Measurement noise and signal processing

Sources of measurement noise

In a measurement process electrical signals from measurement sensors and transducers are corrupted by induced noise. This induced noise arises both within the measurement circuit itself and also during the transmission of measurement signals to remote points.
Noise voltages can exist either in serial mode or common mode forms. Serial mode noise voltages act in series with the output voltage from a measurement sensor or transducer, which can cause very significant errors in the output measurement signal. The extent to which series mode noise corrupts measurement signals is measured by a quantity known as the signal-to-noise ratio. This is defined as:

$$\text{Signal-to-noise ratio} = 20\log_{10}\left(\frac{V_s}{V_n}\right)$$

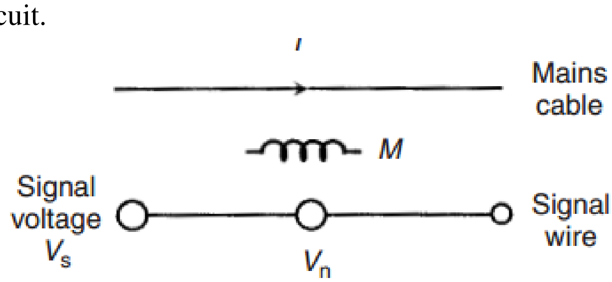
Where V_S is the mean voltage level of the signal and V_n is the mean voltage level of the noise. In the case of AC. noise voltages, the root-mean squared value is used as the mean.

Common mode noise voltages are less serious, because they cause the potential of both sides of a signal circuit to be raised by the same level, and thus the level of the output measurement signal is unchanged. However, common mode voltages do have to be considered carefully, since they can be converted into series mode voltages in certain circumstances.

Noise can be generated from sources both external and internal to the measurement system. Induced noise from external sources arises in measurement systems for a number of reasons that include their proximity to mains-powered equipment and cables (causing noise at the mains frequency), proximity to fluorescent lighting circuits (causing noise at twice the mains frequency), proximity to equipment operating at audio and radio frequencies (causing noise at corresponding frequency), switching of nearby DC and AC circuits, and corona discharge (both of the latter causing induced spikes and transients). Internal noise includes thermoelectric potentials, shot noise and potentials due to electrochemical action.

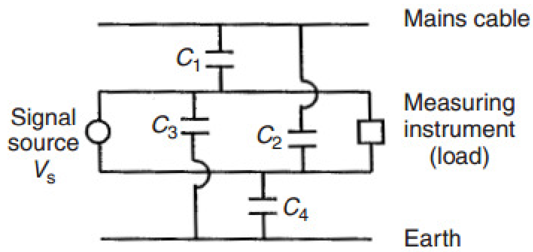
Inductive coupling

The primary mechanism by which external devices such as mains cables and equipment, fluorescent lighting and circuits operating at audio or radio frequencies generate noise is through inductive coupling. If signal-carrying cables are close to such external cables or equipment, a significant mutual inductance M can exist between them, as shown in figure, and this can generate a series mode noise voltage of several mV given by V_n = MI, where IP is the rate of change of current in the mains circuit.



Capacitive (electrostatic) coupling

Capacitive coupling, also known as electrostatic coupling, can also occur between the signal wires in a measurement circuit and a nearby mains-carrying conductor. The magnitude of the capacitance between each signal wire and the mains conductor is represented by the quantities C_1 and C_2 in figure. In addition to these capacitances, a capacitance can also exist between the signal wires and earth, represented by C_3 and C_4 in the figure. It can be shown (Cook, 1979) that the series mode noise voltage V_n is zero if the coupling capacitances are perfectly balanced, i.e. if $C_1=C_2$ and $C_3=C_4$. However, exact balance is unlikely in practice, since the signal wires are not perfectly straight, causing the distances and thus the capacitances to the mains cable and to earth to vary. Thus, some series mode noise voltage induced by capacitive coupling usually exists.



Noise due to multiple earths

As far as possible, measurement signal circuits are isolated from earth. However, leakage paths often exist between measurement circuit signal wires and earth at both the source (sensor) end of the circuit and also the load (measuring instrument) end. This does not cause a problem as long as the earth potential at both ends is the same. However, it is common to find that other machinery and equipment carrying large currents is connected to the same earth plane. This can cause the potential to vary between different points on the earth plane. This situation, which is known as multiple earths, can cause a series mode noise voltage in the measurement circuit.

Noise in the form of voltage transients

When motors and other electrical equipment (both AC and DC) are switched on and off, large changes of power consumption suddenly occur in the electricity supply system. This can cause voltage transients ('spikes') in measurement circuits connected to the same power supply. Such noise voltages are of large magnitude but short time duration. Corona discharge can also cause voltage transients on the mains power supply. This occurs when the air in the vicinity of high voltage DC circuits becomes ionized and discharges to earth at random times.

Thermoelectric potentials

Whenever metals of two different types are connected together, a thermoelectric potential (sometimes called a thermal e.m.f.) is generated according to the temperature of the joint. This is known as the thermoelectric effect and is the physical principle on which temperature-measuring thermocouples operate (see Chapter 14). Such thermoelectric potentials are only a few millivolts in magnitude and so the effect is only significant when typical voltage output signals of a measurement system are of a similar low magnitude.

Shot noise

Shot noise occurs in transistors, integrated circuits and other semiconductor devices. It consists of random fluctuations in the rate of transfer of carriers across junctions within such devices.

Electrochemical potentials

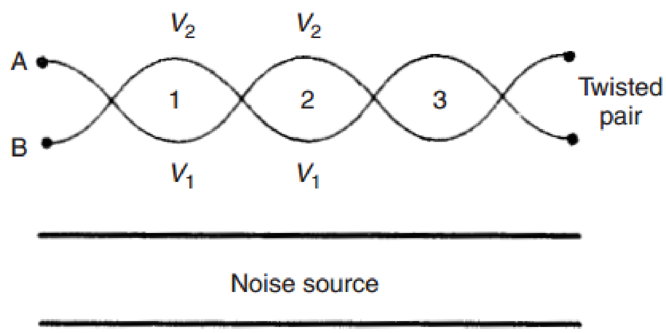
These are potentials that arise within measurement systems due to electrochemical action. Poorly soldered joints are a common source.

Techniques for reducing measurement noise

Prevention is always better than cure, and much can be done to reduce the level of measurement noise by taking appropriate steps when designing the measurement system.

Location and design of signal wires

Both the mutual inductance and capacitance between signal wires and other cables are inversely proportional to the square of the distance between the wires and the cable. Thus, noise due to inductive and capacitive coupling can be minimized by ensuring that signal wires are positioned as far away as possible from such noise sources. A minimum separation of 0.3 m is essential, and a separation of at least 1 m is preferable. Noise due to inductive coupling is also substantially reduced if each pair of signal wires is twisted together along its length. This design is known as a twisted pair, and is illustrated in figure. In the first loop, wire A is closest to the noise source and has a voltage V_1 induced in it, whilst wire B has an induced noise voltage V_2. For loop 2, wire B is closest to the noise source and has an induced voltage V_1 whilst wire A has an induced voltage V_2. Thus the total voltage induced in wire A is $V_1 + V_2$ and in wire B it is $V_2 + V_1$ over these two loops. This pattern continues for all the loops and hence the two wires have an identical voltage induced in them.



Earthing

Noise due to multiple earths can be avoided by good earthing practices. In particular, this means keeping earths for signal wires and earths for high-current equipment entirely separate. Recommended practice is to install four completely isolated earth circuits as follows:

- Power earth: provides a path for fault currents due to power faults.
- Logic earth: provides a common line for all logic circuit potentials.
- Analogue earth (ground): provides a common reference for all analogue signals.
- Safety earth: connected to all metal parts of equipment to protect personnel should power lines come into contact with metal enclosures.

Shielding

Shielding consists of enclosing the signal wires in an earthed, metal shield that is itself isolated electrically from the signal wires. The shield should be earthed at only one point, preferably the signal source end. A shield consisting of braided metal eliminates 85% of noise due to capacitive coupling whilst a lapped metal foil shield eliminates noise almost entirely. The wires inside such a shield are normally formed as a twisted pair so that protection is also provided against induced noise due to nearby electromagnetic fields. Metal conduit is also sometimes used to provide shielding from capacitive coupled noise, but the necessary supports for the conduit provide multiple earth points and lead to the problem of earth loops.

