IRE 215: Sensor Technology

Voltage and Current Measurement

Introduction

Ammeters and voltmeters

1. Moving-iron type (both for D.C./A.C.)
   (a) the attraction type
   (b) the repulsion type
2. Moving-coil type
   (a) permanent-magnet type (for D.C. only)
   (b) electrodynamic or dynamometer type (*for D.C./A.C.*)
3. Hot-wire type (both for D.C./A.C.)
4. Induction type (for A.C. only)
   (a) Split-phase type
   (b) Shaded-pole type
5. Electrostatic type-for voltmeters only (for D.C./A.C.)

Introduction

Wattmeter

6. ***Dynamomometer type*** (both for D.C./A.C.),
7. ***Induction type*** (for A.C. only)
8. *Electrostatic type* (for D.C. only)

Energy Meters

9. ***Electrolytic type*** (for D.C. only)
10. **Motor Meters**
    - *(i)* ***Mercury Motor Meter.*** For d.c. work only. Can be used as amp-hour or watt-hour meter.
    - *(ii)* ***Commutator Motor Meter.*** Used on D.C./A.C. Can be used as Ah or Wh meter.

(iii) ***Induction type.*** For A.C. only.

11. Clock meters (as Wh-meters).

Introduction

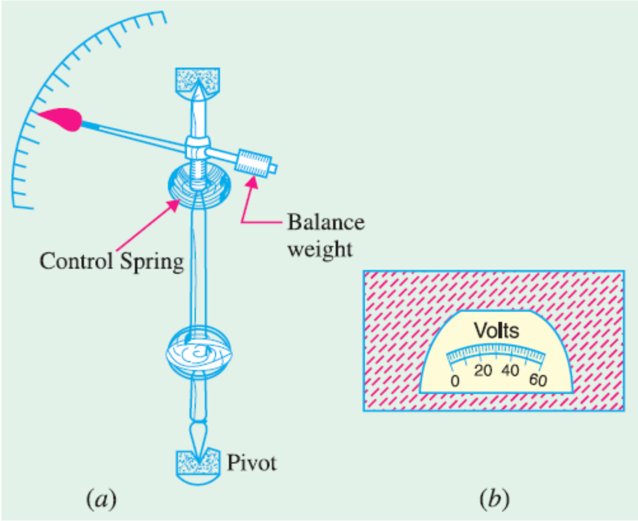
The moving system is subjected to the following three torques :

1. A deflecting (or operating) torque
2. A controlling (or restoring) torque
3. A damping torque.

The damping force can be produced by *(i) air frictions (ii) eddy currents* and *(iii) fluid friction* (used occasionally).

A damping force is a force that opposes the motion of an object and reduces its energy, typically in oscillatory systems.

(a) Spring Control



Deflection Torque:

$$T_d \propto I$$

for spring control $T_c \propto \theta$

As $T_c = T_d$

$$\therefore \quad \theta \propto I$$

Eddy Current

Eddy currents are loops of electric current induced within conductors when they are exposed to a changing magnetic field. According to Faraday's Law of Electromagnetic Induction, a time-varying magnetic field creates an electromotive force (EMF), which drives the eddy currents in the conductor.

Damping Force via Eddy Currents

When a conductor moves through a magnetic field or when the magnetic field near a stationary conductor changes, eddy currents are generated. These currents create their own magnetic field, which opposes the change in motion or magnetic flux (as per **Lenz's Law**). This opposition leads to a damping force, which resists the motion of the conductor.

Steps in Damping Force Creation:

1. **Relative Motion/Field Change**: A conductor experiences relative motion with respect to a magnetic field (e.g., falling through a magnetic region) or a time-varying magnetic field is applied to it.
2. **Induction of Eddy Currents**: The changing magnetic flux induces circulating currents in the conductor.
3. **Opposing Magnetic Field**: The eddy currents create their own magnetic field, which opposes the original magnetic field's change.
4. **Damping Effect**: The interaction between these opposing forces creates a resistive force, dissipating the kinetic energy of motion as heat.

