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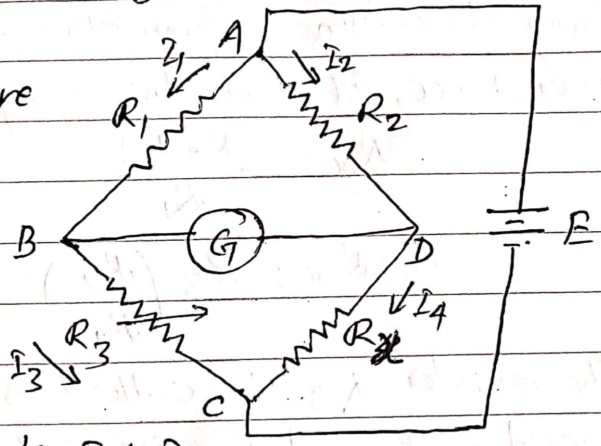
The schematic of wheatstone bridge circuit is shown in the fig. below.



The bridge consists of four resistive arms, a source of emf (battery) and a null detector, usually a galvanometer or other current sensitive meter. The current thru the galvanometer depends on the potential difference betn points B & D.

The bridge is said to be balanced when the potential difference across the galvanometer (i.e. points B and D) is 0 V. so that there is no current thru the galvanometer. This condition occurs when the voltage from point B to point A equals to the voltage from point D to point A or voltage from point B to point C and voltage from point D to point C are equal.

The bridge is balanced when

$$I_1 R_1 = I_2 R_2 \quad \text{(I)}$$

If the galvanometer ckt is zero, the following condition also exists:

$$I_1 = I_3 = \frac{E}{R_1 + R_3}$$

$$I_2 = I_4 = \frac{E}{R_2 + R_x}$$

Substituting these values in eqn (I) we get,

$$\frac{R_1}{R_1 + R_3} = \frac{R_2}{R_2 + R_x}$$

$$\text{or, } R_1 R_2 + R_1 R_x = R_1 R_2 + R_2 R_3$$

$$\text{or, } R_1 R_x = R_2 R_3 \quad \text{(II)}$$

This is the eqn for balance of the wheatstone bridge.

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If three of the resistances have known values, the fourth arm may determined from the eq^n (1). Hence, if R_x is unknown resistance, it can be expressed as:

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

$$\text{or, } R_x = R_3 \left(\frac{R_2}{R_1}\right) \quad \text{——— (iii)}$$

The resistor R_3 is called standard arm of the bridge and resistors R_2 and R_1 are called the ratio arms.

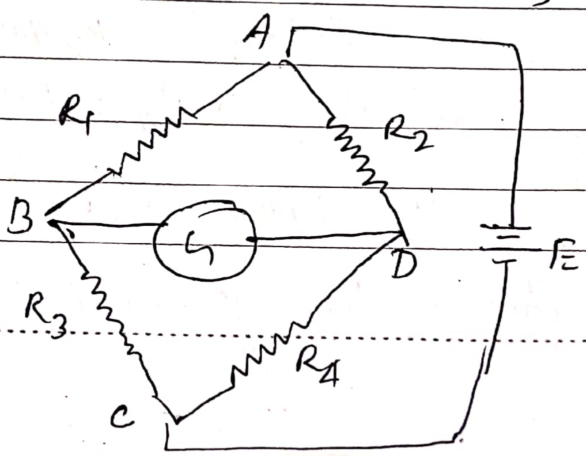
Measurement Errors :-

(i) Limiting errors in the three known resistors. (Tolerance).
(ii) Changes in the known resistance values of the bridge arms due to self heating effect of the current thru the resistors.
(iii) Balance point error caused by insufficient sensitivity of the null detector.

Unbalance Condition :-

When the bridge is in unbalance condition, current flows thru the galvanometer. In order to calculate the current flowing thru the galvanometer, we first consider that the bridge is slightly unbalanced. Then we calculate the equivalent voltage and equivalent resistance. Given the value of internal resistance and sensitivity of the galvanometer, we calculate the galvanometer current and then the deflection.

