5.0 Electrical Measurements

In order to quantify statements, measurements need to be made. Without measurements only qualitative statements may be made. Measurements may be made either by comparison with a reference quantity of the same kind or by calculation using known quantities of other types. For example, a resistance may be determined by comparison with a known resistance, or it may be determined by the measurement of voltage, current and the law relating resistance, voltage and current.

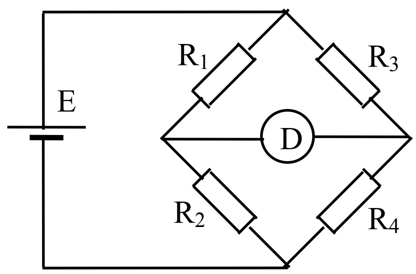
Applications: Electrical measurements are not restricted to the measurement of electrical quantities such as current, voltage, power and resistance but also non electrical quantities such as speed (tachometer), temperature (thermocouple), pressure (strain gauge), and a host of other quantities. Devices that convert one form of energy to another form for measurement and control, such as above, are known as transducers.

5.1 Accuracy of Measurements

The accuracy need for a measurement depends on the application. For example if we were measuring time using a watch, we would like it not to have to be reset more than once a month at the most. Maybe an error of 1 minute per month may be considered acceptable. [i.e. 1 minute in 30×24×60 minutes or 43,200. i.e. an accuracy of 1 in 43,200 or about 0.0023 %]. On the other hand, a one hour lecture might actually take about 1 hour ± 5 minute [i.e. 5 minute tolerance in 60 minutes or 1 in 12 or 8.33 %]

Accuracy also depends on whether a null deflection method is used (bridge method) or a direct deflection method is used. With a null deflection method higher accuracy is obtained, as the error may be successively reduced, but it is obviously time consuming. This is similar to the use of a knife-edge balance (null deflection) or a spring balance (direct deflection) to weigh something.

5.2 Wheatstone Bridge



The simple 4 arm Wheastone Bridge is a null deflection method.

The detector (or galvanometer) is made more and more sensitive near the balance point, where the detector current becomes zero and the potential difference across the detector also becomes zero. Under this condition, using potential divider action, it can be easily shown that

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

It must be noted that the balance condition of the bridge does not depend on the source voltage E, nor on the detector impedance. At balance, if three of the resistances are accurately known, the remaining resistance will also be calculated to the same accuracy. For good sensitivity, all 4 arms should have similar values of resistance.

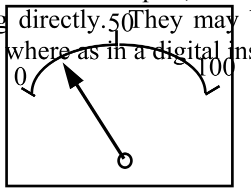
The principle of the Wheatstone Bridge can also be extended to a.c. bridges having inductances and capacitances in addition to resistances. In this case the balance condition is a complex equation and the source would be an a.c. source.

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4}$$

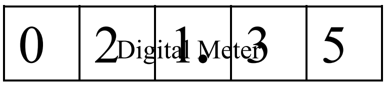
Bridges are mostly used when accurate measurements are required such as in calibrating an indicating instrument.

Indicating Instruments

Unlike null deflection techniques, which require a number of steps in the balance process, indicating instruments give the reading directly. They may be either analogue or digital. Analogue instruments give a continuous range of values, where as in a digital instrument only an exact number appears.



Analogue Meter



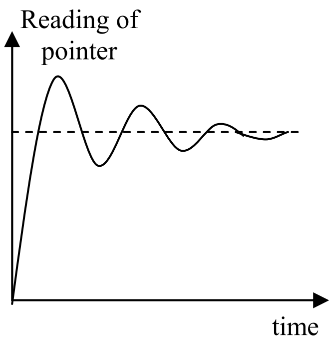
Digital Meter

Analogue meters may be direct deflecting (such as an ammeter or voltmeter), integrating (such as an energy meter) or recording (such as a graph plotter).

5.3 *Principle of operation of analogue deflecting meters*

Analogue meters show a particular deflection for a given input quantity. For this to happen, there are three main torques (rotary type of deflection) or forces (linear type). These are (a) the deflecting torque, (b) the controlling torque and (c) the damping torque.

The deflecting torque is produced by the measured quantity or a value proportional to it. This causes the pointer or needle to move away from the zero position. However, unless there is a balancing torque, the pointer will continue to move and increase the deflection. This is controlled by a controlling force, which is most commonly produced by a spring (where the torque is proportional to the deflection from the initial position). As in any system, unless damping is provided, the two forces would cause the needle to oscillate about the final position making reading very difficult. Thus damping is provided, which does not affect the final position, but reduces the over swing making the final position to be achieved quickly.