Introduction

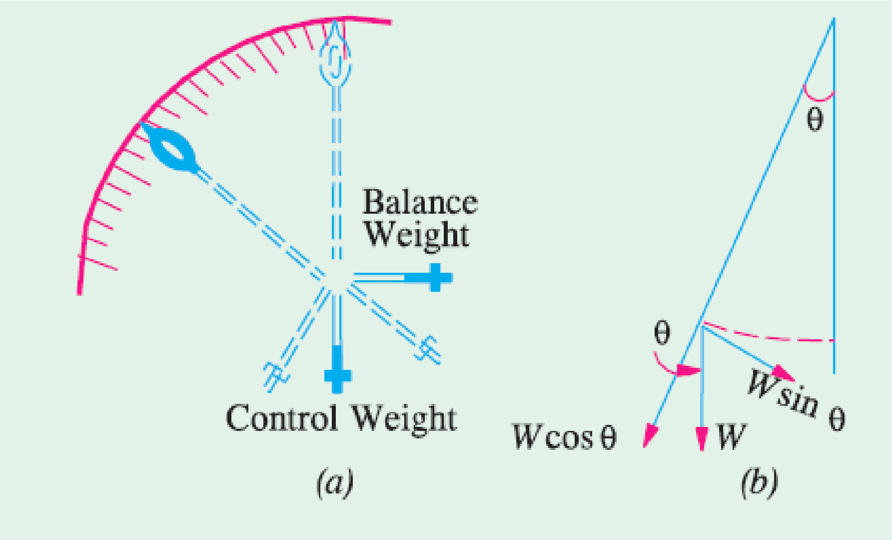
(*b*) Gravity Control

$$T_c \propto \sin\theta$$

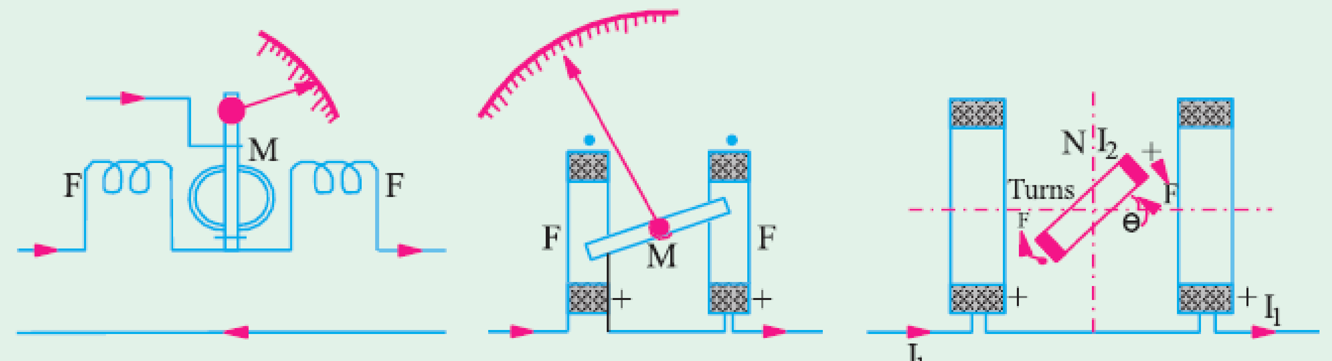
$$T_d \propto I$$

$$T_d = T_c$$

or $$I \propto \sin\theta \ (not\ \theta)$$



Electrodynamometer Type Instruments



(a)

(b)

An electrodynamic instrument is a moving-coil instrument in which the operating field is produced, not by a permanent magnet but by another fixed coil. This instrument can be used either as an ammeter or a voltmeter but is generally used as a wattmeter.

Deflecting Torque in terms of Change in Self-induction

Suppose that when a direct current of I passes through the instrument, its deflection is θ and inductance L. Further suppose that when current changes from I to $(I + dI)$, deflection changes from θ to $(\theta + d\theta)$ and L changes to $(L + dL)$. Then, the increase in the energy stored in the magnetic field is

$$dE = d\left(\frac{1}{2}LI^2\right) = \frac{1}{2}L2I.dI + \frac{1}{2}I^2dL = LI.\,dI + \frac{1}{2}I^2.\,dL \text{ joule.}$$

If $T\frac{1}{2}$N-m is the controlling torque for deflection θ, then extra energy stored in the control system is $T \times d\theta$ joules. Hence, the total increase in the stored energy of the system is

$$LI.dI + \frac{1}{2}I^2.\,dL + T \times d\,\theta \qquad \ldots(i)$$

The e.m.f. induced in the coil of the instrument is $e = N.\dfrac{d\Phi}{dt}$ volt

$$L = NF/I \quad \therefore \quad \Phi = LI/N \quad \therefore \quad \frac{d\Phi}{dt} = \frac{1}{N}.\frac{d}{dt}(LI)$$

Deflecting Torque in terms of Change in Self-induction

Induced e.m.f. $e = N.\frac{1}{N}.\frac{d}{dt}(LI) = \frac{d}{dt}(LI)$

The energy drawn from the supply to overcome this back e.m.f is

$$= e.Idt = \frac{d}{dt}(LI).Idt \;=\; I.d(LI) = I(L.dI + I.dL) = LI.dI \;+ I^2.dL \qquad \ldots(ii)$$

Equating (*i*) and (*ii*) above, we get $LI.dI + \frac{1}{2}I^2dL + T.d\theta = LI.dI + I^2.dL \quad \therefore \; T = \frac{1}{2}I^2\frac{dL}{d\theta}$ N-m

the value of torque of a moving-coil instrument is

$$T_d \;=\; \frac{1}{2}I^2\; dL/d\theta\; N - m$$

The equivalent inductance of the fixed and moving coils of the electrodynamic instrument is

$$L \;=\; L_1 + L_2 + 2M$$

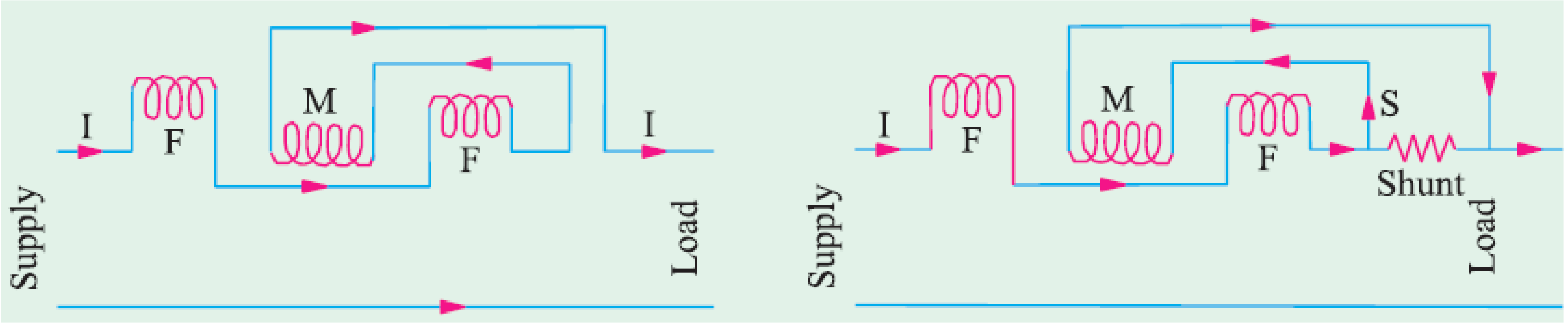
where M is the mutual inductance between the two coils and L_1 and L_2 are their individual self-inductances.

