AMMETERS

The term “ammeter” is a short form of “amperemeter” and any instrument used to measure amperes or fractions of it (such as mA, μA) is given the name ammeter, sometimes with the prefix of “milli” or “micro” depending on the range. The ammeter is the most commonly used electrical indicating instrument for current and other measurable quantities which are usually transduced to the form of a current.

In this article, we first review the permanent magnet moving-coil instrument, which, by itself, is suitable for only dc measurement. Then we consider ammeters which measure both dc and ac and discuss the following types under this category: dynamometer, moving-iron, and thermocouple. Under the topic of ammeters which measure only ac, we discuss the rectifier type. The bolometer bridge is included as a special high-frequency ac measuring instrument, and electronic ammeters and Hall effect ammeters are briefly mentioned. The article concludes with a brief discussion of measuring very large alternating currents and current standards.

THE PERMANENT MAGNET MOVING-COIL (PMMC) INSTRUMENT: A DC AMMETER

Most dc ammeters utilize some form of the d’Arsonval movement, that is, a current-carrying coil supported so that it rotates in the magnetic field of a permanent magnet, as shown schematically in Fig. 1. The angle through which the coil rotates indicates the amount of current passing through it. A remarkable amount of precision and care goes into the mechanical construction and choice of materials so as to result in the desired accuracy, ruggedness, and range. The details can be found in any of the first eight books mentioned in the Bibliography. Two important features in such instruments relate to the uniformity of flux density perpendicular to the coil side and the use of artificially aged permanent magnets made from high coercivity materials such as Alnico and Alcomax to ensure constancy of flux over long periods of use. In the usual construction, an inner soft iron cylinder and outer pole pieces with faces ground to cylindrical surfaces provide a uniform radial flux density of 0.2 Tesla to 0.4 Tesla in the region of the coil movement.

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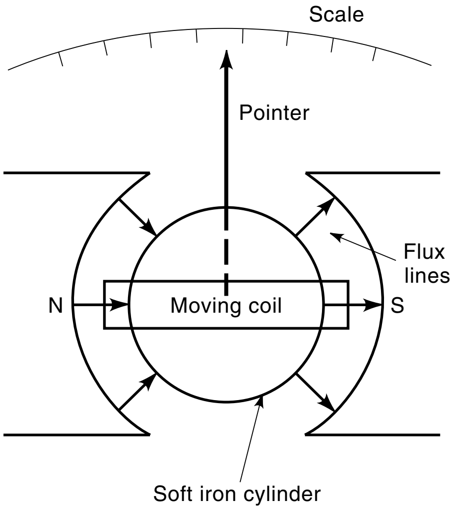

Figure 1. Essentials of a permanent magnet moving-coil (PMMC) system.

The deflection torque T_d produced in the coil, which is usually rectangular in shape, is given by

$$T_d = BNAI \tag{1}$$

where B = flux density in the air gap, N = number of turns in the coil, A = cross-sectional area of the coil, and I = current in the coil. This torque is opposed by a restoring torque T_r exerted by the control springs attached to the coil, which is proportional to the angle θ through which the coil rotates. At equilibrium,

$$BNAI = S\theta \tag{2}$$

where S = spring constant. Thus

$$I = [S/(BNA)]\theta = K\theta \tag{3}$$

where K is a constant. Since the deflecting torque is proportional to current, the coil would experience an alternating torque on the application of an alternating current. Except at low frequencies of the order of a few hertz, the inertia of the moving system provents the coil from executing oscillations and the pointer shows a deflection corresponding to the average value of the alternating current, which is zero for a sinusoid. Thus the instrument is essentially suitable for direct current measurements only.

