistive Current Sensing

Resistive current sensing exploits the voltage drop associated with an electrical current flowing through a resistor, as shown in Figure 7-1.

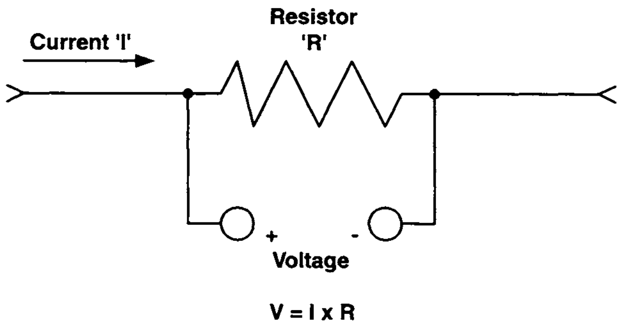

Figure 7-1: Current sensing with a resistor.

The voltage measured across a resistive current sensor is proportional to the current passing through the resistor, and is given by $V = IR$. Because resistors are inexpensive and are readily available in a number of forms, power ratings, and precisions (accuracies of 0.1% and better are readily obtainable), resistive current sensing is both popular and useful in many applications. Resistive current sensing does, however, have a few disadvantages. Among the more significant are:

- Lack of electrical isolation
- Common-mode voltage
- Voltage drop and energy loss

Lack of electrical isolation between the power-handling circuit and measurement circuit can be a major drawback with resistive current-sensing techniques. Because it is necessary to measure the voltage at the terminals of the resistor, the current-sensing instrument must become part of the circuit being monitored. For some applications, particularly ones operating at low voltage and power levels, this may not be an issue. For other applications, however, safety concerns will make it mandatory that the measurement circuit be separated from the power-handling circuit. This is often the case when monitoring current in systems that operate at line (117/220 VAC) voltage or higher. To provide isolation for a resistive current sensor requires the addition of significant amounts of electronics.

The requirement of measuring the voltage across the resistor can also become a problem, especially if the voltages at both of those terminals are significantly above the measurement system's ground reference. As an example, consider a 0.1Ω current sensing resistor in a 50V line. Each ampere of current will only result in 0.1V of signal across the resistor. For the case of 1A of current, the voltages at each side of the resistor with respect to system ground will be 50V and 49.9V. Discriminating this small differential signal (0.1V) riding on a large common mode signal ($\approx$ 50V) can be a difficult measurement problem. One way to deal with this situation is to add electrical isolation circuitry to the measurement system, and allow part of the measurement system to "float" at the higher voltage. This is essentially what happens when one uses a handheld DVM (digital voltmeter) to measure current; the meter electronics "float" up to whatever voltage is present at the input terminals.

Voltage drop and its associated energy loss is the third major problem with resistive current sensing. In order to sense current, one needs to develop a voltage drop across the resistor. This voltage drop is given by $I \times R$. What constitutes an acceptable voltage drop is determined by the application; usually the smaller, the better. For purposes of measurement accuracy, however, one typically wants as much voltage drop as possible. The designer must therefore make the appropriate trade-off between signal magnitude and the degree to which the measurement interferes with the system being measured.

The voltage drop across the measuring resistor is also associated with power dissipation, in the form of heat. Power dissipation is given by $P = I^2R$, and is significant for two reasons. The first is that this is energy that is lost from the system under measurement, and its loss results in reduced efficiency. The second reason is that enough power dissipated in a resistor will make that resistor hot, and may require special measures to keep it cool. For sensing small amounts of current (100 mA) resistor power dissipation may not be a major concern. For larger currents, such as those that might be found in a battery charger or large switch-mode power supply (>100A), power dissipation in a sense resistor can literally become a burning issue.

Now that we have discussed a few of the more important shortcomings of resistive current sensing, we can talk about magnetic current sensing. The main advantage of magnetic current sensing is that it doesn't interfere with the circuit in which the current is being sensed (at least for DC currents). Because one is measuring the magnetic field around a conductor, there is no electrical connection to that conductor. This automatically provides electrical isolation from the circuit being monitored. This also means that common-mode measurement effects disappear, because a magnetic current sensor doesn't care what voltage potential the line being measured is at, provided, of course, that it is within the designed safety limits of the sensor assembly (e.g., the insulation doesn't break down). Because a resistive component is not added in series with the circuit, there are no additional *IR* voltage losses or I^2R power dissipation effects. This allows magnetic current sensors to be used to measure high current levels without excessive power dissipation.

7.2 Free-Space Current Sensing

Conceptually, a current sensor can be made by placing a linear Hall-effect sensor in close proximity to a current-carrying conductor. The sensor should be oriented so that the magnetic flux lines, which circle the conductor as shown in Figure 7-2, can be detected.

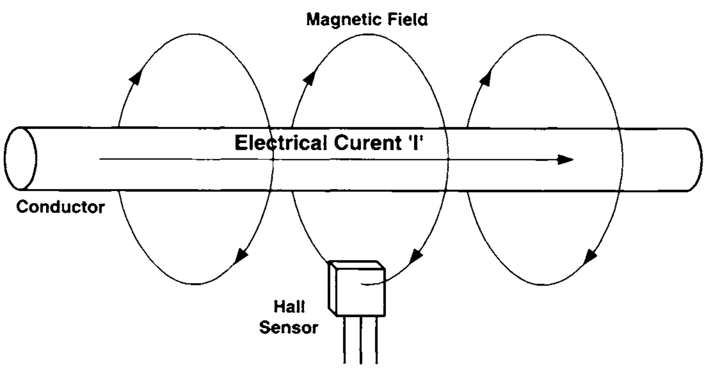

Figure 7-2: Current sensing in free space around conductor.

Assuming that nothing other than empty space surrounds the conductor, the conductor has a circular cross-section, and extends off in a straight line to infinity in both directions, the magnitude of the sensed field is given by Equation 7-1.

$$B = \frac{\mu_0 I}{2\pi r} \qquad \textbf{(Equation 7-1)}$$

where r is the distance from the centerline of the conductor to the sensor.

