Electrical and Electronic Measurements:

Resistance Measurement

1

PART I

Resistance Measurement in VOM

2

Resistance and Conductance

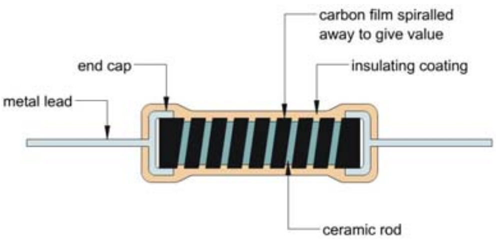
- Resistance, R (Ohm – Ω), is the tendency of a material to impede the flow of electric charges through it.
- The instantaneous voltage across a resistor is directly proportional to the current flowing through it. The relation was discovered by George Simon Ohm in 1836, $V = IR$ or $I = GV$ where $G = 1/R$ is conductance (Siemens – S).

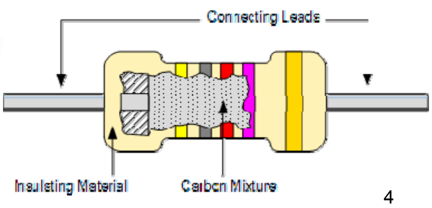
resistor, rheostat (variable resistor), and potentiometer

3

Resistor

- Resistors are made of materials that conduct electricity but posses a large resistance compared to the resistance of the wires and the contacts, e.g. carbon film, carbon composition, wirewound, metal film, liquid (H_2O+$CaCO_3$).

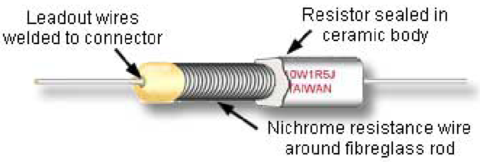


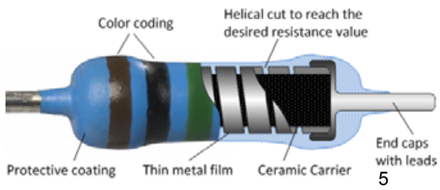


4

Resistor (Cont'd)

- They are used for many purposes, e.g. electric heater, voltage dividing elements, current-limiting devices.
- Resistors of 50μΩ-1000 MΩ are manufactured.
- Acceptable tolerances range from ±20% (serving as heating element) to ±0.001% (more precious for sensitive measuring instruments)





5

Preferred Resistor Values

- The letter and digit code for resistance and capacitance values and tolerances, known as RKM code or "R notation", is a notation to specify the values defined by the International Electrotechnical Commission, e.g. the international standard IEC 60062 since 1952.
- The values of resistors are of course quoted in Ohms (Ω), though with high values, Kilohms (KΩ) or Megohms (MΩ) are common units.
- With low values a circuit diagram may state a resistance value as for example 15R instead of 15Ω.

6

Preferred Resistor Values (Cont'd)

- When a value contains some fraction of a Kilohm or Megohm, e.g. 4.7KΩ or 5.6MΩ it will often be written 4K7 or 5M6 respectively. This is done for clarity. It avoids using the point (.) or the Omega (Ω) symbol, both of which may be misread when the printing is very small either on printed diagrams, or on actual components.
- To manufacture resistors of every possible value would be impractical. Instead Resistors are made in a restricted range of values and each value is quoted as a specific number of ohms plus or minus a percentage of the quoted value, this range of possible values is called the tolerance of the resistor.

7

Preferred Resistor Values (Cont'd)

- A 100KΩ resistor having a +/-10% tolerance might be any value between 90KΩ and 110KΩ. Therefore there is no need to manufacture resistors with values between these upper and lower limits.
- If a resistor of exactly 100KΩ is needed (an unusual situation) a resistor with the exact value can be selected from within this range or (more likely) a resistor with a closer tolerance can be used.

8

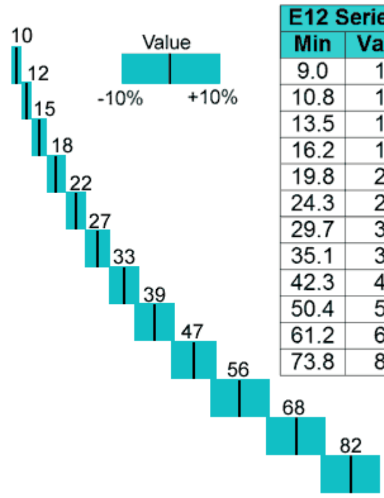
Preferred Resistor Values (Cont'd)

- For example, the E12 series of resistors to cover (almost) all possible values of resistance between 10Ω and 100Ω.
- The E12 series is so called because 12 'Preferred Values' of resistor, each having a tolerance range of ±10% covers all values from 10Ω to 100Ω.
- This range of values is called a decade, and the next higher range (decade) in the E12 series covers values between 90Ω (100Ω -10%) and 902Ω (820Ω +10%) and so on.
- The E12 range with its 10% tolerance therefore has 12 values per decade.

