Methods of Current Measurement

Design Engineers will find practical information in this review of resistive shunt, current transformer, and Hall Effect current sensors.

Bill Drafts, P.E.

The three most common ways to sense current are the resistive shunt, the current transformer, and the Hall effect current sensor.

Resistive Shunt

The resistive shunt (so named because it is a shunt with respect to the voltmeter or system wiring) is simply a resistor placed in series with the load. According to Ohm's law, a voltage is developed across the shunt that is directly proportional to the current flowing through the load:

$$\mathbf{I} = E/R \qquad (1)$$

where:

$\mathbf{I}$ = current (amperes)
$\mathbf{E}$ = electromotive force (volts)
$\mathbf{R}$ = resistance (ohms)

Most shunts are termed DC shunts because of their inherent added series inductance, which limits the frequency response of the device. The DC shunt offers the lowest cost and most accurate solution to low current measurement requirements where the measured current is less than ~3 A. Additional advantages and disadvantages of the DC resistive shunt are summarized in Table 1.

If the resistive shunt is manufactured to minimize it's inductance, it is termed an AC shunt. AC shunts have the highest operating frequency range of any current sensing method, with 3 db points in the several hundred megahertz range.

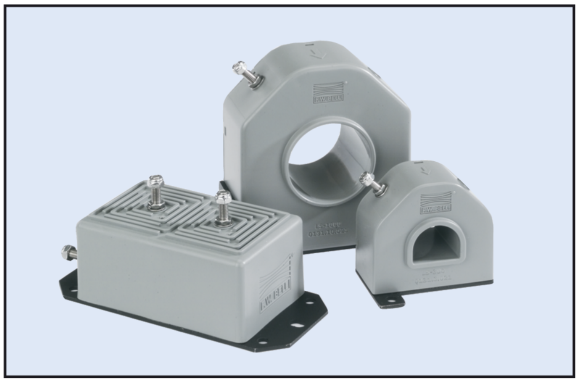

Photo 1. Sensors are available that are capable of measuring 0-15 kA DC to 200 kHz AC in a variety of packages.

These shunts, however, are a great deal more expensive than their DC counterparts. The fundamental operating characteristics of the AC shunt are the same as the DC's (see table 2).

Table 1: DC Resistive Shunt Comparison

Advantages	Disadvantages
Lowest cost method of measuring DC current (<500 A)	No electrical isolation, presenting noise and potential safety hazard
Easy to understand (simply Ohm's law)	Insertion loss, resulting in heat (energy dissipation) and voltage drop in system, difficult to install
Extremely reliable	Generally, amplification required of output
No external power requirements	Good only for DC current measuring and low frequency AC (<100Hz)
Zero output for zero current flow (no offset)	Very large size and weight as measured currents increase

Table 2: AC Resistive Shunt Comparison

Advantages	Disadvantages
Easy to understand (simply Ohm's law)	Excessive cost due to non-inductive design
Extremely reliable	No electrical isolation, presenting noise and potential safety hazard
No external power requirements	Insertion loss, resulting in heat (energy dissipation) and voltage drop in system, difficult to install
Zero output for zero current flow (no offset)	Generally, amplification required of output
Can measure DC and AC current to high frequencies (> 500 kHz)	Very large size and weight as measured currents increase

Current Transformer

The current transformer and the Hall effect current sensor are based on the fact that for a given flow, a proportional magnetic field is produced in accordance with Ampere's law. The current transformer couples this magnetic field into the secondary, providing a proportional current output. The operation of the device is identical to that of any voltage step-up transformer. The sensed, or aperture, current forms the primary turn, while the large number of turns wound on the magnetic core forms the secondary. The turns ratio determines the current output. For example, for a single turn of 1000A, a secondary of 1000 turns would provide 1A of secondary current. Two types of current transformers are commercially available: high-volume, low-cost, lower frequency devices and lower volume, dramatically higher frequency, higher cost research-grade devices. The former is intended for low, constant-frequency (60 Hz or 400 Hz, for example) applications, while the research-grade devices generally focus on high-frequency (in the megahertz) RF and pulsed applications. Table 3 summarizes the characteristics of the low-cost type.

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Table 3: AC Current Transformer Comparison

Advantages	Disadvantages
Low-cost method of measuring AC current (<100 A)	Measures AC current only
Provides voltage isolation	Produces AC insertion loss
Provides current output, ideal for noisy environments and easily converted to a voltage	Output is frequency dependent
Very reliable	Very large size and weight as measured currents increase
No external power requirements	Higher susceptibility to stray AC magnetic fields

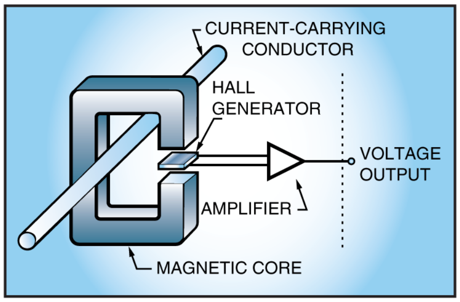

Figure 1. The open-loop Hall effect current sensor relies on the magnetic core to concentrate the magnetic field onto the Hall generator. The signal is then amplified to a useful output.