Considering slightly unbalance condition, we can write,



$$E_{BD} = E_B - E_D$$

$$\text{or, } E_{BD} = E_{AB} - E_{AD}$$

$$\text{or, } E_{BD} = I_1 R_1 - I_2 R_2$$

Now, for the calculation of current thru the galvanometer, we have to draw Thevenin's equivalent ckt referring point B and D. Thevenin's voltage is given by

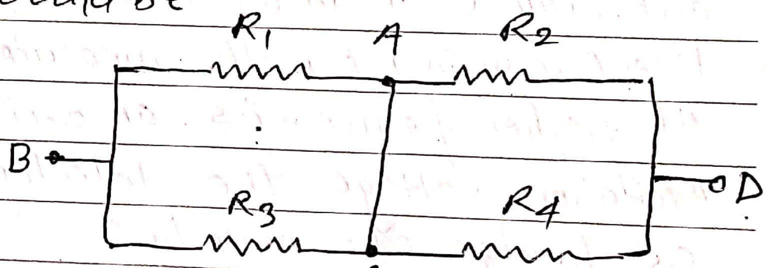
$$E_{th} = E_{BD} = I_1 R_1 - I_2 R_2$$

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

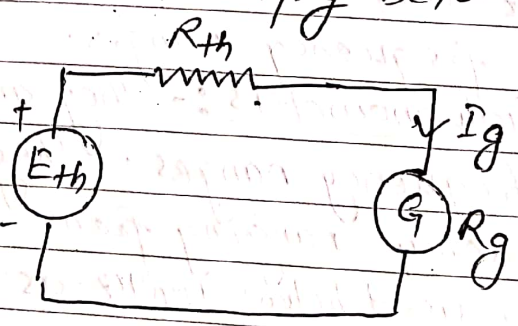
$$\therefore E_{th} = E\left[\frac{R_1}{R_1 + R_3} - \frac{R_2}{R_2 + R_4}\right] \quad \text{—— (I)}$$

The resistance of Thevenin's equivalent circuit is found by looking back into terminal B and D and replacing the battery by its internal resistance. The internal resistance of the battery is assumed to be zero. Therefore the Thevenin's equivalent resistance would be

$$R_{th} = \frac{R_1 R_3}{R_1 + R_3} + \frac{R_2 R_4}{R_2 + R_4} \quad \text{—— (II)}$$



The equivalent ckt of the ~~there~~ wheatstone bridge ckt therefore reduces to as shown in the fig below:



when the null detector is now connected to the o/p terminal of equivalent ckt, the galvanometer current (I_g) is found to be

$$I_g = \frac{E_{th}}{R_{th} + R_g} \quad \text{—— (III)}$$

where R_g is the internal resistance of galvanometer.

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2.9.2 Ac bridges and their Application:-

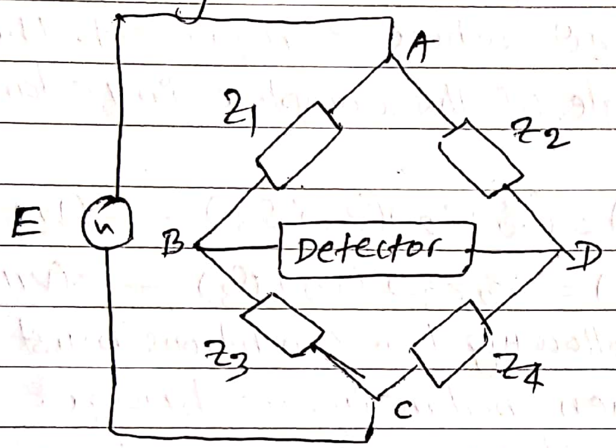
The ac bridges methods are of outstanding importance for measurement of electrical quantity. Measurement of inductance, capacitance, storage factor, dissipations factor, quality factor may be made conveniently and accurately by employing ac bridge n/w. These circuits also find applications in communication systems and complex electronic circuits: amplifiers, filtering out undesirable signals and measuring frequency of audio signals.

The basic form of ac bridge consists of four arms as impedances, an ac source and a detector. The impedances may be the resistance or its combination with capacitance or inductance. The source is usually the power lines (ac mains) for the measurement at low frequencies. At higher frequencies, an oscillator generally supplies the excitation voltage. The detectors generally used for the ac bridge ckt may be:

- Headphones:- At frequency range of 250 Hz up to 3-4 KHz. and are cheapest and most sensitive detectors for this frequency ranges.
- Galvanometers:- They are used for power and low audio frequency ranges. They are manufactured to work at frequency ranging from 5 Hz to 1 KHz but are more commonly used below 100 Hz as they are more sensitive than headphones below this range.
- Tunable Amplifiers:- This is the most versetile of the detectors. The transistor amplifiers can be tuned electrically and thus can be made to respond to a narrow bandwidth at the bridge frequency.

2.9.3 Condition for bridge balance :-

The general eqn for the bridge balance is obtained by using complex notation for the impedances of the bridge ckt. (Bold case type is used to indicate quantities in complex notation). These quantities may be impedances or admittances as well as voltages or currents.



