Analog and Digital Meters

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By

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Cambridge
Scholars
Publishing

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This book first published 2024

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-5275-6596-3
ISBN (13): 978-1-5275-6596-8

Dedicated to my loving wife
S. Latha

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PREFACE

Having more than 33 years of experience on working with analog and digital meters, I decided to write a book on it. Starting with the basic PMMC movement up to the most popular 7107 DVM IC, I have described more details on analog and digital meters. When it comes to thinking about system performance, it is essential to study the metering industry and metering as a component in the engineering process. Even though analog meters are being replaced by new digital meters, it is essential to study analog meters to understand their basic structure of measurements.

I am highly indebted to my

(i) Mentor Prof. Dr. V.G.K. Murti who taught me about Function Circuits
(ii) Philosopher Prof. Dr. P. Sankaran who introduced me to the IIT Madras
(iii) Teacher Prof. Dr. K. Radha Krishna Rao who taught me operational amplifiers
(iv) Gurunather Prof. Dr. V. Jagadeesh Kumar who guided me in the proper way of scientific world
(v) Trainer Dr. M. Kumaravel who trained me to do experiments with op-amps
(vi) Encourager Prof. Dr. Enakshi Bhattacharya who encouraged me to get this result
(vii) Director Prof. Dr. V. Kamakoti who motivated me to do this work
(viii) Leader Prof. Dr. Devendra Jalihal who kept me in a happy and peaceful official atmosphere
(ix) Supervisor Prof. Dr. Nagendra Krishnapura who supervised all my research work in IIT Madras

I thank my father Mr. Venkatappa Chinthambi Naidu, mother Mrs. C. Suseela, wife S. Latha, elder son S. Devakumar and younger son S. Jagadeesh Kumar for keeping me in a happy and peaceful residential atmosphere.

I thank my apprentice trainee batch mats and friends Mrs. T. Padmavathy, Mr. V. Selvaraju, Dr. C.R. Jeevandos and Mrs. P.V. Suguna, with whom I started my career in Central Electronics Centre of IIT Madras during 1987.

I also thank my friends Prof. Dr. K. Sridharan, Prof. Dr. R. Sarathi, Dr. Balaji Srinivasan, Dr. T.G. Venkatesh, Dr. Bharath Bhikkaji, Dr. Bobey George, Dr. S. Anirudhan, Dr. Aravind and Dr. Anantha Krishnan for their constant encouragement throughout my research work. I thank all other staff, students and faculty of Electrical Engineering Department, Indian Institute of Technology Madras, for their immense help during the experimental setups, manuscript preparation and proof readings.

CHAPTER 1

PMMC METERS

A Permanent Magnet Moving Coil (PMMC) meter, D'Arsonval meter or galvanometer is an instrument that allows you to measure the current through a coil by observing the coil's angular deflection in a uniform magnetic field. A PMMC meter places a coil of wire (i.e., a conductor) between two permanent magnets to create a stationary magnetic field. According to Faraday's Laws of electromagnetic induction, a current-carrying conductor placed in a magnetic field will experience a force in the direction determined by Fleming's left-hand rule. The magnitude (strength) of this force will be proportional to the amount of current through the wire. A pointer is attached to the end of the wire, and it is put along a scale. When the torques are balanced, the moving coil will stop, and its angular deflection can be measured by the scale. If the permanent magnet field is uniform and the spring linear, then the pointer deflection is also linear. Hence, we can use this linear relationship to determine the amount of electrical current passing through the wire.

PMMC instruments (i.e., D'Arsonval meters) are only used for measuring the Direct Current (DC) current. If we use Alternating Current (AC), the current direction will be reversed during the negative half cycle, and hence, the direction of torque will also be reversed. This results in an average value of zero torque—hence, no net movement against the scale. Despite this, PMMC meters can accurately measure DC current.

1.1 PMMC movement

Fig. 1.1 shows PMMC movement. When a current-carrying conductor is placed in a magnetic field, it experiences a force and tends to move in the direction as per Fleming's left-hand rule. If the first and the second finger and the thumb of the left hand are held so that they are at a right angle to each other, then the thumb shows the direction of the force on the conductor, the first finger points towards the direction of the magnetic field and the second finger shows the direction of the current in the wire.

