CHAPTER 2

ELECTROMECHANICAL INSTRUMENTS

Elements of Electronic Instruments عناصر أجهزة القياس الإلكترونية

(١) محول طاقة Transducer : لتحويل الكميات المقاسة غير الكهربائية إلى كميات كهربائية

(٢) معدل إشارة Signal Modifier: لتعديل الإشارة الكهربائية الآتية من محول الطاقة ليجعلها مناسبة للتطبيق على جهاز البيان. فقد تكون الإشارة الكهربائية مثلاً صغيرة ويتطلب ذلك تكبيرها لكي يستطيع جهاز البيان أن يشعر بها فهو يعمل في هذه الحالة كمكبر للإشارة؛ والعكس صحيح أيضا ، فقد تكون الإشارة الكهربائية كبيرة ويتطلب ذلك تخفيضها إلى الدرجة التي يتحملها جهاز البيان فهو يعمل في هذه الحالة كمخفض للإشارة.

(٣) جهاز بيان Indicating Device : وهو جهاز قياس كهربائي عادي ذو ملف متحرك ومؤشر وتدريج مثل جهاز قياس الجهد الكهربائي (Voltmeter) أو جهاز قياس التيار (Ammeter).

وأجهزة القياس الإلكترونية تستخدم في العادة لقياس إما الكميات الكهربائية المباشرة مثل: الجهد الكهربائي والتيار الكهربائي والمقاومة الكهربائية أو الكميات الفيزيائية بعد تحويلها عن طريق المبدل إلى كمية كهربائية مثل: الضغط الجوي، أو درجة الحرارة، أو الرطوبة النسبية، أو مستوى الصوت، أو مستوى الإضاءة أو العديد من الكميات الفيزيائية الأخرى. إلا أنه في جميع الأحوال فإن انحراف مؤشر الجهاز يكون بسبب تدفق التيار الكهربائي في ملف الجهاز ويعاير تدريج الجهاز ليقرأ الكمية الفيزيائية المنوط بالجهاز قياسها.

اختيار واستخدام والعناية بأجهزة القياس

Selection, Usage and Care of Measuring Instruments

في الواقع فإن معظم أجهزة القياس هي أجهزة حساسة ويجب أن تعامل بعناية خاصة وبطريقة صحيحة. وفي الحقيقة فإن أكثر الأجهزة المتاحة دقة، قد لا تعطي قراءات صحيحة إذا عوملت بطريقة غير صحيحة، ولذلك فإن هناك بعض القواعد الأساسية التي تؤمن سلامة الجهاز ودقة نتائج القراءات.

قبل استخدام الجهاز لابد أن تكون معتاداًعلى طريقة استخدامه. وأفضل مصدر للمعلومات المطلوبة عن طريقة التعامل مع الجهاز وطريقة تشغيله هو كتيب التعليمات الخاص بالجهاز (الكتالوج الخاص به) أو (The operating and instructions manual)، الذي يحتوي كل البيانات التي ترجوها لاستخدام الجهاز. وهذا الكتالوج يجب أن يقرأ بكل عناية قبل استخدام الجهاز لأول مرة للحصول على المعلومات اللازمة لوظائف الجهاز و طرق استخدامه وطرق حفظه وتخزينه والإجراءات التي يجب اتباعها لتأمين سلامته وموانع ونواهي استخدامه (حدود الاستخدام). ولاختيار الجهاز بصورة صحيحة، طبقاً للوظيفة بطبيعة الحال، فإن درجة الدقة المطلوبة من الجهاز تتناسب مع سعر الجهاز. وبعد اختيار الجهاز لابد من فحص بصري للجهاز لملاحظة أي عيب ظاهر به مثل: مؤشر معوج، أطراف توصيل تالفة، تدريج غير ظاهر، وخلافه. ويجب أيضا فحص بطارية الجهاز وتغييرها إذا لزم الأمر. وعند توصيل الجهاز في الدائرة الكهربائية يجب التأكد من أن مفتاح اختيار الوظيفة مضبوط على الوضع الصحيح. يجب أيضاً التأكد من الاختيار الصحيح لمدى القياس، أو اختيار أكبر مدى للقياس لضمان سلامة الجهاز، ثم يعاد اختياره أثناء القراءة إذا كان المدى غير مناسب وذلك للحصول على القراءة أقرب ما يكون للمدى الأقصى كما ذكر سابقاً.

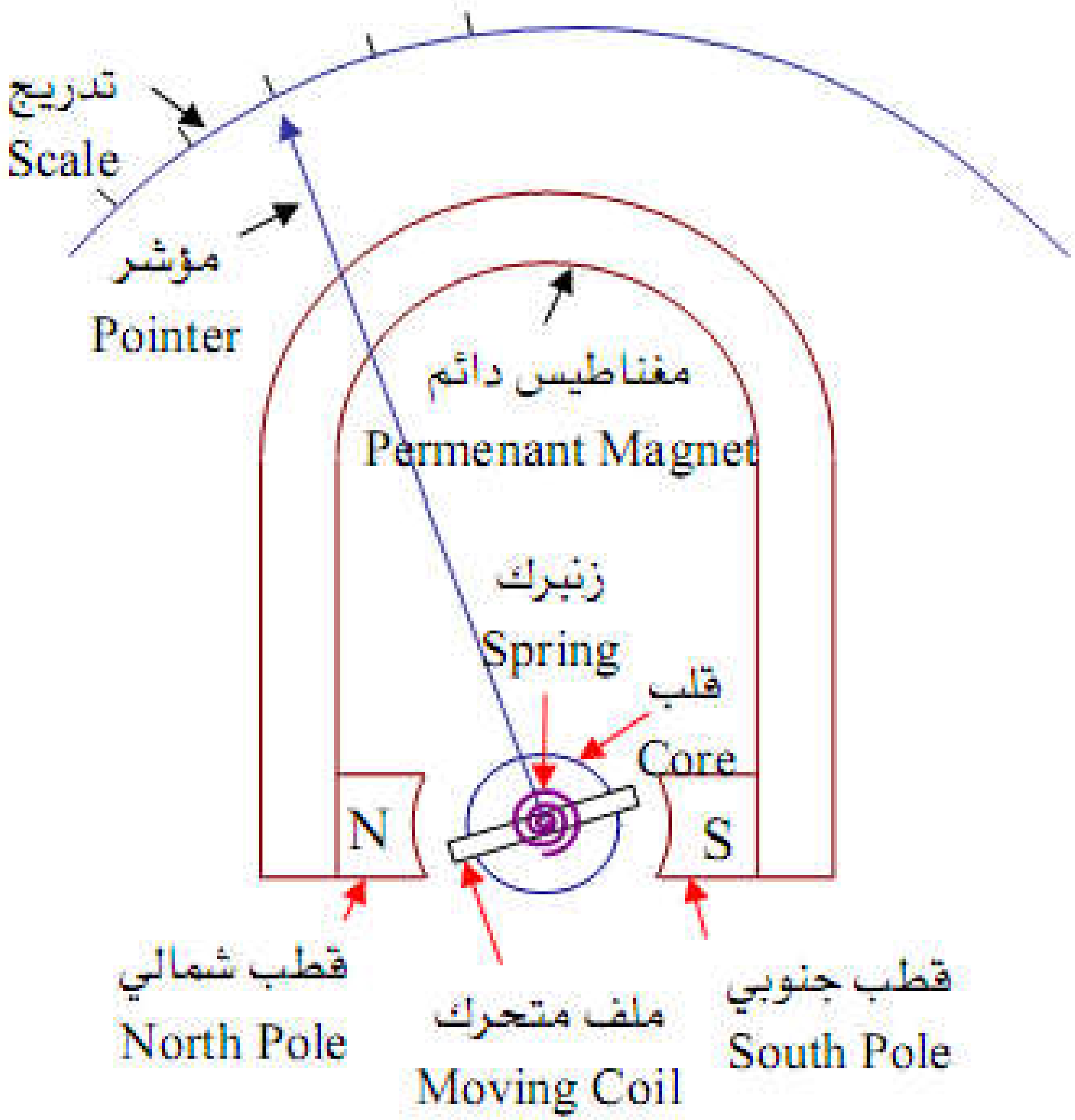
Learning Outcomes

- At the end of the chapter, students should be able to:
  - Understand construction and operation of permanent magnet moving-coil (PMMC) instrument.
  - Describe how PMMC instruments are used as galvanometers, dc ammeters, dc voltmeters, ac ammeters, and ac voltmeters.

Introduction

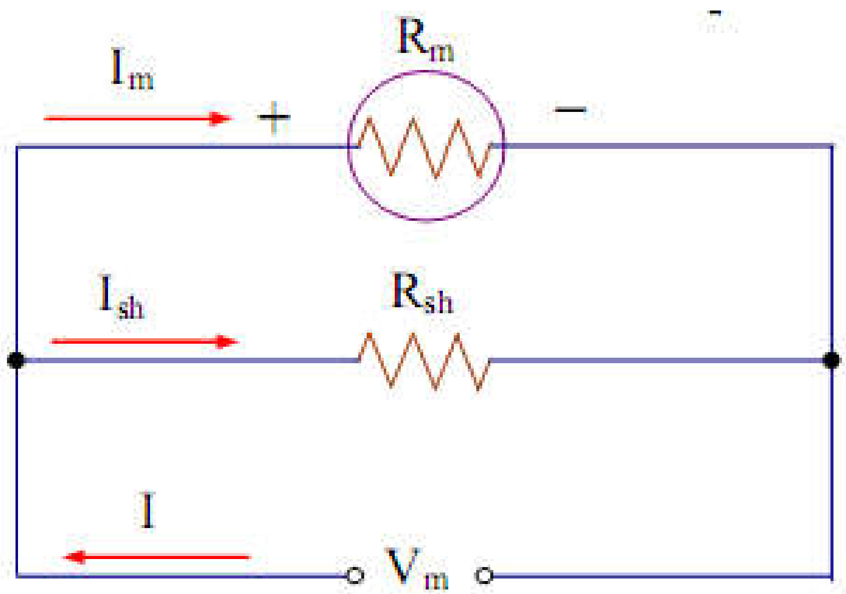
- PMMC instrument consists basically of a lightweight coil of copper wire suspended in the field of a permanent magnet. Current in the wire causes the coil to produce a magnetic field that interacts with the field from the magnet, resulting in partial rotation of the coil. A pointer connected to the coil deflects over a calibrated scale, indicating the level of current flowing in the wire.

- The PMMC instrument is essentially a low-level dc ammeter.


تدريج
Scale
مؤشر
Pointer
مغناطيس دائم
Permenant Magnet
زنبرك
Spring
قلب
Core
N
S
قطب شمالي
North Pole
ملف متحرك
Moving Coil
قطب جنوبي
South Pole

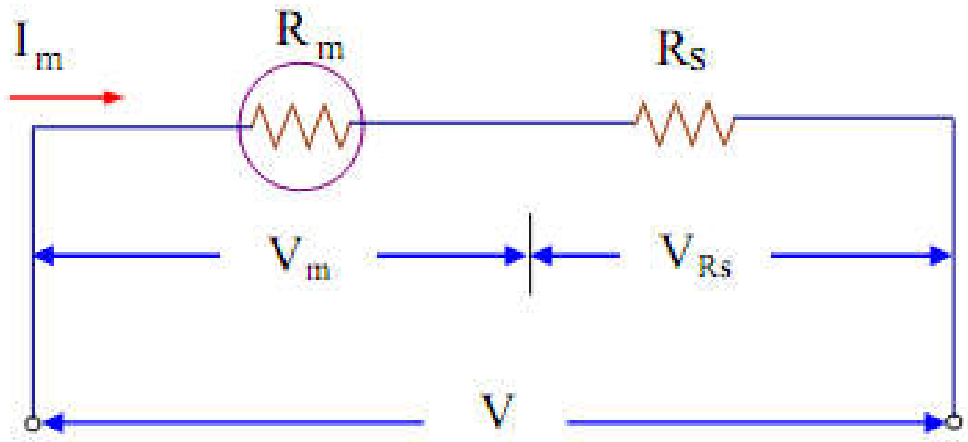
Introduction

- It can be employed to measure a wide range of direct current dc levels with the use of parallel-connected resistors.

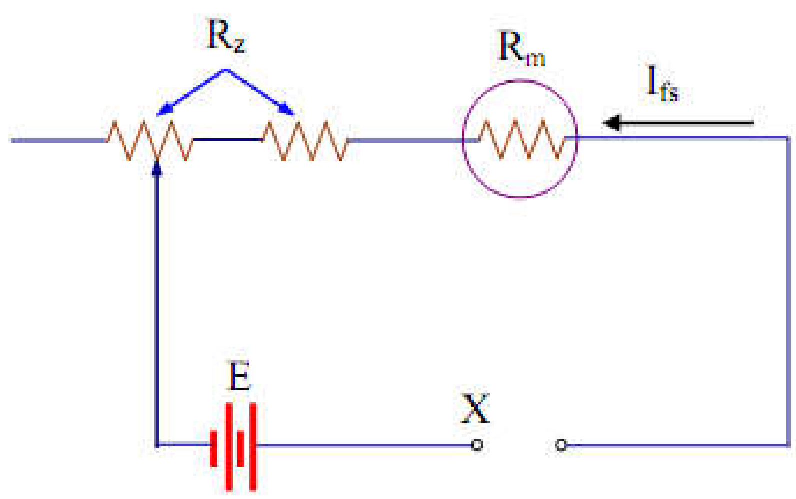


الدائرة الأساسية لزيادة مدى قياس التيار.