While this scheme is simple and elegant, several difficulties can arise when trying to implement it in the real world. First, you don't get very much field for a given amount of current, at least for macroscopic conductor-to-sensor spacings. A 10-A current develops only about 2 gauss at a 1-cm distance. One consequence of this is that the sensor will be influenced by external fields. Considering that the earth's magnetic field is about ½ gauss, a current sensor implemented in this manner (with a 1-cm spacing) could experience as much as ±2.5A of error based just on the direction in which it is pointing (north-south-east-west). While potentially useful for current sensors intended for measuring large currents (hundreds or thousands of amperes), this approach may not be suitable for measuring smaller currents where extraneous fields could cause significant measurement errors.

A second difficulty with this scheme is that it is highly sensitive to positioning errors between the conductor and sensor. This becomes especially true when the separation is small. To make an effective current sensor, it is necessary to tightly control the location of the sensor.

A third difficulty is that the sensitivity given above assumes the existence of an "infinitely long, straight conductor" (as the physicists like to say). Unfortunately, you can't buy this kind of conductor anywhere, and you will probably have to settle for one of the short, bent variety found in the real world. Conductor geometry will have some effect on the sensitivity of one's current sensor. This is bad news if the conductor can change shape or flex after installation and calibration.

One situation where it may be possible to overcome many of these problems is when both the conductor and the Hall-effect sensor are rigidly mounted on a printed-circuit board, as shown in the examples illustrated in Figure 7-3. By using the PCB traces to carry current, it is possible to tightly control the conductor geometry and spacing to the sensor. Note that the Hall-effect sensor is not placed over the conductor, but next to it. This is because the magnetic flux immediately over the conductor runs parallel to the surface of the board, and is therefore not coincident with the sensor's sensitive axis. The flux does, however, run perpendicular to the board past the edge of the conductor, and this is where the sensor should be placed, as shown in Figure 7-3a.

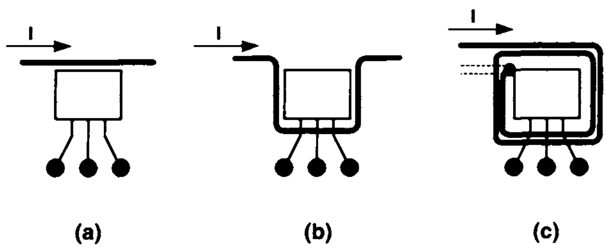

Figure 7-3: Current sensors on printed circuit boards.

When making a PCB-based current sensor, one can employ a number of techniques to get more field per unit current and increase the system's sensitivity. The first is to use as narrow a PCB trace as is possible consistent with safely handling the expected current flow. Flux lines resulting from a given current have a shorter path when looping around a narrow PCB trace than a thicker one, resulting in more field per unit of current. Note, however, that as you reduce the width of the PCB trace, its resistance increases and its maximum allowable current ratings will decrease. Additionally, if you encapsulate the PCB, the maximum current that can be safely handled may vary considerably depending on the thermal conductivity of the encapsulation material.

Another flux-intensification technique is to form a cul-de-sac into which the sensor is inserted (Figure 7-3b). This effectively superimposes the fields from the three sides of the cul-de-sac onto the sensor. One can also extend this idea further, and create loops (Figure 7-3c) in the PCB trace, and place the sensor in the middle. This geometry, will requires either a double-layered board or the use of jumpers. Be very cautious when using ordinary PCB plated-though "vias" for carrying high currents, as they can have relatively high resistance and become prone to failure when carrying high currents.

Note that, because the conductor geometries of the above examples have departed far from the physicists' ideal, the magnitude of the field is no longer given by Equation 7-1. Because of these more complex geometries, finite-element analysis (on a computer) or sophisticated mathematical analysis (by hand) are necessary to accurately predict the resulting magnetic fields.

Another issue, previously alluded to, that arises from using PCB traces for current sensing is that they have nonzero resistance. While this results in heating effects and imposes thermal limits on how much current can be safely handled, excessive resistance also can interfere with the measurement process. If you use a long-enough PCB trace, you may add enough resistance to the current-carrying circuit to interfere with its operation, and consequently reduce the accuracy of the current measurement. Adding series resistance into the measurement circuit reduces one of the primary benefits of using magnetic current sensors.

As a final note, electrical isolation can become a serious issue with PCB-based current sensors. Because the current-carrying traces are in close proximity to the sensor (and associated measurement electronics), sufficiently high voltage differences can cause current to flow between them. Typical leakage paths are through the PCB substrate (insulation breakdown), over the PCB surface (creepage), or through the air above the PCB (arcing). If safety or electrical isolation are a concern when implementing this kind of sensor, consult with the relevant safety agencies (e.g., UL, CSA, TUV) to obtain guidelines and standards for construction techniques suitable for various environments and applications.

7.3 Free-Space Current Sensors II

While using a Hall-effect sensor placed near a conductor as a current sensor may not be the most practical solution to most current-sensing problems, it can be useful in applications where very high current levels need to be sensed, and conductor geometry can be controlled. Increasing the effectiveness of potential designs requires that we take a look at some of the underlying physics in more detail.

Equation 7-1, describing the field around a conductor, is a special case of one of Maxwell's equations. A more basic relationship, valid for all geometries of current flow and magnetic field (in empty space), is given by Equation 7-2.

$$\oint B \cdot ds = \mu_0 I \qquad \text{(Equation 7-2)}$$

To illustrate what this means from a physical standpoint, consider Figure 7-4a, where a current-carrying conductor of arbitrary shape and size is completely enclosed by an arbitrary path around it. The only constraint is that the path must completely enclose all of the current. If one makes a single circuit of this path, integrating the magnetic field tangent to the path direction as one moves along, the integral of the field will be $\mu_0 I$.

