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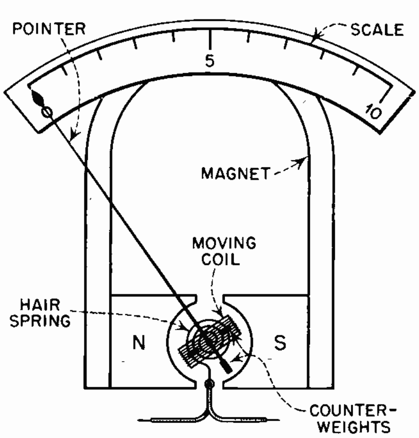
The Direct-Current Meter

By the Engineering Department, Aerovox Corporation

ALTHOUGH the o.c. meter is a standard tool around the laboratory, service bench or "ham shack," it's usefulness may be greatly enhanced by a better understanding of the principles underlying it's construction and applications. Despite the fact that the judicious use of electrical instruments is an unfailing hallmark of the skilled electronics technician, there is a tendency on the part of many to accept the meter at it's face value without ever gaining an intimate knowledge of it's internal functioning. Actually, a complete familiarity with the capabilities and limitations of the d.c. meter can be gained only through a study of it's electrical and mechanical characteristics. This paper will discuss these characteristics and point out certain precautions to be observed in the use of such measuring instruments. Because the moving-coil, permanent-magnet type known as the D'Arsonval meter forms the basis of about 90% of the meters in common use, being used to measure current, voltage and resistance with different auxiliary circuitry, the present discussion will be restricted to this type.

The D'Arsonval Movement

The fundamental principle of all general types of electrical meters is the same; the electrical quantity to be measured is converted into a mechanical motion which is calibrated in terms of that electrical quantity by means of a scale and pointer. In the D'Arsonval type, direct current flowing in the turns of a coil suspended in a steady magnetic field produces an electromotive force which rotates the armature against the counter-torque of a hair—by an amount proportional to the current flowing. A light attached to the armature indicates the rotation of the coil, and therefore the current value, on a semicircular calibrated scale. Figure 1 illustrates the usual form of this arrangement. The current-carrying coil is wound on a light-weight frame or armature which, in turn, is supported between sapphire-jewelled pivot bearings which allow it to rotate freely. The electrical connections to the coil are made through spiral hair-springs at each end of the armature. These fine alloy springs perform several vital functions. Besides providing the current-carrying path between the armature and the stationary parts of the meter, they provide the counter-force against which the meter torque or rotational force acts, as well as supplying the restorative force which returns the pointer to zero when current ceases to flow. The coil thus mounted is immersed in a strong magnetic field which is usually provided by a permanent magnet. The stability and permanency of this magnet are of importance, as well as the uniformity of the magnetic field produced between it's poles. The pole tips are usually semicircular in shape to fit closely around the moving coil. The uniformity of field is greatly improved by the use of a cylinderical core of soft iron mounted in the center of the armature so that the moving coil revolves around it. The indicating pointer is affixed to the armature at one end and a system of small adjustable counterweights is used on the tail-piece and cross arm of the pointer to balance the complete armature assembly. The angular movement of the moving coil assembly is restricted by a set of cushioned stops.



ESSENTIAL PARTS OF D.C. METER
FIG. 1

The completed assembly is extremely delicate and precise. It is interesting to note that most of the

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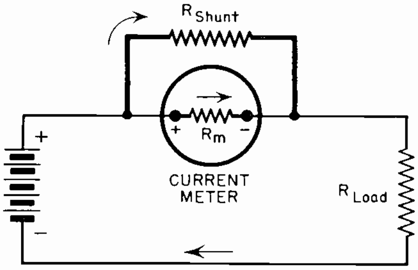


$$R_{Shunt} = \frac{R_m}{(N-1)}$$

R_m = Internal meter resistance.
N = Desired scale multiplying factor.

