# Lecture No. 4

Electrical Measurement and Instrumentation

# Suspension Galvanometer

- Early measurements of direct current  required a suspension galvanometer
- The Instrument …forerunner of the moving-coil instrument
  - dc indicating movements currently used
- Works on the principle of Electromagnetic Force
- Constitutes of
  - A Permanent magnet
  - A moving coil
  - Calibrated Scale
  - Pivoted Mirror
  - Beam light source
  - Assembly to hold the parts together

# Torque and Deflection in Galvanometer

- **Steady-State Deflection**
  - Permanent magnet moving-coil mechanism
  - The equation for the developed torque, derived from the basic law for electromagnetic torque, is

$$T = B \times A \times I \times N$$

where

- T = torque [newton-meter (N-m)]
- B = flux density in the air gap [webers/square meter (tesla)]
- A = effective coil area [square meters]
- I = current in the movable coil
- N = turns of wire on the coil

# Torque And Deflection Of The Galvanometer

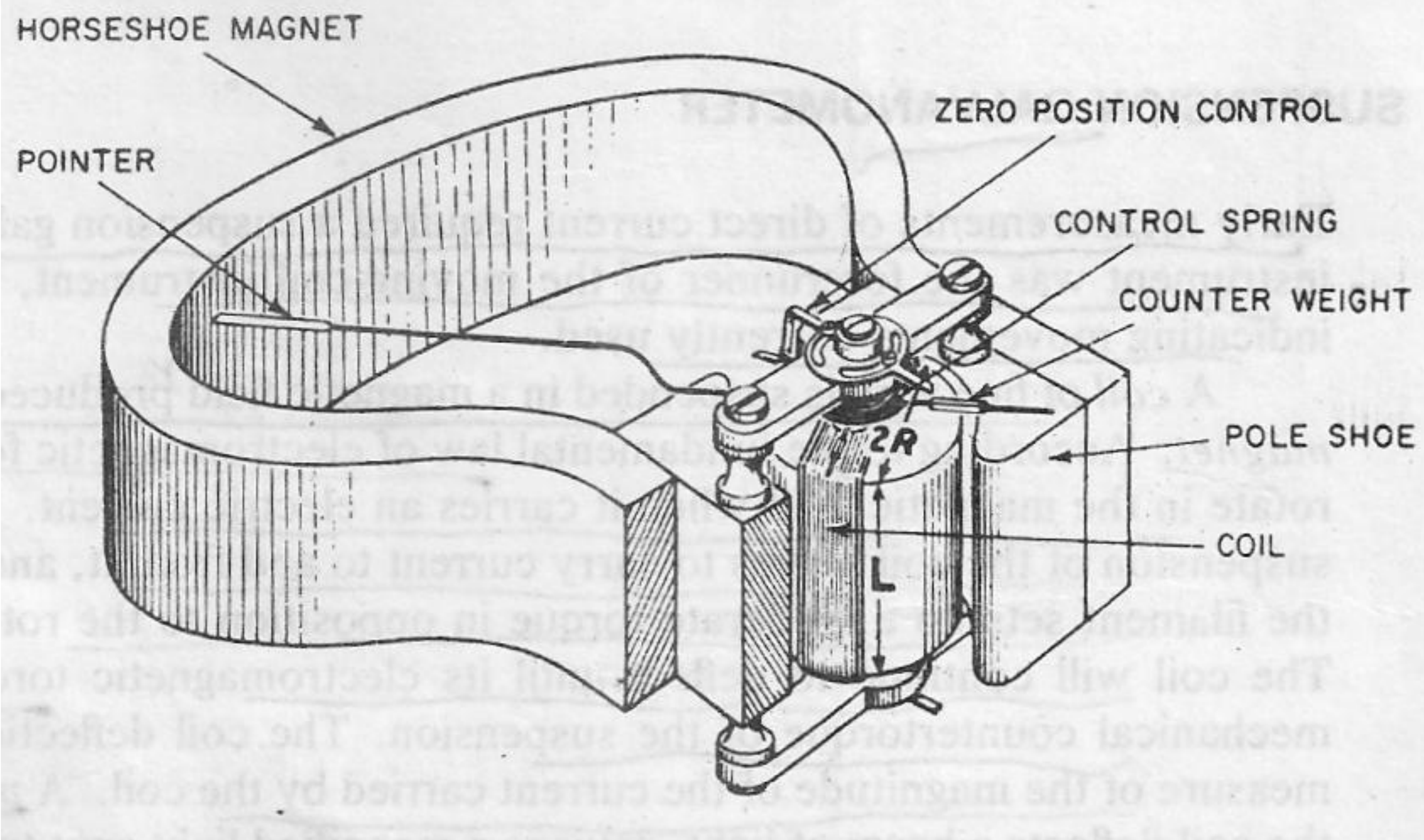


**Figure 4-1** Construction details of the external magnet PMMC movement. (Courtesy of Weston Instruments, Inc.)

# Torque and Deflection in Galvanometer….

- Flexibility
  - Fixed no. of turns
  - The practical coil area generally ranges from approximately 0.5 to 2.5 $cm^2$.
  - Flux densities for modern instruments usually range from 1,500 to 5,000 gauss (0 15 to 05 tesla).
  - Provided flexibility to the designer to meet many different measurement applications.

# Torque and Deflection in Galvanometer….

- Dynamic Behavior
  - The dynamic behavior of the galvanometer (such as speed of response, damping, overshoot) can effect its performance
  - The motion of a moving coil in a magnetic field is characterized by three quantities:
    - The moment of inertia (J) of the moving coil about its axis of rotation
    - The opposing torque (S) developed by the coil suspension
    - The damping constant (D)

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# Torque and Deflection in Galvanometer….

- Damping Mechanisms
- Galvanometer is provided with two types of Damping mechanisms:
  1. Mechanical Damping
     - Motion of the coil
     - Suspension springs
  2. Electro-magnetic Damping
     - Induced effect of the coil rotating inside magnetic field (eddy current).
- We Can also nullify the effect of damping through
  - Use of Aluminum Vane
  - Movable coil wound on aluminum frame
  - Critical Damping Resistance External (CDRX)----ckt resistance

# Damping Conditions

- **Overdamped**
    - The case in which the coil returns slowly to its test position, without overshoot or oscillations.
    - The pointer seems to approach the steady-state position in a sluggish manner.
    - This case is of minor interest
- **Underdamped**
    - The case in which the motion of the coil is subject to damped sinusoidal oscillations.
    - The rate at which these oscillations die away is determined by
        - the damping constant (D),
        - the moment of inertia (J),
        - and the counrer torque (S) produced by the coil suspension.