Deflecting Torque in terms of Change in Self-induction

Since L_1 and L_2 are fixed and only M varies,

$$\therefore \qquad dL/d\theta = 2dM/d\theta \qquad \therefore \quad T_d \frac{1}{2} I^2 \times 2.dM/d\theta = I^2.dM/d\theta$$

Electrodynamometer Type Instruments

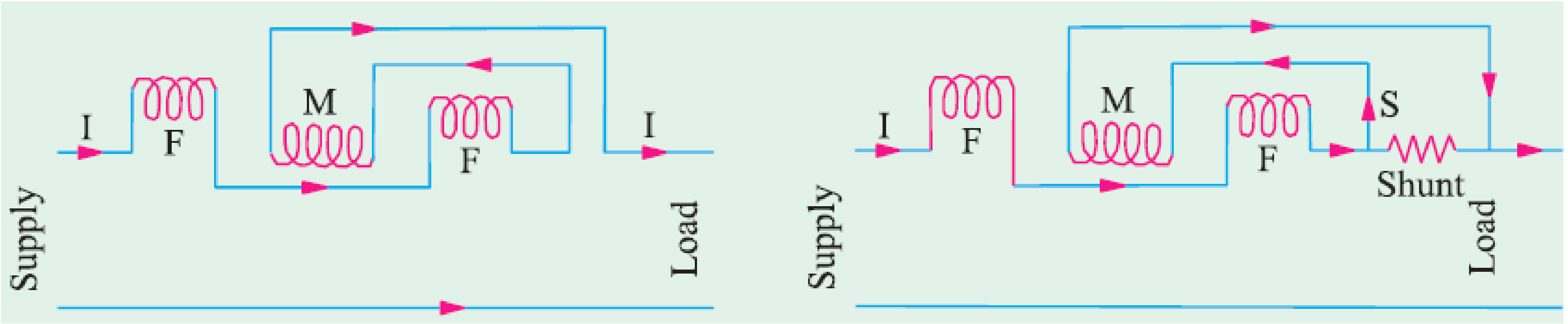


Electrodynamometer Type Ammeter

The production of the deflecting torque can be understood from Fig. 10.24. Let the current passing through the fixed coil be I_1 and that through the moving coil be I_2. Since there is no iron, the field strength and hence the flux density is proportional to I_1.

$\therefore \quad B = KI_1 \quad$ where K is a constant

Electrodynamometer Type Instruments



Electrodynamometer Type Ammeter

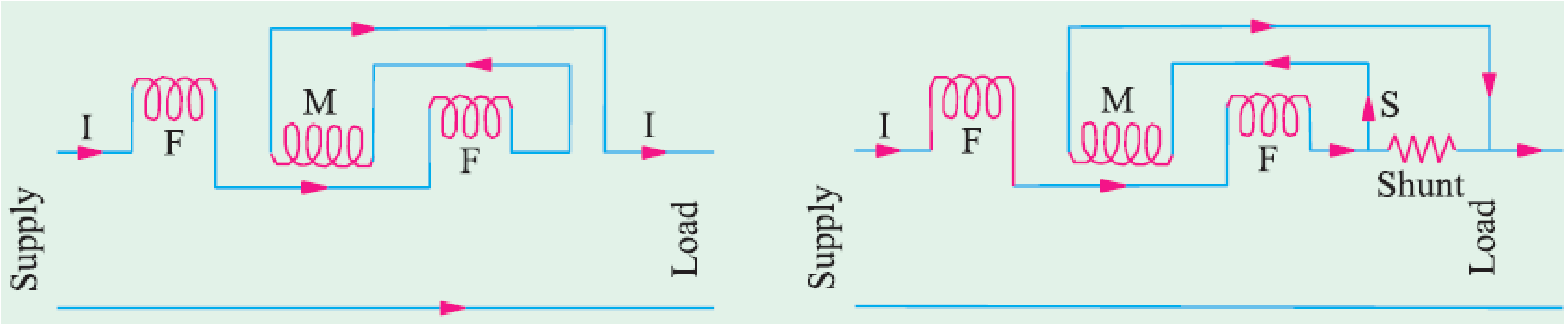
Let us assume for simplicity that the moving coil is rectangular (it can be circular also) and of dimensions $l \times b$. Then, force on each side of the coil having N turns is $(NBI_2 l)$ newton.

The turning moment or deflecting torque on the coil is given by

$$T_d = NBI_2 lb = NKI_1 I_2 lb \text{ N-m}$$

Now, putting $NKlb = K_1$, we have $T_d = K_1 I_1 I_2$ where K_1 is another constant.

Electrodynamometer Type Instruments

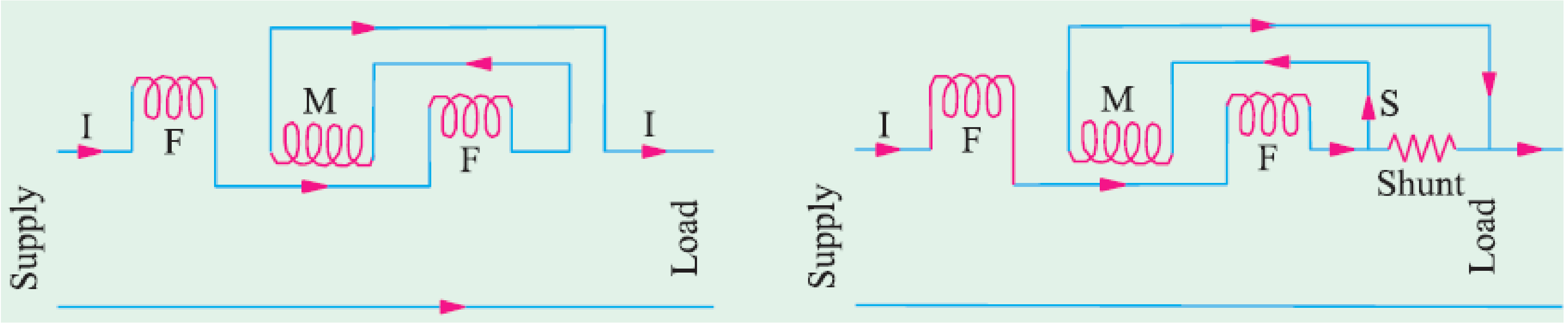


Electrodynamometer Type Ammeter

It shows that the deflecting torque is proportional to the product of the currents flowing in the fixed coils and the moving coil. Since the instrument tis spring-controlled, the restoring or control torque is proportional to the angular deflection θ.