The interaction between the induced field and the field produced by the permanent magnet causes a deflecting torque, which results in rotation.

The three important torques involved in this instrument are:

Deflecting torque:

The force F, which will be perpendicular to both the direction of the current flow and the direction of the magnetic field as per Fleming's left-hand rule, can be written as

$$F=BILN \tag{1.1}$$

where N = turns of wire on the coil

B is the flux density in the air gap

I is the current in the movable coil

L is the vertical length of the coil

Theoretically, the torque (here, the electro-magnetical torque) equals the multiplication of force with distance to the point of suspension.

Hence, torque on the left side of the cylinder T_L = NBIL x W/2 and torque on the right side of the cylinder T_R = NBIL x W/2

Therefore, the total torque will be = $T_L + T_R$

$$T_D = BILNW \text{ or } BINA \tag{1.2}$$

where A is an effective area (A= LW)

Controlling torque

This torque is produced by the spring action and opposes the deflection torque so that the pointer can rest at the point where these two torques are equal (electromagnetic torque = control spring torque). The value of the control torque depends on the mechanical design of spiral springs and strip suspensions.

The controlling torque is directly proportional to the coil's deflection angle.

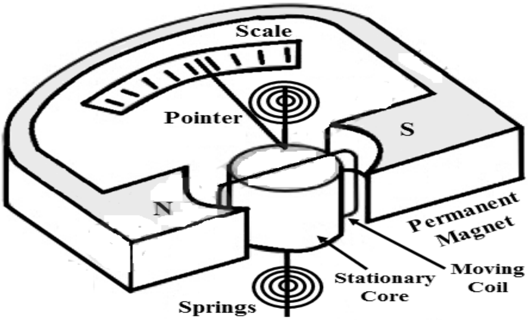

Fig. 1.1(a) PMMC construction

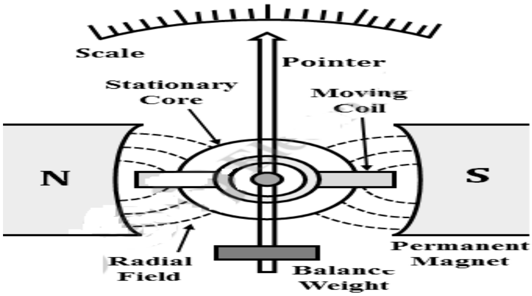

Fig. 1.1(b) PMMC working principle

$$\text{Control torque } T_C = K\theta \qquad (1.3)$$

where, θ = deflection angle in radians and K = spring constant Nm /rad.

Damping torque

This torque ensures the pointer reaches an equilibrium position, i.e., at rest in the scale without oscillating, to give an accurate reading. In PMMC, as the coil moves in the magnetic field, eddy current sets up in a metal former or core on which the coil is wound or in the circuit of the coil itself, which opposes the motion of the coil, resulting in the slow swing of a pointer and then comes to rest quickly with very little oscillation.

At equilibrium

Control Torque (T_C) = Deflecting torque (T_D)

$$K\theta = BILNW \text{ or } BINA \quad (1.4)$$

PMMC instruments are one of the best instruments to measure direct current. They are accurate, sensitive, and work for a longer time without defects/maintenance. These instruments on board are used to measure direct current and voltage. They can also be used as a galvanometer to detect small currents or changes in magnetic flux.

Errors in Permanent Magnet Moving Coil Instruments

There are three main types of errors:

1. Errors due to permanent magnets: The magnets may lose their magnetism to some extent due to temperature effects and magnet ageing. The magnets are generally aged by the heat and vibration treatments.
2. An error may appear in the PMMC instrument due to the ageing of the spring. However, the errors caused by the ageing of the spring and those by the permanent magnet are opposite to each other; hence, both errors are compensated for by each other.
3. Changes in the resistance of the moving coil with temperature**:** Generally, the temperature coefficient of the value of the coefficient of copper wire in a moving coil is a 0.04 per degree Celsius rise in temperature. Due to the lower value of the temperature coefficient, the temperature rises faster, and hence, the resistance increases. Due to this, a significant amount of error is caused.