# Damping Conditions…..

- **Critically damped**
  - case in which the pointer returns promptly to its steady-state position, without oscillations.
- Ideally, the galvanometer response should be such that the pointer travels to its final position without overshoot;
  - hence, the movement should be critically damped.
- In practice, the galvanometer is usually slightly underdamped,
  - causing the pointer to overshoot a little before coming to rest.

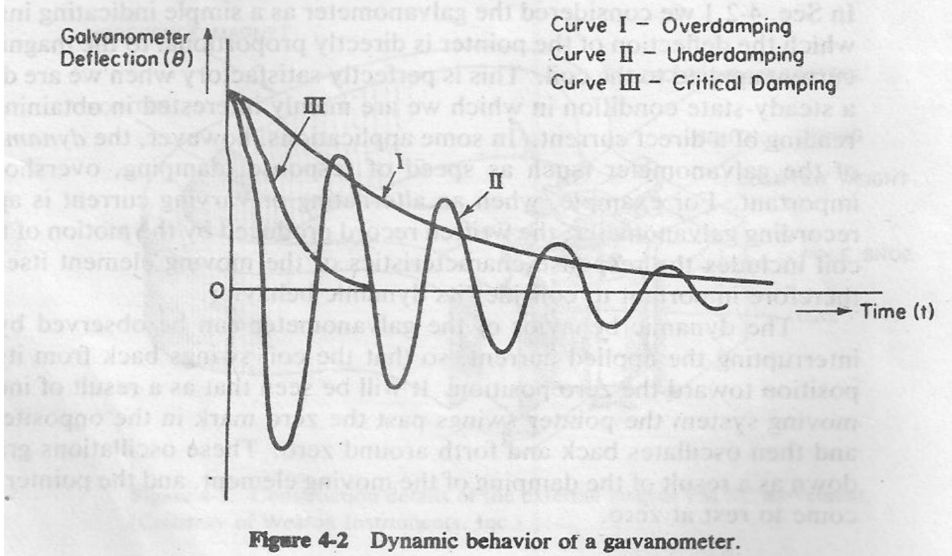



**Figure 4-2** Dynamic behavior of a galvanometer.

# Permanent-magnet Moving-coil Mechanism

- D' Arsonval Movement
  - Horse-shoe magnet with soft iron pieces
  - Soft-iron cylinder
  - Coil wound on light metal frame
  - Pointer and graduated scale
  - Phosphorus-bronze control springs
  - The entire moving system is statically balanced for all deflection positions by three balance weights
  - Pivot supported by **jewel bearings**
    - V-jewel bearing (least fractioned)
    - Spring-back jewel bearings

# Permanent-magnet Moving-coil Mechanism…

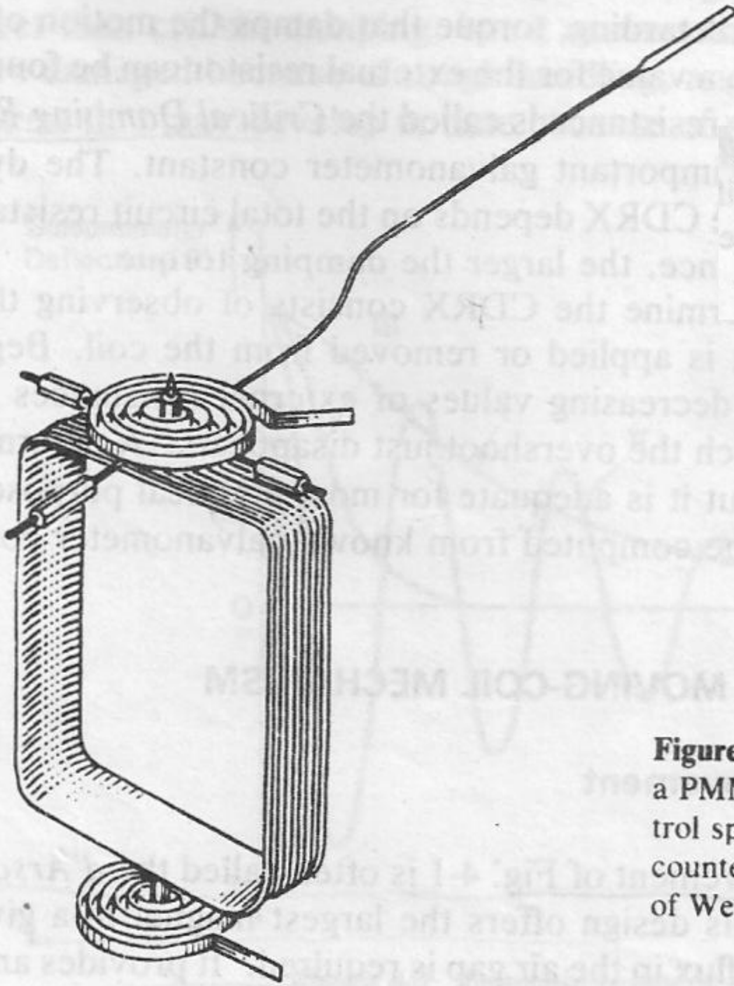


Figure 4-3 Details of a moving coil for a PMMC movement showing the control springs and the indicator with its counterbalance weights. (Courtesy of Weston Instruments, Inc.)