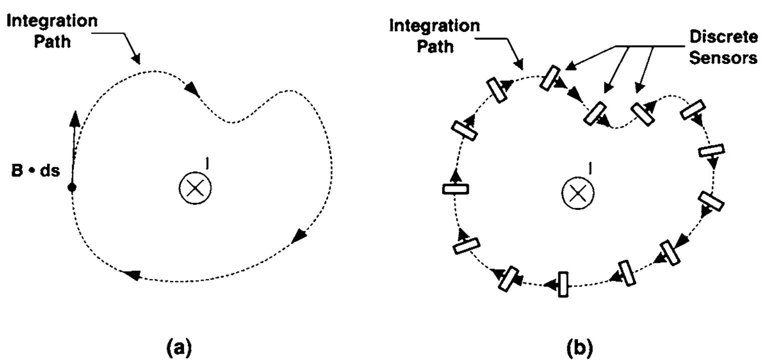

Figure 7-4: Integration of flux around a closed path (a) and discrete approximation (b).

This integral may also be approximated by taking a large number of discrete measurements at evenly spaced points along the path (Figure 7-4b). Again, the axis of each measurement has to be tangential to the path at the point at which it is taken. The sum of all these measurements is proportional to the current enclosed by the path, regardless of the geometry of the current or the geometry of the path. Additionally, this aggregate measurement will be relatively insensitive to current sources outside of the sensor path, provided enough measurement points are used.

The relationship defined by Equation 7-2 is exploited by an inductive current sensor called a Rogowski coil (Figure 7-5), where a coil of many turns of wire is wound on a long, flexible carrier. To measure current, the carrier is wrapped once around the current-carrying conductor, and a voltage read from the coil. Because it is inductive, the Rogowski coil is only useful for measuring AC currents. Because of its physical flexibility, however, it is very useful for making measurements in places where physical accessibility may be limited.

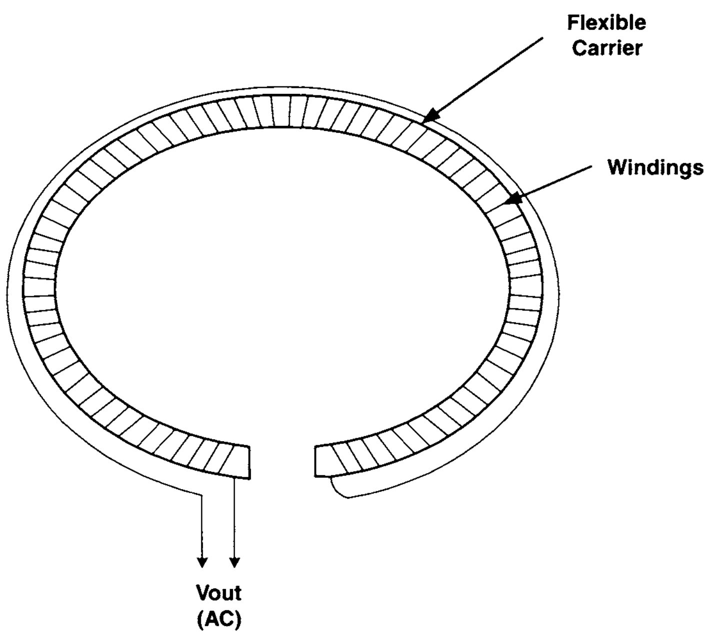

Figure 7-5: Rogowski coil AC current sensor.

While one could build a Hall-effect version of a Rogowski coil, using a large number of discrete Hall-effect sensors instead of wire windings, it would be an expensive proposition; good linear Hall-effect sensors cost considerably more than copper wire. Some of the benefit of the ring-of-sensors concept can also be obtained by using just a few devices. Consider the example shown in Figure 7-6, where four sensors are placed along a circle of radius r at 90° increments. Note that the orientation and polarity of each sensor is arranged to provide a positive response to magnetic flux flowing in a clockwise direction.

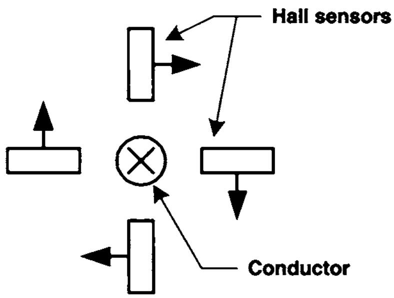

Figure 7-6: Free-space current sensor using four Hall-effect devices.

Although four sensors will not provide a very close approximation to the contour integral of Equation 7-2, they do make for a current sensor that is relatively insensitive to conductor position, at least when compared to the case where one uses a single sensor. By assuming that the central conductor is circular, infinitely long and straight, an analytic expression (Equation 7-3) can be derived for the total flux sensed by the four sensors as a function of conductor position.

$$B_T = \frac{\mu_0 I}{2\pi}\left(\frac{x+r}{\left((x+r)^2+y^2\right)} - \frac{x-r}{\left((x-r)^2+y^2\right)} + \frac{y+r}{\left(x^2+(y+r)^2\right)} - \frac{y-r}{\left(x^2+(y-r)^2\right)}\right)$$

(Equation 7-3)

Each of the terms represents the tangential field seen by each of the four sensors. Although Equation 7-3 is a closed-form solution, it doesn't provide much intuition into the system's behavior. Figure 7-7, a plot of the value of B_T as a function of x and y, yields a bit more insight.

When the conductor is located near the center of the four sensors, the response is relatively uniform; it is within ±2% out to a radius of $0.4r$. When one moves the conductor near any one of the four sensors, however, the response increases dramatically. When one leaves the circle, it drops equally dramatically towards zero. Additionally, consider the effect of a uniform, externally imposed field on the system. Extraneous uniform fields detected by any one sensor will be canceled out by the measurement from the sensor on the other side of the ring. Even for the case of nonuniform external fields (such as what might be obtained from a nearby magnet), the opposing sensors will still often provide some cancellation.

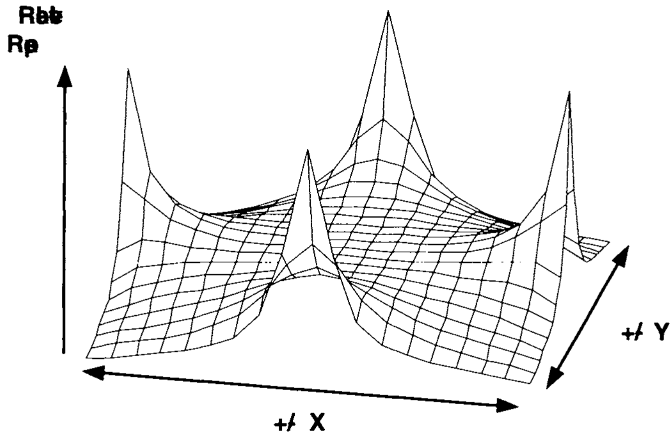

Figure 7-7: Response of four-probe current sensor as function of conductor position.