9

Preferred Resistor Values (Cont'd)

- E12 Series of Overlapping Tolerances

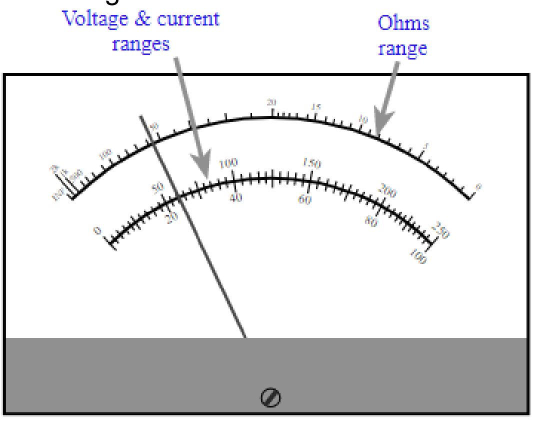


E12 Series +/- 10%		
Min	**Value**	**Max**
9.0	10	11.0
10.8	12	13.2
13.5	15	16.5
16.2	18	19.8
19.8	22	24.2
24.3	27	29.7
29.7	33	36.3
35.1	39	42.9
42.3	47	51.7
50.4	56	61.6
61.2	68	74.8
73.8	82	90.2

10

Analogue Ohmmeter (in VOM)

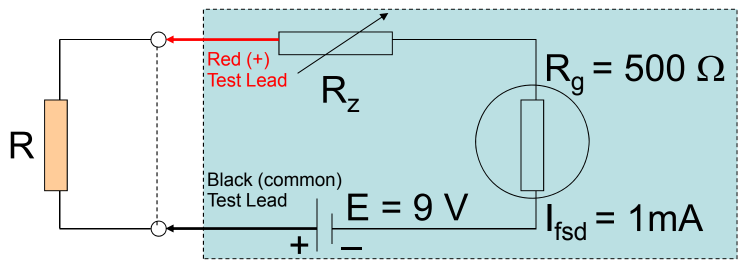
- Using permanent-magnet moving-coil (galvanometer, $\theta \propto I$) with a total internal resistance R_g



11

Analogue Ohmmeter (Cont'd)

- Series type ohmmeter with battery E
- Resistance R to be measured
- Resistance R_z to be zero-ohm-adjusted

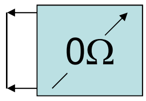


12

Zero-Ohm Adjustment - First!

- Short circuit at the terminals
- Resistance reading should be zero, R = 0 Ω
- Adjust R_z until reach a full-scale current reading (0 Ω at I_{fsd})

$$E = I\,(R_z + R_g)$$
$$I_{fsd} = E / (R_z + R_g)$$



- I_{fsd}, E and R_g are constant.
- R_z has to be adjusted every time the range is changed (current changed by any other additional resistors)

13

Zero-Ohm Adjustment (Cont'd)

- for the measurement of series type ohmmeter

$$E = I\,(R + R_z + R_g)$$
$$I = E / (R + R_z + R_g)$$

- R increased, I decreased, θ decreased (scale ∞ ↔ 0)
- Relationship between I and R is non-linear, it means a non-linear resistance scale.
- R_z and R_g are small, therefore for high resistances, the scale points are very close together!

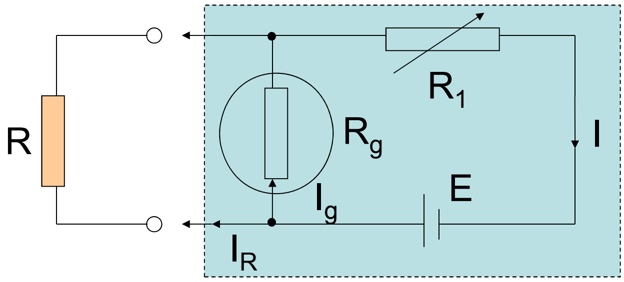
14

Shunt Type Ohmmeter

- When $R \rightarrow \infty$ (open circuit), R_1 is adjusted for a full-scale reading.

$$E = I\,(R_1 + R_g)$$

$$I_{fsd} = E / (R_1 + R_g)$$



15

Shunt Type Ohmmeter (Cont'd)