Other techniques

The phase-locked loop is often used as a signal-processing element to clean up poor quality signals. Although this is primarily a circuit for measuring the frequency of a signal; it is also useful for noise removal because its output waveform is a pure (i.e. perfectly clean) square wave at the same frequency as the input signal, irrespective of the amount of noise, modulation or distortion on the input signal.

Lock-in amplifiers are also commonly used to extract DC or slowly varying measurement signals from noise. The input measurement signal is modulated into a square-wave AC signal whose amplitude varies with the level of the input signal. This is normally achieved by either a relay or a field effect transistor. As a relay is subject to wear; the transistor is better. An alternative method is to use an analogue multiplier. Also, in the case of optical signals, the square wave can be produced by chopping the measurement signals using a set of windows in a rotating disc. This technique is frequently used with transducers like photodiodes that often generate large quantities of noise.

Electrical indicating and test instruments

Digital meters

All types of digital meter are basically modified forms of the digital voltmeter (DVM), irrespective of the quantity that they are designed to measure. Digital meters designed to measure quantities other than voltage are in fact digital voltmeters that contain appropriate electrical circuits to convert current or resistance measurement signals into voltage signals. Digital multimeters are also essentially digital voltmeters that contain several conversion circuits, thus allowing the measurement of voltage, current and resistance within one instrument.

Digital meters have been developed to satisfy a need for higher measurement accuracies and a faster speed of response to voltage changes than can be achieved with analogue instruments. They are technically superior to analogue meters in almost every respect. However, they have a greater cost due to the higher manufacturing costs compared with analogue meters. The binary nature of the output reading from a digital instrument can be readily applied to a display that is in the form of discrete numerals. Where human operators are required to measure and record signal voltage levels, this form of output makes an important contribution to measurement reliability and accuracy, since the problem of analogue meter parallax error is eliminated and the possibility of gross error through misreading the meter output is greatly reduced. The availability in many instruments of a direct output in digital form is also very useful in the rapidly expanding range of computer control applications. Quoted inaccuracy figures are between ±0.005% (measuring DC voltages) and ±2%. Additional advantages of digital meters are their very high input impedance (10 M compared with 1 – 20 k for analogue meters), the ability to measure signals of frequency up to 1 MHz and the common inclusion of features such as automatic ranging, which prevents overload and reverse polarity connection etc.

The major part of a digital voltmeter is the circuitry that converts the analogue voltage being measured into a digital quantity. As the instrument only measures DC quantities in its basic mode, another necessary component within it is one that performs AC – DC conversion and thereby gives it the capacity to measure AC signals. After conversion, the voltage value is displayed by means of indicating tubes or a set of solid-state light-emitting diodes. Four-, five- or even six-figure output displays are commonly used, and although the instrument itself may not be inherently more accurate than some analogue types, this form of display enables measurements to be recorded with much greater accuracy than that obtainable by reading an analogue meter scale.
Digital voltmeters differ mainly in the technique used to effect the analogue-to-digital conversion between the measured analogue voltage and the output digital reading. As a general rule, the more expensive and complicated conversion methods achieve a faster conversion speed. Some common types of DVM are discussed below.

Voltage-to-time conversion digital voltmeter

This is the simplest form of DVM and is a ramp type of instrument. When an unknown voltage signal is applied to the input terminals of the instrument, a negative-slope ramp waveform is generated internally and compared with the input signal. When the two are equal, a pulse is generated that opens a gate, and at a later point in time a second pulse closes the gate when the negative ramp voltage reaches zero. The length of time between the gate opening and closing is monitored by an electronic counter, which produces a digital display according to the level of the input voltage signal. Its main drawbacks are nonlinearities in the shape of the ramp waveform used and lack of noise rejection, and these problems lead to a typical inaccuracy of ±0.05%. It is relatively cheap, however.

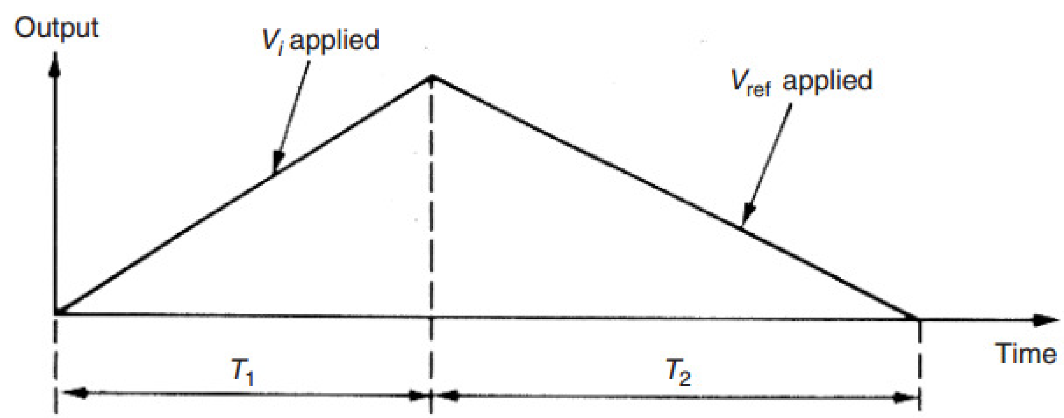
Potentiometric digital voltmeter

This uses a servo principle, in which the error between the unknown input voltage level and a reference voltage is applied to a servo-driven potentiometer that adjusts the reference voltage until it balances the unknown voltage. The output reading is produced by a mechanical drum-type digital display driven by the potentiometer. This is also a relatively cheap form of DVM that gives excellent performance for its price.

Dual-slope integration digital voltmeter

This is another relatively simple form of DVM that has better noise-rejection capabilities than many other types and gives correspondingly better measurement accuracy (inaccuracy as low as ±0.005%). Unfortunately, it is quite expensive. The unknown voltage is applied to an integrator for a fixed time T_1, following which a reference voltage of opposite sign is applied to the integrator, which discharges down to a zero output in an interval T_2 measured by a counter. The output time relationship for the integrator is shown in figure, from which the unknown voltage V_i can be calculated geometrically from the triangle as:

$$Vi = V_{ref}\ (T1/T2)$$



Voltage-to-frequency conversion digital voltmeter

In this instrument, the unknown voltage signal is fed via a range switch and an amplifier into a converter circuit whose output is in the form of a train of voltage pulses at a frequency proportional to the magnitude of the input signal. The main advantage of this type of DVM is its ability to reject AC noise.

Digital multimeter

This is an extension of the DVM. It can measure both AC. and DC voltages over a number of ranges through inclusion within it of a set of switchable amplifiers and attenuators. It is widely used in circuit test applications as an alternative to the analogue multimeter, and includes protection circuits that prevent damage if high voltages are applied to the wrong range.

Analogue meters

Analogue meters are relatively simple and inexpensive and are often used instead of digital instruments, especially when cost is of particular concern. Whilst digital instruments have the advantage of greater accuracy and much higher input impedance, analogue instruments suffer less from noise and isolation problems. In addition, because analogue instruments are usually passive instruments that do not need a power supply, this is often very useful in measurement applications where a suitable mains power supply is not readily available. Many examples of analogue meter also remain in use for historical reasons.

Analogue meters are electromechanical devices that drive a pointer against a scale. They are prone to measurement errors from a number of sources that include inaccurate scale marking during manufacture, bearing friction, bent pointers and ambient temperature variations. Further human errors are introduced through parallax error (not reading the scale from directly above) and mistakes in interpolating between scale markings. Quoted inaccuracy figures are between ±0.1% and ±3%.

