# ELECTRICAL MEASUREMENTS AND SENSORS

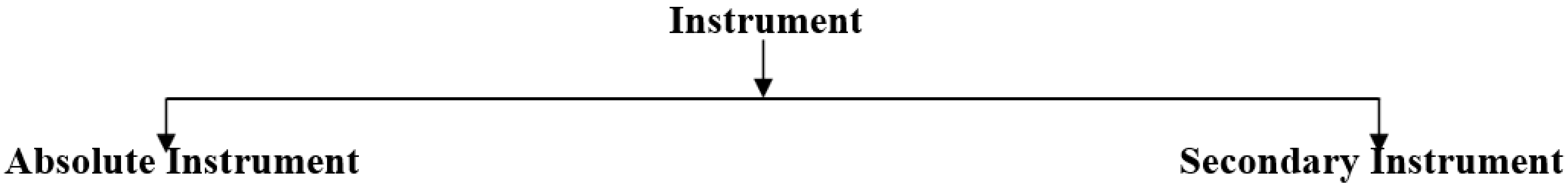
NARSIMHA REDDY ENGINEERING COLLEGE
UGC AUTONOMOUS INSTITUTION
Maisammaguda (V), Kompally - 500100, Secunderabad, Telangana state, India

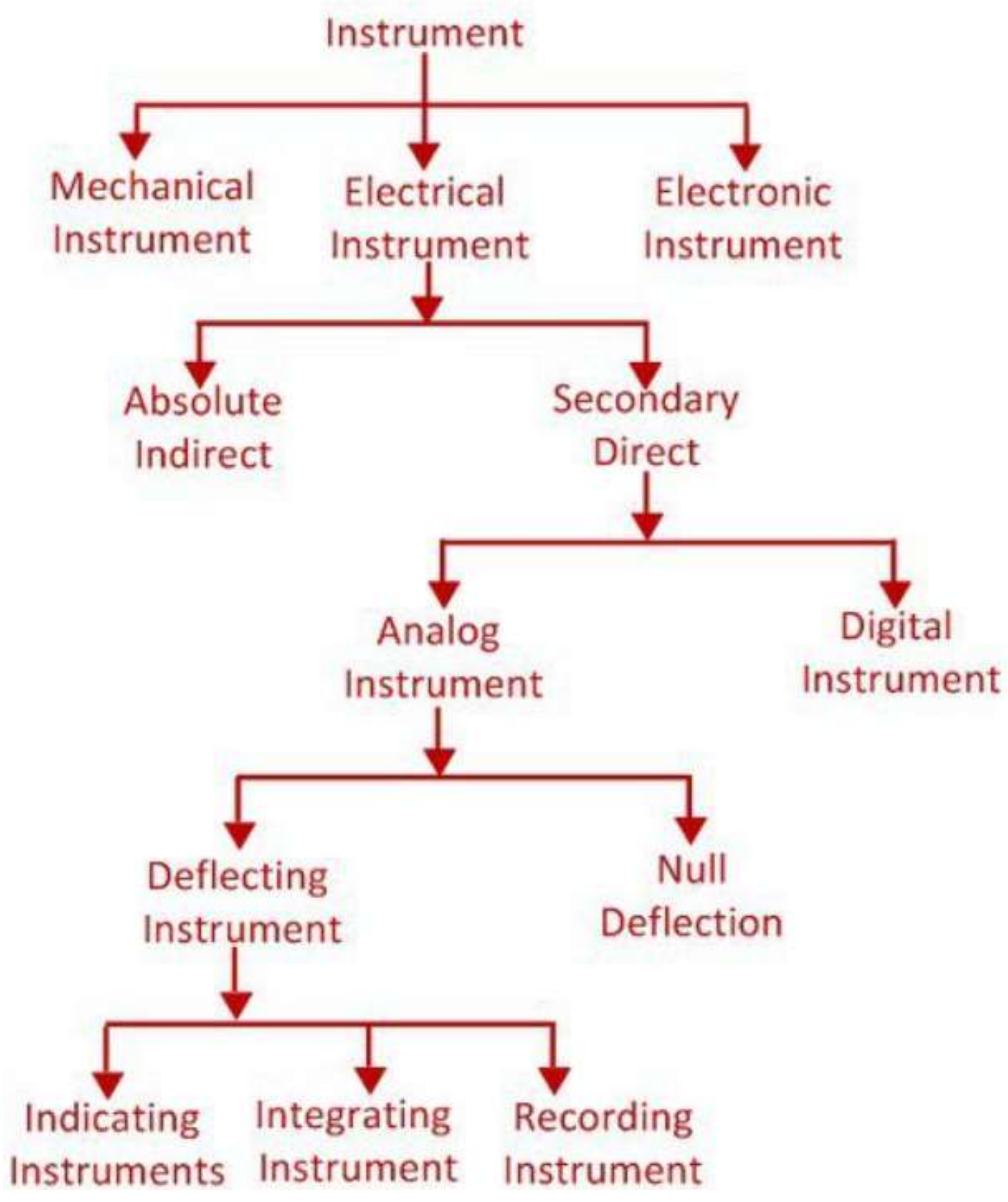
Accredited by NBA & NAAC with 'A' Grade
Approved by AICTE
Permanently affiliated to JNTUH

# UNIT – I
# INTRODUCTION TO MEASURING INSTRUMENTS

## 1. Definition of instruments

An instrument is a device in which we can determine the magnitude or value of the quantity to be measured. The measuring quantity can be voltage, current, power and energy etc. Generally instruments are classified in to two categories.




Instrument
Mechanical Instrument
Electrical Instrument
Electronic Instrument
Absolute Indirect
Secondary Direct
Analog Instrument
Digital Instrument
Deflecting Instrument
Null Deflection
Indicating Instruments
Integrating Instrument
Recording Instrument

## Absolute instrument

An absolute instrument determines the magnitude of the quantity to be measured in terms of the instrument parameter. This instrument is really used, because each time the value of the measuring quantities varies. So we have to calculate the magnitude of the measuring quantity, analytically which is time consuming. These types of instruments are suitable for laboratory use. Example: Tangent galvanometer.

## Secondary instrument

This instrument determines the value of the quantity to be measured directly. Generally these instruments are calibrated by comparing with another standard secondary instrument.

Examples of such instruments are voltmeter, ammeter and wattmeter etc. Practically secondary instruments are suitable for measurement.

# Functions of instrument and measuring system

- Functions of instrument and measuring system can be classified into three. They are:

  i) Indicating function.

  ii) Recording function.

  iii) Controlling function.

- Application of measurement systems are:

  i) Monitoring of process and operation.

  ii) Control of processes and operation.

  iii) Experimental engineering analysis.

## Indicating instrument

This instrument uses a dial and pointer to determine the value of measuring quantity. The pointer indication gives the magnitude of measuring quantity.

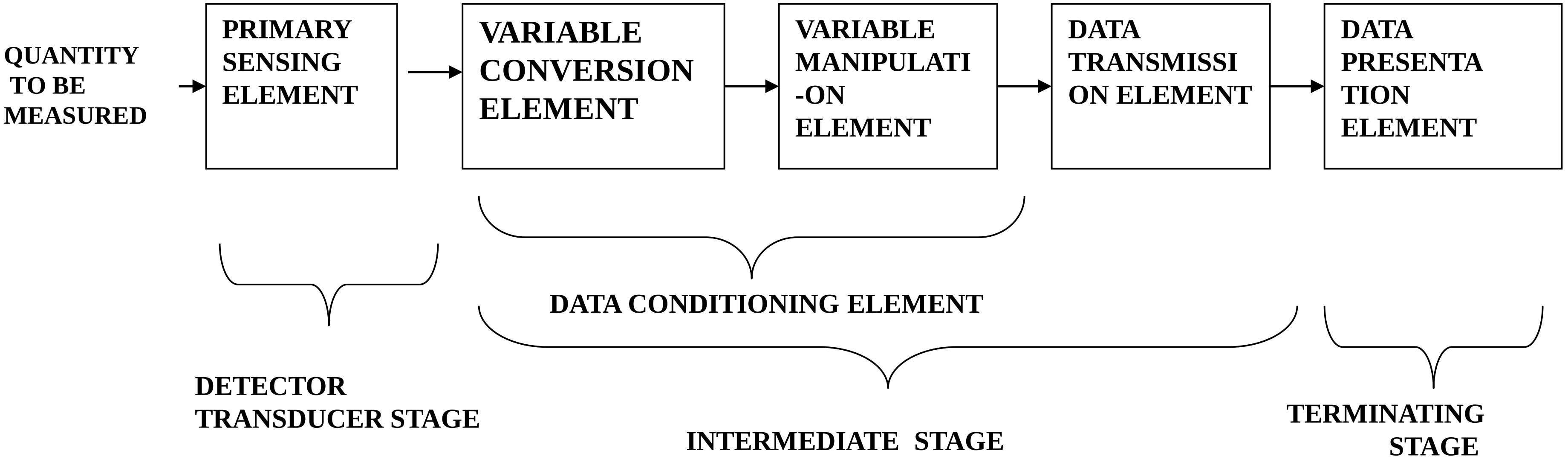
## Recording instrument

This type of instruments records the magnitude of the quantity to be measured continuously over a specified period of time.

## Integrating instrument

This type of instrument gives the total amount of the quantity to be measured over a specified period of time.

# Functional elements of a generalised measuring system



# Principles and types of analog ammeter, voltmeter & multimeter

- Analog Instruments
  - An analog device is one in which the output or display is a continuous function of time and bears a constant relation to its input
- Classification
  - 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, Integrating.
  - Classified based on method used for comparing the unknown quantity. (Direct / Comparison measurement )

- Essential requirements of an instrument:
    - Deflecting system producing deflection torque Td
    - Controlling system produces controlling torque Tc
    - Damping system producing damping torque

- Deflecting system
  - Deflecting system uses on of the following effects produced by current or voltage to produce deflecting torque
      - Magnetic Effect.
      - Thermal Effect.
      - Electrostatic Effect
      - Induction Effect.
      - Hall Effect

- Controlling system
  - There are two types of control system
    - Gravity control
    - Spring control

- Damping system

  - The damping torque should be of such a magnitude that the pointer quickly comes to its final steady state position, without overshooting.

- To damp out the oscillation quickly, a damping force is necessary. This force is produced by different systems.

