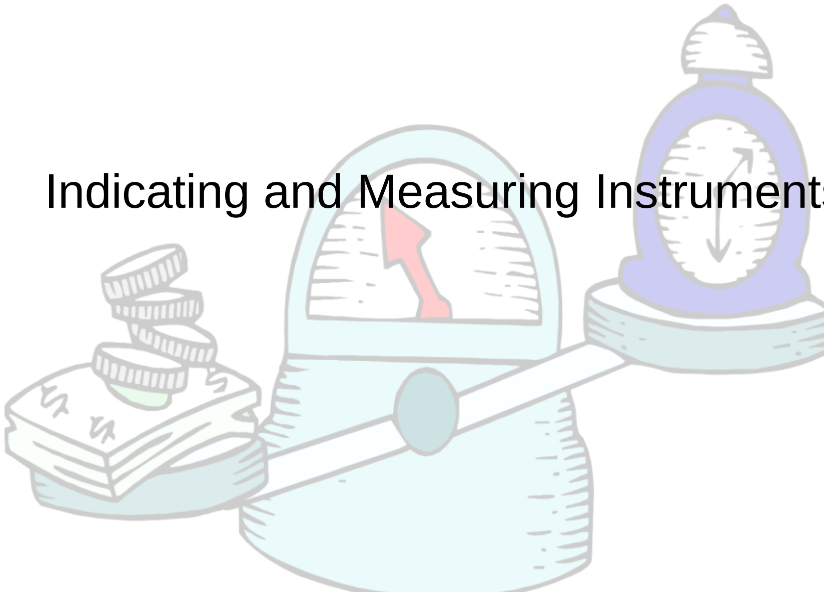
Indicating and Measuring Instruments

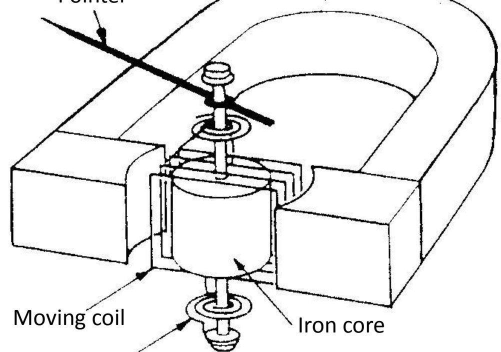


Moving Coil Instruments

- There are two types of moving coil instruments namely,:
  - ***Permanent magnet moving coil (PMMC)*** type which can only be used for ***direct*** current, voltage measurements
  - ***Dynamometer*** type which can be used on either ***direct or alternating*** current, voltage measurements with limited frequency.

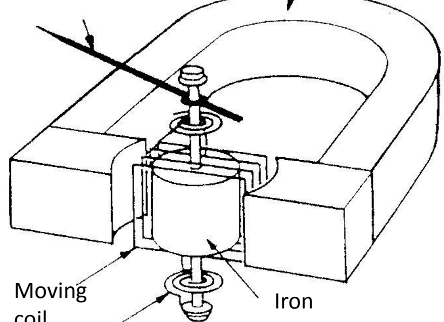
PMMC Meter

- **PMMC meter or (D'Arsonval) meter or galvanometer all are the same instrument, it works as follows :**
- **A coil of fine wire is suspended in a magnetic field produced by permanent magnet.**
- **According to the fundamental law of electromagnetic force, the coil will rotate in the magnetic field when it carries an electric current due to electromagnetic (EM) torque effect.**



Permanent Magnet Moving Coil Mechanism(PMMC)

- **A pointer attached to the movable coil will deflect according to the amount of current to be measured and which is applied to the coil.**
- **Springs attached to the movable coil provide mechanical torque to counter balance the (EM) torque.**
- **When the torques are balanced the moving coil will stop and its angular deflection represent the amount of electrical current to be measured against a fixed reference, called a scale.**
- **If the permanent magnet field is uniform and the spring linear, then the pointer deflection is also linear**.



