Douglas P. McNutt. "Current Measurement."

Current Measurement

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Current measuring devices are selected for:

- Precision
- Stability
- Frequency response, including dc
- Galvanic isolation
- Presentation of the data
- Effect on measured circuit

A few of the most common sensors will be introduced in this chapter. Details and some less common sensors will follow after definitions and a bit of magnetic theory, which can be skipped. Any magnetic field sensor can be used as a current sensor and there are some exotic examples, such as quantum effects in low-temperature superconductors used to measure currents in neurons within the brain. This discussion is limited to measurement of currents in wires with commercially practical devices.

An isolated current sensor is free of any metallic connection to the circuit being measured. It is also essentially free of capacitive coupling so that it is safe to use with grounded amplifiers and other equipment. The quality of the isolation is measured in volts and is usually the breakdown potential of an insulator. 5 kV is typical for personal safety around light industrial power.

By far, the simplest current-to-voltage converter is the resistor. In current measuring service, it is called a shunt although it is typically placed in series with the load. That is because shunts are sometimes used to increase the range of another current-measuring device using a connection that bypasses part of the current around a meter. Frequency response of a shunt is good and includes dc. Shunts produce a voltage output that can be presented by a variety of secondary meters, including analog meters, digital meters, oscilloscopes, and 4- to 20-mA converters. Shunts provide no isolation and have a potentially unacceptable effect on the circuit being measured. Shunts used for dc are as accurate as the resistance and the associated voltmeter.

The common moving-coil meter, the D'Arsonval movement [1, 2], probably with an internal shunt and/or rectifier, is an easily used device and still available. Its isolation is by means of the human eye since that is the only way to read out the result. It is useful for power panels where an operator needs quick data. Accuracy is no better than 2%.

For power frequency, 25 Hz to 400 Hz service, the current transformer, called a "donut" transformer, or CT in the trade, is commonly employed. The current-carrying conductor is passed through the hole in a toroid of magnetic material. A shorted secondary winding of n turns carries current, which is $1/n$ times the measured current, and is typically passed to another ammeter or used as the current input to a power measuring device. Isolation is as good as the insulation on the primary conductor; frequency response is fair but does not include dc; there is minimal effect on the measured circuit, and the cost is low. Operational safety is an issue; see the note below.

A variety of noncontact sensors is available for dc sensing. Most depend on the Hall effect and all require a source of operating power. Frequency response from dc to 200 kHz is advertised. Because operating power is available, output to later processing can be voltage, current, or digital. Accuracy is whatever one wants to pay for. Long-term stability depends on dc-coupled operational amplifiers and can exhibit zero drift. Externally, these look much like CTs.

CTs, Hall devices, and other similar noncontact schemes are available in wrap-around form so they can be installed without disconnecting power. The wrapping process always involves breaking a magnetic path, and consistency of reassembly becomes a limit on precision. Everything from current-sensing probes for oscilloscopes to CTs for 10000-A circuits can be found as wrap-arounds.

38.1   Definition of the Ampere

There is perpetual argument about the number of "fundamental" quantities required to describe our environment. Is there a fundamental unit of electricity or are the electrical units derived from more basic things such as mass, length, and time? Standards laboratories such as the U.S. National Institute of Standards and Technology, NIST, measure the force between current carrying wires to compare the ampere to the meter, the kilogram, and the second, and provide a standard stated as "that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 m apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length" [3]. For the rest of this discussion, it is assumed that instrumentation is "traceable to the NIST," meaning that one way or another, an electrical unit as measured is compared to a standard ampere maintained by NIST. Absolute calibrations using the quantum properties of the Hall effect and the Josephson junction are not practical in the field.

For practical reasons, it is often easier to distribute a voltage standard than a current standard. Chemical cells and, more recently, semiconductor voltage references are quite stable and do not depend on the length of the wires used to connect them together during calibration and use. As a result, current measuring is usually a matter of conversion of current to an equivalent voltage.

An exception is current measurement by comparison to magnetic forces provided by a permanent magnet and that might be why the older unrationalized centimeter-gram-second, the cgs units, with no separate electrical unit is still found in specifications of magnetic quantities. The gauss and the oersted are particular examples of these now deprecated units. It is this confusion of units that frightens many who would measure current away from even attempting calculations involving magnetic devices.

38.2 Magnetics

Magnetic current sensors have advantages over shunts. To understand them, one should delve into the interaction between currents and magnetic fields. Following Maxwell by way of Sommerfeld [4], it is convenient to describe magnetic effects in terms of two vector fields, **B** and **H**. **H** is the field created by an electric current, and **B** is the field that acts on a moving charge or a current carrying wire. **B** and **H** are related by characteristics of the material in which they coexist. Strictly speaking, **B** is the flux density and **H** is the field, but they are both called the field in less than precise usage.

The SI units of **B** and **H** are the tesla (T) and the ampere per meter (A m^{-1}). They are called rationalized because a ubiquitous 4π has been suppressed in the underlying equations.

For practical engineering, it is still necessary to understand the unrationalized equivalents, the gauss and the oersted, because they are universally used in specifications for magnetic materials. To convert from gauss to tesla, divide by 10^4. To convert from oersted to amperes per meter, multiply by $1000/(4\pi)$, a number that is commonly approximated as simply 80; but strictly speaking, the units of **H** in the two systems are dimensionally different and cannot be converted.

The relationship between **B** and **H** is most generally a tensor that reflects spatial anisotropy in the material, but for common magnetic materials used in current sensing, a scalar value μ applies. In SI units, **B** and **H** have different physical dimensions and are not equal in vacuum. The "permeability of free space" μ_0 is defined so that the μ for a material is a dimensionless constant. Thus,

$$\mathbf{B} = \mu\mu_0\mathbf{H} \tag{38.1}$$

where μ_0 is exactly $4\pi \times 10^{-7}$ H m^{-1}. (H here is the henry, the SI unit of inductance, base units m^2 kg s^{-2} A^{-2}). For many problems, μ will be a constant of the magnetic material, but when magnetic saturation needs to be considered it will be a variable. For engineering calculations, μ is often treated as though it depends on frequency. Values of μ range from less than 100 for high-frequency ferrite to 5000 for transformer iron, to 10^5 for carefully annealed magnetic alloys.