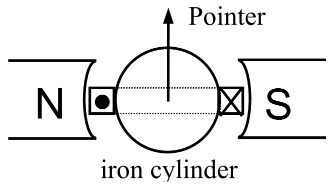


5.3.1 Principle types of analogue meters

The principle types of analogue meters in common use are the (a) permanent magnet moving coil meters or commonly referred to as moving coil instruments, (b) moving iron meters, (c) dynamometer type moving coil meters, (d) electrostatic meters and (e) induction type meters.

(a) Permanent magnet moving coil meters

In this instrument, a moving coil is suspended between the poles of a permanent magnet. When a current is passed through the coil, the coil becomes an electromagnet and tries to align with the permanent magnet. The deflecting torque becomes proportional to the strength of the electromagnet and hence to the current.

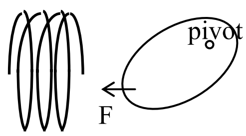


A coil spring is used which produces a controlling torque proportional to the deflection. Thus at balance, the deflection becomes proportional to the current. When the current is unidirectional, as with d.c., the deflection would be to one particular side. When the current is varying at a rate which the needle cannot follow, what will be indicated by the meter is the mean value, due to the inertia of the movement.

Thus the moving coil meter always measures the mean value or d.c. value of a given waveform.

(b) Moving iron meters

When a piece of iron is placed in the axis of the magnetic field produced by a coil, magnetism of opposite polarity would be induced in the iron. Since opposite poles attract, it would be attracted towards the coil, independent of the direction of magnetism (hence of the current in the coil). The force of attraction would be proportional to the product of the magnetism caused by the coil and the induced magnetism in the piece of iron.

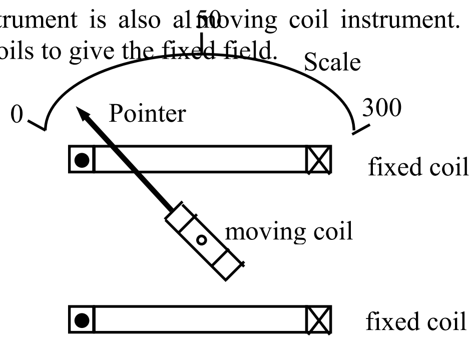


Since the latter is proportional to the former, and the former is proportional to the current in the coil, the force of attraction would be proportional to the square of the current. Thus if a controlling torque is provided by a spring, the deflection at balance would be proportional to the square of the current, or since the movement would normally not be able to respond at the rate at which the supply is alternating due to its inertia, the deflection would be proportional to the mean value of the square of the current. If the square root of this indication is taken, it would correspond to the root mean square value or rms value. This value can be measured for both a.c. and d.c.

Thus the moving iron meter always measures the r.m.s. value of a given waveform.

(c) Dynamometer type instrument

The dynamometer type instrument is also a moving coil instrument. In this case, the permanent magnet is replaced by a pair of fixed coils to give the fixed field.

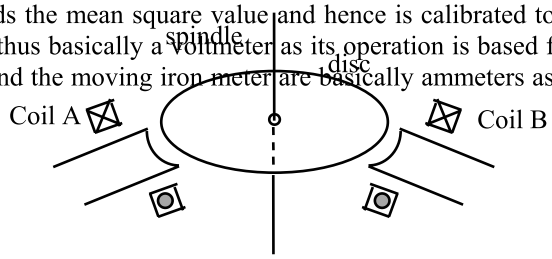


In this case, the deflection would be proportional to the product of the two magnetic fields, and hence to the product of the currents in the fixed coils and the moving coil. Thus, if used as an ammeter will measure the mean square value, or usually calibrated to read the r.m.s. value.

(d) Electrostatic meters

Electrostatic meters basically work on the principle that the force (or torque) of attraction is proportional to the product of the charges. Since a single voltage produces the charges, the force is proportional to the square of the voltage. Thus this meter too reads the mean square value and hence is calibrated to read the root mean square value. The electrostatic meter is thus basically a voltmeter as its operation is based fundamentally on a voltage, where as the moving coil meter and the moving iron meter are basically ammeters as their performance is based on current.