i.e. $T_c \propto = K_2\,\theta \quad \therefore \quad K_1 I_1 I_2 = K_2\theta \;\text{ or }\; \theta \propto I_1 I_2$

Electrodynamometer Type Instruments

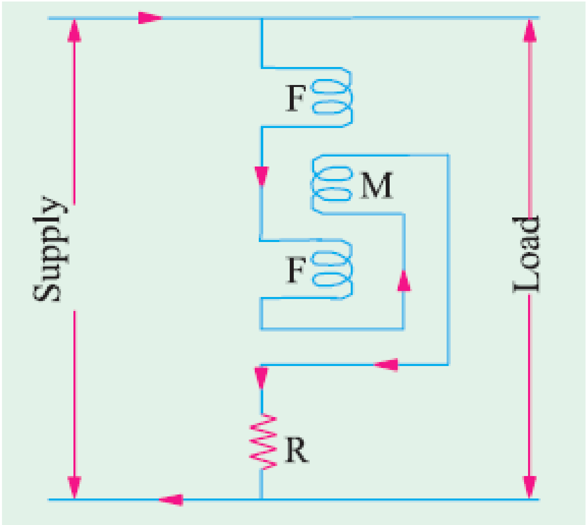


Electrodynamometer Type Ammeter

When the instrument is used as an ammeter, the same current passes through both the fixed and the moving coils as shown in Fig. 10.25.

In that case $I_1 = I_2 = I$, hence $\theta \propto I^2$ or $I \propto \sqrt{\theta}$.

Electrodynamometer Type Instruments

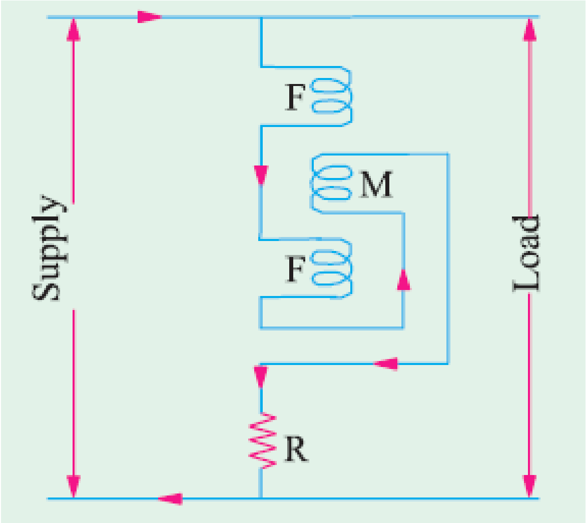


Electrodynamometer Type Voltmeter

When used as a voltmeter, the fixed and moving coils are joined in series along with a high resistance and connected as shown in Fig. 10.27. Here, again $I_1 = I_2 = I$, where $I = \frac{V}{R}$ in d.c. circuits an $I = V/Z$ in a.c. circuits.

$$\therefore \quad \theta \propto V \times V \quad \text{or} \quad \theta \propto V^2 \quad \text{or} \quad V \propto \sqrt{\theta}$$

Electrodynamometer Type Instruments



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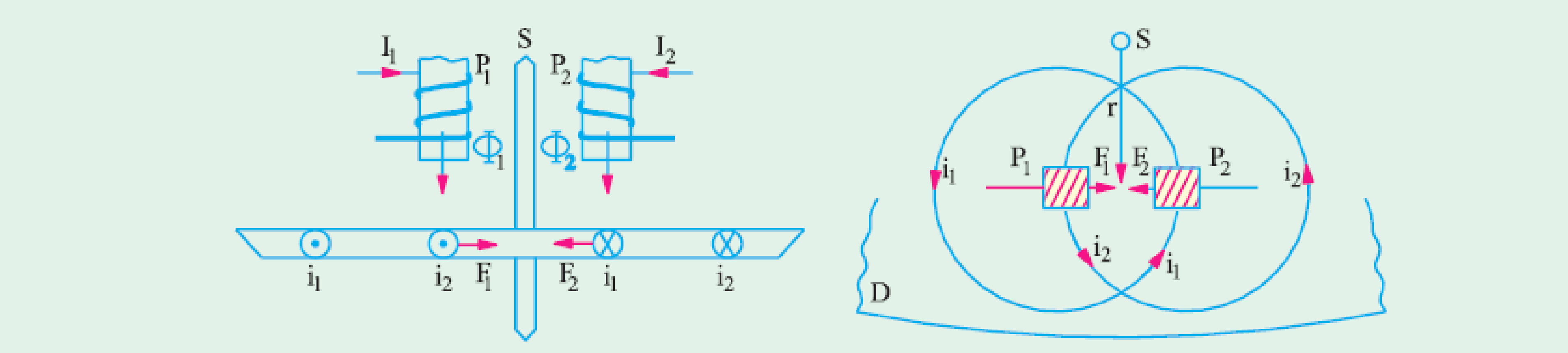
Induction Type Instruments



(a) (b)