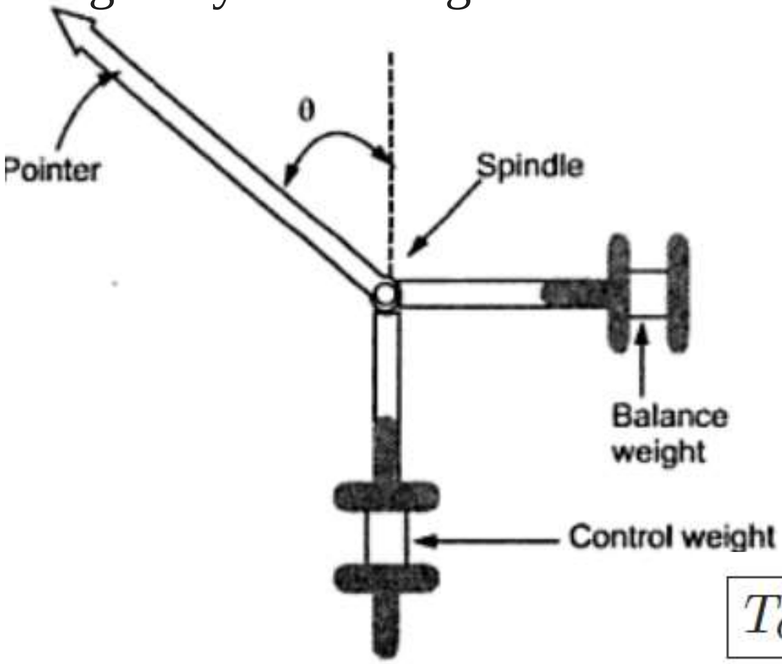
    (a) Air friction damping

    (b) Fluid friction damping

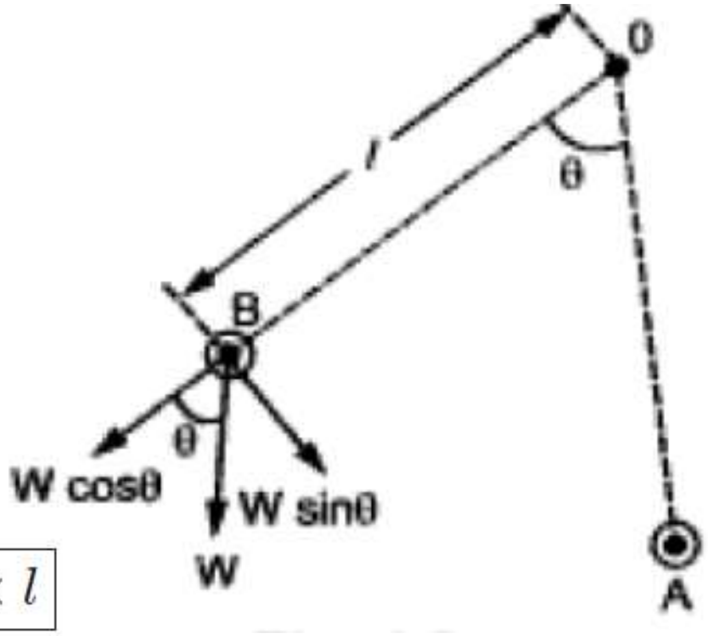
    (c) Eddy current damping

# Gravity control

This type of control consists of a small weight attached to the moving system whose position is adjustable. This weight produces a controlling torque due to gravity. This weight is called **control weight.**




Gravity Control



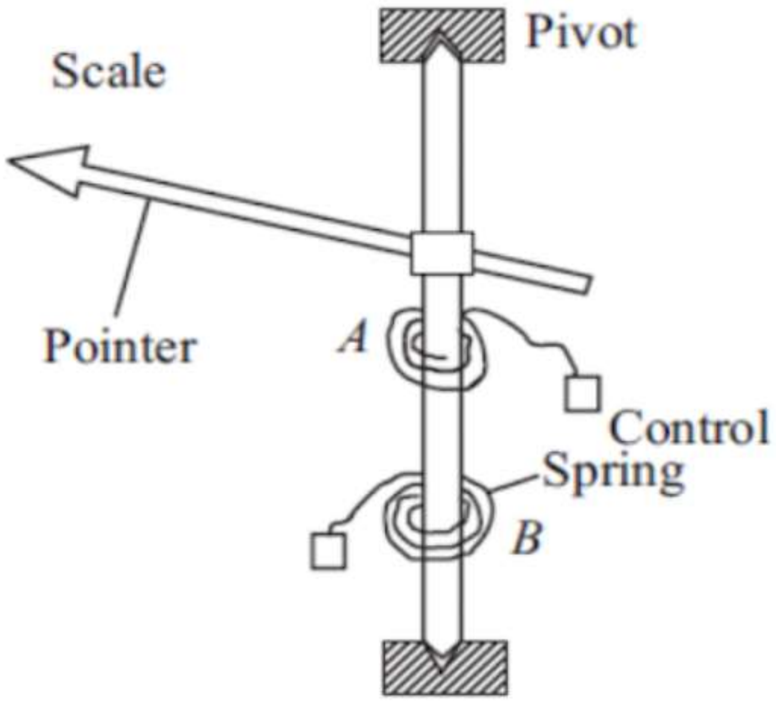

$$\boxed{T_C = W\sin\theta \times l}$$

$$= K\sin\theta$$

Here, $K = Wl$

= Gravity Constant

# Spring control




The controlling torque produced by the spiral spring is given by,

$$\boxed{T_c = \frac{E\, b\, t^3}{12\, L}\,\theta}$$

E = Young's modulus of spring material in N/m²
t = thickness in meters
b = depth in meters
L = length in meters

$$K_s = \text{Spring constant} = \frac{E\, b\, t^3}{12\, L}$$

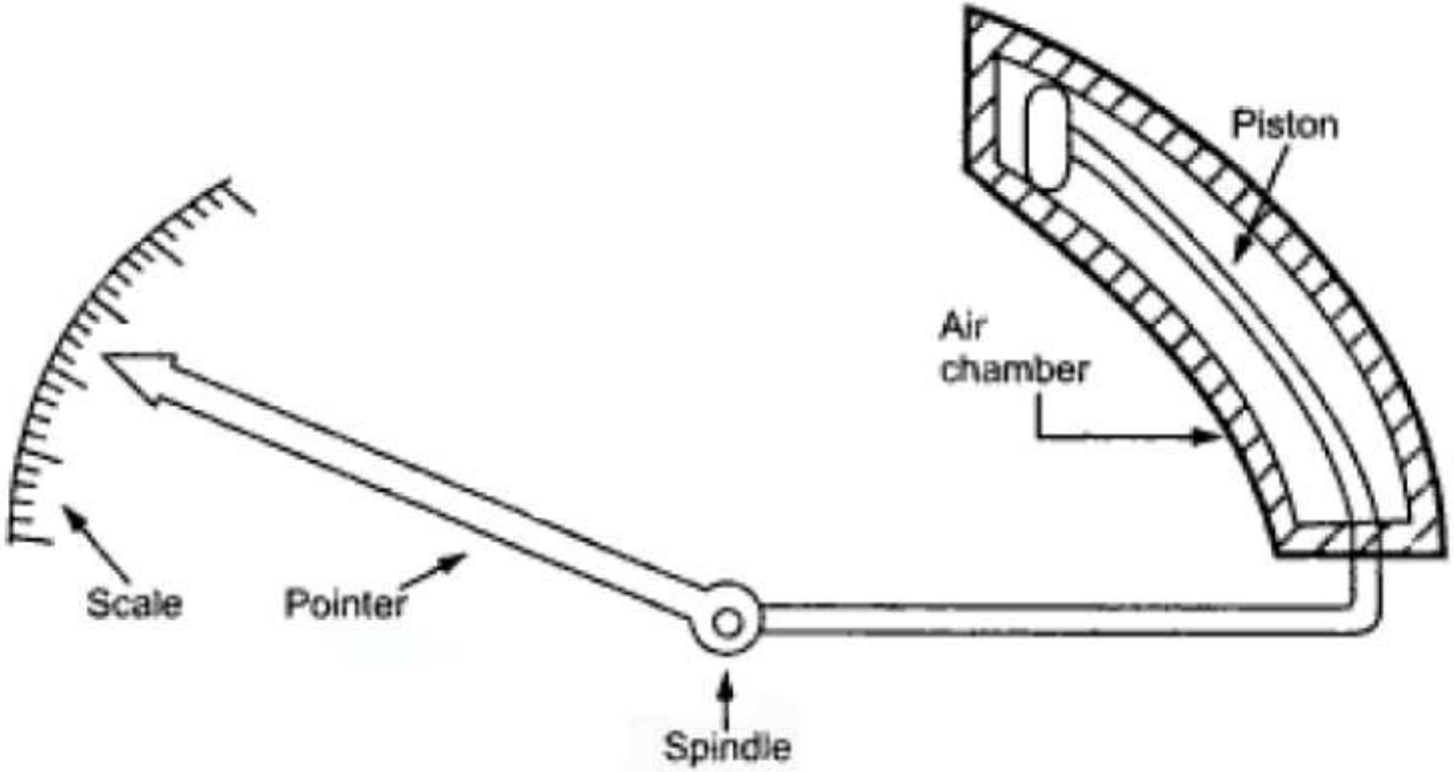
$$\boxed{\therefore\ T_c \propto \theta}$$

# Comparison between Spring Control and Gravity Control Mechanism

| Sr. No. | Gravity Control | Spring Control |
|---|---|---|
| 1. | Adjustable small weight is used which produces the controlling torque. | Two hairsprings are used which exert controlling torque. |
| 2. | Controlling torque can be varied. | Controlling torque is fixed. |
| 3. | The performance is not temperature dependent. | The performance is temperature dependent. |
| 4. | The scale is non-uniform. | The scale is uniform. |

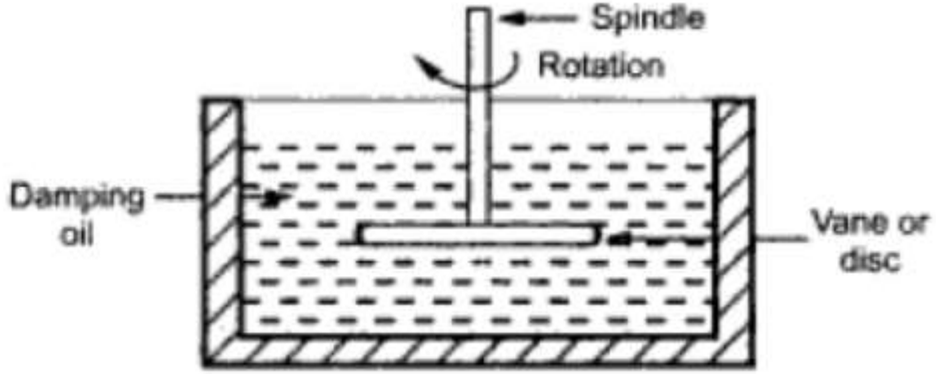
| | | |
|---|---|---|
| 5. | The controlling torque is proportional to sin $\theta$ | The controlling torque is proportional to $\theta$ |
| 6. | The reading can not be taken accurately. | The readings can be taken very accurately. |
| 7. | The system must be used in a vertical position only. | The system need not be necessarily in a vertical position. |
| 8. | Proper leveling is required as gravity control. | The leveling is not required. |
| 9. | simple, cheap but delicate. | Simple, rigid but costlier compared to gravity control. |
| 10. | rarely used for indicating and portable instruments. | Very popular and used in most instruments. |