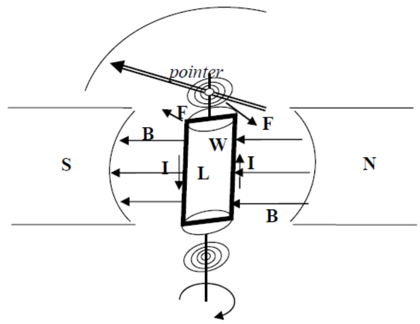
Mathematical Representation of PMMC Mechanism

Assume there are (N) turns of wire and the coil is (L) in long by (W) in wide. The force (F) acting perpendicular to both the direction of the current flow and the direction of magnetic field is given by:

$F = N \cdot B \cdot I \cdot L$ where N: turns of wire on the coil I: current in the movable coil B: flux density in the air gap L: vertical length of the coil

Electromagnetic torque is equal to the multiplication of force with distance to the point of suspension

$T_{I1} = NBIL\frac{W}{2}$ in one side of cylinder $T_{I2} = NBIL\frac{W}{2}$ in the other side of cylinder



The total torque for the two cylinder sides

$$T_I = 2\left(NBIL\frac{W}{2}\right) = NBILW = NBIA$$ where A: effective coil area

This torque will cause the coil to rotate until an equilibrium position is reached at an angle θ with its original orientation. At this position

Electromagnetic torque = control spring torque

$T_I = Ts$

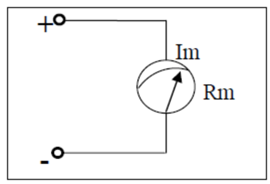
Since $Ts = K\theta$

So $\theta = \frac{NBA}{K}I$ where $C = \frac{NBA}{K}$ Thus $\theta = CI$

The angular deflection proportional linearly with applied current

DC Ammeter

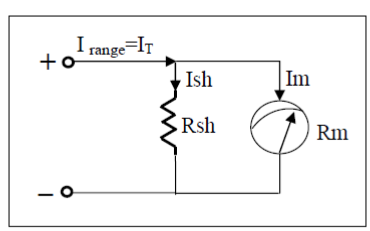
- An Ammeter is always connected in series with a circuit branch and measures the current flowing in it
- Most d.c ammeters employ a d'Arsonval movement,
- An ideal ammeter would be capable of performing the measurement without changing or distributing the current in the branch but real ammeters would possess some internal resistance.



Extension of Ammeter Range

- Since the coil winding in PMMC meter is *small and light*, they can carry only small currents (µA-1mA).
- Measurement of large current requires ***a shunt external resistor*** to connect with the meter movement, so only a fraction of the total current will passes through the meter.

$$Vm = Vsh$$
$$\text{Im}\, Rm = Ish Rsh$$
$$Ish = I_T - \text{Im}$$
$$\boxed{Rsh = \frac{\text{Im}\, Rm}{I_T - \text{Im}}}$$



Example:

If PMMC meter have internal resistance of 10Ω and full scale range of 1mA. Assume we wish to increase the meter range to 1A.

Sol.

So we must connect shunt resistance with the PMMC meter of

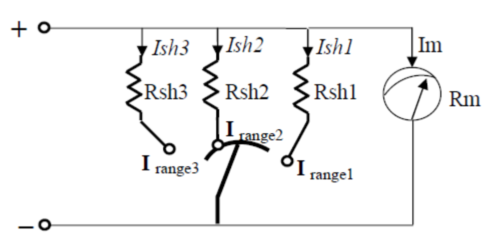
$$\boxed{Rsh = \frac{\mathrm{Im}\, Rm}{I_T - \mathrm{Im}}} \qquad Rsh = \frac{1\times10^{-3}\cdot 10}{1-1\times10^{-3}} = 0.01001\Omega$$

DC Ammeter Method (Ayrton Shunt)

a) ***Direct D.c Ammeter Method (Ayrton Shunt):***

- The current range of dc ammeter can be further extended by a number of shunts selected by a range switch
- Such an ammeter is a multirange ammeter

$$R_{sh*} = \frac{I_m R_m}{I_{r*} - I_m}$$

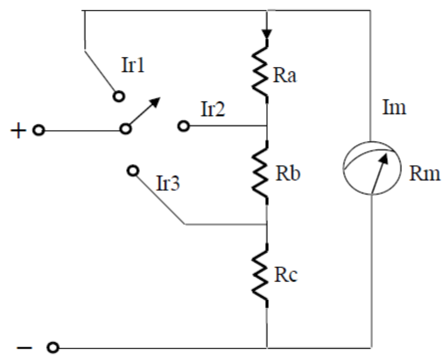


Indirect Method

$$\frac{I_{r*}}{I_m} = \frac{R_m + R}{r*}$$

Where R=Ra+ Rb+ Rc
And r = parallel resistors branch with the meter +

- $$R_{sh*} = \frac{I_m R_m}{I_{r*} - I_m}$$



Example (1):

Design a multirange ammeter by using ***direct method*** to give the following ranges 10mA, 100mA, 1A, 10A, and 100A. If d'Arsonval meter have internal resistance of 10Ω and full scale current of 1mA.

