ELECTRIC CURRENT MEASUREMENT

Current measurements are used to monitor, control, and protect relaying. Current measurements are often the basis for estimating many other physical quantities. Electric current is measured in amperes. It is a measure of the rate of flow of electrons. Traditional direct measurement methods are based on passing the current through a measuring device. Although the device is not supposed to alter the current, direct measurement methods are generally intrusive by their very nature. The indirect measurement methods are based on measuring an effect of the current flow.

The galvanometer is an electromechanical device invented around A.D. 1794. It is based on measuring a magnetic field caused by a current flow. A sensitive magnetic needle deflects in response to the current through a coil. The galvanometer is the basis for many modern display meters.

Electric current measurement techniques have evolved through the years. The developments have addressed the need for better current transducers, for measurement of very large, very small, very fast, and very high voltage currents, and for measurement of current in unapproachable areas, like the human body and inside motors.

Maintenance of a current standard is not as straightforward as that for a resistance, mass, length, and the like. This is due to the fact that current measurement is intrusive by the very nature of the quantity. The earlier current standard was based on the Kelvin current balance (1). The balance is based on four fixed coils and two suspended coils all carrying the same current. The torque produced on the moving coils is balanced by precise weights. An indirect current standard based on the voltage standard and the resistance standard has better acceptance.

CLASSICAL MEASUREMENT METHODS

Techniques (1,2) based on magnetic field, electric field, and heat have been in existence almost since electricity was discovered. They were basically designed for steady currents. The devices could also measure current variations slowly enough to be visible to the human eye. The dc (direct current) measurement was the standard. When ac (alternating current) was introduced, many of the dc instruments were adapted to measure equivalent dc currents.

Magnetic Field

Current flow in a conductor creates a magnetic field around it. This is called the Hall effect. The magnetic field is concentrated by allowing the current to pass through a coil. A ferromagnetic material experiences a mechanical force when placed in a magnetic field. This force is converted to a torque, and an indicator is allowed to move. This movement is used to measure the current flowing through the coil. This principle is the basis of a galvanometer. The galvanometer is still a common method for current measurement.

The wire resistance, wire inductance, and induced currents in other metal parts cause a burden on the measuring circuit. The burden can alter the current being measured. Several refinements have been made to increase sensitivity and reduce the current being diverted through the measuring circuits. Refinements include delicate balancing, use of springs for damping, and use of permanent magnets to amplify the response. If the current is alternating or varying very fast, the indication is the mean value. This method is suited for measuring the steady or average direct current. A common way of measuring alternating current is to use a rectifying bridge to measure the mean value of each half cycle. The mean value of half cycle of a pure sine wave is about 0.9 times the root mean square of the full cycle.

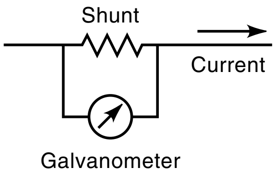

Figure 1. Current shunt.

Electric Field

An electric potential creates an electric field around it. At normal voltages, the electric field is too small to be measured accurately by an electromechanical method. Instruments to measure the electric field have usually been very costly. Traditional voltage-measuring techniques have relied on measuring a current proportional to the voltage. At very high voltages, the electric field can be high enough to permit reliable measurements. The principle used is that there is a force of attraction between surfaces charged at a high voltage and surfaces at ground potential. This force is used to actuate sensitively balanced needles or mirrors. The resulting motion gives a measure of the voltage. This is an expensive method of very low intrusion and suitable for very high voltages.

Heat

The flow of current through a resistance results in part of the electric energy being converted to heat. The amount of energy converted is proportional to the square of current. If the current to be measured is made to flow through a thin wire, the heat expands the wire. The expansion can be made to actuate a needle or some other mechanical position indicator. The indication is a measure of the mean square of the current. Instruments based on heat is immune to ambient electromagnetic fields. However, their accuracy is affected by the ambient temperature and will need recalibration to account for this.