Classification

Analog ammeter can be classified into different categories:

- Classified based upon the quantity they measure (ammeter, voltmeter)
- Classified according to the current that can be measured by them.(DC,AC)
- Classified according to the effects used for working.
- Classified as Indicating, Recording, And Integrating.
- Classified on the basis of method used for comparing the unknown quantity. (Direct / Comparison measurement)

Principle of operation

Analog ammeter is designed based on following operating principle:

- Magnetic Effect
- Thermal Effect
- Electrostatic Effect
- Induction Effect
- Hall Effect

Types of Instruments

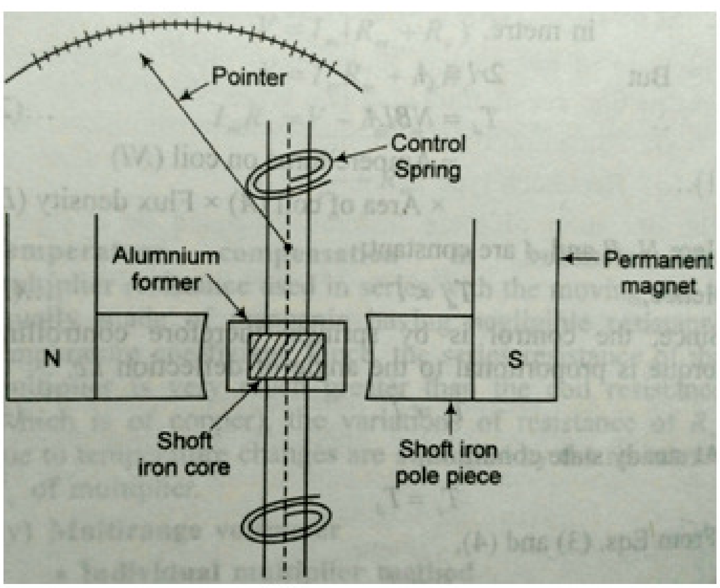
- Permanent magnet moving coil (PMMC).
- Moving Iron
- Electro-dynamometer type.
- Hot wire type.
- Thermocouple type.
- Induction type.
- Electrostatic type.
- Rectifier type.

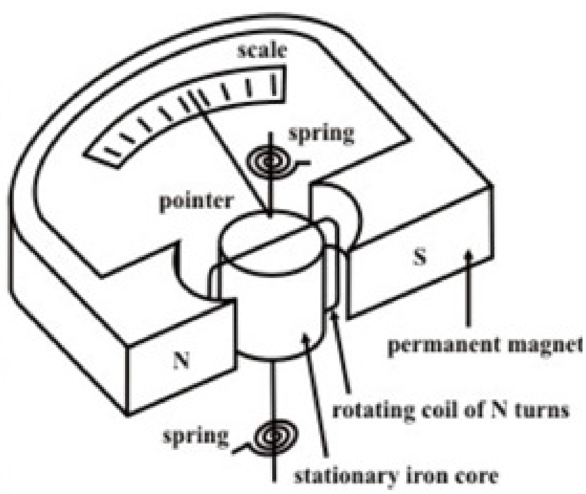
Permanent Magnet Moving Coil (PMMC) instrument

One of the most accurate types of instrument used for D.C. measurements is PMMC instrument.

The permanent magnet moving coil instrument or PMMC type instrument uses two permanent magnets in order to create stationary magnetic field. These types of instruments are only used for measuring the DC quantities as if we apply AC current to these type of instruments the direction of current will be reversed during negative half cycle and hence the direction of torque will also be reversed which gives average value of torque zero. The pointer will not deflect due to high frequency from its mean position showing zero reading. However it can measure the direct current very accurately. Main components of PMMC are-

- Stationary Part or Magnet System: In the present time we use magnets of high field intensities, high coercive force instead of using U shaped permanent magnet having soft iron pole pieces. The magnets which we are using nowadays are made up of materials like alcomax and alnico which provide high field strength.
- Moving Coil: The moving coil can freely moves between the two permanent magnets as shown in the figure given below. The coil is wound with many turns of copper wire and is placed on rectangular aluminum which is pivoted on jeweled bearings.
- Control System: The spring generally acts as control system for PMMC instruments. The spring also serves another important function by providing the path to lead current in and out of the coil.
- Damping System: The damping force hence torque is provided by movement of aluminum former in the magnetic field created by the permanent magnets.
- Meter: Meter of these instruments consists of light weight pointer to have free movement and scale which is linear or uniform and varies with angle.





Principle of operation

When D.C. supply is given to the moving coil, D.C. current flows through it. When the current carrying coil is kept in the magnetic field, it experiences a force. This force produces a torque and the former rotates. The pointer is attached with the spindle. When the former rotates, the pointer moves over the calibrated scale. When the polarity is reversed a torque is produced in the opposite direction. The mechanical stopper does not allow the deflection in the opposite direction. Therefore the polarity should be maintained with PMMC instrument.

If A.C. is supplied, a reversing torque is produced. This cannot produce a continuous deflection. Therefore this instrument cannot be used in A.C.

Mathematical Expression

Let,

T_d = deflecting torque

T_C = controlling torque

θ = angle of deflection

K = spring constant

B = width of the coil

L = height of the coil or length of coil

N = No. of turns

I = current

B = Flux density

A = area of the coil

The force produced in the coil is given by

$$F = BIL \sin\theta$$

When $\theta = 90^o$, For N turns, $F = NBIL$

Torque produced, $T_d = F \times \text{distance}$

$T_d = NBIL \times b = NBIA$; where A is effective area.

$T_d = GI$; where $G = NBA$ = constant

Since controlling torque produced by the springs mounted on jewel bearing and the spring provides the restoring torque to the moving coil which is expressed as,

$$T_C = K\theta$$

Now, since the controlling and deflecting torque should be in equilibrium; we have:-

$$T_d = T_C$$

$$GI = K\theta$$

So, $\theta = (G/K)\, I$

And $I = (K/G)\, \theta$

Again, $T_d = GI$

Or $T_d \infty I$

Thus the deflection is directly proportional to the current passing through the coil. The pointer deflection can therefore be used to measure current.

Advantages

The following are the advantages of the PMMC Instruments.

- The scale of the PMMC instruments is correctly divided.
- The power consumption of the devices is very less.
- The PMMC instruments have high accuracy because of the high torque weight ratio.
- The single device measures the different range of voltage and current. This can be done by the use of multipliers and shunts.
- The PMMC instruments use shelf shielding magnet which is useful for the aerospace applications.

Disadvantages

The following are the disadvantages of the PMMC instruments.

- The PMMC instruments are only used for the direct current. The alternating current varies with the time. The rapid variation of the current varies the torque of the coil. But the pointer cannot follow the fast reversal and the deflection of the torque. Thus, it cannot use for AC.
- The cost of the PPMC instruments is much higher as compared to the moving coil instruments.
- The magnetism loss in permanent magnet, temperature and friction shows some error.

Error in PMMC Instruments

In PMMC instruments the error occurs because of the ageing and the temperature effects of the instruments. The magnet, spring and the moving coil are the main parts of the instruments which cause the error. The different types of errors of the instrument are explained below in details.

Magnet – The heat and vibration reduce the lifespan of the permanent magnet. This treatment also reduced the magnetism of the magnet. The magnetism is the property of the attraction or repulsion of the magnet. The weakness of the magnet decreases the deflection of the coil.

Springs – The weakness of the spring increases the deflection of moving coil between the permanent magnet. So, even for the small value of current, the coil show large deflection. The spring gets weakened because of the effect of the temperature. One degree rise in temperature reduces the 0.004 percent life of the spring.

Moving Coil – The error exists in the coil when their range is extended from the given limit by the use of the shunt. The error occurs because of the change of the coil resistance on the shunt resistance. This happens because the coil is made up of copper wire which has high shunt resistance and the shunt wire made up of Magnin has low resistance.

To overcome from this error, the swamping resistance is placed in series with the moving coil. The resistor which has low-temperature coefficient is known as the swamping resistance. The swamping resistance reduces the effect of temperature on the moving coil.

Applications

The PMMC has a variety of uses onboard ship. It can be used as:

(a) **Ammeter:** When PMMC is used as an ammeter, except for a very small current range, the moving coil is connected across a suitable low resistance shunt, so that only small part of the main current flows through the coil. The shunt consists of a number of thin plates made up of alloy metal, which is usually magnetic and has a low-temperature coefficient of resistance, fixed between two massive blocks of copper. A resistor of the same alloy is also placed in series with the coil to reduce errors due to temperature variation.

