Electrical and Electronic Measurements:

Electrical Indicating Instruments

1

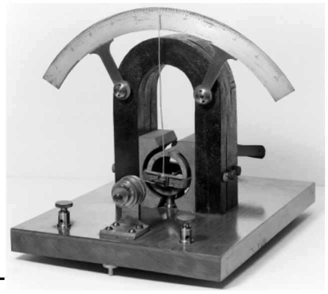
Analog Multimeter

- A multimeter or a multitester, a.k.a.VOM (volt-ohm-milliammeter), is an electronic measuring instrument that combines several measurement functions in one unit.
- A typical multimeter can measure voltage (V), current (I), and resistance (R).
- Analog multimeters use a micro-ammeter with a moving pointer to display readings.
- Digital multimeters (DMM), having a numeric display, are now far more common due to their cost and precision, but analog multimeters are still preferable in some cases, for example when monitoring a rapidly varying value.
- A multimeter can be a hand-held device useful for basic fault finding and field service work, or used for troubleshoot electrical problems in a wide array of industrial and household devices.

2

History

- The first moving-pointer current-detecting device was the galvanometer in 1820.
- These were used to measure resistance and voltage by using a Wheatstone bridge, and comparing the unknown quantity to a reference voltage or resistance.
- While useful in the lab, the devices were very slow and impractical in the field.
- These galvanometers were bulky and delicate.
- The term "galvanometer", in common use by 1836, was derived from the surname of Italian electricity researcher Luigi Galvani, who in 1791 discovered that electric current would make a dead frog's leg jerk.



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History (Cont'd)

- Multimeters were invented in 1923 as radio receivers and other vacuum tube electronic devices became more common.
- The invention of the first multimeter is attributed to British Post Office engineer, Donald Macadie, who became dissatisfied with the need to carry many separate instruments required for maintenance of telecommunications circuits.
- Macadie invented an instrument which could measure amperes, volts and ohms, so the multifunctional meter was then named "AVOmeter".

4

History (Cont'd)

- The Automatic Coil Winder and Electrical Equipment Company (ACWEECO), founded in 1923, was set up to manufacture the Avometer and a coil winding machine also designed and patented by MacAdie.
- Although a shareholder of ACWEECO, Macadie continued to work for the Post Office until his retirement in 1933.
- His son, Hugh S. Macadie, joined ACWEECO in 1927 and became Technical Director.
- The first AVO was put on sale in 1923, and many of its features remained almost unaltered through to the last Model 8 Mark VII.

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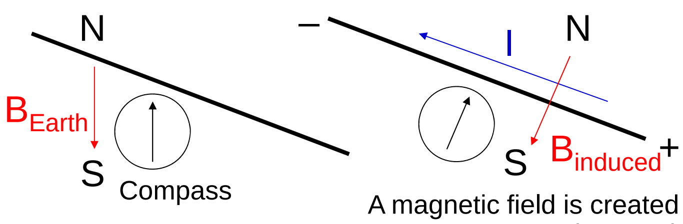
Analogue Meter's Concept

- Hans Ørsted, a Danish physicist and chemist, noted his finding about a relationship of electricity and magnetism without any explanation in 1820.

  https://youtu.be/RwilgsQ9xaM



A magnetic field is created around a current carrying conductor.

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Analogue Meter’s Concept (Cont’d)

- Magnetic Field for line of current by Biot Savart's Law

Electric current (A) — Line segment vector (m)

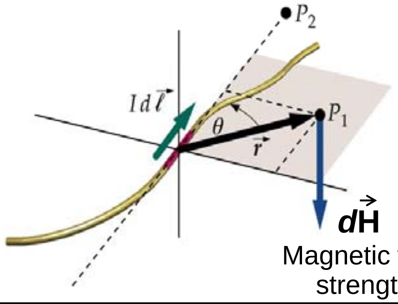
Magnetic field or Magnetic flux density (T or Wb/m^2)

$$\vec{B} = \mu_0 \int \frac{I d\vec{l} \times \vec{r}}{4\pi r^3}$$

Distance vector of a position from a current line (m)