(e) Induction type meters

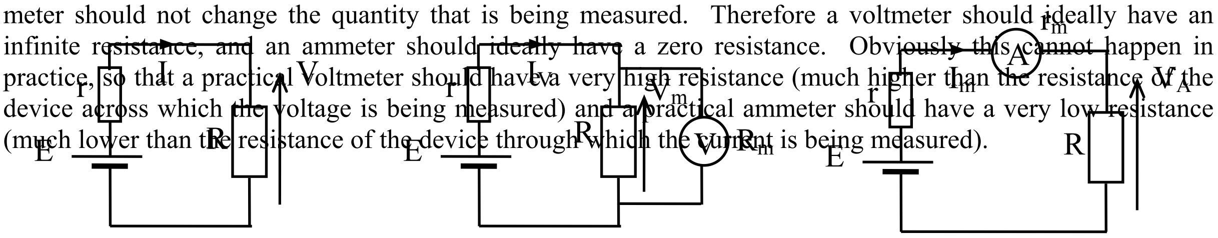


The induction meter depends on the torque produced by the reaction between a flux (whose value depends on the value of the current in coil A) and the eddy currents which are induced in a non-magnetic disc (usually aluminium) by another flux (produced by current in coil B). Since the action depends on induction, they can be used to measure alternating quantities only. The meter would have a deflection proportional to the product of the two currents. A damping magnet ensures that the speed of rotation is constant for a given set of currents and the meter is not normally used as an ammeter or voltmeter, but as an integrating meter, where the number of revolutions would be proportional to the integral of the product of the two currents.

5.4 Voltmeters and Ammeters

Voltmeters for the measurement of voltage, and ammeters for the measurement of current are generally based on the same principle. However, there is one basic difference in their use. While voltmeters are connected in parallel to measure the voltage, ammeters are connected in series to measure the current.

A good meter should not interfere with the quantity that is being measured. That is, the introduction of the meter should not change the quantity that is being measured. Therefore a voltmeter should ideally have an infinite resistance, and an ammeter should ideally have a zero resistance. Obviously this cannot happen in practice, so that a practical voltmeter should have a very high resistance (much higher than the resistance of the device across which the voltage is being measured) and a practical ammeter should have a very low resistance (much lower than the resistance of the device through which the current is being measured).



$$I = \frac{E}{R + r}, \qquad V = E.\frac{R}{R + r}$$

$$I_V = \frac{E}{R \,//\, R_m + r} = \frac{E}{R.R_m / (R + R_m) + r}, \qquad V_m = I_V.\frac{R.R_m}{R + R_m} = \frac{E.R.R_m}{R.R_m + r.(R + R_m)}$$

$$I_m = \frac{E}{R + r + r_m}, \qquad V_A = E.\frac{R}{R + r + r_m}$$

Example

A source with an emf of 12 V and internal resistance of 20 Ω, supplies a load of resistance 1000 Ω. Find the current supplied to the load and the voltage across it. The voltage is measured using a voltmeter with an effective resistance of 5 kΩ. Find the voltmeter reading. The current is then measured using a milliammeter with an effective resistance of 120Ω. Find the reading of the ammeter.

Solution

Load current = 12/(20+1000) = 0.011764 = 11.77 mA, Load voltage = 0.01177×1000 = 11.77 V

When voltmeter is connected, reading V_m = 12×1000×5000/(1000×5000+20×(1000+5000)) = 11.72 V

When ammeter is connected, reading I_m = 12/(1000+20+120) = 0.01053 = 10.5 mA

It can be seen that the meters do not read the exact value, but as can be seen the error is quite small. Voltmeter usually have a much higher resistance (order of 100 kΩ) and ammeters a much lower resistance (order of 10 mΩ) so that the errors would generally be even smaller.

5.4.1 Measurement of d.c. quantities

Direct quantities are usually measured using the permanent magnet moving coil (p.m.m.c.) instrument. The moving iron (m.i.) instrument and the induction instrument can also be used to measure direct quantities.