USE OF SHUNT RESISTANCE TO EXTEND CURRENT-METER RANGE

FIG. 2

components serve several purposes. For instance, the armature frame not only provides the form upon which the current-carrying coil is supported, but is also a closed-loop conductor in which eddy currents are induced which oppose the motion of the armature and so provide *damping* of the meter movement. Excessive overswing or oscillation of the pointer is thus avoided.

The Current Meter

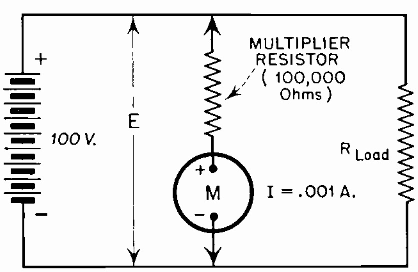
Essentially, the D'Arsonval meter is a current measuring device. The flow of current through the moving coil sets up a magnetic field around the coil which interacts with the fixed field produced by the permanent magnet to cause rotation of the coil. The turning torque developed is proportional to the strength of the permanent magnet. The number of turns in the coil, and the amount of current flowing in the coil. The pointer deflection which results is determined by the strength or counter-torque of the spiral springs. At any given meter deflection, the torque produced by the interaction of the current in the coil and the magnetic field is exactly equal to the countertorque of the hair springs and an equilibrium results. Since in any given meter design the current in the coil is the only variable, the deflection of the pointer is directly proportional to the amount of current flowing. The scale graduations in properly designed d.c. meters of this type are therefore linear.

The amount of direct current required to deflect the pointer to the highest graduation on the scale is called the *full scale sensitivity* of the meter. Instruments are manufactured in a wide range of sensitivities ranging from amperes down to a practical limit of about 20 microamperes. In addition to the above, high-sensitivity instruments are available with sensitivities of ½ microamperes for full scale deflection. Such high sensitivities are achieved by the use of powerful permanent magnets, lightweight multi-turn coils, and very delicate hair-springs.

Meters having sensitivities of one milliampere or less may be used for measuring any larger value of current by the proper use of *shunts*. If a conductor having a resistance equal to the internal resistance of the meter is connected in parallel with it, the current will divide equally between the two paths and hence twice as much current will be required to give full-scale deflection of the meter. If a shunt is chosen which has one-fourth the resistance of the meter coil, the currents through the parallel resistances divide in the ratio of 4 to 1, and since only *one-fifth* of the total current flows through the meter, it's full-scale indication is multiplied by a factor of *five*. Figure 2 shows the connection of a shunt to a direct-current meter and the equation commonly used to determine the shunt resistance required to extend the scale by a factor N. The internal resistance of the meter may be determined from the published characteristics of that type, or by measurement. In multi-range instruments it is usual to select shunts which multiply the scale calibration by multiples of ten for ease in reading.

The D. C. Voltmeter

The same basic movement which is used to measure direct current is also employed in voltmeters. In this case, resistance is added in *series* with the meter in the manner shown in Fig. 3. Such external *multiplier resistors* may be used with a high sensitivity milliameter or microameter to measure voltages ranging from millivolts to kilovolts. The meter is still performing it's original function as a current measuring instrument, but in this case it is measuring the current which an unknown voltage causes to flow in a known resistance. The voltage is therefore determined by Ohm's Law (E=IR) and the meter scale may be calibrated directly in terms of voltage. Meters for voltmeter applications are classified according to "ohms-per-volt" ratings, i.e., the number of ohms which much be contained in the voltmeter circuit for each volt which the meter is to indicate. For example, to limit a voltmeter using a one-milliampere basic movement to full scale deflection when 10 volts is impressed, the total resistance of the circuit must equal 10.000 ohms, by Ohm's Law. A total of 15,000 ohms would be required for 15 volts full scale, etc. Thus a .001 ampere meter one milliampere full scale is rated at "1000 ohms-per-volt". The same meter can be made to read 500 volts full scale by using a 500,000 ohm multiplier in series with it. In such cases, where the required multiplier resistance is very large compared with the internal meter resistance, the latter is usually ignored since the error introduced is much less than the reading accuracy of the meter. However, if it were desired to make a 1000 ohms-per-volt meter read 1 volt full scale, it would be necessary to include the meter resistance in the total value of 1000 ohms required. If the internal resistance of the meter is 100 ohms, the correct value of the multiplier would be 900 ohms since a 10% error would be introduced if the meter resistance were neglected.