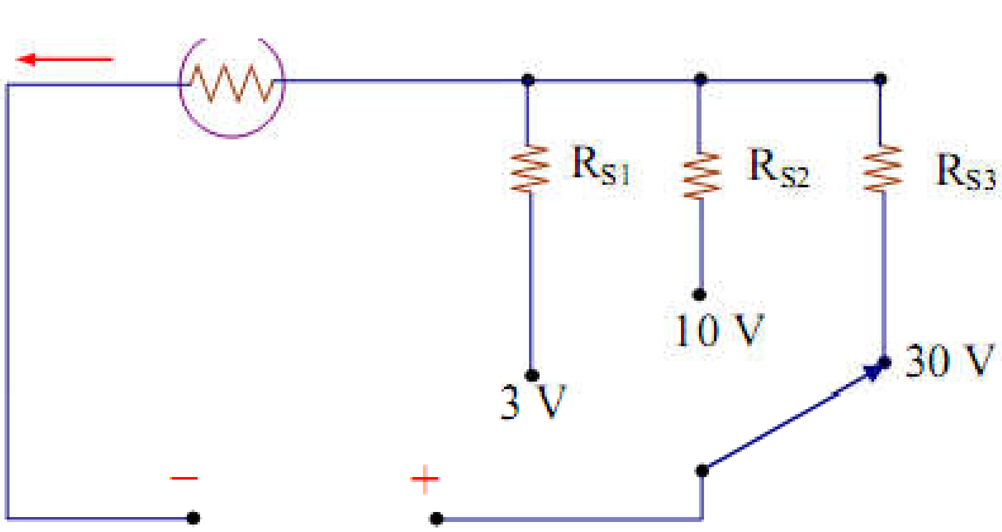
- **The instrument may also be used as a dc voltmeter by connecting appropriate-value resistors in series with the coil.**



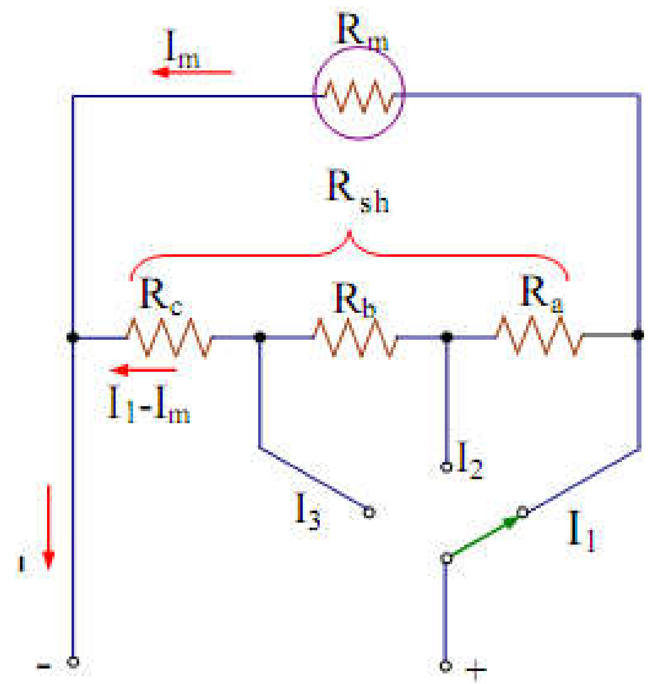
- **Ohmmeters can be made from precision resistors, PMMC instrument, and batteries.**



- **Multirange meters are available that combine ammeter, voltmeter, and ohmmeter functions in one instrument**

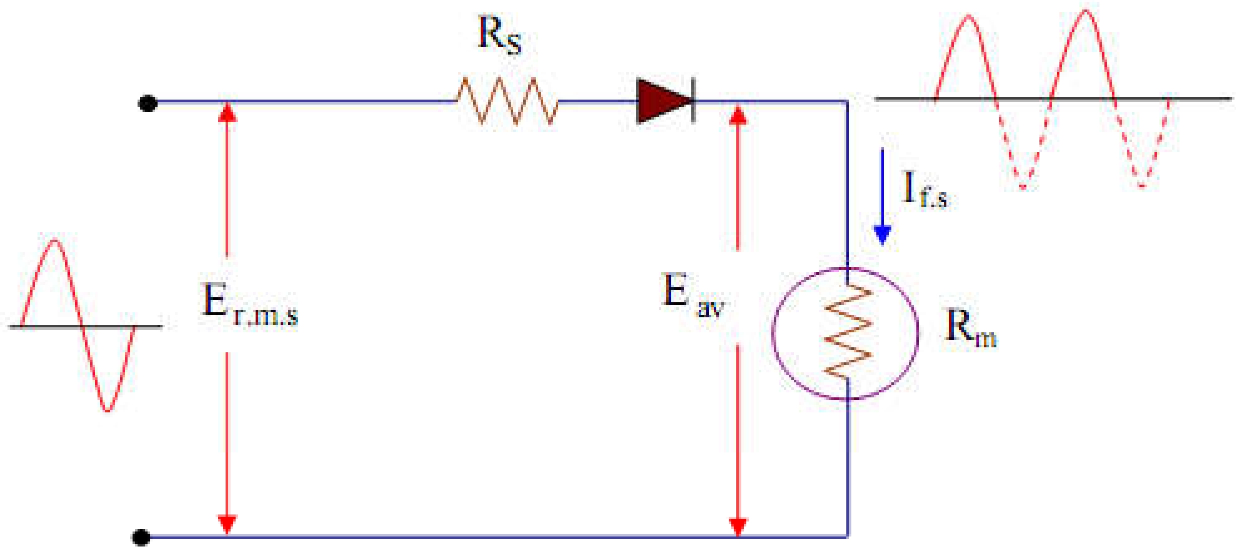


Mutlirange Voltmeter



Mutlirange Ammeter

- Ac ammeters and voltmeters can be constructed by using rectifier circuits with PMMC instruments.



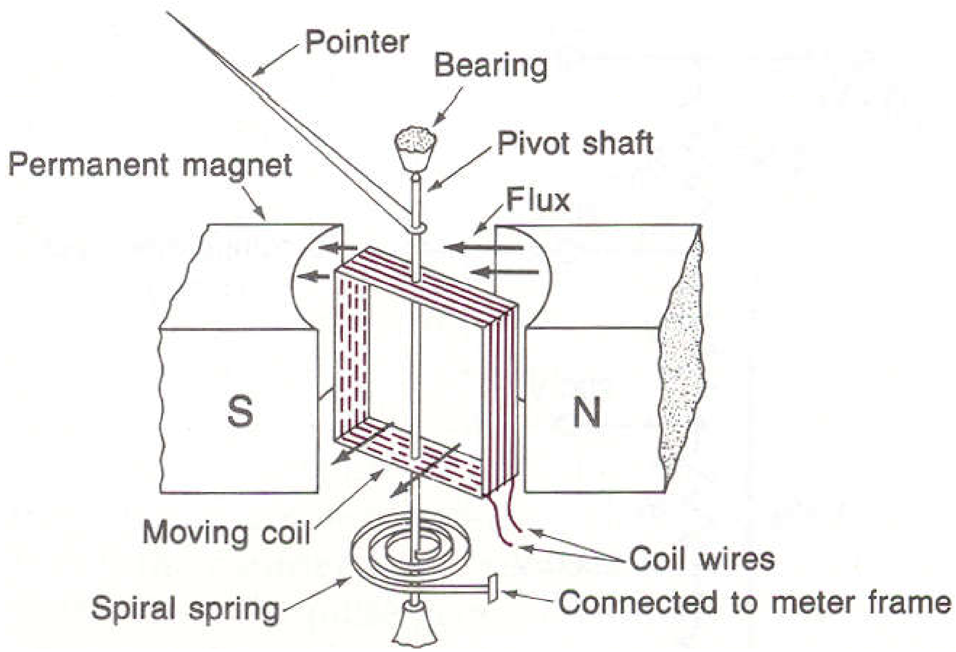
The Half wave rectifier

Deflection Instrument Fundamentals

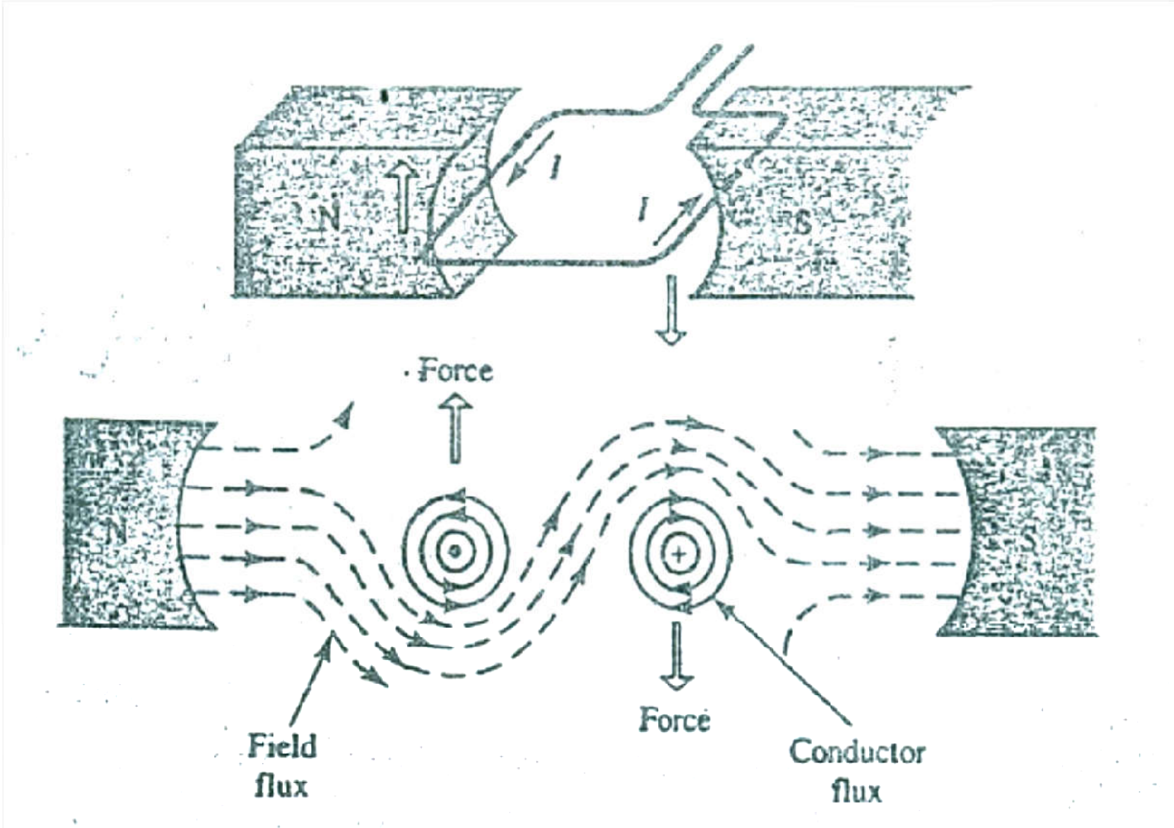
- A deflection instrument uses a pointer that moves over a calibrated scale to indicate a measured quantity.
- Three forces are operating in the electromechanical mechanism inside the instrument:
  - Deflecting force
  - Controlling force
  - Damping force

Deflecting Force

- The deflecting force causes the pointer to move from its zero position when a current flows.
- In the PMMC instrument, the deflecting force is magnetic.



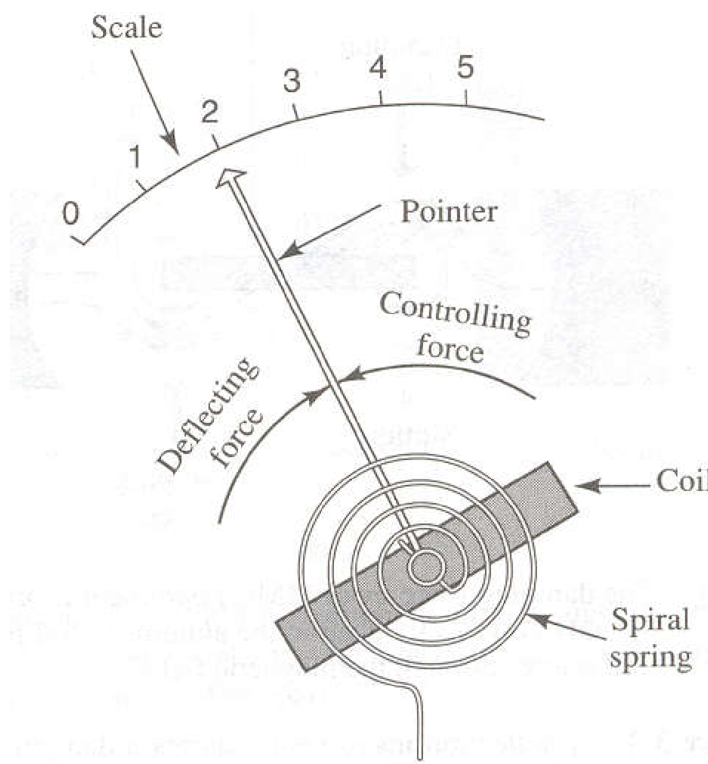
The pointer is fixed to the coil
So, it moves over the scale as
The coil rotates



The deflecting force in the PMMC instrument is provided by A current-carrying coil pivoted in a magnetic field.

Controlling Force

- The controlling force in the PMMC instrument is provided by spiral springs.
- The springs retain the coil & pointer at their zero position when no current is flowing.
- The coil and pointer stop rotating when the controlling force becomes equal to the deflecting force.
- The spring material must be nonmagnetic to avoid any magnetic field influence on the controlling force.

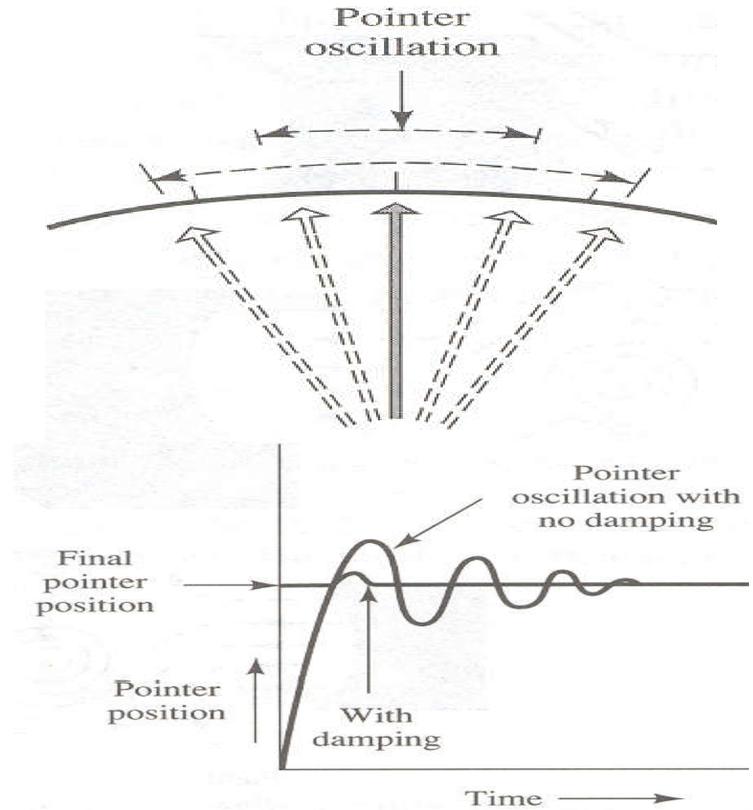


The controlling force from the springs balances the deflecting force.