(b) **Voltmeter:** When PMMC is used as a voltmeter, the coil is connected in series with a high resistance. Rest of the function is same as above. The same moving coil can be used as an ammeter or voltmeter with an interchange of above arrangement

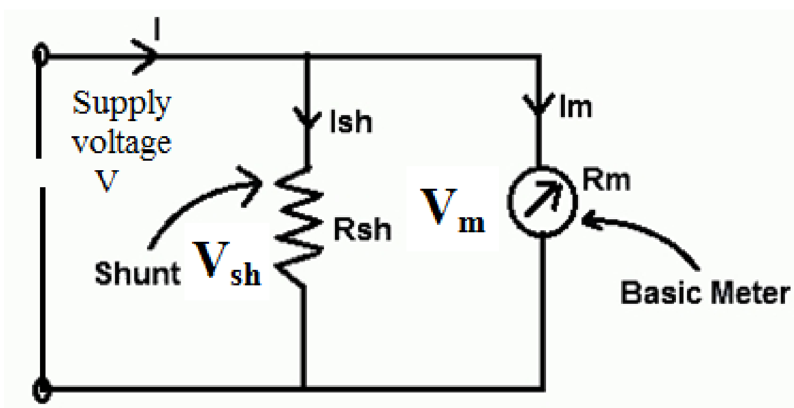
(c) **Galvanometer:** The galvanometer is used to measure a small value of current along with its direction and strength. It is mainly used onboard to detect and compare different circuits in a system.

(d) **Ohm Meter:** The ohm meter is used to measure the resistance of the electric circuit by applying a voltage to a resistance with the help of battery. A galvanometer is used to determine the flow of current through the resistance. The galvanometer scale is marked in ohms and as the resistance varies since the voltage is fixed, the current through the meter will also vary.

Extension of range of PMMC instrument

Case-I: Shunt

A low shunt resistance connected in parallel with the ammeter to extent the range of current. Large current can be measured using low current rated ammeter by using a shunt.



Let,

R_m =Resistance of meter

R_{sh} =Resistance of shunt

I_m = Current through meter

I_{sh} =current through shunt

I= current to be measure

As, $V_m = V_{sh}$

$I_m R_m = I_{sh} R_{sh}$

Or, $I_m/I_{sh} = R_{sh}/R_m$

Apply KCL, $I = I_m + I_{sh}$

Divided by I_m; $I/I_m = 1 + I_{sh}/I_m$

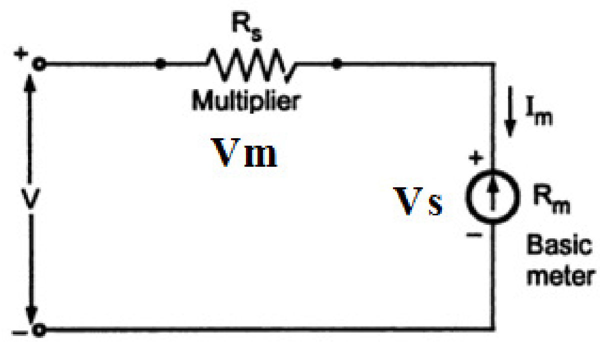
Or, $I/I_m = 1 + R_{sh}/R_m$

So, $I = I_m\,(1 + R_{sh}/R_m)$; here $(1 + R_{sh}/R_m)$ is called multiplication factor

Shunt resistance is made of manganin. This has least thermoelectric emf. The change is resistance, due to change in temperature is negligible.

Case (II): Multiplier

A large resistance is connected in series with voltmeter is called multiplier. A large voltage can be measured using a voltmeter of small rating with a multiplier.



Let,

R_m =resistance of meter
R_s =resistance of multiplier
V_m =Voltage across meter
V_s = Voltage across series resistance
V= voltage to be measured

As both are in series, $I_m = I_s$

$V_m/R_m = V_s/R_s$

$V_s/V_m = R_s/R_m$

Apply KVL, $V = V_m + V_s$

Divided by, V_m; $V/V_m = 1 + V_s/V_m$

Or, $V/V_m = 1 + R_s/R_m$

So, $V = V_m\,(1 + R_s/R_m)$; $(1 + R_s/R_m)$ is multiplication factor

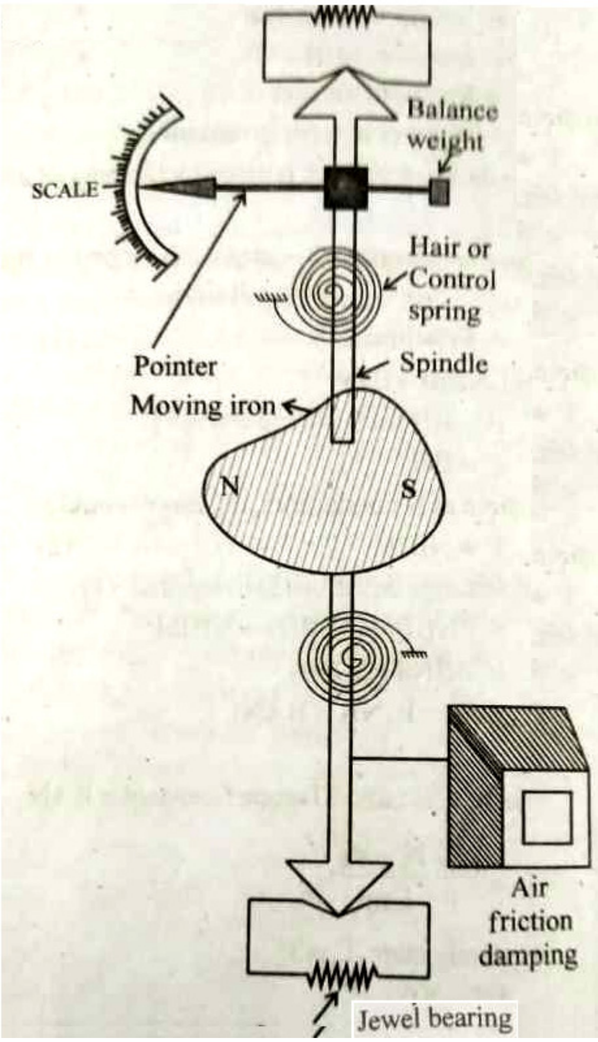
Moving Iron (MI) instruments

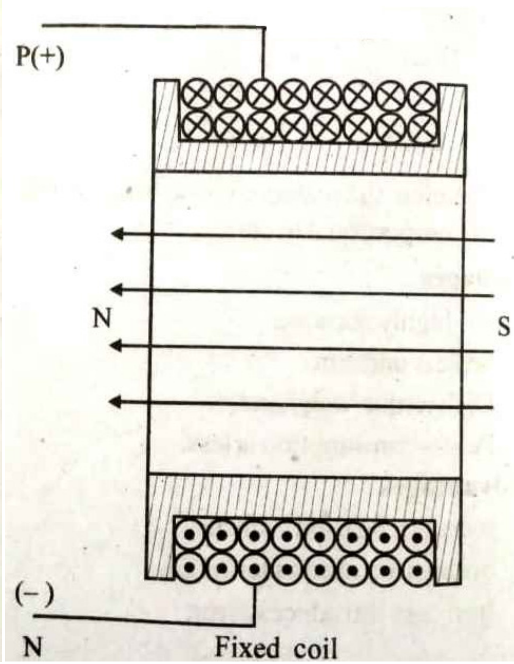
One of the most accurate instruments used for both AC and DC measurement is moving iron instrument. There are two types of moving iron instrument.

- Attraction type
- Repulsion type

Attraction type M.I. instrument

Construction: The moving iron fixed to the spindle is kept near the hollow fixed coil. The pointer and balance weight are attached to the spindle, which is supported with jeweled bearing. Here air friction damping is used.





Principle of operation

The current to be measured is passed through the fixed coil. As the current is flow through the fixed coil, a magnetic field is produced. By magnetic induction the moving iron gets magnetized. The north pole of moving coil is attracted by the south pole of fixed coil. Thus the deflecting force is produced due to force of attraction. Since the moving iron is attached with the spindle, the spindle rotates and the pointer moves over the calibrated scale. But the force of attraction depends on the current flowing through the coil.

