

Measurements and Instrumentations

Lecture 2: Electromechanical Instruments

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Lecture Outline:

- 1 Permanent Magnet Moving Coil (PMMC).
- 2 Galvanometer.
- 3 DC Ammeters.
- 4 DC Voltmeter.
- 5 Ohmmeter.
- 6 AC Voltmeter.
- 7 AC Ammeter.
- 8 Analog Electronic Voltmeters.

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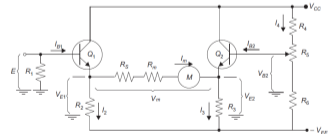
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Permanent Magnet Moving Coil (PMMC):

- Electromechanical instruments are **electrically operated mechanical instruments** used to measure electrical quantities (Volt, Ampere, Ohm).
- A Permanent Magnet Moving Coil (PMMC) is the **basic building block** of all electromechanical instruments: galvanometers, DC ammeters and voltmeters and ohmmeters.

Operation Principle of PMMC:

- 1 A light weight coil of copper wire suspended in the field of permanent magnet.
- 2 The current flowing in the wire produces a magnetic field by the coil which interacts with the field from the magnet thereby resulting in partial rotation of the coil.
- 3 The current flowing in the wire is indicated by the deflection on a calibrated scale through a pointer connected to the coil.

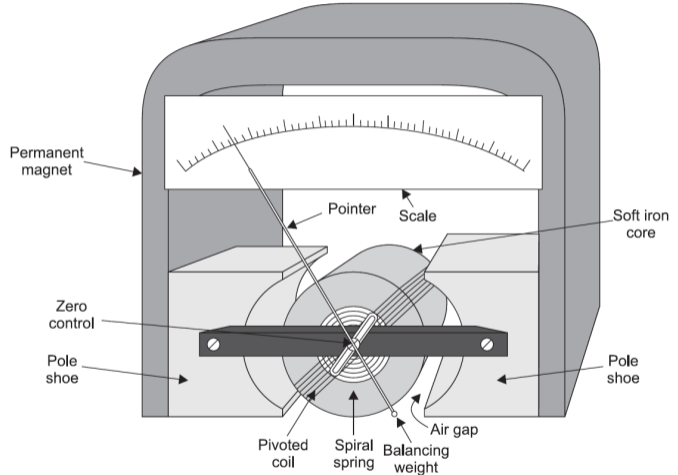


Permanent Magnet Moving Coil (PMMC):

Deflection Instrument Fundamentals:

To move the pointer in PMMC over the scale, three forces are required:

- 1 Deflection force.
- 2 Controlling force.
- 3 Damping force.



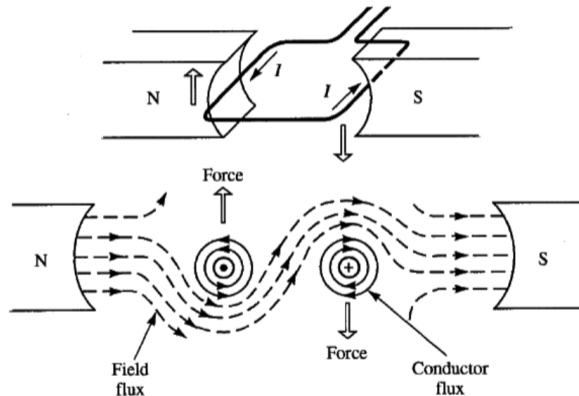
Construction of PMMC

Permanent Magnet Moving Coil (PMMC):

Deflection Instrument Fundamentals:

[1] Deflection force:

- It is the magnetic force that causes the pointer to move from its zero position when a current flows.
- This force is established due to the interaction between the magnetic field from the current flow in the coil and the field from the permanent magnet.

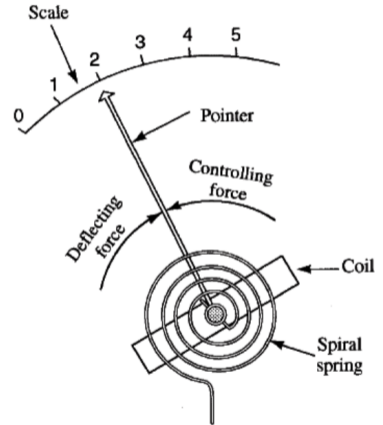


Permanent Magnet Moving Coil (PMMC):

Deflection Instrument Fundamentals:

[2] Controlling force:

- It is provided by a **spiral spring**.
- When **no current** is flowing the spring retain the coil and pointer at their **zero position**.
- When **current flows**, the spring “wind up” as the coil rotates, and its exerted **force on the coil increases**.
- The coil and pointer **stop rotating** when the controlling force becomes equal to the deflecting force.