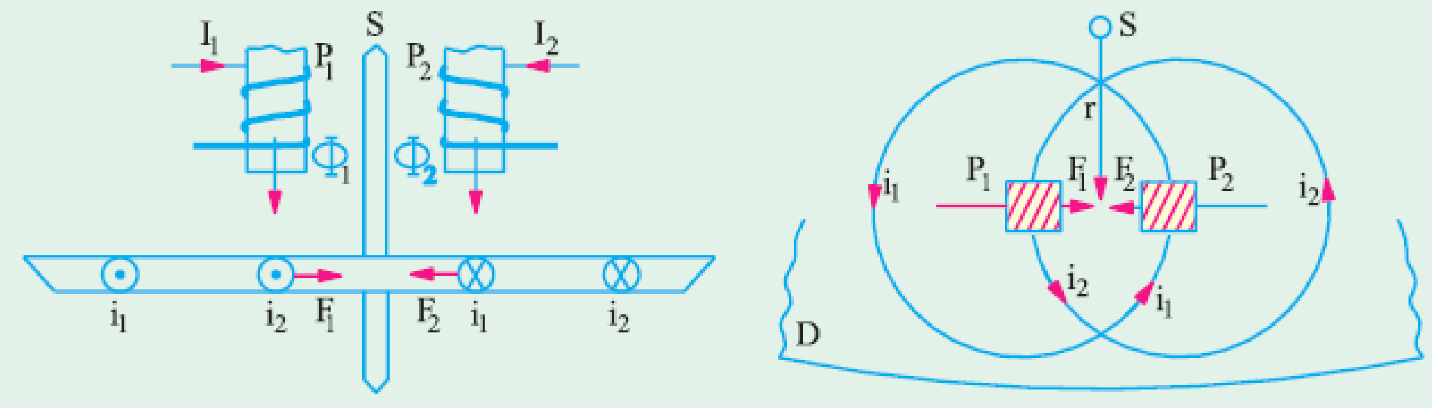
Induction type instruments are used only for a.c. measurements

The portion of the disc which is traversed by flux Φ_1 and carries eddy current i_2 experiences a force F_1 along the direction as indicated. As $F = Bil$, force $F_1 \propto \Phi_1 i_2$. Similarly, the portion of the disc lying in flux Φ_2 and carrying eddy current i_1 experiences a force $F_2 \propto \Phi_2 i_1$.

$\therefore \quad F_1 \propto \Phi_1 i_2 = K \Phi_1 i_2$ and $F_2 \propto \Phi_2 i_1 = K \Phi_2 i_1$.

It is assumed that the constant K is the same in both cases due to the symmetrically positions of P_1 and P_2 with respect to the disc.

Induction Type Instruments



(a) (b)

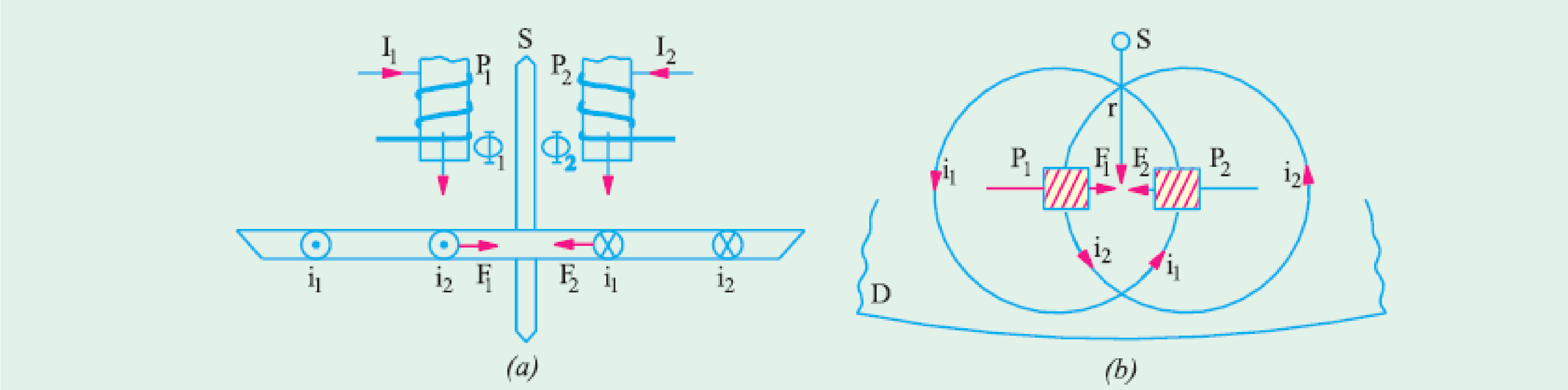
If r is the effective radius at which these forces act, the net instantaneous torque T acting on the disc begin equal to the difference of the two torques, is given by

$$T = r\,(K\,\Phi_1 i_2 - K\,\Phi_2 i_1) = K_1\,(\Phi_1 i_2 - \Phi_2 i_1) \qquad ...(i)$$

Let the alternating flux Φ_1 be given by $\Phi_1 = \Phi_{1m} \sin \omega t$. The flux Φ_2 which is assumed to lag Φ_1 by an angle α radian is given by $\Phi_2 = \Phi_{2m} \sin (\omega t - \alpha)$

Induced e.m.f.
$$e_1 = \frac{d\,\Phi_1}{dt} = \frac{d}{dt}(\Phi_{1m} \sin \omega t) = \omega\,\Phi_{1m} \cos \omega t$$

Induction Type Instruments



$$i_1 = \frac{e_1}{R}$$

Substituting these values of i_1 and i_2

$$T = \frac{K_1\,\omega}{R}[\Phi_{1m}\sin\omega t.\,\Phi_{2m}\cos(\omega t-\alpha)-\Phi_{2m}\sin(\omega t-\alpha)\,\Phi_{1m}\cos\omega t]$$

$$= \frac{K_1\,\omega}{R}.\Phi_{1m}\,\Phi_{2m}[\sin\omega t.\cos(\omega t-\alpha)-\cos\omega t.\sin(\omega t-\alpha)]$$

$$= \frac{K_1\,\omega}{R}.\Phi_{1m}\,\Phi_{2m}\sin\alpha = k_2\,\omega\,\Phi_{1m}\,\Phi_{2m}\sin\alpha\ (\text{putting } K_1/R = K_2)$$

Induction Type Instruments

It is obvious that

(i) if $\alpha = 0$ *i.e.* if two fluxes are in phase, then *net* torque is zero. If on the other hand, $\alpha = 90°$, the net torque is maximum for given values of Φ_{1m} and Φ_{2m}.