How quickly the coil reaches its equilibrium position on a sudden change of current and whether there are overshoots and undershoots depend on the dynamics of the motion, generally characterized by a differential equation of the form

$$J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} + S\theta = GI \tag{4}$$

where J = moment of inertia of the rotating system around the axis of rotation, D = damping constant, and, by comparison of Eqs. (3) and (4) under steady-state conditions,

$$G = BNA \tag{5}$$

Equation (4) is a well-known, second-order differential equation occurring in many physical situations, for example, response of an *RLC* circuit to a step excitation, and its solutions are well documented. The main results are that the solution is underdamped, critically damped, or overdamped depending on whether D^2 is less than, equal to, or greater than $4JS$. In the first case, the response is oscillatory with overshoots and undershoots, and it may take a considerable amount of time to reach the steady state. In the last case, the response is sluggish. The best design is thus obtained when the moving system is critically damped. In practice, a small amount of underdamping is introduced for a faster response. Also, the resulting one or two oscillations in this case assures the user that there is no sticking of the movement affecting the final deflection.

The normal method of damping of the movement is through eddy currents in the aluminum former on which the coil is wound. These currents, which arise only during the motion of the coil, do not affect the final deflection.

Because ammeters are to be connected in series with the load, it is essential that they have as small a resistance as possible. The sensitivity of an ammeter is defined as the current required for full-scale deflection or sometimes as the current for the deflection of one scale division. The *current in the coil* for full-scale deflection in a permanent magnetic moving-coil (PMMC) meter varies from a few tens of microamperes to a few tens of milliamperes. Commercial ammeters with internal shunts have ranges up to a few tens of amperes. The typical voltage drop across the meter for full-scale deflection is of the order of 20 mV to 100 mV.

The range of an ammeter is increased by using a shunt resistance. It is easily shown that, if an ammeter with range I_m and resistance R_m is to be extended to I, the required shunt resistance is given by

$$R_{sh} = R_m/[(I/I_m) - 1] \tag{6}$$

Here, R_m stands for the combined resistance of the coil and a series swamping resistance of about four times the coil resistance, which is inserted to reduce temperature errors when shunts are employed. With the use of external shunts, the range of an ammeter can be extended to about a few kiloamperes. By using switchable shunt resistances of appropriate values, one can use the same meter to make a multirange ammeter.

As is well known, a voltmeter consists of an ammeter in series with an appropriate resistance. If the ammeter (I_m, R_m) is to be converted to a voltmeter of range V, then the series resistance needed is given by

$$R_{se} = (V/I_m) - R_m \tag{7}$$

Again, by using switchable series resistances with proper values, one can use the same ammeter to make a multirange voltmeter. An ammeter is also the basic indicating instrument in an ohmmeter, where in addition to resistors, a battery is also required.

The moving-coil system has the following advantages: low inertia, thereby achieving a high torque-to-weight ratio and consequent reduction of errors due to friction; uniform scale, capable of covering a large range; no error due to hysteresis; immunity to stray magnetic fields due to the localized strong field of the permanent magnet; effective damping within a light structure; and a large variety of applications as already mentioned, besides others to be discussed later. Amongst the disadvantages, the restriction of suitability for dc only, errors due to ageing and the need for delicate handling are important. Nevertheless, of all the instruments available for direct current measurement, the moving-coil permanent magnet type discussed here provides the highest accuracy of 0.05% to 0.1%.

DC/AC AMMETERS

In these instruments, the deflection depends on the square of the current. Hence they are suitable for dc and ac measurements.

The Dynamometer Type

In a variation of the moving-coil type dc ammeter, the permanent magnet is replaced by one or two fixed coils connected in parallel with the moving coil as shown in Fig. 2. Clearly, the deflecting torque in the instrument is then roughly proportional to the square of the current, which makes it suitable for direct as well as alternating current measurements. In fact, the instrument is more suitable for ac because a large number of turns are required to obtain a reasonable magnetic field, resulting in bulkiness and power loss. Also, the scale is not uniform because of the approximate square law. Dynamometer type dc ammeters are not, therefore, in common use. For ac use, these instruments are precise and accurate and are often used as secondary standards. Their main use is in the laboratory for calibrating other types of ammeters and to serve as an ac/dc transfer instrument.