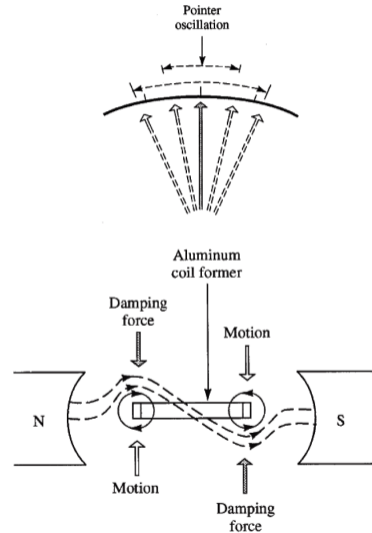


Permanent Magnet Moving Coil (PMMC):

Deflection Instrument Fundamentals:

[3] Damping force:

- A damping force is required to **minimize (or damp out) the pointer oscillations** that could occur before stopping at a certain reading.
- This damping is applied by the **Eddy Current** established in the aluminum frame of the coil.
- Eddy currents induced in the coil former set up a magnetic flux that **opposes the coil motion**, thus **damping the oscillations** of the coil and the pointer.
- This force is provided only **when the coil is moving**.



Permanent Magnet Moving Coil (PMMC):

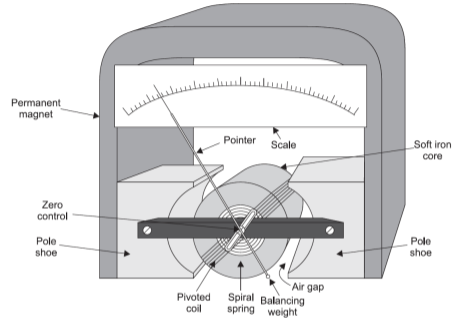
Construction of PMMC:

Zero Control:

the zero-position control can be adjusted to **calibrate** the coil and pointer position when no coil current is flowing.

Balancing weight:

It provides correct mechanical balance of the moving pointer so that there is **no gravitational effect** on the accuracy of the instrument.



Construction of PMMC

PMMC is Polarized:

The current in the coil of a PMMC instrument must flow in one particular direction to cause the pointer to move (positively) from the zero position over the scale.

Permanent Magnet Moving Coil (PMMC):

Force Equation and Scale:

The deflection force acting on each side of the coil:

$$F = BIL \quad \text{newtons}$$

B is the flux density (tesla)

I the current (ampere)

L coil length (meter)

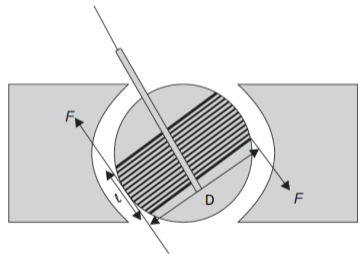
The force acting on two sides with N turns coil:

$$F = 2BILN \quad \text{newtons}$$

The deflection torque acts at radius r :

$$T_d = 2BILNr = BLIND \quad (N.m)$$

D is the coil diameter.



Permanent Magnet Moving Coil (PMMC):

Force Equation and Scale:

The **controlling torque** is proportional to the deflection of the pointer:

$$T_c = K\theta \quad (N.m)$$

K is constant

θ is the deflection angle (rad.)

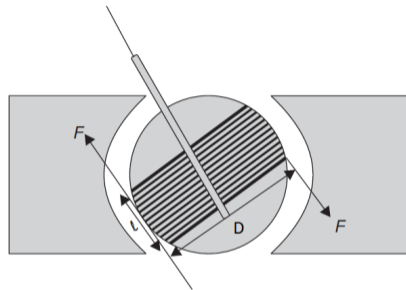
The pointer stops when $T_d = T_c$:

$$K\theta = BLIND$$

All quantities are constants except I and θ ,

$$\theta = CI$$

C : is constant



Note:

The pointer deflection is always proportional to the coil current and the **scale is linear.**

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- 5 Ohmmeter.
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- 8 Analog Electronic Voltmeters.

Galvanometer:

- A galvanometer is essentially a PMMC instrument designed to be **sensitive to extremely low currents** (microamperes).
- Its scale is a **center-zero scale**. The pointer can be deflected to either **right or left** of zero, depending on the direction of current through the moving coil.
- Galvanometers are often employed to detect **zero current or voltage** in a circuit rather than to measure the actual level of current or voltage.

Protection of Galvanometer:

A galvanometer must be protected from the **excessive current flow**. Protection is provided by an **adjustable resistance connected in shunt** with the instrument to limit the input current.