# Air friction damping




**Air friction damping**

# Fluid friction damping




Fluid friction damping

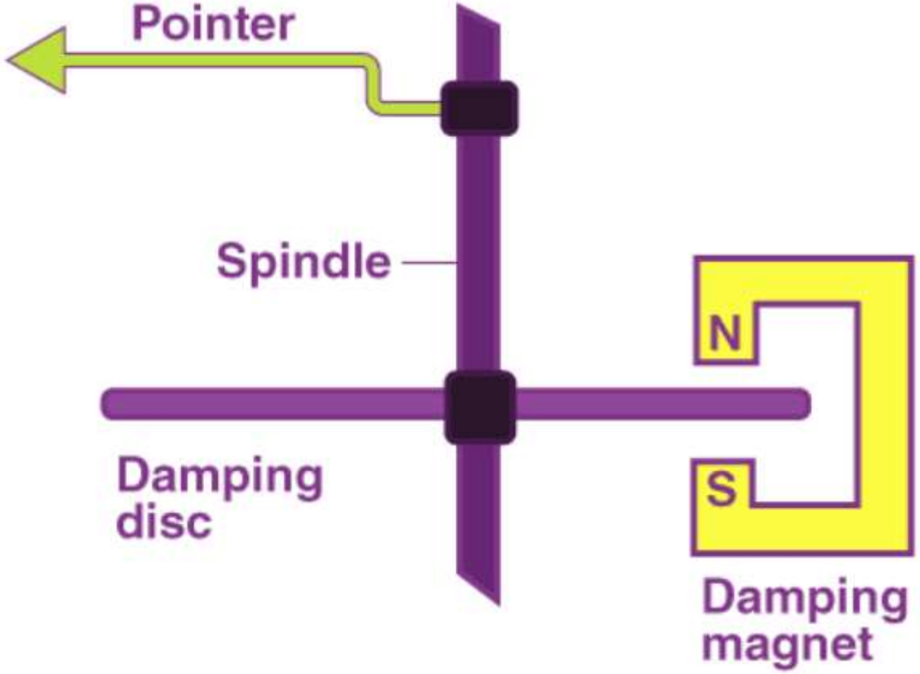
**Advantages of the Fluid Friction damping Method:**

1. Due to the more viscosity of the fluid, more damping is provided.
2. The oil can also be used for insulation purposes.

**Disadvantages of the Fluid Friction damping Method:**

1. This can be only used for instruments that are in a vertical position.
2. Due to oil leakage, the instruments can not be kept clean.

# Eddy current damping




**Advantages :**

- It is the most efficient form of damping compared to other methods.
- It is especially used for moving coil and induction-type instruments.
- It can be used in portable instruments as well.

**Disadvantages :**

- It can't be used for moving iron or dynamo-type instruments.

# Analog Ammeters

- Ammeters are connected in series in the circuit whose current is to be measured. The power loss in an ammeter is $I^2R_a$.Therefore ammeters should have a low electrical resistance so that they cause a small voltage drop and consequently absorb small power.

# Analog Voltmeters

- Voltmeters are connected in parallel in the circuit whose voltage is to be measured. The power loss in a voltmeter is $V^{2}/R_V$. Therefore, voltmeters should have a high electrical resistance so that they cause a small voltage drop and consequently absorb small power.

# Types of Instruments

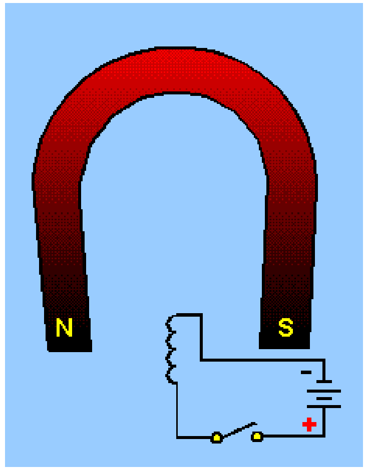
- Permanent magnet moving coil (PMMC).
- Moving Iron
- Electro-dynamometer type.
- Hot wire type.
- Thermocouple type.
- Induction type.
- Electrostatic type.
- Rectifier type.

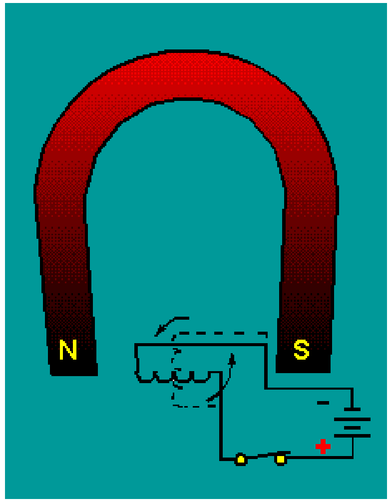
# Permanent magnet moving coil

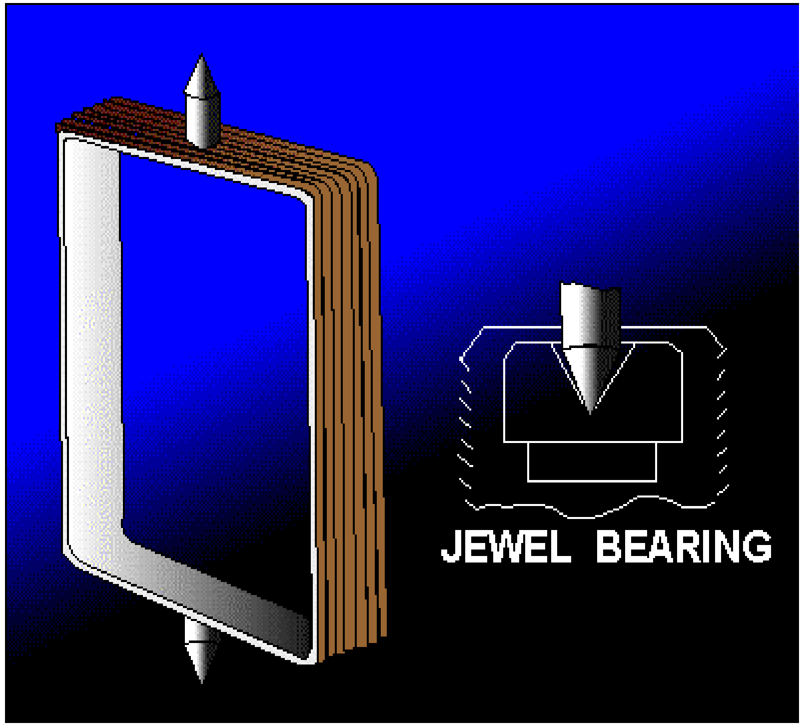
This permanent magnet moving coil meter movement is the basic movement in most analog (meter with a pointer indicator hand) measuring instruments. It is commonly called d'Arsonval movement because it was first employed by the Frenchman d'Arsonval in making electrical measurements.

PMMC is the most accurate type for dc measurements. This type of meter movement is a current measuring device which is used in the ammeter, voltmeter, and ohmmeter. Basically, both the ammeter and the voltmeter are current measuring instruments, the principal difference being the method in which they are connected in a circuit.

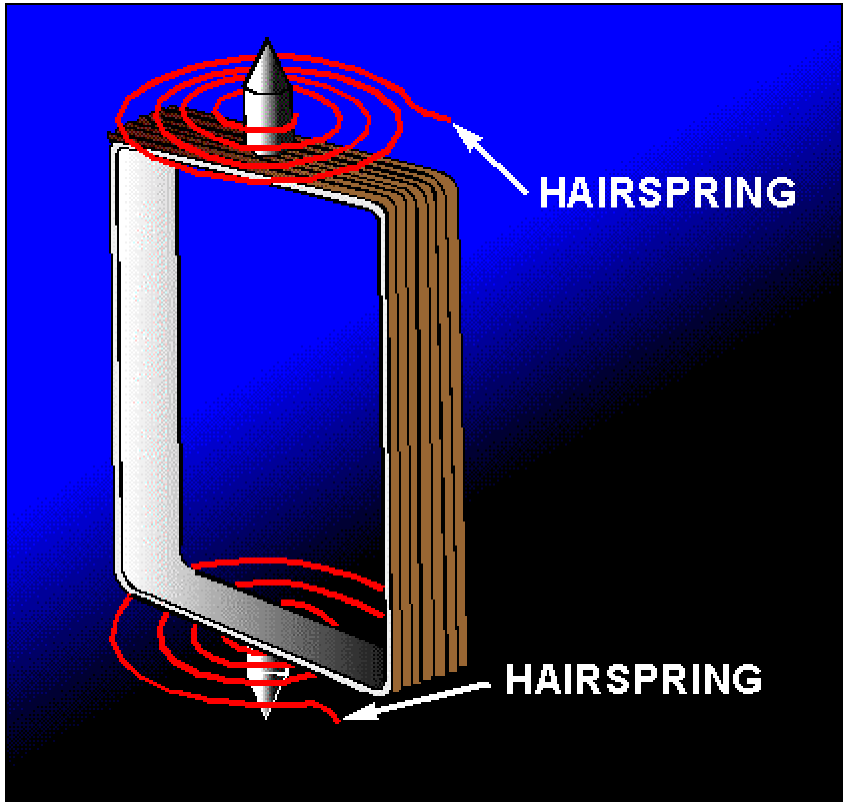
- A permanent-magnet moving-coil movement is based upon a fixed permanent magnet and a coil of wire which can move.
- When the switch is closed, causing current through the coil, the coil will have a magnetic field which will react to the magnetic field of the permanent magnet.
- The bottom portion of the coil in figure will be the north pole of this electromagnet. Since opposite poles attract, the coil will move to the position as shown