E = IR = 100 Volts

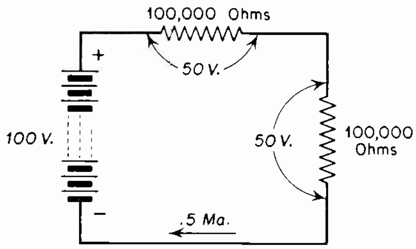
USE OF D.C. METER AS VOLTMETER

FIG. 3

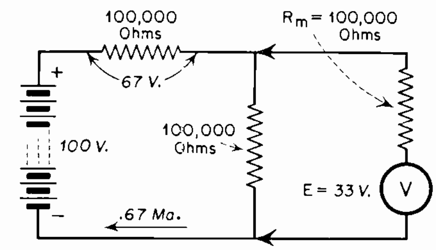
Since the voltmeter is always connected across the voltage drop being measured, it is important to use an instrument having a total resistance which is large compared to the circuit to which it is connected. Otherwise, serious inaccuracies result since a low resistance meter "loads" the circuit being measured so that the voltage drops indicated are not those which exist in the undisturbed circuit. A simplified example of such misuse of the voltmeter is illustrated in Fig. 4. To reduce such errors, basic meters having full-scale sensitivities of 50 microamperes (20,000 ohms-volt) or 100 microamperes (10,000 ohms volt) are used in high quality voltmeters.

The Ohmmeter

Just as the D'Arsonval current meter is used to determine voltage when the current and resistence are known, it may be used equally well to read resistance by indicating the current which flows when a known voltage is impressed across an unknown value of resistance.



UNDISTURBED CIRCUIT CONDITIONS



CIRCUIT "LOADED" BY VOLTMETER

FIG. 4

Such an instrument, calibrated directly in ohms, is called an "ohmmeter" and is widely used in a variety of circuit types of which Fig. 5 is a typical example. In this circuit, a battery or other source of voltage is provided which is capable of producing a full-scale deflection on the meter when the test terminals (A and B in Fig. 5) are shorted. Variations in battery voltage and other circuit constants are compensated for by adjustment of a reostat (R2). If an unknown resistance is inserted between the test terminals, the meter deflection will be reduced proportionately. The meter scale can, therefore, be calibrated directly in terms of the external resistance required to limit the meter current to that value. When the unknown resistance is equal to the internal resistance of the ohmmeter circuit, the meter will read half-scale. The formula used for the calibration of this simple ohmmeter type is also shown in Fig. 5. For the measurement of extremely low or high value of resistance, more complex ohmmeter circuits are employed.

Meter Accuracy

Direct current meters are supplied in many degrees of accuracy according to the requirements of the application. Such applications vary extremely from meters for use as primary laboratory standards having rated accuracies of .1 of 1 percent to mere indicators of the presence or absence of electricity.

Meters rated at better than 1% accuracy fall into the "precision laboratory" catagory and should be used only in protected, "well behaved" circuits *requiring* such high accuracy. They are usually of the "portable" type which are used with the needle in a horizontal position for greater accuracy and have mirror-scales to reduce *parallax* errors in reading.

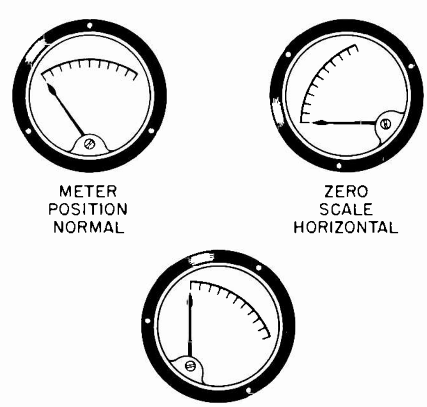
In the accuracy range below 1% are the great majority of "general utility" or "panel" meters which are the "work horses" of the electrical instrument family. They are usually mounted in test equipment panels and switchboards in a vertical position. The average accuracy of this class of meters is about 2%.