The field due to a long straight wire is shown in Figure 38.1 and Equation 38.2. The **H** vector obeys the right-hand rule and is everywhere perpendicular to the wire. The amplitude of **H** is proportional to the current and falls off linearly with the radial distance from the wire. This is the field that makes noncontact sensing of current possible.

$$\mathbf{H} = \frac{\mathbf{l}}{2\pi r} \tag{38.2}$$

The field at the center of a circular loop of wire is shown in Figure 38.2 and Equation 38.3. It obeys the right-hand rule, is proportional to the current, and inversely proportional to the radius of the loop.

$$\mathbf{H} = \frac{\mathbf{l}}{r} \tag{38.3}$$

A magnetic field can often be calculated by direct application of Maxwell's relations in integral form [4]. The line integral over any closed path of **H•dl** is equal to the current passing through a surface delimited by the closed path.

Magnetic flux passing through a surface, usually denoted by ϕ, is the integral of **B•n** d*A* over the surface with normal vector **n.** The SI unit of ϕ is the weber. The unrationalized unit, the line of force, is best relegated to history except that the lines, which form continuous loops, dramatize the fact that it does not matter how a surface is drawn to close a bounding line. The flux is the same. It is convenient to think of magnetic lines, forming closed loops, that can be bent but not interrupted or removed.
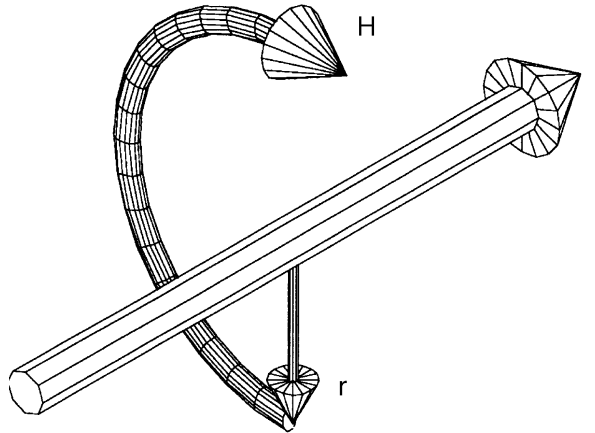
FIGURE 38.1   The magnetic field associated with a current-carrying long wire. It is this field that makes contactless sensing of current possible.
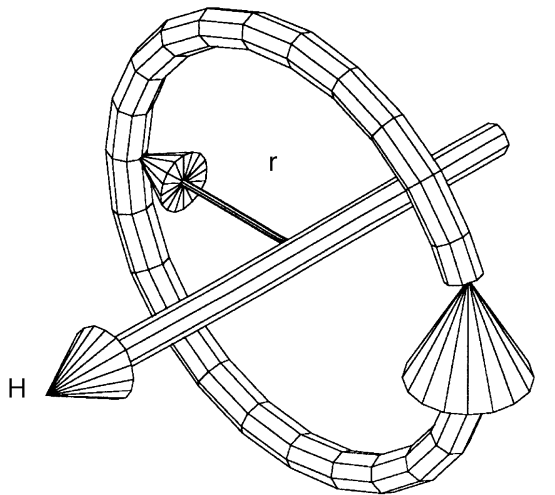

FIGURE 38.2   The magnetic field at the center of a loop of wire. This is the starting point for many calculations involving inducators and transformers.

A carrier of charge, an electron in a wire, a particle in vacuum, or a hole in a semiconductor, moving in a magnetic field is acted on by a force that is perpendicular to the field and the velocity. For positive charge, the force obeys the right-hand rule. The magnitude of the force is proportional to the magnitude of **B**, the velocity **V**, and the sine of the angle between them.

$$\mathbf{F} = \mathbf{V} \times \mathbf{B} \tag{38.4}$$

A carrier, moving or not, is affected in a similar way by a changing magnetic field. The result is an electromotive force, *EMF*, in a loop of wire through which a changing magnetic flux passes. The *EMF* is equal to the rate of change of the flux enclosed by the loop with a change of sign. That is Faraday's law of induction.
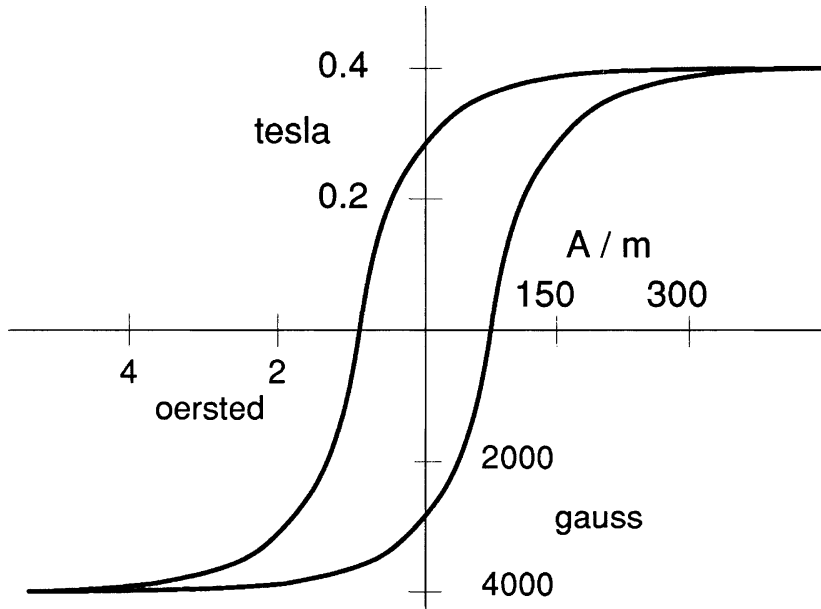
FIGURE 38.3   A hysteresis curve for some rather poor transformer iron. Unrationalized units are shown below and left of the origin because that remains standard practice in the industry.

$$EMF = -\frac{d\phi}{dt} \tag{38.5}$$

Most magnetic materials exhibit hysteresis. That is, the relationship between **B** and **H** depends on the history of the applied **H**. A plot of **B** vs. **H** is called a hysteresis loop and a sample is shown as Figure 38.3. The area of the loop represents an energy. If a magnetic core is repeatedly driven around its hysteresis loop, there is a power loss due to hysteresis that is proportional to the area of the loop and the frequency. A material with very large hysteresis is a permanent magnet.