To illustrate this type of sensor, consider four A1301 linear Hall-effect sensors placed on a 2.5-cm diameter ring, mounted into a PCB to fix their positions (Figure 7-8a). A 1-cm hole is provided to pass a conductor through. The outputs are tied together through 10 kΩ resistors so that they are averaged together (Figure 8-8b). A 0.1-μF capacitor is also included for power supply decoupling.

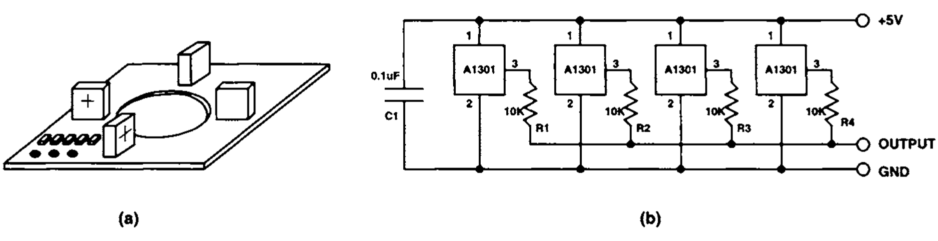

Figure 7-8: Example of ring sensor. Physical layout (a), schematic (b).

If one assumes the conductor is centered in the ring, the field-per-unit-current seen by all four sensors will be equal, and is given by:

$$\frac{B}{I} = \frac{\mu_0}{2\pi r} = \frac{4\pi \times 10^{-7}\,(\mathrm{H/m})}{2\pi \cdot 0.0125\mathrm{m}} = 1.6 \times 10^{-5}\ \mathrm{H/m^2}\ (\mathrm{T/A}) = 0.16\ \mathrm{G/A}$$

(Equation 7-4)

Tying the outputs together through resistors has the effect of averaging them, so the overall sensitivity of this sensor is the same as the average of the sensitivities of the individual A1301's, nominally 2.5 mV/G. Multiplying this by the magnetic gain of the circuit gives an overall sensitivity of:

$$\frac{V_{OUT}}{I} = \frac{0.16\text{G}}{\text{A}} \times \frac{2.5\text{mV}}{\text{G}} = 0.4\text{mV / A} \qquad \textbf{(Equation 7-5)}$$

Because the A1301 will provide linear output for fields over the approximate range of ±800 gauss, this current sensor assembly will be able to measure current over a span of ±5000A (800G / (0.16G/A)). Because we only used four sensors to approximate a true integration, there will be significant sensitivity to current outside the ring (as indicated above), and the shape and path of the conductor as it passes through the ring will also influence the sensitivity as measured in volts/ampere.

7.4 Toroidal Current Sensors

Because free-space current sensors suffer from the dual problems of lack of sensitivity and susceptibility to outside interference, they are often not the best choice for most applications. Fortunately, there is a simple way to make highly sensitive current sensors that are very immune to external interference. This is accomplished by placing a high-permeability flux path around the conductor to concentrate flux at the sensor. Although many structures can be used to perform this function, toroidal flux concentrators are commonly used for this purpose, and for the purposes of this discussion are also amenable to simple analysis.

When one places a high-permeability toroid around a current-carrying conductor, the flux flowing around the toroid can be significantly greater than that in the space around it. When the conductor is centered in the toroid, the toroid's presence will not alter the shape of the field (circular, as shown in Figure 7-9a), but will cause significant increase in flux density (Figure 7-9b) when one enters the interior of the toroid.

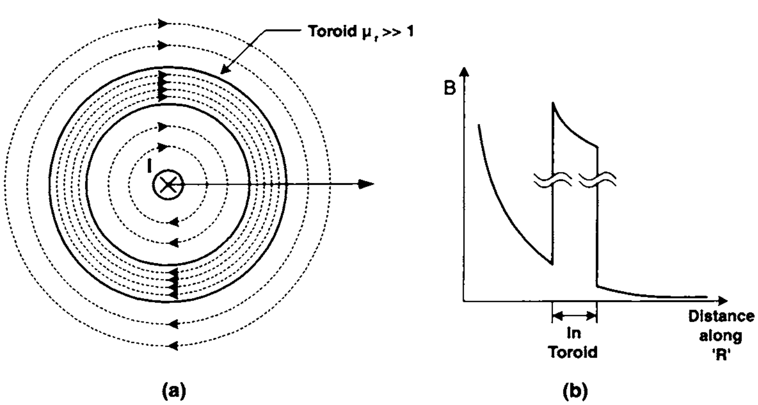

Figure 7-9: Magnetic field in and near toroid (a) and intensity profile (b).

For a toroid constructed of an idealized linear magnetic material, where μ_r is constant with respect to magnetic flux, the field in the toroid can be calculated by:

$$B = \frac{\mu_0 \mu_r I}{2\pi r} \qquad \textbf{(Equation 7-6)}$$

where r is the radius of the toroid at the point of interest and μ_r is the relative permeability of the toroid. A material's relative permeability can be thought of as how well it can "conduct" a magnetic field as compared to free space.

When the relative permeability of the toroid is very high (>100–1000), the field in the toroid becomes less dependent on exact placement of the conductor. This occurs for two reasons. First, magnetic flux density can't suddenly drop without diverging. This means that the flux flowing around the toroid is constrained to flow around the toroid; for the most part it can't take a shortcut through the air in the middle. A small amount of the flux does do this, however, but the more permeable the toroid is, the smaller the portion of leakage flux escapes (exaggerated in Figure 7-10). This containment effect causes the flux to be more or less uniform in the toroid, with a higher intensity near the inner diameter.