- When R is connected, the current passing through the meter is reduced by shunt resistor,

$$1/R_{parallel} = 1/R + 1/R_g$$

$$R_{parallel} = RR_g / (R + R_g)$$

and

$$\begin{aligned} E &= I\,(R_1 + R_{parallel}) \\ &= I\,(R_1 + RR_g/(R + R_g)) \\ &= I\,(R_1R + R_1R_g + RR_g) / (R + R_g) \\ &= I\,(R_1R_g + R(R_1 + R_g)) / (R + R_g) \end{aligned}$$

$$I = E\,(R + R_g) / (R_1R_g + R(R_1 + R_g))$$

16

Shunt Type Ohmmeter (Cont'd)

- The current I is divided into two parts,

$$I_g = I - I_R = I - I_gR_g/R \qquad , I_gR_g = I_RR$$

therefore

$$I_g = E(R + R_g)/(R_1R_g + R(R_1 + R_g)) - I_gR_g/R$$

$$I_g(1+R_g/R) = E(R + R_g)/(R_1R_g + R(R_1 + R_g))$$

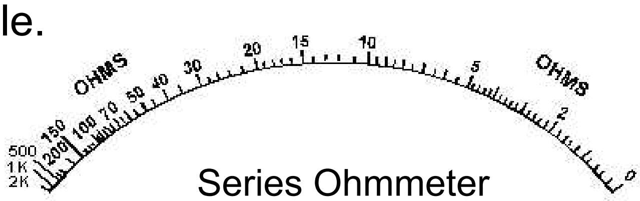
$$I_g(R+R_g)/R = E(R + R_g)/(R_1R_g + R(R_1 + R_g))$$

$$\mathbf{I_g} = E\mathbf{R} / (R_1R_g + \mathbf{R}(R_1 + R_g)) \rightarrow \text{nonlinear}$$

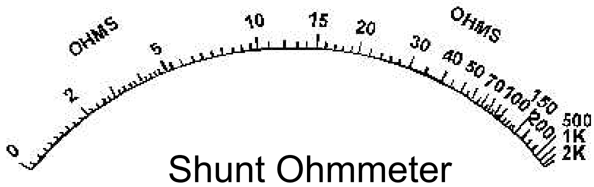
- Meter reading depends on the value of R, then it is useful when R is a low resistance.
- R increased, I_g increased, θ increased $(0 \leftrightarrow \infty)$

Resistance Logarithmic Scales

The most accurate resistance measurement made by an ohmmeter is made when the needle is positioned at the center of the scale.



Series Ohmmeter



Shunt Ohmmeter

Ex-1 A series type ohmmeter uses a moving coil meter with a resistance of 50Ω and a full-scale deflection of 1mA. If the battery has an e.m.f. of 2V, what should be the value of the resistor for the zero adjustment?

Short circuit at the terminals,

$$E = I_{fsd} (R_z + R_g)$$

$$R_z = E/I_{fsd} - R_g$$

$$= (2V)/(1mA) - 50\Omega$$

$$= 1950\ \Omega$$

19

Mid-Scale Reading

For series type,

at 0-Ω, $I_{fsd} = E / (R_z + R_g)$

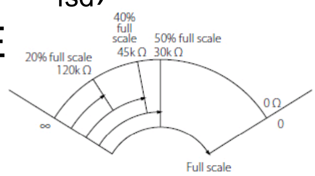
Measure, $I = E / (R + R_z + R_g) = E / (R + E/I_{fsd})$

$$I_{mid} = I_{fsd}/2 = E / (R_{mid} + E/I_{fsd})$$

$$2E = I_{fsd}R_{mid} + E$$

$$R_{mid} = E/I_{fsd}$$

$$\text{or} \quad R_{mid} = R_z + R_g$$

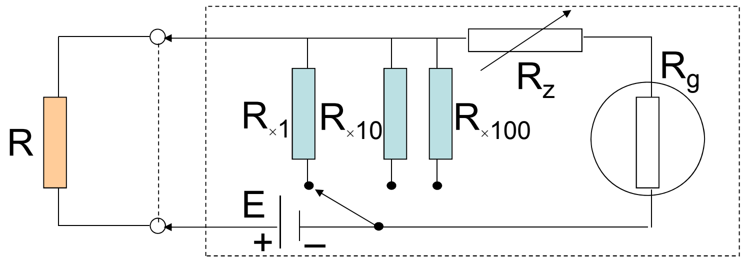


It means that a resistance to be measured should be equal to an internal resistance of the meter (to make middle scale reading).

20

Ranges of Ohmmeter

Ohmmeter usually has several operational ranges indicated by R×1, R×10, R×100, R×1k, R×100k and R×1M.