The condition of bridge balance requires that the potential difference from B to D be zero i.e. null reading in the detector. This occurs when the voltage drop from A to B equals the voltage drop from A to D. in both magnitude & phase. General eqn for bridge balance is obtained by complex notation for the impedances. In complex notation we can write:

$$E_{AB} = E_{AD}$$

or $I_1 Z_1 = I_2 Z_2$ ——— (i)

Also for zero detector, currents are

$$I_1 = \frac{E}{Z_1 + Z_3} \text{ ——— (ii) and,}$$

$$I_2 = \frac{E}{Z_2 + Z_4} \text{ ——— (iii)}$$

Substituting the values of I_1 and I_2 from eqn (ii) & (iii) in eqn (i) and solving we get,

$$Z_1 Z_4 = Z_2 Z_3 \text{ ——— (iv)}$$

or when using admittances instead of impedances,

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$$Y_1 Y_4 = Y_2 Y_3 \quad \text{--- (v)}$$

Eqⁿ (iv) is the required condition for the bridge balance which states that the product of the impedance of one pair of opposite arms must be equal to the product of the impedances of other pair of opposite arms, with the impedances expressed in complex notation. If the impedance is written in the form $Z = Z\angle\theta$, where Z represents the magnitude and θ represents the phase angle of the complex impedance. Thus in complex form;

$$(Z_1\angle\theta_1)(Z_4\angle\theta_4) = (Z_2\angle\theta_2)(Z_3\angle\theta_3) \quad \text{--- (vi)}$$

$$\therefore Z_1 Z_4 \angle(\theta_1+\theta_4) = Z_2 Z_3 \angle(\theta_2+\theta_3) \quad \text{--- (vii)}$$

The eqⁿ (vii) Shows that the following two conditions must be satisfied simultaneously when balancing ac bridge.

(1) The product of the magnitudes of the impedances of opposite arms must be equal. i.e. $Z_1 Z_4 = Z_2 Z_3$

(2) The sum of the phase angles of the impedances of opposite arms must be equal.

i.e. $\angle(\theta_1+\theta_4) = \angle(\theta_2+\theta_3)$.

The unknown can be found from eqⁿ (iv). If Z_4 is the unknown (say Z_x) then it can be found from eqⁿ (iv) as:

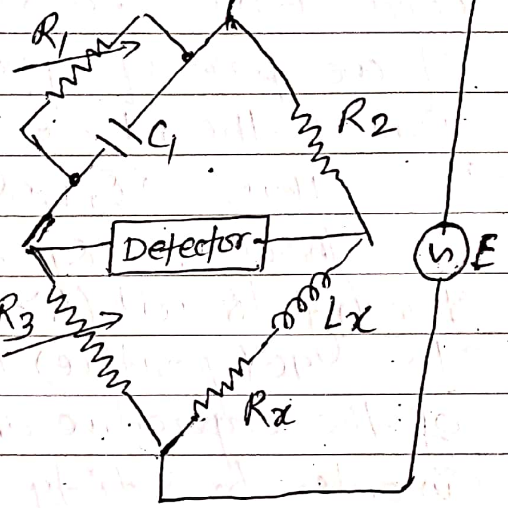
$$Z_x = \frac{Z_2 Z_3}{Z_1}$$

$$\therefore Z_x = Z_2 Z_3 Y_1.$$

The various bridges are defined according to the elements presents in the impedance arm.

2.3.4 Types of AC Bridge :-

(i) Maxwell Bridge :- The Maxwell Bridge, shown in figure below, is used to measure the unknown inductance in terms of Known capacitance. One of the ratio arms has a resistance and a capacitance in parallel. It is will be easier to write the balance equations using the admittance of arm 1 instead of its impedance. The Maxwell Bridge is used for the accurate measurement of the inductance of medium Q-coils ($1 < Q < 10$).



We know that the eqn for bridge balance is

$$Z_x = Z_2 Z_3 Y_1 \quad \text{—— (i)}$$

where,

L_x is the unknown inductance having effective resistance (due to winding of the coil) R_x.

R_2 = the non-inductive resistor

R_3 = the variable standard resistor.

C_1 = the standard capacitor

R_1 = variable resistor in parallel with C_1.

Here,

$$Z_1 = R_1 \parallel C_1 = \frac{R_1 (1/j\omega C_1)}{R_1 + 1/j\omega C_1} = \frac{R_1}{1 + jR_1 C_1 \omega}$$

$$\therefore Y_1 = \frac{1}{R_1} + j\omega C_1$$

$$Z_2 = R_2, \quad Z_3 = R_3$$

$$Z_x = R_x + j\omega L_x$$

Substituting these values in eqn (1), we get,

$$R_x + j\omega L_x = R_2 R_3 \left(\frac{1}{R_1} + j\omega C_1\right)$$

Comparing real part and imaginary part, we get,

$$R_x = \frac{R_2 R_3}{R_1} \quad \text{—— (ii)}$$

$$L_x = R_2 R_3 C_1 \quad \text{—— (iii)}$$

Thus the unknown inductance L_x and the unknown resistance R_x due to the winding of the inductance coil can be computed.