Hall Effect Sensors

Hall effect current sensors (see Photo 1) incorporate Hall generators, four-terminal solid-state devices that output a voltage proportional to the normal magnetic field and the magnitude of the input control current. Table 4 summarizes the pertinent data. These detectors are either open loop or closed loop; apart from their use of a Hall generator, core and amp, the two technologies are markedly different.

Open-Loop

Open-loop Hall effect current sensing is the easier to understand. The hall generator is mounted in the air gap of a magnetic core. A current-carrying conductor placed through the aperture of the core produces a magnetic field proportionate to the current. The core concentrates the magnetic field, which is measured by the Hall generator. The signal from the Hall generator is low and is therefore amplified to a useful level, which becomes the output of the sensor. (see Figure 1).

To understand open-loop Hall effect current sensing, some fundamentals of the Hall generator must be reviewed. Recall that the Hall generator is a four-terminal solid-state device most commonly made of a thin film of silicon, germanium, indium arsenide, indium antimonide, or gallium arsenide. Two leads provide the voltage output; the other two require a voltage or current source input. The voltage output is a differential voltage between the two leads that is dependent on the normal magnetic field and the control current flowing through the input leads. Certain basic characteristics of the Hall generator vary over temperature, such as I/O resistance, misalignment voltage (offset voltage), and sensitivity. When designing with Hall generators, a constant current source is therefore used to power the device, allowing the output to be a function of the incident magnetic field and not dependent on the temperature-varying input resistance. A constant current source is also added to help correct the change in sensitivity over temperature. Typically, the sensitivity of an indium arsenide or gallium arsenide Hall generator drifts approximately -0.05%/°C over temperature. This drift can be minimized by injecting a positive 0.05%/°C coefficient in the control current, which significantly reduces the drift in sensitivity over temperature. (For clarity, the temperature-compensated constant-current source is not shown in Figure 1).

The open-loop method thus contains four building blocks: the Hall generator, the magnetic core, the amplifier, and the temperature-compensated constant-current source. The linearity of the open-loop sensor is subject to the linearity of the core and the Hall generator. The offset drift over temperature is determined by the offset drift of the Hall generator and the amplifier, and the gain of the amplifier.

Closed-Loop

Closed-loop Hall effect current sensors have five basic building blocks: the Hall generator, the magnetic core, the amplifier, a driver circuit, and a coil wound in series opposition around the magnetic core. The term closed-loop is used because the magnetic field generated by the current-carrying conductor is nulled within the magnetic circuit of the core, thus closing the magnetic loop. This technique allows great improvements in sensor performance.

The Hall generator senses the magnetic field generated by the conductor under measure and concentrated by the magnetic core. (see Figure 2). The Hall generator output voltage is amplified by a very large gain amplifier, essentially operating at an open-loop (no feedback) gain. The amplifier output is fed into a push-pull driver stage that drives the coil wound in series opposition on the magnetic core. This produces a magnetic field that is equal but opposite to the magnitude of the aperture current, thus driving the core to near zero flux. The output of the sensor is one lead of the coil, and connecting it to ground through a sense resistor completes the circuit. Operating the core at near zero flux eliminates the dependence on the linearity of the core and Hall generator and also effectively eliminates the temperature dependence of the Hall generator's sensitivity. The Hall generator will still drift in sensitivity over temperature, but this drift times an effectively zero field equals zero. The generator therefore does not need a temperature-compensated constant-current source.

Table 4: Hall Effect Current Sensing Comparison

Advantages	Disadvantages
Measures DC and AC currents	Outputs signal for zero current flow (has offset)
Lowest cost method of measuring larger AC and DC currents (>500 A)	Requires external power supply
Provides electrical isolation	Difficult to understand
Very reliable	Technical considerations required for over temperature performance, overcurrent and power supply variations

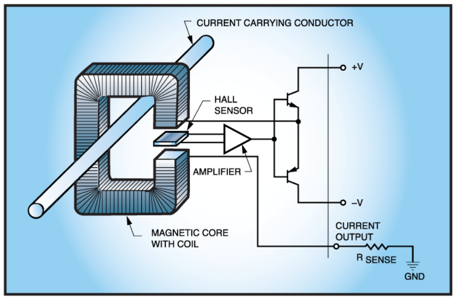

Figure 2. The closed-loop current sensor adds a push-pull amplifier that drives a nulling coil. This results in the sensors always operating at or near zero magnetic flux, eliminating dependence on the linearity of the core and hall generator.

The output of the closed-loop sensor is therefore proportionate to the aperture current and the number of turns of the coil. A sensor with a 1000-turn coil will provide an output of 1mA/A. This output current is then converted to a voltage by connecting a resistor to the output of the sensor and ground. The output can be scaled by selecting different resistor values within specified limits.