- **The springs are also used to make electrical connection to the coil, they mush a low resistance(Phosphor bronze is the material usually employed).**

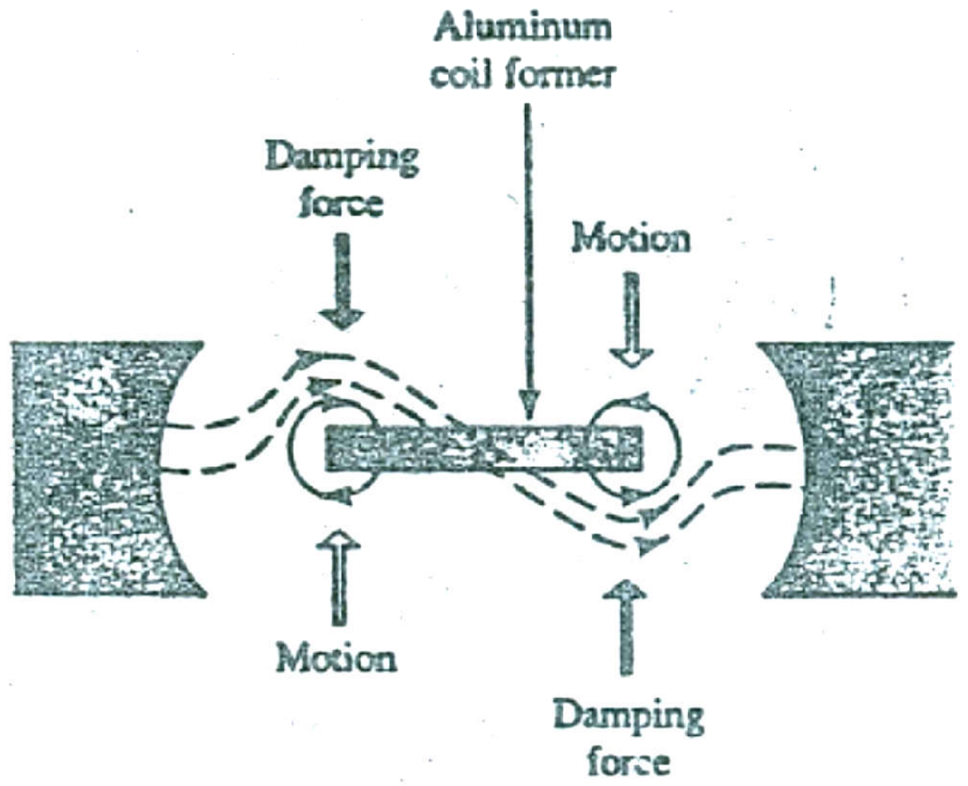
Damping Force

- The damping force is required to minimize (or damp out) oscillations of the pointer and coil before settling down at their final position.
- The damping force must be present only when the coil is in motion; thus it must be generated by the rotation of the coil.
- In PMMC instruments, the damping force is normally provided by eddy currents.
- Eddy currents induced in the coil set up a magnetic flux that opposes the coil motion, thus damping the oscillations of the coil.



Damping Force

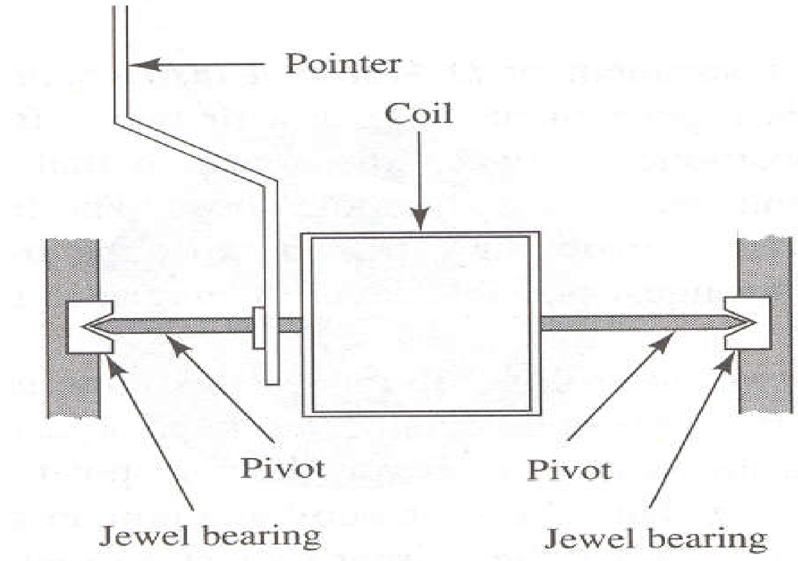
- The damping force in a PMMC instrument is provided by eddy currents induced in the aluminum coil former as it moves through the magnetic field.

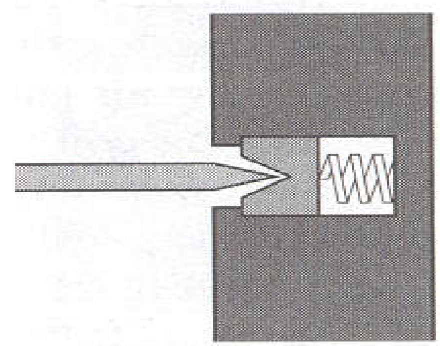


The methods of supporting the moving system of a deflection instrument

1. Jeweled-bearing suspension

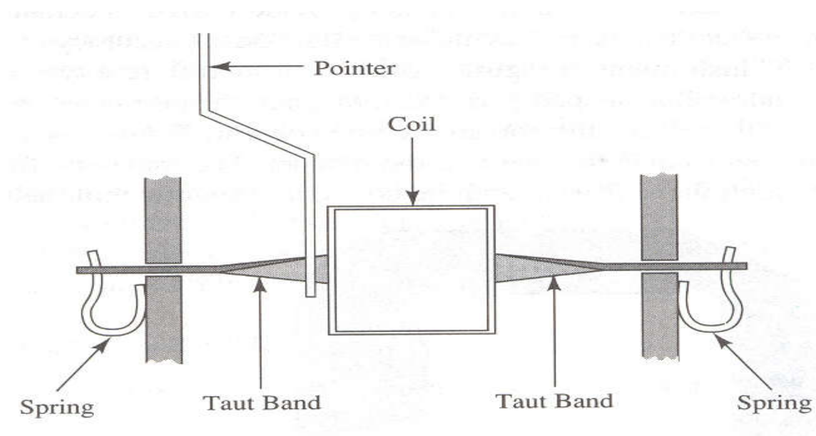
- Cone-shaped cuts in jeweled ends of shafts or pivots *(mat be broken by shocks).*
- low possible friction.
- Some jewel bearings are spring supported to absorb such shocks.





Spring-supported jewel bearing

2. Taut-band method



- Much tougher than jeweled-bearing.
- Two flat metal ribbons (phosphor bronze or platinum alloy) are held under tension by spring to support the coil.
- Because of the spring, the metal ribbons behave like rubber under tension. Thus, the ribbons also exert a controlling force as they twist.
- The metal ribbons can be used as electrical connections to the moving coil.
- Much more sensitive than the jeweled-bearing type because there is less friction.
- Extremely rugged, not easily be shattered.

PMMC Construction

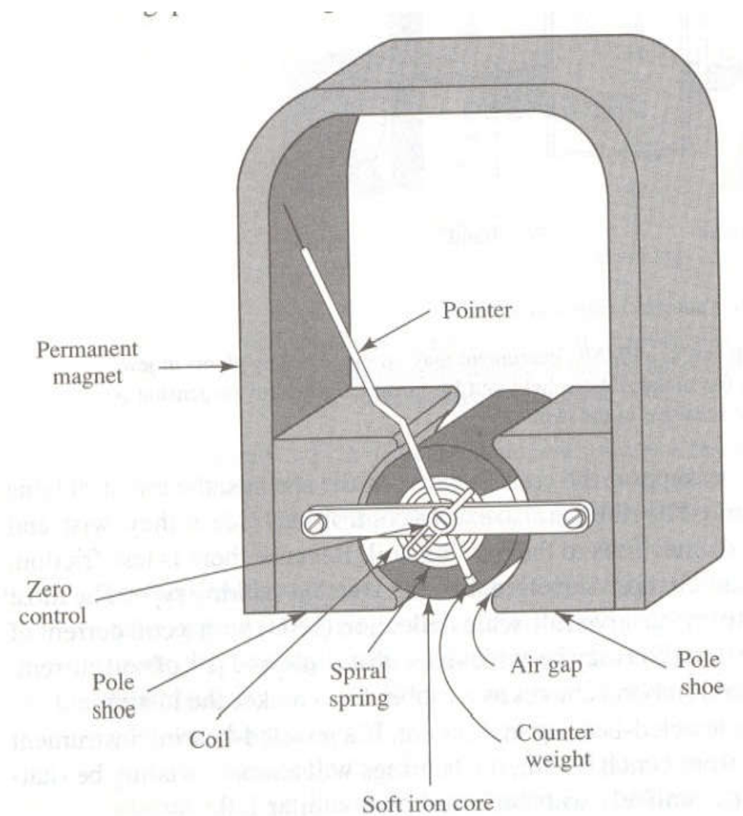
- The main feature is a permanent magnet with two soft-iron pole shoes.
- A cylindrical soft-iron core is positioned between the core and the faces of the pole shoes.
- The lightweight moving coil pivoted to move within these narrow air gaps.
- The air gaps are made as narrow as possible in order to have the strongest possible level of magnetic flux crossing the gaps.

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.
Because the PMMC is polarized, it can be used directed to measure alternating current.

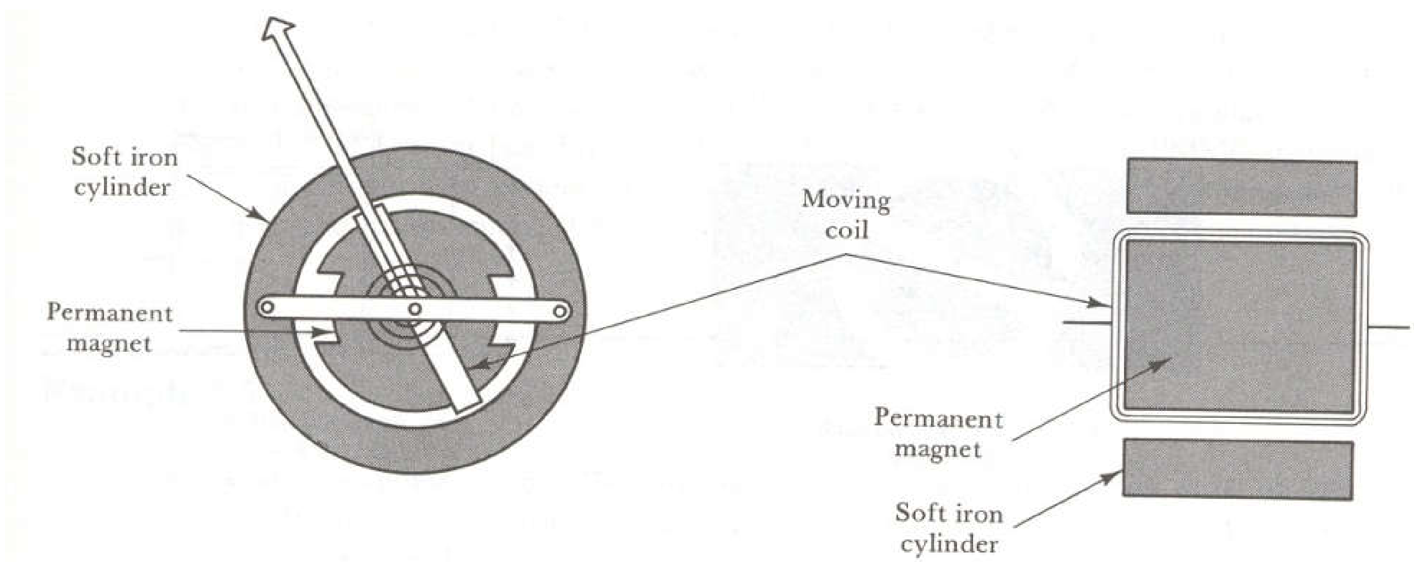
PMMC Construction

D’Arsonval or horseshoe magnet

جهاز دارسونفال للقياس ذي الملف المتحرك



Core-magnet

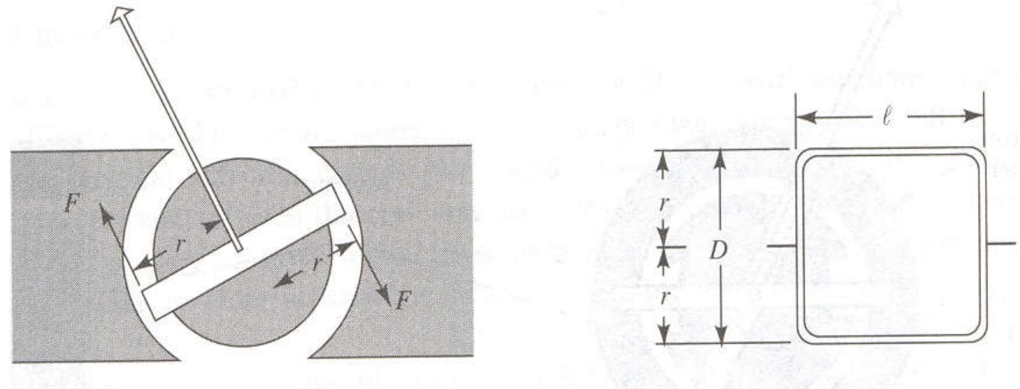


Torque Equation and Scale

- When a current I flows through a one-turn coil situated in a magnetic field, a force F is exerted on each side of the coil

$$F = (BIl) \times N \quad \text{newtons}$$

$$\textit{where } N \textit{ is the number of turns}$$



(a) Force F acts on each side of the coil

(b) Area enclosed by coil is $D \times \ell$

- Total force on each side of the coil of N turns:

$$F = 2\,B\,I\,l\,N \quad newtons$$

- **The force on each side acts at a radius *r*, producing a deflecting torque:**

$$T_D = 2\,B\,l\,I\,N\,r \quad (N.m)$$

$$= B\,l\,I\,N\,(2r)$$

$$T_D = B\,l\,I\,N\,D$$

$$T_D = BlIN\left(2r\right) = BlIND = BAIN$$

$A = l.D$, Where D is the coil diameter

- The controlling torque exerted by the spiral springs is directly proportional to the deformation or windup of the springs.

- Thus, the controlling torque is proportional to the actual angle of deflection of the pointer.

$$T_C = K\theta \quad \text{where } K \text{ is a constant}$$

- For a given deflection, the controlling and deflecting torques are equal:

$$K\theta = BlIND$$

$$\theta = \frac{BlND}{K} I = CI \quad \text{where } C \text{ is a constant}$$

This equation shows that the pointer deflection is always proportional to the coil current.

Consequently, the scale of the instrument is linear, or uniformly divided.

Example 1

- A PMMC instrument with a 100-turn coil has a magnetic flux density in its air gaps of B = 0.2 T. The coil dimensions are D = 1 cm and ***l*** = 1.5 cm. Calculate the torque on the coil for a current of 1 mA.