The accuracy rating of all d.c. meter types is usually given in terms of the percentage of full-scale reading to which the meter is guaranteed. A single range meter reading 100 volts full scale and rated at 1% accuracy would thus read within 1 volt of the correct value at any deflection. At 10 volts this meter could, therefore, be in error by as much as 1 volt, or 10%. Good engineering practice dictates that meters be used at a minimum of one-third full-scale deflection for this and other reasons.

Factors Effecting Meter Accuracy

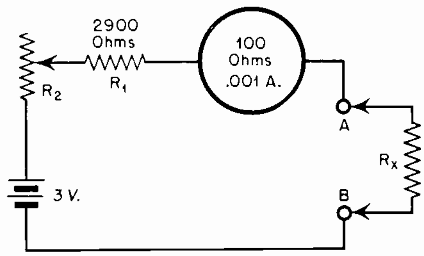
The manufacturers nominal accuracy rating does not insure accurate results from a meter in the hands of an inexperienced technician or an instrument which has been subjected to abuse. The following tabulates some of the mechanical and operational factors which may cause large errors in the reading of d.c. meters of the D'Arsonval type:

(a) Stray Magnetic Field Errors. Since the deflection of the meter depends on the strength of the permanent magnet, serious errors may be introduced by stray magnetic fields from other meters, current carrying



TEST FOR MOVEMENT BALANCE

FIG. 6



$$R_x = R_c\left(\frac{I_s - I_x}{I_x}\right)$$

Where:

R_x = Unknown resistance.

R_c = Circuit resistance (A and B shorted).

I_s = Meter current (A and B shorted).

I_x = Meter current (R_x in circuit).

TYPICAL OHMMETER CIRCUIT

FIG. 5

conductors, magnets and other ferrous materials. Expensvie meters are usually provided with adequate magnetic shielding. Some errors are also caused by mounting small meters in heavy steel panels. Meters especially calibrated for such mounting are usually so marked.

(b) Balance Errors. The delicate system of counterweights which balance the moving-coil assembly may cause "zeroing" or reading errors if improperly adjusted. The balance of the movement may be checked by holding the meter in the three positions shown in Fig. 6. If the pointer does not indicate zero in each position, the movement is not perfectly balanced. Unbalance is most serious in vertical mounted meters.

(c) Overload Errors. Permanent damage or burn-out may be caused by repeated or heavy overloads of the meter movement. Excessive current through moving-coil types causes heating of the coil and springs. Heating of the latter results in "annealing" or loss of spring tension which impairs accuracy. Overloads also cause needle "banging" which may damage pointer or pivots.

(d) Sticky Movement Errors. The meter movement may be prevented from moving freely by several mechanical defects. Chief among these is chipped jewels or damaged pivots due to rough handling. Sticking may be manifest in the failure of the meter to reproduce a known reading when approached from values above and below the known value. Light tapping of the meter case is frequently resorted to as a cure. Meter sticking is also caused by small magnetic particles which may be gathered by the magnet of a meter which is removed from it's case and left unprotected.

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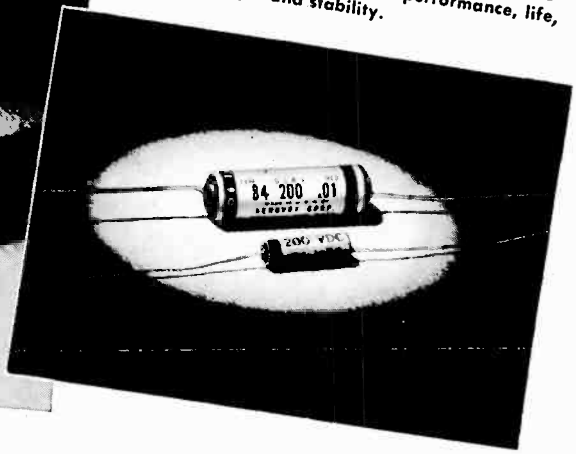

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