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Reference Book

Measurement & Error

Def^n :

- Instrument :- device used for determining value or magnitude of a quantity.

- Accuracy - closeness with which an instrument reading approaches true value of variable being measured.

- Precision - measure of reproducibility of the instrument i.e measure of degree of successive measurements.

- Sensitivity - ratio of output/response of instrum to the change in input.

- Resolution - smallest change in measured value to which the instrument will respond.

- Error - deviation from true value of measured variable

Precision Characteristics → conformity
→ number of significant figures

More significant figures, more is the precision of an instrument

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Range of error = $E_{max} - E_{avg}$ (1) & ~~E_{max}~~ $E_{avg} - E_{min}$ (2)

Avg range of error = $\frac{(1)+(2)}{2}$

* Result of 2 numbers with different degree of accuracy is only as accurate as the least accurate measurement.
{Same for multiplication}

Doubtful part i.e k in num ± k is always added irrespective of addition or subtraction.

% Range of doubt = $\frac{k}{num} \times 100$

Subtraction of measurement is avoided as range of doubt vastly increases.

- **Instrument**: A device ~~th~~ for determining the value or magnitude of a quantity or variable.

- **Accuracy**: Closeness with which an instrument reading approaches the true value of the variable being measured.

- **Precision**: A measure of reproducibility of the ~~instrument~~ measurement.

- **Sensitivity**: Ratio of o/p signal or response of instrument to change of input or measured variable.

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Resolution: Smallest change in measured values to which the instrument will respond.

Error: Deviation from true value of the measured variable.

eg: $\boxed{1\ kg}$

0.99 kg — instrument 1

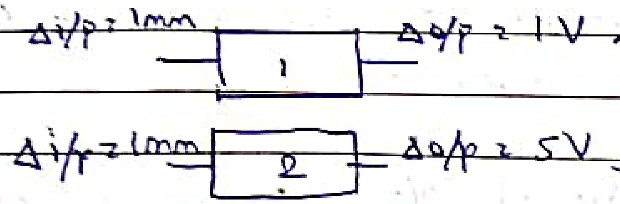
1.01 kg — instrument 2

Equally accurate

	Accurate	Precise (prominent choice)
eg:	instrument 1	instrument 2
	1.01 kg	1.05 kg
	0.99 kg	1.05 kg
	0.98 kg	1.09 kg
	1.02 kg	1.05 kg

Precise instrument may be accurate but accurate instrument is less likely to be precise.

$$\text{Sensitivity} = \frac{\Delta o/p}{\Delta i/p}$$



Depends on requirement (user & application)

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Beam balance of vegetable vendor would have resolution different from a jeweller.

~~Sign~~ Significant figures

SF conveys the actual information regarding the magnitude of the ~~measurement~~ measurement ~~and~~ precision of a quantity.

Q) A resistor R is specified as having a value of 68 Ω (i.e the value is closer to 68 Ω than to 67 Ω or 69 Ω)
True value = 67.8 Ω

* Population of Nagpur = 40,00,000
= 4×10^6 → b/w 3×10^6 & 5×10^6
= 40×10^5 → b/w 39×10^5 & 41×10^5

Q) A set of ~~costumer~~ measurements 117.02 V, 117.11 V, 117.08 V, 117.03 V.

Range of error
lower value = $E_{avg} - E_{min}$ = 117.06 − 117.02 = 0.04
higher value = $E_{max} - E_{avg}$ = 117.11 − 117.06
= 0.05

** check ambiguity of value not significant figures

Q) R_1 = 18.7 Ω
R_2 = 3.624 Ω
(series (calculate R_{eq} till) (appropriate significant figures))
R_{eq} = 22.324 = 22.3 Ω

i = 3.18 A
R = 35.68 Ω
V = ? appropriate significant figures

V = 113.464
= 113 V

35.68
× 3.18
28544
3568×
10704××
113.4624

Types of error

Classifications :

- Gross Error

Caused by human error
- → misreading
- → incorrect adjustment
- → improper selection & use of instrument
- → computational mistake

- Systematic error

* Shortcoming of instrument
  - Defective
  - Wear & tear
  - effect of environment

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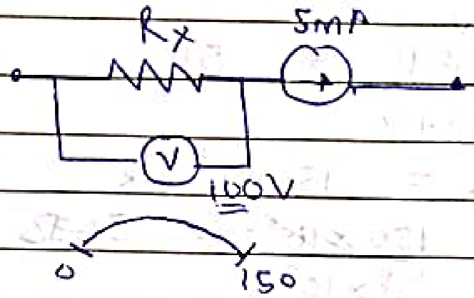
- Random errors

The error whose causes cannot be directly established due to random ~~variable~~ variation of parameters.

eg.:



find: i) apparent resistance
ii) True resistance
iii) Error

Sensitivity = 1000 Ω/V

$R_{voltmeter} = \frac{1000\,\Omega}{\cancel{V}} \times 150\,\cancel{V}$

$= 150\,k\Omega$

Apparent resistance $= \frac{100\,V}{5\,mA} = 20\,k\Omega$

True resistance $= R_x \parallel R_V = R_T$

$R_T = \frac{R_x \cdot R_V}{R_x + R_V} = \frac{150R}{150+R} = 20$

$15R = 300 + 2R$

$13R = 300$

$[R_x = 23.05\,k\Omega]$

Error $= \frac{3.05\,k\Omega}{23.05} \times 100$

$= 13.23\%$

Repect same if $\overset{\text{read}}{i = 800mA}$ $\overset{\text{read}}{V = 40V}$.

$R_V = 150k\Omega$

$R_{app} = 50\,\Omega$

$\frac{R_x \cdot R_V}{R_x + R_V} = R_{app}$

$\frac{150 \times 10^3 R}{150 \times 10^3 + R} = 50$

$3 \times 10^3 R = 150 \times 10^3 + R$

$R = \frac{150 \times 10^3}{3 \times 10^3} \Rightarrow 50.01\,\Omega$

$\text{Error} = \frac{0.01}{50.01} \times 100$

$= 0.0199\% \simeq 0.02\%$

Systematic Error

a) Instrumental Error

- inherent due to mechanical structure
- friction
- irregular spring tension
- excess pulling of spring ⇒ overloading the instrument
- calibration ~~excess~~ error.

b) Environmental Error

- change in temperature
- humidity
- pressure

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• electrostatic magnetic field

c) Random error
→ Take average of multiple readings

x ——— x ——— x ——— x

Reference :

a) Gross error : class of errors which mainly covers human mistakes in reading or using instruments and recording and computing measurement result.
• Using scale that does not correspond to setting of range control of the voltmeter.

b) Systematic error :
i) Instrumental error : error inherent in measuring instruments because of their mechanical structure
eg : friction in bearings, improper spring tension, calibration error.
Removing errors by : i) calibrating to proper standard
ii) Applying correction factors
iii) Selecting suitable instrument
ii) Environmental error : errors due to conditions surrounding the instrument
Change in temp., humidity, pressure etc
↳ change in elastic property

iii) Static & Dynamic
Static: caused by limitation of measuring instrument
Dynamic: ↳ instrument not responding fast enough for a change in measured variable

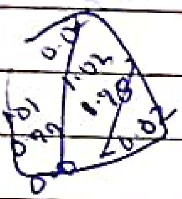
Random error : Error due to unknown cause when all statistical error are accounted. Removing error is by increasing number of readings & using statistical mean for best approximation.

---------- x ---------- x ---------- x

Statistical Analysis

i) Arithmetic Mean

$$\overline{x} = \frac{x_1 + x_2 + \cdots + x_n}{n} = \frac{\sum_{i=1}^{N} x_i}{N}$$



ii) Deviation from Mean

$$d_1 = x_1 - \overline{x}$$

$$d_2 = x_2 - \overline{x}$$

$$\vdots$$

$$d_n = x_n - \overline{x}$$

$$\boxed{\sum d_i = 0}$$

iii) Average deviation

It is an indication of precision of an instrument.

$$\left[D = \frac{|d_1| + |d_2| + |d_3| + \cdots |d_n|}{n} \right]$$

$$D = \frac{\sum |d_i|}{n}$$

IV) <u>Standard Deviation</u>

$$\sigma = \sqrt{\frac{d_1^2 + d_2^2 \cdots + d_n^2}{n}}$$

$$\sigma = \sqrt{\frac{\Sigma d_i^2}{n}}$$ (if i is too large) (in exam)
(for ∞ data pts)

$$\sigma = \sqrt{\frac{\Sigma d_i^2}{n-1}}$$ ~~generally~~ (for finite data pts)

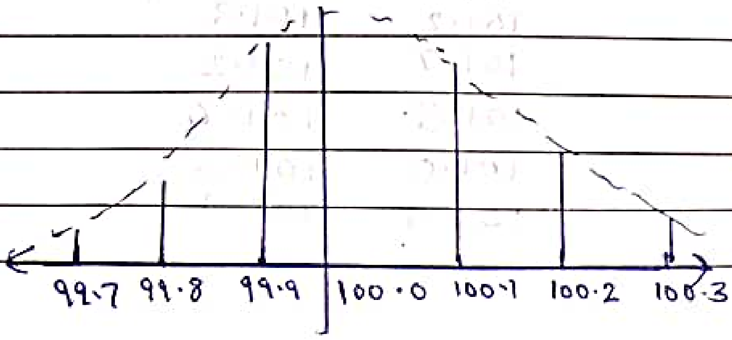
Variance $= \sigma^2$

<u>Probability of Errors</u>

(1) Normal Distribution

eg:

Voltage Reading	No. of Reading
99.7	1
99.8	4
99.9	12
100.0	19
100.1	10
100.2	3
100.3	1

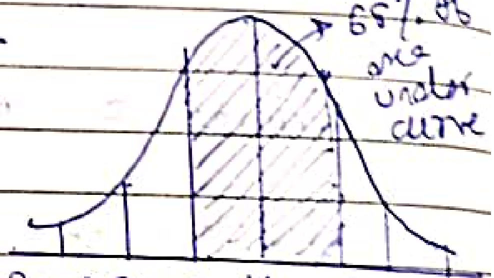


Normal law

* All observation include small error.
* Errors can be +ve as well as -ve
* Equals probability of +ve & -ve errors
* Small errors are more probable.
* Large errors are more probable.

Probable error (P.E)

$$PE = \pm 0.6745 \times \sigma$$



Limiting Error

* certain percentage of guaranteed value.
  eg: Resistor, digital thermometer.

σ	Area under cur
0.6745	50%.68
1	6
2	95.
3	99.

* given by manufacturer

H.W: find avg., deviation & probable error in

101.2	101.3
101.7	101.2
101.3.	101.4
101.0	101.3
101.5	101.1

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Q) A 0-150V voltmeter has a guaranteed accuracy of 1% full-scale reading. The voltage measured by this instrument is 83V. Calculate limiting error in %.

Magnitude of limiting Error = 1% of 150V

$= \pm 1.5V$

limiting or ~~limiting~~ Error $= \frac{1.5}{83} \times 100 = 1.8072$

Q) The voltage in a ckt is equally dependent on value of 3 resistors $V_{out} = \frac{R_1 \cdot R_2}{R_3}$. If tolerance of each resistor is 0.1%. Find max error of generated voltage.

$$\log V_{out} = \log R_1 + \log R_2 - \log R_3$$

$$100 \times \left(\frac{\Delta V_{out}}{V_{out}}\right) = \left(\frac{\Delta R_1}{R} + \frac{\Delta R_2}{R} - \frac{\Delta R_3}{R}\right) \times 100$$

$\% V_{out}$ max = $0.1 + 0.1 + 0.1 = 0.3\%$

$\% V_{out}$ min = $-0.1 - 0.1 - 0.1 = -0.3\%$

M2

$$V_{out} = \frac{1.01 R_1 \quad 1.01 R_2}{0.99 R_3} = 1.003 \left(\frac{R_1 R_2}{R_3}\right)$$

$= 3\%$

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Q) Current passing through resistor ~~100 ± 0~~ of 100 ± ... is 2.00 ± 0.01 A. Using $P = I^2 R$ find limiting error in power dissipation.

$$P = I^2 R$$

$$\log P = 2\log I + \log R$$

$$\frac{\Delta P}{P} = \frac{2\Delta I}{I} + \frac{\Delta R}{R}$$

$$= 2 \times (0.01) + 0.02$$

$$= 0.02 + 0.2$$

$$= 0.22$$

$$= \left(2 \cdot \frac{0.01}{2} + \frac{0.2}{100}\right) \times 100$$

$$= (1 + 0.2)\ \%$$

$$\boxed{\% P = 1.2\%}$$

Functional Elements of an instruments

Application of Measuring System

Measuring → instrument

i) Monitoring of a process or operation
ii) ~~Maintoring of a proces~~
Control the process
iii) Experimental Engineering

Elements of a Measuring System

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Primary Sensing Element [PSE]

- ~~measured~~ measurand : quantity to be measured
- measurand is first detected by the PSE
- PSE should withdraw minimum energy from the measurand.
- PSE may or may not be in direct physical contact with the measurand.

ii) Variable Conversion Element [VCE]

- converts PSE signal from one form to another while preserving the information content.
  Eg : ADC

iii) Variable Manipulation Element

- increase / decrease the strength of VCE signal.
- Signal conditioning

iv) Data Presentation Elements

- conveys information of measurement

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Transducer

- converts one form of energy to another form.

i) Active Transducer ~~self generating~~
- These are ~~externally~~ powered transducer
- Eg - all digital instrument transducer.

ii) Passive Transducer
Externally powered
- ~~self~~ generating type transducer
- Eg piezo-electric crystal

Types of Instruments

i) Deflection type

- o/p is in the form of deflection
- less accurate
- less sensitivity
- suitable for dynamic measurement.
- Eg- speedometer

ii) Null type

- It attempts to maintain the deflection at 0 suitable application of an ~~opposite~~ opposing force to the measured value.

- Eg : Weight - Balance

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- More ~~or~~ accurate
- High sensitivity.
- Not suitable for dynamic measurement

Problems

1) Scale = 0 – 100V
No of div = 200
Each div reads = 0·5V
~~1 div~~ 0·5 of div reads
= 0·25V

2) No of div = 9999
Full scale Reading ~~Sa~~ = 9.999 V
∴ 1 div reads = $\frac{9.999}{9999}$ = 0.001 V → Resolution

3) (a) ~~B~~ 3
(b) 2
(c) 4
(d) 5
(e) ~~0~~ 1
(f) 1

4) R_1 = 28.4 Ω R_2 = 4.25 Ω
R_3 = 56.605 Ω R_4 = 0.75 Ω
R_{series} = 90.0 Ω

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(ii) $P = VI\cos\theta$

$\cos\theta = \cos^{-1}\left(\frac{P}{VI}\right)$

$= 0.699$

Error in $\theta = 0$

Youtube

Error = True value − Measured value

$dI = I_t - I_m$

↓

Absolute error → remains constant throughout

% Relative error = $\frac{\text{True} - \text{Measured}}{\text{True}} \times 100$

$\epsilon_r = R.E = \frac{dA}{A_T}$ → Absolute error $= \epsilon$

$\epsilon_r = \left(\frac{A_m}{A_T} - 1\right)$

$A_T = \left(\frac{1}{1+\epsilon_r}\right) A_m$

↓

CF → correction factor

$$\boxed{A_T = CF \times A_m}$$

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$(10 \pm (1))\,A$ → (Error) ε_a $\qquad$ $(10 \pm 10\%)\,A$ → ε_r

Relative error decreases as we approach the full-scale reading.

7) $V = (200 \pm 2\%)\,V$

$R = (42 \pm 1.5\%)\,\Omega$

$\boxed{\frac{2}{100} \times 200 \quad (4\,V) \quad 0.63\,\Omega}$

$P = V^2/R$

$= \frac{200 \times 200}{42} = 952.38\,W$

$\frac{\Delta P}{P} \times 100 = 2\frac{\Delta V}{V} \times 100 + \frac{\Delta R}{R} \times 100$

$\% \varepsilon_r = 2 \times 2 + 1.5$

$= 5.5\%$

$P = (952.38 \pm 5.5\%)\,W$

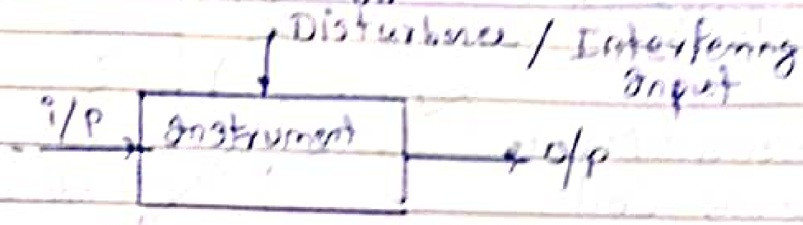
$R_{eq} = R_1 + R_2$

$dR_{eq} = dR_1 + dR_2$

$R_{eq} \cdot \frac{dR_{eq}}{R_{eq}} = R_1 \frac{dR}{R_1} + R_2 \frac{dR_2}{R_2}$

For multiplication
for addition/subtraction
just add normally

Input Output Configuration of an Instrument



i) **Desired I/P**

It is the i/p for which instrument is designed to be sensitive

ii) **Interfering I/P**

It is the i/p for which instrument is unintentionally sensitive.

iii) **Modifying Input**

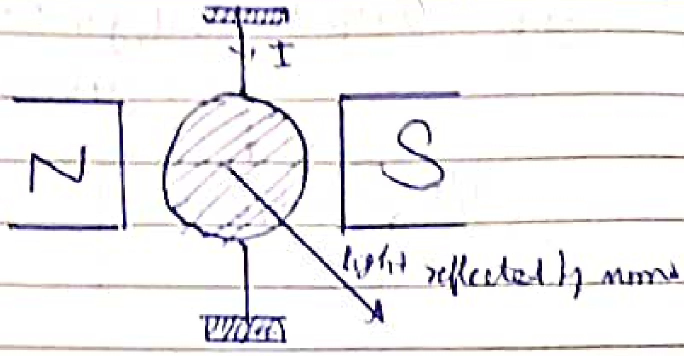
It is the i/p for which changes the input - output relationship of an instrument

Electromechanical

Electrochemical Indicating Measurement

PMMC

Permanent Magnet Moving Coil



- coil is fine wire
  - else → more energy would be consumed, heating causes variation in readings.
- suspended in a magnetic field is produced by permanent magnet.
- coil starts rotating when it carries current
- Mirror to the coil

Features

~~Advantages~~ →
- weightless pointer with ∞ le
- Not portable
- Not practical
- Used in modern devices

$$T = BAIN$$

where $T \rightarrow$ Torque (Nm)

$B \rightarrow$ flux of air gap (w/m^2 or tesl

$A \rightarrow$ Area in m^2

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Practical value

$A = 0.5\,cm^2$ to $2.5\,cm^2$
$B = 1500$ gauss to 5000 gauss or 0.15 tesla to 0.5 tesla.

$N \simeq 100$
$I \simeq 1\,mA$
$J \sim 3 \times 10^{-6}\,Nm$

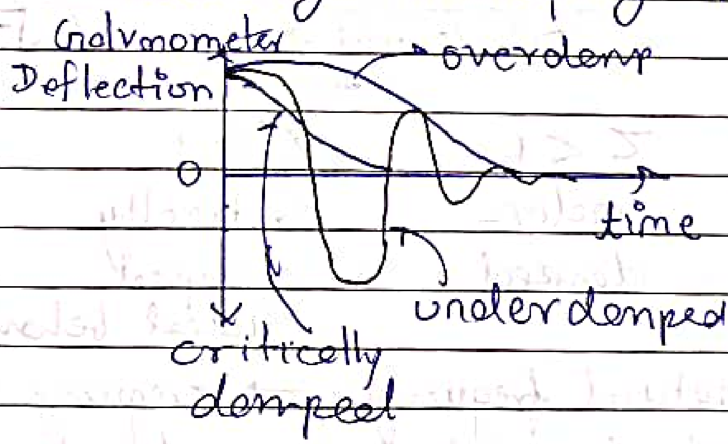
Q) What will happen if we apply AC to PMMC

→ Fine vibrations occur instead of deflection
Won't be able to measure current.

Q) What will happen if DC is suddenly removed?

Dynamic Behaviour (DB)

- Dynamic Behaviour can be observed by suddenly interupting the applied current.



HW: Read CRDRX

Dynamic behaviour

- In PMMC meters a set of torques are considered: developed torque & control.