Advantages of Permanent Magnet Moving Coil Instruments

The advantages of PMMC instruments are:

1. The scale is uniformly divided as the current is directly proportional to the deflection of the pointer. Hence, it is very easy to measure quantities from these instruments.
2. Power consumption is also very low in these types of instruments.
3. High torque to weight ratio.

4. These have multiple advantages. A single instrument can be used for measuring various quantities by using different values of shunts and multipliers.

Disadvantages of Permanent Magnet Moving Coil Instruments

1. These instruments cannot measure AC quantities.
2. The cost of these instruments is high as compared to moving iron instruments.

1.2 PMMC ammeter

Current is the rate of flow of electric charge. If this electric charge flows only in one direction, the resultant current is called Direct Current (DC). The instrument used to measure the Direct Current is called a DC ammeter. If we place a resistor in parallel with the PMMC galvanometer, the entire combination acts as a DC ammeter. The parallel resistance used in a DC ammeter is called shunt resistance or simply shunt. The value of this resistance should be considered too small to measure the DC of a large value.

The DC ammeter's circuit diagram is shown below Fig.1.2.

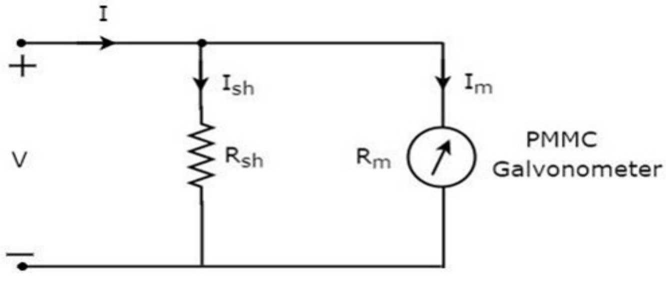

Fig. 1.2 PMMC Ammeter

We have to place this DC ammeter in series with the branch of an electric circuit, where the DC current will be measured. The voltage across the elements, which are connected in parallel, is the same. So, the voltage across the shunt resistor, *Rsh* and the voltage across galvanometer resistance, *Rm,* is the same since those two elements are connected in parallel in the above circuit. Mathematically, it can be written as

$$I_{SH} R_{SH} = I_M R_M$$

$$R_{SH} = \frac{I_M R_M}{I_{SH}} \tag{1.5}$$

$$I_{SH} = I - I_M \tag{1.6}$$

Equation (1.6) in (1.5) gives

$$R_{SH} = \frac{I_M R_M}{(I - I_M)} \tag{1.7}$$

Where, R_{SH} is the shunt resistance, R_M is the internal resistance of the galvanometer

I is the total Direct Current that is to be measured, I_M is the full-scale deflection current

The ratio of the total Direct Current that is to be measured, I and the full-scale deflection current of the galvanometer, *Im,*

is known as the multiplying factor, m. Mathematically, it can be represented as

$$m = \frac{I}{Im}, \mathrm{Im} = \frac{I}{m}$$

$$R_{SH} = \frac{IR_M}{\mathrm{m}(I - I/m)} = \frac{R_M}{m-1} \tag{1.8}$$

1.2.1 **MULTI RANGE DC AMMETER**

As previously discussed, a DC ammeter is obtained by placing a resistor in parallel with the PMMC galvanometer. This DC ammeter can measure a particular range of Direct Currents.

If we want to use the DC ammeter for measuring the Direct Currents of multiple ranges, then we have to use multiple parallel resistors instead of a single resistor, and this entire combination of resistors is in parallel to the PMMC galvanometer. The multi-range DC ammeter's circuit diagram is shown below in Fig. 1.3.