- Solution:

$$T_D = B\,l\,I\,N\,D$$

$$= 0.2 \times (1.5 \times 10^{-2}) \times 0.001 \times 100 \times (1 \times 10^{-2})$$

$$T_D = 3 \times 10^{-6}\ N.m$$

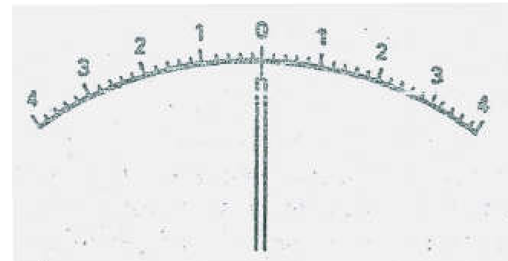
Galvanometer

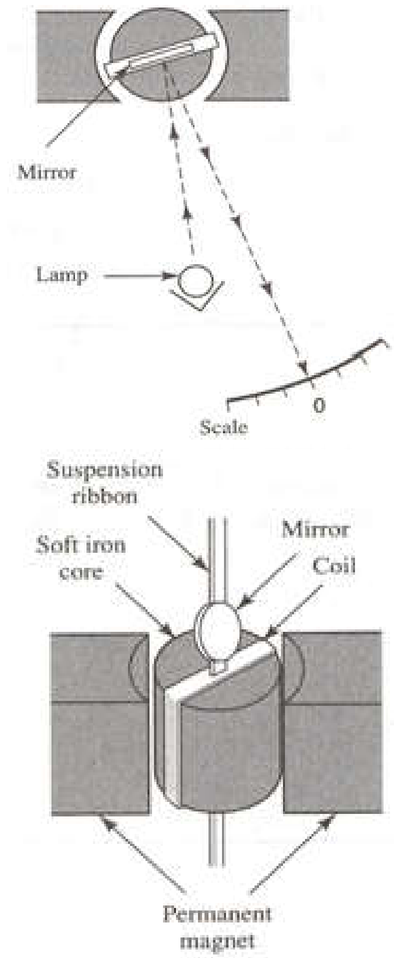
- It is a *PMMC instrument* designed to be sensitive to extremely low current levels.
- The simplest galvanometer is a very sensitive instrument with the type of ***center-zero scale.***

- Galvanometers are often employed *to detect zero* current or voltage in a circuit rather than to measure the actual level of current or voltage.

- The most sensitive moving-coil galvanometer use *taut-band suspension*, and the controlling torque is generated by the twist in the suspension ribbon.

- For the for greatest sensitivity, the weight of the pointer can create a problem. The solution is by *mounting a small mirror* on the moving coil instead of a pointer

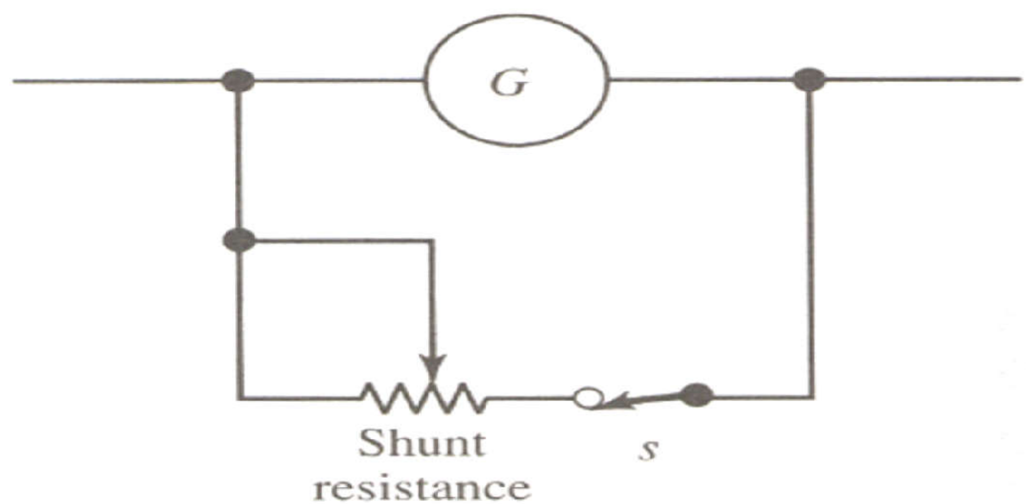




Basic deflection system of
a galvanometer using a light beam

- An adjustable shunt resistor is employed to protect the coil of a galvanometer from destructively excessive current levels.

- The shunt resistance is initially set to zero, then gradually increased to divert current through the galvanometer.



Example 2

- A galvanometer has a current sensitivity of 1 μA/mm and a critical damping resistance of 1 kΩ. Calculate (a) the voltage sensitivity and (b) the megaohm sensitivity.
- Solution:

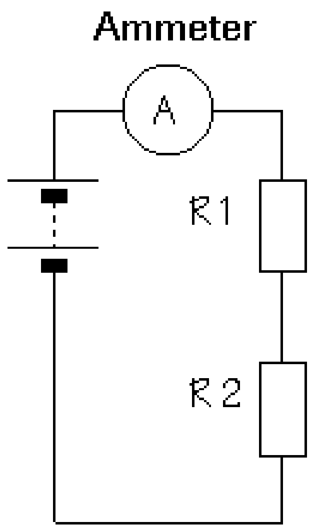
$$Voltage\ sensitivity = 1\,\mathrm{k\Omega} \times 1\,{}^{\mu A}\!/_{\mathrm{mm}}$$

$$= 1\,\mathrm{mV/mm}$$

For a voltage sensitivity of 1 V/mm,

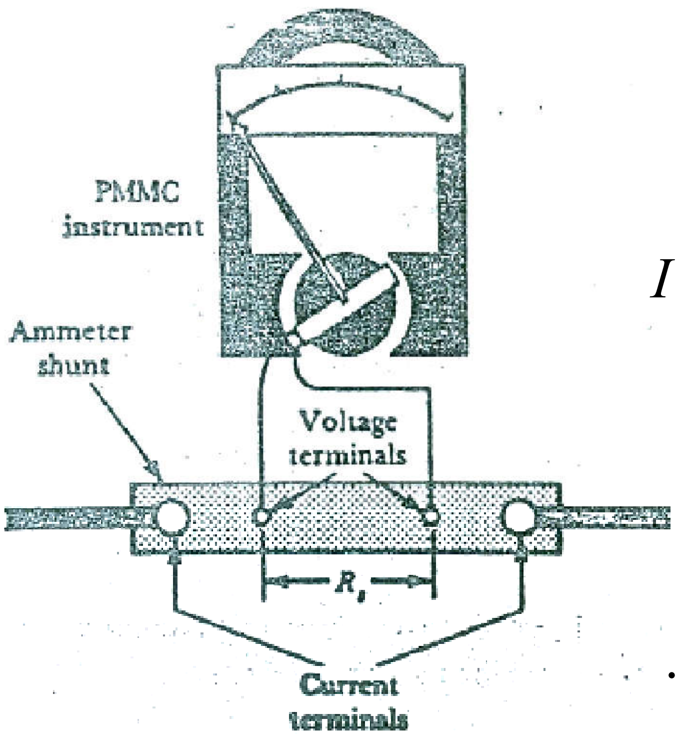
$$megohm\ sensitivity = \frac{1\,\mathrm{V/mm}}{1\,{}^{\mu A}\!/_{\mathrm{mm}}} = 1\,\mathrm{M\Omega}$$

DC Ammeter



- An ammeter is always connected in series with a circuit in which current is to be measured.
- To avoid affecting the current level in the circuit, the ammeter must have a resistance much lower than the circuit resistance.
- For larger currents, the instrument must be modified so that most of the current to be measured is shunted *(a very low shunt resister)* around the coil of the meter.
- Only a small portion of the current passes through the moving coil.

- A dc ammeter consists of a PMMC instrument and a low-resistance shunt.



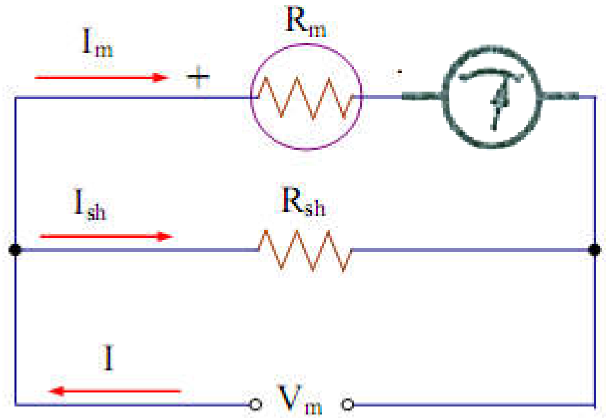
$$V_{sh} = V_m$$

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

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

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

$$\therefore R_{sh} = \frac{I_m R_m}{I - I_m}$$



R_{sh}: مقاومة التوازي

R_m: المقاومة الداخلية للجهاز (مقاومة الملف)

I_{sh}: التيار المار في مقاومة التوازي

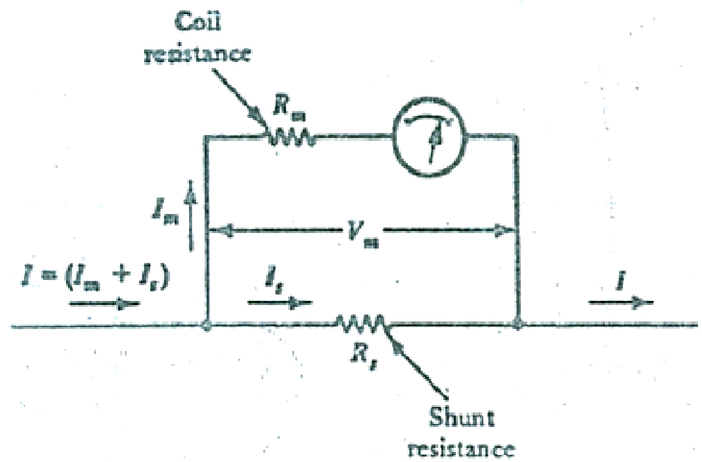
I_m: أقصى تيار يتحمله الملف المتحرك وهو أيضاً التيار الدال على أقصى انحراف للمؤشر

I: التيار الكلي المراد قياسه

Example 3

- A PMMC instrument has FSD of 100 μA and a coil resistance of 1 kΩ. 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) FSD = 100 mA

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

$$I = I_s + I_m$$

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

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

(b) FSD = 1 A

$$V_m = I_m R_m = 100\ mV$$

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

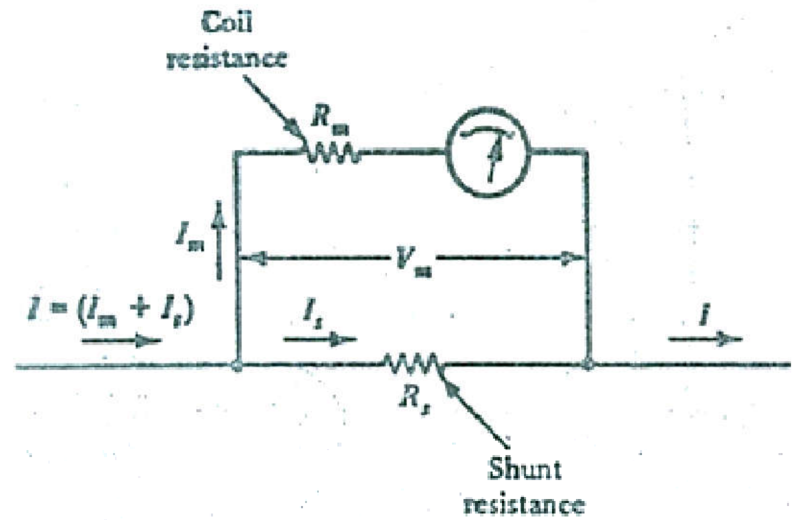
$$R_s = \frac{V_m}{I_s} = \frac{100\ mV}{999.9\ mA} = 0.1001\ \Omega$$

Example: An ammeter has a PMMC instrument with a coil resistance of R_m = 99Ω and FSD current of 0.1 mA. Shunt resistance R_s = 1Ω. Determine the total current passing through the ammeter at :

a) FSD,

b) 0.5 FSD, and

c) 0.25 FSD



Solution

(a) At FSD

$$\text{meter voltage } V_m = I_m R_m$$
$$= 0.1\,\text{mA} \times 99\,\Omega = 9.9\,\text{mV}$$
$$\text{and} \qquad I_s R_s = V_m$$
$$I_s = \frac{V_m}{R_s} = \frac{9.9\,\text{mV}}{1\Omega} = 9.9\,\text{mA}$$
$$\text{total current} \quad I = I_s + I_m = 9.9\,\text{mA} + 0.1\,\text{mA}$$
$$= 10\,\text{mA}$$

(b) At 0.5 FSD

$$I_m = 0.5 \times 0.1\,mA = 0.05\,mA$$

$$V_m = I_m R_m = 0.05\,mA \times 99\Omega = 4.95\,mV$$

$$I_s = \frac{V_m}{R_s} = \frac{4.95\,mV}{1\Omega} = 4.95\,mA$$

$$\textit{total current} \qquad I = I_s + I_m = 4.95\,mA + 0.5\,mA = 5\,mA$$

(c) At 0.25 FSD

$$I_m = 0.25 \times 0.1\,mA = 0.025\,mA$$

$$V_m = I_m R_m = 0.025\,mA \times 99\Omega = 2.475\,mV$$

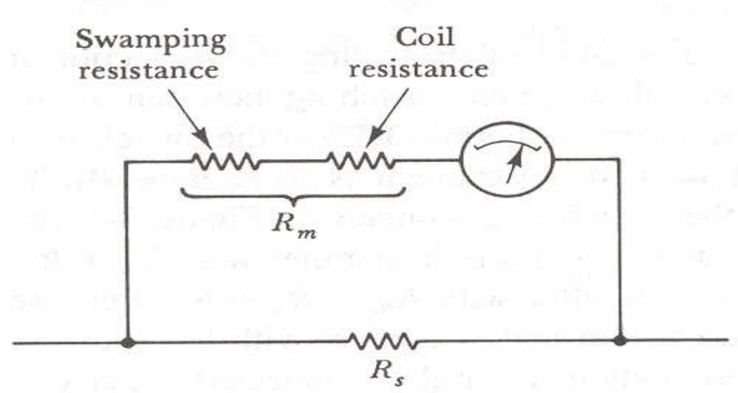
$$I_s = \frac{V_m}{R_s} = \frac{2.475\,mV}{1\Omega} = 2.475\,mA$$

$$\textit{total current} \qquad I = I_s + I_m = 2.475\,mA + 0.025\,mA = 2.5\,mA$$

Thus, the ammeter scale may be calibrated *linearly* from zero to 10mA

Ammeter Swamping Resistance

- The moving coil in a PMMC instrument is wound with thin copper wire, and its resistance can change significantly when its temperature changes.
- The heating effect of the coil current may be enough to produce a resistance change, which will introduce an error.
- To minimize this error, ***a swamping resistance*** made of manganin or constantan is connected in series with the coil: (manganin and constantan have resistance temperature coefficients very close to zero).