- Developed torque causes pointer to deflect to a steady-state position where it is balanced by the opposing control spring torque:

$$T = J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} + K\theta$$

T = actuating torque; J = inertia of system (to overcome inertia); D = damping coefficient (to overcome damping); K = spring constant; θ = angular deflection (to overcome restoring spring constant)

Damping ratio $\zeta = \dfrac{D \text{ (damping const.)}}{D' \text{ (critical damping constant)}} = \dfrac{D}{2\sqrt{KJ}}$

$\zeta > 1$	$\zeta < 1$	$\zeta = 1$
over-damped	under-damped	critically damped (ideal behaviour)

Undamped natural frequency: frequency of oscillation of transient when damping is zero.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{J}}$$

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→ Instrument, in practice, is slightly underdamped, causing pointer to overshoot a little ∴ Decreases response time but prevents damage to instrument

→ ~~CRDX~~ CDRX (Critical Damping Resistance External)
constant in galvanometer which determines the value of external resistance that produce critical damping. To determine CDRX observe galvanometer swing when current is applied / removed in galvanometer. Decreasing value of external resistance are tried until a value is found for which overshoot just disappear i.e CDRX

Youtube

1) T.V = 80V
M.V = 79V
Abs. error = 1V

2) $\text{error} = \frac{150 \times 1}{100} = 1.5\text{ V}$

$\%\text{ limiting error} = \frac{1.5}{75} \times 100 = 2\%$

3) $\text{error} = 2/100 \times 200 = 4\text{ V}$

$\%\text{ error} = 4/100 \times 100 = 4\%$

4) $\text{error} = 2/100 \times 300 = 6\text{ V}$

Range = 24 – 36V

B) ~~error~~ avg = 110.2

~~|diff|~~

~~Range/max = 110.3 - 110.2 / 0.1 V~~

$d_1 = 0.1V$

$d_2 = 0V$

$d_3 = 0.05$

$d_4 = -0.1$

$d_5 = -0.05$

~~0.1+0.05+0.1~~ ~~Range = 110.3 - 0.1~~

range = 110.3 − 110.2 = 0.1

110.2 − 110.1 = 0.1

range = $\frac{0.1+0.1}{2} = \pm 0.1$

$\therefore$ Range of error (use $\pm$) $= \frac{(I_{max} - E_{avg}) + (E_{avg} - E_{min})}{2}$

C) ~~$R_1 + R_2 = 0$~~ $R_S = \Sigma R$

$R_S = 100\Omega$

$R_1 + R_2 + R_3 = R$

$\frac{dR_1}{R_1} \cdot R_1 + \frac{dR_2}{R_2} \cdot R_2 + \frac{dR_2}{R_3} \cdot R_3 = \frac{dR}{R}$

$2 \times 10 + 3 \times 20 + 70 \times 5 = 100$

$\% R = \frac{20 + 60 + 350}{100} = 4.3\%$

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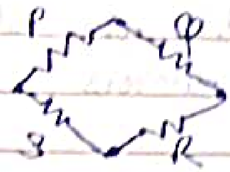
(all about electrons)

Q: $P = 10 \pm 2\%$
$Q = 20 \pm 3\%$
$S = 70 \pm 5\%$



$$P \cdot R = Q \cdot S$$
$$R = \frac{Q \cdot S}{P}$$
$$= \frac{20 \times 70}{10} = 140\ \Omega$$

dR

$$\log R = \log Q + \log S - \log P$$
$$\frac{dR}{R} \times 100 = \frac{dQ}{Q} \times 100 + \frac{dS}{S} \times 100 + \frac{dP}{P} \times 100$$
$$= 2 + 3 + 5$$
$$= 10\%$$

* Significant errors

Rules:

1. All non zero digits are significant
2. Zero preceding first non-zero digit are not significant
   eg 0.00125 → 3
3. Zeros b/w 2 non zero digits are significant
   eg: 5.012 → 4
4. Zeroes at end or right are significant provided they are on same side of decimal point.
   100.00 → 5
   4.000 → 4
5. Exact numbers have ∞ significant figures

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eg// 1.213 + 3.43 + 2.3

Addition / Subtraction : Result cannot have more digits to the right of decimal pt. than either of original numbers.

$1.213 + 3.43 + 2.3$

$= 6.943 \rightarrow 6.9$

Multiplication / Division : The result must be reported with no more significant figures as there are in measurement with the few significant figures.

$\overset{2}{1.4} \times \overset{3}{2.35} = 3.276 \rightarrow 3.3$

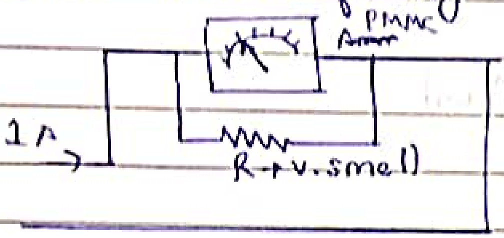
$\overset{4}{6.213} \div \overset{3}{3.43} = 1.8113 = 1.81$

* DC Ammeter

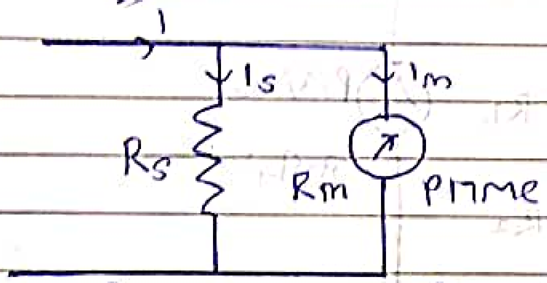
* PMMC or d'Arsonal's Movement or Galvanometer

* PMMC can handle very small current.

* Reduce current flowing through PMMC.



or



$\{I_s R_s = I_m R_m\}$

[which device how much length used for resistance ?]

Q) A 1 mA movement with an internal resistance of 100 Ω is to be converted to ammeter b/w 0-100 mA. Calculate shunt resistance.

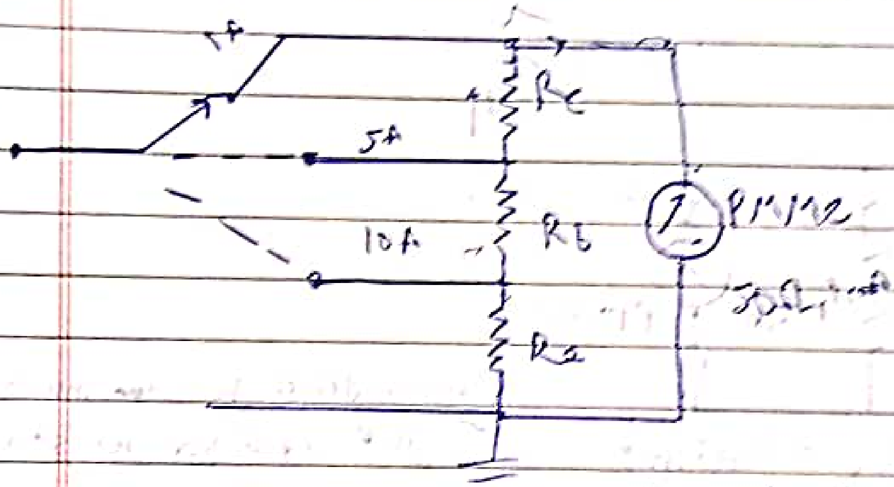
$$1 \times 100 = 99 R_s$$

$$R_s = 100/99$$

$$\approx 1.001\ \Omega$$

★ Multirange Ammeter

Ayerton Shunt / Universal Shunt



Design an Ayerton Shunt to provide an ammeter with current range of 1A, 5A, 10A. A PMMC with an internal resistance of 50 Ω & FSD of 1mA is to be used.

$0.999\,(R_a + R_b + R_c) = (0.001)\,50$

$999\,(R_a + R_b + R_c) = 50 \quad \text{--- (1)}$

$4.999\,(R_b + R_a) = (50 + R_c)\,0.001$

$4999\,R_b + 4999\,R_a - R_c = 50 \quad \text{--- (2)}$

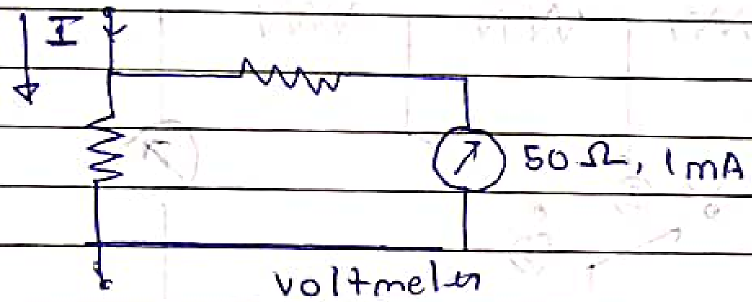
$9.999\,R_a = (50 + R_c + R_b)$

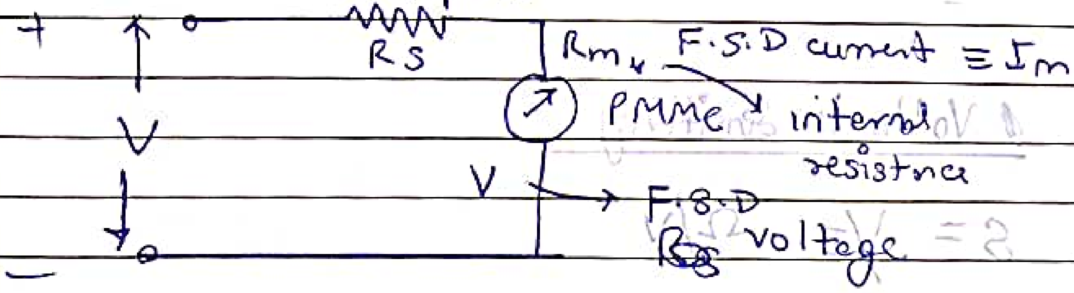
$9999\,R_a - R_b - R_c = 50$

R_c $R_a = 0.05\ \Omega$
R_b $R_b = 10^{-5}\ \Omega$
R_c $R_c = 10^{-5}\ \Omega$

$R_a = 5\ m\Omega$
$R_b = 5\ m\Omega$
$R_c = 0.04\ \Omega$
$= 40\ m\Omega$

DC Voltmeters



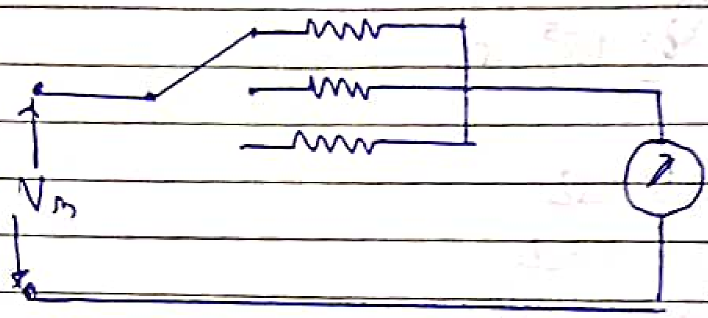


$$V = I_m(R_s + R_m)$$

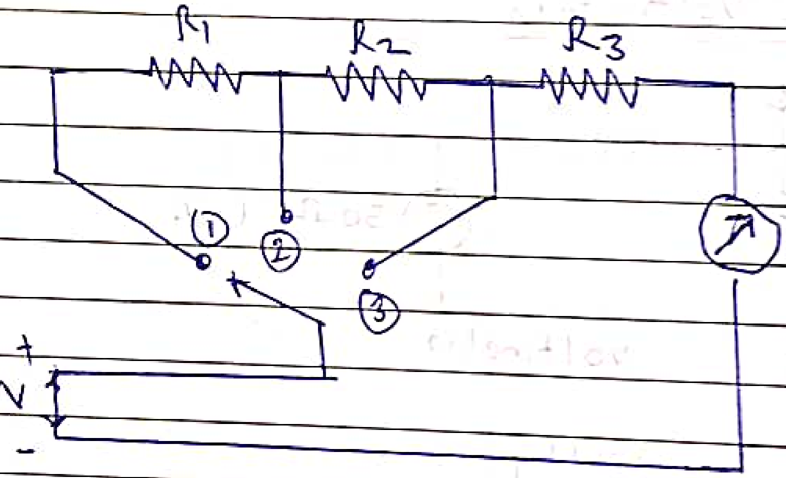
$$\left\{ R_s = \frac{V}{I_m} - R_m \right\}$$

~~Multimeter~~

* Multirange Voltmeter



* Another Arrangement



Voltmeter Sensitivity

$$S = 1/I \quad \Omega/V$$

for Fig 1,

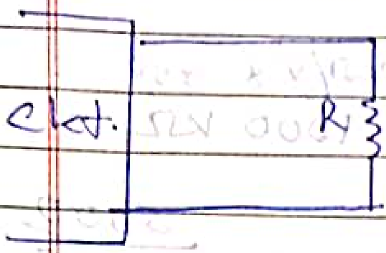
Total resistance = R_T

$$R_T = S \times V$$

$$R_0 = R_T - R_m = SV - R_{mm}$$

Vcm, 5Ω

Loading effect

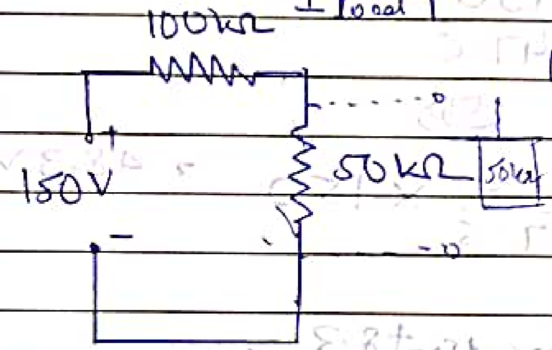


$\begin{cases} \text{Full load } R_L = \infty\ \Omega \text{ (open ckt)} \\ \text{No load } R_L = 0\ \Omega \text{ (short ckt)} \end{cases}$

loading effect is caused by low sensitivity devices.

$S = \dfrac{1}{I_{load}} \uparrow$

Q)



Measure voltage across 50kΩ & using

Voltmeter 1 sensitivity = 1000 Ω/V = 1 kΩ/V

Voltmeter 2 sensitivity = 20000 Ω/V = 20 kΩ/V

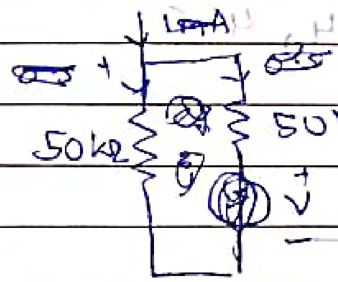
$i = 1\text{ mA}$

$\left\{ V_{50k\Omega} = 50\text{ V} \right\}$

$150 - 100i - 25i = 0$

$i = \dfrac{150}{125}$

① $1\ k\Omega/\cancel{V} \times 50\cancel{V} = 50\ k\Omega$



~~50 − 50 / 0.~~

~~V = 50 × 0.5~~

$V_{across\ 50k\Omega} = \dfrac{150}{125} \times \dfrac{2}{50}$

$V_{across\ voltmeter} = \dfrac{150}{1250 \times 2} \times 50$

$= 1/5 \times 150$

$= 30\text{ V}$

$= \dfrac{150}{125 \times 2} \times 25$

$= 30\text{ V}$

$Error\% = 40\%$

$R_{volt} = 20\ k\Omega/V \times 50 = 1000\ k\Omega$

$$\frac{5000}{105}$$

$$R_{eq} = \frac{50 \times 1000}{1050} = \frac{5000}{105} = 47.6\ k\Omega$$

$$i = \frac{150}{147.6}$$

$$V_{volt} = \frac{47.6}{147.6} \times 150 = 48.3\ V$$

$$\%\ Error = \frac{50 - 48.3}{50} \times 100 = 3.28\%$$

* Assignment
Sample 4-3, 4-4, 4-6

Series Type Ohmmeter

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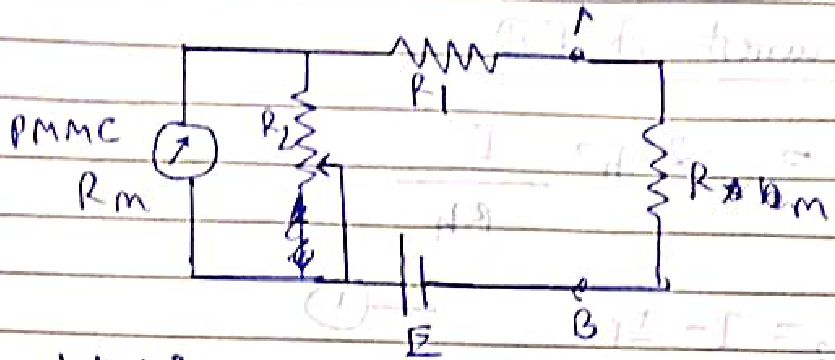

Working

- Short ckt AB
- Adjust R_2 until FSD
- Mark the PMMC ~~position~~ position as 0Ω.
- Open ckt A.B
- PMMC indicates zero.
- Mark this position as $\infty\ \Omega$.
- Use known resistors ~~to~~ make intermidiate marking.

Drawbacks

- Calibration
- internal battery slowly discharges

Half Scale Deflection

R_h : Half Scale Deflection

$$R_h = \left(R_1 + \frac{R_2 \cdot R_m}{R_2 + R_m}\right)$$

$$\left(\frac{R_m R_2}{R_m + R_2}\right) + R_1 = R_h$$

$$I_{h} = \frac{E}{2R_h}$$

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Total current at FSD

$$= 2I_h = \frac{E}{R_h}$$

$$I_2 = I - I_{FSD} \quad \text{——} \; 1$$

voltage across shunt = voltage across PMMC

$$I_2 R_2 = I_{fsd} R_m$$

$$R_2 = \frac{I_{fsd} R_m}{I_2} \quad \text{——} \; 2$$

$$R_2 = \frac{I_{fsd} R_m}{I_T - I_{FSD}} \qquad I_T = \frac{E}{R_h}$$

$$= \frac{I_{fsd} R_m}{\frac{E}{R_h} - I_{FSD}}$$

$$R_2 = \frac{(I_{FSD} R_m) R_h}{E - I_{FSD} R_h}$$

we know

$$R_1 = R_h - \frac{R_2 R_m}{R_2 + R_m}$$

$$\frac{R_2 R_m}{R_2 + R_m} = R_h - R_1$$

$$\frac{R_m}{1 + \frac{R_m}{R_2}} = R_h - R_1$$

$$\frac{1}{1 + \frac{R_m}{R_2}} = \frac{R_h - R_1}{R_m}$$

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$$1 + \frac{R_m}{R_2} = \frac{R_m}{R_h - R_1}$$

$$\frac{R_m}{R_2} = \left(\frac{R_m}{R_h - R_1} - 1\right)$$

$$\left\{ R_2 = \frac{R_m}{\frac{R_m}{R_h - R_1} - 1} \right\}$$

$$\frac{\cancel{R_m}}{\frac{R_m}{\cancel{R_h - R_1}} - 1} = \frac{I_{FSD} \cancel{R_m} R_h}{E - I_{FSD} R_h}$$

$$\frac{R_m}{R_h - R_1} - 1 = \frac{E - I_{FSD} R_h}{I_{FSD} R_h}$$

$$\frac{R_m}{R_h - R_1} = \frac{E - I_{FSD} R_h + 1}{I_{FSD} R_h}$$

$$\cancel{R_m}$$

$$\frac{R_h - R_1}{R_m} = \frac{I_{FSD} R_h}{E} \qquad \frac{I_{FSD} R_h}{E - \cancel{I_{FSD} R_h} + \cancel{I_{FSD} R_1}}$$

$$R_h - R_1 = \frac{R_m I_{FSD} R_h}{E}$$

$$R_1 = R_h - \frac{R_m I_{FSD} R_h}{E}$$

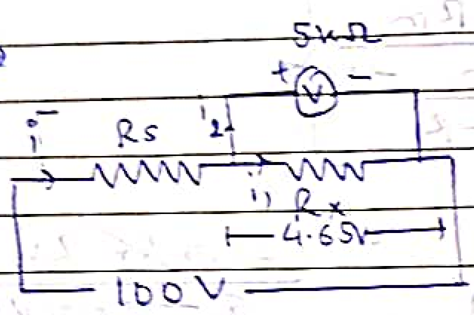
$$\left\{ R_1 = R_h \left(1 - \frac{R_m I_{FSD}}{E}\right) \right\}$$

Assignment Example 4-7

Assignment question

4-7) $R_V = \frac{100\ \Omega}{V} \times 50\ V$

$= 5000\ \Omega = 5\ k\Omega$



$4.65 = i_1 R_x$ —— ①

$\left(\frac{5000 R_x}{5000 + R_x} + R_S\right) i = 100$ —— ②

$i = \cancel{i_2} + i_1 + i_2$ —— ③

$R_S \cdot i = 95.35\ V$ —— ④

$5000\, i_2 = 4.65$ —— ⑤

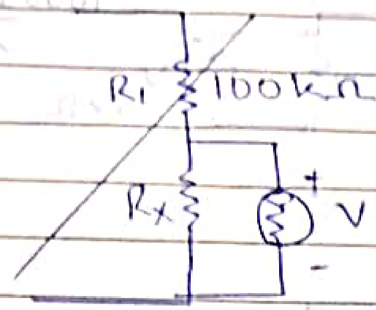
$i_2 = 9.3 \times 10^{-4}\ A$

$\left(\frac{5000 R_x}{5000 + R_x}\right) i = 4.65$

$\frac{(5000 R_x)(i_1 + 9.3 \times 10^{-4})}{1} = 23250 + 4.65 R_x$

$5000 R_x i_1 + 4.65 R_x = 23250 + 4.65 R_x$

4-7)

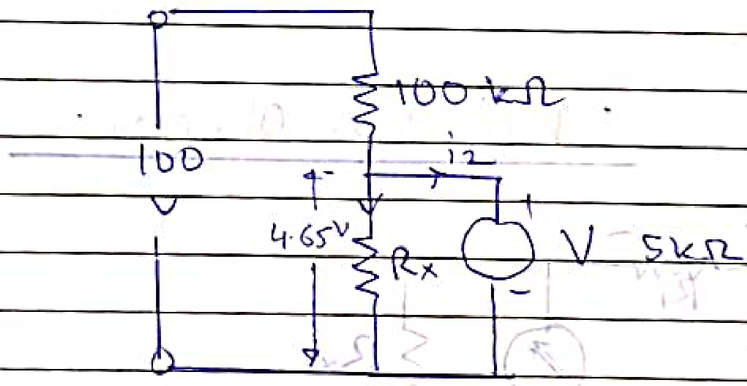


5 kΩ , 4.65V

$i = 0.9535\ A$

$$\cancel{\frac{4767.5 R_x}{5000 + R_x} = 4.65}$$

$\cancel{4762.85 R_x = 23250}$

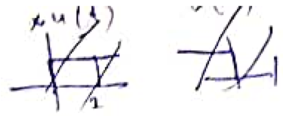


$i = \cancel{953}\ 0.9535\ mA$

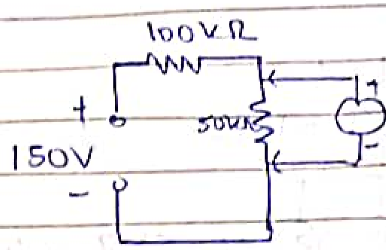
$i_2 = \cancel{5000}\ 0.93\ mA$

$i_1 = 0.0265\ mA$

$\{R_x = 180\ k\Omega\}$

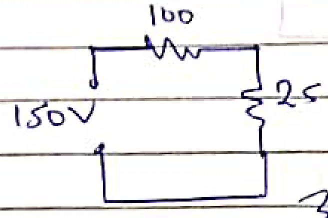


4-6)