Open and closed-loop compared

Each of these two Hall effect technologies offers technical and economical advantages (see Table 5). The closed-loop sensor has superior linearity, low temperature drift, fast response time, and a wide frequency range. Open-loop technology offers excellent performance with respect to price and is preferable for battery-operated applications where power consumption, size, and weight are dominant concerns. Two points identified in Table 5 require further explanation. As previously noted, the open-loop sensor is the device of choice for low power consumption designs because it consumes the same amount of power regardless of aperture current. The closed-loop sensor requires more current as the aperture current increases because more current is required to null the flux.

The second point is that open-loop sensors can operate at excessive overcurrents indefinitely and suffer no damage. The closed-loop sensor cannot because the larger the aperture current, the larger the push-pull driver current and the higher the heat dissipation in the coil and the sense resistor. These components all have power limits, a characteristic that limits the sensor's overcurrent measuring capability. When considering an overcurrent condition using a closed-loop sensor, the designer must consider both the peak aperture current and the duty cycle of that current. If the highest performance is required by the system design, the closed-loop sensor is the sensor of choice. However, this improved performance comes at a cost in weight and dollars (see Figures 3 and 4), both of which increase with the closed loop sensor's current rating.

(Note that the prices are from the manufacturers' catalog and are used only to indicate the relative differences in cost as the current rating of the sensor increases. This is due to the added turns and current required to null the larger magnetic fields. As the currents increase, a single drive stage is no longer adequate and larger compliance voltages are required. This results in more complex circuitry, more weight and additional cost).

Applications

Hall effect current sensors are used in power supplies, motor drives, and general load applications.

Power Supplies

Used in virtually all electronic equipment in one form or another, power supply applications range from lasers to computers to nuclear power plants. A power supply may use current sensing to shut down during an overcurrent condition and protect internal components from damage or for personal safety. The sensor can also be used as a feedback element to regulate the current, as in electroplating, arc welders and battery chargers.

Motor Drives

Trains, factories, elevators, and air handlers all rely on motor drives, where motor torque is proportional to the motor's electrical current. Monitoring the current provides load information. If the motor becomes unloaded, as in the case of a broken tool bit or cavitating pump, the current decreases and can be used to signal an operator to replace the bit or reprime the pump. Motor drives not only allow greater control of the motor but also dramatically increase efficiency, which saves money when it comes time to pay the electric bill.

General load applications

These are a diverse group. Lighting on airport runways and tall structures (cellular towers, for example) is required for safety. Measuring the current to those lights provides feedback on their condition. If the circuit opens (no current), an automated signal could be generated to a technician to indicate the need for a bulb change. In plastic injection molding machines, the plastic is preheated to a given temperature to insure a proper mold. If a heater element burns out, the plastic will not be at the appropriate temperature, causing a yeild problem. A current sensor monitoring the heater current can signal an operator if the element burns out.

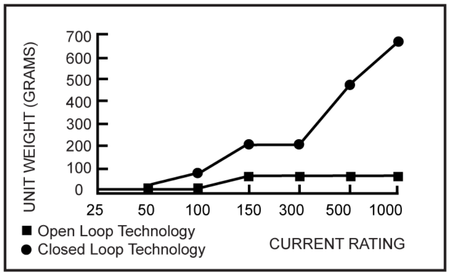

Figure 3. Due to the added output stages and increased number of windings required to null the larger magnetic fields, the closed-loop current sensor dramatically increases in weight as the measured current increases.

Table 5: Open-Loop vs. Closed-Loop Hall Effect Current Sensing

Advantages of Open-Loop

Lowest cost in higher current ranges (>100 A)
Low, constant power consumption regardless of sensed current
Smallest size, lowest weight in higher current ranges (>100 A)
No damage from excessive overcurrents (>10x rating)

Advantages of Closed-Loop

Highest accuracy at ambient and over temperature
Provides a current output, ideal for noisy environments and easily converted to a voltage
Higher frequency range (>150 kHz)
No magnetic hysteresis of offset

Trends in current sensing

As system requirements increase, with voltage slew rates >5000 V/µs and current slew rates >200 A/µs, demands on the sensor also increase. Researchers are investigating not only improvements in Hall effect sensing but also alternative technologies such as magnetorestrictive, magnetoresistive, magneto-optic, magnetodiode, and magnetotransistor sensors. There is movement toward self-test features, more durable packaging, and smaller footprints. Split-aperture sensors, or configurations where the core is split in two, greatly facilitate both initial and field service installation. Development of a 4-20 mA output current sensor allows simple system interface to a PLC. Higher noise immunity is of particular interest because as the electronics become more remote from the sensor installation, frequency and system noise increase.

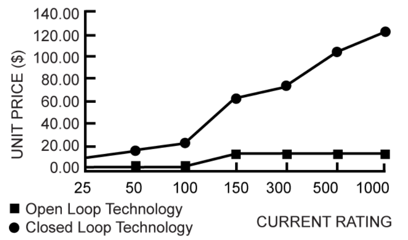

Figure 4. Similar to the case in Figure 3, the cost of the closed-loop current sensor increases with the measured current.