(ii) the net torque is in such a direction as to rotate the disc from the pole with leading flux towards the pole with lagging flux.

(iii) since the expression for torque does not involve '*t*', it is independent of time *i.e.* it has a steady value at all time.

(iv) the torque *T* is inversely proportional to *R*-the resistance of the eddy current path. Hence, for large torques, the disc material should have low resistivity. Usually, it is made of Cu or, more often, of aluminium.

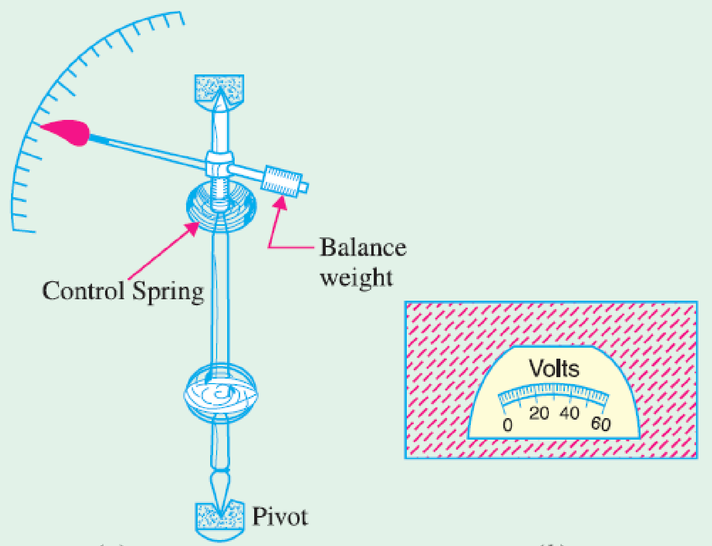
Example 10.1 *The torque of an ammeter varies as the square of the current through it. If a current of 5 A produces a deflection of 90°, what deflection will occur for a current of 3 A when the instrument is (i) spring-controlled and (ii) gravity-controlled.*

(Elect. Meas. Inst and Meas. Jadavpur Univ.)

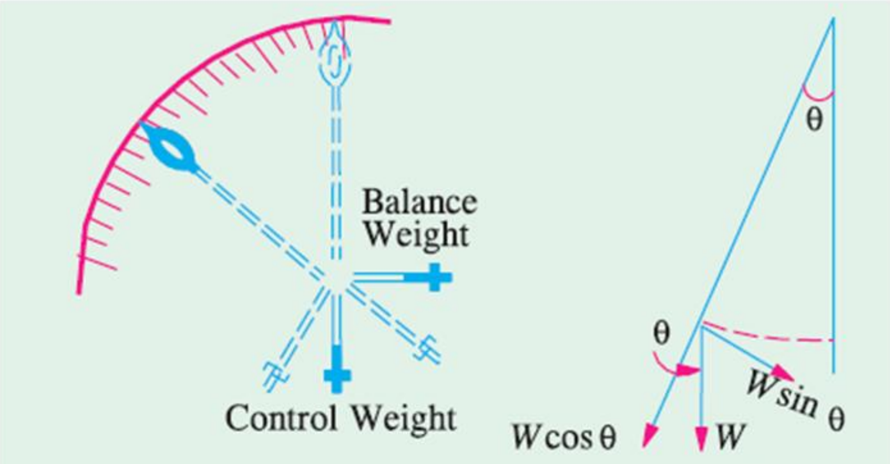
Hints:

For spring control, $\theta \propto I^2$

For gravity control, $\sin\theta \propto I^2$



(a) (b)



(a) (b)

Example 10.1 *The torque of an ammeter varies as the square of the current through it. If a current of 5 A produces a deflection of 90°, what deflection will occur for a current of 3 A when the instrument is (i) spring-controlled and (ii) gravity-controlled.*

(Elect. Meas. Inst and Meas. Jadavpur Univ.)

Solution:

(*i*) **For spring control** $90° \propto 5^2$ and $\theta \propto 3^2$; $\theta = 90° \times 3^2/5^2 =$ **32.4°**

(*ii*) **For gravity control** $\sin 90° \propto 5^2$ and $\sin\theta \propto 3^2$