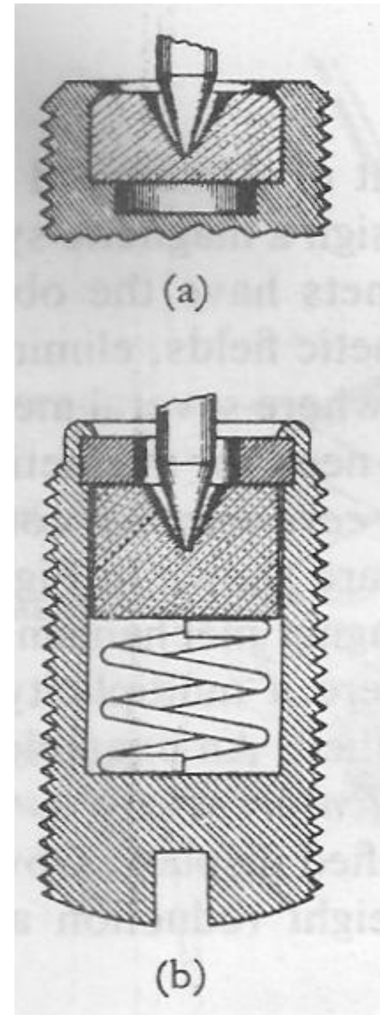


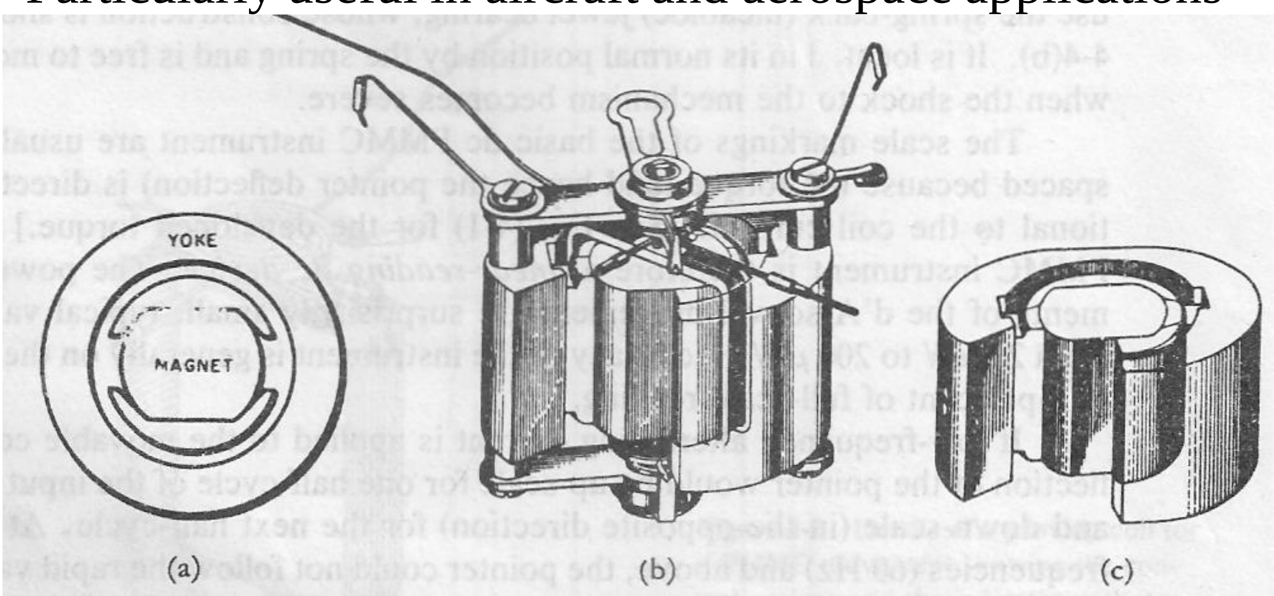

Figure 4-4 Details of instrument bearings: (a) V-jewel bearing; (b) spring-back jewel bearing. (Courtesy of Weston Instruments, Inc.)

# Permanent-magnet Moving-coil Mechanism…

- The scale markings of the basic dc PMMC instrument are usually linearly spaced because the torque
  - hence the pointer deflection is directly proportional to the coil current
- The basic PMMC instrument is therefore a linear-reading dc device.
- The power requirements of the d'Arsonval movement are surprisingly small:
  - typical values range from 25μW to 200μW.
- Accuracy of the instrument is generally on the order of 2 to 5 percent of full-scale reading.
- PMMC instrument is unsuitable for ac measurements, unless the current is rectified before application to the coil.

# Permanent-magnet Moving-coil Mechanism….

- Core-Magnet Construction
  - Alnico and other improved magnetic materials are feasible to design a magnetic system
  - the magnet itself serves as the core.
  - Magnetic Shielding
  - Eliminate magnetic shunting effects(self-shielding)
  - Particularly useful in aircraft and aerospace applications



# Suspension GM and Taut Baud Mechanisms

- Problems of PMMC
  - The suspension galvanometer had to be used in the upright position,
    - sag in the low-torque ligaments caused the moving system to come in contact with stationary members of the mechanism
  - Eliminate magnetic shunting effects(self-shielding)
  - Increased friction caused error
  - Less Accurate Result
  - Higher sensitivity as compare to pivot and jewel mechanism

# Suspension GM and Taut Baud Mechanisms….

- **Taut-baud Suspension**
- Taut-baud Suspension is a new setup
- The taut-band instrument  has the advantage of eliminating the friction of the jewel-pivot suspension
- The movable coil is suspended by means of two torsion ribbons.
- The ribbons are placed under sufficient tension to eliminate any sag
- This tension is provided by a tension spring
- the instrument can be used in any position.
- Generally speaking, taut-band suspension instruments can be made with higher sensitivities than those using pivots and jewels
  - relatively insensitive to shock and temperature
  - capable of withstanding greater overloads

