Electrical and Electronic Measurements:

Measurement of Alternating Current

1

Sources and Loads

- An electrical circuit consists of nothing more than “sources” and “loads”.
- Source is to produces an electrical energy, e.g. a chemical battery, an electronic power supply, or a mechanical generator.
- Load is to be powered by that electrical energy, e.g. a light bulb, an electronic clock, an electric fan, or just a resistor.
- What sources are AC? And what kinds of loads do not care which way current flows through them?

2

Faraday’s Law of Induction

- Any change in the magnetic environment of a coil of wire will cause an elctromotive force to be induced in the coil.
- The Maxwell–Faraday equation is a generalization of Faraday's law, and is listed as one of Maxwell's equations.

Michael Faraday (1791-1867)

Voltage generated (V)

Magnetic flux density (Wb/m^2)

$$\varepsilon = -N\frac{\Delta(BA)}{\Delta t}$$

Identical turn of coil of wire

Surface area of moving surface (m^2)

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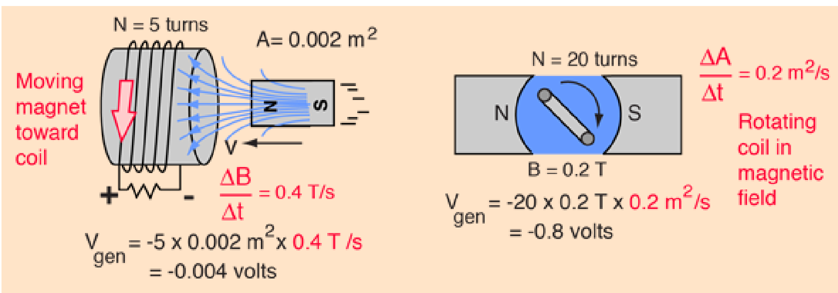
Faraday’s Law of Induction (Cont’d)

- No matter how the change is produced, the voltage will be generated.



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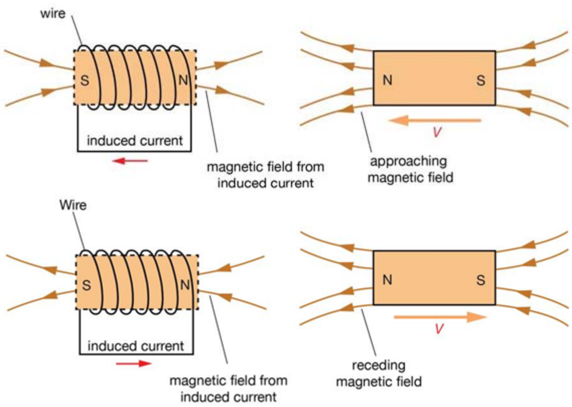
Lenz's Law

- The direction of current induced in a conductor by a changing magnetic field due to induction is such that it creates a magnetic field that opposes the change that produced it.

Emil Lenz
(1804-1865)



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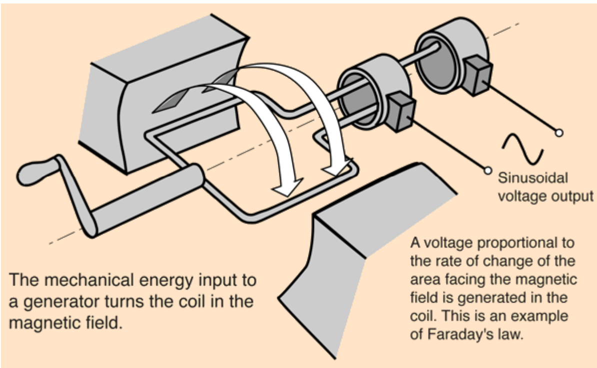
AC Generator

- The turning of a coil in a magnetic field produces motional EMFs in both sides of the coil which add.