$\frac{1000\,\Omega}{\cancel{V}} \times 50V$

$5\times10^4\,\Omega = 50k\Omega$

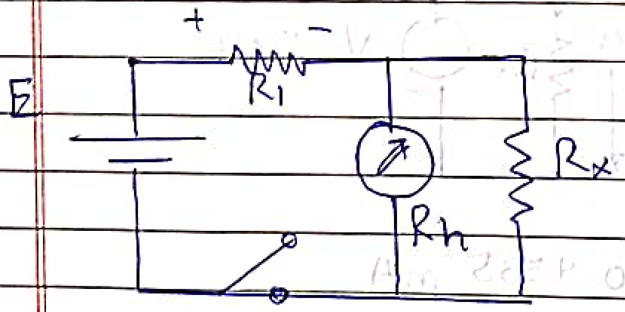


$i_T = \frac{150}{125}$

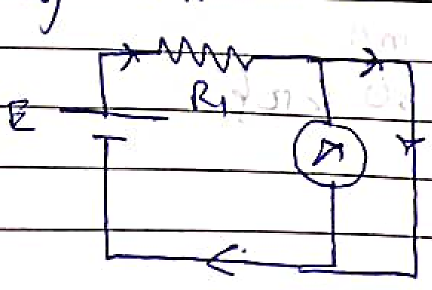
$V_{50k\Omega} = \frac{\cancel{75}^{\,3}}{\cancel{125}_{\,\cancel{25}}} \times \cancel{50}^{\,10} = 30V$

4-4 ( )

Shunt Type Ohmeter



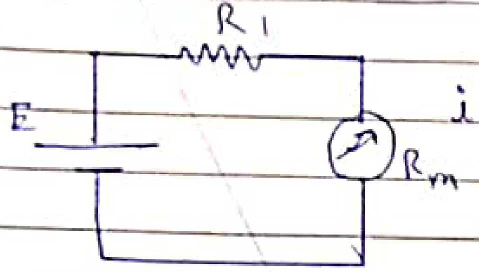
i) $R_x = 0\,\Omega$



$i = \frac{E}{R_1}$

current through PMMC = 0

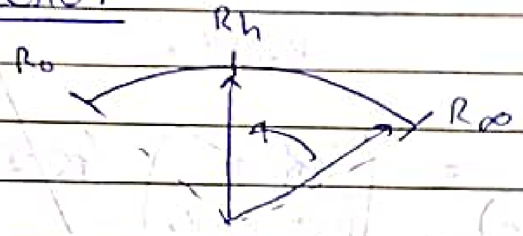
ii) $R_x = \infty$

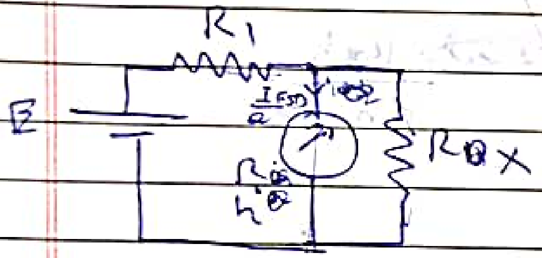


$i = E/(R_1+R_m)$

$I = I_{FSD}$

Holf Scale deflection





$R_{eq} = \left(R_1 + \frac{R_h \cdot R_m}{R_h+R_m}\right)$

$i_{FSD} = \frac{E}{R_{eq}} = \frac{E}{R_1 + \frac{R_h \cdot R_m}{R_h+R_m}}$

$\frac{i_{FSD}}{2} = \frac{E}{R_1 + \frac{R_h \cdot R_m}{R_h+R_m}} = \left(\frac{E}{R_1+R_m}\right)\frac{1}{2}$

$2R_1 + 2R_m = R_1 + \frac{R_h \cdot R_m}{R_h+R_m}$

$R_1 = \frac{R_h \cdot R_m}{R_h+R_m} - 2R_m$

$\left\{ R_1 = R_m\left(\frac{R_h}{R_h+R_m} - 2\right)\right\}$

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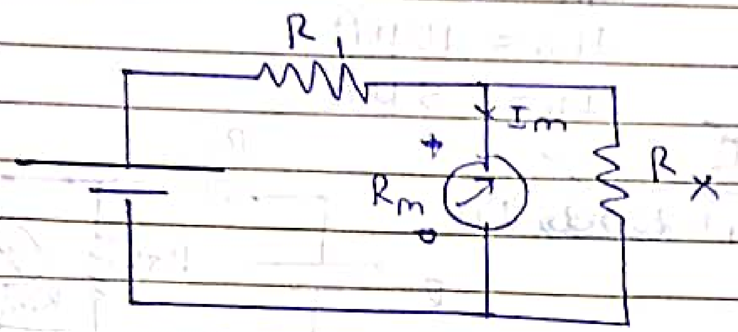
$$2R_1R_m + R_1R_x + R_1 + R_mR_x + R_mR_x = 2R_1 + 2R_m$$

$$2R_1R_m + 2R_1R_x + R_1 + R_mR_x = 2R_1 + 2R_m$$

$$R_x = \frac{R_1 + 2R_m - 2R_1R_m}{2R_1 + R_m}$$



$$i_T = \frac{E}{R_1 + \frac{R_mR_x}{R_m + R_x}}$$

$$I_m = \left(\frac{R_x}{R_x + R_m}\right)\left(\frac{E}{R_1 + \frac{R_mR_x}{R_m + R_x}}\right)$$

$$S = \frac{I_m}{I_{FSD}} = \frac{R_x(R_1 + R_m)}{R_m(R_1 + R_x) + R_1R_x}$$

$$R_p = \frac{R_1R_m}{R_1 + R_m} \qquad \therefore S = \frac{R_x}{R_x + R_p}$$

for HSD, $R_m = R_x$ $\quad I_m = \frac{I_{FSD}}{2}$

$$0.5\, I_{FSD} = \frac{ER_x}{R_1R_m + R_1R_x + R_mR_x}$$

$$\therefore \left\{R_h = \frac{R_1R_m}{R_1 + R_m}\right\}$$

Multimeter

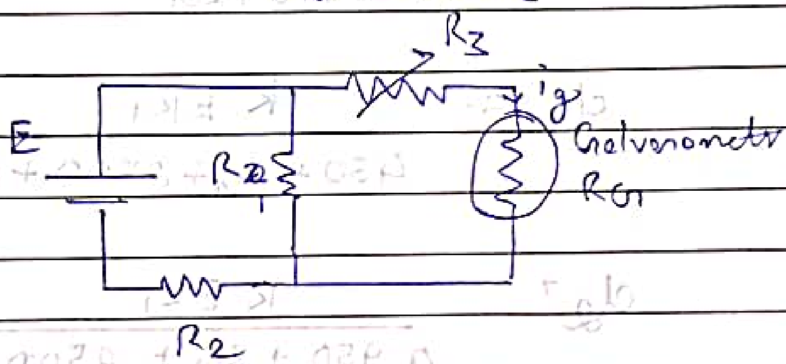
- multimeter range ~~ammeter~~ ammeter (low internal R)
- multirange voltmeter (high internal R)
- multirange ohmmeter (high internal R)

Eg 4.1

$E = 1.5V$

$R_1 = 1\Omega$

$R_2 = 2500\Omega$



i) $R_3' = 450\Omega$

$d_1 = 150$ mm

$R_3'' = 950\Omega$

$d_2 = 75$mm

$$E = i_T \times \left[\frac{R_1(R_3+R_G)}{R_3+R_G+R_1} + R_2 \right]$$

$R_3 + R_G = R_S$

$$i_T = \frac{E}{\frac{R_1 R_S}{R_S+R_1} + R_2}$$

$$i_g = \left(\frac{E}{\frac{R_1 R_S}{R_1+R_S} + R_2}\right)\left(\frac{R_1}{R_1+R_S}\right) \qquad i_g \propto d$$

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$$\frac{i_{g1}}{i_{g2}} = \frac{d_1}{d_2} = \frac{\left(\dfrac{E R_1}{\dfrac{R_1(R_3' + R_G)}{(R_1 + R_3' + R_G)} + R_2} \times \dfrac{1}{(R_1 + R_3' + R_G)}\right)}{\left(\dfrac{E R_1}{\dfrac{R_1(R_3'' + R_G)}{(R_1 + R_3'' + R_G)} + R_2} \times \dfrac{1}{(R_1 + R_3'' + R_G)}\right)}$$

$$d_1 = \left[\frac{E R_1}{\dfrac{(450 + R_G)}{1 + 450 + R_G} + 2500} \times \frac{1}{1 + 450 + R_G}\right]$$

$$d_1 = \frac{K E R_1}{450 + R_G + 2500 + 1125000 + 2500 R_G}$$

$$d_2 = \frac{K E R_1}{\dfrac{950 + R_G}{1 + 950 + R_G} + 2500} \times \frac{1}{1 + 950 + R_G}$$

$$d_2 = \frac{K E R_1}{950 + R_G + 2500 + 2375000 + 2500 R_G}$$

$$2 = \frac{d_1}{d_2} = \frac{2378450 + 2501 R_G}{1127950 + 2501 R_G}$$

$$2501 R_G = 122550$$

$$\{R_G = 49\,\Omega\}$$

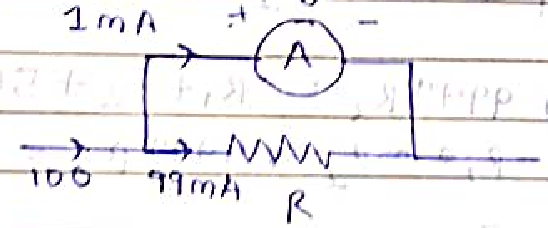
$$S = \frac{i_{g1}}{d_1}$$

$$i_{g1} = \left(\frac{E}{\frac{R_1 R_s}{R_1 + R_s} + R_2} \right) \frac{R_1}{R_1 + R_s}$$

$$i_{g1} = \cancel{\frac{3\ mA}{150\ mm}} \quad (0.6\ mA) \times 2 \times 10^{-3}$$
$$= 1.2\ \mu A$$

$$\cancel{\frac{3 \times 1.2\ \mu A}{150\ mm}} \qquad S = d/i$$
$$= 125\ mm/\mu A$$

4.2 $\quad i \quad R_g = 100\,\Omega$



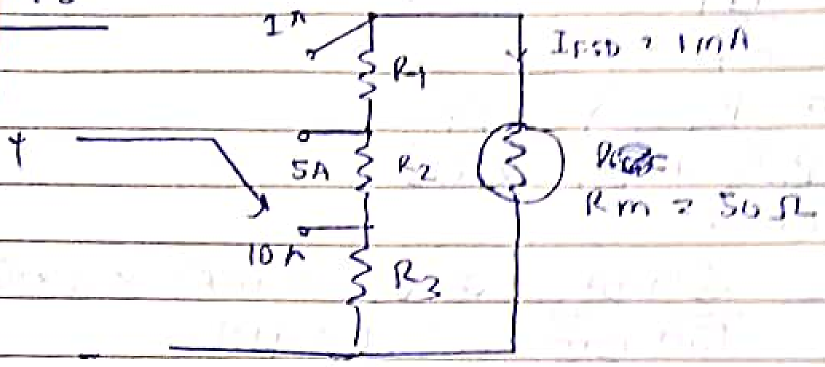
$$100 \times \left(\frac{R_g}{R_g + R} \right) = 99$$

$$\frac{100}{100 + R} = 0.99$$

$$100 = 99 + 0.99R$$

$$R = 1/0.99$$
$$= 1.01\ \Omega$$

4.3



$$999(R_1 + R_2 + R_3) = 50$$
$$R_1 + R_2 + R_3 = 0.05 \quad — (1)$$

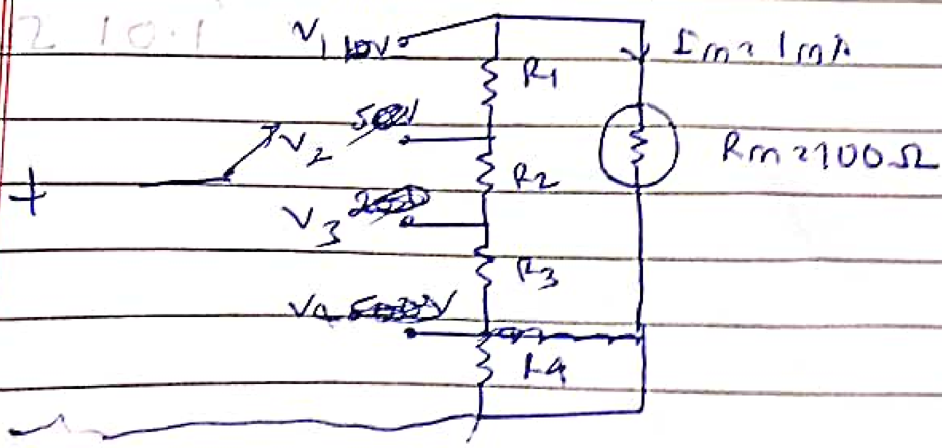
$$4999(R_2 + R_3) = R_1 + 50$$
$$-R_1 + 4999R_2 + 4999R_3 = 50 \quad — (2)$$

$$9999R_3 = R_1 + R_2 + 50$$
$$-R_1 - R_2 + 9999R_3 = 50 \quad — (3)$$

$$\left\{\begin{array}{l} R_1 = 0.039\ \Omega \\ R_2 = 5.005 \times 10^{-3}\ \Omega \\ R_3 = 5.005 \times 10^{-3}\ \Omega \end{array}\right\}$$

4.4

$R_m = 100\Omega$



$R_{eq} = \frac{\cancel{v}\ 10}{1\,mA}$

$R_{eq} = 10000$

$R_1 = 10000 - 100$

$= 9900\ \Omega$

$R_{eq} = \frac{50}{1\,mA} = 50000\ \Omega$

$50000 = 9900 + 100 + R$

$R = 40\,k\Omega$

$R_T = S \times V$

$\left\{ R_S = S \times V - R_m \right\}$

Resistance of multiplier

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

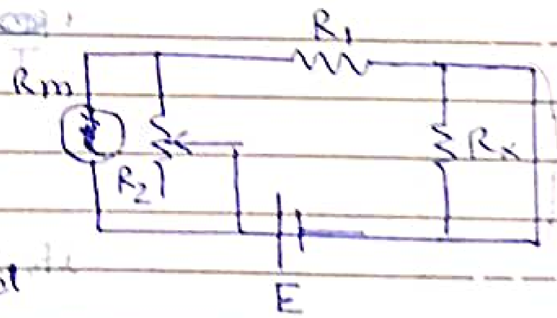
4-8

$R_m = 50\ \Omega$

$i_{fsd} = 1\,mA$

$E = 3V$

$R_h = 2000\ \Omega$



$$\left(\frac{R_2}{R_m + R_2}\right) \frac{E}{\frac{R_2 R_m}{R_2 + R_m} + R_1} = i_{fsd}$$

$$\left(\frac{R_2}{R_m + R_2}\right) \frac{E}{\frac{R_2 R_m}{R_2 + R_m} + R_1 + R_h} = i_{fsd}$$

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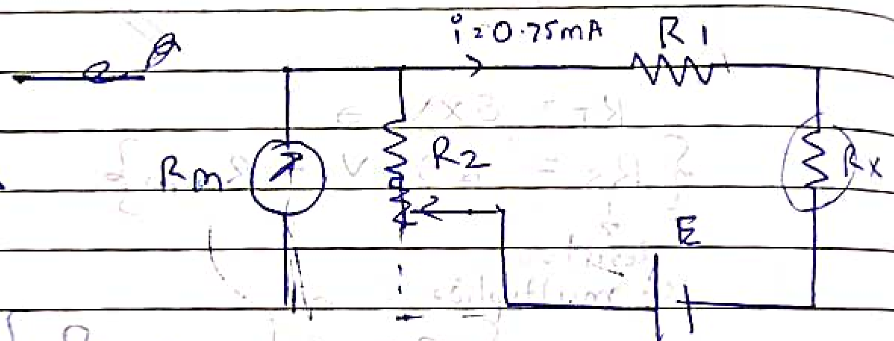
$$\left(\frac{R_2}{50+R_2}\right)\left(\frac{3}{\frac{50R_2}{50+R_2}+R_1}\right) = 1$$

$$1 = \frac{3R_2}{(50+R_2)(50R_2+50R_1+R_1R_2)}$$

$$2500R_2 + 2500R_1 + 50R_1R_2 + 50R_2^2 + 50R_1^2 + R_1R_2^2 = 3R_2$$



for full scale deflection

$R_2 = 0$

R_x = Total Resistance of ckt in [illegible]

$$i_{fsd} = \frac{1}{2}\left(\frac{E}{2R_h}\right)$$

$$= \frac{3}{2000} = 1.5\,mA$$

$i_{fsd} = 1\,mA$

$i_{R_2} = 0.5\,mA$

$i_{fsd} R_m = i_2 R_2$

$$R_2 = \frac{1 \times 50}{0.5} = 100\,\Omega$$

$i_{hsd} = 0.5\,mA$

$$0.5 \times 50 = 2/100 \times i_2$$

$i_2 = 0.25\,mA$

$$25 + 0.75R_1 + 2000 \times 0.75 = 3$$

$$R_p = \frac{R_m R_2}{R_m + R_2} = 33.3\,\Omega$$

$$R_1 = R_h - R_p = \boxed{1966.7\,\Omega}$$

* IMP points

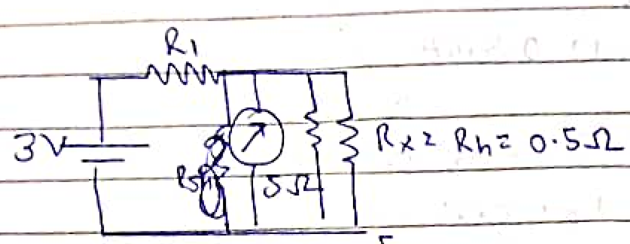
Series Type Ohmmeter

→ ~~for full scale deflection~~ In fsd, ~~put $R_2 = 0$~~ .. The current through battery $\neq$ current through galvanometer.

→ Use $i_T = \dfrac{E_{battery}}{(R_x)}$ → {half scale deflection resistance = Total Resistance during hsd}

→ $\{R_x = R_p + R_{series}\}$

4.9



$V_m = 5 \times \cancel{10}^{5}\ mA$

$= {}^{25}\cancel{50}\ mV$

$i_h = \frac{\cancel{50}\ 25}{0.5}$

$i_h = \cancel{100}\ 50\ mA$

$i_{sh} = 50 - 5$

$= 45\ mA$

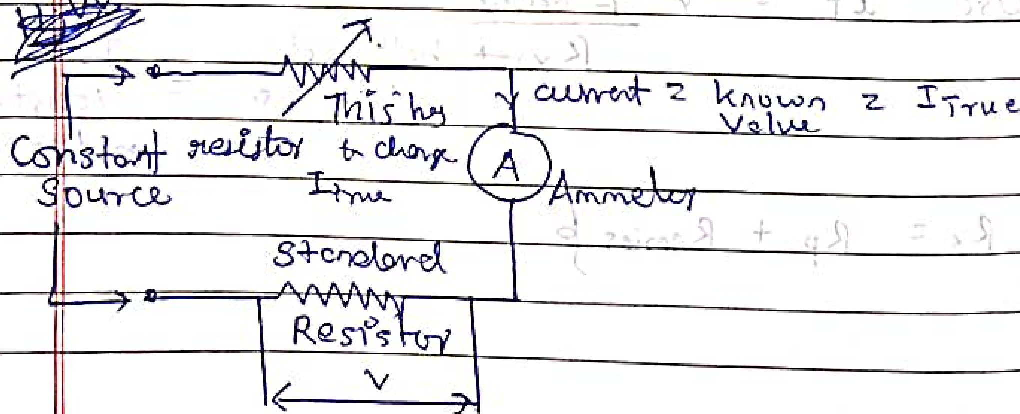
$\boxed{\cancel{i_b = 3/0.5 = 30/5 = 6A}}$

$R_{sh} = \frac{25}{45} = 5/9\ \Omega$

→ Multirange Voltmeter → Multirange Ammeter → Multirange Ohmmeter

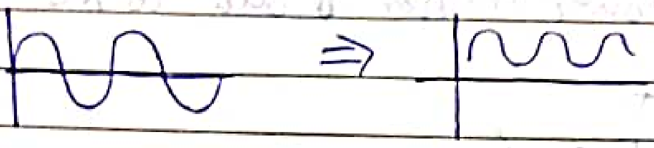
Calibration of instrument

HW



H.W. 5.0) ~~Determine~~ Derive a method to calibrate a voltmeter.