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Limitations of Maxwell Bridge:

(i) Maxwell's Bridge is suited for measurement of medium Q coils ($1 < Q < 10$).

This can be shown by considering the second balance cond^n which states that the sum of the phase angles of one pair of opposite arms must be equal to the sum of the phase angles of the other pair.

Here, $\angle\theta_2 + \angle\theta_3 = 0$

Therefore, $\angle\theta_1 + \angle\theta_4$ must be equal to 0.

For high Q-coils ($Q > 10$) the phase angle will be nearly equal to $90°$ (positive) which requires that the phase angle of the capacitive arm must also be very nearly $90°$ ($-ve$). in order to satisfy the second balance condition (phase angle) of bridge ckt. This in turn means that the resistance of R_1 must be very large, which can be impracticable for high Q-coils. For measuring the inductance of high Q-coils we use Hay Bridge.

(ii) Also not suited for very low Q-coils ($Q < 1$) due to balance convergence problem. Very low Q occur in inductive resistors or in RF coil if measured at low frequency. As seen from the eq^ns for R_x and L_x, adjustment for inductive balance balance by R_3 upsets the resistive balance by R_1 and gives rise to sliding balance effect, since R_3 is present in both the eq^ns. When we balance with R_1 and then with R_3 then go back to R_1 we find a new balance point. The balance point appears to move or slide towards its final value after many adjustments. Interaction doesnot appear when R_1 and C_1 are used to balance. But a variable capacitor is not always suitable.

The usual procedure for balancing the Maxwell Bridge is by first adjusting R_3 for inductive balance and then adjusting R_1

for resistive balance. Returning to the R_3 adjustment, we find that the resistive balance is being disturbed and moves to a new value. This process is repeated and gives slow convergence to final balance. For medium Q- coils, the resistance effect is not pronounced & balance is obtained after few adjustments.

Advantages :-

(i) This bridge permits the measurement of inductance in terms of capacitance and a capacitor has always advantages in comparision to inductor as it gives practically no field, so it is more compact and is easier to shield.

(ii) In this bridge, balance cond^{ns} are independent of frequency as the term frequency doesnot appear in any of the balance eq^{n}.

(iii) with the help of this bridge Q-factor of coil can be determined very easily.

$$Q\text{-factor} = Q = \frac{X_{Lx}}{R_x} = \frac{\omega L_x}{R_x} = \frac{\omega C_1 R_2 R_3}{\frac{R_2 R_3}{R_1}} = \omega R_1 C_1$$

Disadvantages :-

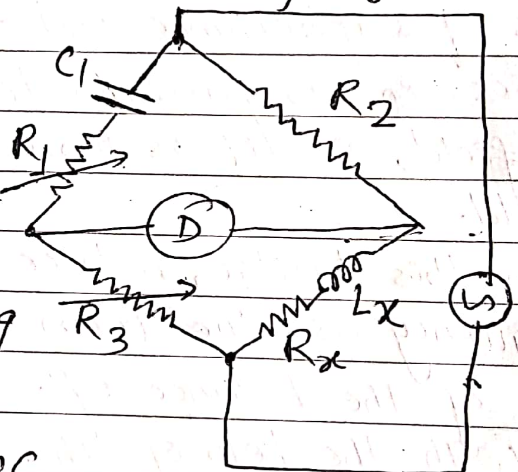
(i) It requires variable standard capacitor, it is an expensive component when calibrated to a high accuracy.

(ii) Only useful for the determination of inductance having medium Q-factor (i.e. $1 < Q < 10$).

(iii) Balance Convergence Problem.

(ii) Hay bridge :-

Hay bridge shown in the figure is best suited for the measurement of inductance of high Q-coils. It also uses a standard capacitor as a comparision element for determining the unknown inductance. However, the capacitor (C_1) is in series with a resistor (R_1) in one arm of the bridge rather than in parallel. It is evident that for large phase angle, R_1 should have a very low value and so this ckt is suitable for the measurement of inductance of high Q-coils.



where,

C_1 = Standard capacitor

R_1, R_2, R_3 = known non-inductive resistance

L_x = Unknown inductance having a resistance R_x.