Sol:

Rm=10Ω Im=1mA

$$Rsh_* = \frac{Im\,Rm}{Ir_* - Im}$$

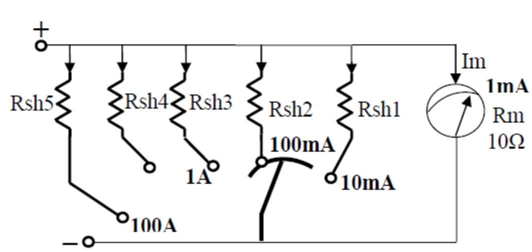
$$Rsh1 = \frac{1\times10^{-3}\cdot 10}{(10-1)\times10^{-3}} = 1.11\Omega$$

$$Rsh2 = \frac{1\times10^{-3}\cdot 10}{(100\text{-}1)\text{x } 10^{-3}} = 0.101\Omega$$

$$Rsh3 = \frac{1\times10^{-3}\cdot 10}{1\text{-}1\ )\times10^{-3}} = 0.0101\Omega$$

$$Rsh4 = \frac{1\times10^{-3}\cdot 10}{10-1\times10^{-3}} = 0.0011\Omega$$

$$Rsh5 = \frac{1\times10^{-3}\cdot 10}{100-1\times10^{-3}} = 0.00011\Omega$$



Example (2):

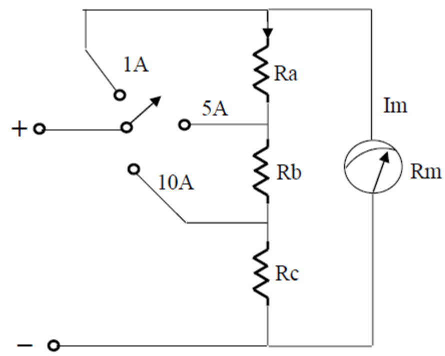
Design an Ayrton shunt by ***indirect method*** to provide an ammeter with current ranges 1A, 5A, and 10A, if PMMC meter have internal resistance of 50Ω and full scale current of 1mA.

Sol.:

Rm=50Ω I_{FSD}=Im=1mA

$$\frac{Ir_*}{Im} = \frac{Rm + R}{r_*}$$

Where R=Ra+ Rb+ Rc
And r = parallel resistors branch with the meter



1- ***For 1A Range:***

$$\frac{I1}{Im} = \frac{Rm + R}{R}$$

$$\frac{1A}{1mA} = \frac{50 + R}{R}$$ R=0.05005Ω

2- ***For 5A Range:***

$$\frac{I2}{Im} = \frac{Rm + R}{Rb + Rc}$$ r =Rb+Rc

$$\frac{5A}{1mA} = \frac{50 + 0.05005}{Rb + Rc}$$ Rb+Rc= 0.01001Ω

Ra=R-(Rb+Rc) **Ra**=0.05-0.01001=0.04004 Ω

3- ***For 10A Range:***

$$\frac{I3}{Im} = \frac{Rm + R}{Rc}$$ r =Rc

$$\frac{10A}{1mA} = \frac{50 + 0.05005}{Rc}$$ **Rc**=5.005×10^{-3} Ω

Rb=0.01001-5.005×10^{-3}= 5.005×10^{-3} Ω

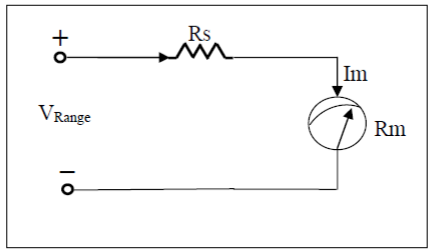
DC Voltmeter

- A voltmeter is always connected in parallel with the element being measured, and measures the voltage between the points across which its' connected.
- Most d.c voltmeter employ PMMC meter with series resistor as shown. The series resistance should be much larger than the impedance of the circuit being measured, and they are usually much larger than Rm.

$$Rs = R_T - Rm$$

$$Rs = \frac{V_{range}}{Im} - Rm$$

$Im = I_{FSD}$



Example:
We have a micro ammeter and we wish to adapted it so as to measure 1volt full scale, the meter has internal resistance of 100Ω and I_{FSD} of 100μA.