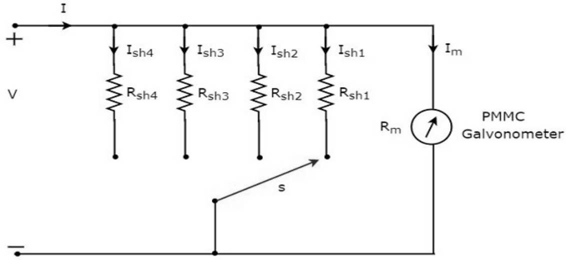

Fig. 1.3 a multi range DC Ammeter

The multi-range DC ammeter can be placed in series with the branch of an electric circuit, where the Direct Current of a required range is to be measured. The desired range of currents is chosen by connecting switch *s* to the respective shunt resistor.

Let $m1$, $m2$, $m3$ and $m4$ be the multiplying factors of the DC ammeter when we consider the total Direct Currents to be measured as I_1, I_2, I_3 and I_4, respectively. The formulae corresponding to each multiplying factor are:-

$$m1 = \frac{I_1}{I_m} \quad (1.9)$$

$$m2 = \frac{I_2}{I_m} \quad (1.10)$$

$$m3 = \frac{I_3}{I_m} \quad (1.11)$$

$$m4 = \frac{I_4}{I_m} \quad (1.12)$$

There are four shunt resistors, R_{SH1}, R_{SH2}, R_{SH3} and R_{SH4} in Fig. 1.3

The formulae corresponding to these four resistors are:-

$$R_{SH1} = \frac{R_m}{m1 - 1} \quad (1.13)$$

$$R_{SH2} = \frac{R_m}{m2-1} \tag{1.14}$$

$$R_{SH3} = \frac{R_m}{m3-1} \tag{1.15}$$

$$R_{SH4} = \frac{R_m}{m4-1} \tag{1.16}$$

1.3 PMMC voltmeter

A DC voltmeter is a measuring instrument which is used to measure the DC voltage across any two points of an electric circuit. If we place a resistor in series with the PMMC galvanometer, then the entire combination together acts as a DC voltmeter.

The series resistance, which is used in a DC voltmeter, is also called series multiplier resistance or simply a multiplier. It basically limits the amount of current that flows through the galvanometer in order to prevent the meter current from exceeding the full-scale deflection value. The circuit diagram of the DC voltmeter is shown in Fig.1.4.

We have to place this DC voltmeter across the two points of an electric circuit where the DC voltage is to be measured.

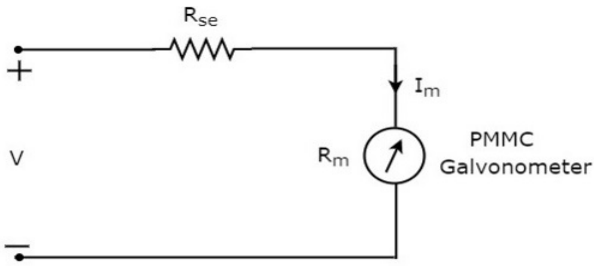

Fig. 1.4 PMMC voltmeter

Apply KVL around the loop of the above circuit.

$$V - ImRse - ImRm = 0$$

$$V - ImRm = ImRse$$

$$Rse = \frac{V - \mathrm{Im}\, Rm}{\mathrm{Im}}$$

$$Rse = \frac{V}{\mathrm{Im}} - Rm \qquad (1.17)$$

where,

Rse is the series multiplier resistance

V is the full-range DC voltage that is to be measured

Im is the full-scale deflection current

Rm is the internal resistance of the galvanometer

The ratio of full range DC voltage that is to be measured is *V,* and the DC voltage drop across the galvanometer is *Vm* is known as the multiplying factor, m. Mathematically, it can be represented as

$$m = \frac{V}{Vm} \qquad (1.18)$$

The full-range DC voltage is given as

$$V = ImRse + ImRm$$

The DC voltage drop across the galvanometer, *Vm,* is the product of the full-scale deflection current, *Im* and internal resistance of the galvanometer, *Rm*. Mathematically, it can be written as

$$Vm = ImRm$$

$$m = \frac{\mathrm{Im}\, Rse + \mathrm{Im}\, Rm}{\mathrm{Im}\, Rm} = \frac{Rse + Rm}{Rm}$$

$$Rse = Rm(m - 1) \qquad (1.19)$$

1.3.1 MULTI RANGE DC VOLTMETER

As previously discussed, a DC voltmeter is obtained by placing a multiplier resistor in series with the PMMC galvanometer. This DC voltmeter can be used to measure a particular range of DC voltages.