Here, $Z_1 = R_1 + 1/j\omega C_1 = R_1 - j/\omega C_1$

$Z_2 = R_2,\ Z_3 = R_3$ &

$Z_x = R_x + j\omega L_x$

we know for bridge balance,

$Z_1 Z_x = Z_2 Z_3$

or, $(R_1 - j/\omega C_1)(R_x + j\omega L_x) = R_2 R_3$

or, $R_1 R_x + j\omega R_1 L_x - \dfrac{jR_x}{\omega C_1} + \dfrac{L_x}{C_1} = R_2 R_3$

Comparing real and imaginary parts, we get,

$R_1 R_x + \dfrac{L_x}{C_1} = R_2 R_3$ ——— (i)

& $\omega L_x R_1 = \dfrac{R_x}{\omega C_1}$ ——— (ii)

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from eqⁿ (II),

$$R_x = \omega^2 C_1 L_x R_1 \quad \text{——— (III)}$$

Substituting the value of R_x in eqⁿ (I)

$$\omega^2 C_1 L_x R_1^2 + \frac{L_x}{C_1} = R_2 R_3$$

or, $$L_x \left[\frac{\omega^2 C_1^2 R_1^2 + 1}{C_1}\right] = R_2 R_3$$

$$\therefore L_x = \frac{C_1 R_3 R_2}{\omega^2 R_1^2 C_1^2 + 1} \quad \text{——— (IV)}$$

Again, substituting the value of L_x in eqⁿ (III), we get,

$$R_x = \omega^2 C_1 R_1 \left[\frac{C_1 R_2 R_3}{(\omega^2 R_1^2 C_1^2 + 1)}\right]$$

$$\therefore R_x = \frac{\omega^2 C_1^2 R_1 R_2 R_3}{(\omega^2 R_1^2 C_1^2 + 1)} \quad \text{——— (V)}$$

Thus, we can compute the value of inductance using Hay bridge.

Now

$$Q\text{-factor} = \frac{X L_x}{R_x} = \frac{\omega L_x}{R_x} = \frac{\omega C_1 R_2 R_3}{(\omega^2 R_1^2 C_1^2 + 1)} \times \frac{(1 + \omega^2 R_1^2 C_1^2)}{\omega^2 C_1^2 R_1 R_2 R_3}$$

$$\therefore Q\text{-factor} = \frac{1}{\omega R_1 C_1}$$

Now, substituting the value of Q in eqⁿ (IV) and (V)

$$L_x = \frac{C_1 R_2 R_3}{(1/Q)^2 + 1} \quad \& \quad R_x = \frac{\omega^2 C_1^2 R_1 R_2 R_3}{(1/Q)^2 + 1}$$

for high Q-coils i.e. $Q >> 10$, we get

$$\boxed{L_x = C_1 R_2 R_3} \quad \& \quad \boxed{R_x = \omega^2 C_1^2 R_1 R_2 R_3}$$

i.e. for high Q-coils the balance eqⁿ becomes much more simpler.

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Advantages :-

(i) This bridge gives very simple expression for unknown inductance for high Q-coils, and is suitable for coils having $Q > 10$.

(ii) The bridge also gives a simple expression for Q-factor

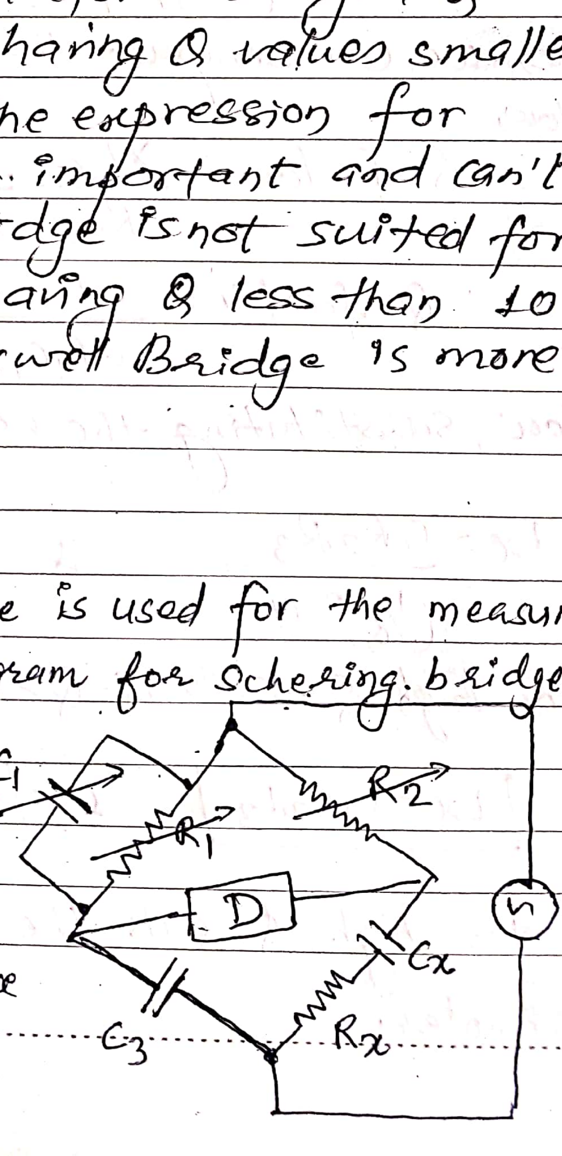
(iii) Here, $Q = 1/\omega C_1 R_1$

we find that the resistance R_1 appear in the denominator and hence for high Q coils, it's value should be small. Thus, the bridge requires only a low value resistor for R_1 whereas the Maxwell bridge requires a parallel resistor R_1 of very high value.