The Moving-Iron Type

Moving-iron ammeters are of two types, attraction and repulsion. In either type, the current to be measured is passed through a coil of wire. In the attraction type instrument, a small piece of iron is drawn into the core of the coil and the pointer, which moves over a calibrated scale, is attached to this piece. In the repulsion type instrument, there are two pieces of iron inside the coil, one fixed and the other movable, both of which are similarly magnetized when a current flows through the coil. Hence, they repel each other, irrespective of the direction of the current. Similarly, in the attraction type, the iron piece is attracted to the coil whatever the direction of the current. Obviously, as in the dynamometer type, the deflecting torque is roughly proportional to the square of the current. Hence, this type of instrument is also useful for ac and dc, and its scale obeys a square law. However, by suitable design of the moving-iron piece(s), a linear movement over 80% to 90% of the range is possible. The sensitivity of the instrument is no better than 10 mA and the range is as high as 200 A. The frequency range of operation is limited to about 500 Hz. This upper limit is set by eddy currents and hysteresis effect in the iron piece(s). With special compensation, moving-iron ammeters have been made for use up to 2.5 kHz.

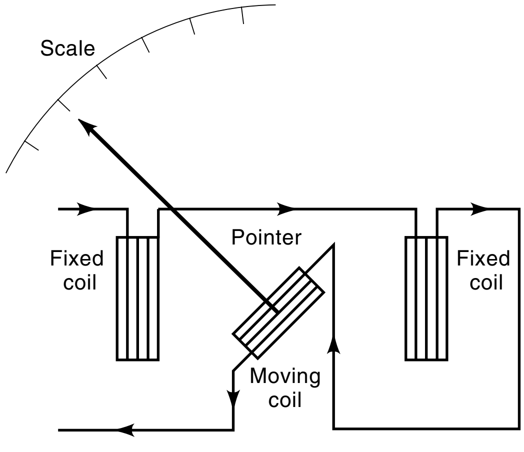

Figure 2. Basic arrangement of a dynamometer type ammeter.

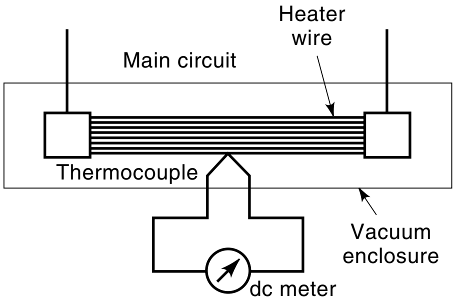

Figure 3. Basic thermocouple type ammeter.

The moving-iron type of ammeter is the most commonly used form of indicating instrument for ac use and is the least expensive among all of its competitors. With proper design and adjustment, the accuracy is very high—up to 0.2%.

For dc use, moving-iron instruments suffer from hysteretic effects in iron. They read low with increasing current and high with decreasing current. Hence they must be calibrated on ac by a dynamometer-type standard.

The Thermocouple Type

In the thermocouple type of ammeter, again suitable for both dc and ac, a short, high-efficiency heater wire is welded to one junction of a thermocouple of two dissimilar metals, as shown in Fig. 3, or kept in close proximity to the thermocouple junction with the aid of an electrically insulating bead. When a current passes through the heater wire, the temperature of this junction rises, and a small voltage, proportional to the temperature rise, is generated. This, in turn, is applied to a dc millivoltmeter calibrated in terms of current. The temperature rise of the heater depends on the square of the current. Thus the instrument scale again follows a square law. The dial is marked in terms of the rms value of the current. For high sensitivity, the thermoelement is placed in a vacuum bulb to eliminate heat losses due to convection.