Suppose we want to use the DC voltmeter for measuring the DC voltages of multiple ranges. In that case, we have to use multiple parallel multiplier resistors instead of single multiplier resistors, and this entire combination of resistors is in series with the PMMC galvanometer. The circuit diagram of the multi-range DC voltmeter is shown below in Fig. 1.5

The multi-range DC voltmeter across the two points of an electric circuit is placed, where the DC voltage of the required range is to be measured. We can choose the desired range of voltages by connecting the switches to the respective multiplier resistor.

Let $m1$, $m2$, $m3$ and $m4$ be the multiplying factors of the DC voltmeter when we consider the full-range DC voltages to be measured as V_1, V_2, V_3 and V_4, respectively. The formulae corresponding to each multiplying factor are:

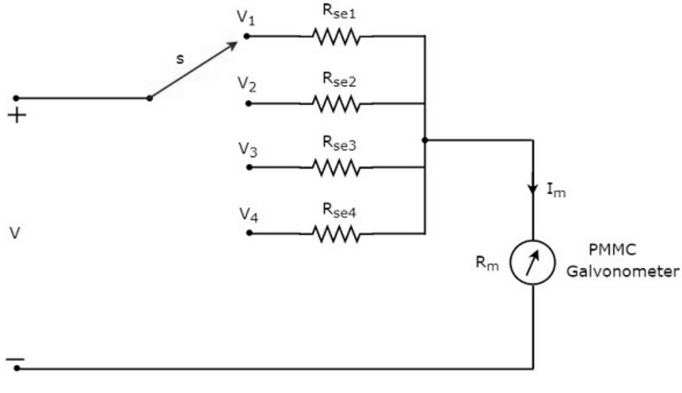

Fig. 1.5 multi range DC the voltmeter

$$m1 = \frac{V_1}{V\text{m}} \tag{1.20}$$

$$m2 = \frac{V_2}{V\text{m}} \tag{1.21}$$

$$m3 = \frac{V_3}{V\text{m}} \tag{1.22}$$

$$m4 = \frac{V_4}{V\text{m}} \tag{1.23}$$

There are four series multiplier resistors, $Rse1$, $Rse2$, $Rse3$ and $Rse4$ in Fig. 1.5

The formulae corresponding to these four resistors are:

$$Rse1 = \frac{Rm}{(m1-1)} \tag{1.24}$$

$$Rse2 = \frac{Rm}{(m2-1)} \tag{1.25}$$

$$Rse3 = \frac{Rm}{(m3-1)} \tag{1.26}$$

$$Rse4 = \frac{Rm}{(m4-1)} \tag{1.27}$$

The resistance values of each series multiplier resistor can be calculated by using the above formulae.

1.3.2 SENSITIVITY OF PMMC THE VOLTMETER

The current sensitivity of a voltmeter of a moving coil type, like a PMMC voltmeter, is defined as the deflection per unit current in the coil. If Θ is the angular deflecting of a needle of a voltmeter for current I through the moving coil, then the sensitivity of the voltmeter is given as

$$S = \frac{\theta}{I} \tag{1.28}$$

As the deflecting torque in PMMC type instrument is given as

$$T_D = BILNW$$

Where N = Number of turns

I = Current through coil

B = Magnetic flux density

L = Length of moving coil

W = Width of moving coil

For a given instrument, the number of turns in the coil, length and width of the moving coil and magnetic flux density are constant; therefore, we can assume that:

$$G = BLNW = \text{Constant}$$

Therefore, deflecting torque $T_D = GI$

But this deflecting torque is controlled by spring torque, hence

$$K\,\Theta = T_D$$

$K\Theta = GI$, where K is the spring constant.

$$\frac{\theta}{I} = \frac{G}{K}$$

Therefore,

Sensitivity of the voltmeter

$$S = \Theta / I = G/K \qquad (1.29)$$

Thus, the sensitivity of the voltmeter of a moving coil type can be increased either by increasing the value of G or by reducing the value of K. Now, for a given coil of given cross-sectional area, i.e., A = LW and given the magnetic flux density, the value of G can be increased by using many turns of the thin wire coil. Again, the value of the spring constant can be reduced by using a light flat spring and the coil assembly lightly pivoted. Thus, it can be stated that the more the sensitivity of the voltmeter, the more the resistance of its coil, as many turns are wound with the fine wire.