Disadvantages :-

This bridge is suited for the measurement of high Q inductors, especially those inductors having a Q greater than 10. For inductors having Q values smaller than 10, the term $(1/Q)^2$ in the expression for inductance L_x becomes rather important and can't be neglected. Hence, this bridge is not suited for the measurement of coils having Q less than 10 & for these applications a Maxwell Bridge is more suited.

(iii) Schering Bridge :- This bridge is used for the measurement of unknown capacitance. The ckt diagram for Schering bridge is shown in figure below:



where,

C_1 = a variable capacitor

R_1 = a variable non-inductive resistance in parallel with variable capacitor C_1

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R_2 = non-inductive resistance.

C_3 = a standard capacitor (loss free)

C_x = Capacitor whose capacitance is to be determined.

R_x = a series resistance representing the loss in the capacitor C_x

Here,

$$Z_1 = R_1 \parallel X_{C_1} = (R_1 \parallel 1/j\omega C_1) = \frac{R_1 \times 1/j\omega C_1}{R_1 + 1/j\omega C_1} = \frac{R_1}{1+j\omega R_1 C_1}$$

$$\therefore Y_1 = 1/R_1 + j\omega C_1$$

$$Z_2 = R_2, \quad Z_3 = -j/\omega C_3$$

$$Z_4 = R_x - j/\omega C_x$$

we know, for the bridge balance,

$$Z_1 Z_x = Z_2 Z_3$$

$$\text{or, } Z_x = Z_2 Z_3 Y_1$$

Substituting the values, we get,

$$(R_x - j/\omega C_x) = R_2(-j/\omega C_3)(1/R_1 + j\omega C_1)$$

$$\text{or, } (R_x - j/\omega C_x) = \frac{-jR_2}{\omega C_3 R_1} + \frac{C_1 R_2}{C_3}$$

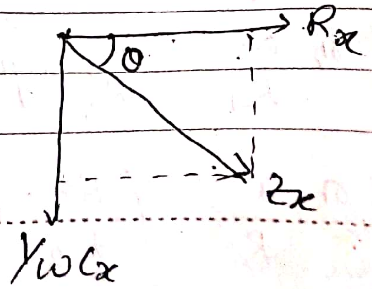
Comparing real and imaginary parts, we get,

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

$$\text{and } \frac{1}{\omega C_x} = \frac{R_2}{\omega C_3 R_1}$$

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

In this way, we can measure the value of unknown capacitance with the help of standard capacitance.



$$\text{power factor (p.f.)} = \cos\theta = \frac{R_x}{Z_x}$$

For phase angle very close to 90°

i.e. $\theta \to 90°$

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$$P.F. = \frac{R_x}{X_{Cx}} = \omega R_x C_x$$

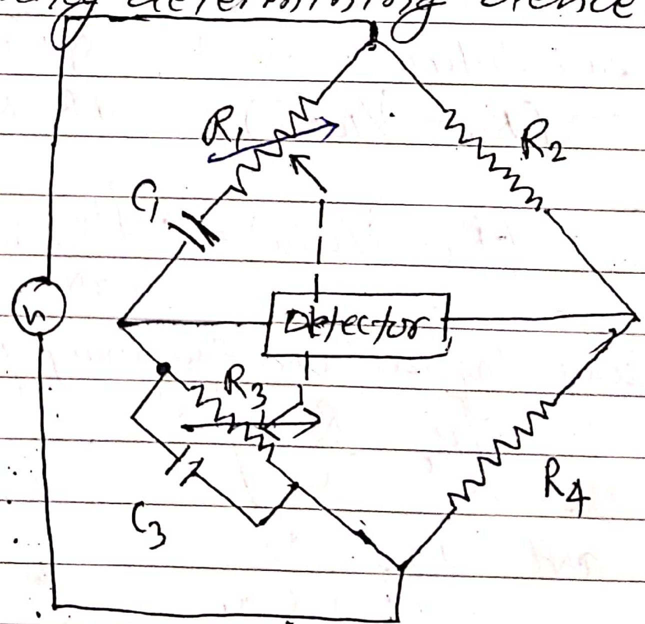
Dissipation factor (D) = $\cot\theta$

$$= \frac{R_x}{X_{Cx}} = \omega R_x C_x$$

Substituting value of R_x & C_x in D, we get;

$$D = \frac{\omega R_2 C_1}{C_3} \cdot \frac{R_1 C_3}{R_2} = \omega R_1 C_1$$

(iv) Wein Bridge :- The Wien Bridge can be used to measure frequency. This bridge also finds its application as an oscillator and notch filter in harmonic analyses. Here Wein Bridge is used as a frequency determining device.