CURRENT TRANSDUCERS

It is often not practical to allow the current to be measured to flow through the measurement circuit. Two common methods to divert a small current proportional to the current to be measured are resistive shunts and current transformers. Rogowski coils and optical and wireless methods are some of the novel tranducing techniques. A combination of these techniques is often proposed as the optimized solution offering advantages in special situations.

Resistive Shunts

A shunt is used to divert a small portion of the current into a measuring circuit. See Fig. 1. The diverted current is proportional to the unknown current. The effect on the unknown current is thus minimized. The resistive shunts are simple in concept and are widely used for steady direct current and steady alternating current as well as transient currents. The shunts should have very low resistance to minimize dissipated power. Their inductance should be negligible while measuring ac and transients. Typical values of shunt resistors are from 1.0 Ω to 0.01 Ω.

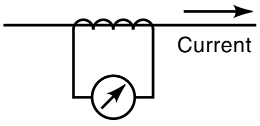

Figure 2. Current transformer.

Current Transformers

Current transformers (CT) are the most versatile transducers for use in alternating current measurement. See Fig. 2. They are based on the existence of a magnetic field around any current-carrying conductor, which is called the Hall effect. They are used with currents up to 5000 A and 1000 Hz. frequency in power systems. These provide acceptable performance up to 1000 A. At higher levels, they suffer from drift problems and core saturation. They may need compensation methods while measuring harmonic currents much higher than 1000 Hz. An acceptable level of electrical insulation is required between the CT and the high-voltage connection. Any measuring device connected to the secondary of the CT causes a burden on the main current flow. The burden should be as small as possible to avoid altering the current. For a given primary current, the burden is proportional to the core flux. Large lead distances increase the burden. High voltages require thick insulation and a large distance. Thus the use of conventional CT becomes very difficult at high voltages.

A current transformer cannot be used in direct current measurement. However, a proposed method (3) uses the effect of direct current and the magnetization curve of a transformer on its inductance characteristics. An *RL* multivibrator circuit with a nonlinear transformer is used to produce a voltage representing the current to be measured.

Rogowski Coils

The principle of Rogowski coils (4) has been well known since 1912. The Rogowski coil is a solenoidal air core winding of a small cross section looped around a conductor carrying the large transient current. The voltage induced across the terminals of the coil is proportional to the derivative of the current. The induced voltage is also proportional to the number of turns. See Fig. 3. The principle of using a Rogowski coil for current measurement is illustrated in Ref. 5. If the Rogowski coil is connected to a passive *RC* network (6), integrated effect of the voltage induced can be measured. That gives a measure of the current in the main conductor.

Rogowski coils can respond to rise times of a few nanoseconds. They have a decay time of several microseconds. They usually have been used for the measurement of very large currents such as hundreds of kiloamperes, which last for a very short duration, such as less than a microsecond. Such currents occur in electron beam accelerators and transient plasmas. They have the advantages of having a very fast response time and being free from nonlinearity and saturation effects.

Rogowski coils are not preferred for small currents because the voltage induced is small. Another disadvantage is the loss of an initial value caused by the integration process. The cost of Rogowski-coil-based current measurement is very high. A Rogowski coil with an operational amplifier integrator (7) has been shown to measure power system currents of the order of 500 kA.

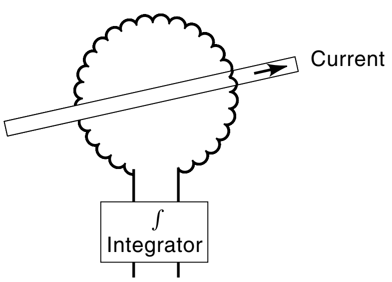

Figure 3. Rogowski coil.

Optical Transducers

The optical measurement of current (8,9) is recognized as a viable option in power systems. It has the following advantages:

- Better immunity to ambient electromagnetic and electrostatic fields. They may be the only option in high electromagnetic field areas.
- Better linearity than iron core transformers. The accuracy can be substantially better.
- A high degree of isolation for safety of instruments and personnel. They are suitable for very high voltages.
- Suitable for very frequency and fast current changes.