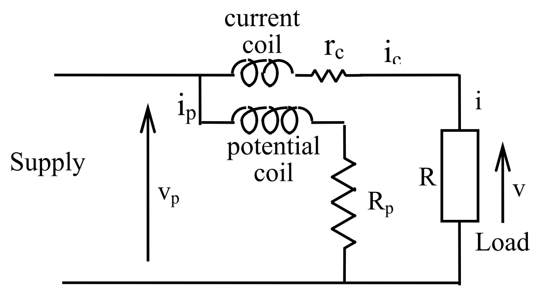
5.4.2 Measurement of a.c. quantities

Alternating quantities (r.m.s. value) may be measured using the moving iron (m.i.) instrument and the induction instrument. The permanent magnet moving coil (p.m.m.c.) instrument with a rectifier bridge arrangement can also be used to measure the r.m.s. value of sinusoidal waveforms, since we know the relation between the rectified average value and the r.m.s. value for a sinusoidal waveform. This factor, known as the form factor has a value of 1.1107 for the sinusoidal waveform. Since the rectifier type moving coil meter is meant to measure only the r.m.s. value of sinusoidal waveforms, the meter is calibrated to read 1.11 times the average value rather than the mean value of the rectified waveform. However, when the effective value of other waveforms are measured, there is an error caused.

5.5 Measurement of Power

As instantaneous power is obtained from the product of the instantaneous values of voltage and current, we could use either the dynamometer instrument or the induction type instrument to measure power. One of the coils (called the current coil) has the current passing through it, while the other coil (called the potential coil) has a current, proportional to the voltage, passed through it by having a high series resistance. Due to the inertia of the instrument, the pointer does not respond to the instantaneous value but to the mean value of the product of the currents and hence to the mean value of the instantaneous power. The dynamometer wattmeter can be used to measure both a.c. as well as d.c., while the induction wattmeter can only be used to measure a.c.

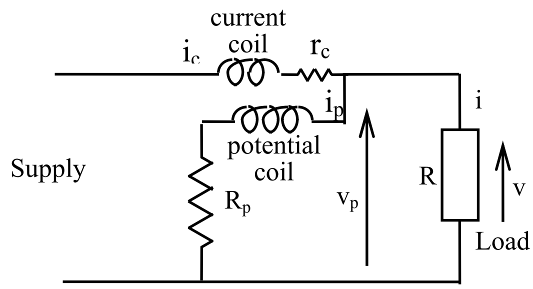
Either the current coil can be exactly in series with the current or the potential coil can be exactly in parallel with the voltage. This is shown in the following diagrams.



$i_c = i,\ \ v_p = v + r_c\, i_c,\ \ v_p = R_p.i_p$

Reading $\propto i_c.i_p \propto i_c.v_p \propto i.(v + r_c.i_c)$

Reading $\propto v.i + r_c.i_c^2$



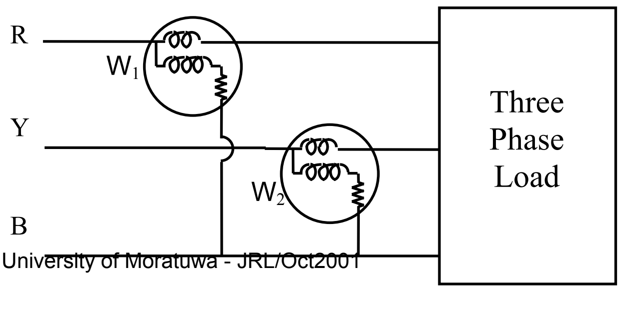
$v_p = v,\ \ i_c = i + i_p,\ \ v_p = R_p.i_p$

Reading $\propto i_c.i_p \propto i_c.v_p \propto (i + i_p).v$

Reading $\propto v.i + v_p.i_p$

The average value of the instantaneous power $\boldsymbol{v.i}$ is the active power $\boldsymbol{P}$ that has to be measured. It is seen that neither of the wattmeter connections give the exact reading. In the first connection shown, there is an error of $\boldsymbol{r_c.i_c^2}$ corresponding to the power loss in the current coil. The current coil of a wattmeter must thus have an almost zero resistance in order for the error to become negligible [since the current coil is in series, this is similar to the case of the ammeter]. In the second connection shown, there is an error of $\boldsymbol{v_p.i_p}$ corresponding to the power loss in the potential coil. The potential coil of a wattmeter must thus have an almost infinite resistance in order for the error to become negligible [since the potential coil is in parallel, this is similar to the case of the voltmeter]. The selection of which connection is to be used, is thus based on which gives the smaller loss.