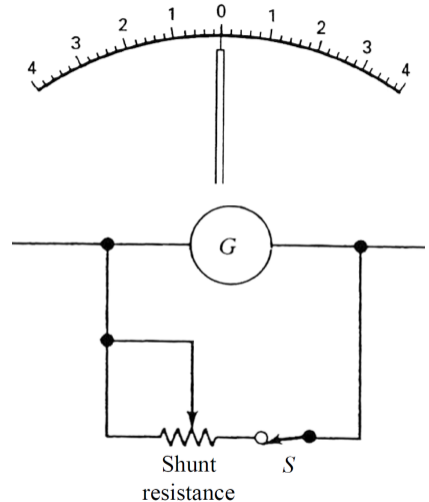


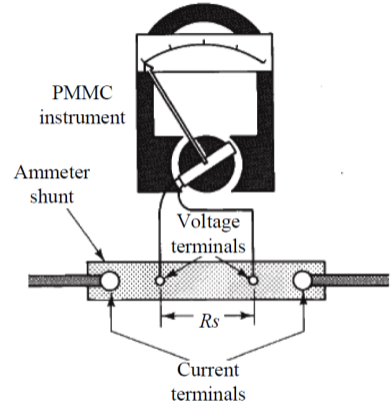
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DC Ammeters:

Ammeter Circuit:

- The PMMC instrument could be used as an ammeter to **measure DC current**. However, the PMMC wire could be quickly **destroyed** by **large currents**.
- For large currents, a PMMC could be modified by adding a **parallel (shunt) resistance** R_s .
- Most of the measured current will pass through R_s and a small portion of it will pass through the moving coil.



Shunt Resistance

It is a small resistance connected in parallel with PMMC to allow measuring large currents. It is a four-terminal resistance to neglect the resistance of the current terminal.

DC Ammeters:

Ammeter Circuit:

Example

An ammeter has a PMMC instrument with a coil resistance of $R_m = 99 \Omega$ and FSD current of 0.1 mA , a shunt resistance $R_s = 1 \Omega$.

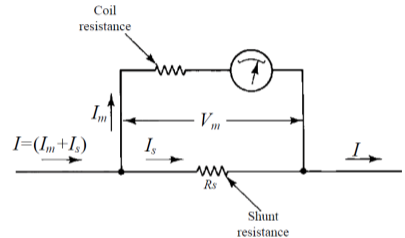
Determine the total current passing through the ammeter at (a) FSD, (b) 0.5 FSD, and (c) 0.25 FSD.

Solution: [a] at FSD:

$$V_m = I_m R_m = 0.1 \times 99 = 9.9 \text{ mV}$$

$$I_s = \frac{V_m}{R_s} = \frac{9.9}{1} = 9.9 \text{ mA}$$

Total current: $I = I_s + I_m = 9.9 + 0.1 = 10 \text{ mA}$



Ammeter circuit

R_m : coil resistance.

R_s : shunt resistance.

DC Ammeters:

Ammeter Circuit:

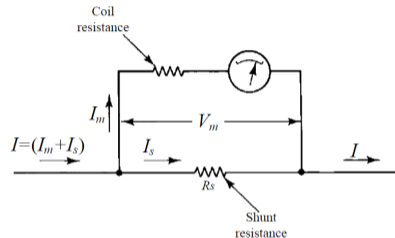
[b] at 0.5 FSD:

$$I_m = 0.5 \times 0.1 \text{ mA} = 0.05 \text{ mA}$$

$$V_m = I_m R_m = 0.05 \times 99 = 4.95 \text{ mV}$$

$$I_s = \frac{V_m}{R_s} = \frac{4.95}{1} = 4.95 \text{ mA}$$

Total current: $I = I_s + I_m = 4.95 + 0.05 = 5 \text{ mA}$



Ammeter circuit

R_m : coil resistance.

R_s : shunt resistance.

Try (c) 0.25 FSD by yourself!

DC Ammeters:

Shunt Resistance:

The shunt resistance values can be determined to **convert a PMMC instrument into an ammeter** for measuring virtually any **desired level of current**.

Example

A PMMC instrument has FSD of $100 \mu A$ and a coil resistance of $1 k\Omega$.

Calculate the required shunt resistance value to convert the instrument into an ammeter with (a) FSD = $100 mA$ and (b) FSD = $1 A$.

Solution: [a] at FSD = $100 mA$

$$V_m = I_m R_m = 100 \mu A \times 1 k\Omega = 100 mV$$

$$I_s = I - I_m = 100 mA - 100 \mu A = 99.9 mA$$

$$R_s = \frac{V_m}{I_s} = \frac{100 mV}{99.9 mA} = 1.001 \Omega$$

DC Ammeters:

Shunt Resistance:

The shunt resistance values can be determined to **convert a PMMC instrument into an ammeter** for measuring virtually any **desired level of current**.