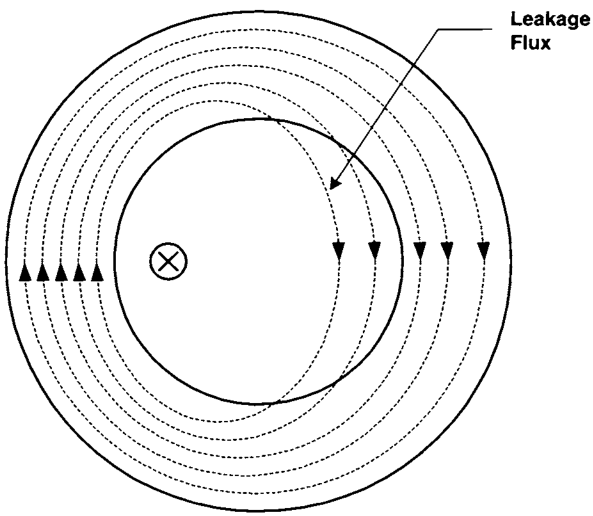

Figure 7-10: Off-center current causes leakage flux to escape toroid.

Because the magnetic flux is constrained to a path, the integral of the flux has to be proportional to the current surrounded by that path. This makes the flux essentially independent of the placement or geometry of the current, as long as it passes through the center of the toroid.

7.5 Analysis of Slotted Toroid

The previous analysis described how magnetic fields behave in a high-permeability closed toroid. To measure the magnetic field, however, requires that a sensor be inserted into the flux path. This can be done most easily by cutting the toroid so that it becomes a C-shaped structure. This slot must be cut all the way through the toroid (Figure 7-11a), flux will tend to seek the shortest path through the uncut section and avoid jumping across the gap (Figure 7-11b).

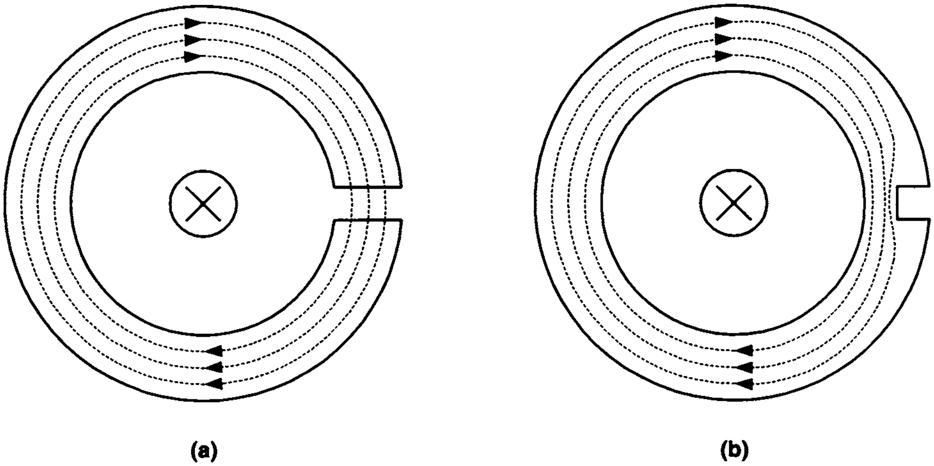

Figure 7-11: Preferred (a) and nonpreferred ways (b) to slot a toroid.

Because the flux must be continuous as it crosses the faces of the toroid forming the gap, it must be the same as the flux inside the toroid. In actuality, the flux will diverge (fringe) as it crosses the gap, so the intensity will decrease a bit. If the gap length is short compared to the linear dimensions of the gap faces, however, this decrease will be relatively small. Conversely, the field strength can drop significantly if the gap width is large compared to the gap face dimensions. When the gap width (g) is small compared to the toroid circumference ($g \ll 2\pi r$), the flux can be approximated by:

$$B = \frac{\mu_0 \mu_r I}{2\pi r + g\mu r} \qquad \textbf{(Equation 7-7)}$$

Furthermore, if $g\mu_r \gg 2\pi r$, which is often the case for a high-permeability toroid, then the expression can be further simplified to:

$$B = \frac{\mu_0 I}{g} \qquad \textbf{(Equation 7-8)}$$

This result means that, if the permeability of the toroid material is sufficiently high, the amount of flux in the toroid is controlled by the gap width g.

Another way of describing a toroid's efficacy at converting current into magnetic field is by its magnetic gain, (A_M) expressed in gauss/ampere. From Equation 7-8, the gain of a toroid of gap g can be expressed:

$$A_M = \mu_0/g \qquad \textbf{(Equation 7-9)}$$

Several manufacturers produce slotted toroids as standard items for current-sensing applications with 0.062" (≈1.5 mm) gap widths; this width accommodates several types of commonly available Hall-effect IC packages. From Equation 7-9, one would expect a gain of 8.4 gauss per ampere. In practice, because of finite permeability, flux leakage, and fringing effects in the gap, one can usually expect to see actual magnetic gains ranging anywhere from 6–8 gauss per ampere.

7.6 Toroid Material Selection and Issues

Although we just finished showing that the gap width is the dominant factor in the sensitivity of a flux-concentrating toroid, there are many material issues that must be addressed in order to get a current sensor to behave as intended.

The magnetic characteristics of the "soft" magnetic materials used for current-sensor toroids can be described by a B-H curve, as are permanent magnet materials. The major difference is that for soft magnetic materials we are more interested in their quadrant I characteristics than those of quadrant II. The B-H curve for a "typical" ferrite core material is shown in Figure 7-12.

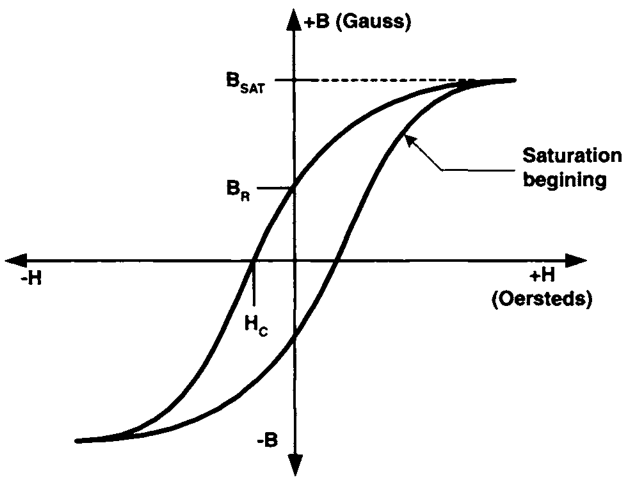

Figure 7-12: B-H curve of soft magnetic material.