- For the mid-scale (series type),

$$R = R_{mid} = R_{\times 1} \mathbin{//} (R_z+R_g)$$
$$= R_{\times 1}(R_z+R_g) / (R_{\times 1}+R_z+R_g)$$

21

Ranges of Ohmmeter (Cont'd)

$$R_{mid} = R_{\times 1}(R_z+R_g) / (R_{\times 1}+R_z+R_g)$$
$$R_{mid} (R_{\times 1}+R_z+R_g) = R_{\times 1}(R_z+R_g)$$
$$R_{mid} (R_z+R_g) = R_{\times 1}(R_z+R_g-R_{mid})$$
$$\mathbf{R_{\times 1}} = \mathbf{R_{mid}} (R_z+R_g) / (R_z+R_g-\mathbf{R_{mid}})$$

The shunt resistance increases for higher ohm ranges and is always equal to the center scale reading on the range and $R_z+R_g > R_{mid}$.

For higher range, higher EMF or more series resistor are needed.

22

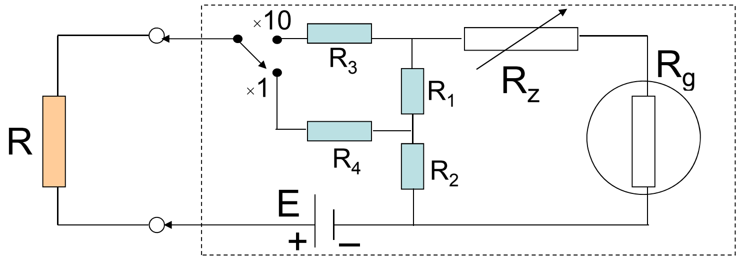
Ex-2 From the series type ohmmeter in Ex-1, what should be the value of the shunt required for the meter if the mid-scale reading of the ohmmeter is to be 1000Ω and 1500Ω?

$$R_{\text{shunt for }1k\Omega} = R_{mid}(R_z+R_g)/(R_z+R_g-R_{mid})$$
$$= \frac{(1000\Omega)(1950\Omega+50\Omega)}{(1950\Omega+50\Omega-1000\Omega)}$$
$$= 2000\ \Omega$$
$$R_{\text{shunt for }1.5k\Omega} = \frac{(1500\Omega)(1950\Omega+50\Omega)}{(1950\Omega+50\Omega-1500\Omega)}$$
$$= 6000\ \Omega$$

23

Range of Ohmmeter (Cont'd)

- Another arrangement,



×10, $I = E / [\ (R_z+R_g)//(R_1+R_2) + R_3 + R\ ]$

$= E / [\ (R_z+R_g)(R_1+R_2)/(R_1+R_2+R_z+R_g) + R_3 + R\ ]$

×1, $I = E / [\ (R_1+R_z+R_g)//R_2 + R_4 + R\ ]$

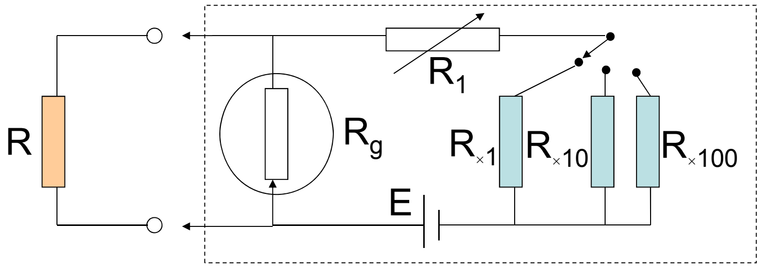
$= E / [\ R_2(R_1+R_z+R_g)/(R_1+R_2+R_z+R_g) + R_4 + R\ ]$

More R paralleled, less total R, higher I

24

Ranges of Ohmmeter (Cont'd)

- For shunt type,



Without $R_\times$, $I_g = ER / (R_g R_1 + R(R_1 + R_g))$

With $R_\times$, $I_g = ER / (R_g(R_1+R_{\times 1}) + R(R_1+R_{\times 1}+R_g))$

$R_\times$ increased, I_g decreased

25

Ranges of Ohmmeter (Cont'd)

- One major problem with this ohmmeter's design is its reliance upon a stable battery voltage. If the battery voltage decreases, as all chemical batteries do with age and use, the scale will lose accuracy.
- From this fact of the logarithmic scale, this type of ohmmeter is never considered to be a precision instrument.
- One final caveat needs to be mentioned is that they only function correctly when measuring resistance that is not being powered by a voltage or current source, not for on a live circuit!