5.6 Measurement of three phase power



Power = *Real* $\{V_{RN}.I_R^* + V_{YN}.I_Y^* + V_{BN}.I_B^*\}$

but $I_R + I_Y + I_B = 0$ Kirchoff's current law

$\therefore P = Real\ \{V_{RN}.I_R^* + V_{YN}.(-I_R^* + -I_B^*) + V_{BN}.I_B^*\}$

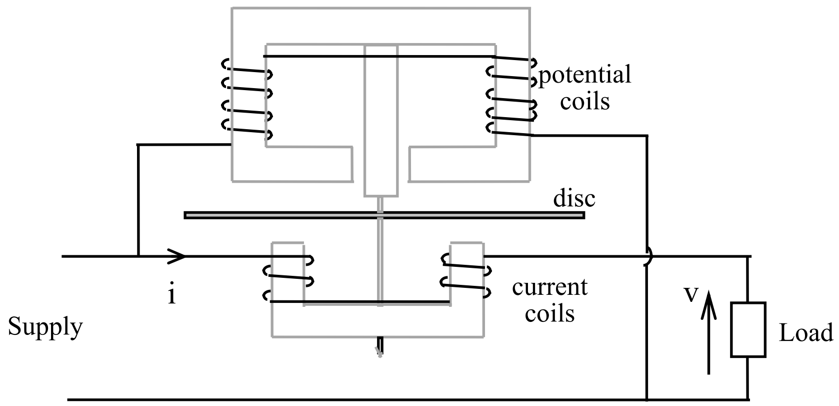
$= Real\ \{(V_{RN} - V_{YN}).I_R^* + (V_{BN} - V_{YN}).I_B^*$

$= Real\ \{V_{RY}.I_R^* + V_{BY}.I_B^*\}$

$= W_1 + W_2$

The power in a three phase system may be measured using three wattmeters between the live and the neutral for each phase. However, in many high power systems, the neutral wire may not be available. Even when the neutral is available, a convenient way of measuring power in a three phase system is the two wattmeter method.

5.7 Measurement of Energy



Electrical energy is the time integral of electrical power. Thus to measure energy, we not only need to obtain an expression for power as in the wattmeter, but also have a time dependent element. This is done by having a continuous rotatation of a disc, rather than a deflection. The number of revolutions at a constant speed would be proportional to the time, and if the speed is made proportional to the power, then energy would be obtained. The a.c. energy meter (also known as the house service meter or the kWh meter) is usually of the induction type.

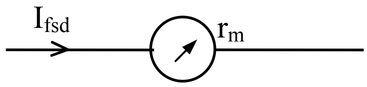
[Note: Since the basis is the instantaneous values of current and voltage, the effect of power factor angle would automatically be taken into account]

5.8 Measurement of Resistance

Resistance can usually be measured using a Wheastone Bridge or a voltmeter-ammeter method. However neither of these methods can be used when the value to be measured is a very low resistance (of the order of mΩ) or a very high resistance (of the order of MΩ). In these cases special care has to be taken to avoid errors caused by contact resistance (Kelvin Double Bridge is commonly used) for very low resistances, and to avoid leakage currents on the surface of instruments (insulation megger is commonly used). Special methods are also used to find the effective earth resistance of an installation. These are outside the scope of this lecture and will not be dealt in this course.

5.9 Extension of Ranges of Instruments

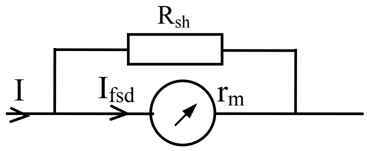
Other than for the electrostatic meter, analogue meters are generally basically designed as micro-ammeters, typically giving a full scale deflection (f.s.d.) for a current of around 25μA to 25 mA.

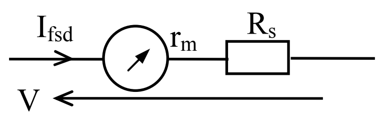


I_{fsd} – current at full scale deflection

r_m – meter internal resistance

They may be used to measure higher currents and also voltages with suitable resistances in parallel (shunts) or series.





Example

A moving coil ammeter has a basic range of 200 μA with an internal resistance of 800Ω. It is to be used as (a) an ammeter with a range of 5A, and (b) as a voltmeter with a range of 100 V. Show how resistances may be connected to obtain the required range.

(a) when I_{fsd} = 200 μA, I = 5 A. ∴ current through shunt path = $5 - 200\times10^{-6}$, $r_m = 800\Omega$

∴ from current division rule, $R_{sh} = 800\times200\times10^{-6}/(5 - 200\times10^{-6}) = 0.032001 = 32\ m\Omega$ in shunt with meter.