Example

A PMMC instrument has FSD of $100 \mu A$ and a coil resistance of $1 k\Omega$.

Calculate the required shunt resistance value to convert the instrument into an ammeter with (a) FSD = $100 mA$ and (b) FSD = $1 A$.

Solution: [b] at FSD = $1 A$:

$$V_m = I_m R_m = 100 \mu A \times 1 k\Omega = 100 mV$$

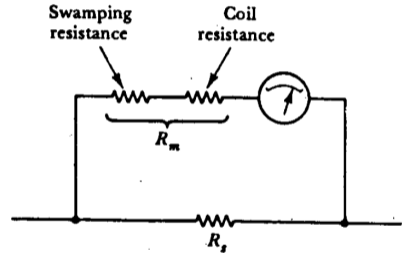
$$I_s = I - I_m = 1 A - 100 \mu A = 999.9 mA$$

$$R_s = \frac{V_m}{I_s} = \frac{100 mV}{999.9 mA} = 0.10001 \Omega$$

DC Ammeters:

Swamping Resistance:

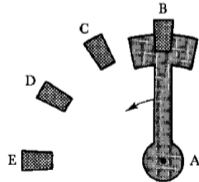
- To minimize the effect of temperature change on the PMMC resistance, a swamping resistance is connected in series with PMMC.
- The swamping resistance is made from *magnain* or *constantan* that have zero temperature coefficients.
- If the swamping resistance is nine times the coil resistance, a 1 % change in coil resistance would result in a total resistance change of 0.1 %.



DC Ammeters:

Multirange Ammeter:

- A rotary switch is employed to select anyone of several shunt resistances with different values.
- A **make-before-break** switch must be used so that the instrument is not left without a shunt in parallel with it even for a brief instant.



Make-before-break switch

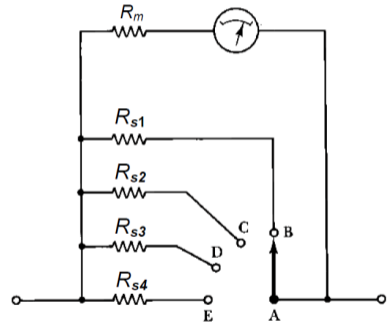


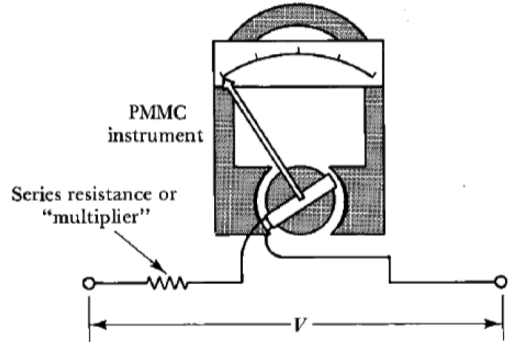
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DC Voltmeter:

Voltmeter Circuit:

- The scale of the PMMC meter could be calibrated to **indicate voltage** since the **current through the coil is proportional to the voltage**.
- The PMMC could be modified by adding a **series resistance** to measure higher voltmeter range.
- Because it increases the range of the voltmeter, the series resistance is termed a multiplier resistance.
- A multiplier resistance that is nine times the coil resistance will increase the voltmeter range by a factor of 10.



Construction of DC Voltmeter

DC Voltmeter:

Voltmeter Circuit:

Example

A PMMC instrument with FSD of $100 \mu A$ and a coil resistance of $1 k\Omega$ is to be converted into a voltmeter. Determine the required multiplier resistance if the voltmeter is to measure $50 V$ at full scale. Also, calculate the applied voltage when the instrument indicates 0.8, 0.5, and 0.2 of FSD.

$$V = I_m(R_s + R_m)$$
$$R_s + R_m = \frac{V}{I_m}$$

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

For $V = 50V$, FSD,

$$I_m = 100 \mu A$$
$$R_s = \frac{50V}{100 \mu A} - 1k\Omega = 499 k\Omega$$

At 0.8 FSD

$$I_m = 0.8 \times 100 \mu A = 80 \mu A$$
$$V = I_m(R_s + R_m)$$
$$= 80 \mu A(499k\Omega + 1k\Omega) = 40V$$

At 0.5 FSD

$$I_m = 0.5 \times 100 \mu A = 50 \mu A$$
$$V = 50 \mu A(499k\Omega + 1k\Omega) = 25V$$