Magnetic constant or permeability of free space $4\pi \times 10^{-7}$ H/m $\approx$ 1.256 T·m/A

Distance of a position from a current line (m)

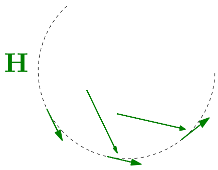


Magnetic field strength

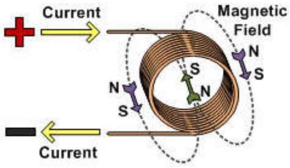
J. B. Biot (1774-1862) F. Savart (1791-1841)

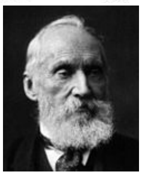
Analogue Meter’s Concept

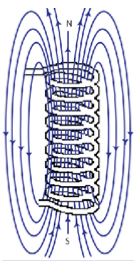
- Right-hand rule



- Lord Kelvin, Scots-Irish mathematical physicist and engineer, made more sensitivity to a current.







Solenoid

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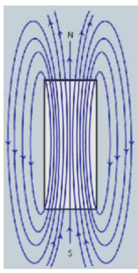

Bar magnet

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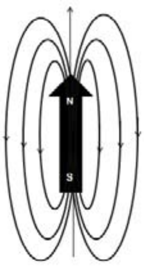
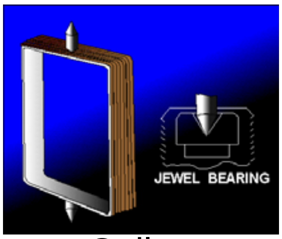
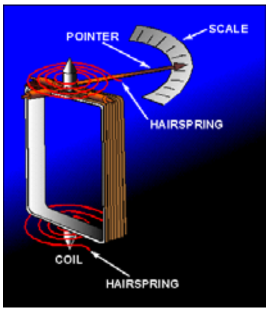


Direct Current Meters

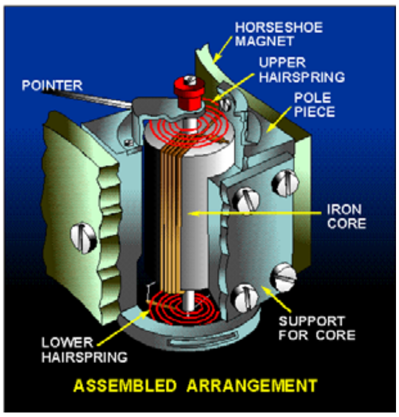
- Moving Coil Galvanometer
  http://youtu.be/_sD_5iyHl3s
- Permanent-Magnet Moving-Coil (PMMC) developed in 1881



Coil

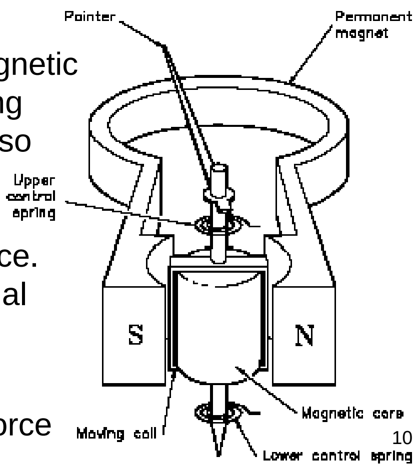


Pointer



Permanent Magnet

- A lightweight coil of copper wire is attached to a shaft that pivots on two jewel bearing.
- The coil can rotate in a space between a cylindrical soft-iron core and two permanent magnetic pole pieces.
- The rotation is opposed by two fine hairsprings.
- The spring material must be nonmagnetic to avoid any magnetic field influence on the controlling force. Since the springs are also used to make electrical connection to the coil, they must have a low resistance. Phosphor bronze is the material usually employed.