Sol.:

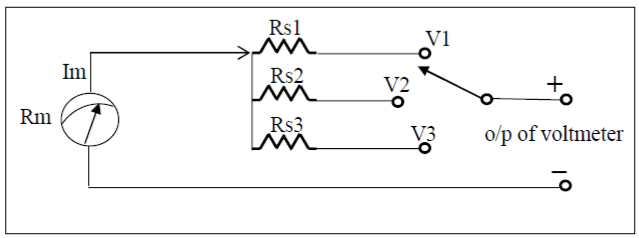
$$Rs = \frac{V}{Im} - Rm \qquad Rs = \frac{1}{0.0001} - 100 = 9900\Omega = 9.9K\Omega$$

So we connect with PMMC meter a series resistance of 9.9KΩ to convert it to voltmeter

Extension of Voltmeter Range:

- Voltage range of d.c voltmeter can be further extended by a number of series resistances selected by a range switch; such a voltmeter is called multi-rage voltmeter.
- ***a) Direct D.c Voltmeter Method:***

$$Rs_* = \frac{V_*}{Im} - Rm$$

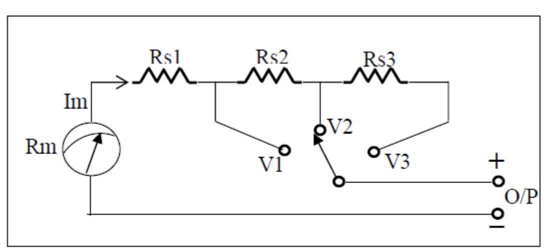


b) **Indirect Method**

$$Rs1 = \frac{V1}{Im} - Rm$$

$$Rs2 = \frac{V2 - V1}{Im}$$

$$Rs3 = \frac{V3 - V2}{Im}$$



Example (1):

A basic d'Arsonval movement with internal resistance of 100Ω and half scale current deflection of 0.5 mA is to be converted by indirect method into a multirange d.c voltmeter with voltages ranges of 10V, 50V, 250V, and 500V.

Example (1):

A basic d'Arsonval movement with internal resistance of 100Ω and half scale current deflection of 0.5 mA is to be converted by indirect method into a multirange d.c voltmeter with voltages ranges of 10V, 50V, 250V, and 500V.

Sol:

$I_{FSD} = I_{HSD} \times 2$

$I_{FSD} = 0.5mA \times 2 = 1mA$

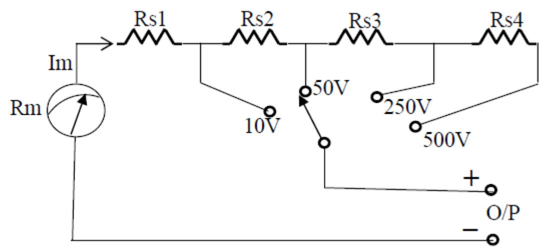
$$Rs1 = \frac{V1}{\text{Im}} - Rm \qquad Rs1 = \frac{10}{1mA} - 100 = 9.9K\Omega$$

$$Rs2 = \frac{V2 - V1}{\text{Im}}$$

$$Rs2 = \frac{50-10}{1\times10^{-3}} = 40K\Omega$$

$$Rs3 = \frac{250-50}{1\times10^{-3}} = 200K\Omega$$

$$Rs4 = \frac{500-250}{1\times10^{-3}} = 250K\Omega$$

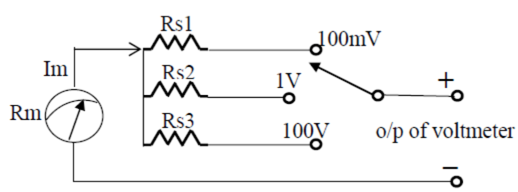


Example (2):

Design d.c voltmeter by using direct method with d'Arsonval meter of 100Ω and full scale deflection of 100μA to give the following ranges: 10mV, 1V, and 100V.

Sol:

$$\boxed{Rs_* = \frac{V_*}{\text{Im}} - Rm}$$



$$Rs1 = \frac{V1}{\text{Im}} - Rm$$

$$Rs1 = \frac{10mV}{100\mu A} - 100 = 0\Omega$$

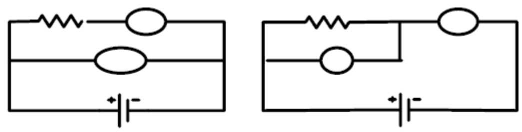
$$Rs2 = \frac{1}{100\times10^{-6}} - 100 = 9.9K\Omega$$

$$Rs3 = \frac{100}{100\times10^{-6}} - 100 = 99.9K\Omega$$

Ohmmeter and Resistance measurement:

a) *Indirect method by ammeter and voltmeter.*

- This method is inaccurate unless the ammeter has a small resistance and voltmeter



- b) ***Series Ohmmeter:***
- Rx is the unknown resistor to be measured, R2 is variable adjusted resistance so that
- the pointer read zero at short circuit test. The scale of series ohmmeter is nonlinear with
- zero at the right and infinity at extreme left. Series ohmmeter is the most generally used
- meter for resistance measurement.