True rms indication and the high-frequency range over which it operates are the two important advantages of the thermocouple-based ac ammeter. The highest frequency of operation, limited by the skin effect in the heater, runs to several hundred MHz with accuracy of ± 1% of the low-frequency value. The two main disadvantages of the instrument are that the heater must operate at 100 °C or more to provide adequate voltage to the thermocouple circuit and that even relatively small overloads burn out the heater. Sluggish response, particularly for high current ranges, is another disadvantage. Commercial instruments in the range 1 mA to 50 A are available. Thermocouple ammeters are also used as ac/dc transfer instruments in a standards laboratory.

ALTERNATING CURRENT AMMETERS

As mentioned earlier, all types of ammeters, except the permanent magnet moving-coil type, are also suitable for alternating current measurements. An instrument which is suitable only for ac is the induction-type ammeter which provides a high working torque and a long scale but is now obsolete because it is prone to large errors. We discuss here the rectifier-type ammeters in which ac is first converted to dc and then measured by a dc ammeter.

The rectifier type ac ammeter uses a moving-coil dc ammeter in conjunction with a rectifier arrangement, which converts ac to dc. Although copper oxide and selenium rectifiers have been used in earlier instruments, they are now obsolete and have been replaced by p–n junction diodes. One may use a half-wave circuit, as shown in Fig. 4(a), or a full wave circuit, such as the bridge rectifier shown in Fig. 4(b). Obviously, the half-wave circuit, in series with the ac circuit, distorts the main current and is used only with a *loosely* coupled transformer. This distortion can be reduced/eliminated by connecting another diode across the secondary to conduct in a direction opposite to that of the diode shown in Fig. 4(a). Alternatively, one can connect a shunt resistance across the secondary of the transformer and use a half-wave rectifier voltmeter to measure the voltage developed across this resistance. With either of these modifications, the current will flow in the main circuit for both half cycles. The full-wave circuit does not cause such distortions and is therefore most commonly used.

Obviously, the rectifier type instrument responds to the average current. It is calibrated in terms of the rms value of a sinusoidal ac, that is, the dc is multiplied by the form factor 1.11. If the waveform is not sinusoidal, errors are introduced. For example, a 50% second harmonic introduces an error of as much as 10%.

High sensitivity and low cost are the two principal advantages of the rectifier type ac ammeter. Commercial instruments are available for ranges of 100 μA to 50 A. Standard units using semiconductor diodes are available with ±3% error at full scale at frequencies up to 10 kHz. Special high-frequency diodes, such as the hot-carrier diodes, extend the frequency range to several hundred MHz with error not exceeding ±5% at full scale.

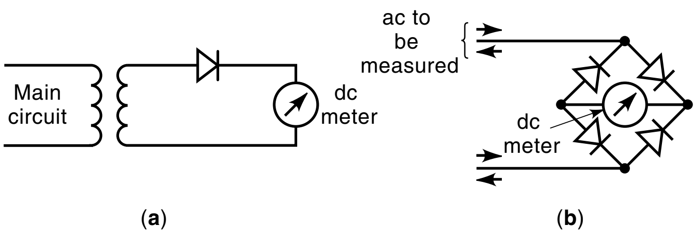

Figure 4. Rectifier type ac ammeter: (a) half-wave type; (b) full-wave type.

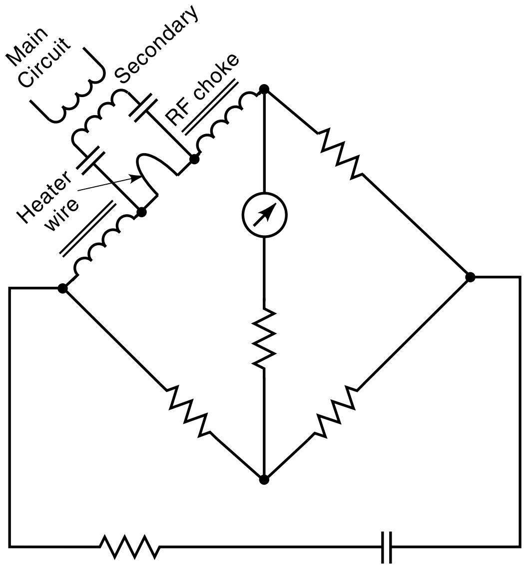

Figure 5. Bolometer bridge arrangement as a high-frequency ammeter.