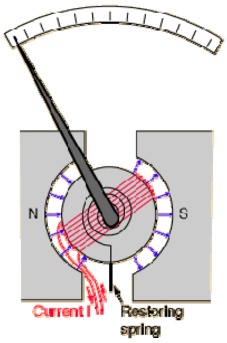
Deflecting Force = Controlling Force

- Jacques D’Arsonval’s Movement

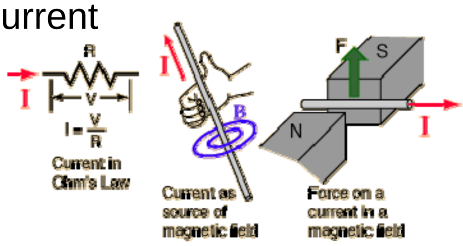
When a current is passed through the coil it rotates, the angle through which it rotates being proportional to the current (0.0000001 – 1 μA).

The magnetic field is designed (magnetic pole piece’s shape) that it is always at the right angles to the coil sides no matter what angle the coil has rotated through.

Jacques-Arsène d'Arsonval
(June 8, 1851 – December 31, 1940)
A French physician and physicist



- Electric Current



- Fleming’s Left-Hand Rule (for motor)

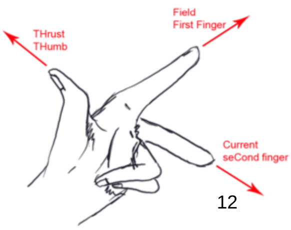
$$F = L\,I \times B$$

Force (Newton)

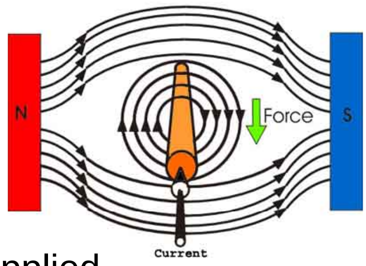
Coil Side Length (Metre)

Current (Ampere)

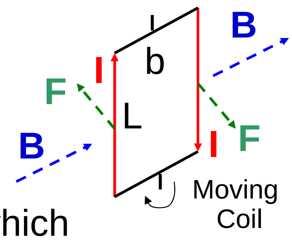
Magnetic Field (Tesla)



- For example, a horizontal magnetic field is applied externally to the conductor.



- A magnetic field around the conductor due to current through it and the externally applied field will interact with each other.
- There will be larger numbers of co-directional magnetic lines of force above the conductor than that of below the conductor.



- As a result, there will be a force which will tend to move the conductor downwards from more concentrated magnetic field to the less.

- Torque (moment) is an angular force defined by linear force multiplied by a radius.

Damping Torque in Coil = F (b/2)

$= B\ I\ L\ b\ /\ 2$

$$Torque_{total} = 2\ (B\ I\ L\ b\ /\ 2) = B\ I\ L\ b$$

$$= B\ I\ A \qquad , \text{Area } A = Lb$$

for N coils, $Torque_{total} = N\ B\ I\ A$

$$= K_{coil}\ I \qquad , K_{coil} = NBA$$

- Controlling torque in springs

$$Torque_{spring} = K_s\,\theta$$

- Critical damping or balancing forces (Newton's 3rd Law)

$$\text{Action} = \text{Reaction}$$

$$Torque_{total} = Torque_{spring}$$

$$K_{coil}\,I = K_s\,\theta$$

$$\theta = (K_{coil} / K_s)\,I$$

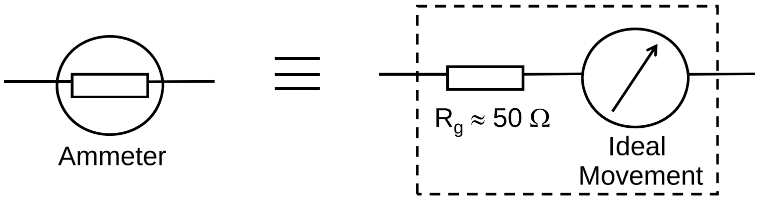
- If the magnetic field is not uniform throughout the entire region, the scales are nonlinear!