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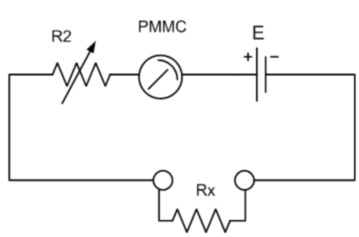
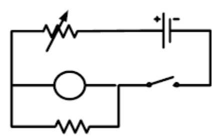
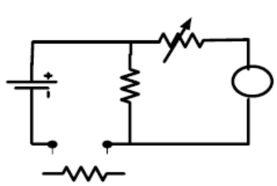


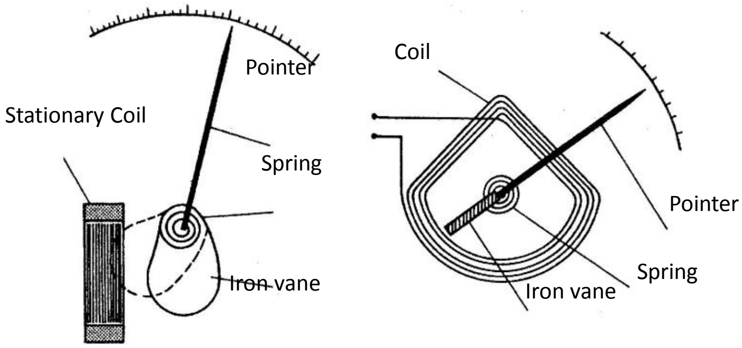
- ***Shunt Ohmmeter:***
- Shunt ohmmeter are used to measure very low resistance values.
- The unknown resistance Rx is now shunted across the meter, so portion of current will pass across this resistor and drop the meter deflection proportionately.
- The switch is necessary to disconnect the battery when the instrument is not used.
- The scale of shunt ohmmeter is nonlinear with zero at the left and infinity at extreme right.



- ***Voltage Divider (potentiometer):***
- The meter of voltage divider is voltmeter that reads voltage drop across Rs which is dependent on Rx.
- This meter will read from right to left like series ohmmeter with more uniform calibration.



Moving Iron meter (only frequency range is important)



- **Used for dc and ac up to 125 Hz**
- Attraction type where the iron vane is drawn into the field of the coil as the current increase
- Repulsion type where the vane is repelled

- For an excitation current I, the torque produced that causes the vane to turn is given by:

$$T = \frac{I^2}{2}\frac{dM}{d\theta}$$

- where M is the mutual inductance. Rotation is opposed by a spring that produces a backwards torque given by:

$$T_s = K\theta$$

- At equilibrium

$$\theta = \frac{I^2}{2K}\frac{dM}{d\theta}$$

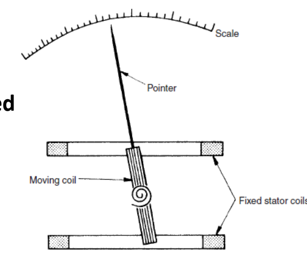
- The instrument thus has a square [illegible] where the deflection is proportional to the square of the signal being measured, i.e. the output reading is a root-mean-squared (r.m.s.) quantity.
- The instrument can typically measure voltages in the range of 0 to 30 volts and range can be extended
- Cheap and widely used

Electro-dynamic meters (or dynamometers) (only frequency range is important)

- **Can measure both d.c. signals and a.c. signals up to a frequency of 2 kHz**
- the instrument has a moving circular coil that is mounted in the magnetic field produced by two separately wound, series-connected, circular stator coils. The torque is dependent upon the mutual inductance between the coils and is given by:

$$T = I_1 I_2 \frac{dM}{d\theta}$$

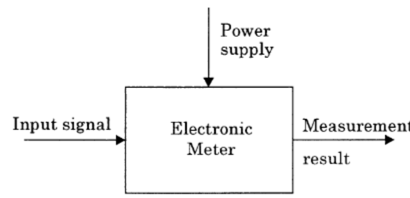
where I1 and I2 are the currents flowing in the fixed and moving coils
Electrodynamic meters are typically expensive but have the advantage of being more accurate than moving-coil and moving-iron instruments



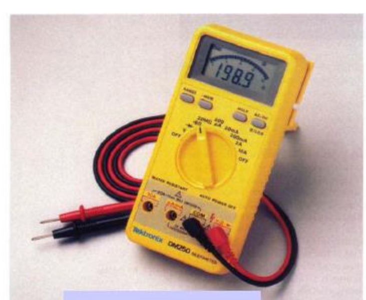
Electronic Voltmeters

- Electronic meters process the input signal by means of semiconductor devices in order to extract the information related to the required measurement
- An electronic meter can be basically represented as a three-port element,
- The input signal port is an input port characterized by high impedance, so that the signal source has very little load.
- The measurement result port is an output port that provides the measurement result (in either an analog or digital form, depending on the way the input signal is processed) along with the power needed to energize the device used to display the measurement result.
- The power supply port is an input port which the electric power required to energize the meter internal devices and the display device flows through.