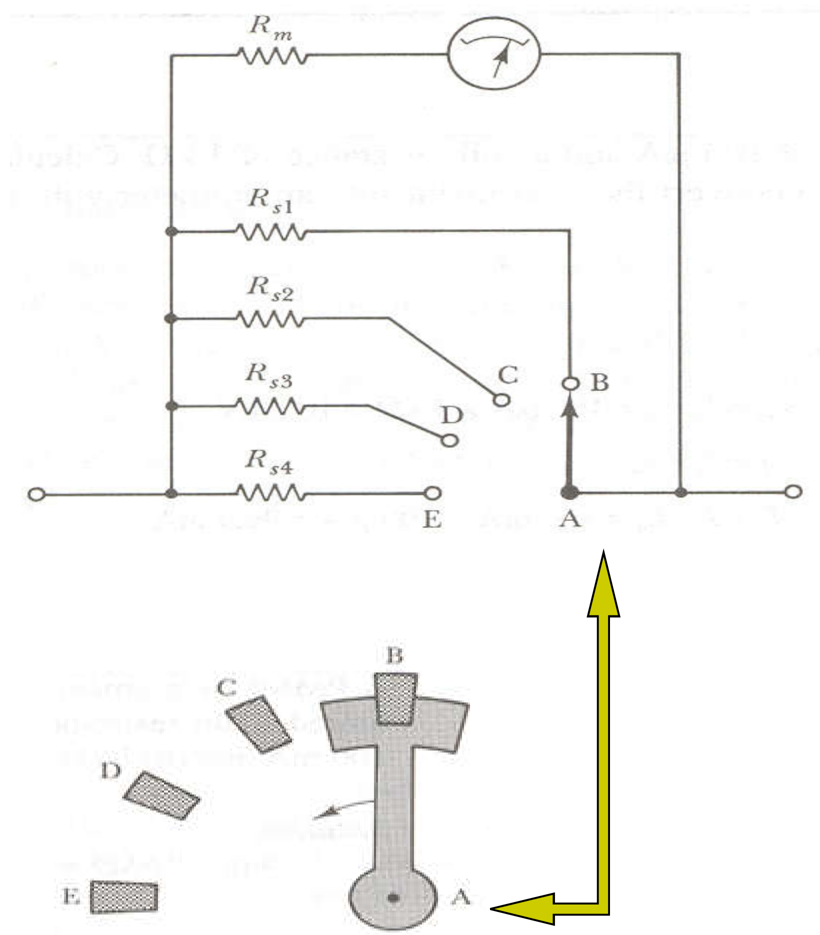
- The ammeter shunt *must also be made* of manganin or constantan to avoid shunt resistance variations with temperature.

Multirange Ammeters

Make-before-break switch

- The instrument is not left without a shunt in parallel with it even for a brief instant. If this occurred, the high resistance of the instrument would affect the current flowing in the circuit.

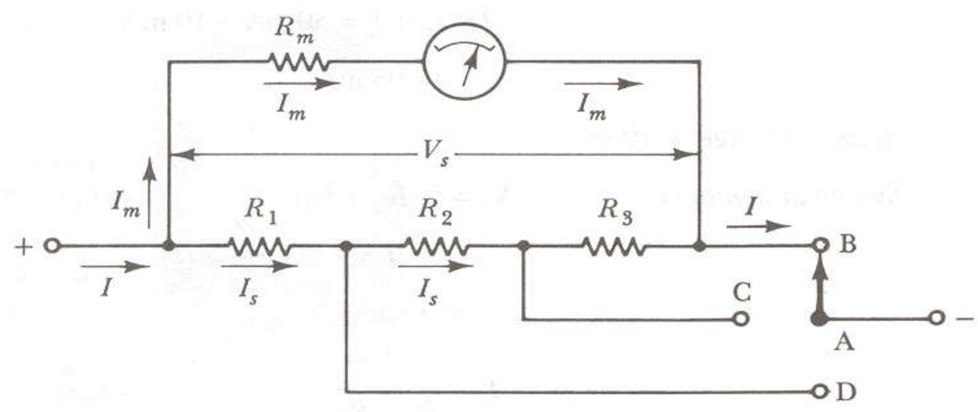
- During switching there are actually two shunts in parallel with the instrument.



Make-before-break switch

Ayrton Shunt

The figure shows another method of protecting the deflection instrument of an ammeter from excessive current flow when switching between shunts. Resistors R_1, R_2, and R_3 constitute an ***Ayrton Shunts***

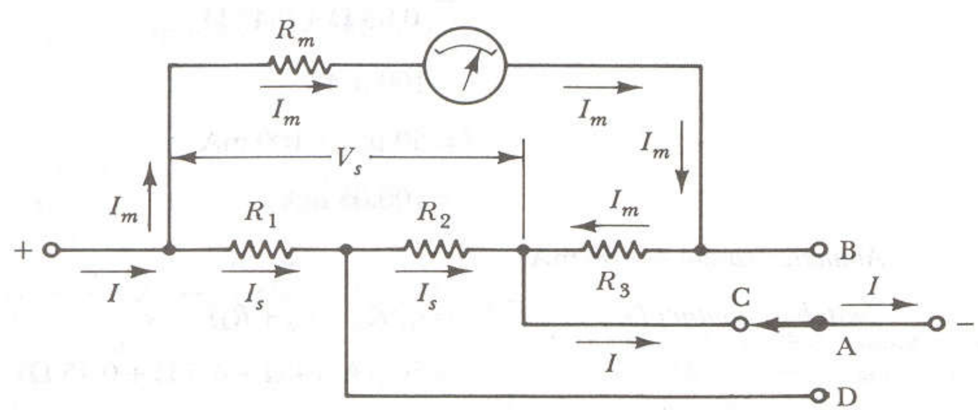


(a) $\underbrace{(R_1 + R_2 + R_3)}_{R_{sh}}$ in parallel with R_m → R_m^*

- Internal Ammeter Resistance: R_{in}

$$R_{in} = \frac{V_s}{I}$$

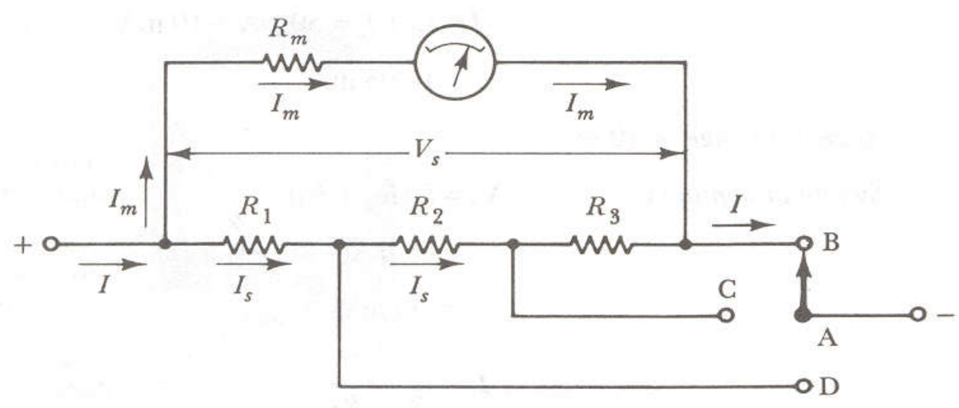
$$R_{in} = R^*_m / / R_{sh} = \frac{R^*_m R_{sh}}{R^*_m + R_{sh}}$$



(b) $\underbrace{(R_1 + R_2)}_{R_{sh}}$ in parallel with $\underbrace{(R_m + R_3)}_{R_m^*}$

Example: A PMMC instrument has a three-resistor Ayrton shunt connected across it to make an ammeter as shown in the figure. The resistance values are $R_1 = 0.05\Omega$, $R_2 = 0.45\Omega$ and $R_3 = 4.5\Omega$. The meter has $R_m = 1k\Omega$ and FSD = $50\mu A$. Calculate the three ranges of the ammeter.

Solution



Switch at contact B

$$V_s = I_m R_m = 50\mu\text{A} \times 1\text{k}\Omega = 50\text{mV}$$

$$I_s = \frac{V_s}{R_1 + R_2 + R_3} = \frac{50\text{mV}}{0.05\Omega + 0.45\Omega + 4.5\Omega} = 10\text{mA}$$

$$I = I_m + I_s = 50\mu\text{A} + 10\text{mA}$$

$$= 10.05\text{mA}$$

Switch at contact C

$$V_s = I_m\left(R_m + R_3\right) = 50\,\mu A\left(1\,k\Omega + 4.5\,\Omega\right) \approx 50\,mV$$

$$I_s = \frac{V_s}{R_1 + R_2} = \frac{50\,mV}{0.05\,\Omega + 0.45\,\Omega} = 100\,mA$$

$$I = I_m + I_s = 50\,\mu A + 100\,mA$$

$$= 100.05\,mA$$

Switch at contact D

$$V_s = I_m\left(R_m + R_3 + R_2\right) = 50\mu 0\left(1k\Omega + 4.5\Omega + 0.45\Omega\right) \approx 50mV$$

$$I_s = \frac{V_s}{R_1} = \frac{50mV}{0.05\Omega} = 1A$$

$$I = I_m + I_s = 50\mu 0 + 1A$$

$$= 1.00005A$$

Accuracy and Ammeter Loading Effects

- Internal resistance of ideal ammeter is zero Ohm, but in practice, the internal resistance has some values which affect the measurement results.
- This error can be reduced by using higher range of measurement.

Let us calculate the relationship between the true value and the measured value

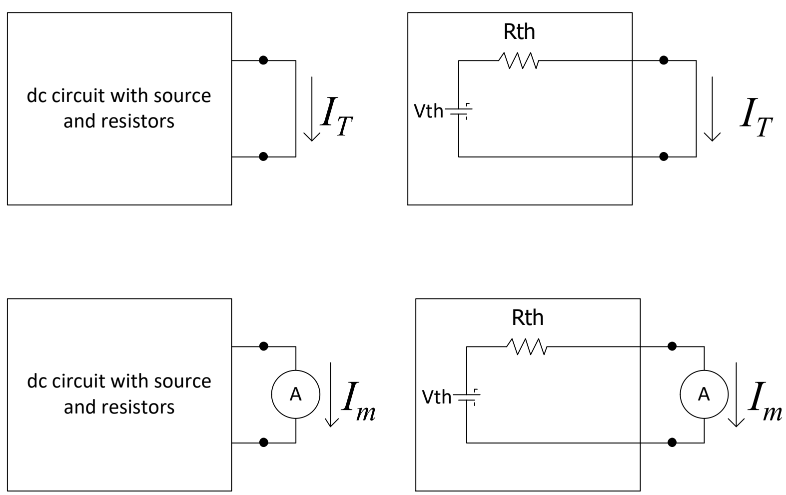
$$I_T\,(true\ value) = \frac{V_{Th}}{R_{Th}}$$

$$I_m\ (measured\ value) = \frac{V_{Th}}{R_{Th} + R_{in}}$$

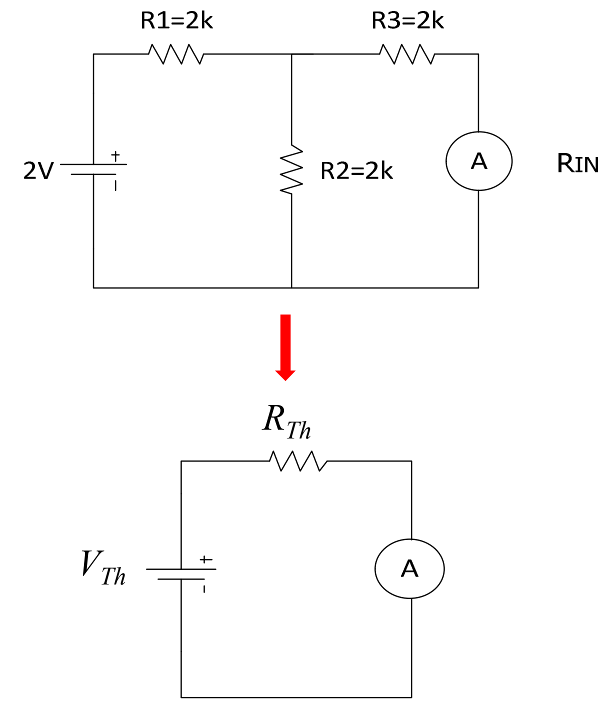
$$\text{Accuracy} = \frac{I_m}{I_T} = \frac{R_{Th}}{R_{Th} + R_{in}}$$

$$\%\ \text{Acc} = \frac{I_m}{I_T} \times 100\%$$

$$= \frac{R_{Th}}{R_{Th} + R_{in}} \times 100\%$$



Example: For a DC Circuit as shown in the figure, given R_1=2kΩ, R_2=2kΩ with voltage of 2V. By measuring the current flow through R_3 with a dc ammeter with internal resistance of R_{in} = 100Ω, calculate percentage of accuracy and percentage of error.



Solution

$$R_{Th} = (R_1 // R_2) + R_3 = 2\,\text{k}\Omega$$

$$V_{Th} = \left(\frac{E}{R_1 + R_2}\right) R_2 = \left(\frac{2\,\text{V}}{2\,\text{k}\Omega + 2\,\text{k}\Omega}\right) \times 2\,\text{k}\Omega = 1\,\text{V}$$

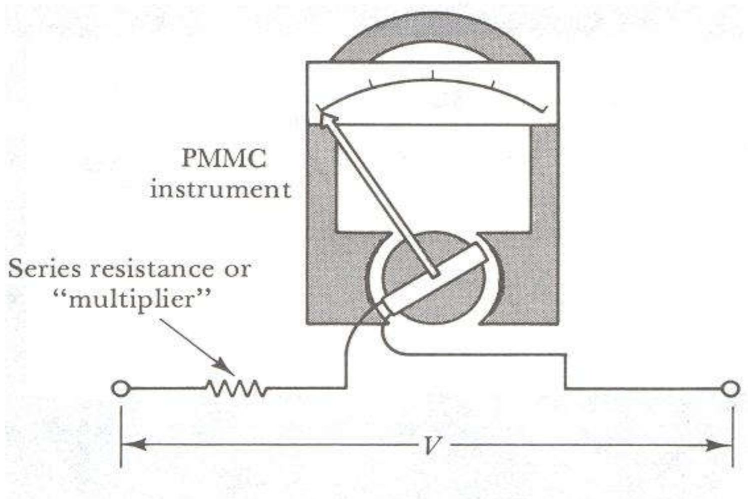
$$I_T = \frac{V_{Th}}{R_{Th}} = \frac{1\,\text{V}}{2\,\text{k}\Omega} = 500\,\mu\text{A}$$

$$I_m = \frac{V_{Th}}{R_{Th} + R_{in}} = \frac{1\,\text{V}}{2\,\text{k}\Omega + 100\,\Omega} = 476.19\,\mu\text{A}$$

$$\%\,\text{Acc} = \frac{\text{I}_\text{m}}{\text{I}_T} \times 100\% = \frac{476.19\,\mu\text{A}}{500\,\mu\text{A}} = 95.24\%$$

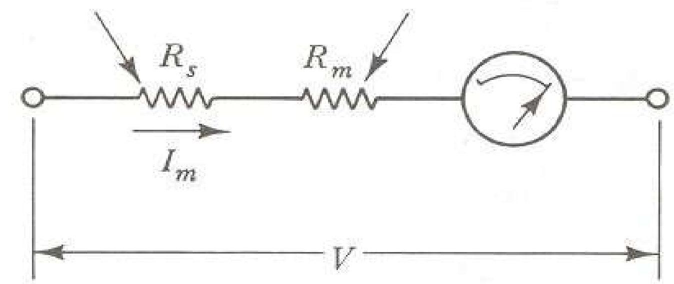
$$\boxed{\%Error = 1 - \%Acc = 1 - 95.24\% = 4.76\%}$$

DC Voltmeter



(a) Construction of dc voltmeter

- The deflection of a PMMC instrument is proportional to the current flowing through the moving coil. The coil current is directly proportional to the voltage across the coil.
- The coil resistance is normally quite small, and thus the coil voltage is also usually very small. Without any additional series (multiplier resistance) resistance the PMMC instrument would only measure very low voltage.
- The voltmeter range is easily increased by connecting a resistance in series with the instrument.