26

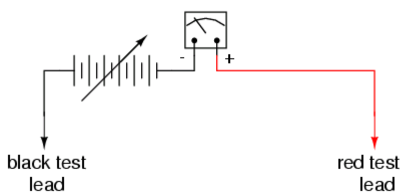
High-Voltage Ohmmeter

- Most ohmmeters of the previous design utilize a battery of low voltage. This is adequate for measuring resistances under several mega-ohms (MΩ), but for extremely high resistances, a 9-V battery is insufficient for generating enough current to actuate the movement.
- Moreover, resistance is not always a stable or linear quantity, especially true of non-metals.

27

High-Voltage Ohmmeter (Cont'd)

- The most direct method of high-voltage resistance measurement involves simply substituting a higher voltage battery in the same basic design of ohmmeter investigated earlier.
- Unfortunately, this would create a calibration problem for the meter.

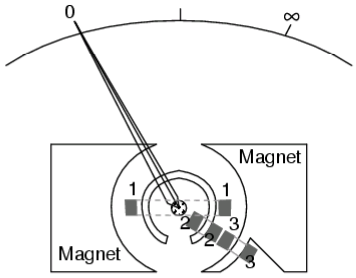


28

Megger Movement

Megohmmeters

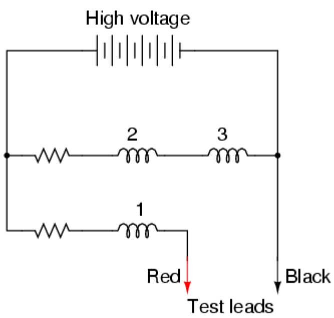
- Needle mechanism moves 3 wire coils without spring to return the needle to a set position.
- When the movement is unpowered, the needle will randomly float.

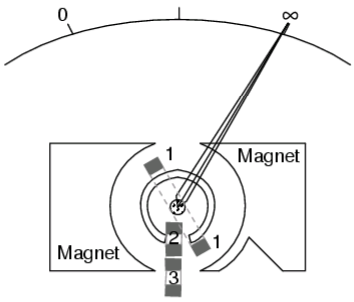


29

Megger Movement (Cont'd)

- When open circuit, there will be no current through coil 1, only through coils 2 and 3.
- These two coils try to center themselves in the gap between the two magnet poles, driving the needle fully to the right of the scale where it points to infinity.





30

Megger Movement (Cont'd)

- Any current through coil 1, and measured resistance between the leads, tends to drive the needle to the left of scale or zero.
- The internal resistance of the meter are calibrated so that when the leads are shorted together, the needle deflects exactly to the 0 Ω position.

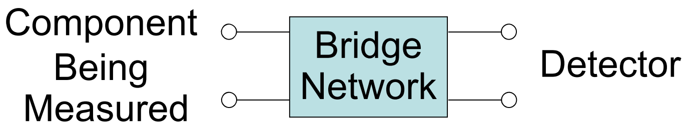
- For maximum safety, most meggers are equipped with hand-crank generators for producing the high DC voltage (≥ 1 kV). If the operator receives a shock from the high voltage, he will naturally stop cranking!

PART II

DC Bridge Method

Bridge Method

- Diode bridge is an arrangement of four or more diodes for AC/DC full-wave rectifier.
- Component bridge methods are used for measurement of resistance, capacitance, inductance, etc.
- The network will be balanced when the detector reading becomes zero.

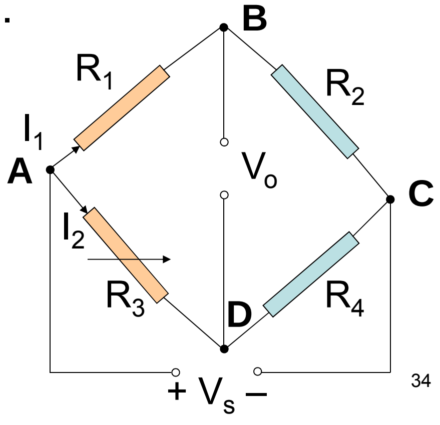


33

Wheatstone Bridge

- Wheatstone bridge was invented by Samuel Hunter Christie in 1833 and improved and popularized by Sir Charles Wheatstone in 1843.
- DC supply, V_s
- Output voltage, V_o

Samuel Hunter Christie (22 March 1784 – 24 January 1865), a British scientist, physicist and mathematician.