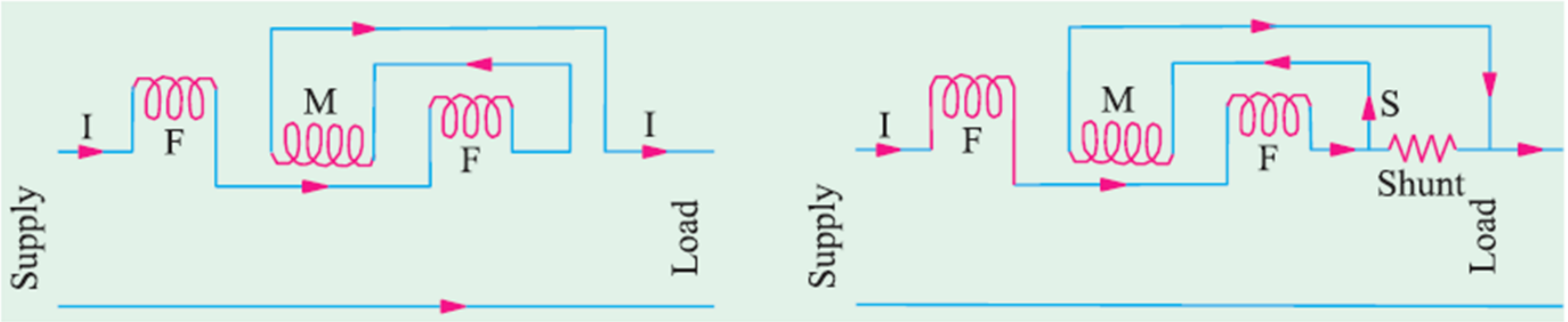
$\sin\theta = 9/25 = 0.36$; $\theta = \sin^{-1}(0.36) =$ **21.1°.**

Example 10.17. *The mutual inductance of a 25-A electrodynamic ammeter changes uniformly at a rate of 0.0035 μH/degree. The torsion constant of the controlling spring is 10^{-6} N-m per degree. Determine the angular deflection for full-scale.*

(Elect. Measurements, Poona Univ.)

Hints:

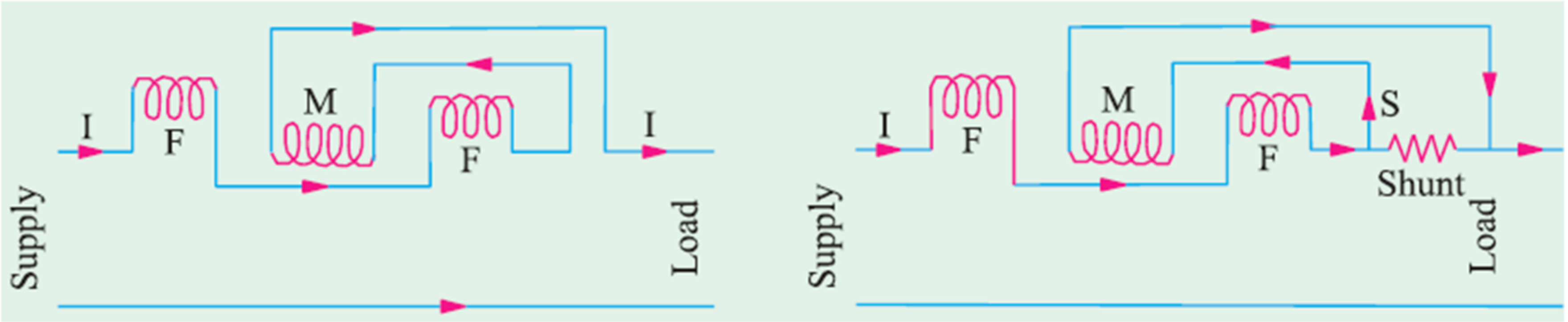
deflecting torque $T_d = I^2 dM/d\theta$



Solution: $I = 25$ A

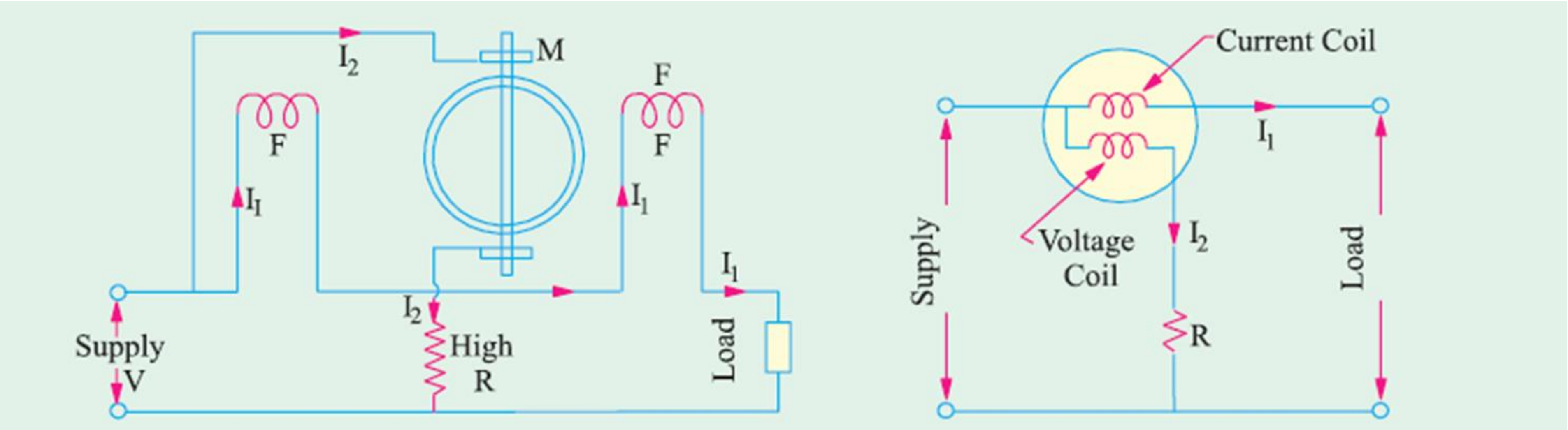
$$dM/d\theta = 0.0035 \times 10^{-6} \text{ H/degree} = 0.0035 \times 10^{-6} \times 180/\pi \text{ H/radian}$$

$$10^{-6} \times \theta = 25^2 \times 0.0035 \times 10^{-6} \times 180/\pi \quad \therefore \ \theta = 125.4°$$