Some of the key characteristics that can be derived from this curve are relative permeability (μ_r), remanent flux (B_r), coercivity (H_c), and saturation flux (B_{sat}). Relative permeability describes the relationship between how much coercive force (H) is applied to the material, and how much flux density (B) will be induced in the material. Note that when B approaches B_{sat}, the effective permeability will begin to fall, as increases in H will no longer produce comparable increases in B.

Once the material has been driven into saturation and the field removed, it will keep a certain remanent flux density B_r in the absence of any coercive force. Note that this remanent flux will only appear in a closed magnetic circuit composed of the material, such as a continuous toroid. Cutting a slot in the toroid will interrupt this path and greatly reduce the flux density. This is why a slotted toroid with a B_r specified as a few hundred gauss will only exhibit a field of a fraction of a gauss in the slot.

After the material has been saturated in the positive direction, a small amount of negative coercive force H is necessary to drive the flux B back to zero. This amount of coercive force is referred to as H_C, the material's coercivity, and is characterized in oersteds (Oe). For a soft ferrite material that might be suitable for a current sensor toroid, where one wants the flux to easily return to zero, very small coercivities (< 1 Oe) are desirable. This is in contrast to the very high coercivities (>10,000 Oe) found in many permanent magnet materials where one wants the material to stay permanently magnetized despite any external fields.

For most current-sensing applications, one will want to select a material with a saturation flux density significantly greater than the flux densities it will see in operation. This is because saturation begins to occur gradually in many materials, with permeability starting to decrease as flux levels increase past a certain point. This effect will manifest itself as gain and nonlinearity errors in the final sensor assembly. In some cases, toroid manufacturers will make your life simpler in this department by specifying the maximum number of ampere-turns that can be applied to a given toroid before it begins to saturate. One problem with relying on a maximum ampere-turns measure is that the provided figure may represent operation sufficiently far up the saturation curve to cause unacceptable linearity errors in your application.

Permeability also can vary significantly over temperature. The main concern here is that the permeability does not drop to the degree that it begins to affect the amount of flux developed in the toroid. This issue can be addressed by using materials that exhibit at least some minimum permeability over the operating conditions under which you will be operating your current sensor.

7.7 Increasing Sensitivity with Multiple Turns

There are three ways of getting more sensitivity out of a toroidal current sensor. The first is to use a more sensitive magnetic transducer. The second is to use a narrower airgap (and a thinner transducer to fit). Finally, the simplest method of all is to loop the conductor through the toroid a multiple number of times. Looping a conductor carrying I amperes through the toroid N times causes NI total current to pass through the toroid.

One frequent question is that of how one counts turns. The answer, to a first-order approximation, is quite simple. A turn is the passage of the conductor through the center of the toroid. It largely doesn't matter what you do with the wire elsewhere. For this reason, turns only occur as integers; you can't have half of a turn. Because of the nonideal characteristics of any given current sensor's magnetic circuit, this is not completely true; conductor placement can and does have a small effect on a current sensor's sensitivity. In many if not most situations, however, one will find that counting turns as wire passages through the toroid will give acceptable results.

7.8 An Example Current Sensor

Because current sensing is a popular application for linear Hall-effect sensors, many vendors supply suitable off-the-shelf components for implementing them. This makes the development of simple current sensors relatively straightforward.

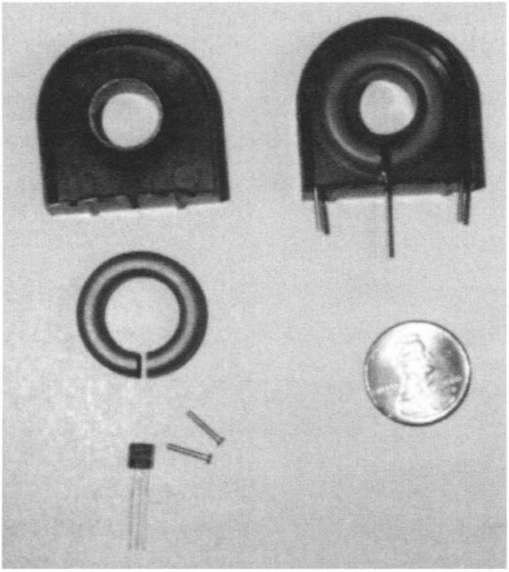

Figure 7-13: Photograph of unassembled and assembled prototype current sensor.

Figure 7-13 shows both unassembled and assembled views of a prototype current sensor. To make a finished unit, all that is needed is to "pot" the toroid and sensor with a suitable encapsulation material. The toroid is a Philips model TX22/14/6.4-3C81, about 7/8" in diameter, made from a material (3C81) with a permeability of about 3000, and good linearity up to around 800 gauss. A 0.062" gap was cut in the toroid, so it will provide about 6–8 gauss/ampere-turn, and will offer linear operation up to around 100–120 ampere-turns. The Hall-effect sensor is an Allegro Microsystems A1373, which provides a linear output with a sensitivity that can be programmed over from 0 to 7 mV/G. Even the enclosure is off-the-shelf, manufactured by Robison Electronics specifically for current-sensor applications. If the Hall-effect sensor is programmed to a sensitivity of 5 mV/G this current sensor will have a gain of about 30 mV/A, with saturation points of roughly ±80A, limited by the Hall-effect sensor's output saturation characteristics. By choosing a programmable sensor such as the A1373, this assembly can be adjusted at manufacture to a high degree of uniformity in both overall gain and offset error.