The sensitivity of the voltmeter specified on the meter dial specifies the resistance of the meter for the one-volt range. The sensitivity of the voltmeter is also defined as

$$S = \frac{1}{I_{fs}} \quad \Omega/V \tag{1.30}$$

Where I_{fs} = Current required for full-scale deflection.

If the sensitivity of the voltmeter is given and you need to find the total resistance of the meter, then you multiply the sensitivity by the voltage range to get the resistance. The sensitivity of the voltmeter also depends on the circuit resistance, which is known as the loading effect. To better understand the sensitivity of the voltmeter, let us consider a simple example.

Example:

Meter A has a range of 0-10 V and a multiplier resistance of 18 kΩ. Meter B has a range of 0-300 V and a multiplier resistance of 298 kΩ. Which meter is more sensitive, assuming both meters' movements have the same resistance of 2 kΩ?

Solution:

Meter A

Total resistance of meter = 18 + 2 = 20 kΩ

Range of Meter = 10 V

Thus current required for full-scale deflection = 10 / 20 = 0.5 A

Therefore, sensitivity = 1/0.5 = 2 Ω/V

Meter B

Total resistance of meter = 298 + 2 = 300 kΩ

Range of Meter = 300 V

Thus current required for full-scale deflection = 300 / 300 = 1 A

Therefore, sensitivity = 1/1 = 1 Ω/V

Thus, we observe that meter A is more sensitive as it requires less current for a given deflection. Here, we have assumed full-scale deflection.

1.4 PMMC ohmeters

The instrument which is used to measure the value of resistance between any two points in an electric circuit is called an **ohmmeter**. It can also be used to find the value of an unknown resistor. The units of resistance are ohms, and the measuring instrument is a meter. So, the word "ohmmeter" is obtained by combining the words **"ohm"** and **"meter"**.

Following are the two types of ohmmeters.

- Series Ohmmeter
- Shunt Ohmmeter

Now, let us discuss these two types of ohmmeters one by one.

1.4.1 SERIES OHMMETER

If the resistor's value is unknown and has to be measured by placing it in series with the ohmmeter, then that ohmmeter is called a series ohmmeter. The circuit diagram of a series ohmmeter is shown below in Fig.1.6.

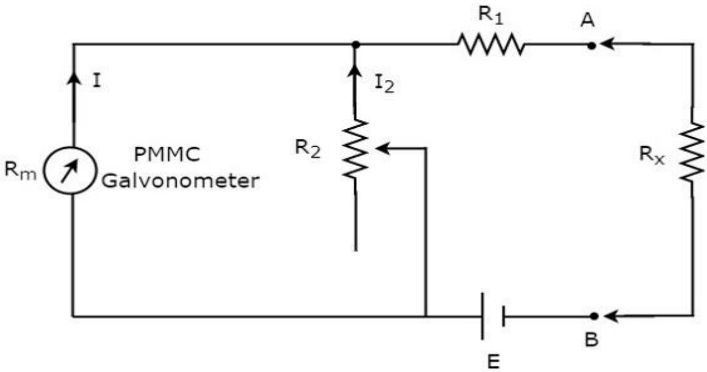

Fig. 1.6 PMMC Series Ohmeter

The part of the circuit on the left side of terminals A and B is a series ohmmeter. So, we can measure the value of unknown resistance by placing it on the right side of terminals A and B. Now, let us discuss the calibration scale of a series ohmmeter.

Case 1: If Rx=0Ω, then the terminals A and B will be short-circuited by each other. So, the meter current becomes divided between the resistors, *R*1 and *R*2. Now, vary the value of the resistor *R*2 in such a way that the entire meter current flows through the resistor, *R*1 only. In this case, the meter shows a full-scale deflection current. Hence, this full-scale deflection current of the meter can be represented as 0Ω.