Here;

$Z_1 = R_1 - j/\omega C_1$

$Z_2 = R_2$

$Z_3 = R_3 \parallel X_{C_3} = \frac{R_3}{1 + j\omega R_3 C_3}$

$\therefore Y_3 = 1/R_3 + j\omega C_3$

$Z_4 = R_4$.

We Know, for bridge balance condⁿ;

$Z_1 Z_4 = Z_2 Z_3$

or, $Z_2 = Z_1 Z_4 Y_3$

or, $R_2 = (R_1 - j/\omega C_1) R_4 (1/R_3 + j\omega C_3)$

or, $\frac{R_2}{R_4} = \frac{R_1}{R_3} + j\omega R_1 C_3 - j/\omega R_3 C_1 + \frac{C_3}{C_1}$

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

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Comparing imaginary and real parts,

$$\frac{R_1}{R_3} + \frac{C_3}{C_1} = \frac{R_2}{R_4} \quad \text{——— (i)}$$

and.

$$\omega R_1 C_3 - 1/\omega C_1 R_3 = 0.$$

$$\text{or, } \omega R_1 C_3 = \frac{1}{\omega C_1 R_3}$$

$$\text{or, } \omega = \frac{1}{\sqrt{R_1 R_3 C_1 C_3}}$$

$$\text{or, } f = \frac{1}{2\pi\sqrt{R_1 R_3 C_1 C_3}} \quad \text{——— (ii)}$$

In most wein Bridge, the components are choosen so that

$R_1 = R_3 = R$

$\& \; C_1 = C_3 = C$

Then above eq^{ns} implies,

$R_2/R_4 = 2$

and $f = \frac{1}{2\pi RC}$

Switches for R_1 and R_3 are mechanically linked so as to fulfil the cond^n $R_1 = R_3$. As long as C_1 and C_3 are fixed capacitors equal in value & $R_2 = 2R_4$, the wein Bridge may be used as a frequency determining device, balanced by a single control. This control may be directly calibrated in terms of frequency. This bridge is suitable for the measurement of frequency for 100 Hz to 100 kHz. It is possible to obtain an accuracy of 0.1 to 0.5%. A wein bridge may also be used for measuring the capacitance also.

It is difficult to balance this bridge (because of its frequency sensitivity). The bridge is not balanced for any harmonics

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present in the applied voltage, so that these harmonics will ~~determines~~ sometimes produce o/p voltage masking the true balance point. This difficulty can be overcome by connecting a filter in series with the Null detector.

PLAN : Kelvin Bridge DATE :

NO : [Measurement of Low Resistance]

→ Modification of Wheatstone bridge.

→ An understanding of the kelvin bridge arrangement may be obtained by a study of the difficulties that arise in a wheatstone bridge on account of the resistance of the leads and the contact resistances while measuring low valued resistances.

Consider the bridge ckt shown alongside where, 'r' represents the resistance of the lead that connects the unknown resistance 'R' to the standard resistance 'S'. The connection of galvanometer may be either to point 'm' or 'n'. When galvanometer is connected to 'm', the resistance of the lead 'r' is added to the standard resistance 'S'. When connection is made to point 'n', the resistance 'r' is added to the unknown resistance 'R'.

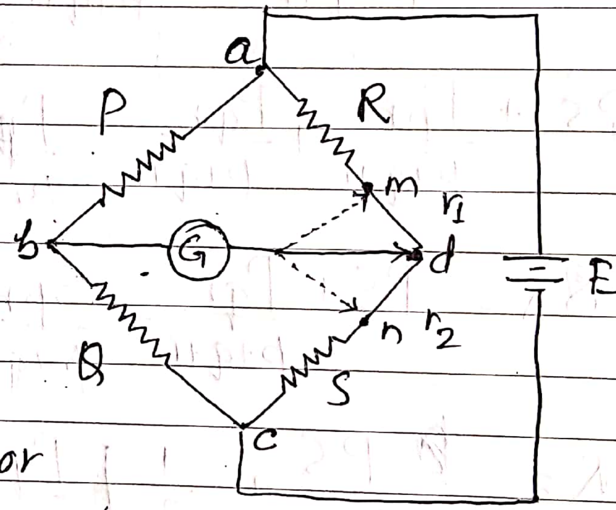

Fig: Kelvin's Bridge

Let galvanometer is connected to the intermediate point 'd' as shown (in fig) by full line. If at the point 'd', the resistance 'r' is divided into two points r_1 and r_2 such that

$$\frac{r_1}{r_2} = \frac{P}{Q} \quad \text{—— (1)}$$

Then the presence of 'r', the resistance of connecting leads, causes no error in the result.