- One of the main characteristics of an electronic meter is that it requires an external power supply.
- Although this may appear as a drawback of electronic meters, especially where portable meters are concerned, note that, this way, the energy required for the measurement is no longer drawn fron




Portable Analog Multimeter


Hand-held DMM


Bench-top DMM

Electronic Analog Meters

- Based on an electronic amplifier and an electromechanical meter to measure the amplifier output signal. The amplifier operates to make a dc current, proportional to the input quantity to be measured, flow into the meter.
- This meter is hence a dc moving-coil milliammeter.
- Different full-scale values can be obtained using a selectable-ratio voltage divider if the input voltage is higher than the amplifier dynamic range, or by selecting the proper amplifier gain if the input voltage stays within the amplifier dynamic range.
- It has high input impedance, high possible gain, and wide possible bandwidth for ac measurements.
- Measurement uncertainty can be lower than 1% of full scale value.
- Because of these features, electronic analog voltmeters can have better performance than the electromechanical ones

Dc Analog Voltmeters

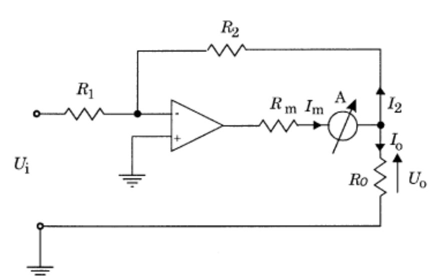
(be able to explain operation when circuit is given)

- Current Im equal:

$$I_m = I_o + I_2 = \frac{U_o}{R_o} + \frac{U_o}{R_2} = -U_i \frac{R_2}{R_1}\frac{R_2 + R_o}{R_2 R_o} = -\frac{U_i}{R_1}\left(1 + \frac{R_2}{R_o}\right)$$

- If *R1 = R2, and the same resistances are far greater than Ro, Equation above can be simplified to:*

$$I_m = -\frac{U_i}{R_o}$$



Rectifier-Based ac Analog Voltmeters

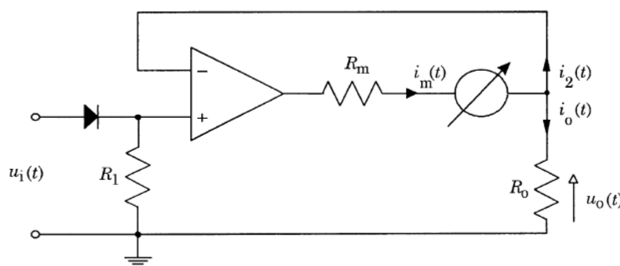
(be able to explain operation when circuit is given)

- A rectifying input stage is used.
- Because of the high input impedance of the electronic amplifier, *i2=0, and the current im=io.*
- *Since the amplifier is* connected in a voltage-follower configuration, the output voltage is given by:

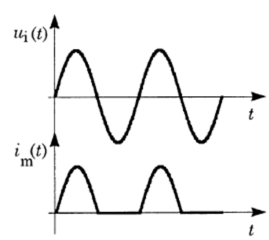
$$u_o(t) = u_i(t)$$

- And: for $u_i(t)>0$

$$i_m(t) = \frac{u_i(t)}{R_o}$$



- For ui(t)<0 , im=0



- The dc moving-coil milliammeter measures the average value *of im(t), which, under the assumption* of sinusoidal signals, is related to the rms value *Ui of ui(t) by:*

$$\bar{I}_m = \frac{\sqrt{2}}{\pi R_o} U_i$$

Electronic, full-wave rectifier-based ac analog voltmeter

- Output of A1:

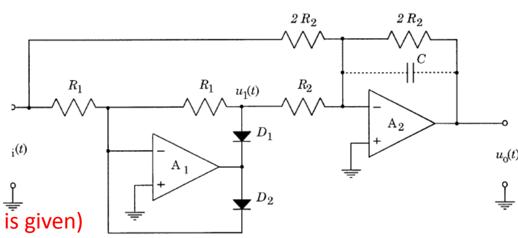
$$u_1(t) = \begin{cases} -u_i(t) & \text{for } u_i(t) \geq 0 \\ 0 & \text{for } u_i(t) < 0 \end{cases}$$