# Permanent-magnet Moving-coil Mechanism……

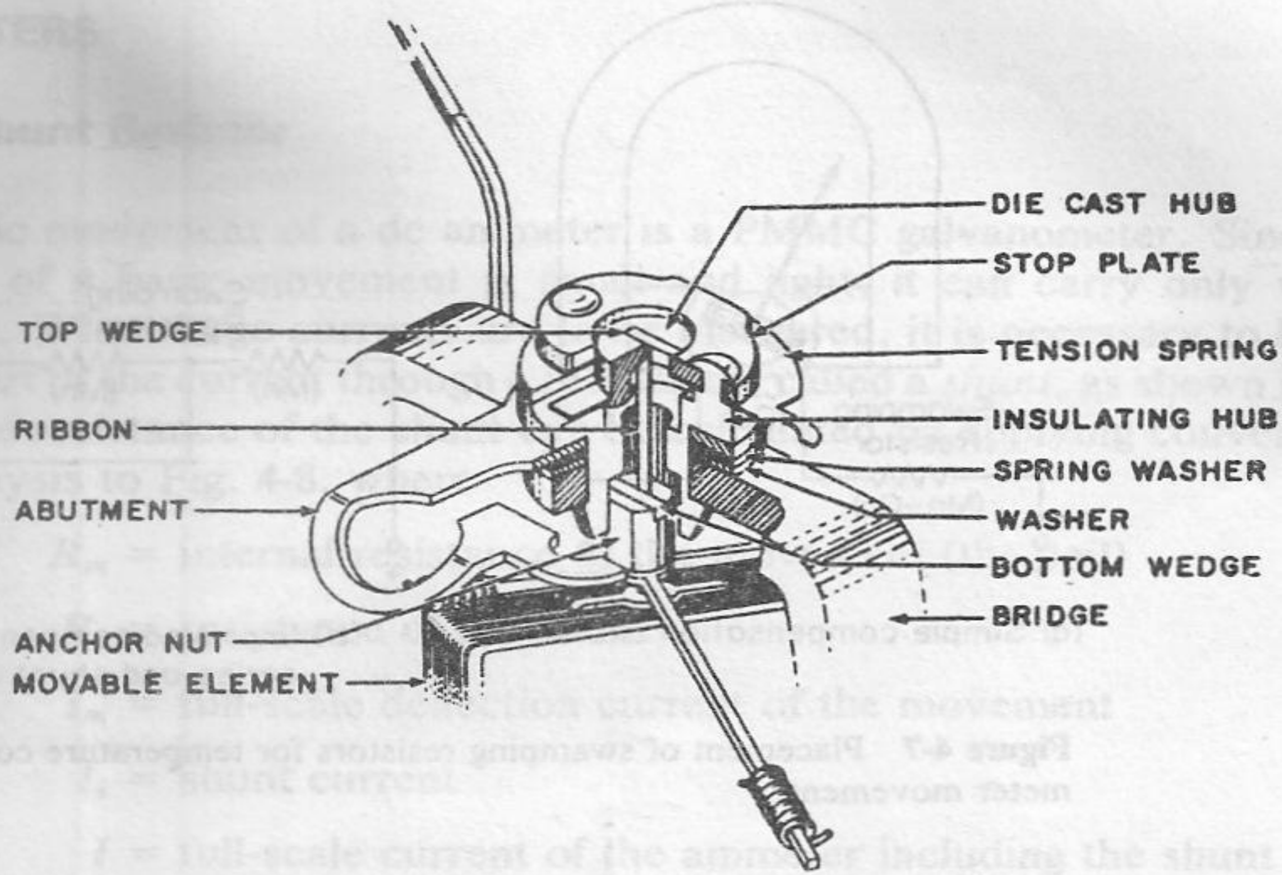



**Figure 4-6** Taut-band suspension eliminates the friction of conventional pivot-and-jewel suspensions. This figure shows some construction details, in particular the torsion ribbon with its tension-spring mechanism. (Courtesy of Weston Instruments, Inc.)

# Temperature Compensation

- The PMMC basic movement is not inherently insensitive to temperature,
  - but it may be temperature-compensated by the appropriate use of series and shunt resistors of copper and manganin.
- Both the magnetic field strength and spring tension decrease with an increase in temperature.
- The coil resistance increases with an increase in temperature
- The spring change, conversely, tends to cause the pointer to read high with an increase in temperature.

# Temperature Compensation…..

- Compensation may be accomplished by using swamping resistors in series with the movable coil, as shown in ***Fig. 4.7(a )***
- The total resistance of coil and swamping resistor increases slightly with a rise in temperature, but only just enough to counteract the change of springs and magnet
- A more complete cancellation of temperature effects is obtained with the arrangement of Fig. 4-7(b).
- Here the total circuit resistance increases slightly with a rise in temperature, owing to the presence of the copper coil and the copper shunt resistor.

# Temperature Compensation…..

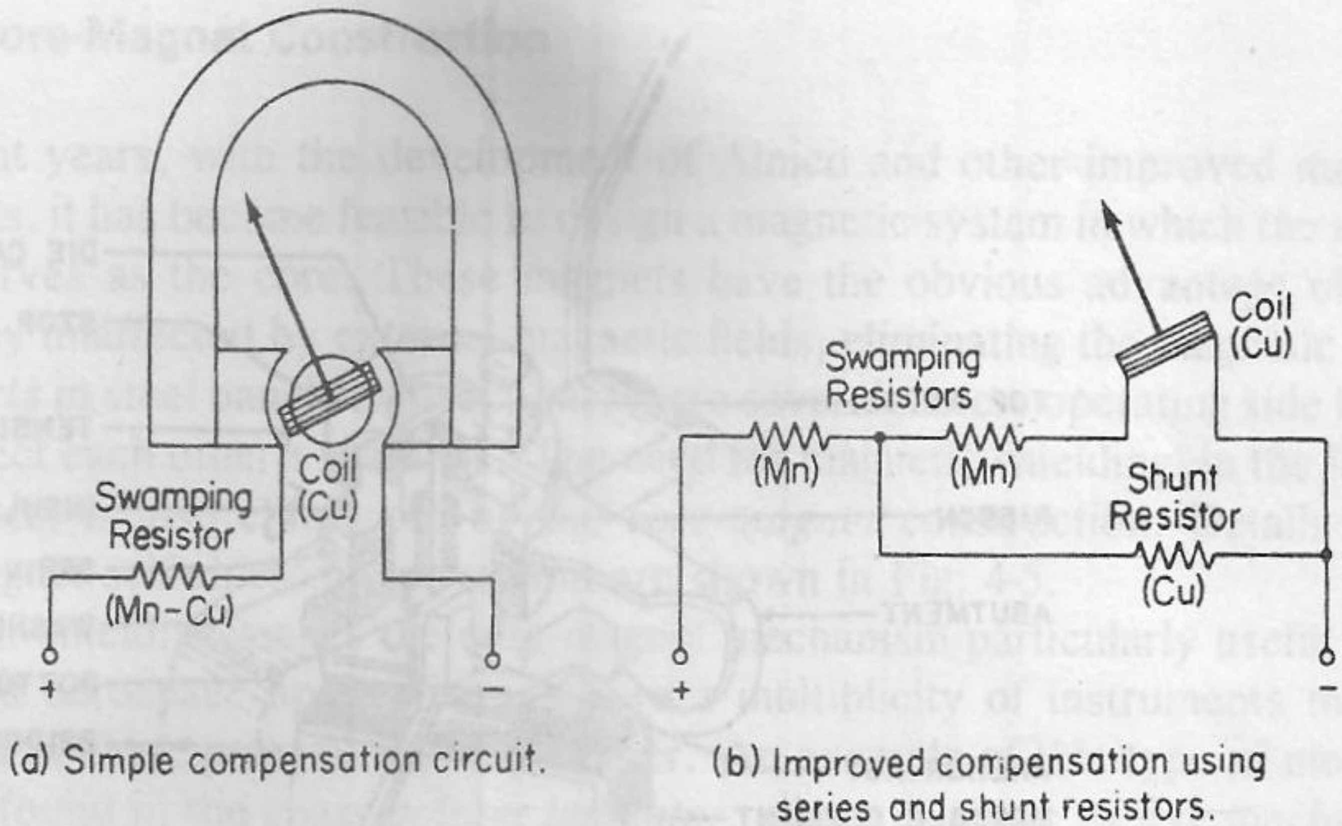



**Figure 4-7** Placement of swamping resistors for temperature compensation of a meter movement.

# DC AMMETERS

## Shunt Resistor

- In PMMC Since the coil winding of a basic movement is small and light, it can carry only very small currents.
- When large currents are to be measured,
  - it is necessary to bypass the major part of the current through a resistance, called a **shunt.**
- The resistance of the shunt can be calculated by applying conventional circuit analysis to Fig. 4-8,

where

- Rm = internal resistance of the movement (the coil)
- Rs= resistance of the shunt
- Im = full-scale deflection current of the movement
- Is = shunt current
- I = full-scale current of the ammeter including the shunt