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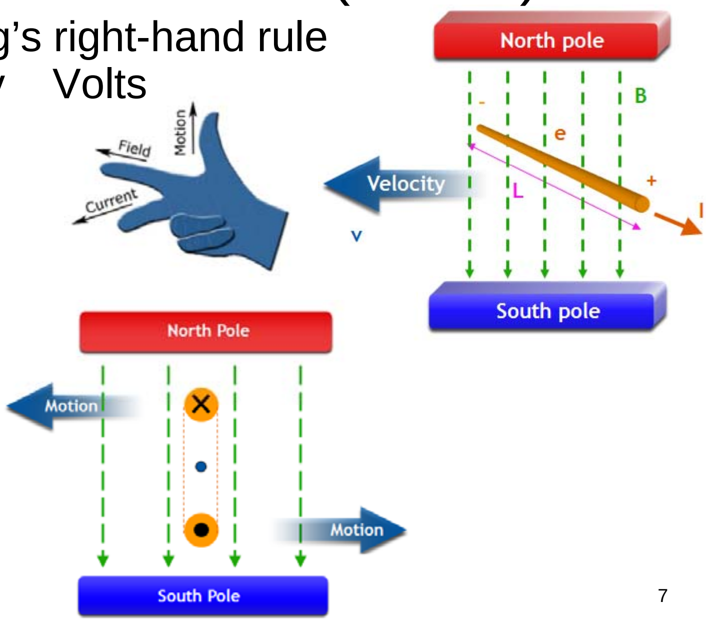
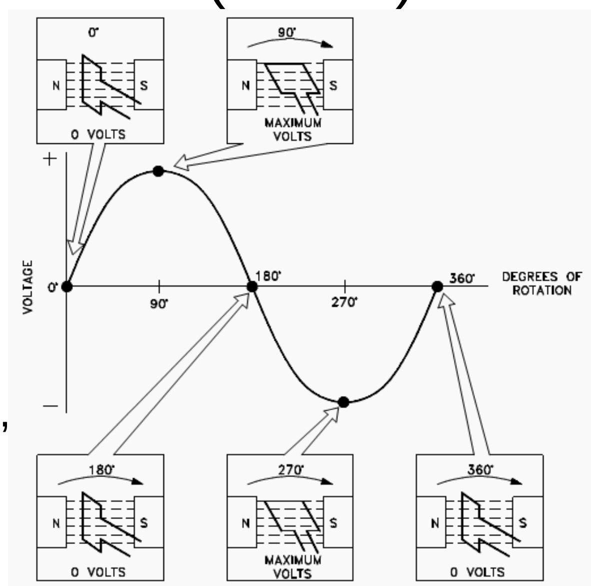
AC Generator (Cont'd)

- Fleming's right-hand rule
  $e = BLv$ Volts



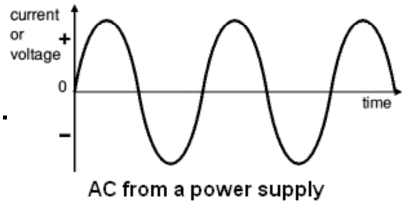
AC Generator (Cont'd)

- Since the component of the velocity perpendicular to the magnetic field changes sinusoidally with the rotation, the generated voltage is sinusoidal.



Alternating Current

- A current flows one way, then the other way, continually reversing direction.
- The usual waveform of an AC power is a sine wave that the change is so regular. The average value is zero (integration in a period).



- Main electricity in Thailand has a frequency of 50 Hz (0.02 sec/cycle), and 60 Hz in US.
- Voltage is continually changing between positive (+) and negative (–). The effective voltage in Thailand is 220 V, and 120 V in US.

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Why Use Alternating Current?

- In transmission of power, $P_{load} = IV$, the overhead wires are not a perfect conductor and exhibit some resistance, R. The absorbed energy is dissipated as waste heat. The lost power is $P_{lost} = I^2R$.
- At the same power, if the current is doubled (voltage reduced by half), $P_{load} = (2I)(V/2)$, the lost power is four times greater, $P_{lost} = (2I)^2R = 4I^2R$. To minimize that loss, we have to use much larger wires, and pay a high price for all that extra copper.

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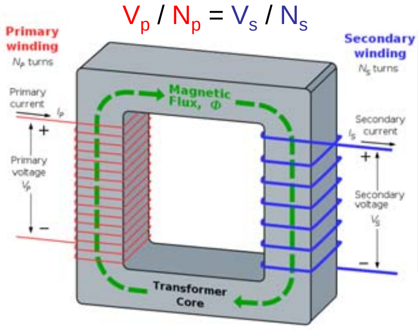
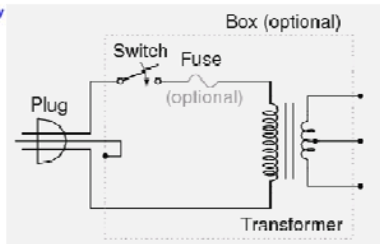
Why Use Alternating Current? (2)

- The solution is to use a transformer that can convert AC power at a higher/lower voltage with very slight losses. In practice, AC generators create electricity at a reasonable voltage, then we use transformers to step it up to very high levels (≈ 100,000 V) for long-distance transmission with a low current, and then use additional transformers to step it back down for local distribution to individual homes in safe value.