- Output of A2 (without C):

$$u_o(t) = -\left[u_i(t) + 2u_1(t)\right]$$

- Which gives a full wave rectifier :

$$u_o(t) = \begin{cases} u_i(t) & \text{for } u_i(t) \geq 0 \\ -u_i(t) & \text{for } u_i(t) < 0 \end{cases}$$



(be able to explain operation when circuit is given)

- Connecting capacitor *C in the feedback loop of amplifier A2 turns it into a first-order low-pass filter,* so that the circuit output voltage equals the average value of $u_o(t)$

$$\overline{U}_o = \overline{\left|u_i(t)\right|}$$

- In the case of sinusoidal input voltage with rms value *Ui, the output voltage is related to this rms value* by:

$$\overline{U}_o = \frac{2\sqrt{2}}{\pi} U_i$$

- Which can be measured by a dc voltmeter.

- Both ac meters are actually average detectors. However, due to the derived equations, their scale can be labeled in such a way that the instrument reading gives the rms value of the input voltage, provided it is sinusoidal.
- When the input voltage is no longer sinusoidal, an error arises that depends on the signal form factor.

$$FormFactor = \frac{r.m.s}{average}$$

For Sine wave and Full wave rectifier case:
rms= $V_p/\sqrt{2}$
Average= $2V_p/\pi$
FF=1.11

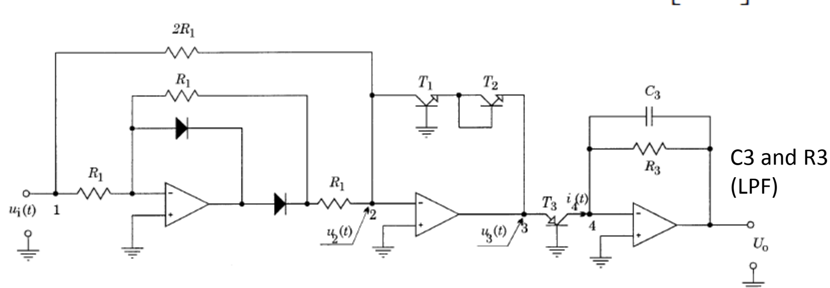
True rms Analog Voltmeters

Remember

$$U_i = \sqrt{\frac{1}{T}\int_0^T u_i^2(t)\,dt}$$

Log multiplier (T1 and T2)

$$u_3(t) = 2k_1\log[u_2(t)] = k_1\log[u_2^2(t)] = k_1\log\left[|u_i(t)|^2\right] = k_1\log[u_i^2(t)]$$



C3 and R3 (LPF)

Full wave rectifier

$$u_2(t) = |u_i(t)|$$

Anti-Log amp (T3)

$$i_4(t) = k_2\exp[u_3(t)] = k_3 u_i^2(t)$$

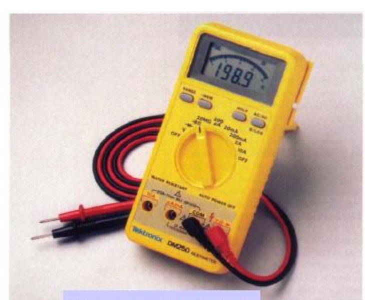
$$U_o = \frac{k}{T}\int_0^T u_i^2(t)\,dt = kU_i^2$$

(be able to explain operation when circuit is given)

- The previous design provides an output signal proportional to the squared rms value of the input signal *ui(t)*
- Quantities *k1, k2, and k depend on the values of the elements in the* circuit.
- Under circuit operating conditions, their values can be considered constant, so that *k1, k2, and k can be considered constant also.*
- If carefully designed, this circuit can feature an uncertainty in the range of +/- 1% of full scale, for signal frequencies up to 100 kHz.

Digital Voltmeters

- A digital voltmeter (DVM) attains the required measurement by converting the analog input signal into digital, and, when necessary, by discrete-time processing of the converted values.
- The measurement result is presented in a digital form that can take the form of a digital front-panel display, or a digital output signal. The digital output signal can be coded as a decimal BCD code, or a binary code.