<u>Alternating current indicating instrument</u>



<u>unidirectional torque</u>

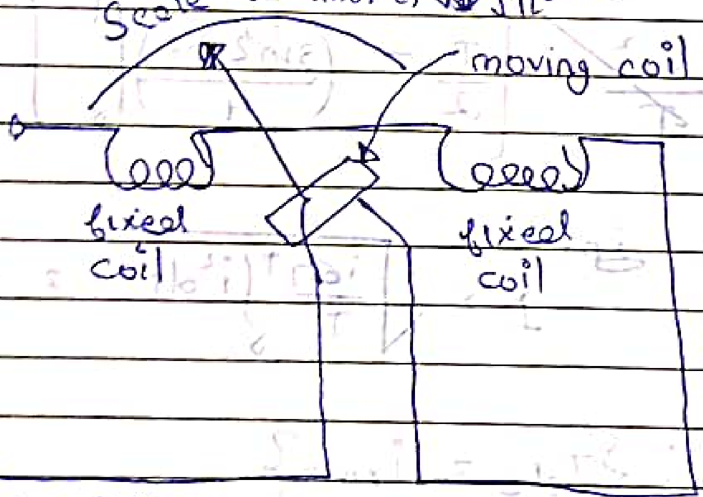
- ~~rectification~~
- heating effect reason

$B \rightarrow$ is function of i

$\cancel{T} \propto T = BANI \rightarrow$ function of i^2

$T \propto i^2$

Scale is written as $\sqrt{i}$ $\{1 \rightarrow 1, 2 \rightarrow 4, 3 \rightarrow 9\}$



$T \propto BANI$

$T \propto i$

$\phi \propto i \therefore \{T \propto i^2\}$

$\theta \propto i^2$

$\{I_{dc} = i_{rms}\}$

* (i) An AC produce heat in a given resistance at same average rate as a DC.

average

* Power Transfer due to DC = I^2R

* Average Power Transfer due to AC = $\frac{1}{T}\int_0^T i^2 R\,dt$

$$I^2 \cancel{R} = \frac{1}{T}\int_0^T i^2 \cancel{R}\,dt$$

$$I^2 = \frac{i_m^2}{T}\int_0^T \left(\frac{1-\cos 2\omega t}{2}\right) dt$$

$$I^2 = \frac{i_m^2}{T}\left[\frac{T}{2} - \left(\frac{\sin 2\omega t}{4}\right)\Big|_0^T\right]$$

$$I = \sqrt{\frac{1}{T}\int_0^T i^2\,dt} = \text{root}\{\text{average}\}$$

$\Downarrow$

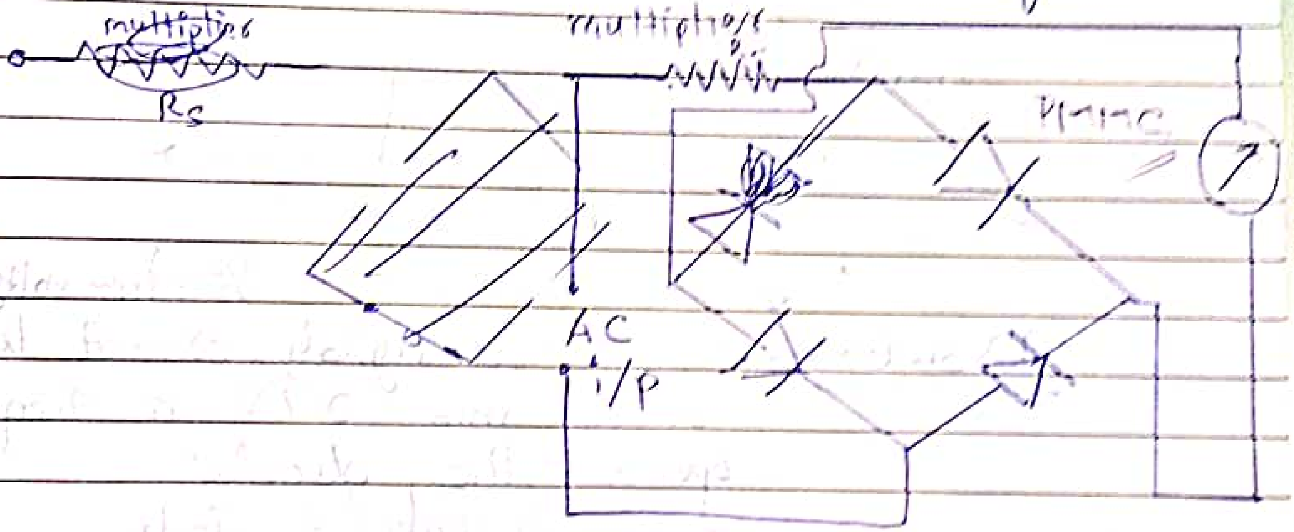
rms

$$\therefore \{I_{dc} = i_{rms}\}$$

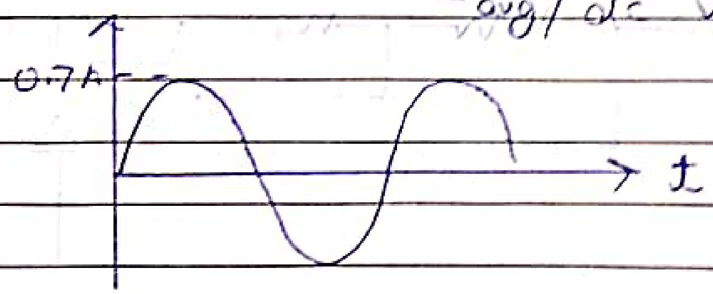
So we can caliberate using DC & use the device for AC measurement with the same scale.

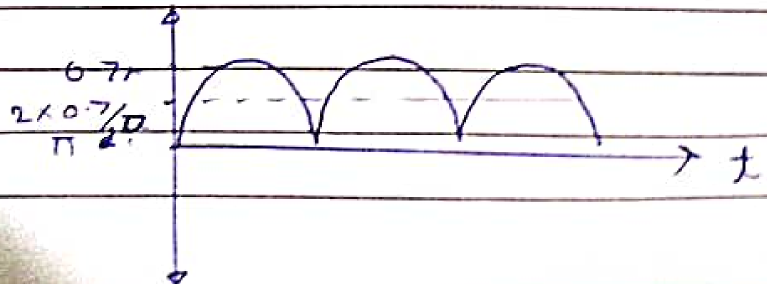
Disadvantages

- cannot measure small current
- High power consumption
- Error due to heating of the coil
- week flux due to air of medium
- impedance of coil as a function of frequency

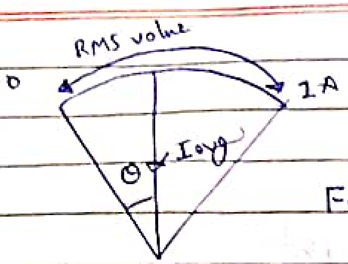


* converts bidirectional AC into unidirection DC
* oscillations occur across avg/dc value (critically damped)





$I_{avg} = 0.36$



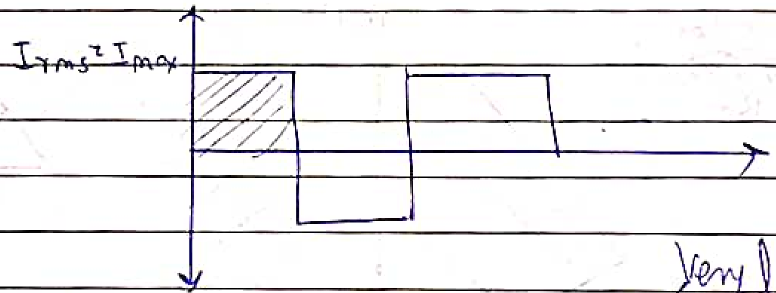
$I_{rms} = I_m/\sqrt{2}$

$I_{avg} = 2I_m/\pi$

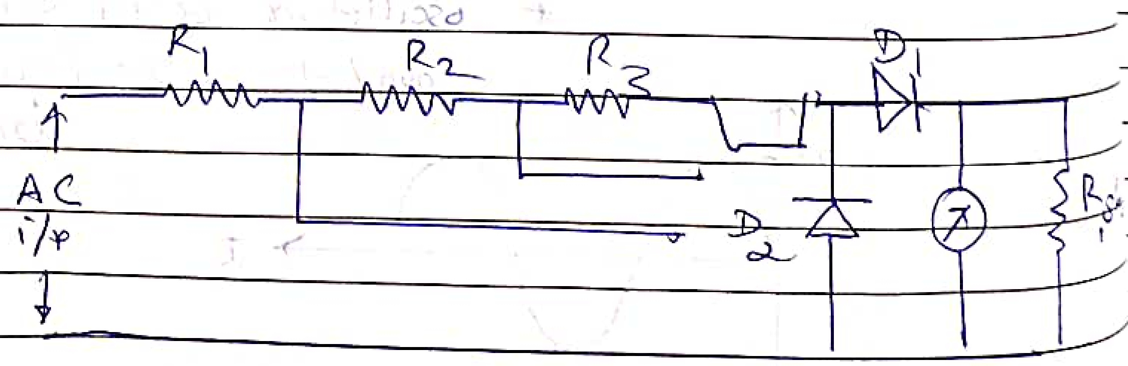
Form factor = $\frac{RMS}{avg.\ value}$ $= \frac{\pi}{2\sqrt{2}}$

= 1.11 (only for sine wave)

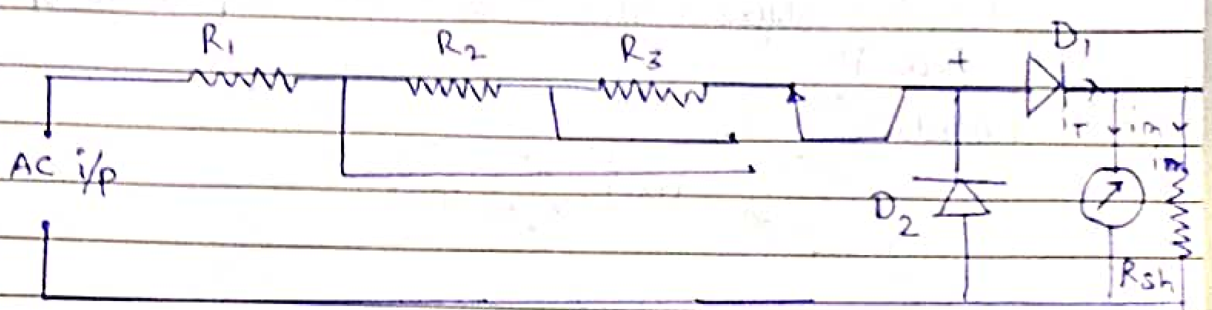
Q) What if signal is not sine wave?
Use basic math to find area under curve.



Drawbacks :
- Small signals / Very low voltage cannot be amplified since min 0.7V is required to operate the diode.
- Non linearity of diode / Non linear operation



Typical Multimeter Circuits

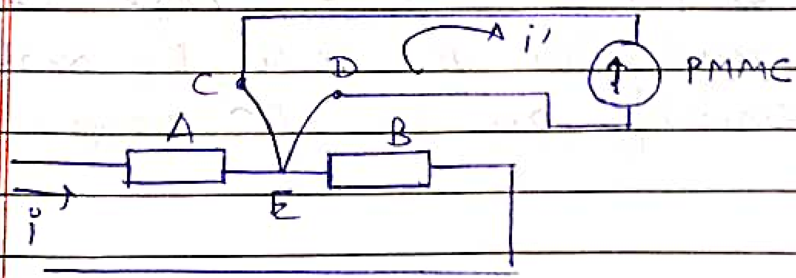


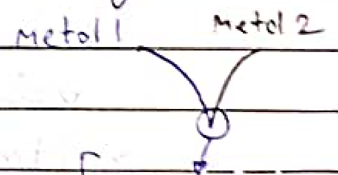
$\{ i_m = \left(\frac{R_{sh}}{R_m + R_{sh}}\right) \times i \}$

- PMMC deflection $\propto$ Avg. values of half cycle
- Rsh : a very low value resistor used to draw more current to push the diode linearly.
- Avg value of half cycle = 0.45 RMS value
- D_2 : prevents reverse saturation current through D_1.
- R_1 R_2 & R_3 are used to have multiple ranges.

Thermoinstrument

- combination of thermocouple is PMMC.
- When two dissimilar metals are in contact a small voltage is generated at the junction





{ Small voltage of junction $\propto T^\circ$ }

~~CE & DE~~ A & B heating elements

Heat $\propto i^2R$

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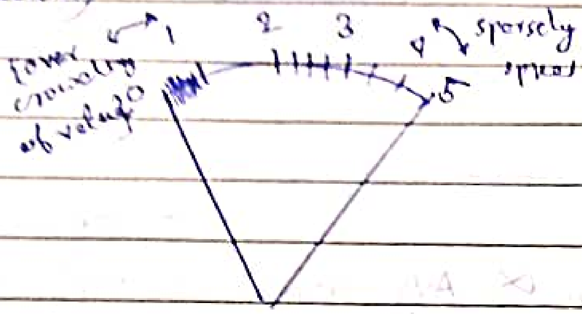
CE & DE : Dissimilar metal joined at E.
Potential difference b/w C & D $\propto$ Temperature of junction
$\theta \propto i^2_{rms}$
(deflection)



Limitation

- Large current (i)
- Ambient temperature (HW How can it be avoided?)

Meter movement

Q) ~~10~~ Internal resistance = 100 Ω and requires 1m DC for full scale deflection. Shunting Resistor placed across movement has resistance = 100 Ω. Diode d_1 and d_2 has average forward resistance of 400 Ω and assume ∞ resistance in reverse direction. For a 10V AC range calculate value of multiplier resistance R_s and the voltmeter sensitivity on the AC range.

$100 \times 1 = 100 \times i_g$

$i_g = 1\,mA$

$i_T = 2\,mA$

$\cdot \times 10 - 2R_s - 400 \times 2 \times 10^{-3} - 100 \times 1 \times 10^{-3} = 0$

$0.45 \times 10 - (800 + 100) \times 10^{-3} = 2R_s \times 10^{-3}$

$4.5 - 900 \times 10^{-3} = 2R_s \times 10^{-3}$

$R_s = \frac{4.5 - 0.9}{2} \times 10^{3}$

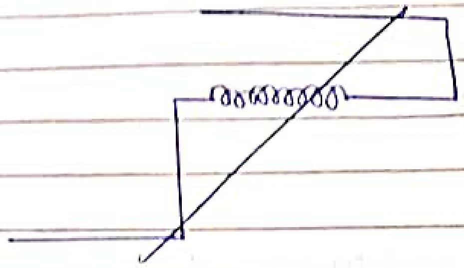
$= \frac{3.6}{2} \times 10^{3}$

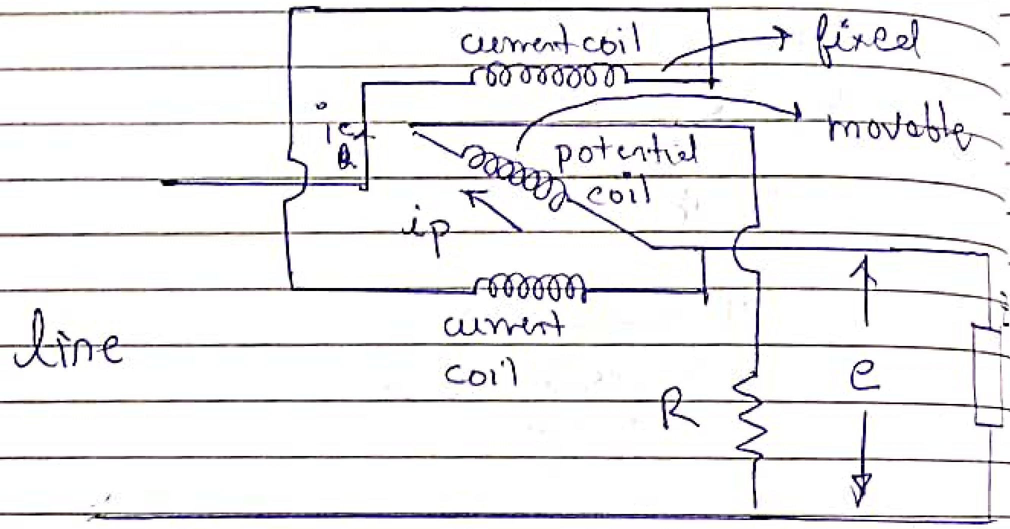
$= 1.8 \times 10^{3}$

$= 1.8\,k\Omega$

$S_{oc} = \frac{2250\,\Omega}{10\,V} = 225\,\Omega/V$

Electrodynemometer in Power Measurement





Deflection $\theta \propto i_p \times i_c$

$$i_p = \frac{e}{R_p}$$

where

$R_p = R +$ resistance of potential coil

$$\theta \propto i_c \cdot \frac{e}{R_p}$$

$$\theta_{avg} = k \cdot \frac{1}{T} \int_0^T \frac{i_c\, e}{R_p}\, dt$$

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$i_c \simeq i$ { R is very high }

$$\theta_{avg} = \frac{k_2}{T}\int_0^T ie\,dt$$

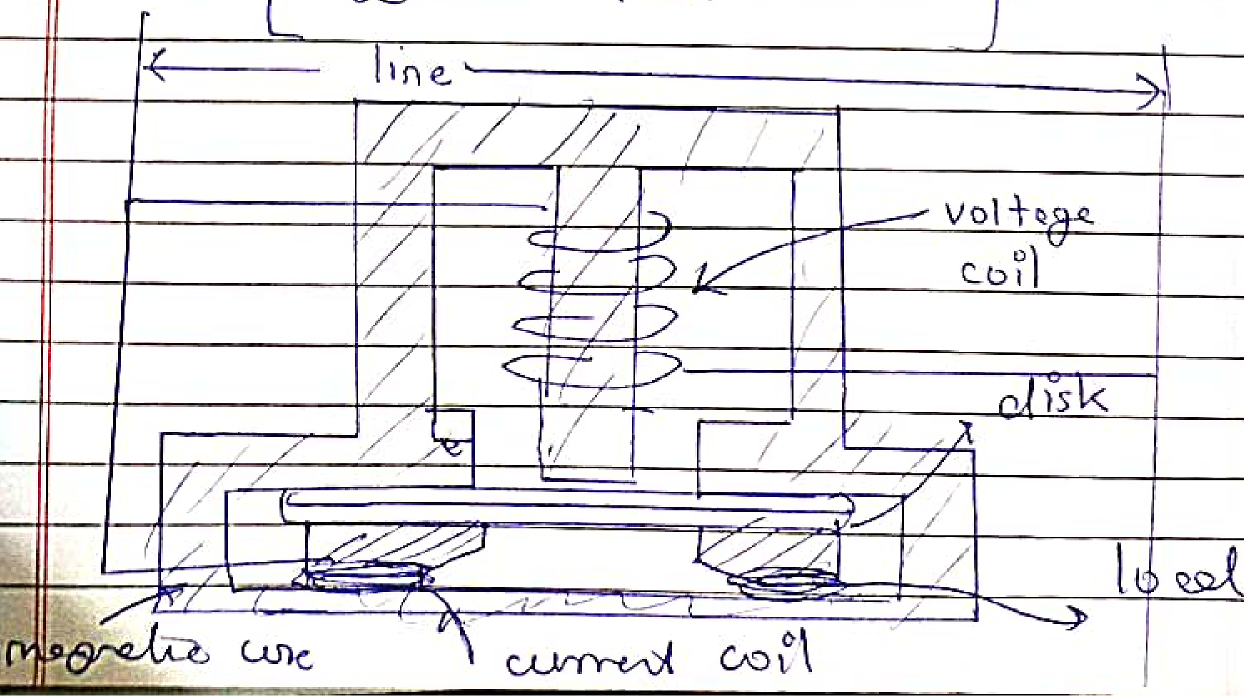
$i = I\sin\omega t$
$e = E\sin\omega t$

$$\frac{k_2 IE}{T}\int_0^T \frac{1-\cos 2\omega t}{2}\,dt$$

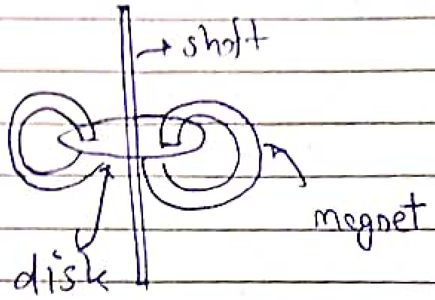
$$\frac{k_2 IE}{T}\left[\frac{T}{2} - \frac{\sin 2\omega t}{2(2\omega)}\right]_0^T$$

$$\frac{k_2 IE}{T}\left(\frac{T}{2} - \frac{\sin 2\omega T}{4\omega}\right)$$

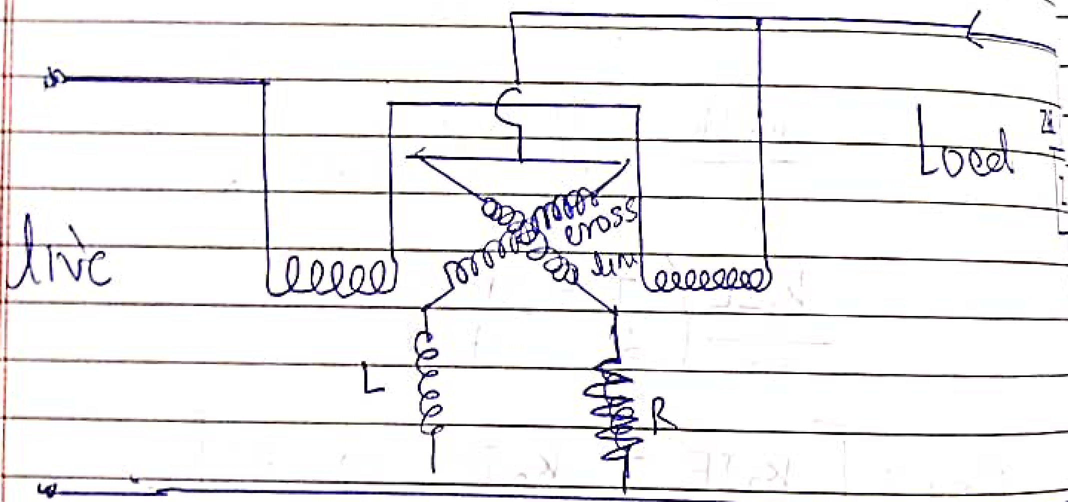
$$\theta_{avg} = \left[\frac{k_2 IE}{2} - \frac{k_2 IE}{4\omega T}\sin 2\omega T\right]$$



Watt hour Meter

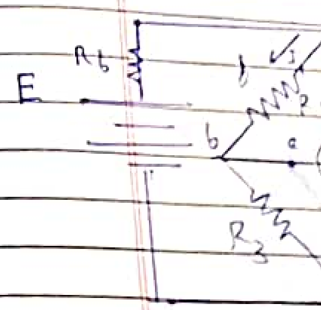


~~Power~~ Power Factor Meter



Bri

Wheatstone



$R_{th} = R_1 \parallel R_3$

$V_{th} = E \frac{R_3}{R_1 + R_3}$

[Wheat

Limit

- lim
- eff

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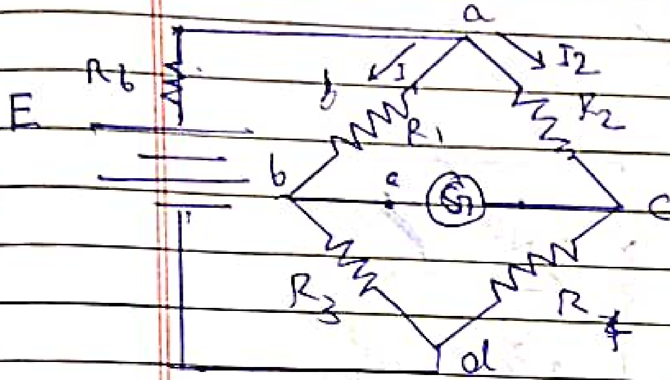
Bridge Measurement

Wheatstone Bridge



$$I_1 = \frac{E}{R_1+R_3}$$

$$I_2 = \frac{E}{R_2+R_4}$$

$V_{ab} = V_{ac}$ $\{V_{bc} = 0\}$ $V_b = V_c$

$$I_1R_1 = I_2R_2$$

$$\frac{\cancel{E}R_1}{R_1+R_3} = \frac{\cancel{E}R_2}{(R_2+R_4)}$$

$R_{th} = R_1 \| R_3$

$V_{th} = E\dfrac{R_3}{R_1+R_3}$

$$\cancel{R_1R_2} + R_1R_4 = \cancel{R_2R_1} + R_2R_3$$

$$R_1R_4 = R_2R_3$$

$$\boxed{\frac{R_1}{R_2} = \frac{R_3}{R_4}}$$

[Wheatstone bridge : 1 Ω to few MΩ]

Limitations —

- limiting error
- effect of change in temp. is not uniform

eg: $R_1 = 1\,M\Omega \pm$ limiting error

$R_2 = R_3 = 1\,k\Omega \pm$ limiting error

$\frac{R_2}{R_1} = \frac{1}{2}$

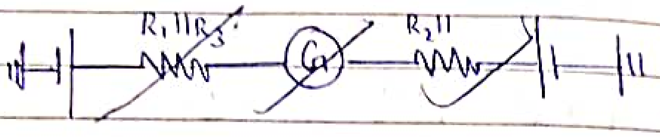
$R_1 = 2\,\Omega$

$R_2 = 1\,\Omega$

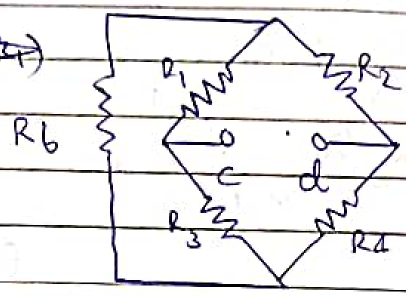
$R_3 = 2\,\Omega$

$R_4 = ? = 1\,\Omega$

- lead resistance



~~Rth~~ (~~R_6~~ ~~R_1~~)



let $R_1 = 0$

$R_{th} = (R_1 \parallel R_3) + (R_2 \parallel R_4)$

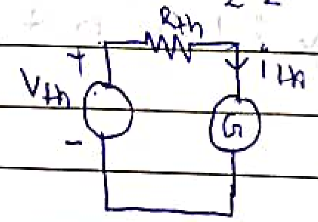
V_{oc}

$E - i_1R_1 - i_1R_3 = 0$

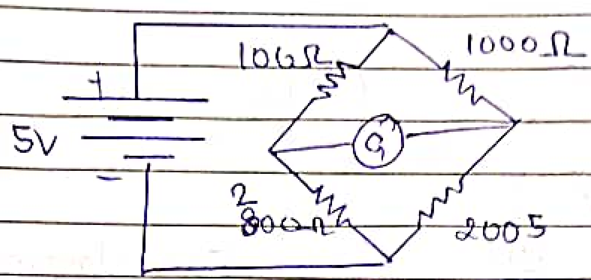
$V_c = i_1R_1 - E$ $\quad$ $V_d = i_2R_2 - E$

$V_{th} = V_c - V_d = i_1R_1 - i_2R_2$

$V_{th} = i_1R_1 - i_2R_2$



Q) The given figure has galvanometer sensitivity 100 mm/μA & resistance of ~~1000~~ 100 Ω. Calculate deflection in galvanometer in terms of mm by 5Ω unbalanced bridge.