34

Wheatstone Bridge (Cont'd)

- When V_o = 0 V, the potential at B must equal to the potential at D

Sir Charles Wheatstone
(6 February 1802 –
19 October 1875),
an English scientist.

$$I_1R_1 = I_2R_3$$
$$I_1R_2 = I_2R_4$$

Hence $I_1R_1 = I_2R_3 = (I_1R_2/R_4)\, R_3$

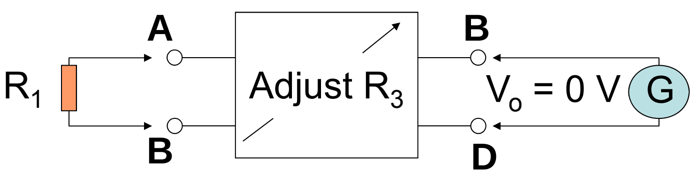
$$R_1/R_2 = R_3/R_4$$

- The balance condition is independent of V_s

35

Wheatstone Bridge (Cont'd)

- R_1 is the input resistance to be measured by comparing to accurately known resistors (standard).
- R_2 and R_4 are known-fixed resistances.
- R_3 can be adjusted to give the zero potential difference condition.



Wheatstone Bridge

36

Wheatstone Bridge (Cont'd)

- Change in R_1, change R_3
- The precision is about 1 Ω to 1 $M\Omega$.
- The accuracy is mainly up to the known resistors and the sensitivity of the null detector ($\pm$ 0.1 to 0.2%).
- Error comes from changes in resistances of the bridge arms by changes in temperatures or thermoelectric EMF in contacts.

37

Sensitivity of the Bridge

- If no galvanometer at the output,

$$V_{AB} = V_s \, R_1/(R_1+R_2)$$
$$V_{AD} = V_s \, R_3/(R_3+R_4)$$

Thus, $V_o = V_{AB} - V_{AD}$

$$\mathbf{V_o} = V_s \, (\mathbf{R_1}/(\mathbf{R_1}+R_2) - R_3/(R_3+R_4))$$

- The relationship between V_o and R_1 is non-linear
- V_o = 0 V when $R_1/R_2 = R_3/R_4$

38

Sensitivity of the Bridge (Cont'd)

- Changing R_1 to $R_1+\Delta R_1$ gives a change of V_o to $V_o+\Delta V_o$

$V_o+\Delta V_o=V_s((R_1+\Delta R_1)/((R_1+\Delta R_1)+R_2) – R_3/(R_3+R_4))$

$$\text{Then } (V_o+\Delta V_o)-V_o = V_s\left(\frac{R_1+\Delta R_1}{R_1+\Delta R_1+R_2} - \frac{R_3}{R_3+R_4}\right) - V_s\left(\frac{R_1}{R_1+R_2} - \frac{R_3}{R_3+R_4}\right)$$

$$\Delta V_o = V_s\left(\frac{R_1+\Delta R_1}{R_1+\Delta R_1+R_2} - \frac{R_1}{R_1+R_2}\right)$$

39

Sensitivity of the Bridge (Cont'd)

- If small changes $\Delta R_1 << R_1$ then the sensitivity of Wheatstone bridge can be computed from,

$$\Delta V_o \approx \Delta R_1 V_s/(R_1+R_2)$$

$$\Delta V_o/\Delta R_1 \approx V_s/(R_1+R_2)$$

- Higher R_1 to be measured, lower sensitivity
- Amplifier can be used to amplify V_o

40

Unbalanced Bridge

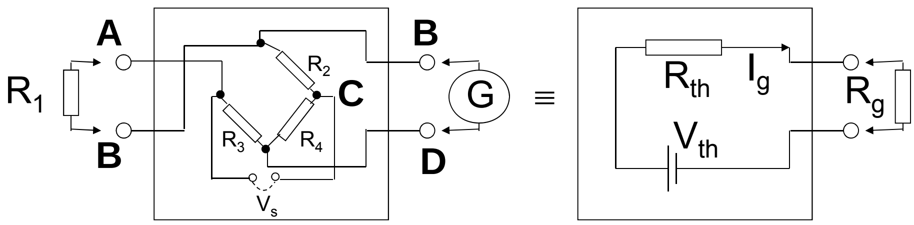
- If there is a galvanometer, R_g, between the two output terminals, the current I_g can be determined by Thévenin equivalent circuit.

$$V_{th} = V_o = V_s \left(R_1/(R_1+R_2) - R_3/(R_3+R_4) \right)$$

- Short voltage source, then Thévenin resistance is $R_1//R_2 + R_3//R_4$

$$R_{th} = R_1R_2/(R_1+R_2) + R_3R_4/(R_3+R_4)$$

Unbalanced Bridge (Cont'd)



For unbalanced bridge,

$$I_g = V_{th} / (R_{th} + R_g)$$

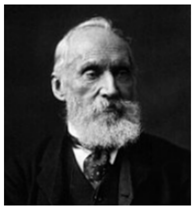
and

$$V_g = I_gR_g = V_{th}R_g/(R_{th}+R_g)$$

If balanced or V_g = 0 V ⇨ like no movement

Kelvin Double Bridge

- Let us categorize the electrical resistances on the basis of view point of measurement. Electrical resistances are classified as follows:
- High Resistance: greater than 0.1 MΩ.
- Medium Resistance: ranging from 1 Ω to 0.1 M Ω.
- Low Resistance: lower than 1 Ω.