Magnetic materials which are also electric conductors have free carriers which are affected by alternating magnetic fields. As they move back and forth they encounter electric resistance and dissipate energy in the form of heat. These eddy currents can be minimized by use of high resistance ferrites, powdered iron, by laminating cores, or by keeping the flux small.

38.3   Shunts

Shunts were introduced above. They dissipate power as heat and the resistance changes in response to the rising temperature. The dissipation is proportional to the voltage across the shunt and a design compromise must be made because low voltage implies less accuracy in the voltmeter. A standard of 50 mV has evolved. Shunts do not provide galvanic isolation between the measured circuit and the measurement device.

Measurement of alternating current using shunts is also affected by skin effect and the inductance of the shunt. Skin effect can be minimized in the design of the shunt by the use of several parallel sheets of thin metal, Figure 38.4, a feature that also improves heat dissipation. There is not much to be done about inductance except to minimize size.

Safety is enhanced if shunts are placed in the ground leg of a circuit; that way, the output leads, usually only at 50 mV, are near ground. However, that introduces a resistance in the ground path and can interfere
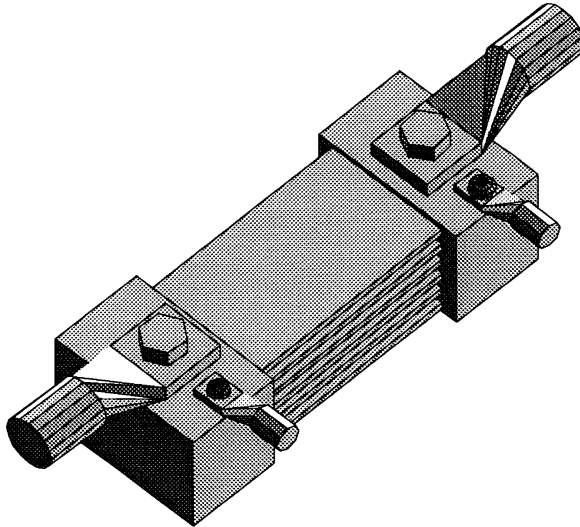
FIGURE 38.4 Multiple sheets of conductor are provided in this shunt to reduce skin effect and allow air cooling. Kelvin connections are provided for the voltmeter so that the voltage drop in the high current connectors is not inadvertently included in the measurement.

with common mode requirements of interdevice signal connections. If the shunt is placed in the high side, care must be taken to protect the wiring and the meter to which it is attached from accidental grounds.

Sometimes, sufficient accuracy can be obtained by measuring the voltage drop along a length of conductor that is otherwise required in the installation. In vehicular service, it is common to sense the voltage drop in a battery cable using a millivoltmeter. Such installations are always high side and should be protected with fuses installed near the points of measurement. It is also wise to provide a connection means that is independent of contact resistance where the current-carrying conductor is installed — a Kelvin connection. Including one lead of an in-line fuse holder in the terminals before they are crimped is one such technique.

38.4   The Moving Magnet Meter

The simplest current indicator balances the force on a permanent magnet created by current in a wire against a spring. A magnetic material is usually placed around the conductor to concentrate the field and reduce the effect of the magnetic field of the Earth. Use is limited to low-precision indicators such as a battery charging meter for a vehicle. It is a dc device.

38.5   The D'Arsonval Meter

This indicator balances the force on a current-carrying wire due to a permanent magnet against a spring. The measured current flows in a coil of wire supported in bearings. It is described in elementary texts [1, 2]. It is generally a dc instrument, but chart recorders have been built with frequency response in the kilohertz range using mirrors on the moving coil. They are then called galvanometers. For ac service, these meters are often equipped with internal copper oxide rectifiers and a nonlinear scale to correct for the diode drop. For current ranges above a few milliamperes, they will have an internal shunt.

The moving magnet meter and the D'Arsonval movement are the only current sensors that do not convert current to voltage and then depend on other devices to read out the voltage.

38.6   The Electrodynamometer

A variation of the D'Arsonval meter for ac service can be built by replacing the permanent magnet with an electromagnet. The force on the moving coil becomes proportional to both the current being measured and the voltage applied to the coil of the electromagnet. It is sensitive to the relative phase of the voltage and current in just the right way to be useful for measurement of power in a circuit with correction for power factor. An electrodynamometer in a power panel is often the load for a current transformer.

38.7   The RF Ammeter and True rms

Current to a radio transmitting antenna is commonly passed through a small resistor, a shunt, that is thermally connected to a thermocouple or other thermometer and mounted in a thermally insulating blanket. The rise in temperature is a measure of the current and is often sensed with a thermocouple.

This is an example of true rms indication. Root mean square current is the square root of the integral of the square of the instantaneous current over an unspecified time divided by that time. It is intended to represent a stationary ac waveform by a single value that is equal to the direct current which would dissipate the same power in a resistive load. The RF ammeter does that precisely. The indication is not particularly linear, but it can easily be calibrated by applying dc to the input.

Other schemes for measuring rms current depend on analog multipliers and subsequent integration. They are limited by crest factor, the ratio of highest instantaneous peak to the rms over a measuring period. Inexpensive meters simply measure the peak, assume a sinusoidal waveform, and scale to rms.

38.8   The Current Transformer

Consider the magnetics of a toroidal core of high-μ material through which a current-carrying conductor passes. Include a secondary winding of *n* turns as shown in Figure 38.5. The secondary winding is connected to a low-resistance load.

In this current transformer, universally referred to as a CT, alternating current in the single-turn primary attempts to magnetize the core but in so doing, creates an emf and current in the secondary that tend to cancel the field. If the secondary truly has zero resistance, the current in it exactly cancels the field due to the primary. The result is a secondary current equal to the primary current divided by the number of secondary turns. The secondary current is in phase with the primary current. Because of the tightly closed magnetic loop, there is little effect from nearby conductors or position of the primary wire in the hole.

The secondary circuit can now be connected to a low-resistance current- or power-sensing device with assurance of calibration. But the secondary resistance is never really zero and the magnetic coupling is never perfect, so there are other considerations.