$R_{th} = (100 \parallel 800) + (1000 \parallel 2005)$

$= \cancel{677.57}\ \cancel{272.75}\ \cancel{755.88}\ 668.22\ \Omega$

$V_{th} = -i_1 R_1 - i_2 R_2$

$= \frac{E R_1}{R_1 + R_3} - \frac{E R_2}{R_2 + R_4}$

$= \cancel{1.1083}\quad 2.773\ mV$

$\boxed{I_g = 1.39\ mA}$

$\boxed{S = 1398.83 \times 10^{6}\ \mu A}$

$\cancel{3.77}\ 4.14$

$I_g = \cancel{10.16}\ \mu A$

$S = \cancel{10.16}\ 3.77 \times 10$

$\cancel{101.6\ mm}$

$37.7\ mm$

Sourav

$R_{th} = (100 \parallel 200) + (1000 \parallel 2005)$

$= 733.88\ \Omega$

$V_{th} = i_1 R_1 - i_2 R_2$

$= E\left(\frac{R_1}{R_1 + R_3} - \frac{R_2}{R_2 + R_4}\right)$

$= 2.77 \times 10^{-3}\ V = 2.77\ mV$

$i_{th} = 3.32\ \mu A$

$S = 33.21\ mm$

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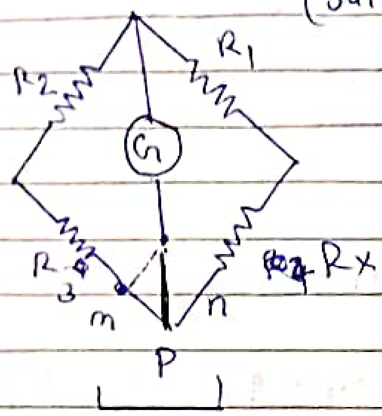
Kelvin Bridge

(suitable < 1Ω)



$R_y \rightarrow$ yoke resistance

For balancing

$(R_1)(R_3+R_{mp}) = R_2(R_x \ldots$

At point P,

$$\frac{R_{np}}{R_{mp}} = \frac{R_1}{R_2}$$

Balanced condition,

$$R_2\left[R_x + R_{n-p}\right] = R_1\left[R_3 + R_{mp}\right]$$

$$R_2R_x + \cancel{R_2R_{n-p}} = R_1R_3 + \cancel{R_1R_{mp}}$$

$$\boxed{R_x = \frac{R_1R_3}{R_2}}$$

Advantages

- Effect of lead resistance is eliminated

Disadvantage

1. Higher sensitivity galvanometer is required.

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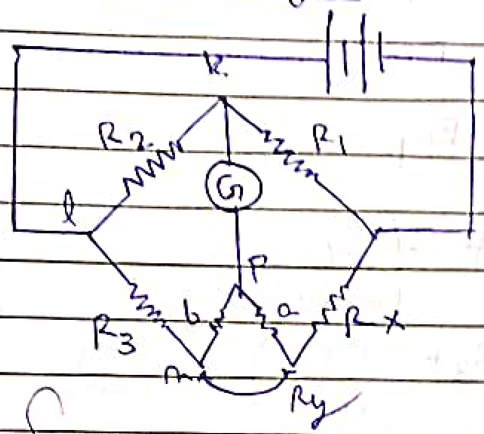
Kelvin Double Bridge



Ratio Arms: R_1 & R_2
Standard Arms: R_3 & R_x

[a, b are acting as ratio arms]

At P,

$$a/b = R_1/R_2$$

Balanced condition

$$R_1(R_3+b) = R_2(R_x+a)$$

$$R_1R_3 + \cancel{R_1b} = R_2R_x + \cancel{R_2a}$$

$$\boxed{R_x = \frac{R_1R_3}{R_2}}$$

$E_{lk} = E_{lmbp}$

$$E_{kl} = R_2 \left[\frac{E}{(R_1+R_2)\,||\,(R_3+a+b+R_x)}\right]\left(\frac{R_3+a+b+R_x}{R_1+R_2+R_3+R_x+a+b}\right)$$

$$= R_2 \frac{E\,\cancel{(R_1+R_2+R_3+R_x+a+b)}}{(R_1+R_2)\cancel{(R_3+R_x+a+b)}} \left[\frac{\cancel{R_3+R_x+a+b}}{\cancel{R_1+R_2+R_3+R_x+a+b}}\right]$$

$$E_{kl} = R_2 \frac{R_2 E}{R_1+R_2} = \frac{R_2}{R_1+R_2} \Big[I \Big(R_3 + R_x + \frac{(a+b)R_y}{a+b+R_y} \Big) \qquad — (1)$$

$$E_{lmp} = E_{lm} + E_{mp}$$

$$= IR_3 + I\left(\frac{R_y}{a+b+R_y}\right)$$

$$E_{lmp} = I\left(R_3 + \frac{R_y}{a+b+R_y}\right) \qquad — (2)$$

equate (1) & (2)

$$\frac{R_2}{R_1+R_2}\left[R_3 + R_x + \frac{(a+b)R_y}{a+b+R_y}\right] = R_3 + \frac{R_y}{a+b+R_y}$$

$$\frac{R_x R_2}{R_1+R_2} = R_3 + \frac{R_y}{a+b+R_y} - \frac{R_2R_3}{R_1+R_2} - \frac{R_2(a+b)R_y}{(R_1+R_2)(a+b+R_y)}$$

$$\cancel{(R_3a + R_3b + R_yR_3)(R_1+R_2)}$$

$$\{aR_2 = bR_1\}$$

$$\frac{R_2R_x}{\cancel{R_1+R_2}} = \frac{\cancel{R_1R_3a} + R_1R_3b + \cancel{R_1R_yR_3} + \cancel{R_2R_3a} + \cancel{R_2R_3b} + \cancel{R_2R_3R_y} + R_yR_1 + R_yR_2 - \cancel{R_2R_3a} - \cancel{R_2R_3b} - \cancel{R_2R_3R_y} - \overset{bR_1}{\cancel{R_2R_ya}} - \cancel{R_2R_yb}}{(a+b+R_y)\cancel{(R_1+R_2)}}$$

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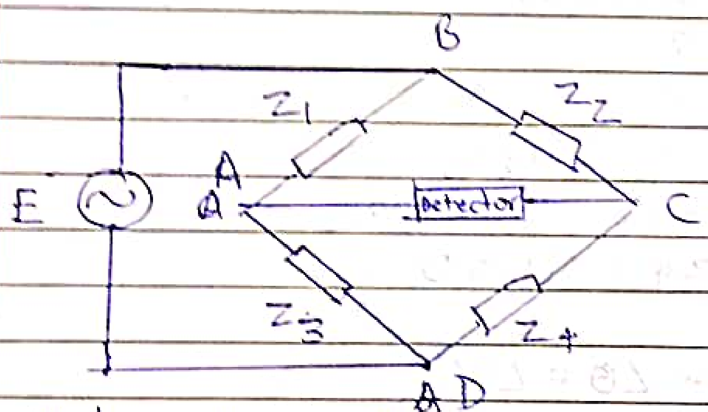
$\cancel{R_y R_1 + R_y R_2}$

$R_1 R_x$

$\cancel{R_2 R_x} = \frac{R_1 R_3 (a+b+R_y)}{(a+b+R_y)}$

$$\left\{ R_x = \frac{R_1 R_3}{R_2} \right\}$$

AC bridges & their Applications



Balanced condition

$$E_{ba} = E_{bc}$$

$$Z_1 i_1 = Z_2 i_2$$

$$i_1 = \frac{E}{Z_1+Z_3} \qquad i_2 = \frac{E}{Z_2+Z_4}$$

$$\frac{Z_1}{Z_1+Z_3} = \frac{Z_2}{Z_2+Z_4}$$

$$\cancel{Z_1 Z_2} + Z_1 Z_4 = \cancel{Z_1 Z_2} + Z_3 Z_2$$

$$Z_1 Z_4 = Z_3 Z_2$$

$$\frac{Z_4}{Z_3} = \frac{Z_2}{Z_1} \Rightarrow \frac{Y_3}{Y_4} = \frac{Y_1}{Y_2}$$

$$\{ Y_1 Y_4 = Y_2 Y_3 \}$$

$z_1 = Z\angle\theta$

$z_1\angle\theta_1 \; z_4\angle\theta_4 = z_2\angle\theta_2 \; z_3\angle\theta_3$

$z_1 z_4 \angle(\theta_1+\theta_4) = z_2 z_3 \angle(\theta_2+\theta_3)$

To balance a bridge $\begin{cases} z_1 z_4 = z_2 z_3 \\ \angle\theta_1 + \angle\theta_4 = \angle\theta_2 + \angle\theta_3 \end{cases}$

Example

$z_1 = 100\angle 80^\circ \; \Omega$

$z_2 = 250\Omega$

$z_3 = 400\angle 30^\circ$

$z_4 = ?$

$z_1 z_4 = z_2 z_3$

$100 \times z_4 = 250 \times 400$

$\{z_4 = 1000\ \Omega\}$

$\angle 80 + \angle\theta = \angle 30^\circ$

$\{\angle\theta = -50^\circ\}$

$\{z_4 = 1000\angle -50^\circ\ \Omega\}$

Example:

~~$z_{ab} = 400\Omega$~~

~~$z_{bc} =$~~

$z_1 = 450\Omega$

$z_2 = $ ~~900.58Ω~~ $600.58j + \ldots$

$= 671.33\angle -63.46$

$z_3 = 999.026j + \ldots$

$= 1018.\ldots$

$z_4 = ?$

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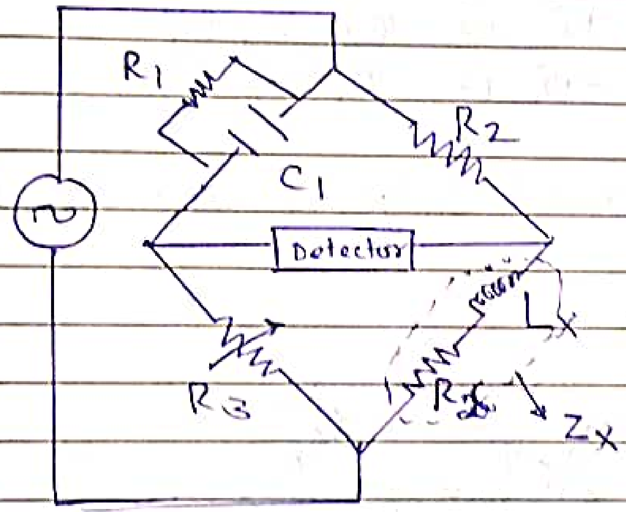
$Z_4 = 1519.95 \angle 15.22°$

Maxwell Bridge

It is used to find unknown inductance in terms of known capacitance. $(1 < Q < 10)$



In balanced condition
$R_x =$
$L_x =$

$\{Z_x = Z_2 Z_3 Y_1\}$

$\frac{R_1 X_C}{R_1 + X_C}$, R_2 , R_3 , $\{R_x + X_L\}$

$R_2 R_3 \frac{R_1 - X_C j}{-R_1 X_C j}$

$R_x + X_L j = \frac{R_2 R_3 R_1}{-R_1 X_C j} + \frac{R_2 R_3 X_C j}{R_1 X_C j}$

$R_x + X_L j = \frac{R_2 R_3}{X_C} j + \frac{R_2 R_3}{R_1}$

$\left\{ R_x = \frac{R_2 R_3}{R_1} \right\}$, $\left\{ X_L = \frac{R_2 R_3}{X_C} \right\}$

$R_x = \frac{R_3R_2}{R_1}$

$L_x = R_2R_3C_1$

$Q = \frac{\cancel{2}X_L}{R} = \frac{\omega L}{R}$ $\quad 1 < Q < 10$

$\angle\theta_2 + \angle\theta_3 = 0$ {Resistances}

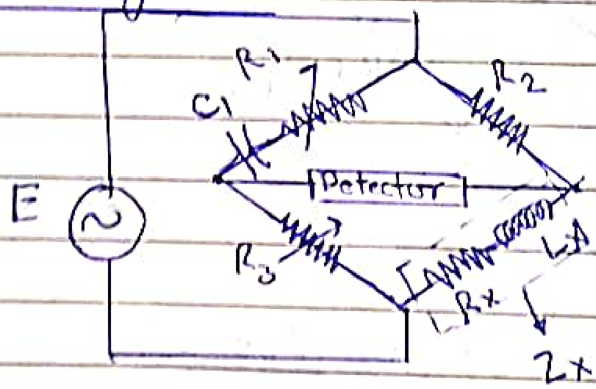
$\angle\theta_1 + \angle\theta_4 = 0$

$\theta \to 90°$ i.e Q is very high

$\theta \to -90°$ i.e $R_1 \to \infty$

H.W: Why Maxwell Bridge is unsuitable for Q<1

Hay Bridge



$i_1(X_{C_1}j + R_1) = i_2 \, R_2$

$\frac{E}{R_1 - X_{C_1}j + R_3}(X_C j + R_1) = \frac{E}{R_x + X_L j + R_2} \cdot R_2$

$-R_xX_{C_1}j + R_1R_x + X_CX_L + R_1X_Lj - R_2X_Cj + R_1$

$= R_2R_1 - R_2X_Cj + R_3R_2$

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j

$$(-R_xX_C + R_1X_L - \cancel{R_2X_C} + \cancel{R_2X_C})j$$
$$+(R_1R_x + X_CX_L + \cancel{R_1R_2} - \cancel{R_1R_2} - R_3R_2) = 0$$

$$R_1R_x + X_CX_L = R_2R_3$$

$$R_1X_L - R_xX_C - \cancel{R_2X_C}\,\phi = 0$$

$$X_L = \frac{R_xX_C}{R_1}$$

$$R_1R_x + X_C\,\frac{R_xX_C}{R_1} = 0$$

$R_x^3 \quad X_C^3$

$$R_x = \frac{\omega^2C_1^2R_1R_2R_3}{1+C_1^2R_1^2\omega^2} \qquad \& \quad L_x = \frac{R_2R_3C_1}{1+\omega^2C_1^2R_1^2}$$

$$Q = \tan\theta_L = \frac{\omega L_x}{R_x}$$

$$\tan\theta_L = \tan\theta_C$$

$$\frac{\omega L_x}{R_x} = \frac{1}{\omega C_1R_1}$$

$$L_x = \frac{R_2R_3C_1}{1+(1/Q)^2}$$

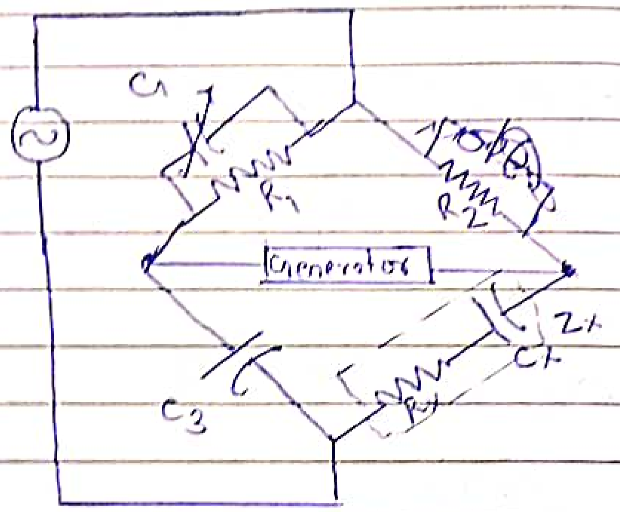
$Q = 10$

$(1/Q)^2 = 0.01$

so $Q > 10$ does not affect L_x

Schering Bridge

- it is used for measurement of unknown capacit



$$\frac{\cancel{E}\left(-X_{C_1}j + R_1\right)}{R_1 - \left(X_{C_1} + X_{C_3}\right)j} = \frac{R_2\cancel{E}}{R_2 + R_x - X_{C_x}j}$$

$$\cancel{R_1R_2} + R_1R_x - \left(X_{C_x}j\right)R_1 - R_2X_{C_1}j - R_xX_{C_1}j$$

$$= \cancel{R_1R_2} - X_{C_1}R_2 j - X_{C_3}R_2 j$$

$$\cancel{R_x\left(R_1 - X_{C_1}j\right)}$$

$$R_1R_x - X_{C_1}X_{C_x} = 0$$

$$\frac{R_1}{X_{C_x}} = \frac{X_{C_1}}{R_x} \quad \text{—— (1)}$$

$$-X_{C_x}R_1 - \cancel{R_2X_{C_1}} - R_xX_{C_1} + \cancel{X_{C_1}R_2} + X_{C_3}$$

$$-\frac{R_1^2}{X_{C_1}R_x} - R_xX_{C_1} + X_{C_3}R_2 = 0$$

$$R_1^2 - R_x^2X_{C_1}^2 + X_{C_3}R_2$$

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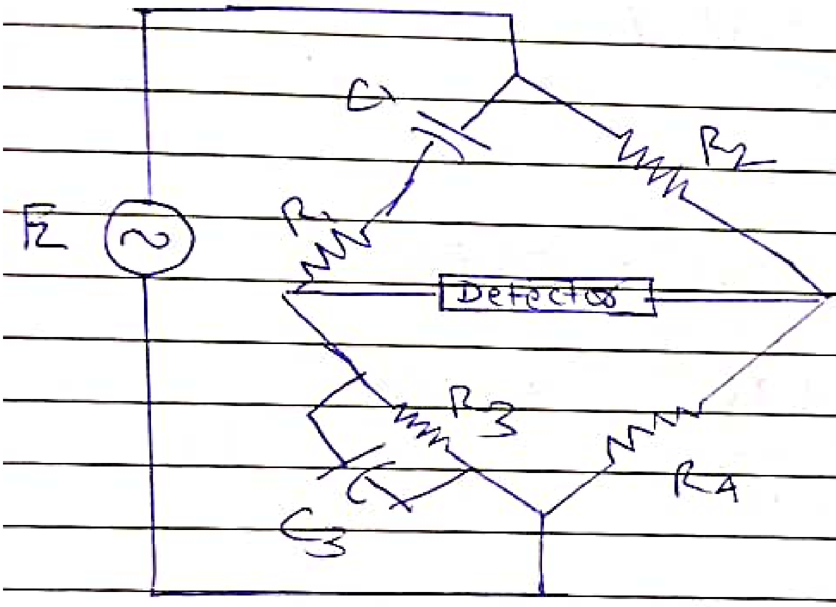
$$R_x = \frac{R_2 C_1}{C_3}$$

$$C_x = \frac{R_1}{R_2} C_3$$

Wien Bridge

Used to measure frequency



$$\left(R_3 \parallel \frac{1}{\omega C_3} j\right) R_2 = \left(R_1 - \frac{1}{C_1\omega} j\right) R_4$$

$$R_3 R_2 - \frac{R_2}{C_3 \omega} j = R_1 R_4 - \frac{R_4}{C_1 \omega} j$$

$$\boxed{\frac{R_2}{C_3} = \frac{R_4}{C_1 \omega}}$$

$$\left(\frac{-R_3 \frac{1}{\omega C_3} j}{R_3 + \frac{1}{\omega C_3} j}\right) R_2 = R_1 R_4 - \frac{R_4}{C_1 \omega} j$$

$$-\left(\frac{R_2 R_3 j}{R_3 C_3 \omega + j}\right) = R_1 R_4 - \frac{R_4}{C_1 \omega} j$$