# DC AMMETERS…..

Shunt Resistor

- Since the shunt resistance is in parallel with the meter movement, the voltage drops across the shunt and movement must be the same and we can write
- $V_{shunt} = V_{movement}$

Or

- $I_sR_s = I_m R_m$ and $\frac{I_m R_m}{I_s}$ (4-2)
- Since $I_s = I - I_m$, we can write
- $R_s = \frac{I_m R_m}{I - I_m}$ (4-3)
  - For each required value of full-scale meter current we can then solve for the value of the shunt resistance required.

# Example 4-1

- A 1-mA meter movement with an internal resistance of 100Ω is to be converted into a 0-100-mA ammeter. Calculate the value of the shunt resistance required.
- SOLUTION
- $I_s = I – I_m = 100 – 1 = 99$ mA

$$R_s = \frac{I_m R_m}{I_s} = \frac{1\text{mA} \times 100\Omega}{99\text{mA}} = 1.01\Omega$$

- The shunt resistance used with a basic movement may consist of a length of constant-temperature resistance wire within the case of the instrument or it may be an external (manganin or constantan) shunt having a very low resistance.
- Figure 4-9 shows an external shunt.
- It consists of evenly spaced sheets of resistive material welded into a large block of heavy copper on each end of the sheets..

# Example 4-1

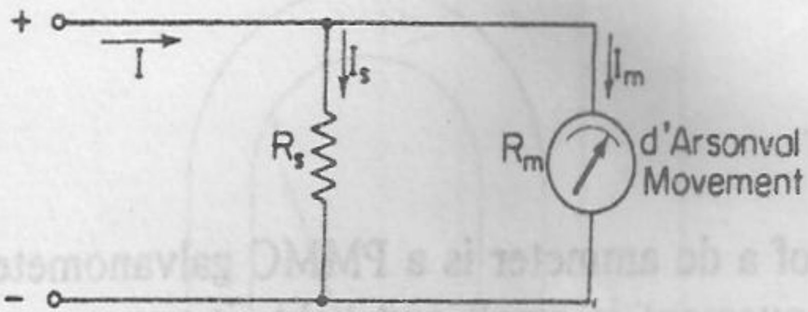



**Figure 4-8** Basic dc ammeter circuit.

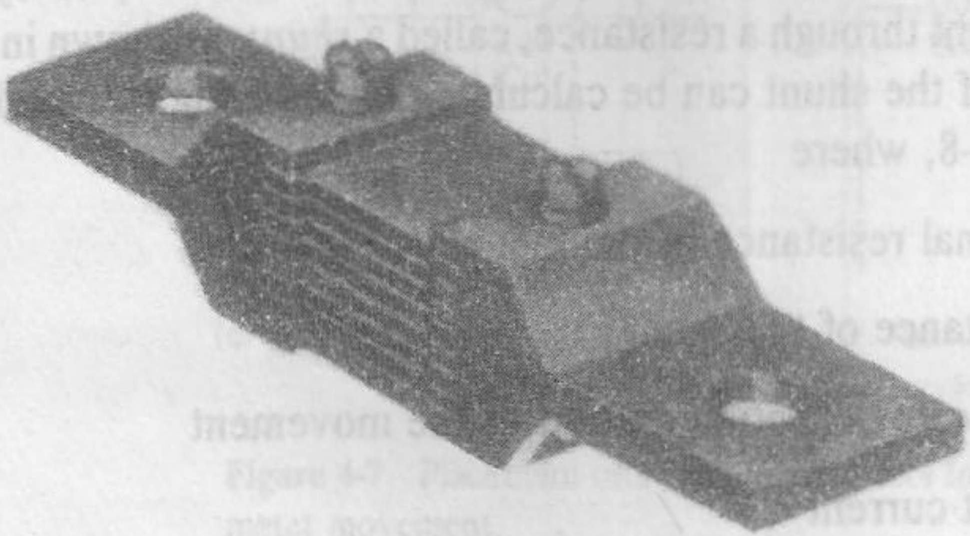


**Figure 4-9** High-current shunt for a switchboard instrument. (Courtesy of Weston Instruments, Inc.)

# Ayrton Shunt

- The current range of the dc ammeter may be further extended by a number of shunts, selected by a range switch.
- Such a meter is called a multirange ammeter.
  - Figure 4-10 shows the schematic diagram of a multirange ammeter.
- The circuit has four shunts, RQ, Rb, R, and Rd. which can be placed in parallel with the movement to give four different current ranges.
- Switch S is a multi-position, **make-before-break type** switch,
  - so that the movement will not be damaged, unprotected in the circuit, without a shunt as the range is changed.
- The universal, or Ayrton, shunt of Fig. 4-11 eliminates the possibility of having the meter in the circuit without a shunt.
- This advantage is pined at the price of a slightly higher overall meter resistance.
- The Ayrton shunt provides an excellent opportunity to apply basic network theory to a practical circuit.