The Bolometer Bridge Arrangement as a High-Frequency Ammeter

The term bolometer is used for an instrument based on the change of resistance of a wire which is heated by the current being measured. Figure 5 shows the so-called bolometer bridge arrangement for measuring high-frequency ac. The current to be measured induces a current in the secondary which has a closed path through the capacitors and the heater wire. The current cannot pass to other arms of the Wheatstone bridge because of the RF chokes. The bridge resistances are chosen so that in the absence of an induced ac, it is balanced for dc and the dc meter reads zero. The resistance of the heater arm is contributed by the dc resistance of the heater wire in series with those of the chokes. The capacitors do not allow dc to flow through the secondary. When an ac is present in the secondary, the bridge loses balance, and the meter indication is a measure of the ac. Needless to say, the arrangement is very sensitive and must be well protected from air currents so that the dc balance is not disturbed.

ELECTRONIC AMMETERS

Using a sensitive dc microammeter in conjunction with modern precision rectifiers and versatile amplification systems, one can expand the range of measurement and the frequency of operation and improve sensitivity almost to the theoretical limit. In fact, wideband commercial ammeters are now available with ranges of 10 nA full scale to 1 mA with 14 overlapping ranges.

The usual arrangement in an electronic ammeter is to first allow the current to develop a proportional voltage across either a shunt resistance or the feedback resistor in a current-to-voltage converter using a high gain amplifier. The voltage is then sensed by using one of the standard methods and the final reading in terms of amperes is obtained in analog form on a PMMC meter or in digital form on a digital display.

HALL EFFECT AMMETERS

As the name implies, this instrument uses the Hall effect in a semiconductor. Consider a rectangular slab of semiconductor and a coordinate system x,y,z along its three dimensions as shown in Fig. 6. When a dc is passed along the x direction and magnetic field is impressed along the z direction, a displacement of holes occurs in one y direction and electrons in the opposite y direction, thus creating a potential difference (pd) along the y axis. This pd, called the Hall voltage, is proportional to the current and the strength of the magnetic field and changes its polarity if either the current direction or the magnetic field is reversed. Accordingly, there are several possible schemes for ac or dc measurement by using the Hall effect. The Hall generator is a broadband active device and is used to measure current from dc to several hundred megahertz. While this wide bandwidth is an advantage, it also results in loss of sensitivity due to noise. Also, being a semiconductor device, the temperature sensitivity of the device causes problems unless special compensation networks minimize thermal effects.

Hall effect has been used with feedback to measure current using zero flux principle. A ring type magnetic core surrounds the conductor carrying the current i_p to be measured. A Hall probe carrying a reference current (fed from an auxiliary source) and placed in a small radial air gap in the ring senses the flux density in the latter. The Hall voltage generated in the probe is amplified and then used to drive a current i_s through a magnetizing winding of N_s turns wound on the ring so as to oppose the existing flux. This feedback arrangement can be adjusted to have zero flux in the core and zero Hall voltage. Under these circumstances, $i_s = i_p/N_s$. The auxiliary current is a replica of the main current, may be arranged to be of a more convenient size, and may be read on an ammeter or converted to a voltage, as may be needed. This method of current sensing is suitable for a wide range of current levels, waveforms and frequencies (from dc to a few megahertz). It lends itself to a clamp-on type meter construction and eliminates the need to break the main circuit. It also entails negligible power and voltage demands on the latter; as such, this type of sensor is eminently suited for power electronic circuits and current probes for oscilloscopes.

AMMETERS FOR LARGE ALTERNATING CURRENTS

Although measurement of large alternating currents is carried out with resistance shunt and low-range ammeters, the power losses in the shunt are prohibitive. In such cases, one uses a current transformer whose primary is connected in series with the load, as shown in Fig. 7. Because the current is stepped down in the secondary, the open circuit voltage of the secondary is very high and may break the winding insulation, and endanger human beings.