Galvanometer

- Galvanometer with a zero at the center of the scale used in DC instruments that can detect current flow in either direction
- Galvanometer with a zero at the left end of the scale indicates an upscale reading only for the proper way of connecting the meter into the circuit

Equivalent Ammeter Circuit

- The resistance of the meter coil and leads introduces a departure from the ideal ammeter behavior. The model usually used to describe an ammeter in equivalent circuit is a resistance R_g in series with an ideal ammeter (no resistance)



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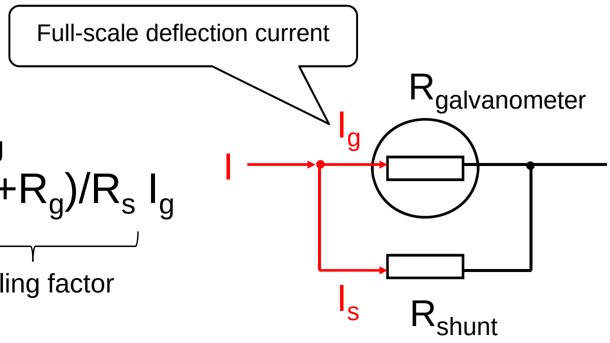
Full-Scale-Deflection Currents

- Current range is 10 μA – 20 mA
- Shunt resistor connected in parallel

$$V_s = V_g$$
$$(I - I_g)R_s = I_gR_g$$
$$I = \underbrace{(R_s+R_g)/R_s}_{\text{Scaling factor}}\ I_g$$



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Ex Calculate the value of the shunt resistance required to convert a 1mA meter movement with a 100Ω internal resistance into an ammeter having a range of 0-100 mA.

$I_s = I – I_g = 100 \text{ mA} – 1 \text{ mA} = 99 \text{ mA}$

$$R_s = V_g / I_s = I_g R_g / I_s$$
$$= (1 \text{ mA})(100\ \Omega) / (99 \text{ mA})$$
$$= 1.01\ \Omega$$

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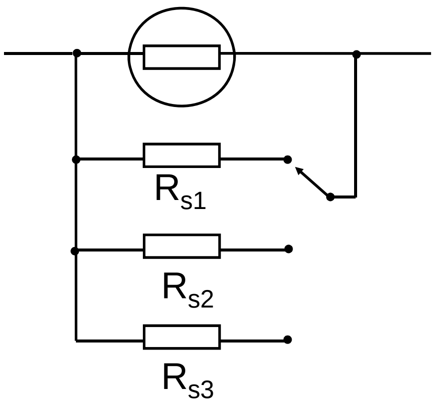
- Multi-range shunt can be made by switching into a circuit



- It is make-before-break switch and there is a possibility of having a meter without a shunt which is a serious concern!

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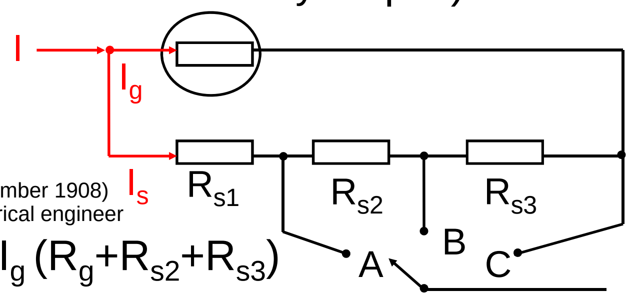
- Note:

In a switch where the contacts remain in one state unless actuated, such as a push-button switch, the contacts can either be normally open (NO) until closed by operation of the switch, or normally closed (NC) and opened by the switch action.

These may be "make-before-break" (shorting) which momentarily connects both circuits, or may be "break-before-make" (non-shorting) which interrupts one circuit before closing the other.