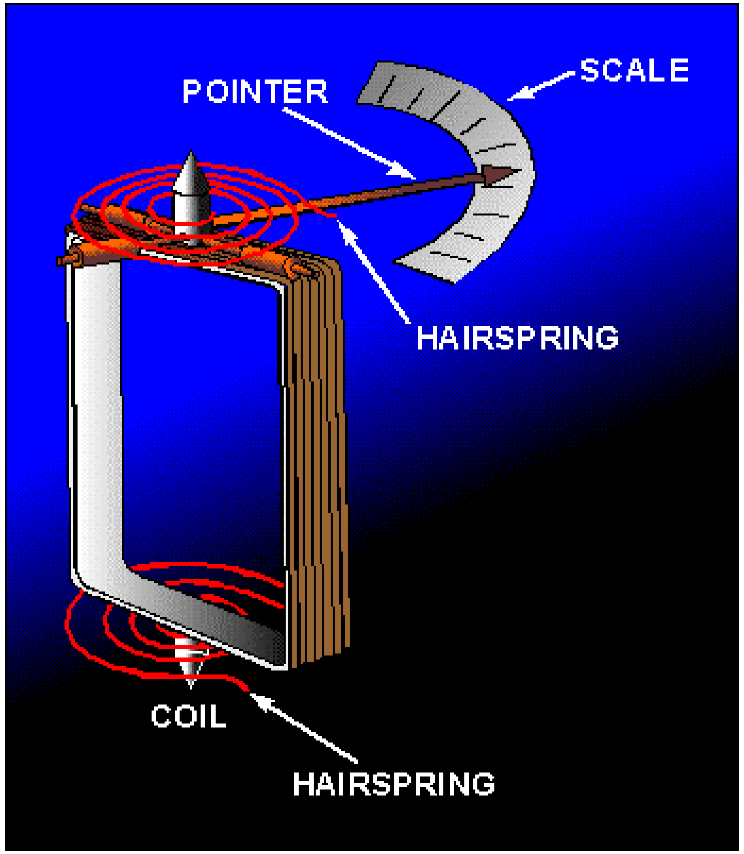





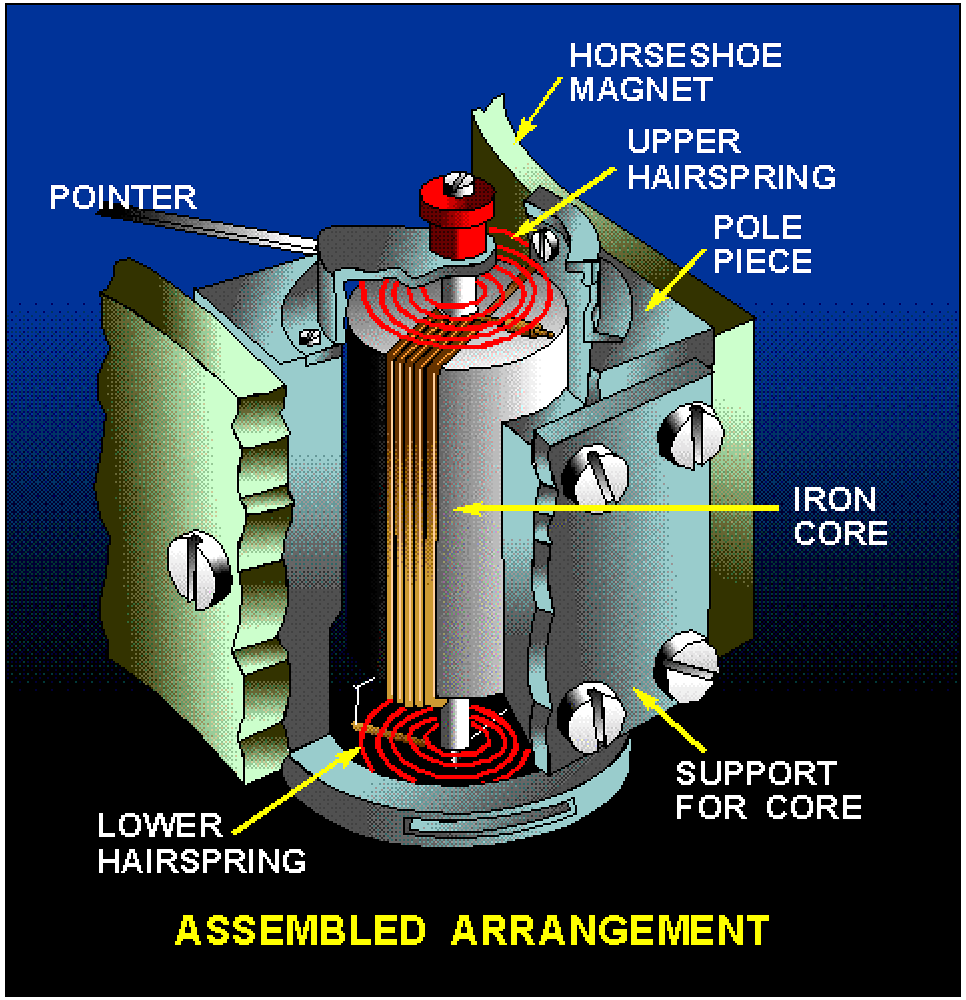

A basic coil arrangement




Coil and hairsprings




A complete coil.




Assembled meter movement

small friction torque.

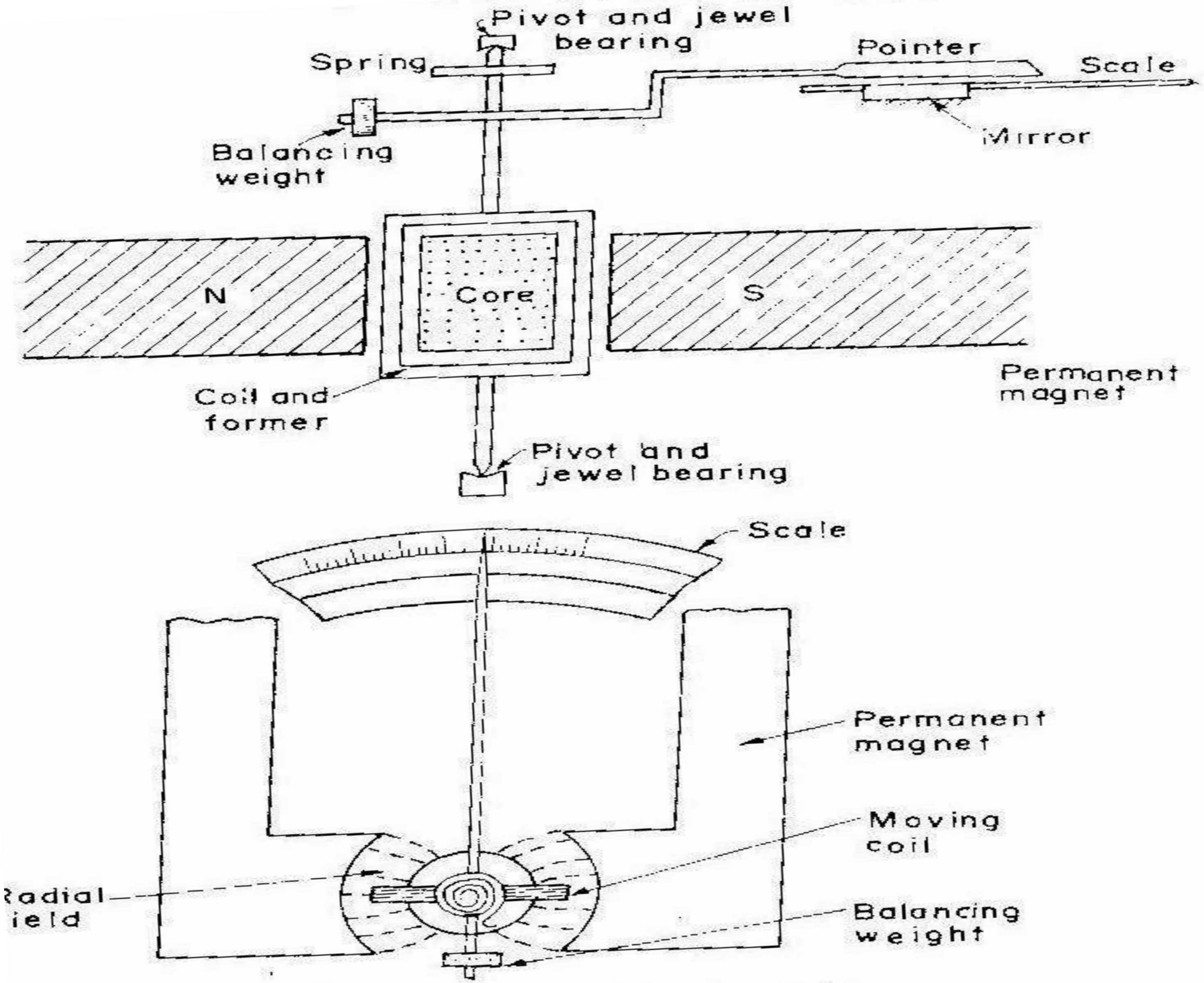
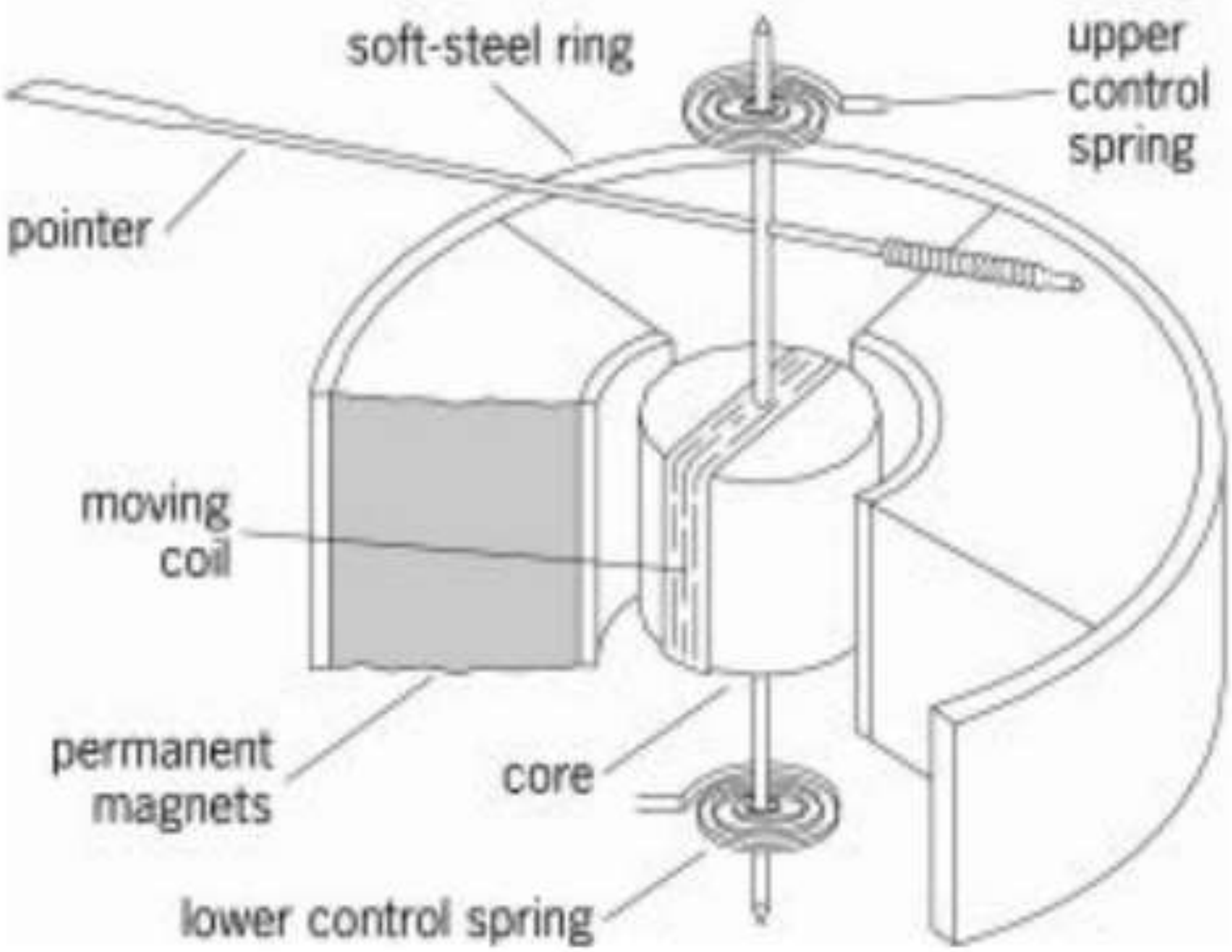