At 0.2 FSD

$$I_m = 0.2 \times 100 \mu A = 20 \mu A$$
$$V = 20 \mu A(499k\Omega + 1k\Omega) = 10V$$

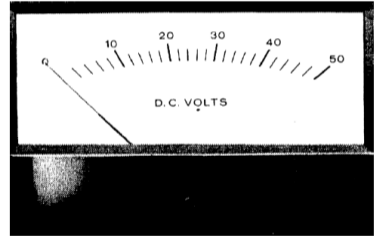
DC Voltmeter:

Voltmeter Sensitivity:

The sensitivity of a voltmeter is equal to the resistance per volt:

$$S_v = \frac{R_m + R_s}{FSD} \quad \Omega/V$$

- The voltmeter sensitivity is always specified by the manufacturer.
- If the sensitivity is known, the total voltmeter resistance is easily calculated as (sensitivity \times range).
- Ideally, a voltmeter should have an extremely high resistance.
- If the **voltmeter resistance** is too low, it can alter the circuit voltage. This is known as voltmeter **loading effect**.



DC Voltmeter:

Multirange Voltmeter:

- A multirange voltmeter consists of a PMMC with several multiplier resistors, and a rotary switch.
- The range of this voltmeter is:

$$V = I_m(R_m + R)$$

where R can be R_1 , R_2 , or R_3 .

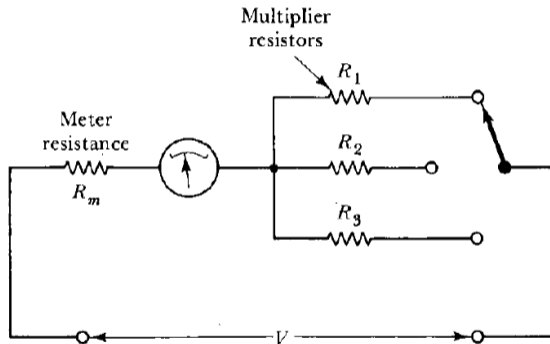


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Ohmmeter:

Basic Circuit:

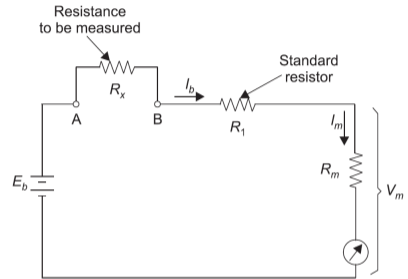
Series Ohmmeter:

- The series ohmmeter consists of a PMMC with a battery voltage E_b connected in series.
- The unknown resistance is connected between terminals, A and B.
- A standard (known) resistance R_1 is connected to protect the device from high current when low resistance is connected.

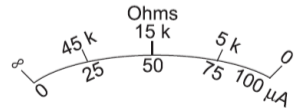
$$I_m = \frac{E_b}{R_1 + R_x + R_m}$$

If $R_x = 0$, $I_m = FSD$ and if $R_x = \infty$, $I_m = 0$.

If $0 < R_x < \infty$, $FSD < I_m < 0$



Construction of DC Voltmeter



Ohmmeter:

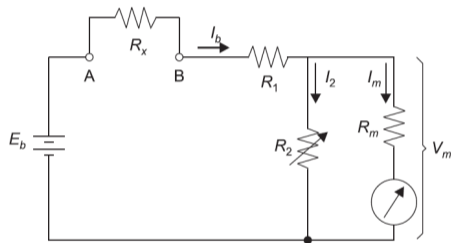
Ohmmeter with Zero Control:

- In the series ohmmeter, if the battery voltage drops, the instrument scale no longer gives correct reading.
- An adjustable resistor R_2 is connected in parallel with the meter to adjust the falling battery voltage.

$$I_m = V_m / R_m, \quad V_m = I_b \cdot (R_2 // R_m)$$

$$I_m = I_b \cdot \frac{R_2 // R_m}{R_m}$$

- Ohmmeter is calibrated by making $R_x = 0$ and adjusting R_2 to give FSD (0Ω).



Modified Series Ohmmeter With Adjustable Resistor

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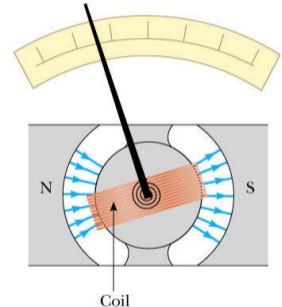
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AC Voltmeter:

Introduction:

PMMC as AC instrument:

- When an alternating current with a **very low frequency (0.1 Hz)** is passed through a PMMC, the **pointer will follow the instantaneous level** of the ac signal.
- Since the PMMC is polarized, **the pointer will move when ac goes positive only** and will stop when ac goes negative.
- With higher frequencies, the PMMC will **not be able to follow** the changing ac level **due to its damping force** and the pointer will stop on the average level (zero for pure sinusoidal wave).
- So, a modification has to be done on PMMC to measure alternating current and voltage.