$V_p / N_p = V_s / N_s$





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Averaging Power for AC

- $P(t) = I^2(t)\, R$ is just an instantaneous power at a time t.
- Mean power or the total energy converted in one cycle is

$$
\begin{aligned}
P &= 1/T \int_{t=0\to T} P\, dt \qquad , T = \text{period} \\
&= 1/T \int_{t=0\to T} I^2 R\, dt \\
&= R\, [\, 1/T \int_{t=0\to T} I^2\, dt\,] \\
&= R\, [\, \mathrm{sqrt}(1/T \int_{t=0\to T} I^2\, dt)\,]^2 \\
&= R\, (I_{rms})^2
\end{aligned}
$$

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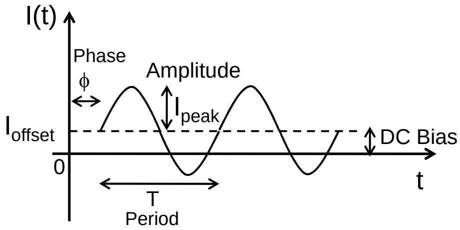
Sine Wave

- $y = \sin(\theta)$
  $= \sin(\omega t)$
  $= \sin(2\pi t/T)$, $\omega = 2\pi/T$ for sinewave
  $= \sin(2\pi f t)$, $f = 1/T$
- $I(t) = I_{offset} + I_{peak}\sin(\omega t - \phi)$



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RMS or Effective Value

For only sinusoidal wave, $\omega = 2\pi/T$

$I_{root\text{-}mean\text{-}square} = \mathrm{sqrt}(I^2_{average}) = \mathrm{sqrt}(1/T\int_{t=0\rightarrow T} I^2(t)dt)$

$= \mathrm{sqrt}(\ 1/T \int_{t=0\rightarrow T} [\ I_{peak}\sin(\omega t)\ ]^2\ dt\ )$

$= \mathrm{sqrt}(\ (I_{peak})^2/T \int_{t=0\rightarrow T} \sin^2(\omega t)\ dt\ )$

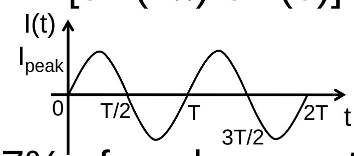
$= \mathrm{sqrt}(\ (I_{peak})^2/2T \int_{t=0\rightarrow T} 1-\cos(2\omega t)\ dt\ )$

$= \mathrm{sqrt}(\ (I_{peak})^2/2T\ \{\ T - [\sin(4\pi)-\sin(0)]\ \}\ )$

$= \mathrm{sqrt}(\ (I_{peak})^2/2\ )$

$= I_{peak}\ /\ \mathrm{sqrt}(2)$

$= 0.707\ I_{peak}$ (70.7% of peak current)



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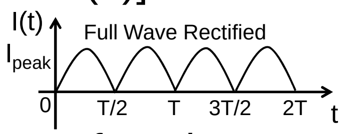
Positive Half-Cycle Averaging

For only sinusoidal wave, $T=2\pi$ and $\omega=2\pi/T=1$

$$I_{+\text{ half cycle}} = I_{average} = 1/(T/2) \int_{t=0\to T/2} I(t)\,dt$$
$$= 2/T \int_{t=0\to T/2} I_{peak}\sin(\omega t)\,dt$$
$$= 2I_{peak}/T \int_{t=0\to T/2} \sin(\omega t)\,dt$$
$$= 2I_{peak}/T\,[\,-\cos(\omega t)\,]_{t=0\to T/2}$$
$$= 2I_{peak}/T\,[\,-\cos(\omega T/2) + \cos(0)\,]$$
$$= 2I_{peak}/T\,[-\cos(\pi)+\cos(0)]$$
$$= 4I_{peak} / T$$
$$= 2I_{peak} / \pi$$
$$= 0.636\ I_{peak}\quad \text{(63.6\% of peak current)}$$