Fig. 9.1. Permanent magnet moving coil instrument.


soft-steel ring
upper control spring
pointer
moving coil
permanent magnets
core
lower control spring

- Construction & working of PMMC Instruments
- **Moving coil** is wound with many turns of enameled or silk covered copper wire. Coil is mounted on a rectangular aluminum former which is pivoted on jeweled bearings .
- Voltmeter coils are mount on metal frames to provide electromagnetic damping.
- Ammeter coils are wound on non-metallic former , because coils are shorted by ammeter shunt. Coil moves freely in the field of a permanent magnet.

- **Magnet Systems :** U-shaped PM is used. Alcomax and Alnico are used for making PM (High co-ercive). Flux densities used in PMMC vary from 0.1 $wb/m^2$ to 1 $wb/m^2$. small instrument- small number of turns-reduction in volume. Similarly for large instruments.
- The iron core is spherical if coil is circular and is cylindrical if the coil is rectangular.
- Due to iron core , the deflecting torque increases, increasing the sensitivity of the instrument.
- **Control spring**: Controlling torque is provided by two phosphor bronze hair springs.

- **Eddy current damping**: Damping torque is provided by eddy current damping.
- **Pointer and scale arrangement**: The pointer is carried by the spindle, and it moves over a graduated scale.. The mirror is placed below the pointer to get accurate reading.

When a current carrying conductor is placed in the magnetic field produced by a permanent magnet, the coil experiences a force and moves the coil . As the coil is moving and the magnet is permanent, the instrument is called Permanent Magnet Moving Coil Instrument(PMMC).

## Torque equation

Deflecting Torque, $T_d = BINA$

Where

B = flux density in Wb/m2 (Tesla)

I = current (A).

N = number of turns of the coils.

A = area ( length X wide), (m2).

Controlling torque $T_c = K\theta$

At steady state position $T_d = T_c$

$$I \propto \theta$$

As the deflection is proportional to the current passing through the meter, we get a uniform (linear) scale for the instrument.

- As the direction of the current to the coil changes, the direction of deflection of the pointer also changes. Hence such instruments are well suited for the d.c. measurements.
- In micro and milli ammeters upto 20 mA, the entire current to be measured is passed through the coil. The springs carry current to the coil. Thus, the current carrying capacity of the springs, limits current which can safely be carried.
- For higher currents, the moving coil is shunted by sufficient resistance.
- While the voltmeters having high ranges use a moving coil together with sufficient series resistance, to limit the instrument current.

- Advantages of PMMC:

- It has uniform scale.
- With a powerful magnet, its torque to weight ratio is very high.
- Sensitivity is high.
- Consumes low power, of the order of 25W to 250 μW.
- High accuracy.
- Instrument is free from hysteresis error.
- Extension of instrument range is possible.
- Not affected by external magnetic fields called stray magnetic fields.

# Disadvantages:

1. Suitable for d.c. measurements only.
2. Ageing of permanent magnet and control springs introduces the errors.
3. Cost is high due to delicate construction and accurate machining.
4. Friction due to jewel-pivot suspension.

- **Errors in PMMC instrument:**

- Weakening of PM due to ageing at temperature effects.
    - Weakening of magnets are avoided by heating and vibration treatment. This results in strengthening of magnets.
- Weakening of springs due to ageing and temperature effects.
    - The weakening of magnet cause less deflection while weakening of the control springs cause large deflection, for a particular vale of current.

- Change of resistance of the moving due to temperature effect .
  - Error due to large change in the resistance of copper of the moving coil as compared to manganin shunt. This is because copper has a much high resistance temperature co-efficient as compared to manganin. To reduce, swamping resistor made up of manganin is connected in series with MC, so that copper coil forms only a small fraction of total resistance comprising the coil and additional swamping resistance.

# Moving Iron Instruments

- The instrument in which the moving iron is used for measuring the flow of current or voltage is known as the moving iron instrument. It works on the principle that the iron place near the magnet attracts towards it. The force of attraction depends on the strength of the magnet field. The magnetic field induces by the electromagnet whose strength depends on the magnitude of the current passes through it.

# Construction of Moving Iron Instrument

- The plate or vane of soft iron is used as the moving element of the instrument. The vane is so placed that it can freely move in the magnetic field of the stationary coil. The conductor makes the stationary coil, and it is excited by the voltage or current whose magnitude is used to be measured.
- The moving iron instrument uses the stationary coil as an electromagnet. The electromagnet is the temporary magnet whose magnetic field strength increases or decreases with the magnitude of the current passes through it.

# Working of the Moving Iron Instrument

- The moving iron instruments use the stationary coil of copper or aluminium wire which acts as an electromagnet when an electric current passes through it. The strength of the magnetic field induces by the electromagnet is directly proportional to the current passes through it.
- The plates or vane of the iron pass through the coil increases the inductance of the stationary coil (the inductance is the property of the conductor which increases their electromotive force when the varying current passes through it).

- The electromagnet attracts the iron vane. The vane passes through the coil tries to occupy the minimum reluctance path (the reluctance is the property of the magnet which opposes the flow of electric current).
- The vane passes through the coil experience a force of repulsion caused by the electromagnet. The repulsion force increases the strength of the coil inductance.

- This happens because the inductance and reluctances are inversely proportional to each other.

# Classification of the Moving Iron Instruments

- The attraction and the repulsion are the types of the moving iron instruments. Their detail explanation is shown below.
- 1. Attraction Type – The instrument in which the iron plate attracts from the weaker field towards the stronger field such type of instrument is known as the attraction type instrument.
- Construction of Attraction Type Instrument – The stationary coil of the attraction type instrument is flat and has a narrow opening. The moving element is the flat disc of the iron core. The current flow through the stationary coil produced the magnetic field which attracts the iron coil.

- The iron vane deflects from the low magnetic field to the high magnetic field, and the strength of the deflection is directly proportional to the magnitude of the current flow through it. In short, we can say that the iron coil attracts towards in.

- The attraction type instruments use spring, which provided the controlling torque. The deflection of the coil is reduced by the aluminium piston which is attached to the moving coil.

# Moving Iron attraction Type Instrument

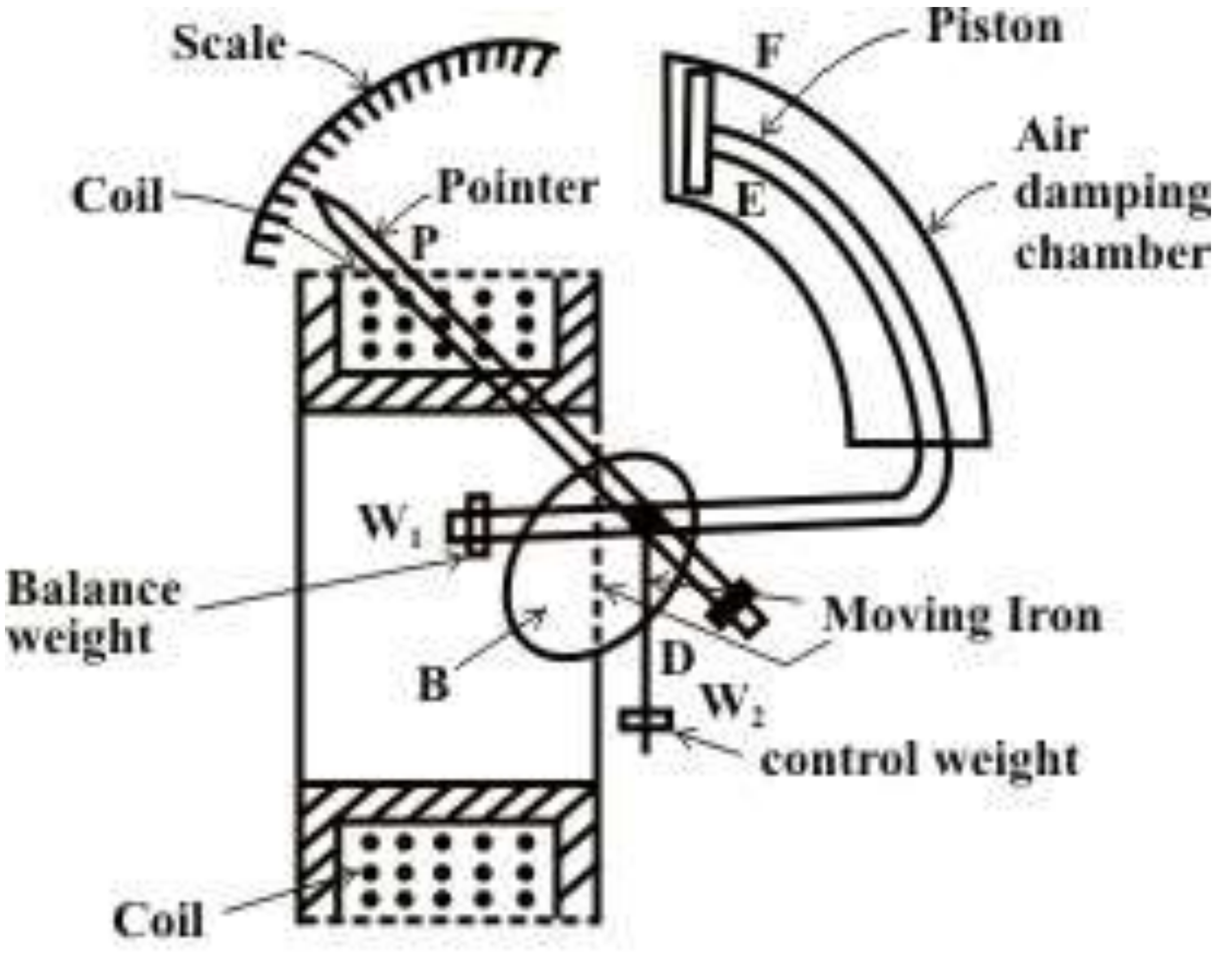
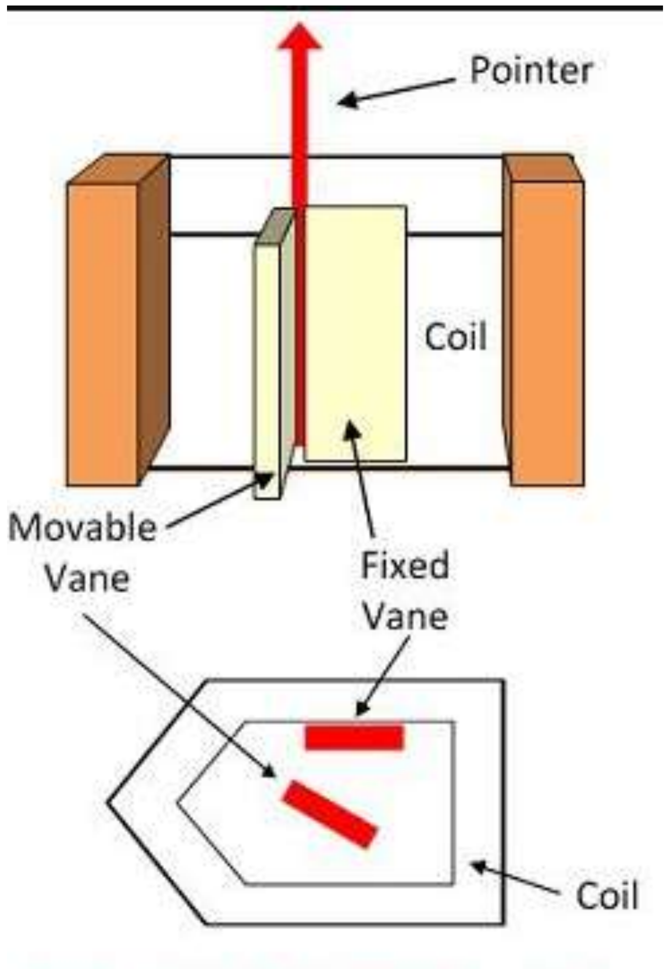