First, the concept of *secondary burden* is introduced. It is called that to avoid calling it a "load" because it behaves differently; the best burden is a short-circuit. Burden is sometimes expressed as a secondary resistance in ohms, but more often as an equivalent power in kVA for a defined current without consideration of phase. When the burden is not a perfect short-circuit, energy is dissipated and the magnetic field present in the core is no longer zero. The secondary current leads the primary current with a phase that depends on frequency.

Manufacturers of CTs have techniques to optimize accuracy of the CT when specified for a particular burden. The finished units might not have the number of secondary turns one would expect, but will nonetheless provide results accurate to a percent or so. They have laminations selected to minimize heating of the core. One will see ratings like 100:5, meaning 100 A in the primary will produce 5 A in the secondary rather than "20 turns." They should be installed in a circuit that provides the burden for which they were calibrated. The voltage across a burden resistor is commonly amplified and passed to a data collection device. CTs for large currents need to be large to avoid magnetic saturation when burdened.
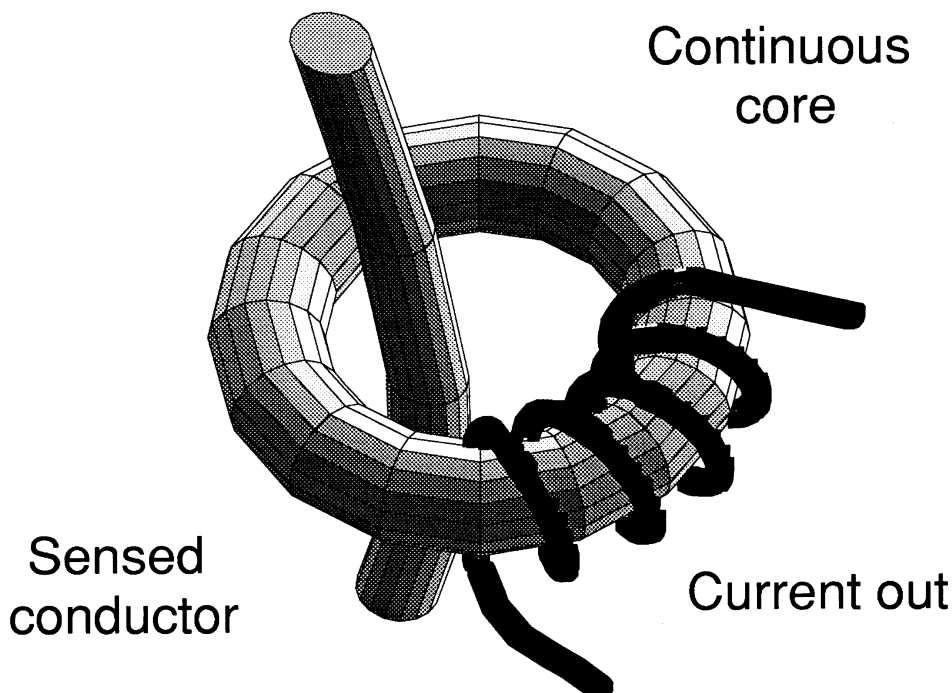
FIGURE 38.5   The ideal current transformer or CT is tightly coupled with no magnetic gap. Current in the secondary exactly balances current in the single-turn primary so that the magnetic flux in the core is zero.

Cores are prepared with laminates of silicon iron in the form of disks, concentric rings, or tape that is wound on a bobbin. Even with the best of materials, eddy current and hysteresis loss are present. When power dissipation is unacceptable, another choice of sensor might be preferable.

Most CTs are used for measurement of low-frequency power and energy. They are found at the front end of kilowatt-hour meters used by power providers. Radio frequency current in transmitting antennas can be measured with suitable core material. Ferrite cores with appropriate compensation are used for sensing pulse width modulated current in switching power supplies. Very large cores are used to sense pulsing beams of high-energy particles. Some oscilloscope probes are highly compensated CTs with a core that can be opened to allow a current-carrying wire to be introduced. With modern winding equipment for toroids, it is possible to put 2000 or more turns on a secondary [Coilcraft]. The CT then begins to look more like a current to voltage converter in its own right without need for very small values of the burden resistor and subsequent voltage amplification.

Safety Note

The secondary of a CT should always remain shorted while there is any possibility of current flow in the primary. With an open secondary, the core can be driven back and forth between saturation in opposite directions, resulting in high-speed changes in the internal B field. The result is very high, dangerous to life, voltages on the open secondary. Insulation in the secondary circuit can be damaged by arcing. Many CTs are made with a provision for shorting the secondary if the circuit must be opened. Use it.

38.9   Gapped Inductive Sensors

It is common practice in the design of transformers to introduce a small gap in the magnetic path. For even very small gaps, the magnetic properties of the magnetic loop become almost completely determined
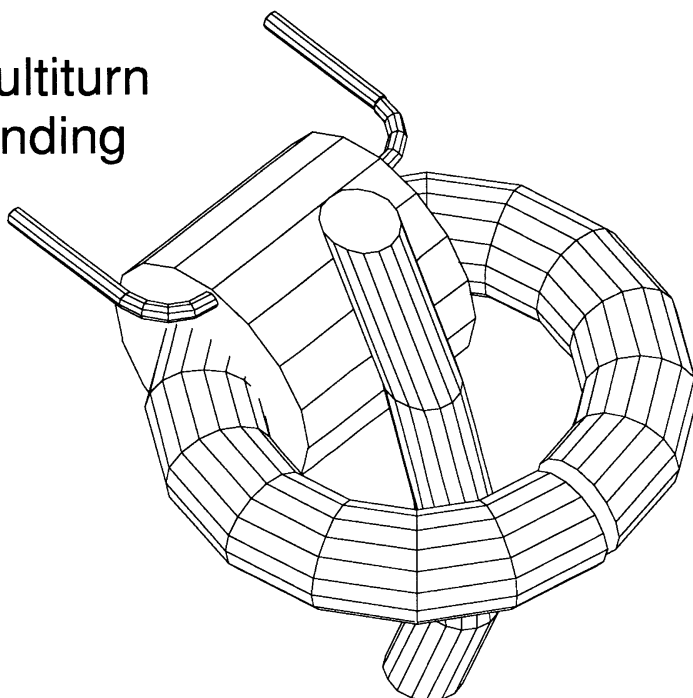
FIGURE 38.6 Placing a gap in the core and dramatically increasing the secondary turns count results in a current-to-voltage converter with high output voltage.

by the length of the gap, the rest of the material serving only to contain the lines of flux. Analysis of such a device begins with understanding that the B field is continuous in the core and through the gap. The H field is not, but it still satisfies the relation that the line integral of **H·dl** around the core is equal to the linked current. For a magnetic path of length s in material of permeability μ with a gap g, the ratio B/H, the effective permeability is given by:

$$\mu_{\text{eff}} = \frac{s}{g + \dfrac{s}{\mu}} \tag{38.6}$$

which applies for g much smaller than s. Note that when μ is sufficiently large, the effective permeability becomes independent of μ.