- Universal shunt (Ayrton shunt) without changing the damping (The voltage drop across parallel branches is always equal)

William E. Ayrton
(14 September 1847 – 8 November 1908)
An English physicist and electrical engineer



A: $(I_A - I_g)R_{s1} = I_g\,(R_g+R_{s2}+R_{s3})$

$$I_A = (R_g+R_{s1}+R_{s2}+R_{s3})/R_{s1}\; I_g$$

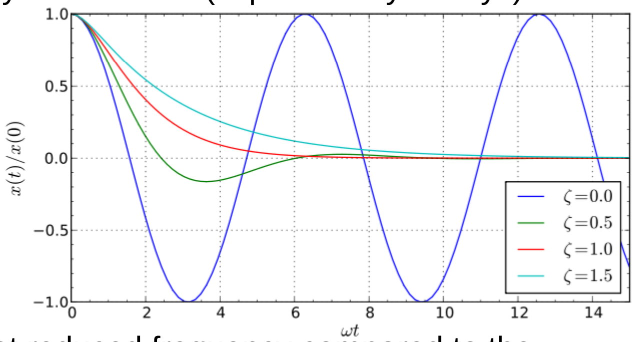
B: $(I_B - I_g)(R_{s1}+R_{s2}) = I_g\,(R_g+R_{s3})$

$$I_B = (R_g+R_{s1}+R_{s2}+R_{s3})/(R_{s1}+R_{s2})\; I_g$$

C: $I_C = (R_g+R_{s1}+R_{s2}+R_{s3})/(R_{s1}+R_{s2}+R_{s3})\; I_g$

Note: **Damping** is an influence within an oscillatory system that has the effect of reducing, restricting or preventing its oscillations.

- *Overdamped*: the system returns (exponentially decays) to equilibrium without oscillating.
- *Critically damped*: the system returns to equilibrium as quickly as possible without oscillating.
- *Underdamped*: the system oscillates (at reduced frequency compared to the undamped case) with the amplitude gradually decreasing to zero.

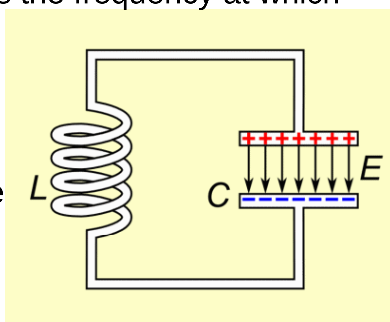


- *Undamped*: the system oscillates at its natural resonant frequency.

e.g. RLC circuit

The ideal LC circuit forms an harmonic oscillator for current by the energy stored in two different ways: in an electric field as the capacitor is charged and in a magnetic field as current flows through the inductor.

The resonance frequency is defined as the frequency at which the impedance of the circuit is at a minimum (impedance is purely real or purely resistive).

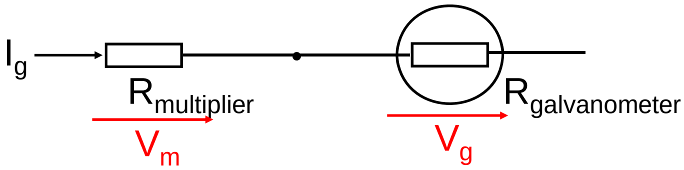


Introducing the resistor increases the decay of these oscillations with time to zero, which is also known as damping (some resistance is unavoidable in real circuits even if a resistor is not specifically included as a component).

Damping determines whether or not the circuit will resonate naturally (that is, without a driving source).