Torque developed by M.I

Let ‘θ’ be the deflection corresponding to a current of ‘i’ amp and the current increases by di, the corresponding deflection is ‘θ + dθ ’

There is change in inductance since the position of moving iron change w.r.t the fixed electromagnets.

Let the new inductance value be ‘L+dL’. The current change by ‘di’ is dt seconds.

If the emf induced in the coil is ‘e’ volt, then

$$e = \frac{d}{dt}(Li) = L\frac{di}{dt} + i\frac{dL}{dt}$$

Multiplying by ‘idt’,

$$e \times idt = L\frac{di}{dt} \times idt + i\frac{dL}{dt} \times idt$$

$$e \times idt = Lidi + i^2 dL$$

So the energy is given by the equation is used in to two forms. Part of energy is stored in the inductance. Remaining energy is converted into mechanical energy which produces deflection.

Change in energy stored=Final energy-initial energy stored

$$= \frac{1}{2}(L + dL)(i + di)^2 - \frac{1}{2}Li^2$$

$$= \frac{1}{2}\{(L + dL)(i^2 + di^2 + 2idi) - Li^2\}$$

$$= \frac{1}{2}\{(L + dL)(i^2 + 2idi) - Li^2\}$$

$$= \frac{1}{2}\{Li^2 + 2Lidi + i^2 dL + 2ididL - Li^2\}$$

$$= \frac{1}{2}\{2Lidi + i^2 dL\}$$

$$= Lidi + \frac{1}{2}i^2 dL$$

Mechanical work to move the pointer by dθ is equal to T_d dθ

By law of conservation of energy,

Electrical energy supplied=Increase in stored energy+ mechanical work done.

Input energy= Energy stored + Mechanical energy

$$Lidi + i^2 dL = Lidi + \frac{1}{2} i^2 dL + T_d d\theta$$

$$\frac{1}{2} i^2 dL = T_d d\theta$$

$$T_d = \frac{1}{2} i^2 \frac{dL}{d\theta}$$

At steady state condition $T_d = T_C$

$$\frac{1}{2} i^2 \frac{dL}{d\theta} = K\theta$$

$$\theta = \frac{1}{2K} i^2 \frac{dL}{d\theta}$$

$$\theta \propto i^2$$

When the instruments measure AC, $\theta \propto i^2_{rms}$

So the scale of the instrument is non uniform.

Repulsion type moving iron instrument

Construction: The repulsion type instrument has a hollow fixed iron attached to it. The moving iron is connected to the spindle. The pointer is also attached to the spindle in supported with jeweled bearing. When there is no current in the coil, both iron bars are nearest to each other.

Principle of operation: When the current flows through the coil, a magnetic field is produced by it. So both fixed iron and moving iron are magnetized with the same polarity, since they are kept in the same magnetic field. Similar poles of fixed and moving iron get repelled. Thus the deflecting torque is produced due to magnetic repulsion. Since moving iron is attached to spindle, the spindle will move. So that pointer moves over the calibrated scale. Air friction damping is used to reduce the oscillation and for controlling spring control is used.

Deflecting Torque of Repulsion Type Moving Iron Instrument

The force between two similarly magnetized iron rods or sheets produces the deflecting torque in this instrument. So, the deflecting torque is proportional to the pole strength of both bars.

$$T_d \propto Repulsive\ Force\ between\ similar\ Poles$$

$$\Rightarrow T_d \propto m_1 \cdot m_2$$

In other words, the deflecting torque is proportional to the product of pole strength of both bars.

Again, pole strength is proportional to the magnetic field strength H.

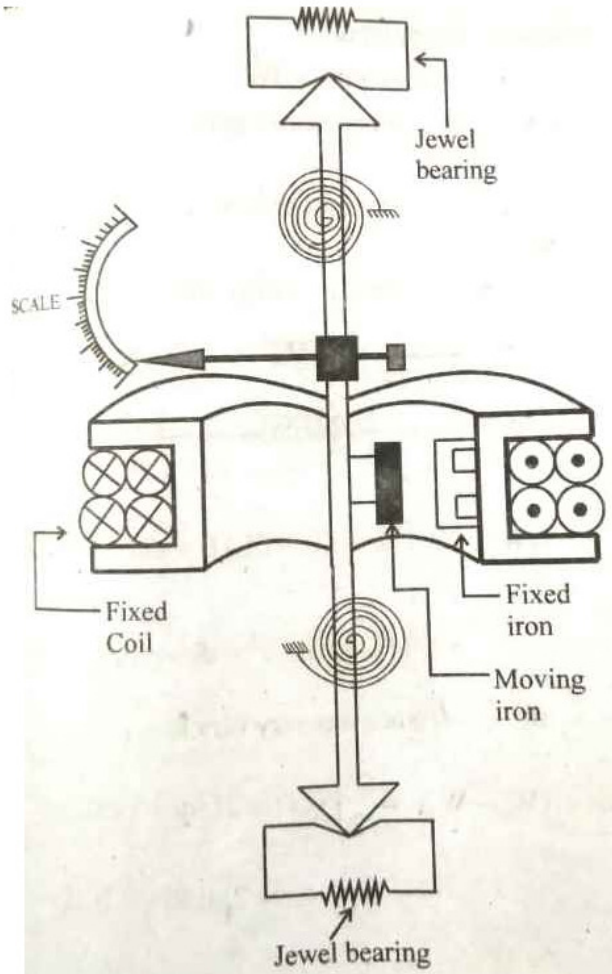
Hence, the instantaneous deflecting torque is proportional to the square of magnetic field strength.

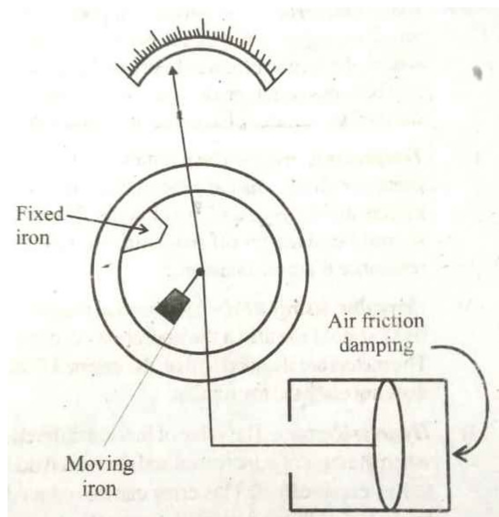
$$T_d \propto H^2$$

Again, the magnetic field strength is directly proportional to the current in the coil. So,

$$T_d \propto I^2$$

As the deflecting torque is proportional to the square of the measuring current, the scale of the instrument is not uniform or even. Although properly the use of properly shaped iron sheet instead of the iron rod in the instrument, the scale becomes quite even.





Errors in the instrument:

- **Frictional error -**The spindle is supported by jewel bearings at both the ends. So when spindle rotates, the friction between the tips of the spindle and bearings results error. Therefore, the tips of the spindle are made semicircular to reduce error.
- **Temperature error -**The resistance of the coil changes with the variation in the temperature. This affects the deflection of instruments. The coil should be made up off magainin, so that the resistance is almost constant.
- **Error due to stray field** -The external magnetic field should not affect the operation of meter. The meters are shielded so that, the external field does not enter the instrument.
- **Hysteresis error -**The value of flux are different when the current is increased and decreased due to hysteresis effect. This error can be reduced by using small iron parts with narrow hysteresis loops.

Advantage of Moving iron Instrument

- It is a universal instrument which can be used for the measurement of AC and DC quantities.
- These types of instruments have high value of torque to weight ratio. Due to this error because of friction is quite low.
- It is very cheap due to simple construction.
- These instruments are quite robust due to its simple construction. Above all, there is no moving part in the instrument which carries current.
- Accuracy of any instrument depends on its design and workmanship. These instruments can be designed to provide precision and industrial grade accuracy. A well designed moving iron instruments have a error of less than 2 % or less for DC. For AC, the accuracy of the instrument may be of the order of 0.2 to 0.3 % at 50 Hz.
- These instruments can withstand large loads and are not damaged even under sever overload conditions.