Example 10.18. *The spring constant of a 10-A dynamometer wattmeter is 10.5×10^{-6} N-m per radian. The variation of inductance with angular position of moving system is practically linear over the operating range, the rate of change being 0.078 mH per radian. If the full-scale deflection of the instrument is 83 degrees, calculate the current required in the voltage coil at full scale on d.c. circuit.* **(Elect. Inst. and Means. Nagpur Univ. 1991)**

Hints: $T_d = I_1 I_2 \, dM/d\theta$ N-m

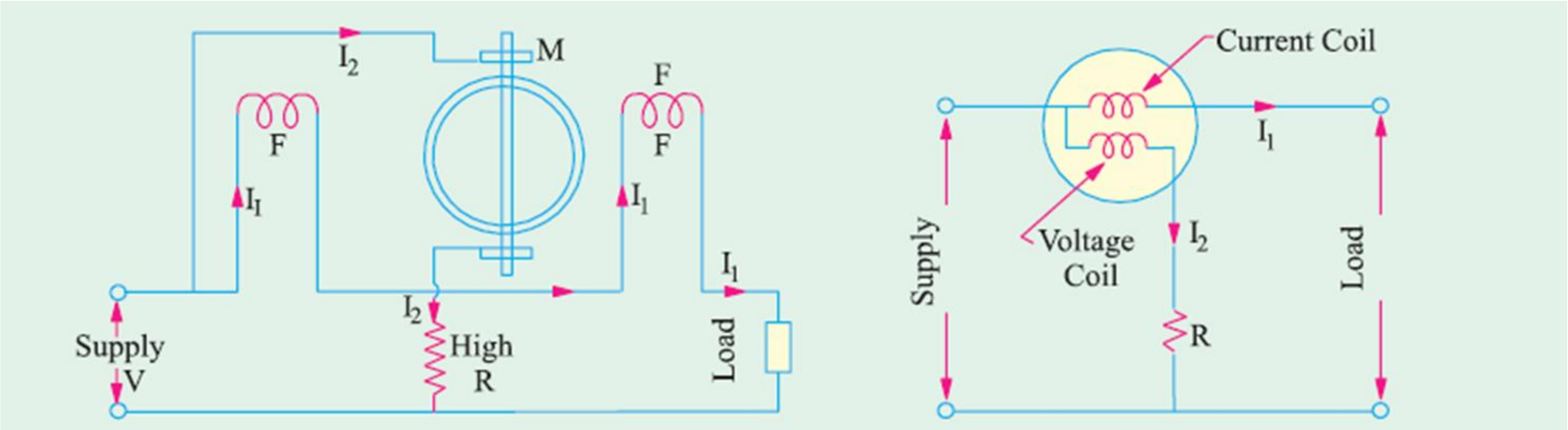


Solution:

Spring constant = 10.5×10^{-6} N/m/rad = $10.5 \times 10^{-6} \times \pi/180$ N-m/degree

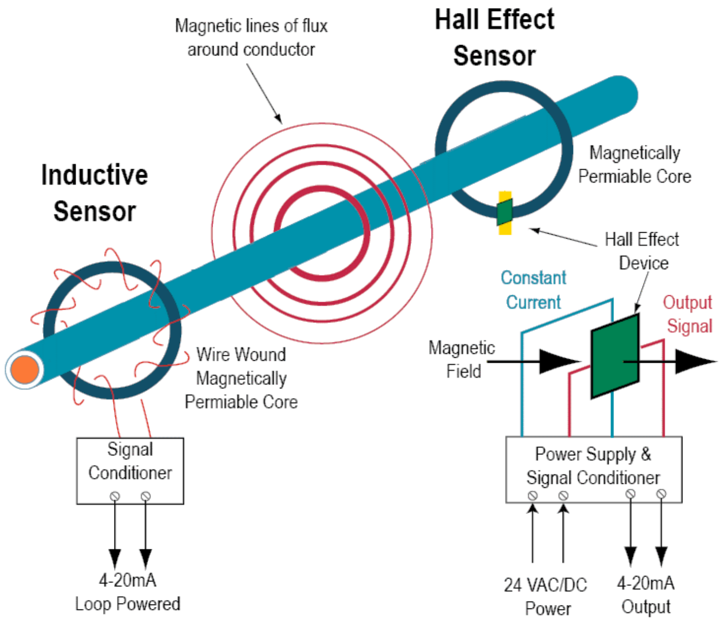
T_d = spring constant × deflection = $(10.5 \times 10^{-6} \times \pi/180) \times 83 = 15.2 \times 10^{-6}$ N-m

$\therefore \quad 15.2 \times 10^{-6} = 10 \times I_2 \times 0.078$; I_2 = **19.5 μA.**



Current Sensor

- For a given current flow, a proportional magnetic field is produced around the current carrying conductor.
- Current can be measured by measuring the magnetic field.
- Hall effect is used to measure DC current.
- Inductive technology is used to measure AC current.



Hall Effect Current Sensor

- The Hall effect sensor consists of three basic components: the core, the Hall effect device, and signal conditioning circuitry.
- The current conductor passes through a magnetically permeable core that concentrates the conductor's magnetic field.
- The Hall effect device is carefully mounted in a small slit in the core, at a right angle to the concentrated magnetic field.
- A constant current in one plane excites it. When the energized Hall device is exposed to a magnetic field from the core, it produces a potential difference (voltage) that can be measured and amplified into process level signals such as 4-20mA or a contact closure.

Inductive Current Sensor

- The inductive sensor consists of a wire-wound core and a signal conditioner. The current conductor passes through a magnetically permeable core that magnifies the conductor's magnetic field.
- AC current constantly changes potential from positive to negative and back again, generally at the rate of 50 Hz or 60 Hz. The expanding and collapsing magnetic field induces current in the windings.
- The current-carrying conductor is generally referred to as the primary and the core winding is called the secondary.
- The secondary current is converted to a voltage and conditioned to output process-level signals such as 4-20mA or contact closures.