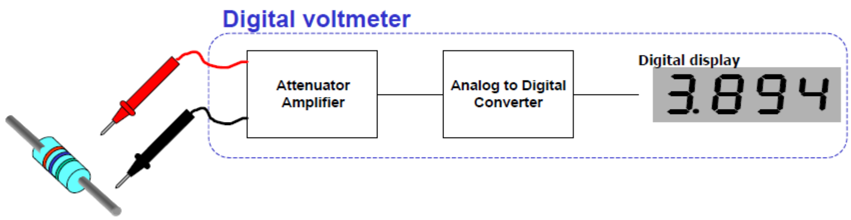


Hand-held DMM

Bench-top DMM

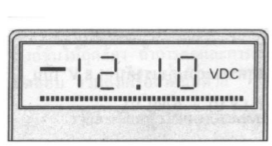
DVM

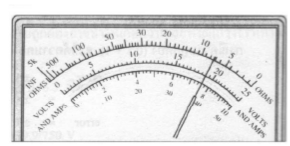
DVM is essentially an Analog to digital converter (A/D) with a digital display



Digital MultiMeter (DMM) **= electronic Volt Ohm Millimeter with digital display**

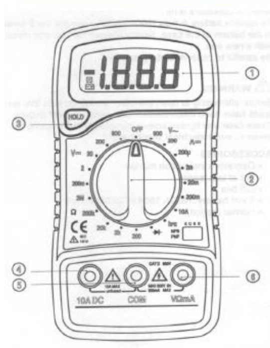
Comparison of Digital and Analog Meter





Digital meter	Analog meter
Leaves no doubt about the measured quantity.	Wrong scale might be used or might be read incorrectly.
Superior resolution and accuracy. (±0.5% or better)	Inferior resolution and accuracy. (±3% in common)
Indicates a negative quantity when the terminal polarity is reversed	Pointer attempts to deflect to the left when the polarity is reversed
No usually damaged by rough treatment	Can be damaged when dropped from bench level

Typical Specification of DMM



General

Maximum voltage between terminals	:600 V
Fuse protection	:200mA/250V
Power	:9V battery
Display	:LCD 31/2 digits, updates 2-3/ sec.
Input impedance	:10 MΩ
Frequency range	:40-400 Hz
Measuring method	Dual-slope integration
Over range indication	Only figure "1" on the display
Polarity indication	"-" displayed for negative polarity

Accuracy of DMM

Indicate as ± (% of reading + No. of digits)

Ex. ± (0.5% of rdg + 1 digits) sometimes simplify as ± (0.5 + 1)

Ex. For an accuracy of ± (0.5 + 1) , calculate the maximum error of in the 1.800 V reading

error = ± (0.5% of 1.800 + 0.001 V)
= ± (0.009 + 0.001 V) = ± 0.01 V or ± 0.56% of reading

Ex A 20 V dc voltage is measured by analog and digital multimeters. The analog instrument is on its 25 V range , and its specified accuracy is ± 2%. The digital meter has 3 ½ digit display and an accuracy of ±(0.6+1). Determine the measurement accuracy in each case.

Analog instrument:

Voltage error = ± 2% of 25 V
= ± 0.5 V

$$\text{error} = \pm \frac{0.5\ \text{V}}{20\ \text{V}} \times 100\% = \pm 2.5\%$$

Digital instrument:

For 20 V displayed on a *3 ½ digit display*

1 Digit = 0.1 V

Voltage error = ± (0.6% of reading + 1 Digit)
= ± (0.12+0.001) V
= ± 0.121 V

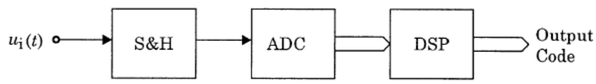
$$\text{error} = \pm \frac{0.121\ \text{V}}{20\ \text{V}} \times 100\% = \pm 0.605\ \%$$

½ digit

3½ digit display

Modern Digital Voltmeter

- For true digital voltmeter and ac signal can be used in the following structure which is truly digital



- The input signal *ui(t) is sampled* at constant sampling rate *fs, and converted into digital by the ADC. The digital samples are stored in the* memory of the digital signal processor (DSP) and then processed
- Assuming that the input signal is periodic, with period *T, and its frequency spectrum* is upper limited by harmonic component of order *N, the sampling theorem is satisfied if at least (2N +*1) samples are taken over period *T in such a way that (2N + 1)Ts = T, Ts = 1/fs being the sampling period*

Modern Digital Voltmeter

- If *ui(kTs) is the kth sample, the rms value of the input signal is given by,*

$$U^2 = \sqrt{\frac{1}{2N+1}\sum_{k=0}^{2N} u_i^2(kT_s)}$$

- This approach can feature a relative uncertainty as low as +/-0.01% of full scale, with an ADC resolution of 12 bits. The instrument bandwidth is limited to half the sampling frequency, according to the sampling theorem.
- To prevent the aliasing, a low-pass filter must be placed at the input stage of any digital meter. The filter cut-off frequency must ensure that all frequency components above half the sampling rate are negligible. If the low-pass, anti-aliasing filter is used, the digital DSP-based meters feature a low-pass frequency response also