Disadvantage of Moving Iron Instrument

- These instruments suffer from error due to hysteresis, frequency change and stray losses.
- The scale of moving iron instrument is not uniform like PMMC instrument. Its scale is non-uniform and cramped at lower end. This is the reason; accurate readings are not possible at lower range.
- The calibration of these instruments should be done for both AC and DC. In fact, its calibration must be carried out at the frequency for which it is used in AC circuit. If it is used at 50 Hz, calibration must also be done at the same frequency i.e. 50 Hz.
- Moving Iron Instruments are suitable for low frequency application. This is because at lower frequency, the eddy current error increases with square of frequency whereas at higher frequency this error is almost constant. Therefore moving iron instruments are not suitable for frequency above 125 Hz.
- The reading of the instrument is affected by temperature variation. Increase in temperature decreases the spring stiffness and increases the resistance of coil.

Dynamometer (or) Electromagnetic moving coil instrument (EMMC)

Dynamometer type measuring instruments are similar to PMMC instrument. Except that the permanent magnetic field coil is replaced by a coil which carries the current to be measured. Such instruments may also serve as transfer instruments. A transfer instrument is that which may be calibrated with dc source and then used on ac without any modifications.

Construction

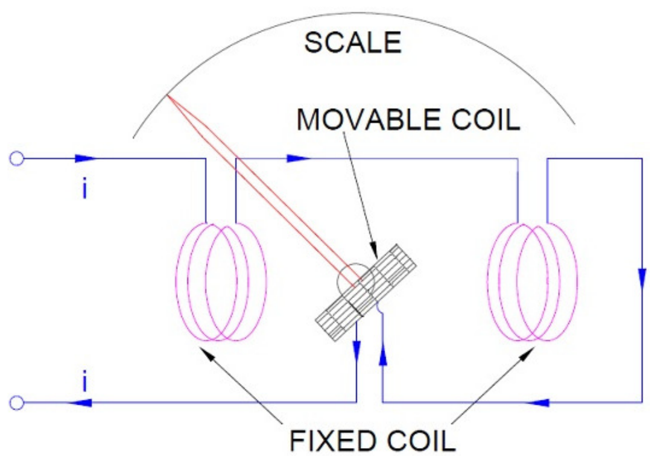
Fixed coil: The magnetic field is produced by the fixed coil which is divided into two sections to give more uniform field near the centre and to allow passage of the instrument shaft.

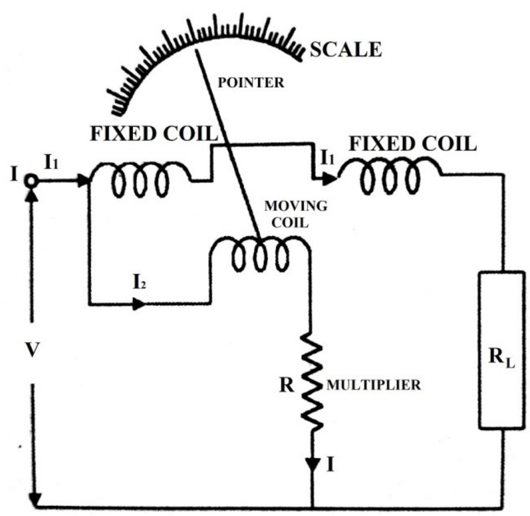
Moving coil: The moving coil is wound either as a self-sustaining coil or else on a nonmagnetic former. A metallic former cannot be used, as eddy currents would be induced in it by alternating field. Light but rigid construction is used for the moving coil. It should be noted that both fixed and moving coils are air cored.

Springs: The controlling torque is provided by two control springs. These hairsprings also act as leads of current to the moving coil.

Dampers: Air friction damping is employed for these instruments and is provided by a pair of Aluminum-vanes attached to the spindle at the bottom. These vanes move in a sector shaped chamber.

Shielding: Since the magnetic field produced by fixed coils is weaker than that in other types of instruments, these meters need a special magnetic shielding. Electro-dynamic instruments are effectively shielded from the effects of external magnetic fields by enclosing the mechanism in a laminated iron hollow cylinder with closed ends.



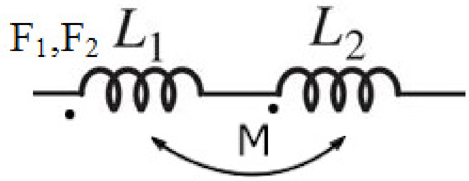


Principle of operation:

When the current flows through the fixed coil, it produced a magnetic field, whose flux density is proportional to the current through the fixed coil. The moving coil is kept in between the fixed coil. When the current passes through the moving coil, a magnetic field is produced by this coil.

The magnetic poles are produced in such a way that the torque produced on the moving coil deflects the pointer over the calibrated scale. This instrument works on AC and DC. When AC voltage is applied, alternating current flows through the fixed coil and moving coil. When the current in the fixed coil reverses, the current in the moving coil also reverses. Torque remains in the same direction. Since the current i_1 and i_2 reverse simultaneously. This is because the fixed and moving coils are either connected in series or parallel.

Torque developed by EMMC:



Let

L_1=Self inductance of fixed coil

L_2= Self inductance of moving coil

M=mutual inductance between fixed coil and moving coil

i_1=current through fixed coil

i_2=current through moving coil

Total inductance of system,

$$L_{Total} = L_1 + L_2 + 2M$$

But we know that in case of M.I

$$T_d = \frac{1}{2} i^2 \frac{d(L)}{d\theta}$$

$$T_d = \frac{1}{2} i^2 \frac{d}{d\theta}(L_1 + L_2 + 2M)$$

The value of L_1 and L_2 are independent of 'θ' but 'M' varies with θ

$$T_d = \frac{1}{2} i^2 \times 2 \frac{dM}{d\theta}$$

$$T_d = i^2 \frac{dM}{d\theta}$$

If the coils are not connected in series $i_1 \neq i_2$

$$\therefore T_d = i_1 i_2 \frac{dM}{d\theta}$$

$$T_C = T_d$$

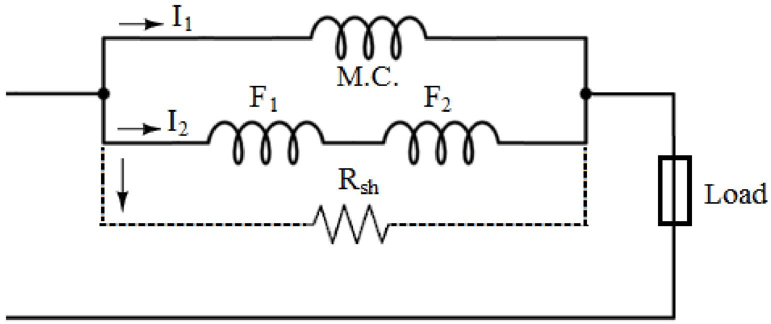
$$\therefore \theta = \frac{i_1 i_2}{K} \frac{dM}{d\theta}$$

Hence the deflection of pointer is proportional to the current passing through fixed coil and moving coil.

Application of EMMC

- **Ammeter connection**

Fixed coil and moving coil are connected in parallel for ammeter connection. The coils are designed such that the resistance of each branch is same. Therefore, $I_1 = I_2 = I$



To extend the range of current a shunt may be connected in parallel with the meter. The value R_{sh} is designed such that equal current flows through moving coil and fixed coil.

$$\therefore T_d = I_1 I_2 \frac{dM}{d\theta}$$

$$\text{Or } \therefore T_d = I^2 \frac{dM}{d\theta}$$

$$T_C = K\theta$$

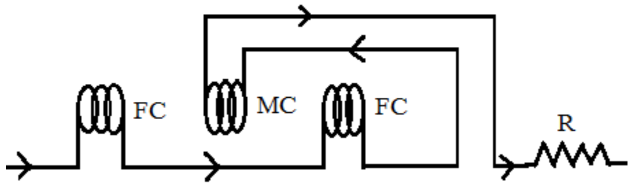
$$\theta = \frac{I^2}{K}\frac{dM}{d\theta}$$

$$\therefore \theta \propto I^2$$

As deflected angle, θ is proportion to square of current, I. So scale is not uniform.