Introducing a gap into what would otherwise be a CT and drastically increasing the secondary turns count to 10000 or more results in a current sensor that is intrinsically safe because the core cannot saturate: Figure 38.6 [SRT]. Because the B field is always small, the heating effect of eddy currents is less important than in the CT. When loaded with an appropriate resistor, the high inductance of the secondary causes the sensor to act like a current source that generates a voltage across the load proportional to the primary current with better than 1% linearity. Useful bandwidths of a sensor can be over 3 decades. The output impedance is high and requires the use of electronic voltmeters. Power dissipation is low, even for very high current models. Output voltage is high enough that simple diode rectifiers can be used to provide for dc output to further processing. In many cases, such a sensor can be used without any special electronics other than a voltmeter.
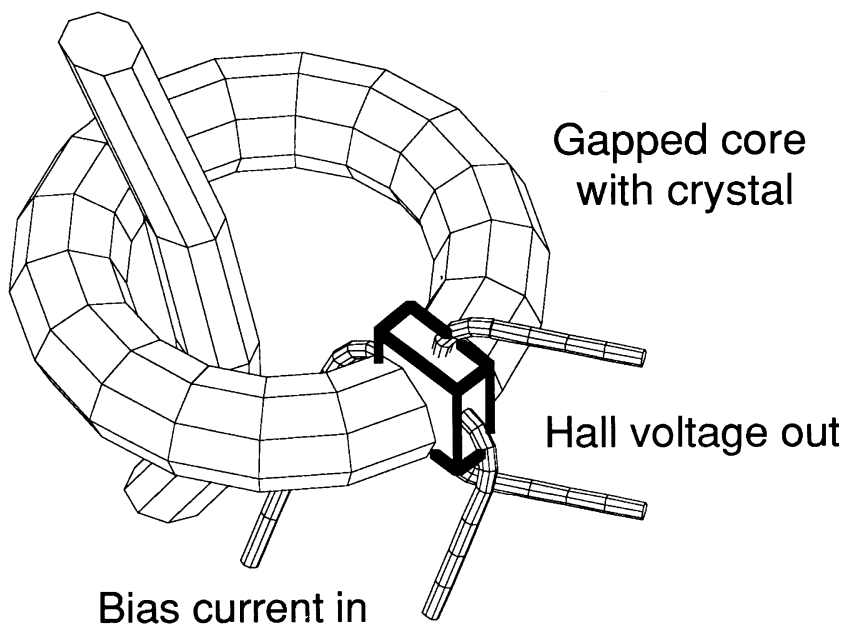
FIGURE 38.7 A semiconducting crystal is placed in the gap of a flux concentrating magnetic core. Bias current on one axis of the crystal produces a Hall voltage on the other.

38.10 Hall Effect Sensor

The *Hall effect* as a sensor for magnetic fields is described in Chapter 48 of this volume and in [5]. It depends on a semiconductor crystal selected for its high carrier mobility and is placed in a magnetic field. A current is passed through the crystal along an axis perpendicular to the field. The carriers assume a mean velocity that causes them to be acted upon by the field and they move toward the other axis perpendicular to the field. The result is an emf at the faces of the crystal that can be measured. The emf is proportional to the field, the bias current, and the mobility.

In principle, such a field sensor could be placed near a current-carrying wire and oriented to sense the field created by the current, Figure 38.1, but the sensitivity is insufficient and there would always be interfering fields from currents in other nearby wires. A flux concentrator that looks like a CT with a large gap is always used. See Figure 38.7.

The device is sensitive to direct current and the polarity is preserved. The Hall voltage is a few millivolts and amplification is always required. Zero drift in the amplifiers must be properly compensated although this is not so important for ac service. The bias current must be carefully controlled and it can be used to provide intrinsic analog multiplication and metering of power if it is made proportional to the circuit voltage.

Sensitivity is best with the smallest gap but there must be room for the crystal so gaps are larger than in the gapped inductive sensors. Fringing of the field in the larger gap reduces the natural shielding of the toroid from unwanted magnetic fields.

The accuracy and linearity of the Hall effect sensor can be improved in closed-loop mode. A feedback winding is added to the core and driven by a servo amplifier. The emf from the Hall device is used to drive the servo amplifier until the field is zero. The output is then the feedback current which is less than the sensed current by the number of turns in the feedback winding. The frequency response of the closed-loop system is surprisingly good, hundreds of kilohertz [F. W. Bell].

38.11   Clamp-on Sensors

It is often desirable to measure current in an existing system without removing power in order to install a device; thus, most of the magnetic devices are available in a clamp-on configuration. The variety ranges from tiny oscilloscope probes to clamps for 3000-A power buses.

Accuracy is always reduced in clamp-on mode because the clamp itself constitutes a gap that is uncontrollable and subject to wear. Some manufacturers provide highly polished surfaces that slide together. Others have iron fingers that interlace as the clamp is closed. Still others do not worry about it because the instrument is intended for field use where accuracy is not so critical.

Some units have handles for one-hand operation; others require a wrench or other tool. An interesting variation is the flexible core by [Flexcorp]. Installation is by bending the core and allowing it to spring back to shape.

38.12   Magnetoresistive Sensors

Most of the features of a Hall effect sensor are available if the Hall crystal is replaced by a device whose resistance changes with magnetic field. The discovery of giant magnetoresistive devices has recently made this idea attractive. [NVE]

Such devices still exhibit rather small resistance change and are sensitive to other effects such as temperature, so it is imperative that they be used in self-compensating bridge circuits in the manner of a strain gage. They are also insensitive to the polarity of the field.