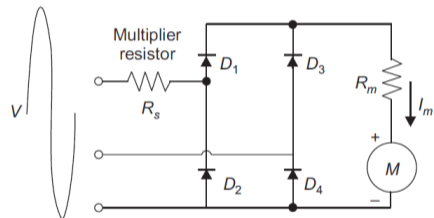


Construction of PMMC

AC Voltmeter:

[1] Full-Wave Rectifier Voltmeter:

- **Four diodes rectifiers** are added to the PMMC to convert the AC signal into a series of **uni-directional current pulses** that pass through the PMMC instrument to cause positive deflection.
- **On positive half cycle:** Diodes D_1 and D_4 conduct and the current flows through the PMMC meter from top to bottom.
- **On negative half cycle:** Diodes D_2 and D_3 to conduct causing the current to flow again through the meter in the same direction.
- The multiplier resistance R_s is connected to **allow higher voltage** to the meter in the same way as in the case of DC voltmeter.

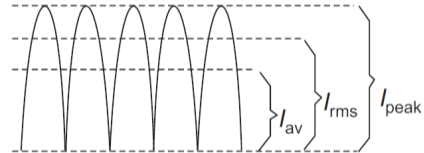


Full-Wave Rectifier Voltmeter

AC Voltmeter:

[1] Full-Wave Rectifier Voltmeter:

- The rectifier meter will **deflect in proportional to the average value** of the current ($0.637 \times$ peak current).
- However, the meter must **indicate the RMS value**, (that is, $0.707 \times$ peak value) of the voltage.
- Therefore, the linear scale of the meter can be calibrated accordingly to indicate the RMS value ($1.11 \times$ average value).
- **Limitation:** The diodes drop will limit the measurement of low levels of AC signals.



AC Voltmeter:

[1] Full-Wave Rectifier Voltmeter:

Example

A PMMC instrument with meter resistance $1\text{ k}\Omega$ gives a full-scale deflection of $80\ \mu\text{A}$. It is to be used as a full-wave rectifier voltmeter to give FSD of 80 V (rms) . Determine the required value of multiplier resistance if silicon diodes are used in the circuit.

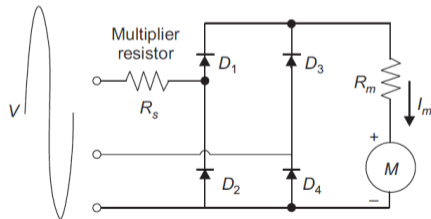
$$I_{m_{peak}} = \frac{V_{m_{peak}} - 2V_D}{R_s + R_m}, \quad V_D = 0.7\text{ V}$$

$$R_s = \frac{V_{m_{peak}} - 2V_D}{I_{m_{peak}}} - R_m$$

$$V_{m_{peak}} = 1.414 \times V_{RMS} = 1.414 \times 80 = 113.12\text{ V}$$

$$I_{m_{peak}} = \frac{I_{av}}{0.637} = \frac{80\ \mu\text{A}}{0.637} = 125.6\ \mu\text{A}$$

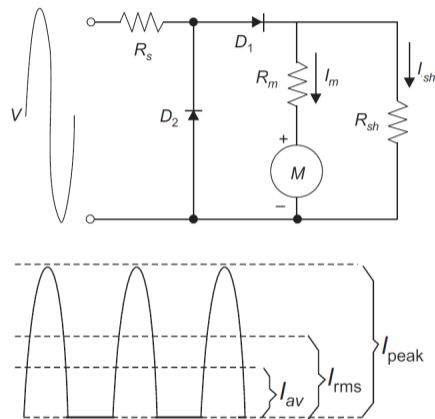
So, $R_s = 888.5\text{ k}\Omega$



AC Voltmeter:

[2] Half-Wave Rectifier Voltmeter:

- D1 is used to rectify the ac signal into the PMMC.
- **On positive half cycle:** Diodes D1 conducts and the current flows through the PMMC.
- **On negative half cycle:** Diodes D1 is OFF and no current flows.
- R_{sh} is added in parallel to **increase the current in diode D1** when a positive half-wave appears at the input (to operate in the linear region of the diode).
- D2 is added to protect the meter **against any reverse voltages**.
- The rectifier meter will deflect in proportional to the average value of the current ($0.5 \times 0.637 \times$ peak current).