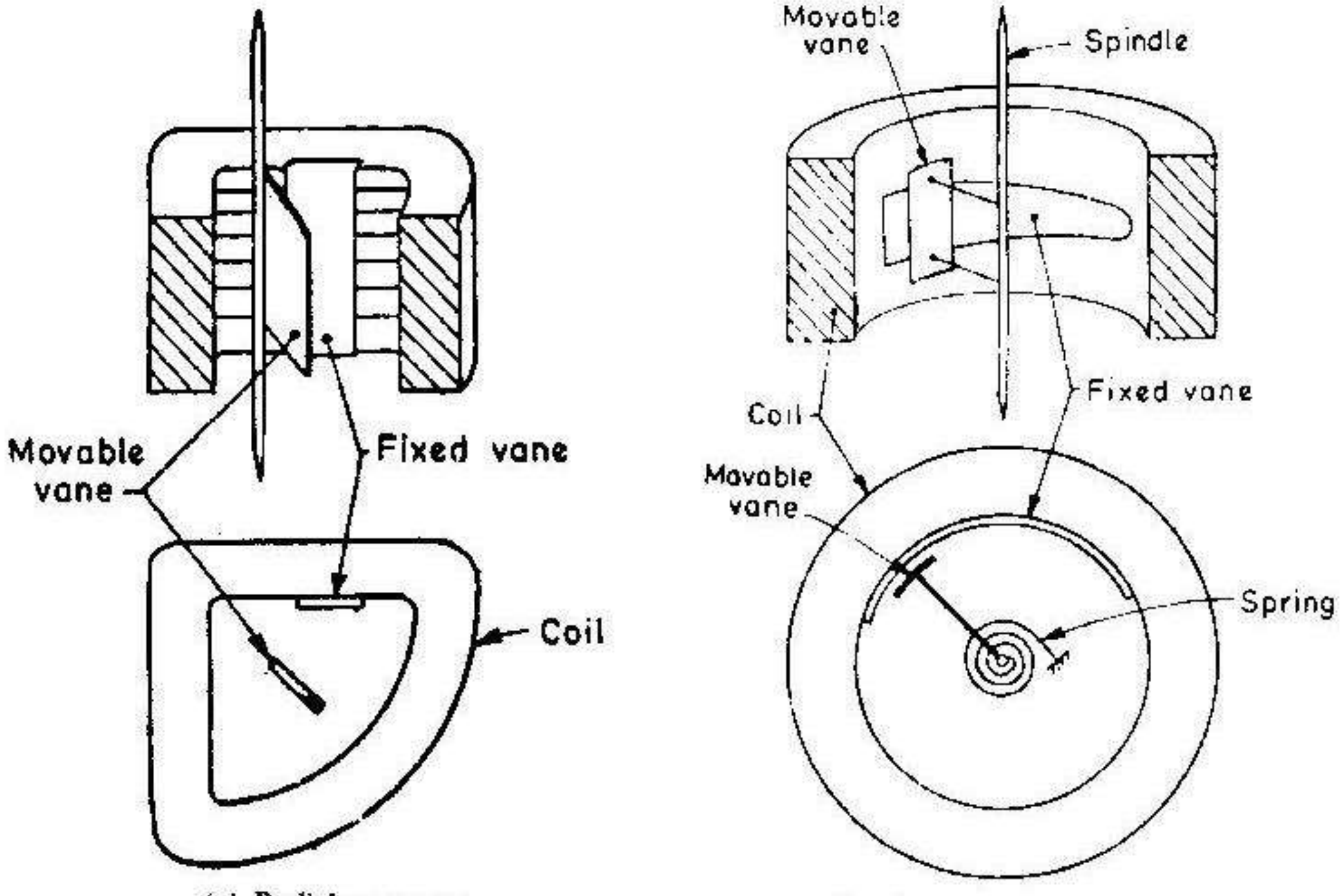

Fig. 42.8: Attraction type

**2. Repulsion Type Instruments** – The repulsion type instrument has two vanes or iron plates. One is fixed, and the other one is movable. The vanes become magnetised when the current passes through the stationary coil and the force of repulsion occur between them. Because of a repulsive force, the moving coil starts moving away from the fixed vane. The spring provides the controlling torque. The air friction induces the damping torque, which opposes the movement of the coil. The repulsion type instrument is a non-polarized instrument, i.e., free from the direction of current passes through it. Thus, it is used for both AC and DC.




Radial Vane Type MI Instruments

# Repulsion Type Moving Iron Instruments




(a) Radial vane type.

(b) Co-axial vane type.

**Fig. 9.25.** Replusion type moving iron instruments.

# Torque equation of MI instrument.

Consider a small increment in current supplied to the coil of the instrument. due to this current let $d\theta$ be the deflection under the deflecting torque $T_d$. Due to such deflection, some mechanical work will be done.

$\therefore$ Mechanical Work = $T_d \ d\theta$

There will be a change in the energy stored i the magnetic field due to the change in inductance. This is because the vane tries to occupy the position of minimum reluctance. The inductance is inversely proportional to the reluctance of the magnetic circuit of coil.

Let,

$I$ = initial current
$L$ = instrument inductance
$\theta$ = deflection
$dI$ = increase in current
$d\theta$ = change in deflection
$dL$ = change in inductance

In order to effect an increment dL in the current, there must be an increase in the applied voltage given by,

$$e = \frac{d(LI)}{dt}$$

$$= I\frac{dL}{dt} + L\frac{dI}{dt}$$ as both I and L are changing.

The electrical energy supplied is given by,

$$e I dt = \left(I\frac{dL}{dt} + L\frac{dI}{dt}\right) I dt$$

$$= I^2\, dL + IL\, dI$$

The stored energy increases from $\frac{1}{2}LI^2$ to $\frac{1}{2}(L+dL)(I+dI)^2$

Hence the change in stored energy is given by,

$$= \frac{1}{2}(L+dL)(I+dI)^2 - \frac{1}{2}LI^2$$

Neglecting higher order terms, this becomes, $IL\, dI + \frac{1}{2}I^2\, dL$

The energy supplied in nothing but increase in stored energy plus the energy required for mechanical work done.

$$\therefore \quad I^2 dL + IL\, dI = IL\, dI + \frac{1}{2}I^2\, dL + T_d \cdot d\theta$$

$$\therefore \quad T_d \cdot d\theta = \frac{1}{2}I^2\, dL$$

$$\therefore \quad \boxed{T_d = \frac{1}{2}I^2\frac{dL}{d\theta}}$$

While the controlling torque is given by,

$$T_c = K\,\theta$$

where $K$ = spring constant

$$\therefore \quad K\,\theta = \frac{1}{2} I^2 \frac{dL}{d\theta} \qquad \text{under equilibrium}$$

$$\therefore \quad \theta = \frac{1}{2}\frac{I^2}{K}\frac{dL}{d\theta}$$

Thus the deflection is proportional to the square of the current through the coil. And the instrument gives square law response.

## Advantages of the MI Instruments

- **Universal use** – The MI instrument is independent of the direction of current and hence used for both AC and DC.
- **Less Friction Error** – The friction error is very less in the moving iron instrument because their torque weight ratio is high. The torque weight ratio is high because their current carrying part is stationary and the moving parts are lighter in weight.
- **Cheapness** – The MI instruments require a smaller number of turns as compared to PMMC instrument. Thus, it is cheaper.
- **Robustness** – The instrument is robust because of their simple construction. And also, because their current carrying part is stationary.

## Disadvantages of Moving Iron Instruments.

- **Accuracy –** The scale of the moving iron instruments is not uniform, and hence the accurate result is not possible.
- **Errors –** Some serious error occurs in the instruments because of the hysteresis frequency and stray magnetic field.
- **Waveform Error –** In MI instrument the deflection torque is not directly proportional to the square of the current. Because of which the waveforms error occurs in the instrument.
- **Difference between AC and DC calibration –** The calibration of the AC and DC are differed because of the effect of the inductance of meter and the eddy current which is used on AC. The AC is calibrated on the frequency at which they use.

# Errors in moving Iron instrument

## Hysteresis Error

This error occurs as the value of flux density is different for the same current when ascending and descending. The value of flux density is higher for descending values of current and, therefore, the instrument tends to read higher for descending values of current (and voltage) than for ascending values.

This **error can be minimized** by making the iron parts small so that they demagnetize themselves quickly.

## Temperature Error

The effect of temperature changes on moving iron instruments arises chiefly from the temperature coefficient of spring. The error may be 0.02 percent per °C. In voltmeters, errors are caused due to self-heating of coil and series resistance.