Zetex has delivered magnetoresistive current sensors using thin-film permalloy in a variety of printed circuit packages. They are constructed in the form of a bridge and require bias and a differential amplifier. Measured current up to 20 A passes through the chip via its solder pins.

38.13   The Magnetic Amplifier

The efficiency of a transformer can be adjusted by a dc or low-frequency current that moves the operating point on a hysteresis curve. Excitation, a pump, is required at a higher frequency; it is passed through the transformer and then synchronously rectified and filtered into a higher power representation of the low-frequency signal. The magnetic configuration must be designed so that the pump does not put power into the signal circuit. Figure 38.8 shows one such arrangement. The pump coils are phased in series so that the associated flux cancels in the center leg of the E-E transformer core. The output coils are also in series and phased to add. When dc is applied to the center winding, it saturates both sides and reduces the signal on the output coils. More complicated arrangements can preserve polarity in the phase of the output.

As a current measuring device the magnetic amplifier leaves much to be desired in linearity and frequency response, but it does provide isolation and is limited in sensitivity only by the number of turns placed on the center winding. The 20 mA dc off-hook current in a telephone is one such application.

38.14   Fluxgates

In its simplest form, a *fluxgate magnetometer* uses a driving coil to drive a high-permeability rod into saturation, first in one direction and then in the other. A second winding observes the rate of change of the *B* field inductively. In the absence of an external magnetic field, the observed signal is symmetric; but when an external field shifts the hysteresis loop to the right or left, the symmetry is lost. An amplifier tuned and phase-locked to the second harmonic of the driving frequency can be used to determine the amplitude of the external field.

In principle, such a fluxgate could be used to sense the field in the gap of a flux concentrator as with the Hall sensor, but it is too big and the linearity would be unacceptable. It is better to think of a way
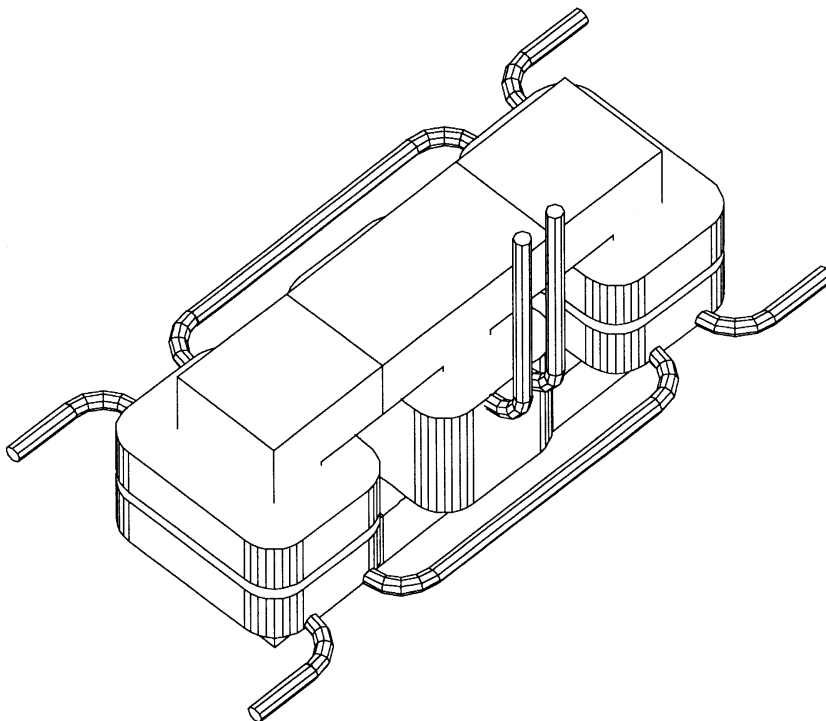
FIGURE 38.8 The windings of a magnetic amplifier. For simple current detection, the coils can be as little as two turns on ferrite toroids using an RF pump.

to drive the whole flux concentrator with a pumping frequency similar to that used in a magnetic amplifier.

Driving a toroid this way has the undesirable effect of coupling the pump energy into the circuit being measured, but one can pump two toroids in opposite directions. Now a current to be sensed passes through both cores and biases one in one direction and one in the other relative to the pump. A pickup winding senses second harmonic, which is demodulated with a phase-locked sensor to preserve the direction of the sensed current.

Linearity is improved by adding one more winding through both toroids; it is driven by a servo amplifier that is satisfied only when the amplitude of the second harmonic is zero; the flux at the measured frequency is zero. This is now the ideal current transformer. At the frequency of the sensed current, which might be dc, there is zero average flux in the toroids and the output of the servo amplifier is a true representation of the current being measured, reduced by the turns count of the servo winding.

Unfortunately, complicated electronics and considerable power are required to accomplish all of this, but the resulting accuracy is significantly better than anything other than precision shunts. Two suppliers — GMW and Holec — provide equipment that uses similar principles. Many of the details are either patented or proprietary.

38.15   Optical Sensors

The Faraday effect is a rotation of the plane of polarization of light as it passes in a transparent medium parallel to a magnetic field. Optical fibers that do not randomize polarization are available with a small Faraday coefficient. Winding such a fiber on a form to be installed around a wire so that the light propagates parallel to the field produced by current in the wire, Figure 38.1, results in a sensor. A measurable rotation proportional to the current comes about because of the long optical path. When

the myriad problems of preparation are solved, the result is a sensor that looks externally like a current transformer but has no wires. Using a reflecting ring made of yttrium-iron-garnet with a large Faraday coefficient, NIST reports sensitivity of 220 nA [6]. Matsushita Electric Industrial Company makes sensors using thin garnet films.

Analysis of the polarization requires a polarized light source and a polarization analyzer at the other. An advantage of such a sensor is that the fiber leading to and from can be long enough to allow isolation for very high voltages.

Winding and annealing of fiber sensors without destroying the polarization-preserving properties of the fiber and temperature sensitivity of the Faraday coefficient must be addressed. Further information on these sensors can be found in [7–9]. ABB, Sweden, reports a maximum detectable current of >23 kA, a sensitivity of about 2 A, and a relative error of ±0.15% [7].

38.16   Fault Indicators

Latching indicators which save an indication of high pulse current which was present sometime in the past are needed for power distribution systems subject to lightning strikes. Such indicators are often a bar magnet that moves into a latched position when a current pulse occurs. Readout is visual and they can be reset and installed on live wires using high-voltage tools.