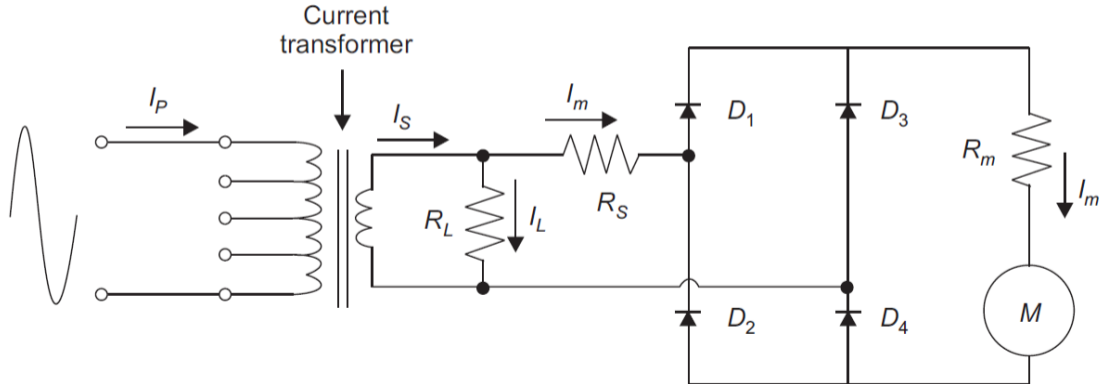
Half-Wave Rectifier Voltmeter

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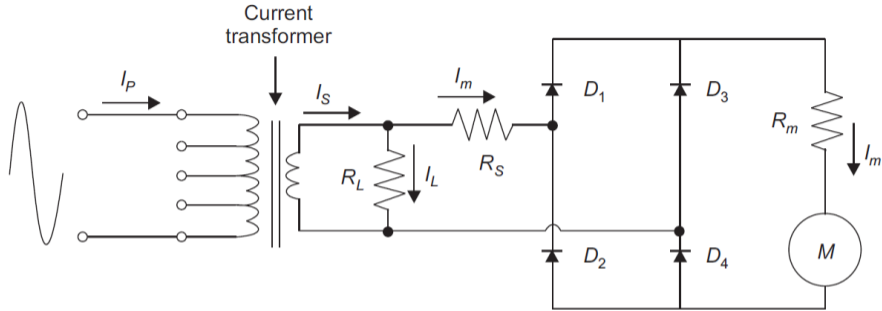
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AC Ammeter:

- The requirement of the AC ammeter is to **have very low resistance which implies that a very low (typically less than 100 mV) voltage drop.**
- Thus, a rectifier PMMC circuit **is not suitable to directly measure AC currents.**
- A **step-up transformer** is used to measure AC current:



AC Ammeter:



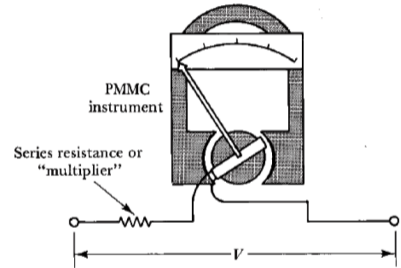
- Using a current transformer with a rectifier instrument provides a **very low terminal resistance and low voltage drop**.
- In step-up transformer, the input voltage gets stepped up so that **sufficient voltage can be provided for rectifier** operation.
- A multi-range AC ammeter could be provided by **changing the number of primary turns** in the transformer.

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Introduction:

- The electromechanical instruments have some limitations: as **having low resistance (loading effect)** and **cannot measure very low voltages**.
- The low input voltages need to be **amplified** to measurable levels and electronic circuits are required to **offer high input resistance**.
- Electronic circuits voltmeters with **transistors**, **operational amplifiers** (or op-amp) can be used to amplify small voltage and provide high input resistance .
- These analog circuits include:
 - ① Emitter-Follower Voltmeter.
 - ② FET-input Voltmeter.



Emitter-Follower Voltmeter:

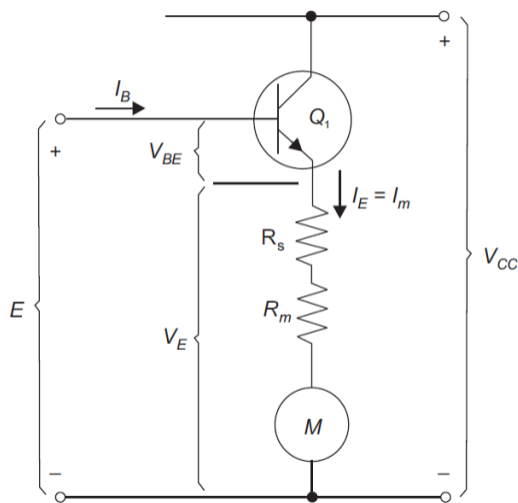
- A BJT emitter follower is used where the PMMC and R_s are connected to the Emitter.
- The voltage to be measured, that is, E , is connected to the base of the transistor.
- The base current, I_b is:

$$I_b = \frac{I_m}{\beta}, \quad \beta : (\text{Transistor gain})$$

- The input resistance, R_i is:

$$R_{in} \approx \frac{E}{I_b}$$

which is **much larger** than $R_s + R_m$ since I_b is small.