Full-Scale-Deflection Voltages

- Since V = IR, the response of a moving coil meter responding to a current is also proportional to the potential difference across the meter.
- However, because R_g and I_g are low, it can only be used for low voltages (≈ 0.05 V).
- Multiplier resistor can be connected in series



$$V = I_gR_m + I_gR_g = (R_m+R_g)\ I_g$$

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<u>Ex</u> Calculate the value of the multiplier resistance required to convert a 50μA meter movement with a 1kΩ internal resistance into a voltmeter having a range of 0-20 V.

$$V_g = I_gR_g = (50\ \mu A)(1\ k\Omega) = 50\ mV$$

$$R_m = (V - V_g) / I_g$$
$$= (20\ V - 50\ mV) / (50\ \mu A)$$
$$= 399\ k\Omega$$

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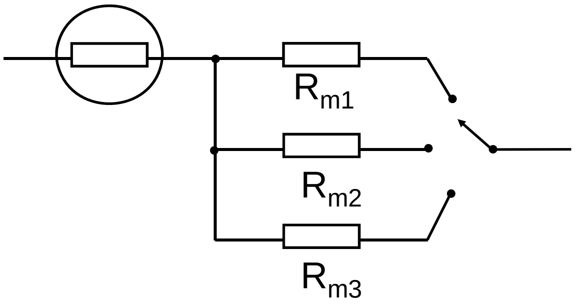
- Multi-range voltmeter



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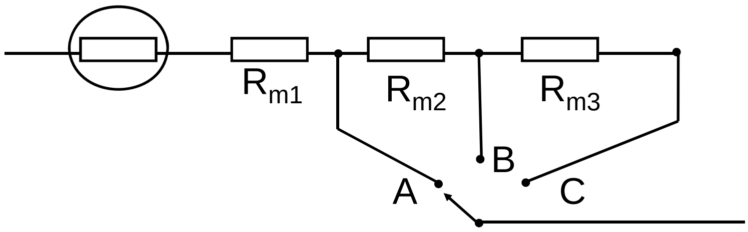
- Multi-range voltmeter with a chain arrangement



A: $V_A = I_gR_g + I_gR_{m1} = (R_{m1}+R_g)\ I_g$

B: $V_B = I_gR_g + I_gR_{m1} + I_gR_{m2} = (R_{m1}+R_{m2}+R_g)\ I_g$

C: $V_C = I_gR_g + I_gR_{m1} + I_gR_{m2} + I_gR_{m3}$

$= (R_{m1}+R_{m2}+R_{m3}+R_g)\ I_g$

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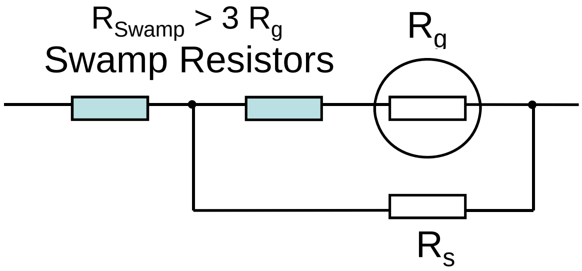
Temperature on Moving-Coil Meter

- Higher temperature of coil (tin copper wire), higher resistance, lower reading ⇒ decrease spring tension
- Measured value is decreased 0.2% for increasing of 1°C temperature.
- Swamp resistor (manganin wire), whose resistance changes slowly with temperature, connected in series
- However, the sensitivity is decreased.



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Sensitivity on Moving-Coil Meter

- Sensitivity = Pointer Change / Input Change

$$S = \theta / I$$

or

$$S = 1 / I_{fsd}$$
$$= R / V_{fsd}$$

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Ammeter & Voltmeter Loading

- Systematic loading error
  $\Rightarrow$ Calculation by using Thévenin's theorem in Lecture 2

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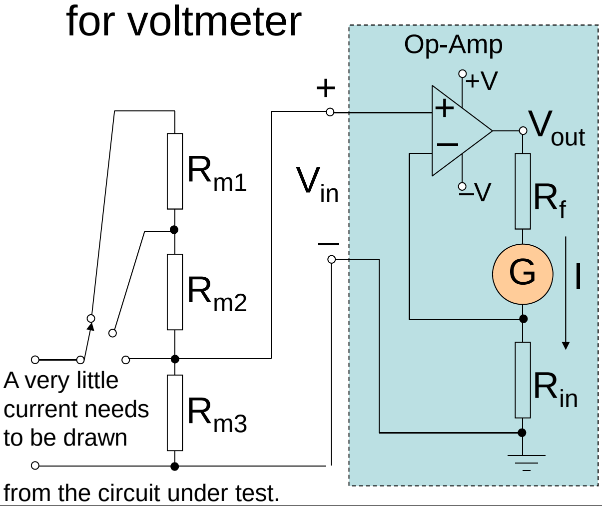
Electronic Instrument