(b) when I_{fsd} = 200 μA, V = 100 V, $r_m = 800\ \Omega$. ∴ $100 = 200\times10^{-6}\ (800 + R_s)$

$\therefore R_S = 499200 = 499.2\ k\Omega$ in series with meter.

5.10 Instrument Transformers

The range of a meter can also be extended by making use of the transformer principle. If we wish to measure a larger or smaller voltage with a given range voltmeter, we could use a step down transformer or a step up transformer to achieve the purpose.

For example, to measure a high voltage of the order of 200 kV with a 100 V range voltmeter, we would use a potential transformer of turns ratio 2000:1 (or voltage ratio 200kV:100V) to reduce the voltage. [You are probably aware that the voltage ratio of a transformer is the same as the turns ratio]

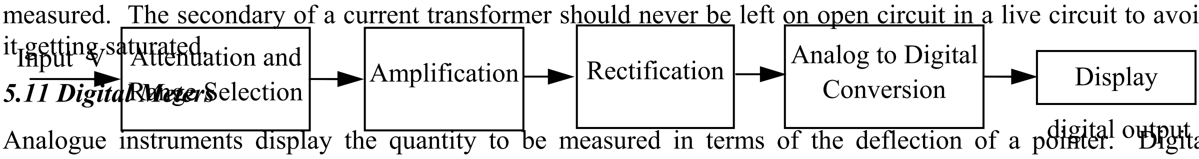
Similarly larger or smaller currents may be measured using current transformers. For example, to measure a current of 200 A using a meter of range 5 A, we would use a current transformer of turns ratio 1:40 (or current ratio 200A:5A) to reduce the current.

Such potential transformers and current transformers are known as instrument transformers. They are specifically designed to have high accuracy in measuring voltages and currents respectively, but cannot handle much power. Like voltmeters, the primary of the potential transformer is connected in shunt with the quantity to be measured, while the primary of the current transformer is connected in series with the quantity to be measured. The secondary of a current transformer should never be left on open circuit in a live circuit to avoid it getting saturated.

5.11 Digital Meters

Analogue instruments display the quantity to be measured in terms of the deflection of a pointer. Digital instruments on the other hand indicate the value of the measured quantity (measurand) in the form of a decimal number. The digital meter works on the principle of sampling and quantization and their output may be fed into digital computers and the like for storage and future computations.

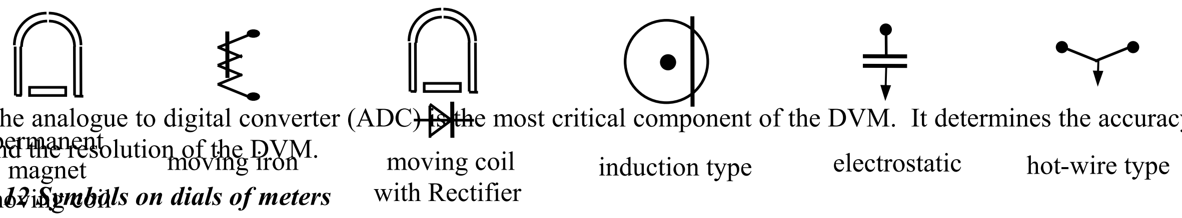
A digital voltmeter (DVM) measuring alternating voltages would typically have the following block diagram.

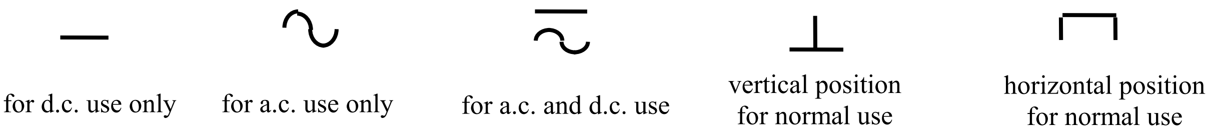


The analogue to digital converter (ADC) is the most critical component of the DVM. It determines the accuracy and the resolution of the DVM.

5.12 Symbols on dials of meters

The following symbols and abbreviations are used to denote the type of measuring element, kind of supply, and normal position of use of a given instrument.





Note: The hot-wire type of thermal instrument has not been described earlier in the notes. It works on the principle of a wire heating up due to the passage of current and causing an expansion. Details beyond this are beyond the scope of the lecture.