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$$-\frac{R_2R_3j\,(R_3C_3\omega+j)}{\sqrt{(R_3C_3\omega)^2+1}} = R_1R_4 - \frac{R_4}{C_1\omega}j$$

$$\frac{R_2R_3}{\sqrt{(R_3C_3\omega)^2+1}} - \frac{R_2R_3^2C_3\omega\, j}{\sqrt{(R_3C_3\omega)^2+1}} = R_1R_4 - \frac{R_4}{C_1\omega}$$

$$\frac{(R_2R_3)^2}{(R_3C_3\omega)^2+1} = (R_1R_4)^2$$

$$(R_2R_3)^2 = (R_1R_4)^2 + \cancel{R_2R_3C}\,(R_3C_3\omega)^2(R_1R_4)^2$$

$$\sqrt{\frac{(R_2R_3)^2-(R_1R_4)^2}{(R_3C_3R_1R_4)^2}} = \omega$$

$$\omega = \frac{1}{R_1R_4R_3C_3}\sqrt{R_2^2R_3^2-R_1^2R_4^2}$$

X

Real parts

$$\frac{R_2}{R_4} = \frac{R_1}{R_3} + \frac{C_3}{C_1}$$

Imag. parts

$$\omega C_3R_1\cancel{R_4} = \frac{\cancel{R_4}}{\omega C_1R_3}$$

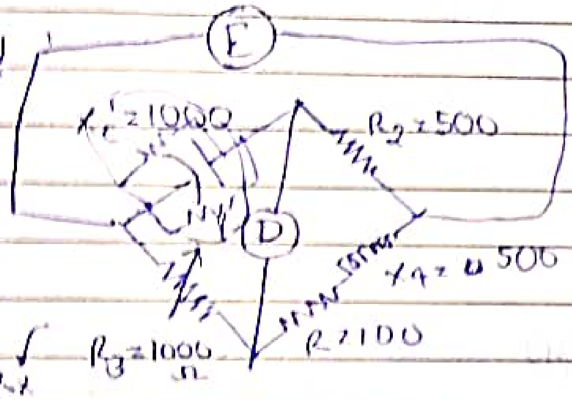
$$\omega = \sqrt{\frac{1}{C_3C_1R_3R_1}}$$

$$f = \frac{1}{2\pi\sqrt{R_1 R_3 C_1 C_3}}$$

if $R_1 = R_3$
$C_1 = C_3$

$$\left\{ f = \frac{1}{2\pi R_1 C_1} \right\}$$

HW



Determine whether bridge is completely balanced.
if not find 2 ways to make it ~~balanced~~

$$1000 \times 500 = (100 + 500j)\left(\frac{-1000 j R_2}{R_2 - 1000j}\right)$$

$$5\times10^5 = \left(\frac{10^8 j R_2}{R_2 - 1000j}\right) + \left(\frac{5\times10^8 j R_2}{R_2 - 1000j}\right)$$

$$1 = \frac{2jR_2 + R_2}{R_2 - 1000j}$$

$$\cancel{R_2} - 1000j = 2jR_2 + \cancel{R_2}$$

$$\{ R_2 = 5\,k\Omega \}$$

$$Z_4 = Z_2 Z_3 Y_1$$

$$Z_4 = Z_2 Z_3 \left(\frac{1}{R_1} + j\omega X_c\right)$$

$$\frac{1}{Z_{eq}} = \frac{1}{R_1} + \frac{1}{(1/\omega C)j}$$

$$\left\{ Y = \frac{1}{R_1} + \omega C j \right\}$$

$$\cancel{500}R_x = 1\left(1\cancel{00} + 5\cancel{00}j\right)\left[\frac{(-10\cancel{00}j)(5\cancel{000})}{5\cancel{000} - 1\cancel{000}j}\right]$$

$$\cancel{5}R_x = (1+5j)\left(\frac{-\cancel{50}^{10}j}{5-j}\right)$$

$$R_x = \frac{-10-50j}{5-j}$$

$$= \frac{(-10-50j)(5+j)}{\cancel{5}\sqrt{25+1}}$$

$$= \frac{\cancel{-50}-10j-250j+\cancel{50}}{\sqrt{26}}$$

$=$

$\cancel{R_3} = R_4 R_2 \quad Z_3 = Z_1 Z_4 Y_2$

100×1000

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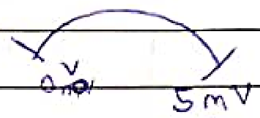
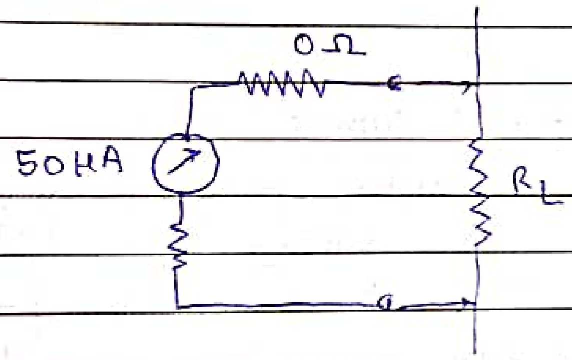
Electronic Instruments for measuring basic parameters

$FSD = 500\ \mu A$

$R_m = 100\ \Omega$

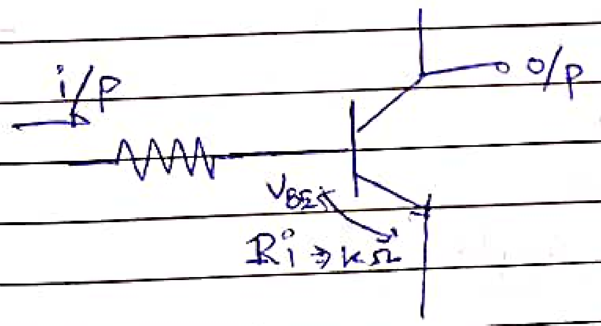
$V_m = \cancel{50}\ 5\,mV$



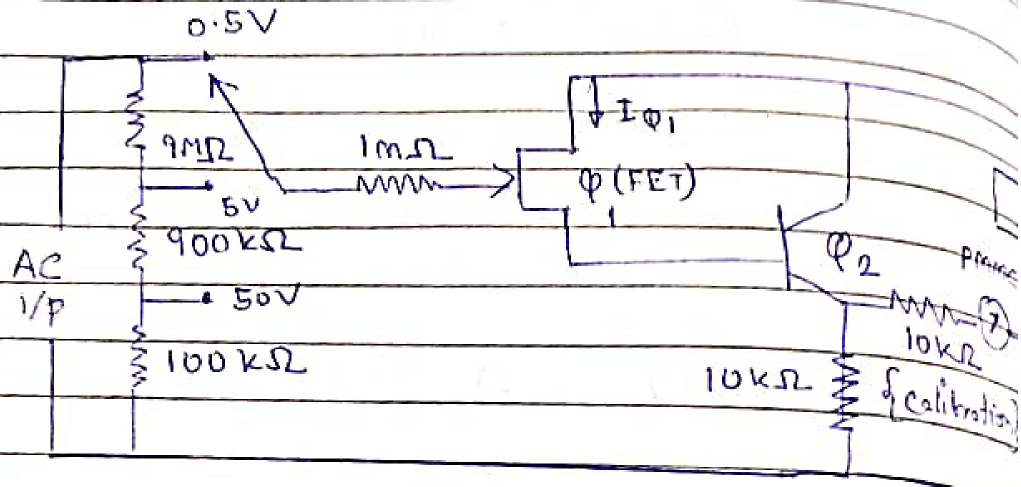


Requirements -

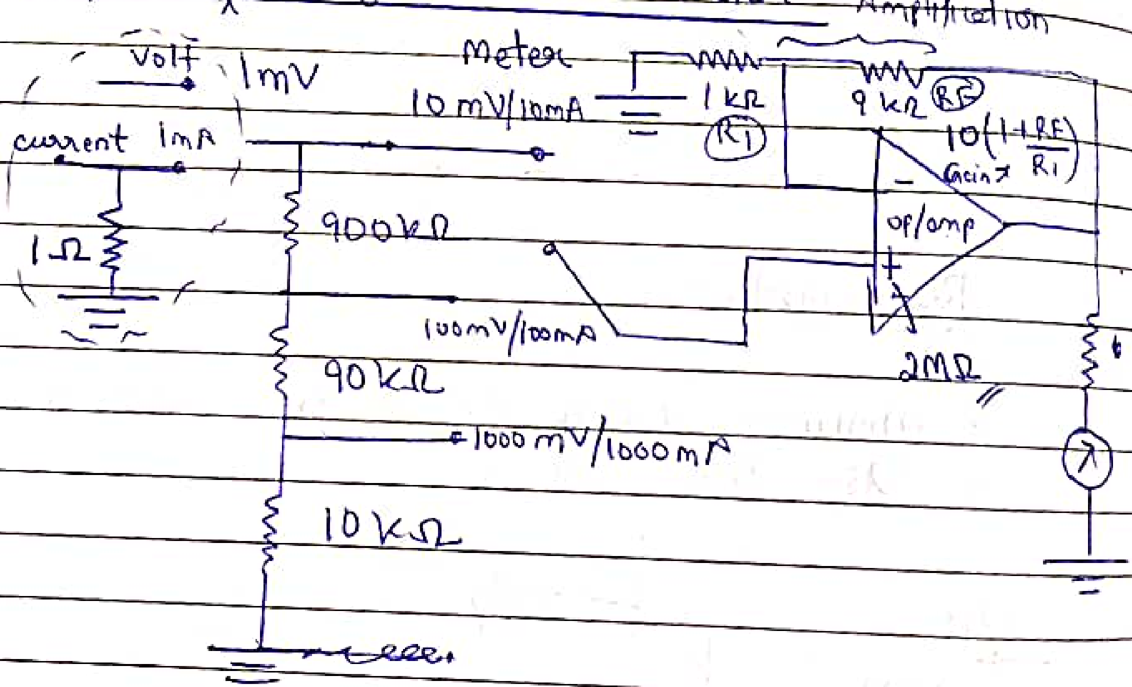
- Minimum energy drawn from measurand
- Use the same PMMC



Amplified DC Voltmeter



Amplified DC Voltage & Current Meter



OP-AMP (Operational Amplifier)

* IC741
* Amplification
* high i/p resistance
* low o/p impedance
* high gain (upto 10^4)
* ckt diagram of op-amp

* min power drawn from measurand
* must provide sufficient current to produce deflection.
* sufficient o/p current to produce deflection in PMMC.

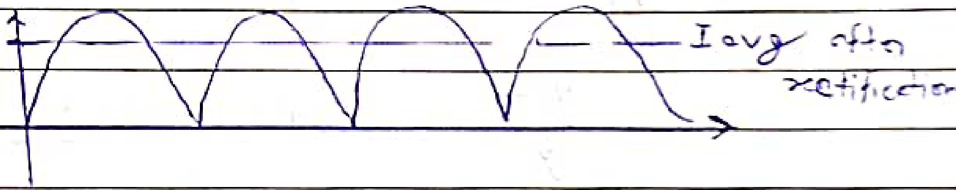
Q) How to measure small value AC signal?

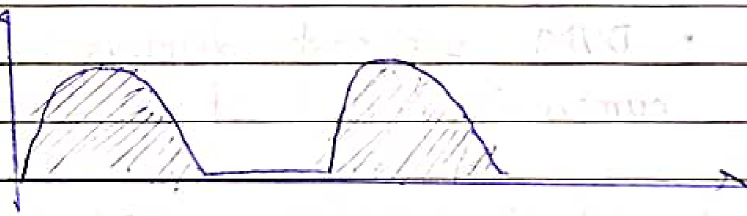
We have → Amplifier box

→ PMMC $[\theta \propto I_{avg}]$

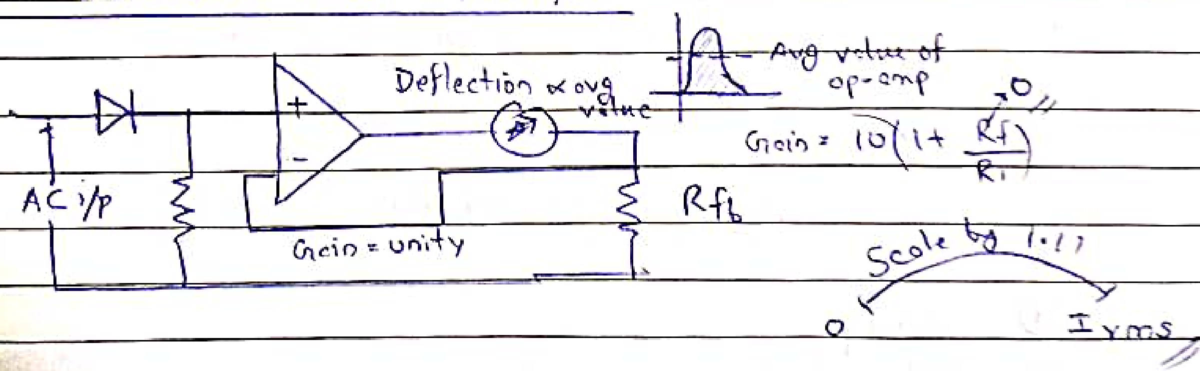
We require a rectifier type arrangement to convert bidirectional AC to DC.

Rectifier o/p ⇒

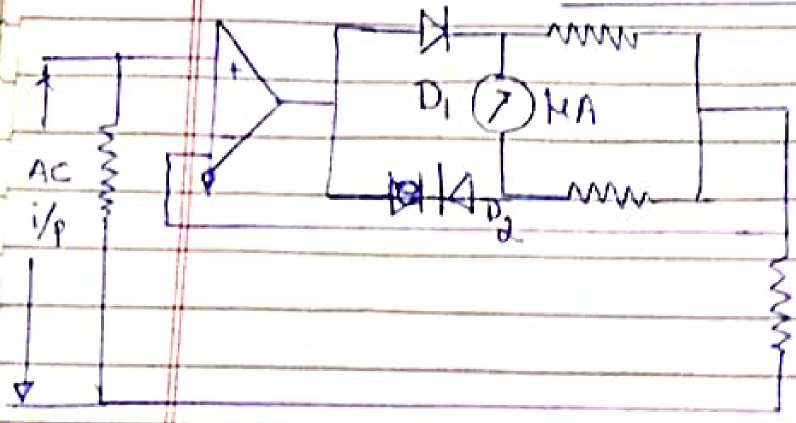




AC Voltmeter with Rectifier



~~Rectifier~~ Amplify → rectify



rectification after amplification –

- average responding type meter
- meter markings are corrected by a factor = Form Fa
- full wave rectification

~~$V/\sqrt{2}$~~
~~$2V_m/\pi$~~
~~2.14~~

Digital Voltmeter

- DVM ~~represent~~ displays measurement as a discrete numerical instead of a pointer deflection.

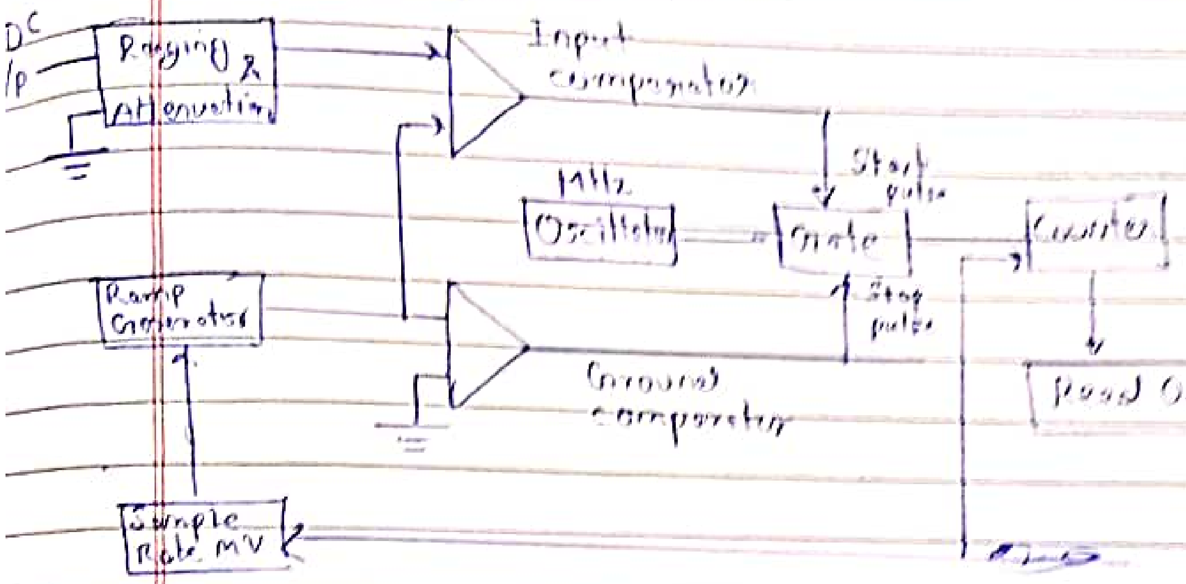
- reduces parallax, reduces time requirement for noting

- o/p is suitable for further processing or recording.

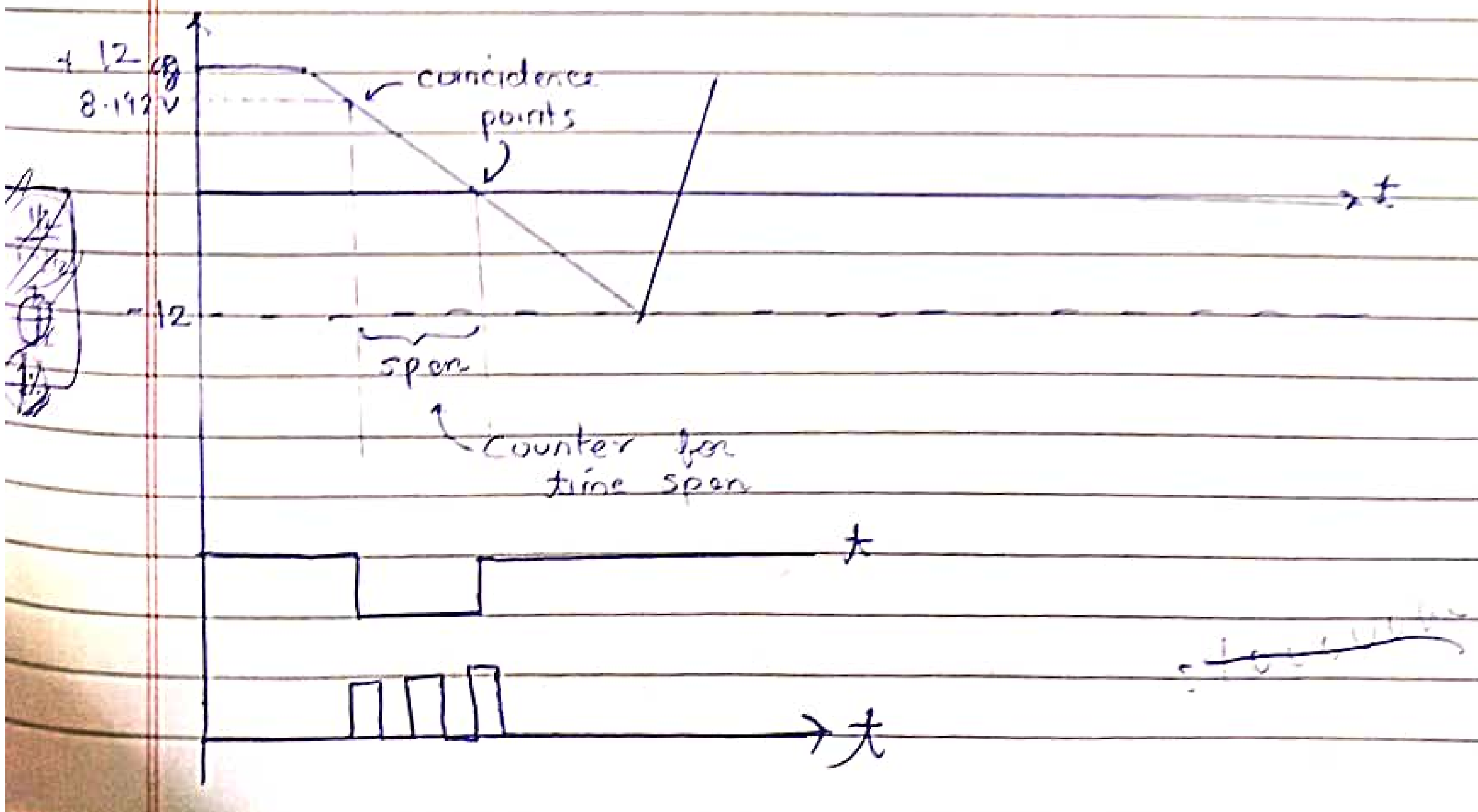
DVM Classification

1. Ramp
2. Integrating
3. Continious Balance
4. Successive Approximation

Ramp-Type DVM

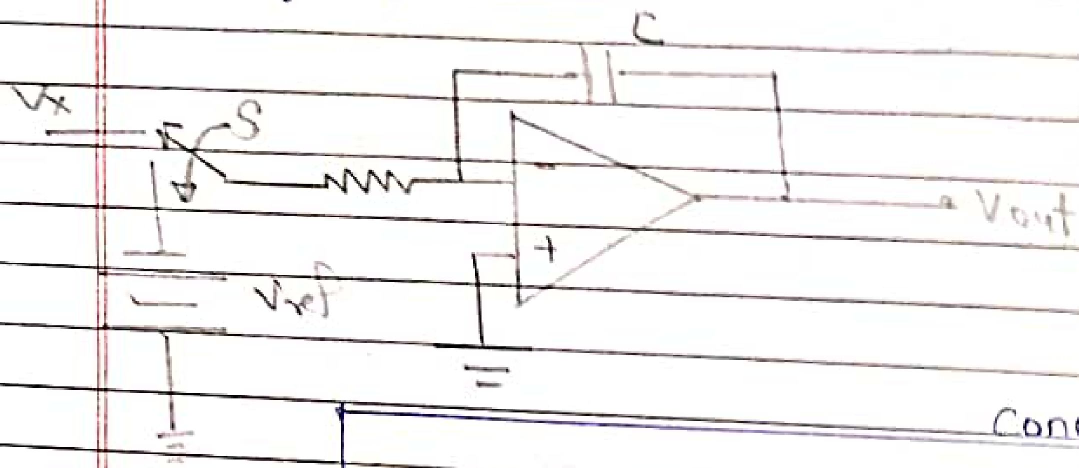


Operating principle: measure the time required for a linear ramp voltage to rise from 0V to the level of input voltage. This time interval is measured with an electronic counter.