The temperature of the coil may increase by 10 to 20°C for a power consumption of 1 W. Therefore, the resistance increases (by about 4 to 8%, causing a decrease in current for a given voltage. This produces a decreased deflection. Therefore, the series resistance should be made of a material like Manganin which has a small temperature co-efficient.

**3) Stray magnetic Field Error**: The operating magnetic field in case of moving iron instruments is very low. Hence effect of external i.e. stray magnetic field can cause error. This effect depends on the direction of the stray magnetic field with respect to the operating field of the instrument.

**4) Frequency Error**: These are related to an ac operation of the instrument. The change in frequency affects the reactance of the working coil and also affects the magnitude of the eddy currents. This cause error in the instrument.

**5) Eddy Current Error**: When instrument is used for ac measurements the eddy currents are produced in the iron parts of the instrument. The eddy current affects the instrument current causing the change in the deflection torque. This produces the error in the meter reading. As eddy current are frequency dependent, frequency changes cause eddy current errors.

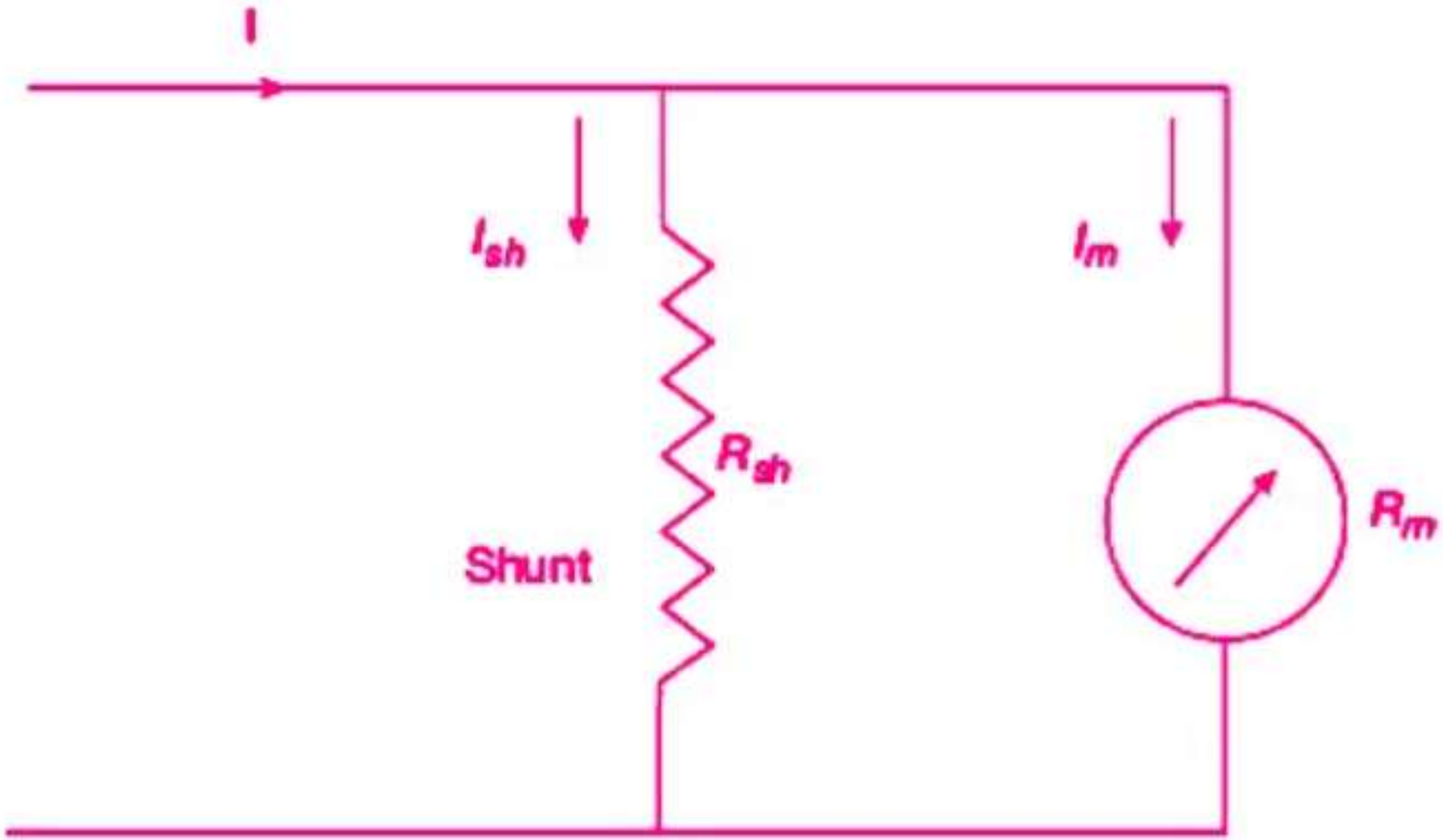
## Extension of Range Of PMMC Instruments

### Ammeter Shunts

When the PMMC instrument is used as an ammeter, its range can be extended with the help of a low-resistance shunt.

The moving-coil instrument has a coil wound with very fine wire. It can carry only a few mA safely to give full-scale deflection.

For measuring higher current, **low resistance is connected in parallel** to the instrument to bypass the major part of the current. The low resistance connected in parallel with the coil is called a **shunt**.




$R_{sh}$ = shunt resistance (Ω)
$R_m$ = coil resistance (Ω)
$I_m$ = Ifs = full-scale deflection current (A)
$I_{sh}$ = shunt current (A)
I = current to be measured (A)

The voltage drop across the shunt and the meter must be the same as they are connected in parallel.

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

$$I = I_{sh} + I_m$$

$$I_{sh} = I – I_m$$

From first equation,

$$R_{sh} = (I_m\ /\ I_{sh}\ )\ R_m$$

$$R_{sh} = (I_m\ /\ I – I_m\ )\ R_m$$

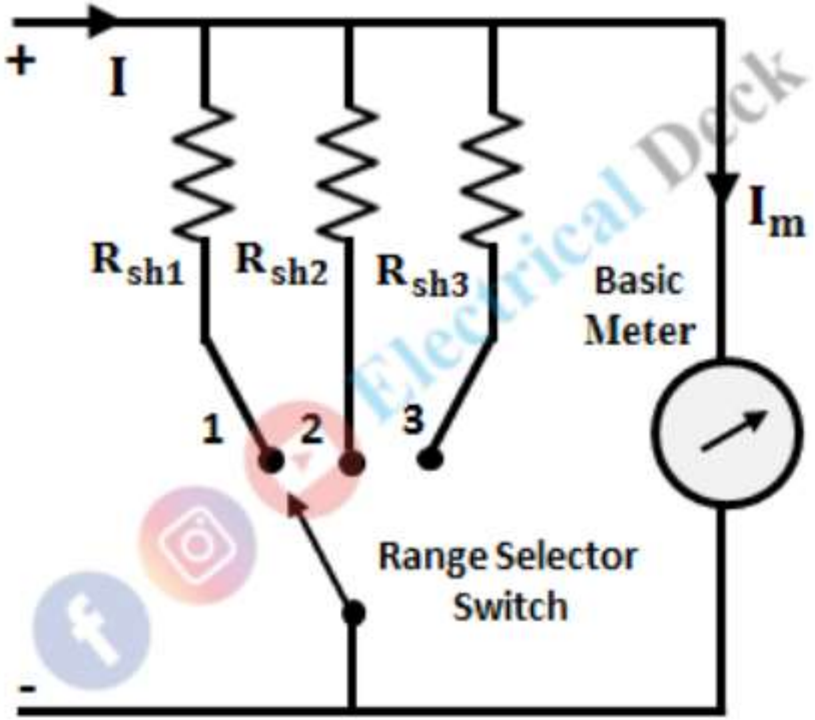
The ratio of the total current to the current in the meter is called the multiplying power of shunt. Multiplying power,

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

$$\mathbf{R_{sh} = R_m\ /(m\text{-}1)}$$

## Multirange Ammeters :

The range of an ammeter can be extended by using a shunt. Hence, by adding a number of shunts, it can be used as a multirange ammeter and such arrangement is shown below.




$$R_{sh1} = \frac{R_m}{m_1 - 1}, R_{sh2} = \frac{R_m}{m_2 - 1}$$

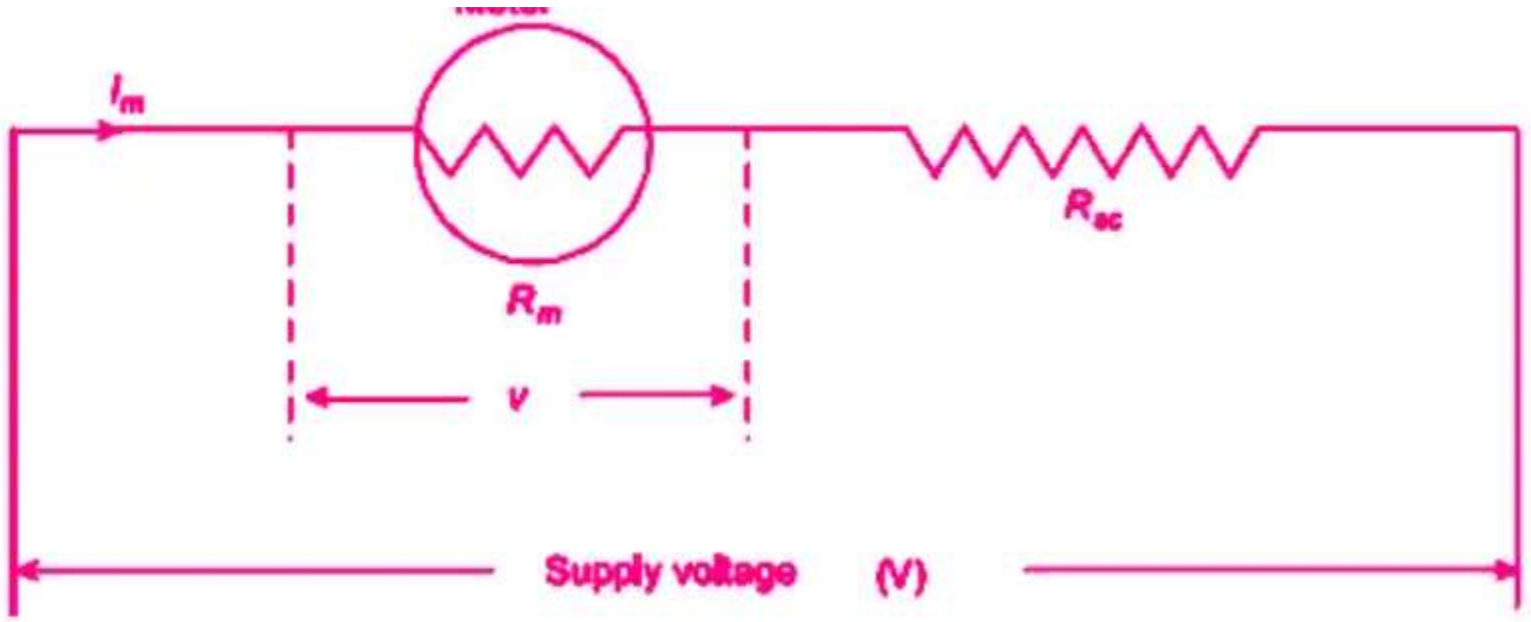
$$R_{sh3} = \frac{R_m}{m_3 - 1}$$

## Voltmeter Multipliers

The range of PMMC instrument, when used as a voltmeter, can be increased by using a high resistance in series with it.