There are various ways of implementing the optical transducer–decoder functions.

- A polarized light beam changes its plane of polarization when it passes through a magnetic field. This is called the Pockels effect. See Fig. 4. Several measurement methods based on Pockels effect have been developed (10). Optical elements like crystals, glass blocks, and fibers (11) have been used for sensing the polarizing effect of the magnetic field surrounding the electric current flow. A fiber-optic cable transmits the optical signal from the transducer to a decoder. The detection at the decoder end requires a polarization decoder.
- A polarized light beam changes its plane of polarization when it passes through an electric field. This effect was reported by Michael Faraday in 1845. This has generally been used for measuring high voltages (12,13). A method for measuring small dc currents on the order of nanoamperes to milliamperes at high voltages is presented in Ref. 14.
- In magetostriction, the sizes of certain materials change as a result of magnetic field. A light beam reflected by or

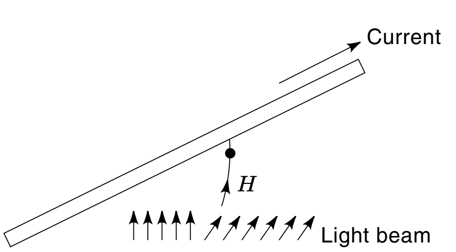

Figure 4. Pockels effect.

passing through such a material can produce light interference patterns caused by the phase difference. The interference will depend on the magnetic field, which in turn depends on the current. The interference pattern will give a measure of the current. A fiber-optic cable transmits the optical signal from the transducer to a decoder, which analyzes the interference pattern of the light received.

- Another method modulates the frequency of an inexpensive light emitting diode (15) and transmits that signal via an optical fiber. This approach avoids sensitive and expensive polarization coding and decoding process. An active electronic circuit, placed at the site of the high-voltage conductor, generates a voltage signal of several hundred kilohertz. The frequency deviation of the signal is proportional to the amplitude of the current. This voltage is used to activate a light emitting diode (LED). The optical fibers carry the signal to a ground station. A photodiode responds to the optical signal and reproduces the signal at the same frequency. Another active electronic circuit at the ground station produces a voltage proportional to the frequency deviation. This voltage gives a measure of the current in the high-voltage conductor.
- Chromatic modulation (16) produced using a liquid crystal is the basis for another method. A current transformer placed on the high-voltage line and a current-to-voltage converter provides a voltage proportional to the line current. A broad band light source illuminates the liquid crystal elements of a modulator. The liquid crystal modulator attenuates a portion of the light source spectrum by an amount depending on the voltage. This light is picked up an optical fiber and brought to a ground station. The decoder consists of a double layer photodiode, with different but overlapping spectral sensitivities. The ratio of the currents produced by the photodiodes is measured with an analog-to-digital converter. This gives a measure of the current in the power line.

Transducers with No Physical Connection

Measurement of current with absolutely no physical connection has enormous advantages in cost and safety. The following methods are still being studied.

- A novel optical method eliminates (17) the use of the fiber optic connection itself. It proposes the use of a laser beam and the Faraday/Pockels effect. The reflected laser beam is used to estimate the current.
- Another method is to locate an active current-measuring device at the high-voltage level and transmit the measurement via radio frequency to a base station several meters away. There are several variations of the transmitted signal and the method of transmission. Recent developments in digital communications area have created new opportunities for investigating this approach.

CURRENT MEASUREMENTS IN SPECIAL SITUATIONS

Different measurement techniques offer different advantages and disadvantages under special circumstances. The costs can vary enormously. Some of the special situations and the preferred techniques for current measurement follow.