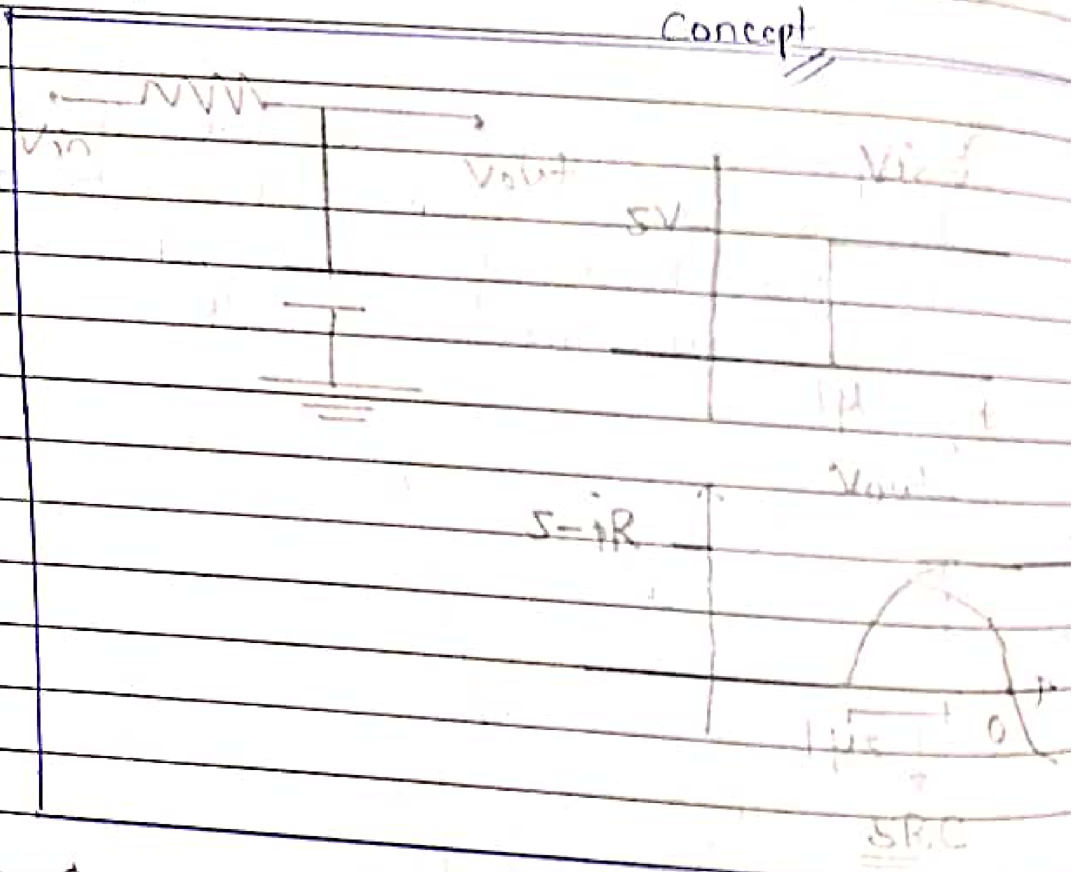


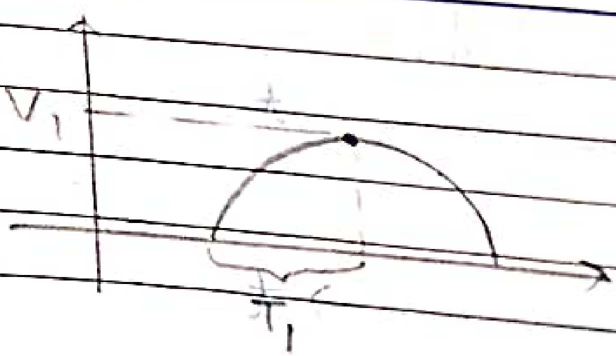
~~Ranging~~

Integrating DVM



Concept





- OPAMP is used as integrator
  o/p of OPAMP as integrator is

$$V_{out} = \frac{-1}{RC} t\, V_{in}$$

when V_x is applied

$$V_{out} = \frac{-1}{RC} t \cdot V_x$$

- we are connecting V_x only for 'T_1' duration and the o/p reaches 'V_1' volts within T_1 time.

$$V_1 = \frac{-1}{RC} T_1 V_x$$

- at T_1 we are changing the position of switch 'S' from V_x to '$-V_{ref}$'.

$$V_{out} = \cancel{V_{ref} \cdot \frac{1}{RC}(t - T_1)}$$

$$= V_1 + \frac{1}{RC} t\, V_{ref}$$

$$\left\{ V_{out} = V_1 + \frac{1}{RC} t\, V_{ref} \right\}$$

it takes 'T_x' time for V_{out} to go to 0V.

$$0 = V_1 + \frac{1}{RC} T_x V_{ref}$$

$$0 = \frac{-1}{\cancel{RC}} T_1 V_x + \frac{1}{\cancel{RC}} T_x V_{ref}$$

$$\left\{ V_x = \frac{T_x}{T_1} V_{ref} \right\}$$

Successive Approximation Conversion

- assume that the "digital" no. to be determines in between 0 to 512.

- Lets assume the Voltage to be digitaliz is 4.99V.

eg Wheatstone Bridge Lab expt.

0.	5	0	1	V ... 0 to 2V
0	0	3	8	mV ... 0 to 500 mV

Steps:

(1) 1^{st} guess : $= 256$

if $x > 256$
Yes

(2) 2^{nd} guess $256 + 128 = 384$
if $x > 384$
Yes

(3) 3^{rd} guess $384 + 64 = 448$
if $x > 448$
Yes

(4) 4^{th} guess $448 + 32 = 480$
if $x > 480$
Yes

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(5) 5^{th} guess $480 + 16 = 496$

$x > 496$ Yes

(6) 6^{th} guess $496 + 8 = 504$

$x > 504$ No

(7) 7^{th} guess $496 + 4 = 500$

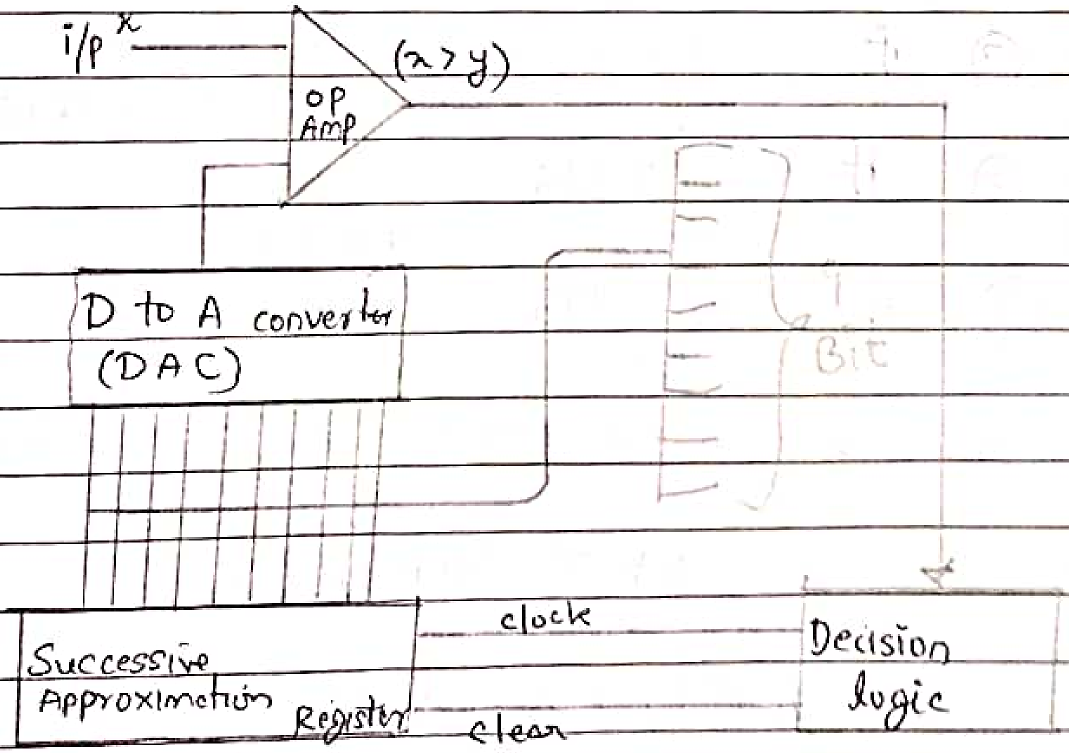
$x > 500$ No

(8) 8^{th} guess $496 + 2 = 498$

$x > 498$ Yes

(9) 9^{th} guess $498 + 1 = 499$

$\boxed{x = 499}$



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10 bit SAC, measurand : 799

① if x > 512
Yes 512 + 256 = 768
② if x > 768
Yes 768 + 128 = 896
③ if x > 896
NO 768 + 64 = 832
④ if x > 832
NO 768 + 32 = 800
⑤ if x > 800
NO 768 + 16 = 784
⑥ if x > 784
Yes 784 + 8 = 792
⑦ if x > 792
Yes 792 + 4 = 796
⑧ if x > 796
Yes 796 + 2 = 798
⑨ if x > 798
Yes
⑩ x = 798 + 1 = 799

~~1 1 0 0 0 0 1 1 1 1~~

~~1 1 1 1 0 0 0 1 1~~

0	0	1	1	0	0	1	1	1	1

2 | 799
| 399

799	1
399	1
199	0
9	

799
399
199

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Quantization Error

499 V is to be converted by 9 bits

12 V is to be converted by 4 bits

12.3 V → 12 V

Error = 0.3 V

Max. error = 0.5 V

For 499 V max error = 0.005 V

Max Error = ± one half value of LSB
This is also called as Quantization error.

Max error = 0.005

Q) What is quantization error while measuring voltage using DVM?

2^9

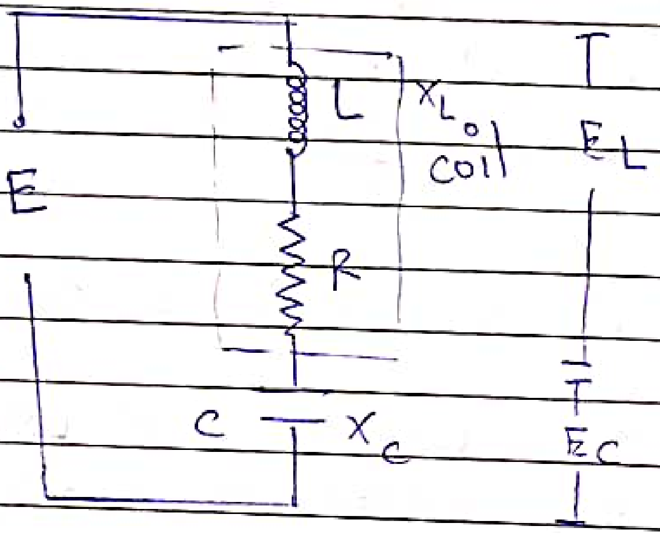
	600 V	→ ~~0.5~~ 9 bits	0.05 V
200×10^{-3}	200 V	→ 0.05 V	
~~0.2~~	20 V	→ ~~0.05~~	0.005 V
~~200~~	200 mV	→ 0.05 mV	

Q-Meter

Working principle : voltage across the coil of a series resonant ckt = Q × Applied voltage ~~of~~

&

voltage across the capacitor of a series resonant ckt = Q × applied volt.



At resonance,

$$X_L = X_C$$

$$E_C = IX_C \qquad E_L = IX_L$$

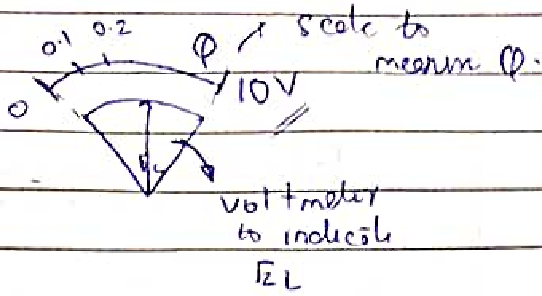
$$E = IR$$

$$E_L = QE$$

$$\frac{E_L}{E} = Q = \frac{X_L}{R} = \frac{X_C}{R}$$

$E_L \Rightarrow$ can be measured using voltmeter

$$\phi = \frac{X_L}{R} = \frac{X_C}{R}$$

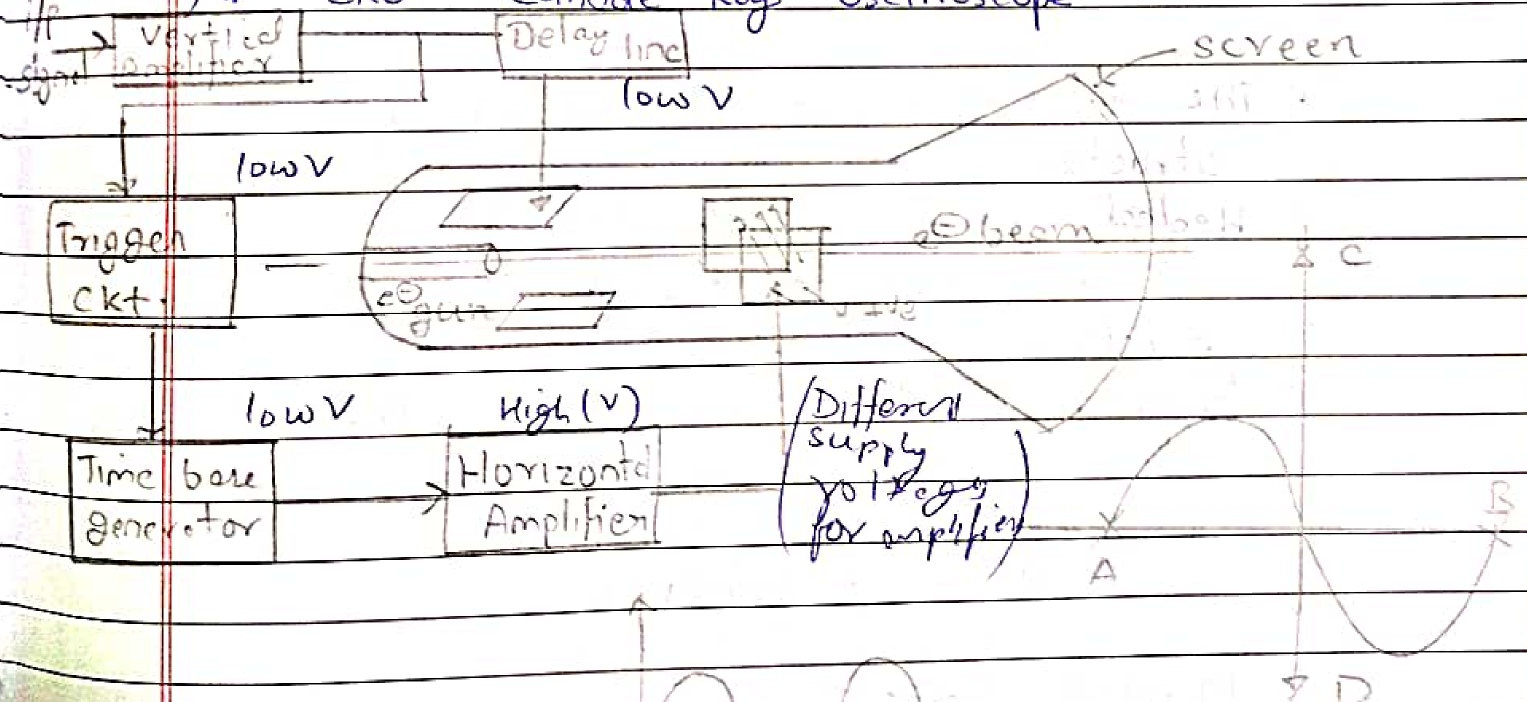


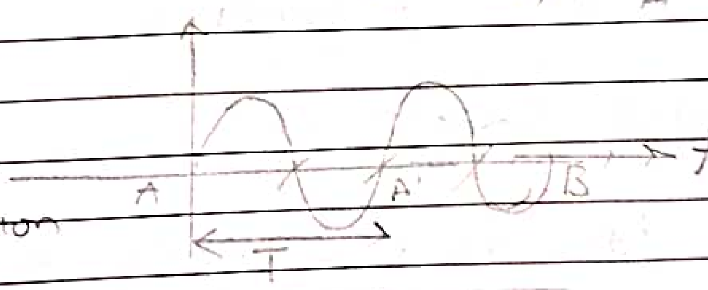
Oscilloscope

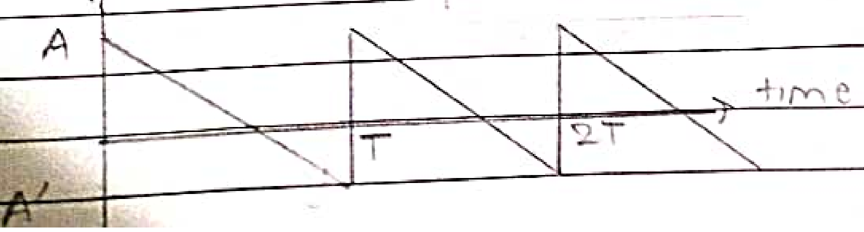
* Ammeter/ Voltmeter (AC, AC) deflection ∝ RMS

* Oscilloscope : shape of waveform

(High V) * CRO : Cathode Ray Oscilloscope

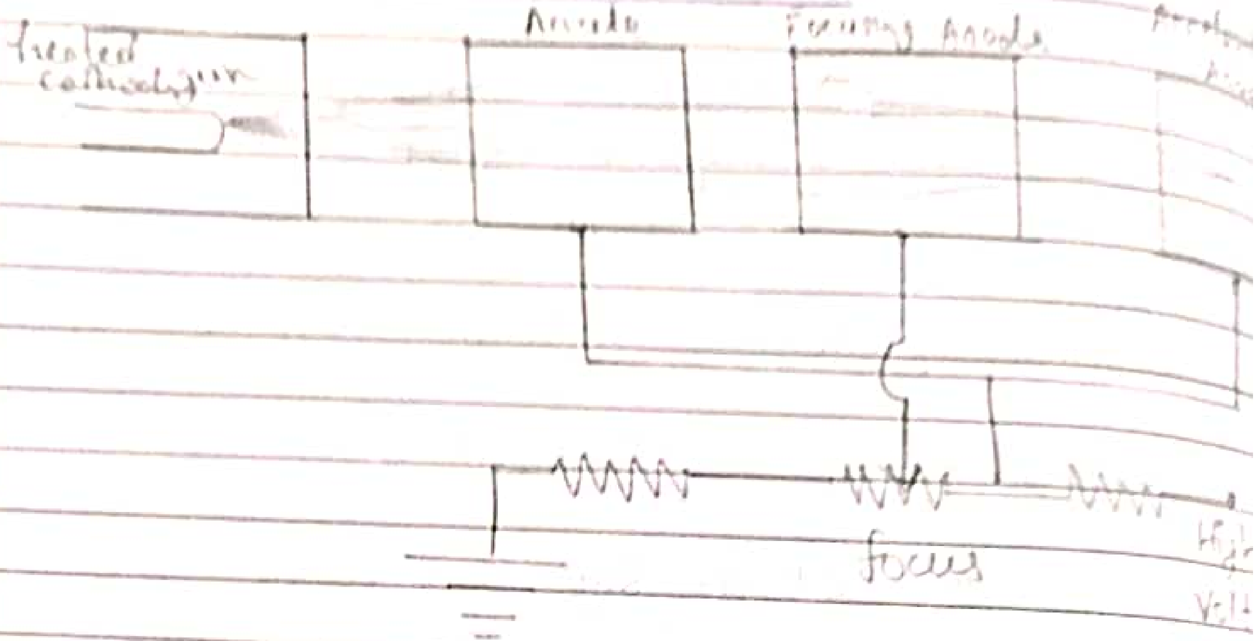






Cathode Ray Oscilloscope

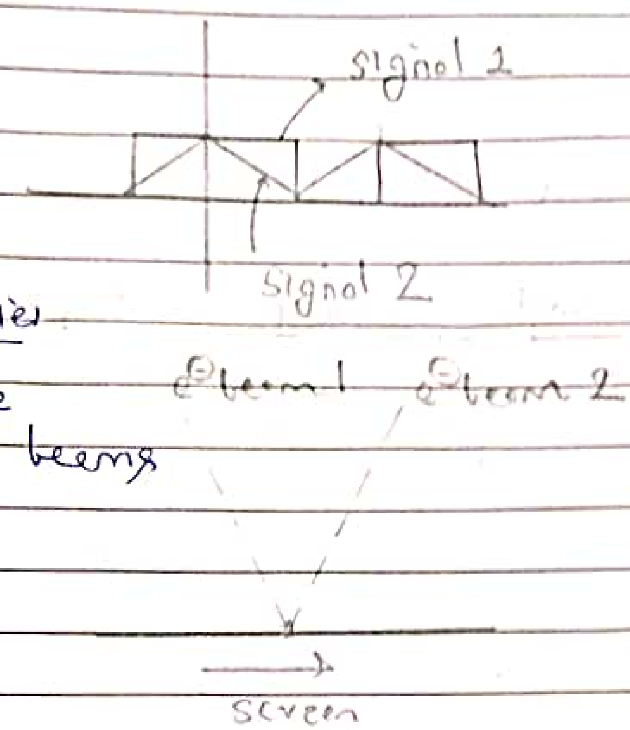
Electron Beam Mechanism



- The above 3 anode are hollow cylindrical structure
- Heated cathode emit the $e^{\ominus}$
- $e^{\ominus}$ are first accelerated by pre-accelerat[ing] anode.
- focusing anode narrows down the $e^{\ominus}$ beam
- Electrostatic lens is formed
  - 1st lens aligns $e^{\ominus}$(s).
  - 2nd lens focuses $e^{\ominus}$(s).