Case 2: If $Rx=\infty\Omega$, then the terminals A and B will be open-circuited by each other. So, no current flows through the resistor, *R*1. In this case, the meter shows a null deflection current. Hence, this null deflection of the meter can be represented as ∞Ω.

In this way, by considering different values of *Rx*, the meter shows different deflections. So, accordingly, we can represent those deflections with the corresponding resistance value.

The series ohmmeter consists of a calibration scale. It has the indications of 0 Ω and ∞Ω at the endpoints of the right hand and left hand of the scale, respectively. A series ohmmeter is useful for measuring high values of resistance.

1.4.2 SHUNT OHMMETER

If the resistor's value is unknown and it is to be measured by placing it in parallel (shunt) with the ohmmeter, then that ohmmeter is called shunt ohmmeter. The circuit diagram of the shunt ohmmeter is shown below in Fig. 1.7.

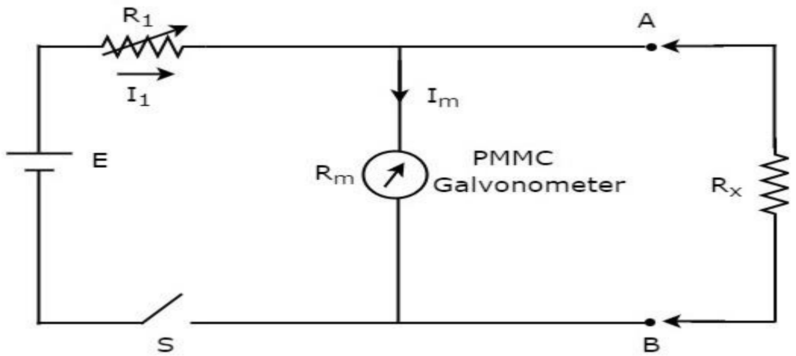

Fig. 1.7 PMMC shunt ohmmeter

The part of the circuit, which is on the left side of terminals A and B, is a shunt ohmmeter. So, we can measure the value of unknown resistance by placing it on the right side of terminals A and B.

Now, let us discuss the calibration scale of the shunt ohmmeter. Close the switch, S of the above circuit, while it is in use.

Case 1: If Rx=0Ω, then the terminals A and B will be short-circuited by each other. Due to this, the entire current, I_1, flows through terminals A and B. In this case, no current flows through the PMMC galvanometer. Hence, the null deflection of the PMMC galvanometer can be represented as 0Ω.

Case 2: If Rx=∞Ω, then the terminals A and B will be open-circuited by each other. So, no current flows through the terminals A and B. In this case, the entire current, I_1, flows through the PMMC galvanometer. If required, vary (adjust) the value of the resistor R_1 until the PMMC galvanometer shows a full-scale deflection current. Hence, this full-scale deflection current of the PMMC galvanometer can be represented as ∞Ω.

In this way, by considering different values of Rx, the meter shows different deflections. So, accordingly, we can represent those deflections with the corresponding resistance values.

The shunt ohmmeter consists of a calibration scale. It has the indications of 0Ω and ∞Ω at the endpoints of the left hand and right hand of the scale, respectively.

A shunt ohmmeter is useful for measuring low values of resistances. So, we can use either a series ohmmeter or shunt ohmmeter based on the values of resistances that are to be measured, i.e., high or low.

WORKED EXAMPLES

1. The coil of a PMMC instrument has 60 turns on a former that is 18 mm wide, the effective length of the conductor being 25 mm. It moves in a uniform field of flux density of 0.5 Tesla. The control spring constant is 1.5×10^{-6} Nm/degree. Calculate the current required to produce a deflection of 10 degrees.