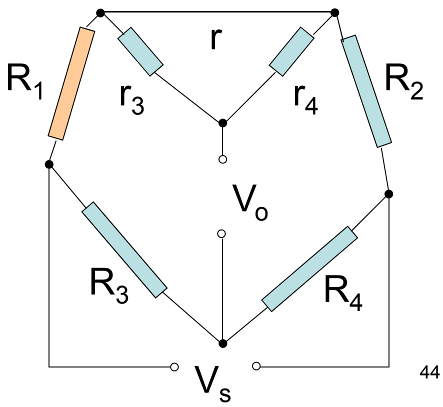


William Thomson (1824-1907),
later Lord Kelvin of Largs,
a Scots-Irish mathematical physicist and engineer.

43

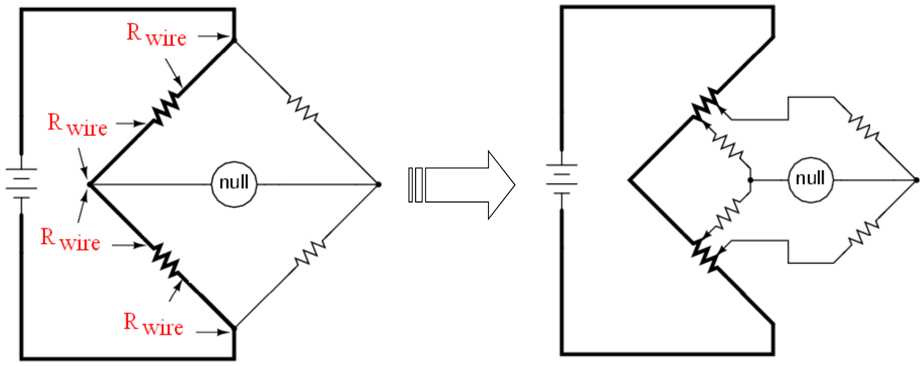
Kelvin Double Bridge (Cont'd)

- A modification of Wheatstone bridge for low resistance measurement ($R_1 < 1\Omega$)
- To overcome the problems of undesirable parasitic resistances caused by non-perfect wire resistances.



44

- Using four-terminal resistors (two for voltage supply and 2 for current supply)

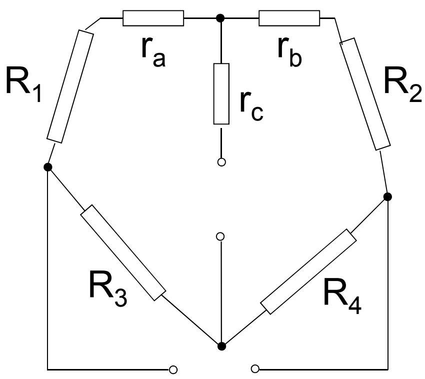


45

- The yoke r is connected to R_1 and R_2
- The relationship between r_3, r_4, R_3 and R_4

$$\mathbf{R_3/R_4 = r_3/r_4}$$

- Using the delta-star transformation, the equivalent circuit



$r_a = r_3 r / (r_3+r_4+r)$
$r_b = r_4 r / (r_3+r_4+r)$

46

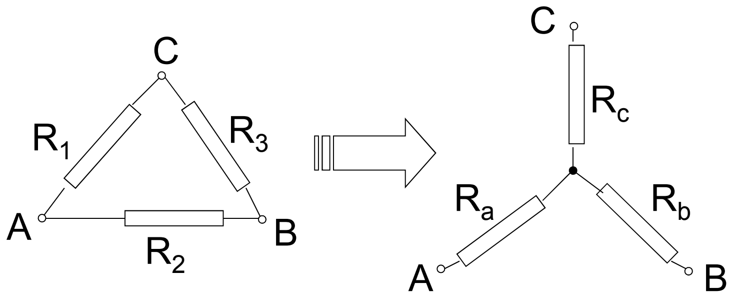
Note

- Δ-Y Transformation

  $R_a = R_1R_2 / (R_1+R_2+R_3)$

  $R_b = R_2R_3 / (R_1+R_2+R_3)$

  $R_c = R_1R_3 / (R_1+R_2+R_3)$



47

- The balance condition is the same as Wheatstone bridge (Null V_o = 0 V)