(b) Voltmeter circuit

- The meter current is directly proportional to the applied voltage, so that the meter scale can be calibrated to indicate the voltage.

- **The voltmeter range is increased by connecting a multiplier resistance with the instrument (single or individual type of extension of range).**

$$R_V = R_s + R_m$$

$$V = I_m R_V = I_m R_s + I_m R_m$$

$$\boxed{R_s = \frac{1}{I_m} \times V - R_m}$$

- **Last equation can be used to select the multiplier resistance value (R_s) for certain voltage range (FSD). In this case I_m will be the full scale current.**
- **A multiplier resistance that is nine times the coil resistance will increase the voltmeter range by a factor of 10 (multiplier resistance + coil resistance)**
- **The *voltmeter sensitivity (S)* is defined as the total voltmeter resistance (*internal resistance R_{in}*) divided by the voltage range (full scale)**

$$Sensitivity\ (S) = \frac{Total\ Resistance\ R_{in}}{Range}$$

$$= \frac{1}{Full\ Scale\ Deflection\ Voltage\ (V_{FSD})} \quad K\Omega/V$$

Example:

A PMMC instrument with FSD of 100 μA and a coil resistance of 1kΩ is to be converted into a voltmeter. Determine the required multiplier resistance if the voltmeter is to measure 50V at full scale and Voltmeter sensitivity. Also calculate the applied voltage when the instrument indicate 0.8, 0.5, and 0.2 of FSD.

Solution

- ***At 50 V FSD***

$$V = I_m R_V = I_m R_s + I_m R_m$$

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

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

- **Since the voltmeter has a total resistance of $R_v = R_s + R_m = 500k\Omega$, then its resistance per volt or *sensitivity* is $500k\Omega / 50V = 10\ k\Omega / V$.**

- ***At 0.8 of FSD***

$$I_m = 0.8 \times 100\,\mu\text{A} = 80\,\mu\text{A}$$

$$V = I_m\left(R_s + R_m\right)$$

$$= 80\,\mu\text{A}\left(499\,\text{k}\Omega + 1\,\text{k}\Omega\right) = 40\,\text{V}$$

- ***At 0.5 of FSD***

$$I_m = 50\,\mu\text{A}$$

$$V = 50\,\mu\text{A}\left(499\,\text{k}\Omega + 1\,\text{k}\Omega\right) = 25\,\text{V}$$

- ***At 0.2 of FSD***

$$I_m = 20\,\mu\text{A}$$

$$V = 20\,\mu\text{A}\left(499\,\text{k}\Omega + 1\,\text{k}\Omega\right) = 10\,\text{V}$$

Thus, the voltmeter scale may be calibrated *linearly* from zero to 50 V

Voltmeter Swamping Resistance

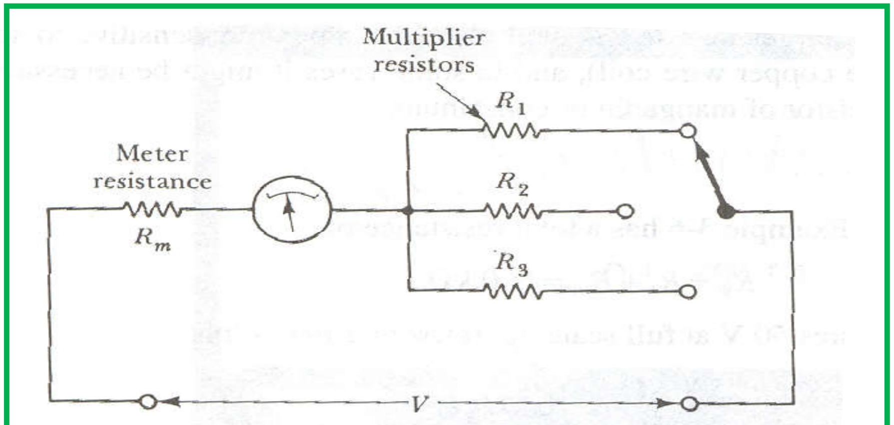
- As in the case of ammeter, the change in coil resistance (R_m) with temperature change can introduce errors in a PMMC voltmeter.

- The presence of the voltmeter multiplier resistance (R_s) tends to swamp coil resistance changes, except for low voltage ranges where R_s is not very much larger than R_m.

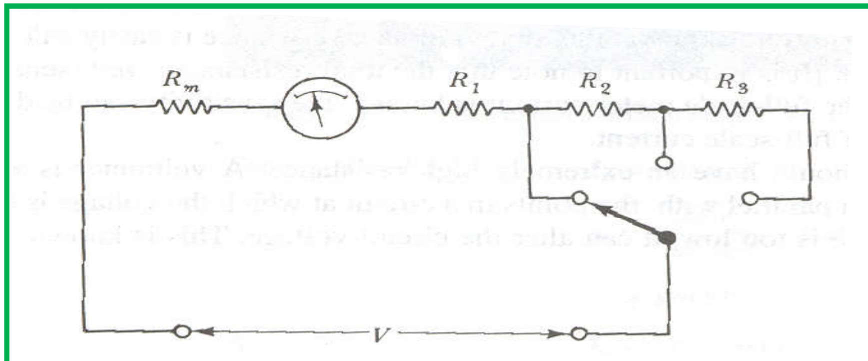
- In some cases it might be necessary to construct the multiplier resistance form manganin or constantan.

Multirange Voltmeters

Individual or *series connected resistors* may be used as shown in the following configurations



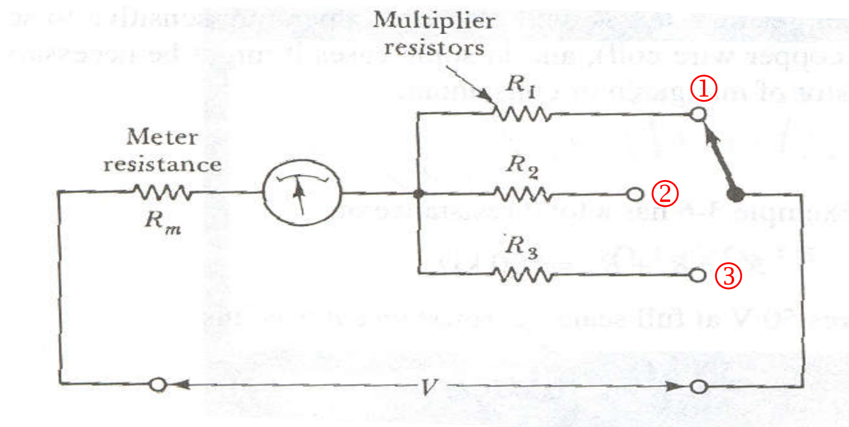
Multirange voltmeter with ranges $V = I_m(R_m+R)$ where R can be R_1, R_2, or R_3



Multirange series voltmeter with ranges $V = I_m(R_m+R)$, where R can be R_1, R_1+R_2, or $R_1+R_2+R_3$

Example:

A PMMC instrument with FSD = 50µA and R_m = 1700Ω is to be employed as a voltmeter with ranges of 10V, 50V, and 100V. Calculate the required values of multiplier resistors for the two circuits shown in the previous slides.



Solution

For the circuit shown

Switch contact at ①

$$R_m + R_1 = \frac{V}{I_m}$$

$$R_1 = \frac{V}{I_m} - R_m$$

$$= \frac{10\,\text{V}}{50\,\mu\text{A}} - 1700\,\Omega = 200\,\text{k}\Omega - 1.7\,\text{k}\Omega$$

$$= 198.3\,\text{k}\Omega$$

Switch contact at ②

$$R_2 = \frac{50V}{50\,\mu A} - 1700\Omega$$

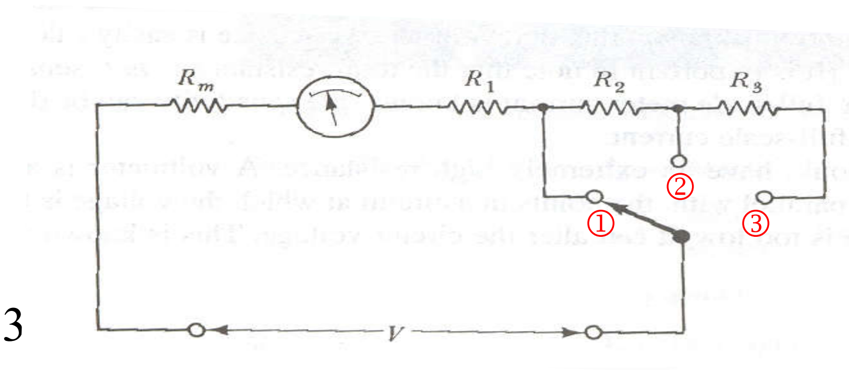
$$= 998.3\,k\,\Omega$$

Switch contact at ③

$$R_3 = \frac{100V}{50\,\mu A} - 1700\,\Omega$$

$$= 1.9983\,M\,\Omega$$

For the circuit shown



Switch contact at ①

$$R_m + R_1 = \frac{V_1}{I_m}$$

$$R_1 = \frac{V_1}{I_m} - R_m = \frac{10\ \text{V}}{50\ \mu\text{A}} - 1700\ \Omega \ = 198.3$$

Switch contact at ②

$$R_m + R_1 + R_2 \ = \frac{V_2}{I_m}$$

$$R_2 = \frac{V_2}{I_m} - R_1 - R_m = \frac{50\ \text{V}}{50\ \mu\text{A}} - 198.3\ \text{k}\Omega - 1700\ \Omega = 800\ \text{k}\Omega$$

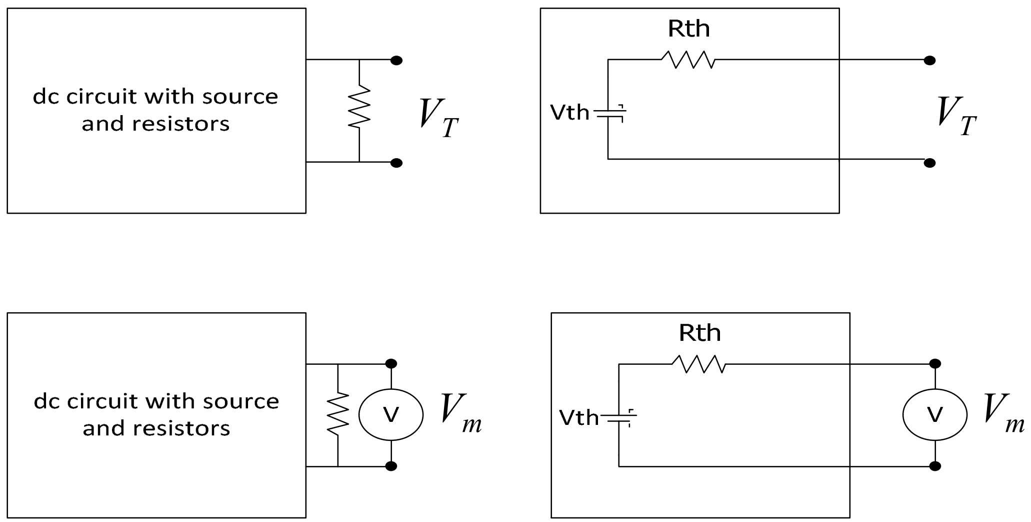
Switch contact at ③

$$R_m + R_1 + R_2 + R_3 = \frac{V_3}{I_m}$$

$$R_3 = \frac{V_3}{I_m} - R_2 - R_1 - R_m = \frac{100\ \text{V}}{50\ \mu\text{A}} - 800\ \text{k}\Omega - 198.3\ \text{k}\Omega - 1700\ \Omega = 1\ \text{M}\Omega$$

Accuracy and Voltmeter Loading Effect

Let us calculate the relationship between the true value (V_T) and the measured value (V_m)



$$V_T = V_{Th}$$

$$V_m = \frac{V_{Th}}{R_{in} + R_{Th}} \times R_{in}$$

$$Accuracy = \frac{V_m}{V_T} = \frac{R_{in}}{R_{in} + R_{Th}}$$

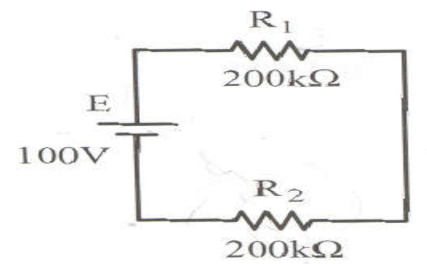
$$\%Acc = \frac{V_m}{V_T} \times 100\%$$

$$\%Acc = \frac{R_{in}}{R_{in} + R_{Th}} \times 100\%$$

Example:

A voltmeter with sensitivity of 20kΩ/V is used for measuring a voltage across R_2 with range of 50V as shown in the figure below.