# Ayrton Shunt

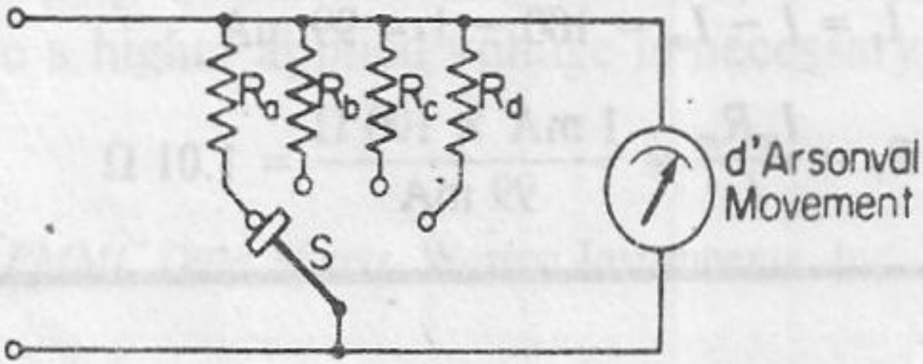



**Figure 4-10** Schematic diagram of a simple multirange ammeter.

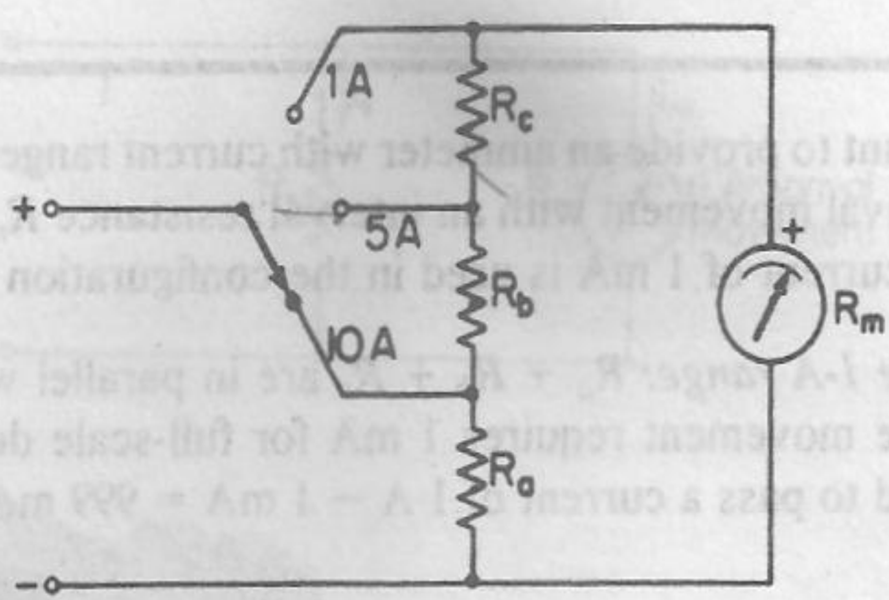



**Figure 4-11** Universal or Ayrton shunt.

# Ayrton Shunt

- The following precautions should be observed when using an ammeter in measurement work:
- Never connect an ammeter across a source of emf.
  - Because of its low resistance it would draw damaging high currents and destroy the delicate movement.
- Always connect an ammeter in series with a load capable of limiting the current.
- Observe the correct polarity.
  - Reverse polarity causes the meter to deflect against the mechanical stop and this may damage the pointer.
- When using a multirange meter, first use the highest current range;
  - then decrease the current range until substantial deflection is obtained.
- To increase accuracy of the observation , use the range that will give a reading as near to full-scale as possible.

## EXAMPLE 4-2

Design an Ayrton shunt to provide an ammeter with current ranges of 1 A, 5 A, and 10 A. A d'Arsonval movement with an interval resistance $R_m = 50\ \Omega$ and full-scale deflection current of 1 mA is used in the configuration of Fig. 4-11.

**SOLUTION** *On the 1-A range:* $R_a + R_b + R_c$ are in parallel with the 50-Ω movement. Since the movement requires 1 mA for full-scale deflection, the shunt will be required to pass a current of 1 A − 1 mA = 999 mA. Using Eq. (4-2), we get

$$R_a + R_b + R_c = \frac{1 \times 50}{999} = 0.05005\ \Omega \qquad \text{(I)}$$

*On the 5-A range:* $R_a + R_b$ are in parallel with $R_c + R_m$ (50 Ω). In this case there will be a 1-mA current through the movement and $R_c$ in series, and 4,999 mA through $R_a + R_b$. Again using Eq. (4-2), we get

$$R_a + R_b = \frac{1 \times (R_c + 50\ \Omega)}{4{,}999} \qquad \text{(II)}$$

*On the 10-A range:* $R_a$ now serves as the shunt and $R_b + R_c$ are in series with the movement. The current through the movement again is 1 mA, and the shunt passes the remaining 9,999 mA. Using Eq. (4-2) again, we get

$$R_a = \frac{1 \times (R_b + R_c + 50\ \Omega)}{9{,}999} \qquad \text{(III)}$$

Solving the three simultaneous equations (I), (II), and (III), we obtain

$$4{,}999 \times \text{(I)}: 4{,}999R_a + 4{,}999R_b + 4{,}999R_c = 250.2$$

$$\text{(II)}: 4{,}999R_a + 4{,}999R_b - R_c = 50$$

Subtracting (II) from (I), we obtain

$$5{,}000R_c = 200.2$$

$$R_c = 0.04004\ \Omega$$

Similarly,

$$9{,}999 \times \text{(I)}: 9{,}999R_a + 9{,}999R_b + 9{,}999R_c = 500.45$$

$$\text{(III)}: 9{,}999R_a - R_b - R_c = 50$$

Subtracting (III) from (I), we obtain

$$10{,}000R_b + 10{,}000R_c = 450.45$$

Substituting the previously calculated value for $R_c$ into this expression yields

$$10{,}000R_b = 450.45 - 400.4$$

$$R_b = 0.005005\ \Omega$$

$$R_a = 0.005005\ \Omega$$

This calculation indicates that for larger currents the value of the shunt resistor may become very small.

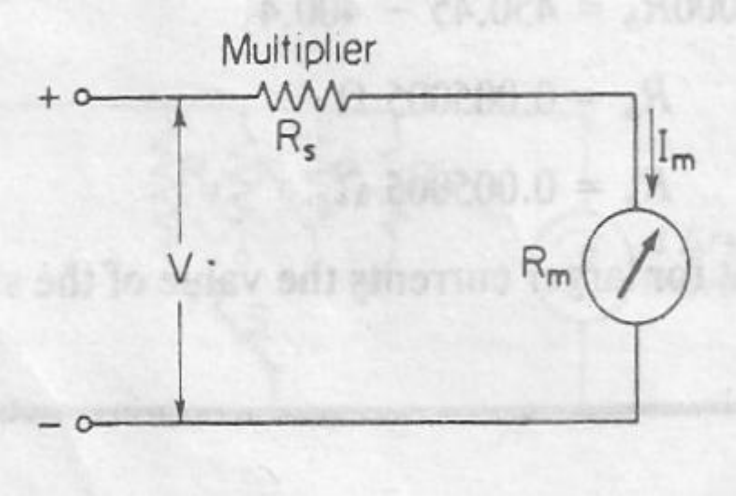
# DC VOLTMETERS

## Multiplier Resistor

- The addition of a series resistor, or multiplier, converts the basic d'Arsonval movement into a de voltmeter, as shown in Fig. 4-12. The multiplier limits the current through the movement so as not to exceed the value of the full-scale deflection current ($I_{fsd}$).