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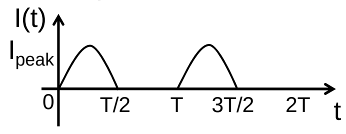
Half-Wave Rectified Sine

For only sinusoidal wave, $T=2\pi$ and $\omega=2\pi/T=1$

$$I_{+\text{ half wave}} = 1/T \int_{t=0\to T} I(t)\,dt$$
$$= 1/T \int_{t=0\to T/2} I_{peak}\sin(\omega t)\,dt$$
$$= I_{peak}/T \int_{t=0\to T/2} \sin(\omega t)\,dt$$
$$= I_{peak}/T\,[\,-\cos(\omega t)\,]_{t=0\to T/2}$$
$$= 2I_{peak}/T$$
$$= I_{peak} / \pi$$
$$= 0.318\ I_{peak}\quad \text{(31.8\% of peak current)}$$



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Form Factor

- Form factor is a calibration constant or the ratio between average rectified value and rms value, $FF = Value_{rms} / Value_{avg}$

  for sin, $FF = (I_{peak}/sqrt(2)) / (2I_{peak}/\pi)$

  $= \pi / 2sqrt(2)$

  $= 1.11$ (111%)

- If the AC signal is not a pure sin wave, the meter still reads an average value of the rectified wave. However, the form factor no longer is 1.11. It is based on the shape of the signal.

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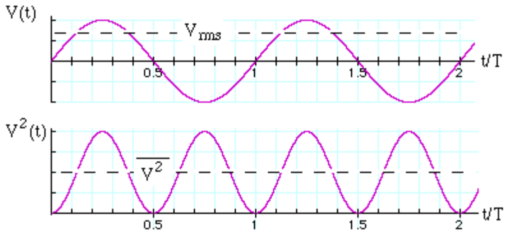
for Sinusoidal Wave

- $I_{rms} = 0.707\ I_{peak}$
- $V_{rms} = 0.707\ V_{peak}$
- $I_{+\text{ half cycle}} = 0.636\ I_{peak}$
- $V_{+\text{ half cycle}} = 0.636\ V_{peak}$
- $FF_{Sinusoidal} = 1.11$



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for Square Wave

- $I_{rms} = \text{sqrt}(\ 1/(T/2) \int_{t=0 \to T/2} I^2(t)\ dt\ )$

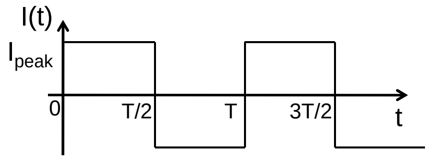
  $= \text{sqrt}(\ 2/T \int_{t=0 \to T/2} I^2_{peak}\ dt\ )$

  $= \text{sqrt}(\ 2I^2_{peak}/T \int_{t=0 \to T/2} dt\ )$

  $= \text{sqrt}(\ 2I^2_{peak}/T\ [\ (T/2) - (0)\ ]\ )$

  $= \text{sqrt}(\ I^2_{peak}\ )$

  $= I_{peak}$
- $V_{rms} = V_{peak}$
- $I_{+\ half\ cycle} = I_{peak}$
- $V_{+\ half\ cycle} = V_{peak}$
- $FF_{Square} = 1$



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for Pulse Train

- $I_{rms} = \text{sqrt}(\ 1/T \int_{t=0 \to \tau} I^2(t)\ dt\ )$

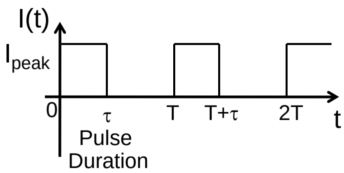
  $= \text{sqrt}(\ 1/T \int_{t=0 \to \tau} I^2_{peak}\ dt\ )$

  $= \text{sqrt}(\ I^2_{peak}/T \int_{t=0 \to \tau} dt\ )$

  $= \text{sqrt}(\ I^2_{peak}/T\ [\ \tau - 0\ ]\ )$

  $= \text{sqrt}(\tau/T)\ I_{peak}$

  $= \text{sqrt}(D)\ I_{peak}$, Duty cycle, $D = \tau/T$



- $V_{rms} = \text{sqrt}(D)\ V_{peak}$
- Average value for DC pulse train signal

  $I_{avg} = 1/T \int_{t=0 \to \tau} I_{peak}\ dt = D\ I_{peak}$

  $V_{avg} = D\ V_{peak}$

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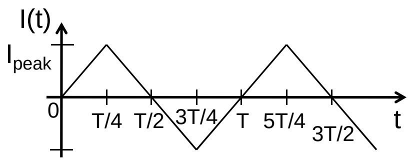
for Triangular Wave