Voltmeter connection

Fixed coil and moving coil are connected in series for voltmeter connection. A multiplier may be connected in series to extent the range of voltmeter.



$$I_1 = \frac{V_1}{Z_1}, I_2 = \frac{V_2}{Z_2}$$

$$T_d = \frac{V_1}{Z_1} \times \frac{V_2}{Z_2} \times \frac{dM}{d\theta}$$

$$T_d = \frac{K_1 V}{Z_1} \times \frac{K_2 V}{Z_2} \times \frac{dM}{d\theta}$$

$$T_d = \frac{KV^2}{Z_1 Z_2} \times \frac{dM}{d\theta}$$

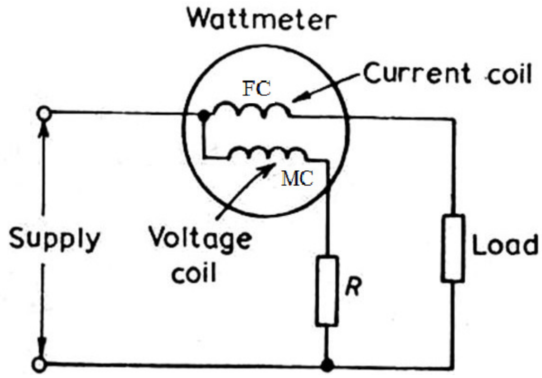
$$T_d \propto V^2$$

$$\therefore \theta \propto V^2$$

As deflected angle, θ is proportion to square of voltage, V. So scale is not uniform.

Wattmeter Connection

When the two coils are connected to parallel, the instrument can be used as a wattmeter. Fixed coil is connected in series with the load. Moving coil is connected in parallel with the load. The moving coil is known as voltage coil or pressure coil and fixed coil is known as current coil.



Assume that the supply voltage is sinusoidal. If the impedance of the coil is neglected in comparison with resistance 'R'. The current,

$$I_2 = \frac{v_m \sin wt}{R}$$

Let the phase difference between the currents I_1 and I_2 is φ

$$I_1 = I_m \sin(wt - \phi)$$

$$T_d = I_1 I_2 \frac{dM}{d\theta}$$

$$T_d = I_m \sin(wt - \phi) \times \frac{V_m \sin wt}{R} \frac{dM}{d\theta}$$

$$T_d = \frac{1}{R}(I_m V_m \sin wt \sin(wt - \phi)) \frac{dM}{d\theta}$$

$$T_d = \frac{1}{R} I_m V_m \sin wt . \sin(wt - \phi) \frac{dM}{d\theta}$$

The average deflecting torque

$$(T_d)_{avg} = \frac{1}{2\Pi} \int_0^{2\Pi} T_d \times d(wt)$$

$$(T_d)_{avg} = \frac{1}{2\Pi} \int_0^{2\Pi} \frac{1}{R} \times I_m V_m \sin wt . \sin(wt - \phi) \frac{dM}{d\theta} \times d(wt)$$

$$(T_d)_{avg} = \frac{V_m I_m}{2\times 2\Pi} \times \frac{1}{R} \times \frac{dM}{d\theta}\left[\int\{\cos\phi - \cos(2wt-\phi)\}dwt\right]$$

$$(T_d)_{avg} = \frac{V_m I_m}{4\Pi R} \times \frac{dM}{d\theta}\left[\int_0^{2\Pi}\cos\phi.dwt - \int_0^{2\Pi}\cos(2wt-\phi).dwt\right]$$

$$(T_d)_{avg} = \frac{V_m I_m}{4\Pi R} \times \frac{dM}{d\theta}\left[\cos\phi[wt]_0^{2\Pi}\right]$$

$$(T_d)_{avg} = \frac{V_m I_m}{4\Pi R} \times \frac{dM}{d\theta}\left[\cos\phi(2\Pi - 0)\right]$$

$$(T_d)_{avg} = \frac{V_m I_m}{2} \times \frac{1}{R} \times \frac{dM}{d\theta} \times \cos\phi$$

$$(T_d)_{avg} = V_{rms} \times I_{rms} \times \cos\phi \times \frac{1}{R} \times \frac{dM}{d\theta}$$

$$(T_d)_{avg} \propto KVI\cos\phi$$

$$T_C \propto \theta$$

$$\theta \propto KVI\cos\phi$$

$$\theta \propto VI\cos\phi$$

Advantages of Dynamometer

- As the instrument has Square Law response so can be used on both the dc as well as on AC.
- These instruments are free from hysteresis and Eddy current errors. It is because of absence of iron in the operating part of the instrument.
- Ammeter up to 10A and voltmeter up to 600V can be constructed with precision grade accuracy.
- Dynamo type voltmeters are useful for accurate measurement of rms value of voltage irrespective of waveform.
- Because of Precision grade accuracy and same calibration for DC and AC measurement instruments are used as transfer and calibration instruments.

Disadvantage of Dynamometer

- The scale is not uniform as the instrument uses Square Law response. These instruments have small torque-weight ratio so the friction error is considerable.
- Owing to heavy moving system friction losses in these instruments are somewhat more than those in other instruments.
- As a result of measures taken to reduce the frictional errors, their cost is more in comparison to moving iron and PMMC instruments. They are more sensitive to overload and mechanical impact and are to be handled with care.
- Adequate screening of the movements against the stray magnetic field is essential.
- The sensitivity of the instrument is typically very low due to poor deflecting torque. The sensitivity of dynamo type wattmeter is 10 to 30 per volt in comparison to the sensitivity of 20 kilo ohm per volt in case of D'Arsnoval movement.
- The power consumption of this instrument is comparatively high because of their construction.

Errors in dynamometer type instruments

- **Frictional Error:** Since the coils are air-cored, therefore the magnetic field produced is of small strength. So they require a large number of ampere-turns to create necessary deflecting torque. This result in the heavy moving system. Therefore small torque-weight ratio. Thus the frictional losses in dynamo type instruments are somewhat larger as compared to other instruments.
- **Temperature errors:** Since the operation of dynamo type instrument required considerable power, self heating in these instruments is appreciable. The error due to self heating may be much as 1% of full scale deflection.
- **Error Due to Stray Magnetic field:** Since the operating magnetic field produced by the fixed coil. In these instruments is somewhat weaker in comparison to that in the instrument of other type. The operation of these instruments is more sensitive to the stray magnetic field.
- **Frequency error:** The change in frequency causes error
  (a) Due to change in reactance of operating coil.
  (b) Due to change in magnitude of Eddy current setup in the metal part of the instrument near to operating portion.

Electrostatic Instrument

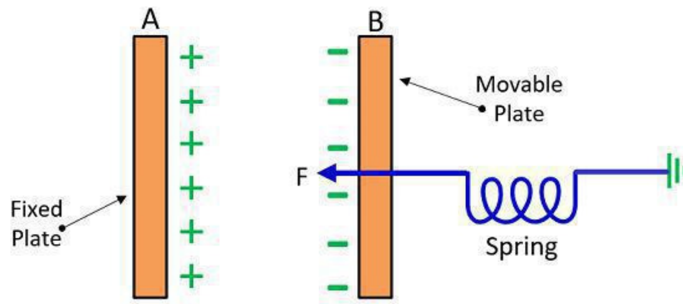
The instrument whose working depends on the principle of attraction or repulsion of electrodes that carry electrical charges such type of instrument is known as the electrostatic instrument. In other words, the instrument which uses the static electric field for producing the deflecting torque is known as the electrostatic instrument. The electrostatic instrument is used for measuring the high and low voltage and also the power of the given circuit.

The electrostatic instrument works on the principle of mechanical interaction of the electrodes that consists the opposite electrical charge. The quantity which is measured by the electrostatic instrument is converted into either AC or DC voltage.