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Here, we have, $(R+r_1) = \frac{P}{Q}(S+r_2)$ —— (11)

But, $\frac{r_1}{r_2} = \frac{P}{Q}$ and $\frac{r_2}{r_1} = \frac{Q}{P}$

or, $\frac{r_1}{r_2} + 1 = P/Q + 1$ or, $\frac{r_2+r_1}{r_1} = \frac{Q+P}{P}$

or, $\frac{r_1+r_2}{r_2} = \frac{P+Q}{Q}$ $\therefore r_1 = \left(\frac{P}{P+Q}\right) r$

$\therefore r_2 = \left(\frac{Q}{P+Q}\right) r$

From eqⁿ (2), we get;

$$R + \left(\frac{P}{P+Q}\right) r = \frac{P}{Q}\left(S + \frac{Q}{P+Q} \cdot r\right)$$

or, $RQ + \frac{PQr}{P+Q} = PS + \frac{PQr}{P+Q}$

or, $\boxed{R = \frac{P}{Q} \times S}$

Therefore, we conclude that making the galvanometer connection at 'd', the resistance of lead doesnot effect the result.

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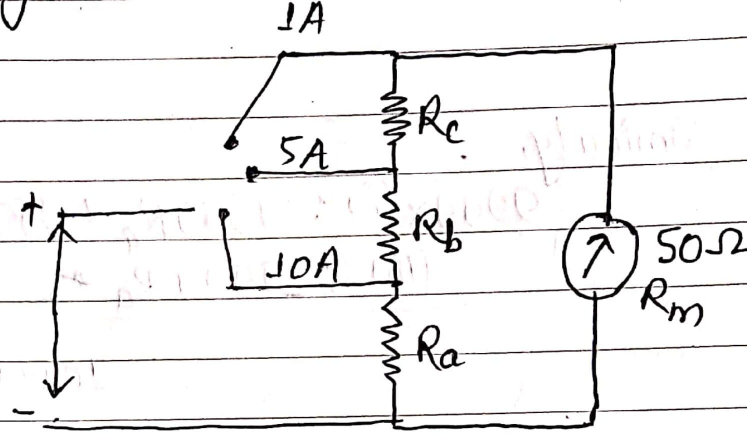
(4) Design an Ayrton shunt to provide an ammeter with current ranges of 1A, 5A and 10A. A D'Arsonval movement with an internal resistance $R_m = 50\Omega$ and full scale deflection current of 1mA is used in the configuration.



⇒ On the 1A range:

$R_a + R_b + R_c$ are in parallel with 50Ω movement. Since the coil requires 1mA for full scale deflection, the shunt will be required to pass a current of 1A − 1mA = 999mA.

So,
$$(R_a + R_b + R_c) \times 999 = 50 \times 1$$

$$\therefore R_a + R_b + R_c = \frac{50}{999} = 0.05005\,\Omega \quad \text{—— (I)}$$

On the 5A range:

$R_a + R_b$ are in parallel with $R_c + 50\Omega$. In this case 1mA current flows thru $(R_c + R_m)$ and 4999mA flows thru $R_a + R_b$. So,

$$(R_a + R_b)\,4999 = (R_c + 50)\,1$$

$$\therefore R_a + R_b = \frac{R_c + 50}{4999} \quad \text{—— (II)}$$

On the 10A range,

R_a is in parallel with $R_b + R_c + R_m$. In this case 1mA flows thru $(R_b + R_c + R_m)$ & 9999mA flows thru R_a. So

$$R_a \times 9999 = (R_b + R_c + R_m) \times 1$$

$$\therefore R_a = \frac{R_b + R_c + R_m}{9999} \quad \text{—— (III)}$$

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Solving these three simultaneous eqs (i), (ii) & (iii), we get,

$$4999 \times (i) : 4999R_a + 4999R_b + 4999R_c = 250.2$$
$$(ii) : 4999R_a + 4999R_b - R_c = 50$$

$$5000 R_c = 200$$

$$\therefore R_c = 0.04004 \Omega$$

Similarly,

$$9999 \times (i) : 9999R_a + 9999R_b + 9999R_c = 500.45$$
$$(iii) : 9999R_a - R_b - R_c = 50$$

$$10,000 R_b + 10,000 R_c = 450.45$$

$$\text{or, } 10,000 R_b + 10,000 \times 0.04004 = 450.45$$

$$\therefore R_b = 0.005005 \Omega$$

$$\& \ R_a = 0.005005$$

The calculation indecates that for larger currents, the value of shunt resistors become very small.