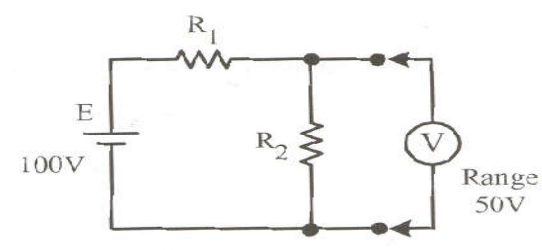
Calculate a) reading voltage. b) accuracy of measurement. c) error of measurement



Solution

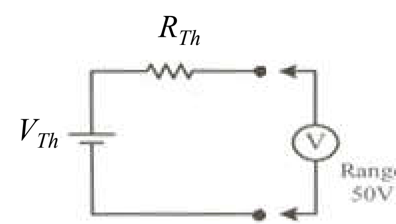
$$V_{Th} = V_T = \left(\frac{E}{R_1 + R_2}\right) R_2 = \left(\frac{100V}{200k\Omega + 200k\Omega}\right) \times 200k\Omega = 50$$

$$R_{Th} = R_1 // R_2 = 200k\Omega // 200k\Omega = 100k\Omega$$



$$\boxed{a) \quad R_{in} = S \times Range = \frac{20k\Omega}{V} \times 50V = 1M\Omega}$$

$$V_m = \left(\frac{R_{in}}{R_{in} + R_{Th}}\right) V_T = \left(\frac{1M\Omega}{1M\Omega + 100k\Omega}\right) \times 50V = 45.45V$$



$$\boxed{b) \quad Accuracy = \frac{V_m}{V_T} = \frac{45.45V}{50V} = 0.909 \quad or \quad \%Acc = 90.9\%}$$

$$\boxed{c) \quad Error = 1 - Acc = 1 - 0.909 = 0.091 \quad \text{or} \quad \%Error = 9.1\%}$$

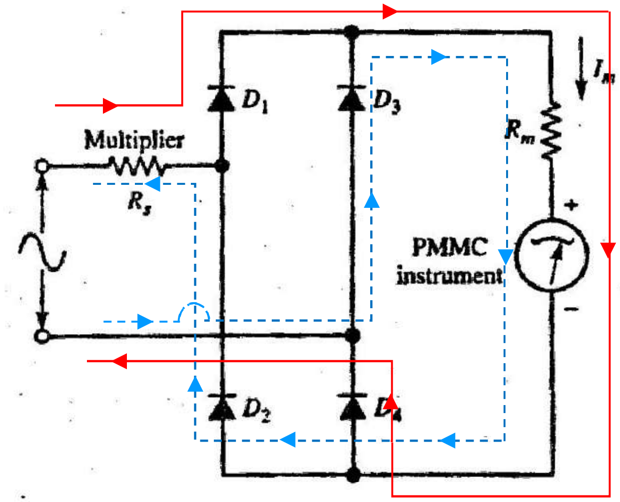
AC Voltmeter

- Full-Wave Rectifier Voltmeter
- Half-Wave Rectifier Voltmeter
- Half-Wave Full Bridge Rectifier Voltmeter

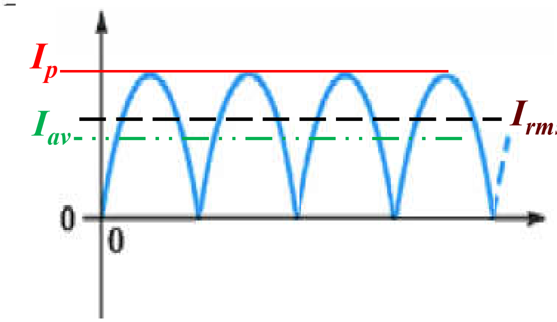
AC Ammeter and Voltmeter

- When *an alternating current* ***(sinusoidal)*** with a very low frequency ***(0.1 Hz or lower)*** is passed through a PMMC instrument, the pointer tends to follow the instantaneous level of the AC.
  - As the current grows positively, the pointer deflection increases to a maximum at the peak of the ac.
  - Then as the instantaneous current level falls, the pointer deflection decreases towards zero.
  - When the ac goes negative, the pointer is deflected (off-scale) to the left of zero.
- **With the *normal 50 Hz or higher* supply frequencies, the damping mechanisms and the inertia of the meter movement prevent the pointer from following the changing instantaneous levels of the signal.**
  - **The instruments pointer *settles at the average value of the current* flowing through the moving coil which is *zero.***
- **PMMC instrument can be modified by one of the following circuits to measure AC signals**

1. Full-Wave Bridge Rectifier Voltmeter



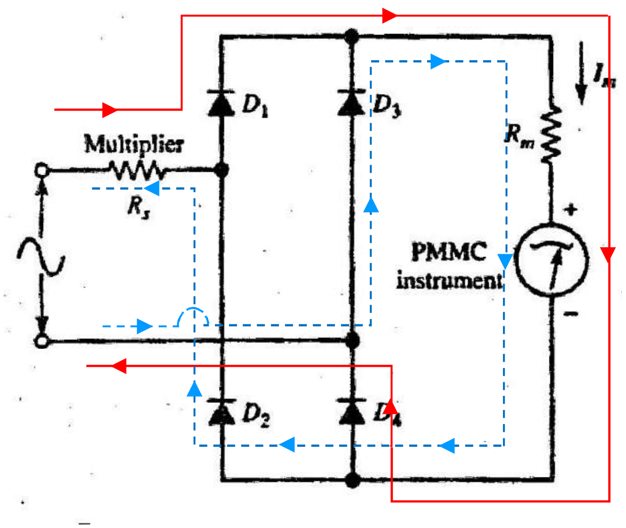
- When the input is positive, diodes D_1 and D_4 conduct, causing current to flow through the meter from top to bottom (red solid path).
- When the input goes negative, diodes D_2 and D_3 conduct, current flows through the meter from the positive to the negative terminal (blue dashed path).

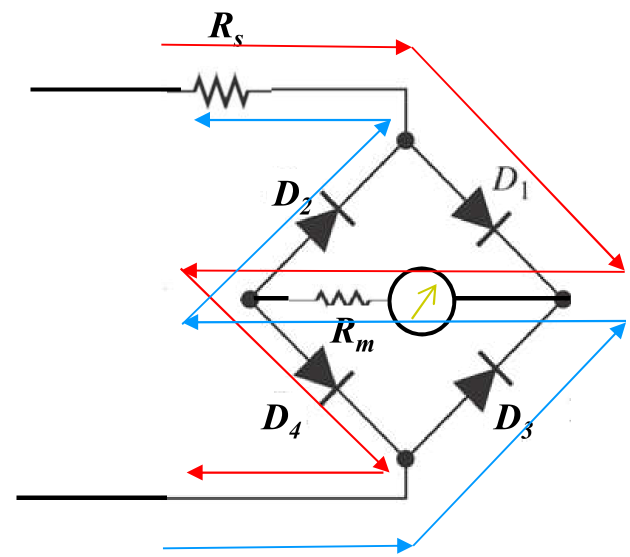


- The ac voltmeter uses a series-connected multiplier resistor (R_s) to limit the current flow through the instrument.
- The meter deflection is proportional to the average current (I_{av}), which is 0.637 × peak current (I_p or I_m).
- But the actual current (or voltage) to be indicated in ac measurement is normally the $I_{rms} = 0.707 \times I_p$ (or I_m) .

  (note $I_{rms} = 1.11 \times I_{av}$ I_p (or I_m) = $1.414 \times I_{rms}$)

- When other than pure sine waves are applied, the voltmeter will not indicate the rms voltage.





$$I_m = \frac{\text{applied peak voltage } (V_p) - \text{rectifiers voltage drop}}{\text{totat circuit resistance}} = \frac{1.414V_{rms} - 2V_F}{R_s + R_m}$$

V_F is rectifier voltage drops for D_1 and D_2 *or* D_3 and D_4

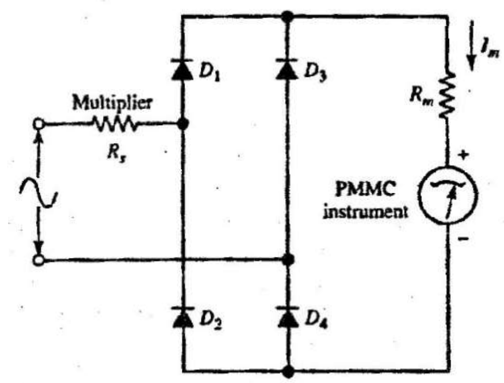
Peak current $I_m = I_{av}/0.637 = I_{FSD}/0.637$

Example:

A PMMC instrument with FSD = 100 μA and R_m = 1 kΩ is to be employed as an ac voltmeter with FSD = 200 V (rms). Silicon diodes with V_F = 0.7 V are used in the bridge rectifier circuit of shown above. Calculate: (a) the multiplier resistance value required, (b) the pointer indications the rms input voltage is (i)100V and (ii) 50 V.

Solution

At FSD, the average current flowing through the PMMC instrument is 100µA



$$I_{\mathrm{m}} = \frac{I_{av}}{0.637} = 157\ \mu A$$

$$V_p = 1.414 V_{rms} = 1.414 \times 200 = 282.8\ Volt$$

(a) $$I_m = \frac{V_p - 2V_F}{R_s + R_m} \Longrightarrow R_s = \frac{V_p - 2V_F}{I_m} - R_m$$

$$= \frac{(282.8 - 1.4)V}{(157 \times 10^{-3})mA} - 1k\,\Omega = 1791.36\,k\,\Omega$$

(b) **i-for the rms input voltage is 100V** $$I_m^{\backslash} = \frac{V_p^{\backslash} - 2V_F}{R_s + R_m} = \frac{1.414 \times 100 - 1.4}{(1791.36 + 1)k\,\Omega} = 78.11\,\mu A$$

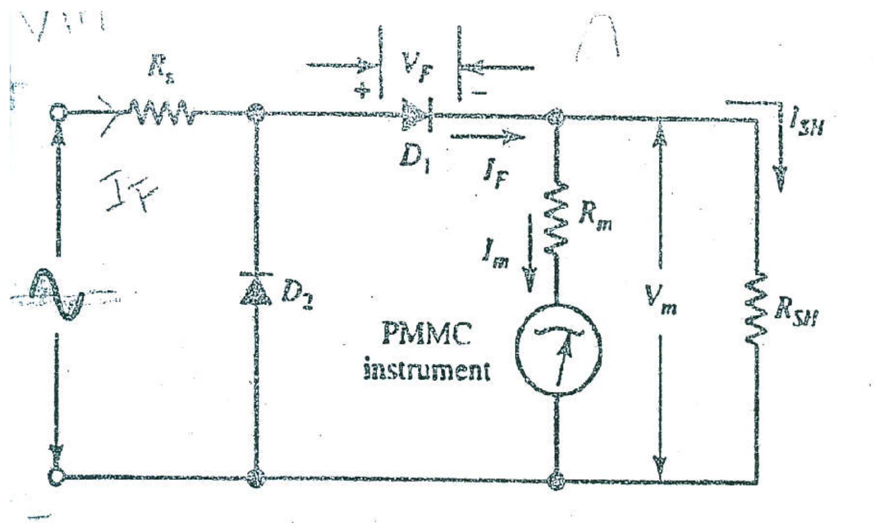
$$I_{av}^{\backslash} = 0.607 \times I_m^{\backslash} = 49.76\ \mu A \cong 50\ \mu A = 0.5FSD$$

ii- Similarly, for the rms input voltage is 50V

$$I_{av}^{\backslash\backslash} \cong 25\mu A = 0.25\,FSD$$

2. Half-Wave Rectifier Voltmeter

- R_{SH} shunting the meter is included to cause a relatively large current to flow through diode D_1 (larger than the meter current) when the diode is forward biased. This is ensure that the diode is biased beyond the knee and will into the linear range of its characteristics.
- Diode D_2 conducts during the negative half-cycles of the input. When conducting, D_2 cause a small voltage drop across D_1 and the meter, thus preventing the flow of any significant reverse leakage current (and reverse voltage) through the meter via D_1.

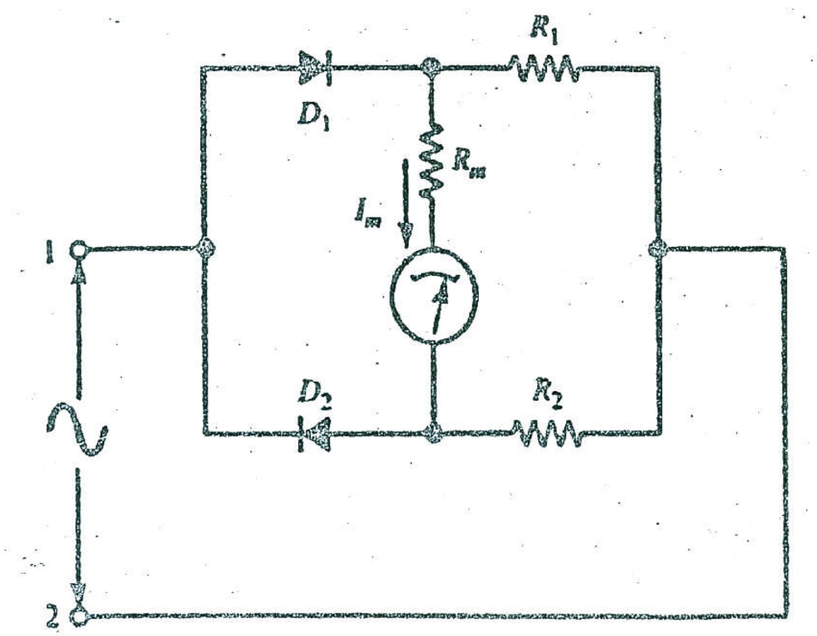


In the half wave rectifier

$$I_{av} = 0.5 * 0.637 I_m$$

Half-Bridge Full-Wave Rectifier Voltmeter

- During the positive half-cycle of the input, diode D_1 is forward biased and D_2 is reverse biased. Current flows from terminal 1 through D_1 and the meter and then through R_2 to terminal 2. but R_1 is in parallel with the meter and R_2. Therefore, much of the current flowing in D_1 pass through R_1 while only part of it flows through the meter and R_2
- During the negative half-cycle, diode D_2 is forward biased and D_1 is reverse biased. Current flows from terminal 2 through R_1 and the meter and then through D_2 to terminal 1. New, R_2 is in parallel with the series connected meter and R_1
- This arrangement forces the diodes to operate beyond the knee of their characteristics and helps to compensate for differences that might occur in the characteristics of D_1 and D_2 .



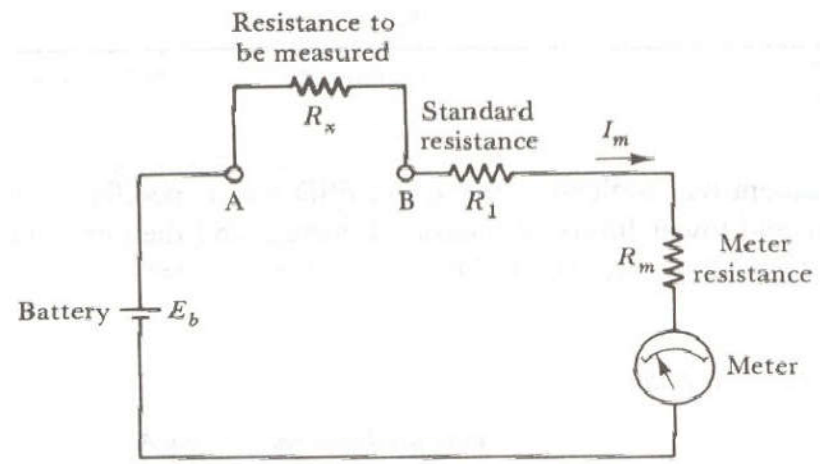
AC Ammeter

- Like a dc ammeter, an ac ammeter must have a very low resistance because it is always connected in series with the circuit in which current is to be measured.
- This low-resistance requirement means that the voltage drop across the ammeter must be very small, typically not greater than 1000 mV.
- The voltage drop across a diode is 0.3 to 0.7 V.
- The use of a current transformer gives the ammeter a low terminal resistance and low voltage drop.