$(R_1+r_a) / (R_2+r_b) = R_3 / R_4$

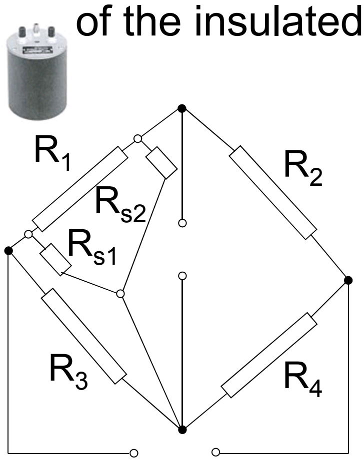
$$R_1 = R_3(R_2+r_b)/R_4 - r_a$$
$$= R_3R_2/R_4 + R_3r_b/R_4 - r_a$$
$$= R_3R_2/R_4 + R_3r_4r/(r_3+r_4+r)R_4 - r_3r/(r_3+r_4+r)$$
$$= R_3R_2/R_4 + r_4r(R_3/R_4 - r_3/r_4) / (r_3+r_4+r)$$
$$R_1 = R_3R_2/R_4$$

Therefore $R_1/R_2 = R_3/R_4 = r_3/r_4$

48

High Resistance Bridge

- For very high resistance, e.g. 1,000 MΩ, there is leakage currents over the surface of the insulated post.



- Using three-terminal resistors (parallel with 2 leakage resistances)
- R_{s1}>>R_3 and R_{s1}//R_3 to avoid the leakage effect
- R_{s2} may affect the detector sensitivity

49

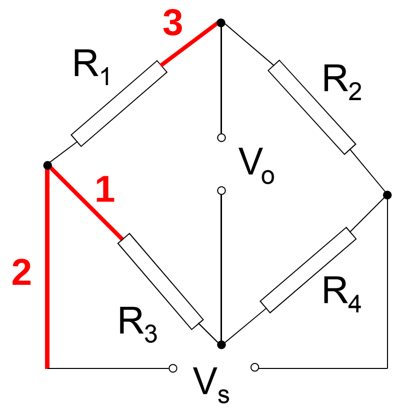
Bridge Compensation

- The resistance of long leads will be affected by changes in temperatures
- To avoid this, 3 leads are required to connect to the coils
- They are all the same length and resistance

50

Bridge Compensation (Cont'd)

- Any changes in lead resistance will affect all 3 leads equally and occur in 2 arms of bridge and will cancel out.



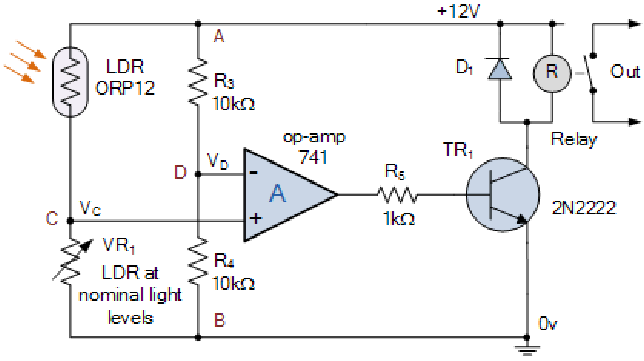
Bridge Controlled Circuits

- The bridge can be used as an error detector in a control circuit, using the potential difference at the output of the bridge that is sensitive to any physical parameters.
- Passive circuit elements such as strain gauges, temperature sensitive resistors (thermistors) or photo resistors are used as one arm of Wheatstone bridge.
- A change in the elements (pressure, heat or light) causes the bridge to be unbalanced.

e.g. Wheatstone bridge light detector

The LDR photocell is connected into the Wheatstone bridge circuit as shown to produce a light sensitive switch that activates when the light level being sensed goes above or below the pre-set value determined by VR_1.

The relay turns “ON” when the voltage at point C is less than the voltage at point D.



53

References

- http://www.faqs.org/docs/electric/DC/DC_8.html
- http://avstop.com/ac/Aviation_Maintenance_Technician_Handbook_General/10-74.html
- http://www.wisc-online.com/Objects/ViewObject.aspx?ID=DCE7104
- Hotek Technologies, Inc webpage : http://www.hotektech.com/
- Yokogawa webpage: http://tmi.yokogawa.com/us/
- MAGNET LAB – Wheatstone Bridge webpage: http://www.magnet.fsu.edu/education/tutorials/java/wheatstonebridge/index.html
- Electronics Demonstrations webpage: http://www.falstad.com/circuit/e-index.html
- http://www.learnabout-electronics.org/Resistors/resistors_05.php
- https://www.electronics-tutorials.ws/blog/wheatstone-bridge.html

54