Emitter-Follower Voltmeter:

Example

A simple emitter-follower voltmeter with: $V_{CC} = 12\text{ V}$, $R_m = 2\text{ k}\Omega$, 1 mA FSD meter current, and current gain $\beta = 50$.

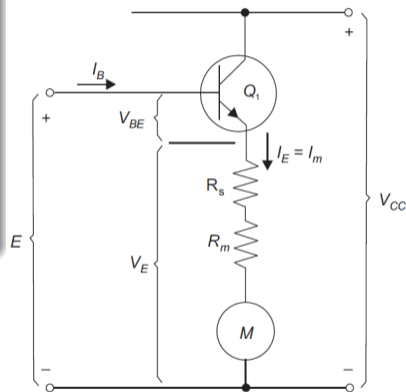
Determine :

- Appropriate multiplier resistance that can give FSD 5 V .
- Input resistance

(a)

$$R_s = \frac{V_E}{I_m} - R_m = \frac{E - V_{BE}}{I_m} - R_m = \frac{5 - 0.7}{1\text{ mA}} - 2 = 2.3\text{ k}\Omega$$

(b) $R_{in} = \frac{E}{I_b} = \beta \cdot \frac{E}{I_m} = 50 \cdot \frac{5}{1\text{ mA}} = 250\text{ k}\Omega$

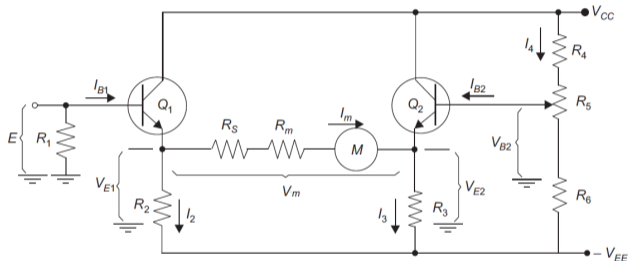


Emitter-Follower Voltmeter:

- To **reduce the drop** V_{BE} , a one more emitter-follower and a voltage divider are used with a $\pm 12\text{ V}$ dual polarity supply is connected.
- When $E = 0$, the resistance R_5 is adjusted to make $V_{E2} = 0.7$ and $V_m = 0$.
- When E is exist, the PMMC voltage is:

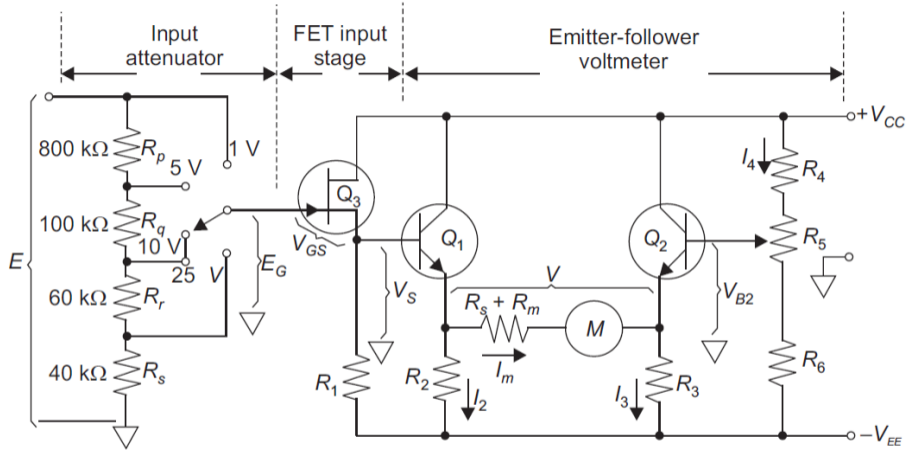
$$V_m = E - 0.7 - (-0.7) = E$$

- So, the voltage drop is removed.



Modified Emitter-Follower Voltmeter

FET-input Voltmeter:



Advantage:

The Field Effect Transistor (FET) provide extremely high input resistance.

End of Lecture

Best Wishes

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