There are two ways of constructions of electrostatic instruments;

- In the electrostatic instrument, the charge is stored between the plates. The electrostatic instrument consist the charges of two opposite polarity and force of attraction occurs between these two plates. Because of the force of attraction, the movable plates move towards the fixed plates and store the maximum electrostatic energy.
- In this type of instruments, there are forces of attraction or repulsion occur between the rotary plate.

The figure below shows the linear electrostatic type instrument. The plates A become positively charged, and the plate B becomes negatively charged. The positive charge plates become fixed, and the negative plates become movable. The spring is connected to the negatively charged plates for controlling the movement.
When the voltage is applied to the plate, then the force of attraction induces between them. The plate tries to moves towards A until the force becomes maximum. The C is the capacitance (in farad) between the plates. The expression gives the total energy stores between the plates.



Torque develop by electrostatic instrument

Let,

V = Voltage applied between vane and quadrant

C = capacitance between vane and quadrant

Energy stored = ½ (CV^2)

Let ‘θ’ be the deflection corresponding to a voltage V. And the voltage increases by dv, the corresponding deflection is ‘θ + dθ’ When the voltage is being increased, a capacitive current flows

$$i = \frac{dq}{dt} = \frac{d(CV)}{dt} = \frac{dC}{dt}V + C\frac{dV}{dt}$$

Multiplying on both side of equation by V × dt

$$Vidt = \frac{dC}{dt}V^2dt + CV\frac{dV}{dt}dt$$

$$Vidt = V^2dC + CVdV$$

$$\text{Change in stored energy} = \frac{1}{2}(C+dC)(V+dV)^2 - \frac{1}{2}CV^2$$

$$= \frac{1}{2}\left[(C+dC)V^2 + dV^2 + 2VdV\right] - \frac{1}{2}CV^2$$

$$= \frac{1}{2}\left[CV^2 + CdV^2 + 2CVdV + V^2dC + dCdV^2 + 2VdVdC\right] - \frac{1}{2}CV^2$$

$$= \frac{1}{2}V^2dC + CVdV$$

$$V^2dC + CVdV = \frac{1}{2}V^2dC + CVdV + F \times rd\theta$$

$$T_d \times d\theta = \frac{1}{2}V^2dC$$

$$T_d = \frac{1}{2}V^2\left(\frac{dC}{d\theta}\right)$$

At steady state condition, $T_d = T_C$

$$K\theta = \frac{1}{2}V^2\left(\frac{dC}{d\theta}\right)$$

$$\theta = \frac{1}{2K}V^2\left(\frac{dC}{d\theta}\right)$$

Advantages of Electrostatic Instrument

- Both the AC and DC voltage can be measured by using the electrostatic instrument.
- The electrostatic type instrument consumes very less power.
- The high value of voltage can be measured by using the instrument.
- In the rotary type electrostatic instrument, in spite of linear displacement, the angular displacement occurs between the fixed and the moving plates.
- The instrument has less Waveform and frequency error.
- No error occurs because of the stray magnetic field.
- The instrument is designed for large voltage.

Disadvantages of Electrostatic type instrument

- The non-uniform scale is used in the instrument.
- The force of very small magnitude involves in the instrument.
- The instrument is quite costly as compared to the other instrument.
- The size of the instrument is also very large.

Clamp-on meter

Current transformer clamp meter: Current transformer clamp meters are equipped with rigid jaws of made of ferrite iron. The jaws are individually wrapped by coils of copper wire. Together, they form a magnetic core during measurements.

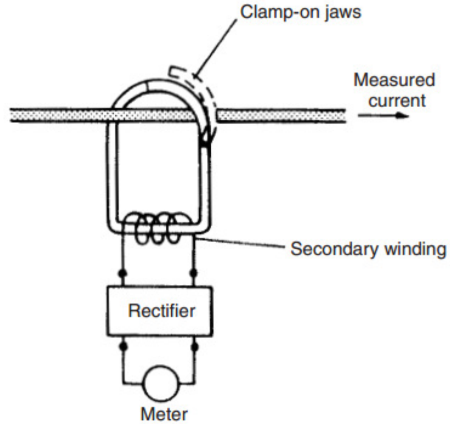
Their basic operation is like that of a transformer. It works with one primary turn, or winding, which in nearly all cases is the conductor being measured. The coils around the jaws serve as a secondary winding of the current transformer.

Current flowing through the conductor generates an alternating magnetic field that rotates around it. This field is concentrated by the clamp's iron core, inducing a flow of current in the secondary windings in the meter. The measure of the amount of magnetic field passing through the conductor (or any surface) is called magnetic flux, Φ_m.

The signal is proportional to the ratio of the turns. A much smaller current is delivered to the meter's input due to the ratio of the number of secondary windings (those wrapped around the jaws of the clamp) vs. the number of primary windings wrapped around the core.

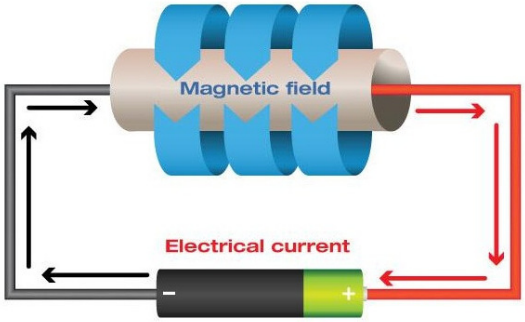
If, for example, the secondary has 1000 windings, then the secondary current is 1/1000 the current flowing in the primary. Thus 1 amp of current in the conductor being measured would produce 0.001 amps, or 1 milliamp, of current at the input of the meter. With this technique, much larger currents can be easily measured by increasing the number of turns in the secondary.

Current transformer clamp meters only respond to ac waveforms.



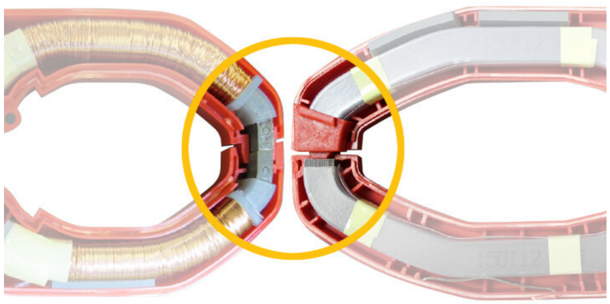
Clamp Meters using Hall Effect for AC & DC Measurements

Hall Effect clamp meters can measure both ac and dc current up to the kilohertz (1000 Hz) range. Like current transformer types, Hall Effect clamp meters use rigid iron jaws to concentrate the magnetic field that encircles the conductor being measured.



Unlike current transformer clamp meters, the jaws are not wrapped by copper wires. Instead, the magnetic field generated by the conductor is focused across one or more gaps in the core after the jaws are clamped around the conductor.

Notice the point where the jaw tips of a Hall Effect clamp meter meet.



A gap exists where the jaw tips of a Hall Effect clamp meter meet, creating an air pocket that the magnetic field must jump. This gap limits the magnetic flux so that the core cannot saturate.

In contrast, the jaws of an ac-only current transformer clamp are flush when closed. When opened, the tips of the jaws show bare metal core faces.

In that gap, covered by thin plastic molding, is a semiconductor known as a Hall Effect sensor a transducer that varies its output voltage when responding to magnetic fields, in this case the magnetic field of the conductor or wire being measured. Its purpose is to measure magnetic flux directly. The output voltage from the sensor then amplified and scaled to represent the current flowing through the conductor that lies inside the jaws of the clamp.

As current flows through a conductor being measured, the iron core formed by the jaws of a Hall Effect clamp meter allows the magnetic field to easily pass through—more easily, in fact, than air. When the magnetic field (flux) comes to that small air gap in the tips of the jaw, the field has to jump that gap. Because the gap is small, the field remains concentrated across the gap, and the Hall Effect sensor which sits in the gap produces a voltage proportional to the magnetic flux in the gap that the clamp translates into a current reading.

In Hall Effect devices, dc magnetic fields are also concentrated through the core, like a permanent magnet sticking to iron. Because of the dc magnetic field of the earth and the possibility of other magnetic fields near the measurement site, these clamps require the reading to be "zeroed" before taking a measurement to eliminate offsets.

** Multi-Ammeter and Multi-Voltmeter** Self study