Total deflecting torque exerted on the coil, Td = BILNW(N-m) = $0.5 \times I \times 25 \times 10^{-3} \times 60 \times 18 \times 10^{-3}$

The control torque of the springs is $T_C = K\,\theta = 1.5 \times 10^{-6} \times 10$

At equilibrium, $Td = T_C = 0.5 \times I \times 18 \times 10^{-3} \times 25 \times 10^{-3} \times 60 = 1.5 \times 10\text{-}6 \times 100$

$I = 1.5 \times 10^{-6} \times 10 / 0.5 \times 18 \times 10^{-3} \times 25 \times 10^{-3} \times 60 = 1.1\text{mA}$

2. A PMMC instrument has a coil of dimensions 15 mm × 12 mm. The flux density in the air gap is 1.8×10^{-3} wb/m2, and the spring constant is 0.14×10^{-6} N-m/rad. Determine the number of turns required to produce an angular deflection of 90° when a current of 4 mA is flowing through the coil.

Total deflecting torque exerted on the coil, Td = BILNW (N-m) = $1.8 \times 10^{-3} \times 4 \times 10^{-3} \times 15 \times 10^{-3} \times 12 \times 10^{-3} \times N$

The control torque of the springs is $T_C = K\,\theta = 0.14 \times 10^{-6} \times 90 \times \pi/180$

At equilibrium, $Td = T_C$

$1.8 \times 10^{-3} \times 4 \times 10^{-3} \times 15 \times 10^{-3} \times 12 \times 10^{-3} \times N = 0.14 \times 10^{-6} \times 90 \times \pi/180$

$N = 0.14 \times 10^{-6} \times 90 \times \pi/180 / 1.8 \times 10^{-3} \times 4 \times 10^{-3} \times 15 \times 10^{-3} \times 12 \times 10^{-3}$

= 170 Turns

3. A PMMC voltmeter with a resistance of 20 Ω gives a fullscale deflection of 120° when a potential difference of 100 mV is applied across it. The moving coil has dimensions of 30 mm × 25 mm and is wound with 100 turns. The control spring constant is 0.575 × 10-6 N-m/degree. Find the flux density in the air gap.

Full-scale deflecting current = Potential difference / Coil resistance = 100mV/20 Ω = 5mA

Total deflecting torque exerted on the coil, Td = BILNW (N-m) =B × 5 × 10-3 × 30 × 10-3 × 25 × 10-3 × 100

The control torque of the springs is $T_C = K\,\theta = 0.575 \times 10^{-6} \times 120$

At equilibrium, $Td = T_C$

$B \times 5 \times 10^{-3} \times 30 \times 10^{-3} \times 25 \times 10^{-3} \times 100 = 0.575 \times 10^{-6} \times 120$

Coil winding resistance = 20 × 0.3 = 6 Ω

Flux density = B = $0.575 \times 10^{-6} \times 120 / 5 \times 10^{-3} \times 30 \times 10^{-3} \times 25 \times 10^{-3} \times 100 = 0.184$ Wb/m^2

4. The coil of a moving-coil voltmeter is 40 mm long and 30 mm wide and has 100 turns on it. The control spring exerts a torque of 240×10^{-6} N-m when the deflection is 100 divisions on full scale. If the flux density of the magnetic field in the air gap is 1 Wb/m^2, find full-scale deflecting current I.

Let the full-scale deflecting current be I amp.

Total deflecting torque exerted on the coil,

Td = BILNW (N-m)

$= 1 \times I \times 40 \times 10^{-3} \times 30 \times 10^{-3} \times 100$

The control torque of the springs is

Tc = K θ

$= 240 \times 10^{-6}$

At equilibrium, Td = T_C

$1 \times I \times 40 \times 10^{-3} \times 30 \times 10^{-3} \times 100 = 240 \times 10^{-6}$

$I = 240 \times 10^{-6} / 1 \times 40 \times 10^{-3} \times 30 \times 10^{-3} \times 100 = 2$mA.

5. A moving-coil the voltmeter has a resistance of 100 Ω. The scale is divided into 150 equal divisions. When a potential difference of 1 V is applied to the terminals of the voltmeter, a deflection of 100 divisions is obtained. Explain how the instrument could be used for measuring up to 300 V.

Let Rse be the multiplier resistance that would be connected in series with the voltmeter. Volt/division = 1/100

The voltage across the meter for producing the full-scale deflecting current v = 150 × 1/100 = 1.5 V

Full-scale meter current Im = 1.5/100 amp