Currents Measurement Inside the Human Body

Human sensation of current is the combined effect of the duration, intensity, and frequency. Guidelines for limiting currents induced in the body for the frequency range of 3 kHz to 300 GHz are available (18). Electromagnetic pulses of 10 A may cause no sensation, and 100 A produces only a tingling sensation. However, steady current threshold of human body is much lower. The effect of induced currents at power frequencies is a matter of ongoing study. The steady currents induced in human body are on the order of milliamperes. The measurement techniques are less disturbing to the person and cause minimal change in the value being measured. Such techniques (19) have been developed for measurement of current in the 1 MHz to 200 MHz range.

Harmonic Current Measurement

The harmonics give a measure of the deviation from a pure sinusoidal waveform. Harmonic voltage measurements have been used as a measure of the quality of voltage in power systems. Harmonic current measurements are essential for apportioning the responsibility (20) for harmonic distortion. Conventional current transformers may not offer a sufficiently wide frequency range. An electronic technique (21) for reducing the flux in the magnetic core, thereby increasing the frequency response, has been developed. Another technique (22) reduces the flux by using two toroidal coils with opposing fluxes to have a similar increase in performance.

High-frequency currents tend to flow near the surface of conductors. Thus the resistance of the conductor varies with the frequency. Methods to compensate for the effect by analytical means (23) as well as by mechanical design (24) have been proposed.

Post Arc Current Measurement

There are arcs during circuit breaker operation, and the currents are usually high. Yet there is a current activity of milliamperes range around the zero crossing immediately following an arc. These currents provide valuable insight regarding the condition of the switchgear. The measurement sensor under these conditions must measure milliamperes with a megahertz bandwidth, without being damaged during high currents. A technique (25) automatically inserts and disconnects a measurement shunt very close to the zero crossing and measures such currents.

Motor Windings Current Measurement

There is no direct means of measuring the current in windings with no brushes. These currents are useful for control and monitoring purposes. They are estimated (26,27) using other measurable currents.

Lightning Current Measurement

Lightning-induced currents are a source of damage in electrical power lines and other conducting structures. Measuring the wave crest value and wave front duration is of interest in order to assess the damaging effects. The amplitude ranges up to thousands of amperes and the duration is on the order of a few microseconds. Some measurement results and techniques are reported in Ref. 28.

Measurement of Currents at High Voltage

The power line voltage necessitates isolation for safety purposes. Optical couplers are available for voltages up to 1000 V. These can be integrated in a circuit board along with other current-conditioning interfaces. High-voltage lines up to 1000 kV need additional levels of safety isolation interfaces. Highly insulated current transformers are commonly used in substations. They are bulky and expensive. Copper winding, iron core CT has been in successful use for 100 years. During that time, several refinements to the design have been made to improve safety and reduce failures (29). The optical (12) and wireless methods offer a great advantage at very high voltages.

Measurement of Large Currents

It is sometimes inconvenient or impossible to dismantle a bus bar for insertion of a current transformer. For these situations there are clamp-on current transformers in which a clip opens the winding for manual insertion. After insertion, the clamp firmly closes the gaps in the winding. The reclosed gap affects the permeability of the magnetic core as well as the resistance of the copper winding. However, the error introduced might not be acceptable at high currents. An electronic technique to increase the permeability of the gap and thus reduce the error has been demonstrated (30). Direct currents up to 25,000 A are measured using permalloy magnetic modulation comparators (31,32). Another design to measure currents up to 100,000 A is discussed in Ref. 33.

Measurement of Small Currents

The currents in the femtoampere range occur often as leakage currents in microelectronics. A method for implementing an in situ amplifier to amplify the small current to measurable levels is illustrated in Ref. 34.

Measurement of Fast Varying Currents

Fast varying currents occur in electron beam accelerators and transient plasmas. Rogowski coils have usually been used for measuring very large currents such as hundreds of kiloamperes, which last for a very short duration, such as less than a microsecond.

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K. SRINIVASAN

ELECTRIC DISCHARGE DETECTION. See PARTIAL DISCHARGES.