7.9 A Digital Current Sensor

Although we have only discussed linear-output current sensors to this point, it is also possible to make current sensors that provide an ON/OFF logic output if a current threshold is exceeded. By putting a switched digital Hall-effect sensor in the toroid gap, one can make a threshold-sensitive current sensor. This sensor turns on when the current exceeds a given threshold (I_{OP}), and turns off when the current drops below a second, lower threshold (I_{RP}). When constructed with a Hall-effect switch with operate and release points B_{OP} and B_{RP}, the resulting current sensor will have I_{OP} and I_{RP} points given by:

$$I_{OP} = B_{OP}/A_M \qquad \textbf{(Equation 7-10)}$$

$$I_{RP} = B_{RP}/A_M \qquad \textbf{(Equation 7-11)}$$

where A_M is the magnetic gain (gauss/ampere) of the toroid.

For example, if a digital Hall-effect switch with a B_{OP} of 200 gauss, and a B_{RP} of 150 gauss were used with a toroid with a gain of 6 gauss/ampere, the resulting assembly would switch on (operate) when the current exceeded (200/6) = 33.3A and switch off (release) when the current dropped below (150/6) = 25A. Note that, because the polarity of the magnetic flux in the toroid will be proportional to the polarity of the current, this device will only turn ON in response to current of a given polarity.

Because most Hall-effect switches have a fairly wide range of B_{OP}/B_{RP} points from unit-to-unit, it would be difficult to make devices with tightly controlled current thresholds. For this application, a Hall-effect switch with programmable B_{OP}/B_{RP} points, such as Allegro Microsystem's A3250, would allow you to trim each sensor on a unit-by-unit basis in production to provide uniform trip-point currents.

7.10 Integrated Current Sensors

As we showed in Section 7.5, the primary factor controlling sensitivity of a toroidal Hall-effect current sensor is the width of the gap into which the sensor is inserted. Most commercially available integrated devices tend to have package thickness ranging from 0.050" to 0.060". This limits the maximum amount of field one can get out of the toroid to roughly 8–10 gauss per ampere-turn.

The actual silicon die on which the sensor and electronics is fabricated is in the order of 0.010" thick. If it were possible to dispense with the device's packaging, it would be possible to realize much more sensitive current sensors. Handling bare dice, however can be difficult, as they tend to be fragile, sensitive to contamination, and require specialized equipment to attach interconnections. For these reasons it will not be practical for most manufacturers to build current sensors using bare dice.

Another alternative is to integrate the current sensor magnetic structures into the sensor packaging. Allegro Microsystems took this approach with their ACS750 series of integrated current sensors [Stauth04]. These devices contain all of the key components of a toroidal current sensor: a flux concentrator, a linear sensor, and also integrate the current-carrying conductor. Figures 7-14a and 7-14b show a photograph and cross-sectional schematic view of this device.

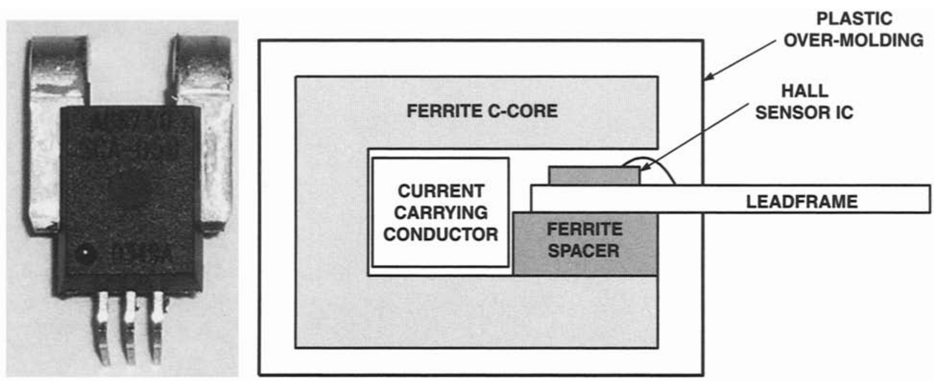

Figure 7-14: ACS750 photograph (a) and cross-sectional view (b).

In the AC750, the Hall-effect sensor die is mounted to the leadframe as it is in more conventionally packaged integrated sensors. The leadframe is then positioned in the gap of a ferrite c-core, along with a ferrite spacer to reduce the effective gap length. A heavy, low-resistance conductor for carrying the current to be measured is also included. Finally, all of these components are overmolded with an epoxy compound that both locks everything in place and protects the integrated circuit and wire bonds. The resulting assembly provides a high-sensitivity current sensor capable of measuring currents up to 100 A that can be inserted into a printed circuit board.

Allegro Microsystem's ACS704 is a recently introduced and related integrated current sensor that is implemented in a SOIC-8 IC package. Again, as in the case of the ACS754, the device provides a conductor for the current to be measured and includes an integrated Hall-effect sensor for measuring the resulting magnetic field. The primary advantage provided by this device is its small physical size, which is approximately 0.3" x 0.3" x 0.06". Because of limitations of the SOIC-8 package, the maximum currents that can be measured with this device are in the range of 5–14A.

7.11 Closed-Loop Current Sensors

Although it is useful for many applications, the toroidal current sensor presented has several limitations that restrict its use as a precision measuring device. Specifically, linearity and gain errors resulting from both the toroid and Hall-effect sensor severely limit the accuracy attainable with this type of device.

In many electronic systems, linearity and gain errors are corrected by using negative feedback, and this technique can also be employed in magnetic current sensors. Figure 7-15 shows how this is done.