38.17   Other Schemes

Cantor of Ford Aerospace has described a flux reset transformer scheme for measurement of direct current [10]. An oscillator and semiconductor switch periodically drive a core into reverse saturation. When the drive current is switched off, the flux rises due to dc in the sense winding and produces a voltage on the drive winding that is sensed synchronously with the oscillator. No commercial device based on this principle is available.

The double-balanced mixer, familiar to RF engineers, is also a sensor for low-frequency current. The IF port is usually dc-coupled through diodes in a ring configuration. dc applied there will modulate an RF pump applied to one of the RF ports and recovered on the other. There are no known products that use this principle.

38.18   Some Generalities and Warnings

Except for very simple loads, the waveform of the current drawn by a load does not resemble the voltage waveform. Besides the well-known phase shift and power factor, current flows in harmonics and sub-harmonics of the power frequency. Bridge rectifiers with capacitor input filters draw pulses of current near the peaks of the voltage waveform. Triacs cause a phase shift of the fundamental and introduce odd harmonics. Triacs in full-cycle mode with zero current switching can draw full current for a few cycles, followed by zero current for a few more introducing frequency components below the power frequency. Frequency changers are likely to draw current in pulse width modulated bursts.

A classic error is to measure true rms voltage and true rms current and multiply the two to get power. Even after correcting for phase, this is usually wrong. In short, accurate measurement demands some knowledge of the characteristics of the load. Beware of sensors labeled "true rms" for they can be anything but.

38.19   Current Actuated Switches and Indicators

Another form taken by current sensors is the current actuated switch. There was a time when contacts were placed on the pointer of a D'Arsonval movement to establish upper and lower limits for a process variable. The modern way is to configure a sensor so that it operates a solid-state switch.

When operating power is available, any of the current sensors can be configured as a switch; but when the switch must be controlled solely by the power that can be extracted from the current being measured, the gapped toroid is superior. The high voltage available can be rectified to control MOSFETs or the base of an open collector Darlington transistor [SRT].

One company — CR Magnetics — markets a light-emitting diode, LED, indicator that shows the presence of alternating current without any connection or external source of power.

Circuit breakers can be implemented with a magnetic coil or with a bimetallic thermal element. For completeness, there is also the fuse.

Ground fault breakers use a toroidal CT through which the line current is passed twice: once on the way to the load and again on the way back to the neutral wire in such a way as to cancel. Any fault current to ground associated with the load causes the return current to be less than the source and induces voltage on the secondary of the toroid. This is amplified and used to trip a switch. This application demands absolute insensitivity to the position of a current-carrying wire in the hole of the toroid. Gapped sensors typically are not suitable because of magnetic leakage.

38.20   Where to Get Current Sensors

CTs, shunts, and some other sensors are commodity items available from a variety of manufacturers and distributors. Well-known manufacturers of switchgear — General Electric and Westinghouse — have their own CTs for use with their power meters. Test equipment manufacturers — Simpson, Tektronix, Fluke, Extech, and the like — offer hand-held current meters. Tables 38.1 and 38.2 show distributors and manufacturers of current sensing equipment. There is no way that a list such as this can be complete. It has selected itself from those companies willing to contribute to the author's library.

TABLE 38.1   Purchasing Current Sensors, Sample Prices in $U.S.

Newark Electronics catalog 114 (1996)	
1365 Wiley Road	
Schaumburg, IL, 60173-4325	
Tel: (708) 310-8980, Fax: (708) 310-0275, (800) 298-3133	
Crompton Instruments CTs, 2 VA burden 50 A to 200 A, 60 Hz	$23
Crompton shunts, 5 A to 200 A, 50 mV, 0.25%	$25
Carlo Gavazzi CTs with 4 mA to 20 mA output circuits	$154
F. W. Bell Hall effect sensors, 100 A to 3000 A AC or DC, ±15 V power required	$285
Honeywell Hall effect sensor using the null balance technique, 1 μS response time, ±15 Vdc required	$40
Amprobe digital clamp-on AC/DC to 600 A	$141
Amprobe harmonic analyzer	$1058
Simpson 0-1 mA D'Arsonval panel meter	$64
The Grainger catalog 387 (1996)	
Tel: (708) 498-1920, (800) 323-0620	
http://www.grainger.com	
Simpson CTs ("donut" transformers), 50 A to 1000 A	$30
Simpson 50-mV shunts	$40
Jensen Tools catalog for 1996	
7815 S. 46th St.	
Phoenix, AZ 85044-5399	
Tel: (602) 968-6231, Fax: (602) 438-1690	
Tel: (800) 426-1194, Fax: (800) 366-9662	
http://www.jensentools.com	
Various Fluke and Extech products	
Yokogawa digital clamp-on AC/DC to 200 A	$279
Tektronix "Pen meter" with clamp-on to 300 A, 1.7%	$104

TABLE 38.1 (continued)   Purchasing Current Sensors, Sample Prices in $U.S.

Techni-Tool, catalog 59 (1997)	
5 Apollo Road	
Plymouth Meeting, PA 19462	
Tel: (610) 941-2400	
http://www.techni-tool.com, techtool@interserv.com	
Fluke clamp-on AC/DC oscilloscope probes, 100 A, dc to 100 kHz	$395
Fluke clamp-on Hall effect current probe, 700 kA, 2%	$297
Fluke clamp-on inductive current probe, 150 A	$79
Extech clamp-on true rms AC/DC complete digital meter	$249
Omega, Data Acquisition Guide (1996)	
One Omega Drive	
P.O. Box 4047	
Stamford, CT 06907-0047	
Tel: (800) 848-4297	
http://www.industry.net/omega	
ac current transducer, 0–5 A for use with CT, 4–20 mA output	$240
CT, 1000:5, 52-mm diam. window, 10 VA burden, 0.6%	$32

TABLE 38.2   Selected Manufacturers of Current Sensors

AEMC Instruments
99 Chauncy St.
Boston, MA 02111-9990
Tel: (617) 451-0227, (800) 343-1391, Fax: (617) 423-2952
Manufactures a selection of clamp-on current transformers suitable for extending the range of other alternating current
  meters.

ABB Inc., with numerous outlets, offers an optical sensor using the Faraday effect.