Disadvantage of moving coil meter

- Low input impedance $\Rightarrow$ High loading error for voltmeter



DC Non-Inverting Amplifier

Higher input impedance ($\approx$ 10 MΩ),
$V_{in} = I\,R_{in}$

$V_{out} = I\,(R_f+R_g+R_{in})$

Gain,
$A_v = (R_f+R_g+R_{in})/R_{in}$
$= 1 + (R_f+R_g)/R_{in}$

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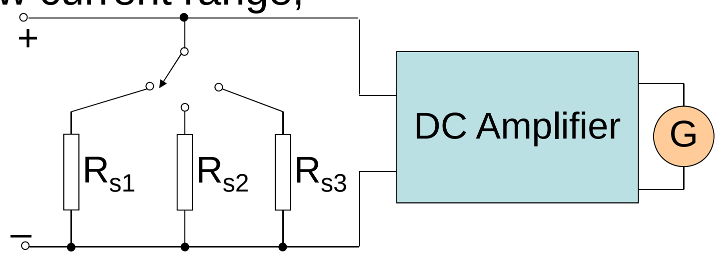
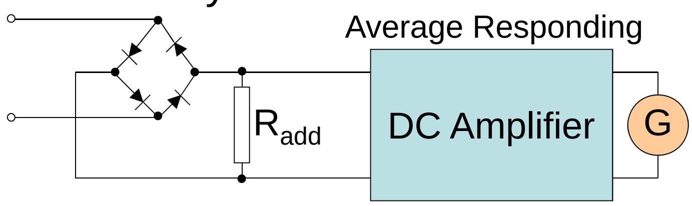
Electronic Instrument (Cont'd)

For low current range,



More disadvantage of moving coil meter

- Low sensitivity when used with a rectifier



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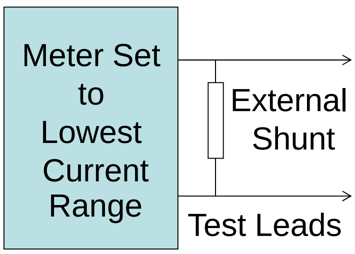
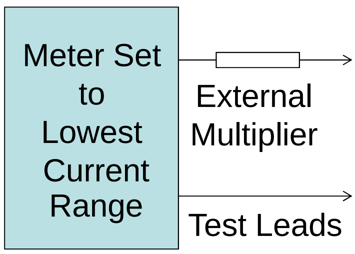
Extending of the Ranges

- The range of an ammeter or voltmeter can be extended to measure high current/voltage values by using external shunt or multiplier connected to the basic movement that is set to the lowest current range (minimum internal additional resistors → finest scale).
- Note that the range of the basic meter cannot be lowered, e.g. for 100 μA with 100 scale division → the pointer deflects by only one division of 1 μA





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Requirements of Shunt Materials

- Soldering of joint should not cause a voltage drop (minimum thermo dielectric voltage drop).
- Resistance of different sizes and values must be soldered with minimum change in value (solderability).

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References

- https://en.wikipedia.org/wiki/Multimeter
- http://www.richardsradios.co.uk/avometers data.html

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Exercises:

Design an Ayrton shunt to provide an ammeter with direct current ranges of 100 mA, 1 A and 10 A. The moving coil meter to be used has a resistance of 50 Ω and gives a full-scale deflection with 1 mA.

Using the above moving coil meter, design a circuit that can be used to provide a multi-range voltmeter with direct voltage ranges of 1 V, 10 V and 100 V.

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