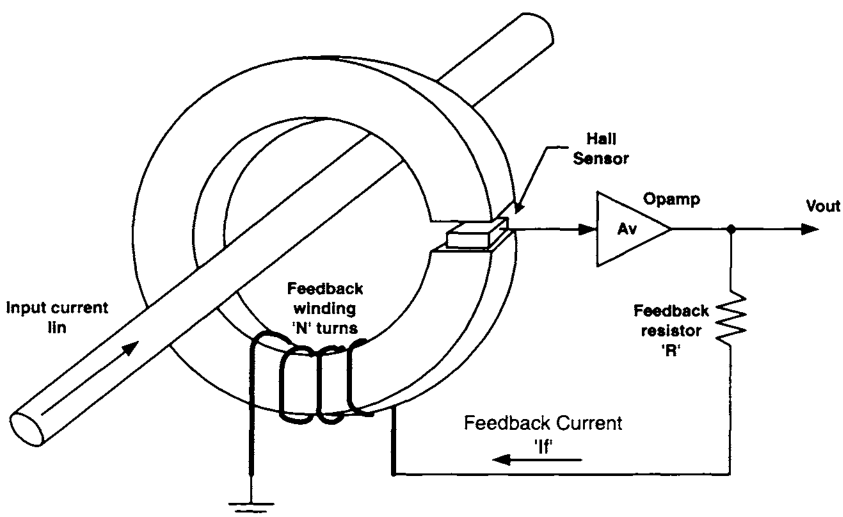

Figure 7-15: Closed-loop current sensor.

Qualitatively, this sensor operates by attempting to balance the input current with an opposing feedback current. When the net current passing through the toroid is zero, the flux through the toroid is also zero. The feedback current is coupled into the toroid through a separate conductor arranged to develop a magnetic field opposed to that of the current being measured. At first glance this would seem to be a serious drawback, as a significant amount of current could be required to perform this cancellation. However, because it is possible to effectively "multiply" a given current through the use of multiple turns, a small current through a large number of turns can be used to balance out a large current through a single turn. This means that, with enough turns in the feedback winding, only a modest amount of feedback current is required. As an example, if the feedback winding has 1000 turns, only 10 mA of feedback current will be required to balance out 10A of input current, which is only present on a single turn.

One significant advantage of using a current-balancing approach is that, since the net flux in the toroid is zero, the range over which input current can be measured is limited only by the available feedback current (multiplied by turns). It is therefore possible to make current sensors that can sense extremely large currents without magnetically saturating the toroid or the Hall-effect sensor.

The next part of the current sensor is the Hall-effect transducer. The only exacting requirement for this device is that it be able to detect when the magnetic flux is zero. Maintaining an exact transducer gain is not critical. Offset errors, on the other hand, are still important, as they prevent one from knowing when the toroid flux is truly zero.

At this point, one could make a manual current-measuring device using a readout from the Hall-effect sensor to indicate zero, and a current source controlled manually with a knob to provide feedback current. One would adjust the current source until the sensor indicated zero flux, read the amount of current required, and multiply by the number of turns in the feedback coil. While this could be done for a laboratory measurement, it is still inconvenient and totally unnecessary, as this function can be performed by a high-gain amplifier placed in a feedback loop.

In the feedback loop employed by this current sensor, the difference between the current to be measured and the feedback current results in an error signal. The amplifier in this circuit attempts to reduce this error signal to zero, by altering its output appropriately. When the error signal is zero (or very close), the output of the amplifier is proportional to the current being measured.

Systems constructed around feedback loops are elegant because they allow minimization of the nonideal effects of many of the components. The DC steady-state behavior of a loop such as this one is straightforward to analyze. The first step is to represent the whole system in block diagram form, as shown in Figure 7-16.

The first operation is the summation of the input current with the feedback current. Next, this is multiplied by the toroid's magnetic gain A_M (in G/A). The next stage is the transducer gain A_H (in V/G) followed by the op-amp voltage gain A_V (in V/V). The resulting output signal is then converted to a current through the feedback resistance ($1/R$), and finally multiplied by the number of feedback windings (N) before completing the loop. A closed-form expression (Equation 7-12) may be derived that relates V_{OUT} to I_{IN}.

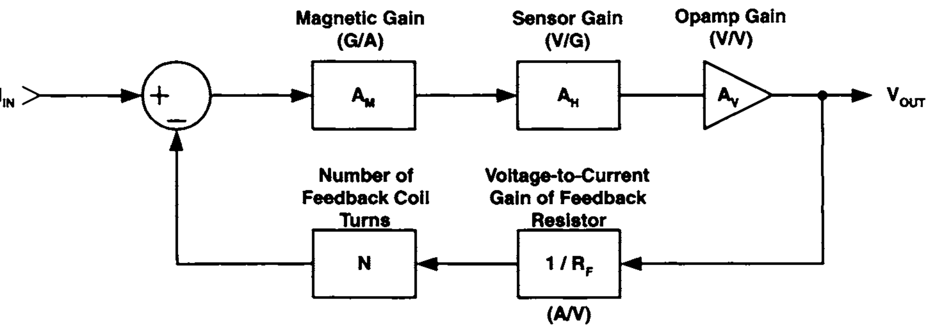

Figure 7-16: System diagram of feedback current sensor.

$$\frac{V_{out}}{I_{in}} = \frac{A_M A_H A_V}{1 + \frac{A_M A_H A_V N}{R}} \qquad \textbf{(Equation 7-12)}$$

In this equation, all of the factors discussed above contribute to the overall gain of the closed-loop current sensor. One of the near-magical properties of negative feedback, however, is that if one makes the gain of the op-amp sufficiently large ($A_V >> A_M A_H N/R$), the relationship between V_{OUT} and I_{IN} can be approximated as:

$$\frac{V_{OUT}}{I_{IN}} = \frac{R}{N} \qquad \textbf{(Equation 7-13)}$$

The only terms remaining are the value of the feedback resistor and the number of feedback turns. Both of these can be controlled to a high degree of accuracy.

The benefits of feedback, however, do not come without a price; neither does feedback magically solve all problems. As mentioned before, the coercivity of the toroid and the offset of the Hall-effect sensor still will contribute offset errors to the same degree as they would in an open-loop current sensor. A more complex issue, however, is that of dynamic stability. By adding a high-gain feedback loop to the system, we have introduced the possibility that it will exhibit oscillatory behavior. Small amounts of instability can manifest themselves as "overshoot" or "ringing" in response to a quick change in input current—with adverse effects on dynamic measurement accuracy. Major instabilities can result in uncontrolled oscillation, where the current sensor outputs a large sinusoidal waveform, even when there is no input. The dynamic behavior of the system will be a complex function of the dynamics of all the components included in the feedback loop. A detailed analysis of system stability issues, however, is beyond the scope of this book.