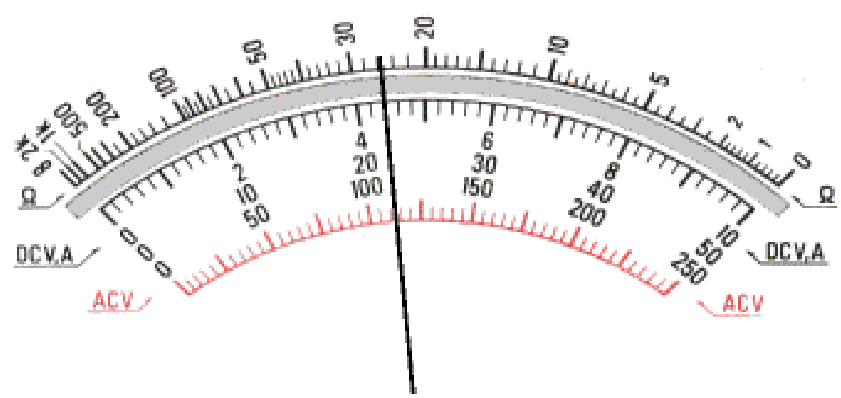
Ohmmeter

A. Series Ohmmeter

- **Basic Circuit and Scale**
  - The simplest circuit consists of a voltage source (E_b) connected in series with a pair of terminals (A & B), a standard resistance (R_1), and a low-current PMMC instrument.



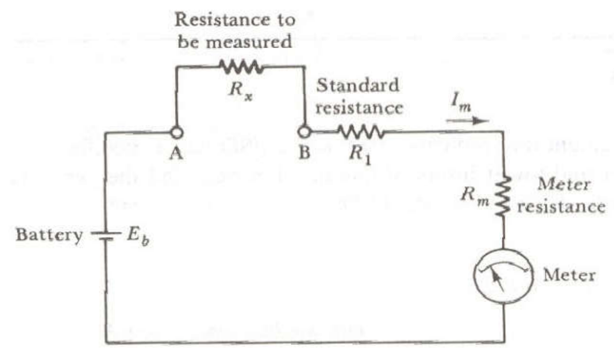
- The resistance to be measured (R_x) is connected across terminal A and B.
- *The meter current* $I_m = E_b/(R_x + R_1 + R_m)$
- When the ohmmeter terminals are shorted ($R_x = 0$) meter full-scale deflection occurs. $I_{FSD} = E_b/(R_1 + R_m)$
- At half-scale deflection $R_x = R_1 + R_m$
- At zero deflection the terminals are open-circuited ($R_x = \infty$).



Example : The series ohmmeter shown in Figure is made up of a 1.5V battery, a 100 μA meter, and a resistance R_1 which makes $(R_1 + R_m) = 15k\Omega$.

a) **Determine the instrument indication when $R_x = 0$.**

b) **Determine how the resistance scale should be marked at 0.75 FSD, 0.5 FSD and 0.25 FSD**



Solution

$$a)\ I_m = \frac{E_b}{R_x + R_1 + R_m} = \frac{1.5V}{0 + 15k\Omega} = 100\mu A\ (FSD)$$

$$b)\ At\ 0.75FSD:\quad I_m = \frac{3\times 100\mu A}{4} = 75\mu A \qquad \&\qquad R_x + R_1 + R_m = \frac{E_b}{I}$$

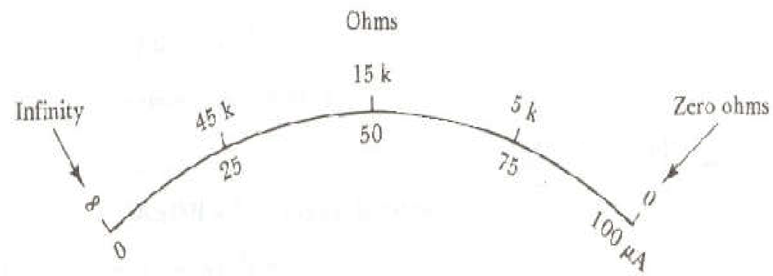
$$R_x = \frac{E_b}{I} - (R_1 + R_m)$$

$$= \frac{1.5V}{75\mu A} - 15k\Omega = 5k\Omega$$

$$At\ 0.5FSD:\quad I_m = \frac{100\mu A}{2} = 50\mu A \qquad \&\qquad R_x = \frac{1.5V}{50\mu A} - 15k\Omega = 15k\Omega$$

$$At\ 0.25FSD:\ I_m = \frac{100\mu A}{4} = 25\mu A \quad \& \quad R_x = \frac{1.5V}{25\mu A} - 15k = 45k\,\Omega$$

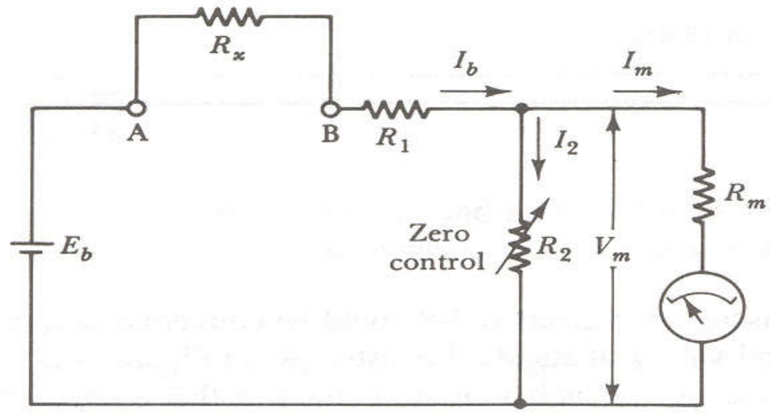
The ohmmeter scale is now marked as shown in the figure. It is clear that the ohmmeter scale is nonlinear.



Comments: disadvantages of simple series ohmmeter

- The simple ohmmeter described in last example will operate satisfactorily as long as the battery voltage remains exactly at 1.5V. When the battery voltage falls, the instrument scale is no longer correct.
- Although $R_{@}$ were adjusted to give FSD when terminals A and B are short-circuited, *the scale would still be in error because now mid-scale* would represent a resistance equal to the new value of $R_1 + R_m$.

Ohmmeter with Zero Adjust



Falling battery voltage can be taken care by an adjustable resistor (R_2) connected in parallel with the meter.

- **With terminals A and B short-circuited, the total circuit resistance is $R_1 + (R_2 // R_m)$.**
- **Since R_1 is always very much larger than $R_2 // R_m$, the total circuit resistance can be assumed to equal R_1**

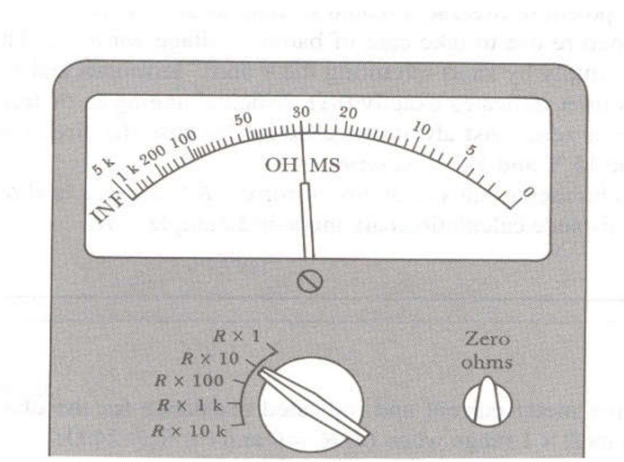
$$I_b = \frac{E_b}{R_x + R_1 + R_2 \| R_m} \qquad \text{if } R_2 \| R_m << R_1 \text{ then} \quad I_b \approx \frac{E_b}{R_x + R_1}$$

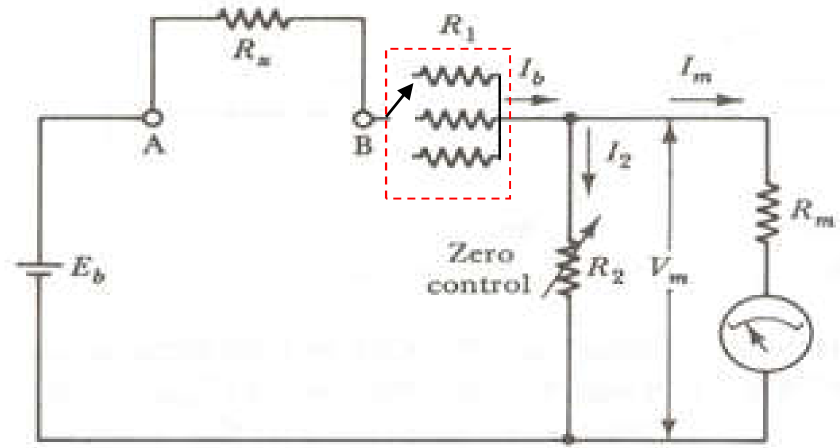
$$Also, \text{ the meter voltage is } V_m = I_b \left(R_2 \| R_m\right) \text{ which give meter current as } I_m = \frac{I_b \left(R_2 \| R_m\right)}{R_m}$$

- **When R_x equal to R_1 the circuit resistance is doubled and the circuit current is halved. This cause both I_2 and I_m to be reduced *to half* of their previous level.** ***Thus the mid-scale measured resistance is again equal to R_1.***

- ***Each time the ohmmeter is used*, terminals A and B are first short circuited, and R_2 is adjusted for zero-ohm indication on the scale**

- The series ohmmeter can be converted to a ***multi-range ohmmeter*** by employing several values of standard resistance R_1 and a rotatory switch

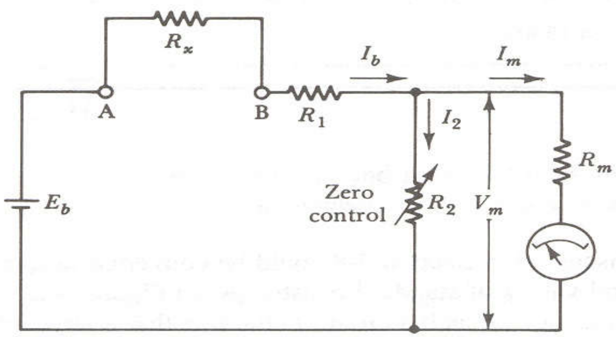




☹ **The major *inconvenience* of such a circuit is that a large adjustment of the zero control (R_2) would have to be made every time the resistance range (R_1) is changed.**

Example:

An ohmmeter as shown in the figure with E_b = 1.5V, R_1 = 15kΩ, $R_m = R_2$ = 50Ω and I_{FSD} = 50µA. Calculate, (a) R_x at 0.5FSD, (b) when E_b = 1.3V what is the value of R_2 to get full-scale current and (c) when E_b = 1.3V what is the value of R_x at half-scale current.



Solution

Since $(R_m // R_2) = 25\ \Omega \ll R_1$ then at half scale $R_x = R_1 = 15\text{k}\Omega$ independent of E_b

(a)

$$V_m = I_m R_m = 25\mu A \times 50\Omega = 1.25mV$$

$$I_2 = \frac{V_m}{R_2} = \frac{1.25mV}{50\Omega} = 25\mu A$$

$$I_b = I_2 + I_m = 25\mu A + 25\mu A = 50\mu A$$

$$R_x + R_1 \approx \frac{E}{I_b} = \frac{1.5V}{50\mu A} = 30k\Omega$$

$$R_x = \left(\frac{E}{I_b}\right) - R_1 = 30k\Omega - 15k\Omega = 15k\Omega$$

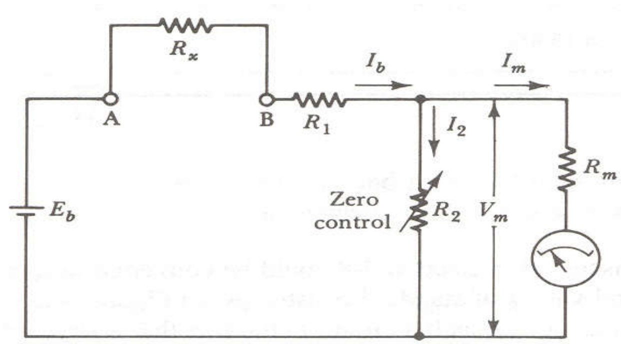
(b)

$$I_b = \frac{E_b}{R_x + R_1} = \frac{1.3V}{0 + 15k\Omega} = 86.67\mu A$$

$$I_2 = I_b - I_{m(FSD)} = 86.67\mu A - 50\mu A = 36.67\mu A$$

$$V_m = I_{m(FSD)} R_m = 50\mu A \times 50\Omega = 2.5mV$$

$$R_2 = \frac{V_m}{I_2} = \frac{2.5mV}{36.67\mu A} = 68.18\Omega$$



(c)

$$V_m = I_m R_m = 25\mu A \times 50\Omega = 1.25mV$$

$$I_2 = \frac{V_m}{R_2} = \frac{1.25mV}{68.18\Omega} = 18.33\mu A$$

$$I_b = I_2 + I_m = 18.33\mu A + 25\mu A = 43.33\mu A$$

$$R_x + R_1 \approx \frac{E}{I_b} = \frac{1.3V}{43.33\mu A} = 30k\Omega$$

$$R_x = 30k\Omega - R_1 = 30k\Omega - 15k\Omega$$

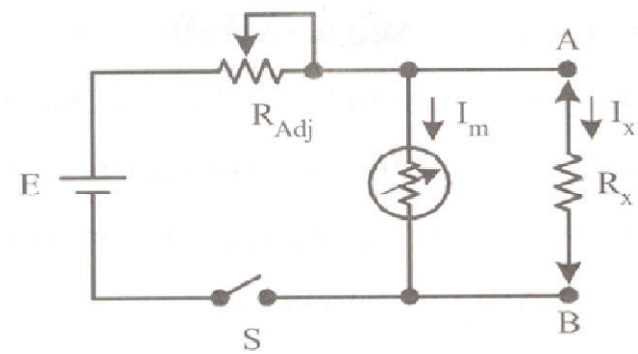
$$R_x = 15k\Omega$$

Since (R_m // R_2) = 28.85 Ω << R_1 then at half scale $R_x = R_1 = 15k\Omega$ independent of E_b

B. Shunt Ohmmeter

– **Basic Circuit and Scale**

- **The simplest circuit consists of a voltage source (*E*) connected with an adjusted Resistor (R_{Adj}) and a low-current PMMC instrument.**

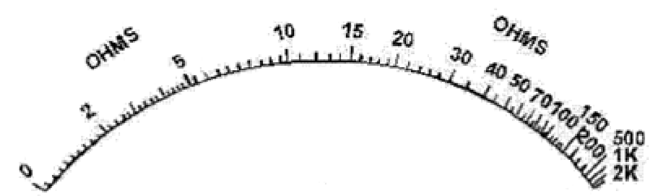


- **The resistance to be measured (R_x) is connected across terminal A and B.**
  - **When R_x = 0, short circuit between A and B, there will be no current flow in the coil branch and the scale point at zero on the left hand side.**
  - **When $R_x = \infty$, open circuit between A and B. Then adjust R_{Adj} to get FSD. The meter will point infinity at the right of the scale.**

$$I_m = I_{FSD} = \frac{E}{R_{Adj} + R_m}$$

  - **For any R_x we have,**

$$I_m = \frac{ER_x}{R_{Adj}R_m + R_x\left(R_{Adj} + R_m\right)}$$



- **Scale of shunt ohmmeter is opposite to the scale of series ohmmeter when connecting with R_x**

THANK YOU FOR YOUR ATTENTION!!