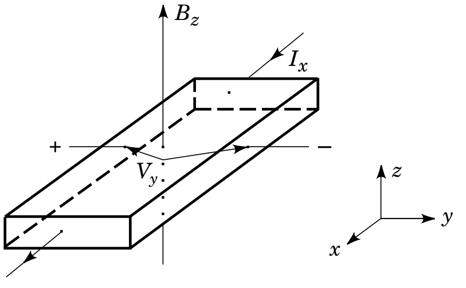

Figure 6. Illustration of the Hall effect.

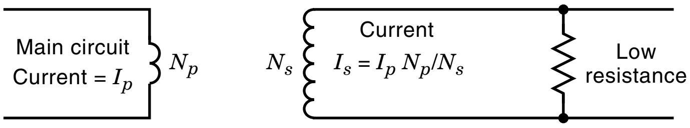

Figure 7. Arrangement for measuring large ac.

The transformer is a frequency-sensitive device and its frequency response is usually of bandpass nature. The response to dc is zero whereas that at high frequencies falls off because of leakage inductance and shunt capacitance. The response may be specified in terms of its two 3 dB frequencies. Typically, the lower 3 dB frequency is a few kilohertz whereas the upper may go as high as 200 MHz.

For measurement of large direct currents, as used in electrochemical industry, for example, use is made of what are often referred to as dc current transformers. The dc busbar carrying a current I_p passes through two identical ring shaped saturable reactors, on which are wound two ac windings of N_s turns each. A local series circuit is formed by an ac voltage source, a rectifier ammeter and the two ac windings [connected in relative opposition to each other with respect to the direct current magnetomotive force (dcmmf) in the core]. The rectified average current I_s in this circuit is given by I_p/N_s, a relation similar to that in a conventional ac current transformer.

CURRENT STANDARD

Absolute measurement of current is carried out in a very precise instrument called the current balance in which the force between a movable coil and a set of fixed coaxial coils is balanced by the gravitational force on a known mass. The force between the coils is computed in terms of the current and the dimensions of the coils, thereby expressing the current in terms of the fundamental units of mass, length, and time. Such instruments are found only in national standards laboratories which are responsible for establishing and maintaining electrical units.

It is worth mentioning that absolute measurement of current is used to assign the emf of standard cells by using a standard one ohm resistance in series with the fixed and moving coils, and comparing the voltage drop across it with the emf of the standard cell. Then the standard cell is used as the voltage standard between the times of absolute ampere measurements.

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AMORPHOUS ELECTRIC CONDUCTORS. See Hopping conduction.

AMORPHOUS SEMICONDUCTORS. See Hopping conduction.

AMORPHOUS SILICON THIN FILM TRANSISTORS. See Thin film transistors.

AMPLIFIER, IMPATT DIODE. See Impatt diodes and circuits.

AMPLIFIER, MICROWAVE. See Klystron.

AMPLIFIERS. See Dc amplifiers.

AMPLIFIERS, CROSSED FIELD. See Crossed-field amplifier.

AMPLIFIERS, DC. See Dc amplifiers.

AMPLIFIERS, DEGENERATE. See Microwave parametric amplifiers.

AMPLIFIERS, DIFFERENTIAL. See Differential amplifiers.

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AMPLIFIERS, FEEDBACK. See Feedback amplifiers.

AMPLIFIERS, INSTRUMENTATION. See Instrumentation amplifiers.

AMPLIFIERS, MICROWAVE. See Crossed-field amplifier; Microwave amplifiers.

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AMPLIFIERS, OPTICAL. See Optical amplifiers.

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AMPLITUDE NOISE MEASUREMENT. See Measurement of frequency, phase noise and amplitude noise.

ANALOG ACTIVE-RC FILTERS. See Analog filters.

ANALOG CIRCUITS. See Cascade networks; Signal amplifiers.