Amecon
1900 Chris Lane
Anaheim, CA 92805
Tel: (714) 634-2220, Fax: (714) 634-0905
Offers a line of smaller CTs

American Aerospace Controls
570 Smith St.
Farmingdale, NY 11735
Tel: (516) 694-5100, Fax: (516) 694-6739
Has a line of ac and dc current sensors for mounting in remote locations with wiring to collect data.

Coilcraft
1102 Silver Lake Rd.
Cary, IL
Tel: (708) 639-6400
Manufactures smaller current transformers usable up to 100 A for mounting on printed circuit boards.

CR Magnetics Inc.
304 Axminister Dr.
Fenton, MO 63026
Tel: (314) 343-8518, Fax: (314) 343-5119
http://www.crmagnetics.com
Provides a full line of current transformers and current actuated switches. Their catalog contains a useful discussion of
  accuracy classes and selection criteria.

Dranetz Technologies, Inc.
1000 New Durham Rd., P.O. Box 4019
Edison, NJ 08818-4019
Tel: (908) 287-3680, (800) DRANTEC, Fax: (908) 248-9240
Offers a line of equipment for analysis of power and is included here although it does not make instruments dedicated to
  current sensing.

TABLE 38.2 (continued)   Selected Manufacturers of Current Sensors

EIL Instruments
10946 Golden West Drive
Hunt Valley, MD 21031-1320
Tel: (410) 584-7400, Fax: (410) 584-7561
Offers a complete line of CTs and other current transducers in a variety of accuracy classes.

Extech Instruments Corporation
335 Bear Hill Road
Waltham, MA 02154-1020
Tel: (617) 890-7440, Fax: (617) 890-7864
Builds a line of hand-held meters suitable for current measurement to 2000 A.

F. W. Bell
6120 Hanging Moss Rd.
Orlando, FL 32807
Tel: (407) 677-6900, (800) 775-2550, Fax: (407) 677-5765
mbuechin@belltechinc.com
Offers noncontact sensors mostly using the Hall effect with a variety of output connections. In closed-loop mode, a 100 Adc
to 100 kHz unit can be bought for $52 plus your cost of the ±15 V to operate it.

Fluke, numerous sales offices and distributors, has a line of sensors for their hand-held instruments.

Flex-Core division of Morlan and Associates
6625 McVey Blvd.
Worthington, OH 43235
Tel: (614) 889-6152, (614) 876-8308, (614) 876-8538
Makes a line of sensors that cover the range of CTs. Of particular interest is their flexible iron core, which can be installed
over an existing conductor by bending it.

GMW Danfysik
P.O. Box 2378
Redwood City, CA 94064
Tel: (415) 802-8292, Fax: (415) 802-8298
Offers a line of laboratory grade equipment for precision noncontact measurement. Precision in the ppm range and prices
to match. Up to 10000 Adc to more than 200 kHz. Large-area CTs suitable for beam current in accelerators under the
Bergoz tradename.

Holec Power Protection B.V.
P.O. Box 4
7550 GA Hengelo
The Netherlands
Tel: +31.74.246.28.50, Fax: +31.74.246.28.00
hppbv@pi.net
Offers "zero-Flux" current transformers using servo amplifiers to drive the secondary actively. Their document 5.20.2 helps
to understand the principles involved that operate from dc to 500 kHz.

LEM U.S.
6643 West Mill Rd.
Milwaukee, WI
Tel: (414) 353-0711
Offers Hall effect sensors in both open- and closed-loop form for ac and dc currents up to 10000 A and up to 200 kHz.

Microswitch Division of Honeywell Inc.
11 W. Spring St.
Freeport, IL 61032-9945
Tel: (815) 235-6600
Offers current sensors mostly using the Hall effect, along with their line of magnetic sensors and switches.

Neilson-Kuljian
P.O. box 328
Palo Alto, CA 94302
Tel: (415) 856-3555

TABLE 38.2 (continued)   Selected Manufacturers of Current Sensors

Nonvolatile Electronics (NVE)
11409 Valley View Road
Eden Prairie, MN 55344-3617
Tel: (612) 829-9217, (800) 467-7141, Fax: (612) 996-1600
info@nve.com, http://www.nve.com
Has a giant magnetoresistive sensor in an SO8 package that could be used to make a sensor. Less than $3. Other companies
  are working with NVE on current sensors, but they prefer not to be known at this time.

Ohio Semitronics
4242 Reynolds Drive
Hilliard, OH
Tel: (614) 777-4611, Fax: (614) 777-4511
http://www.ohiosemi.com
Offers a wide range of current, voltage, and power transducers for ac and dc. They will soon be introducing network-capable
  digital output devices, including such things as harmonic analysis.

Pearson Electronics Inc.
1860 Embarcadero Road
Palo Alto, CA 94303
Tel: (415) 494-6444
Provides high-speed compensated current transformers for pulse work with oscilloscopes.

Smith Research & Technology, Inc. (SRT)
3109 S. Cascade Ave., #201
Colorado Springs, CO 80907-5190
Tel: (719) 634-2259, Fax: (719) 634-2601
http://www.srt_inc.com
Offers gapped inductive sensors with ac, dc, and 4–20-mA output up to 1000A. ac current actuated switches which control
  isolated 200-W loads using no external power for the switch are offered. A combined voltage and current sensor with
  integrated programmable microprocessor is available for harmonic analysis of power systems with network connectivity.

Sprague Electric
San Diego, CA
Tel: (619) 575-9353
Offers their model 97Z current sense transformer, which is for feedback in switching power supplies above 50 kHz.

SSAC
8220 Loop Road
Baldwinsville, NY 13027
Tel: (315) 638-1300, Fax: (305) 638-0333
Has a line of less-expensive switching products that are often found in catalogs issued by distributors.

Tektronix, numerous sales offices and distributors, has announced current sensors and hand-held instruments.

Zetex division of Telemetrix PLC
Fields New Road
Chadderton, Oldham, OL9 8NP, U.K.
Tel: 0161-627-5105, Fax: 0161-627-5467
Tel: (516) 543-7100, Fax: (516) 864-7630 in the U.S.
This supplier of integrated circuits and transistors offers magnetoresistive current and magnetic field sensors for use on
  printed circuit boards.

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