For measuring higher voltages, a high resistance is connected in series with the instrument to limit the current in the coil to a safe value. This value of current should never exceed the current required to produce full-scale deflection.

The high resistance connected in series with the instrument is called a **multiplier**. In the figure, $R_{sc}$ is the multiplier.




The value of multiplier required to extend the voltage range is calculated as under:

$R_{sc}$ = *multiplier resistance (Ω)*

$R_m$ = *meter resistance (Ω)*

$I_m = I_{fs}$ = *full scale deflection current (A)*

$v$ = *voltage across the meter for producing current* $I_m$ *(V)*

$V$ = *voltage to be measured (V)*

$$v = I_m R_m$$

$$V = I_m (R_m + R_{sc})$$

Therefore,

$$R_{sc} = (V - I_m R_m)/I_m = V/I_m - R_m$$

Now multiplying factor for multiplier,

$$m = V/v = I_m (R_m + R_{sc}) / I_m R_m = 1 + R_{sc}/R_m$$

$$\text{Therefore, } R_{sc} = (m-1)R_m$$

# Electrostatic Voltmeters

In the last article, we have seen about electrostatic instruments. An electrostatic instrument is basically a voltmeter that works on the principle of static electric field.

They are used for voltage measurement (especially for high voltages) but can also be used for measuring current and power with the additional arrangement.

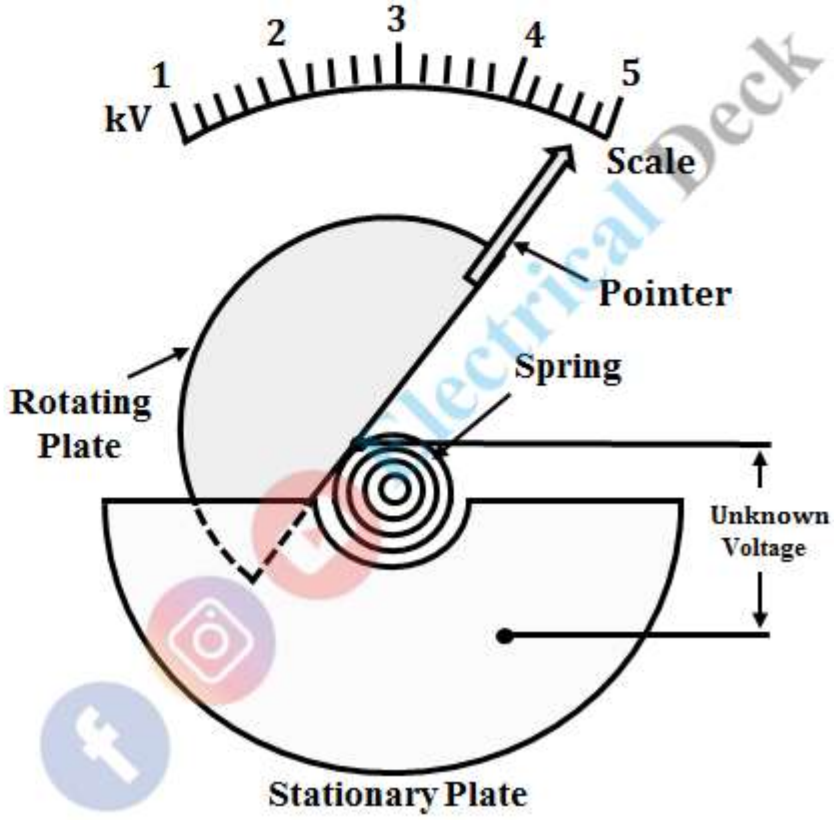
The electrostatic voltmeters are of two types,

- Quadrant type electrostatic voltmeter (used up to 20kV)
- Attracted disc type electrostatic voltmeter (used up to 500kV)

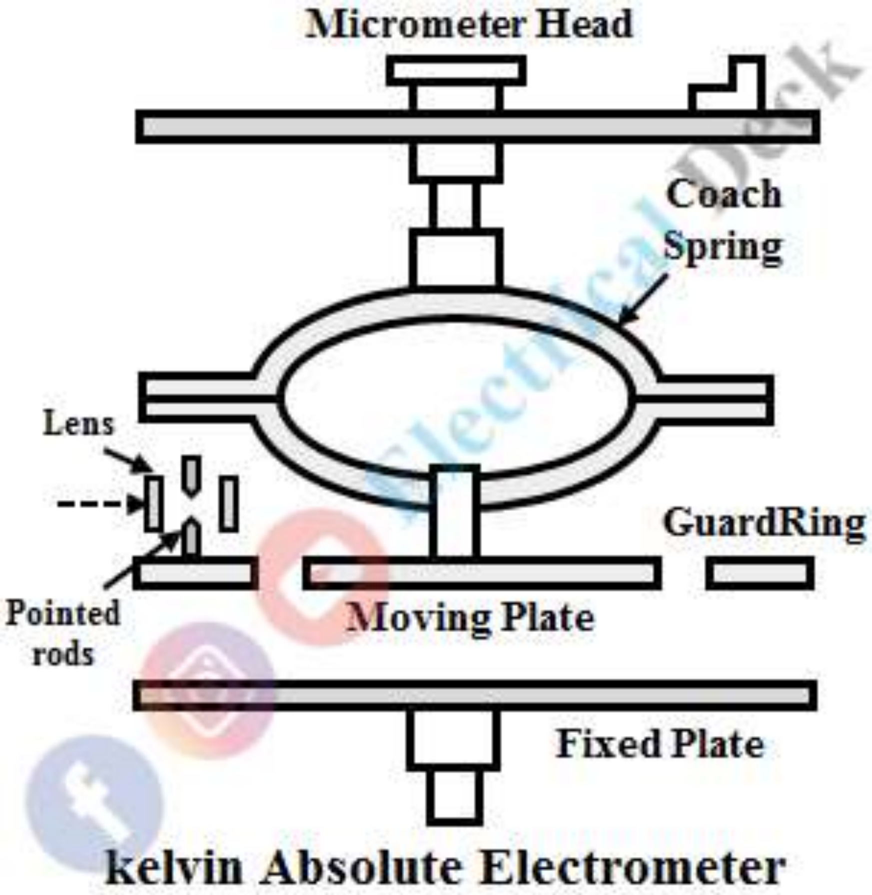
## Attracted Disc Type Electrostatic Voltmeter

An attracted disc type electrostatic instrument is basically known as a portable electrostatic instrument. This device contains two semicircular plates one being stationary and the other rotating. Both the plates are electrically insulated from each other.

The unknown voltage to be measured is applied across the plates, which results in the development of an electrostatic field between the plates. The electrostatic field developed is attractive in nature. The below shows the portable electrostatic instrument.



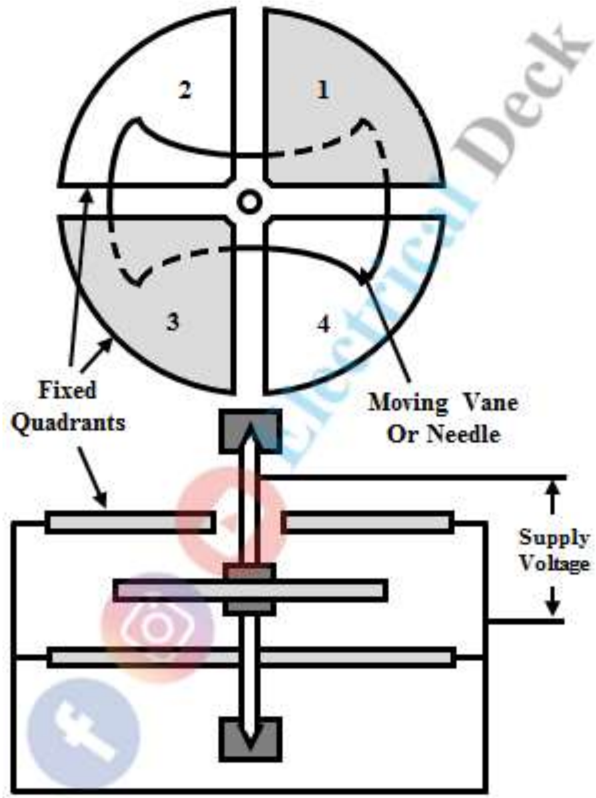
Kelvin's absolute electrometer is an attracted disc type electrostatic voltmeter.



- A voltage that is to be measured is applied between the two plates.
- When a potential difference is applied between the plates then the moving plate will be attracted towards the fixed plate.
- But by rotating the micrometer head the moveable plate can be brought back to its original location.
- A micrometer which is calibrated in terms of force is used to measure the displacement of the moving plate.

## Quadrant Type Electrostatic Voltmeter :

The quadrant electrometer consists of four metallic quadrants and a double sector shaped moving vane or needle as shown in the below figure.

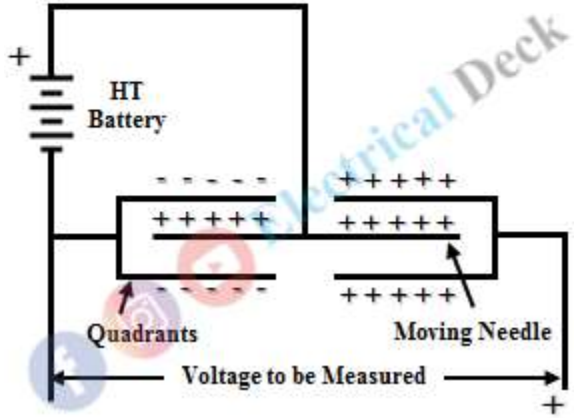


There are two types of connections in a quadrant electrometer. They are,

- Heterostatic connection, and
- Idiostatic connection.

Heterostatic Connection :

In this type of connection voltage to be measured is applied across the fixed quadrants. A high tension (HT) battery is used to charge the moving needle more positively than the fixed quadrants (i.e., voltage to be measured). The heterostatic connection is shown below.



In this type of connection, there is no additional external voltage. The moving needle is connected to any pair of quadrants directly as shown below.