$$R_s = \frac{V - I_m R_m}{I_m} = \frac{V}{I_m} - R_m$$

- The value of a multiplier, required to extend the voltage range, is calculated from Fig. 4-12, where
- $I_m$ = deflection current of the movement (I)
- $R_m$ = internal resistance of the movement
- $R_s$ = multiplier resistance
- V = full-range voltage of the instrument
- For the circuit of Fig. 4-12,
- Solving for $R_s$ gives



# DC VOLTMETERS

- The multiplier is usually mounted inside the case of the voltmeter for moderate ranges up to 500 V. For higher voltages, the multiplier may be mounted separately outside the case on a pair of binding posts to avoid excessive heating inside the case.

## Multirange Voltmeter

- The addition of a number of multipliers, together with a range switch, provides the instrument with a workable number of voltage ranges. Figure 4-13 shows a multirange voltmeter using a four-position switch and four multipliers, $R_1$, $R_2$, $R_3$, and $R_4$, for the voltage ranges $V_1$, $V_2$, $V_3$, and $V_4$, respectively. The values of the multipliers can be calculated using the method shown earlier or, alternatively, by the sensitivity method. The sensitivity method is illustrated by Example 4-4 in Sec. 4-6, where sensitivity is discussed.

# DC VOLTMETERS

## Multirange Voltmeter

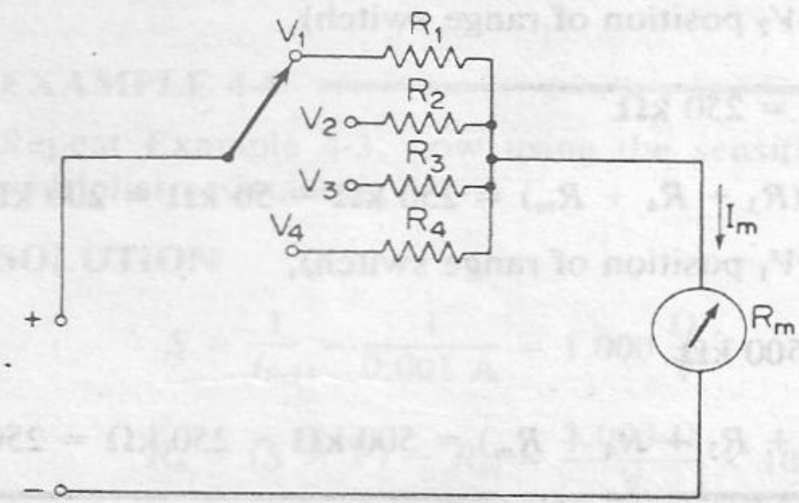



**Figure 4-13** Multirange voltmeter.

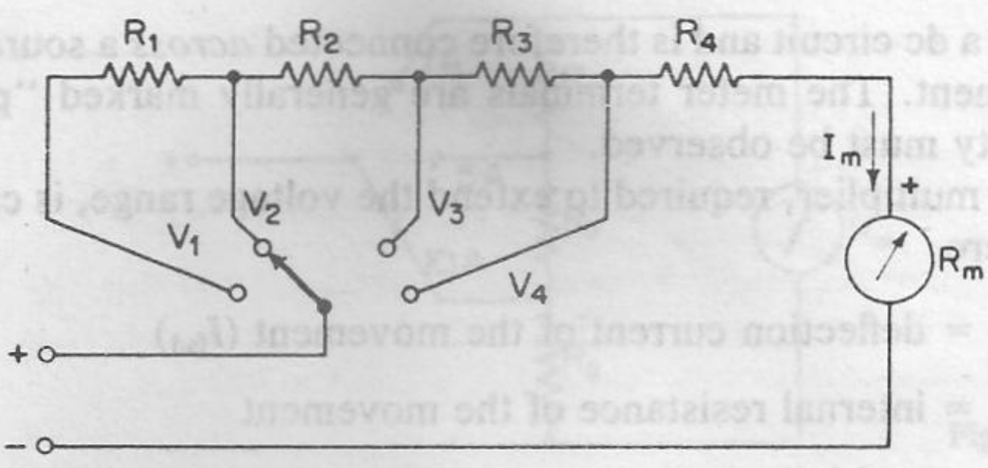



**Figure 4-14** More practical arrangement of multiplier resistors in the multirange voltmeter.

# EXAMPLE 4-3

- A basic d'Arsonval movement with internal resistance, $R_m$ = 100Ω, and full- scale current, $I_{fsd}$ = 1 mA, is to be converted into a multirange dc voltmeter with voltage ranges of 0-10 V, 0-50 V, 0-250 V. and 0-500 V. The circuit arrangement of Fig. 4-16 is to be used for this voltmeter.

- SOLUTION
- For the 10-V range ($V_4$ position of range switch), the total circuit resistance is
- $R_T = \frac{10V}{1mA} = 10k\Omega$
- $R_4 = R_T - R_m$ = 10 kΩ – 100 Ω = 9,900 Ω
- For the 50-V range ($V_3$ position of range switch),

$$R_T = \frac{50V}{1mA} = 50k\Omega \qquad R_3 = R_T - (R_4 + R_m) = 50k\Omega - 10k\Omega = 40k\Omega$$

- For the 250-V range ($V_2$ position of range switch),

$$R_T = \frac{250V}{1mA} = 250k\Omega \qquad R_2 = R_T - (R_3 + R_4 + R_m) = 250k\Omega - 50k\Omega = 200k\Omega$$

- For the 500-V range ($V_1$ position of range switch),

$$R_T = \frac{250V}{1mA} = 500k\Omega \qquad R_2 = R_T - (R_2 + R_3 + R_4 + R_m) = 500k\Omega - 250k\Omega = 250k\Omega$$

- Notice in Example 4-3 that only the low-range multiplier $R_4$ has a nonstandard value.