Multiple Trace

Q) How to view 2 signals on the CRO screen simultaneously?



phosphor coated screen

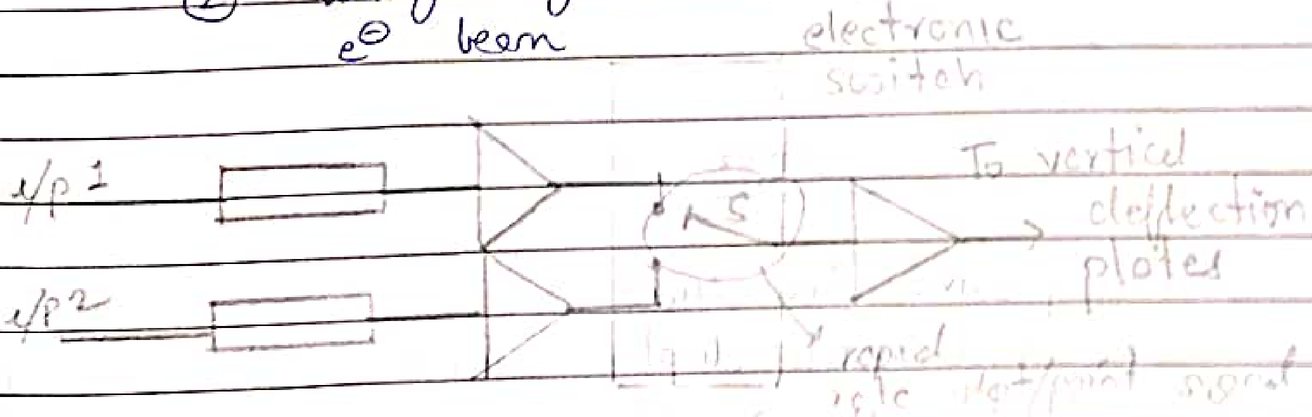
Possibilities

① Use 2 $e^{\ominus}$ beams

- each $e^{\ominus}$ beam would have it's own set of components
- Dual beam CRO
- independent analysis of two signals
- costly
- larger size

~~② How to~~

② using single $e^{\ominus}$ beam

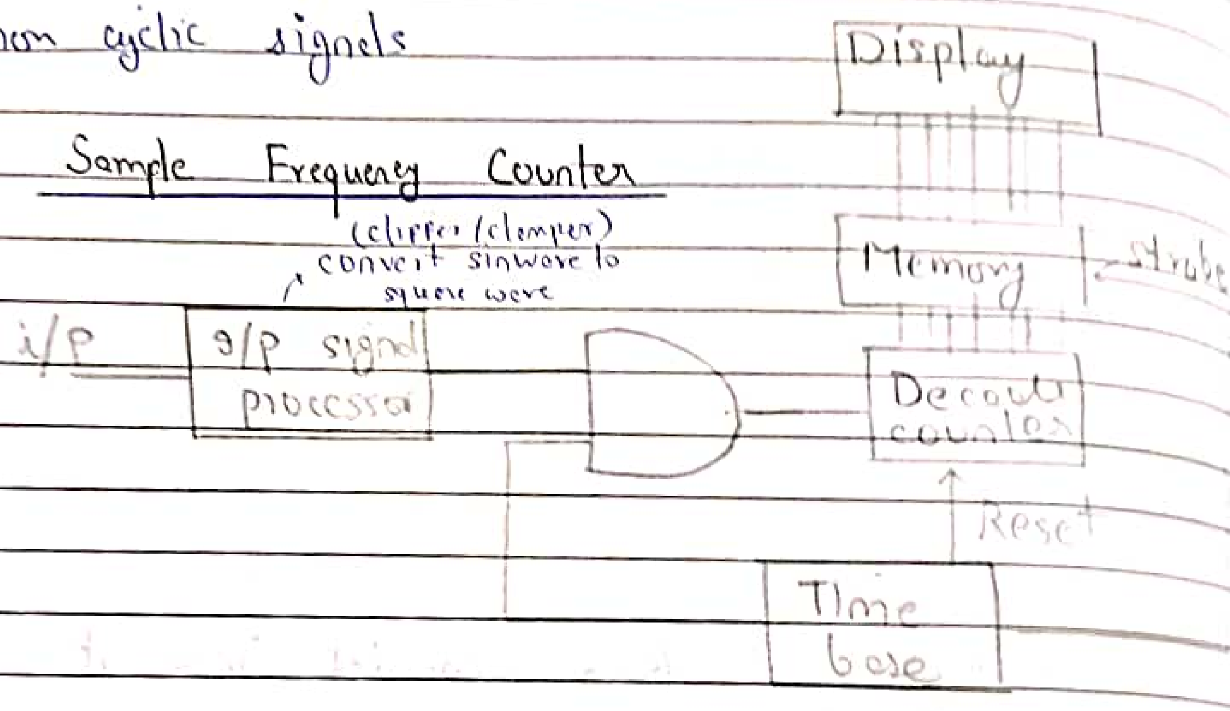


If signals are not multiples of each other's frequencies we cannot keep i/ps out of the CRO box.

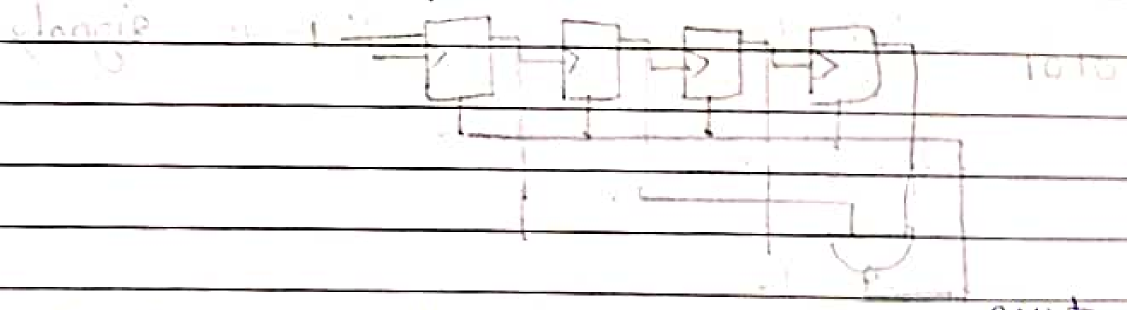
Drawback:

- non cyclic signals

Sample Frequency Counter



Decade counter → Asynchronous MOD = 10 counter



To determine frequency counter should give count pulses 1 sec.

Strain Gauge

- passive transducer
- mechanical displacement into change in resistance
- it is a thin wafer like device that can be attached or bonded to a variety in materials.

- R : Resistance of strain gauge
- ΔR : Change in resistance
- l : actual length
- Δl : Change in length

$$k = \frac{\Delta R / R}{\Delta l / l} = \text{sensitivity}$$

$$\text{Strain } (\sigma) = \frac{\Delta l}{l}$$

$$R = \frac{\rho l}{A} = \frac{\rho \times l}{\pi \times (d^2/4)}$$

where

- ρ : resistivity
- l : length
- A : Area
- d : diameter

Now under stress

$$R_s = \rho \left(\frac{l + \Delta l}{(\pi/4)\left[d^2 - 2d\,\Delta d + \Delta d^2\right]} \right)$$

$$= \frac{\rho \cdot (l + \Delta l)}{d^2 (\pi/4)\left(1 - \frac{2\Delta d}{d}\right)}$$

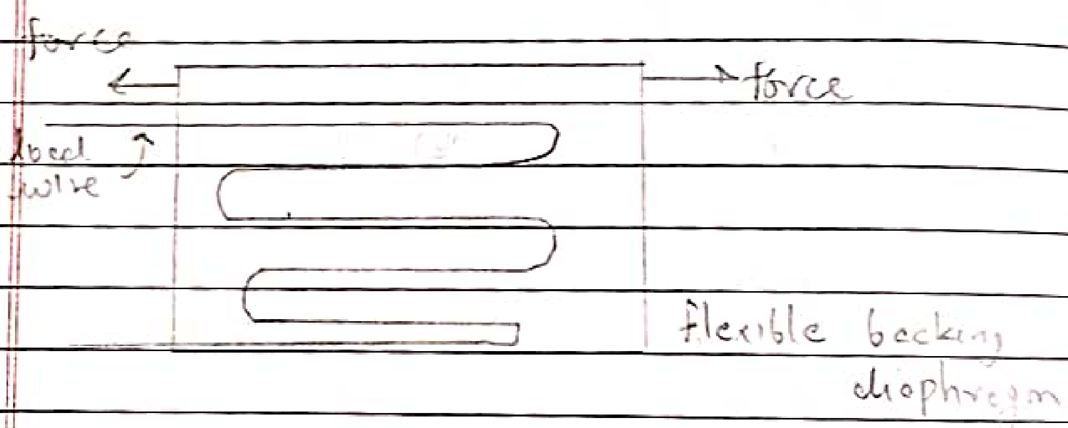
$$\text{Poisson's ratio} = \mu = \frac{\Delta d / d}{\Delta l / l}$$

$$\left[R_s = \frac{\rho l}{(\pi/4) d^2} \left[\frac{1 + (\Delta l / l)}{\cancel{1 + (1+2\mu)\frac{\Delta l}{l}}\ \ 1 - \frac{2\mu \Delta l}{l}} \right] \right]$$

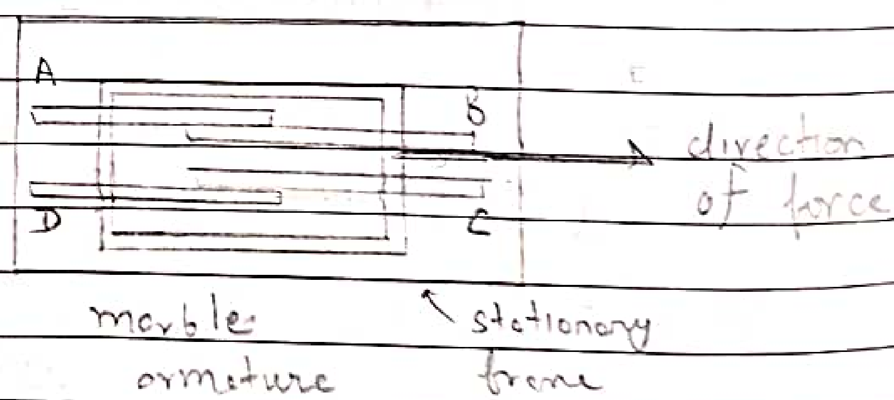
$$R_S = R + \Delta R$$
$$= R\left[1 + (1+2\mu)\frac{\Delta l}{l}\right]$$

$$k = \frac{\Delta R/R}{\Delta l/l} = 1+2\mu$$

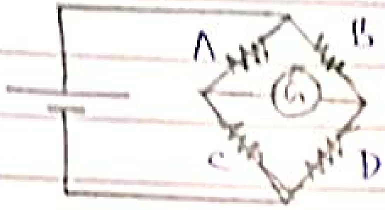
Bonded Strain Gauge



Unbonded Strain Gauge



ΔR can be measured using wheatstone bri



Displacement Transducers

- Force $\xrightarrow{\text{transducer}}$ displacement
- Pressure $\xrightarrow{\text{transducer}}$ displacement

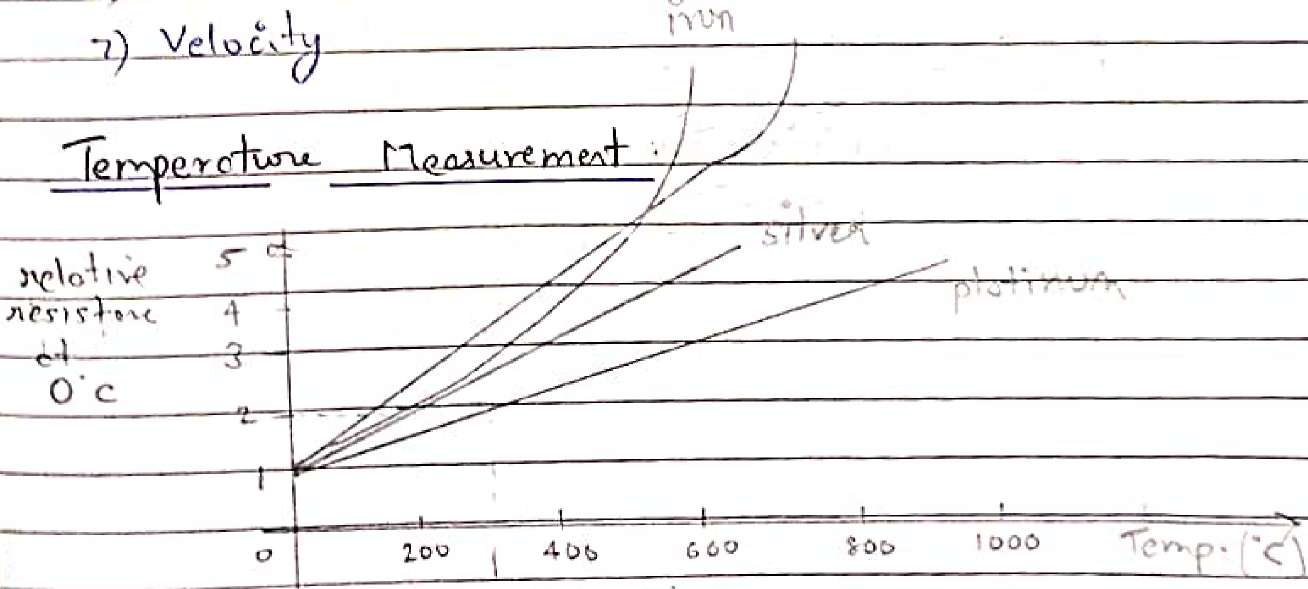
Once displacement is available, it can be measured using strain gauge.

Chp 11 section 4 Assignment :-

Transducers

1) Capacitive
2) Inductive
3) LVDT
4) Oscillation
5) Piezoelectric
6) Potentiometric
7) Velocity

Temperature Measurement :



At 300°C Resistance of platinum doubles

$$R_T = R_{ref}(1 + \alpha \Delta T)$$

where

R_T = resistance of conductor at temp T°C.

α = temp coeff. of resistance

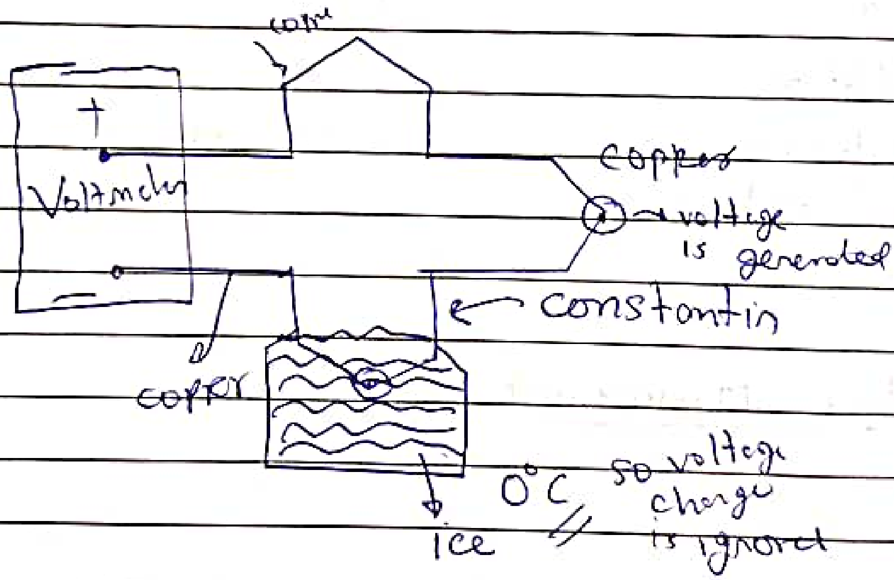
R_{ref} = resistance at 0°C.

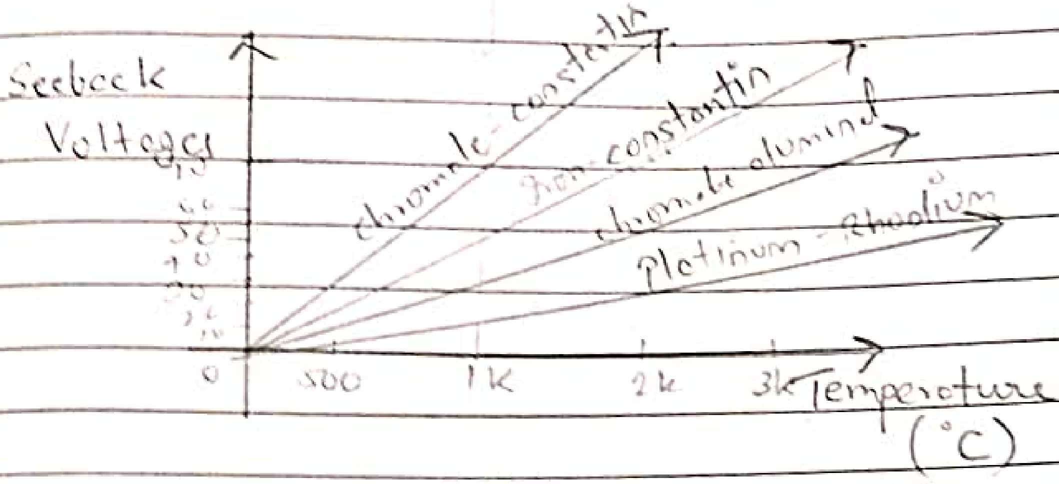
ΔT = t°C − t° ref

H.W: Read table 11.2

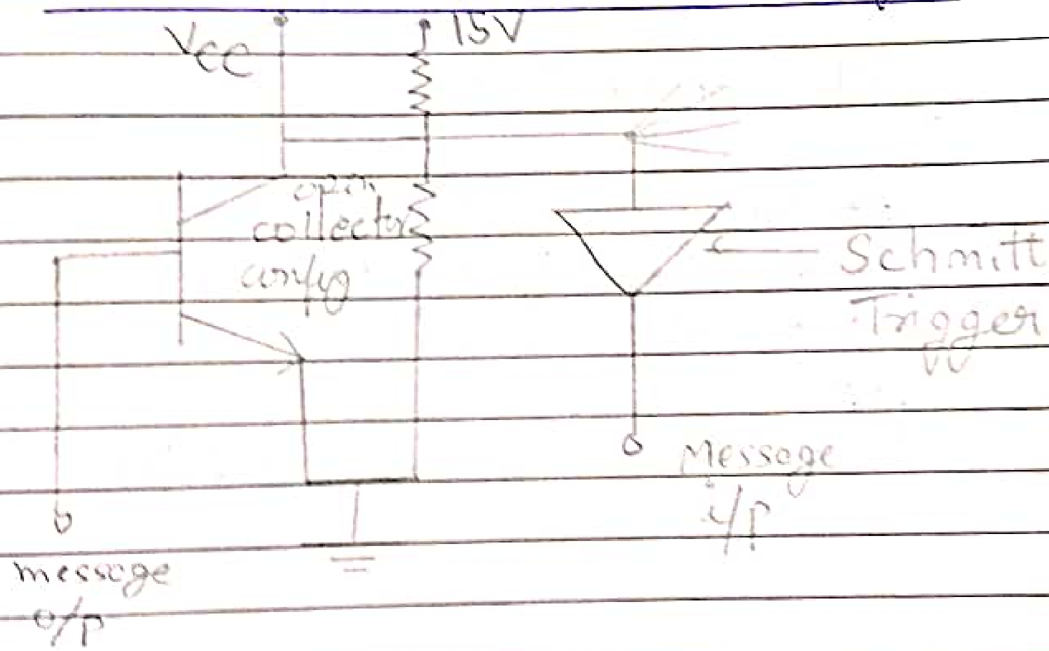
Thermocouple

In 1821, Thomas Seebeck → discovered that when 2 dissimilar ~~method~~ metals are in contact a voltage is generated & the voltage is $\propto$ temperature.



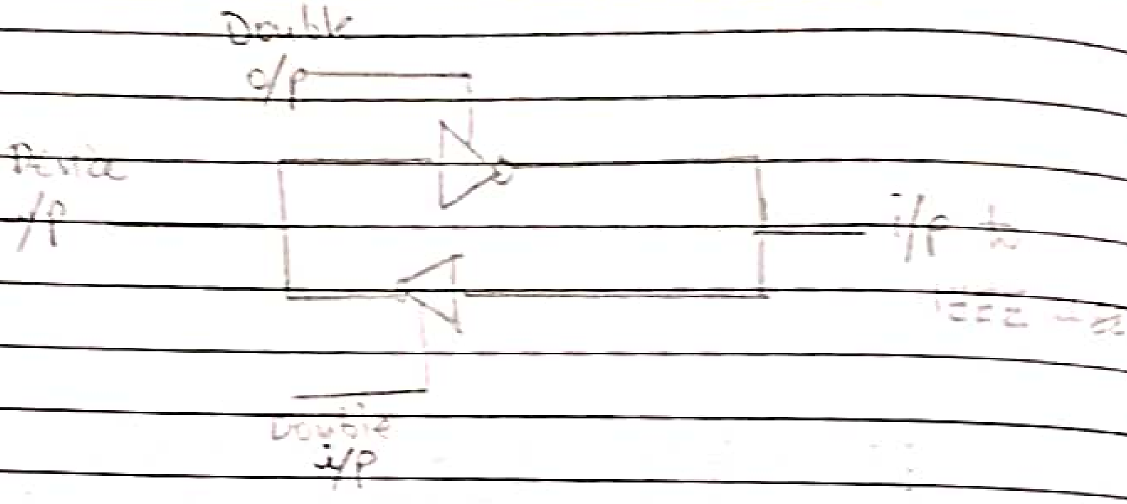


IEEE 488 Electrical Interface



- Wired communication for < 20 m.
- logic '0' ⟶ ~~xxxxxx~~ < 0.8 V but driver should be less than < 0.5.
- logic '1' ⟶ > ~~xx~~ 2.0 V but driver should be > 2.4V
- Noise margin = 0.4 for logic '1'
  = 0.3 for logic '0'.

Three State Bus Transreceiver



Cable requirements -

24 conductor cables
→ 8 data lines
→ 8 status lines
remaining lines
for other signals

Refer Textbook.