# Voltmeter Sensitivity

## Ohms-per-Volt Rating

- the full-scale deflection current $I_{fsd}$ was reached on all voltage ranges when the corresponding full-scale voltage was applied. As shown in Example 4-3, a current of 1 mA is obtained for voltages of 10 V, 50 V, 250 V, and 500 V across the meter terminals. For each voltage range, the quotient of the total circuit resistance $R_T$ and the range voltage V is always 1,000 Ω/V. This figure is often referred to as the sensitivity, or the ohms-per-volt rating, of the voltmeter. Note that the sensitivity, S, is essentially the reciprocal of the full- scale deflection current of the basic movement, or

$$S = \frac{1}{I_{fsd}} \frac{\Omega}{V}$$

- The sensitivity S of the voltmeter may be used to advantage in the sensitivity method of calculating the resistance of the multiplier in a dc voltmeter. Consider the circuit of Fig. 4-14, where
- S = sensitivity of the voltmeter (Ω/V)
- V = the voltage range, as set by the range switch
- $R_m$ = internal resistance of the movement (plus the previous series resistors)
- $R_s$= resistance of the multiplier
- For the circuit of Fig. 4-14,
- $R_T = S \times V$ (4-6)
- $R_S = (S \times V) - R_m$ (4-7)
- Use of the sensitivity method is illustrated in Example 4-4.

# EXAMPLE 4-4

Repeat Example 4-3, now using the sensitivity method for calculating the multiplier resistances.

**SOLUTION**

$$S = \frac{1}{I_{fsd}} = \frac{1}{0.001\ \text{A}} = 1{,}000\ \frac{\Omega}{\text{V}}$$

$$R_4 = (S \times V) - R_m = \frac{1{,}000\ \Omega}{\text{V}} \times 10\ \text{V} - 100\ \Omega = 9{,}900\ \Omega$$

$$R_3 = (S \times V) - R_m = \frac{1{,}000\ \Omega}{\text{V}} \times 50\ \text{V} - 10{,}000\ \Omega = 40\ \text{k}\Omega$$

$$R_2 = (S \times V) - R_m = \frac{1{,}000\ \Omega}{\text{V}} \times 250\ \text{V} - 50\ \text{k}\Omega = 200\ \text{k}\Omega$$

$$R_1 = (S \times V) - R_m \frac{1{,}000\ \Omega}{\text{V}} \times 500\ \text{V} - 250\ \text{k}\Omega = 250\ \text{k}\Omega$$

# Loading Effect

- The sensitivity of a dc voltmeter is an important factor when selecting a meter for a certain voltage measurement.
- A low-sensitivity meter may give correct readings when measuring voltages in low-resistance circuits, but it is certain to produce very unreliable readings in high resistance circuits.
- A voltmeter connected across two points in a highly resistive circuit, acts as a shunt for that portion of the circuit and thus reduces the equivalent resistance in that portion of the circuit.

# Loading Effect

- The meter will then give a lower indication of the voltage drop than actually existed before the meter was connected.
- This effect is called the loading effect of an instrument; it is caused principally. low-sensitivity instruments.
- The loading effect of a voltmeter is illustrated in Example 4-5.

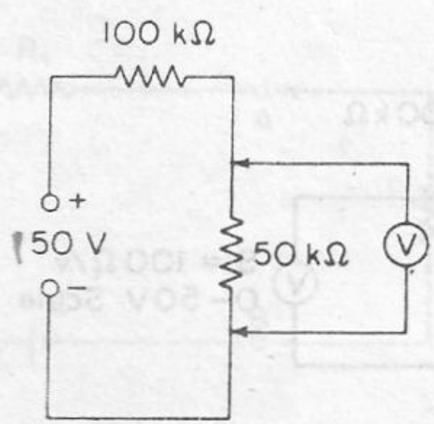



**Figure 4-15** Voltmeter loading effect.

# EXAMPLE 4-5

It is desired to measure the voltage across the 50-kΩ resistor in the circuit of Fig. 4-15. Two voltmeters are available for this measurement: voltmeter 1 with a sensitivity of 1,000 Ω/V and voltmeter 2 with a sensitivity of 20,000 Ω/V. Both meters are used on their 50-V range. Calculate (a) the reading of each meter; (b) the error in each reading, expressed as a percentage of the true value.

**SOLUTION** Inspection of the circuit indicates that the voltage across the 50-kΩ resistor is

$$\frac{50\ \text{k}\Omega}{150\ \text{k}\Omega} \times 150\ \text{V} = 50\ \text{V}$$

This is the *true* value of voltage across the 50-kΩ resistor.

(a) *Voltmeter 1* (*S* = 1,000 Ω/V) has a resistance of 50 V × 1,000 Ω/V = 50 kΩ on its 50-V range. Connecting the meter across the 50-kΩ resistor *causes the equivalent parallel resistance to be decreased to 25 kΩ and the total* circuit resistance to 125 kΩ. The potential difference across the combination of meter and 50-kΩ resistor is

$$V_1 = \frac{25\ \text{k}\Omega}{125\ \text{k}\Omega} \times 150\ \text{V} = 30\ \text{V}$$

Hence the voltmeter indicates a voltage of 30 V. *Voltmeter 2* (*S* = 20 kΩ/V) has a resistance of 50 V × 20 kΩ/V = 1 megohm on its 50-V range. When this meter is connected across the 50-kΩ resistor, the equivalent parallel resistance

# EXAMPLE 4-5…. Discussion

- The calculation of Example 4-5 indicates that the meter with the higher sensitivity or ohms-per-volt rating gives the most reliable result.
- It is important to realize the factor of sensitivity
  - particularly when voltage measurements are made in high-resistance circuits.
- The matter of reliability and accuracy of the test result raises interesting point
- Accuracy is always required in instruments
- Sensitivity is needed only in special applications where loading disturbs that which is being measured.

# EXAMPLE 4-5

equals 47.6 kΩ. This combination produces a voltage of

$$V_2 = \frac{47.6\ \text{k}\Omega}{147.6\ \text{k}\Omega} \times 150\ \text{V} = 48.36\ \text{V}$$

which is indicated on the voltmeter.

(b) The error in the reading of voltmeter 1 is

$$\%\ \text{error} = \frac{\text{true voltage} - \text{apparent voltage}}{\text{true voltage}} \times 100\%$$

$$= \frac{50\ \text{V} - 30\ \text{V}}{50\ \text{V}} \times 100\% = 40\%$$

The error in the reading of voltmeter 2 is

$$\%\ \text{error} = \frac{50\ \text{V} - 48.36\ \text{V}}{50\ \text{V}} \times 100\% = 3.28\%$$

QUESTIONs???