- $I_{rms} = \text{sqrt}(1/(T/4) \int_{t=0\rightarrow T/4} I^2(t)\, dt)$
  $= \text{sqrt}(4/T \int_{t=0\rightarrow T/4} [(4I_{peak}/T)t]^2\, dt)$
  $= \text{sqrt}(4^3\, I^2_{peak}/T^3 \int_{t=0\rightarrow T/4} t^2\, dt)$
  $= \text{sqrt}(4^3\, I^2_{peak}/T^3\, [(T/4)^3/3 – (0)^3/3])$
  $= \text{sqrt}(I^2_{peak} / 3)$
  $= \text{sqrt}(3)/3\, I_{peak}$
  $= 0.577\, I_{peak}$ (57.7% of peak current)
- $V_{rms} = 0.577\, V_{peak}$

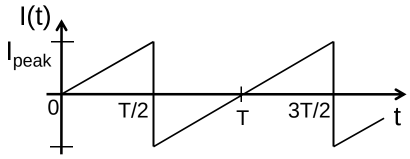


for Triangular Wave (Cont'd)

- $I_{+\ half\ cycle} = 4/T \int_{t=0\rightarrow T/4} (4I_{peak}/T)t\, dt$
  $= 4^2\, I_{peak}/T^2 \int_{t=0\rightarrow T/4} t\, dt$
  $= 4^2\, I_{peak}/T^2\, [(T/4)^2/2 – (0)^2/2]$
  $= I_{peak} / 2$
  $= 0.5\, I_{peak}$ (50% of peak current)
- $V_{+\ half\ cycle} = 0.5\, V_{peak}$
- $FF_{Triangular} = 1.154$ (115.4%)

for Sawtooth Wave

- $I_{rms} = \text{sqrt}(\ 1/(T/2) \int_{t=0\to T/2} I^2(t)\ dt\ )$
  $= \text{sqrt}(\ 2/T \int_{t=0\to T/2} [\ (2I_{peak}/T)t\ ]^2\ dt\ )$
  $= \text{sqrt}(\ 2^3\, I^2_{peak}/T^3 \int_{t=0\to T/2} t^2\ dt\ )$
  $= \text{sqrt}(\ 2^3\, I^2_{peak}/T^3\ [\ (T/2)^3/3 - (0)^3/3\ ]\ )$
  $= \text{sqrt}(\ I^2_{peak} / 3\ )$
  $= \text{sqrt}(3)/3\ I_{peak}$
  $= 0.577\ I_{peak}$ (57.7% of peak current)
- $V_{rms} = 0.577\ V_{peak}$

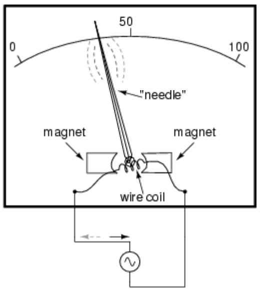


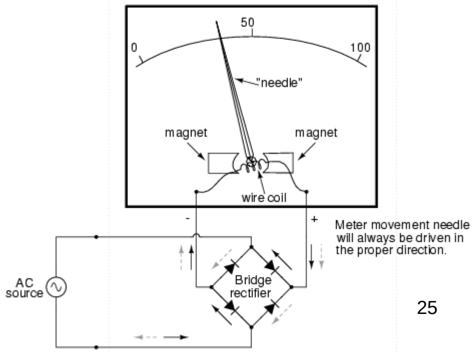
for Sawtooth Wave (Cont'd)

- $I_{+\ half\ cycle} = 2/T \int_{t=0\to T/2} (2I_{peak}/T)t\ dt$
  $= 2^2\, I_{peak}/T^2 \int_{t=0\to T/2} t\ dt$
  $= 2^2\, I_{peak}/T^2\ [\ (T/2)^2/2 - (0)^2/2\ ]$
  $= I_{peak} / 2$
  $= 0.5\ I_{peak}$ (50% of peak current)
- $V_{+\ half\ cycle} = 0.5\ V_{peak}$
- $FF_{Sawtooth} = 1.154$ (115.4%)

AC on Moving-Coil Meter

- Alternating current = alternating torque
- Very low frequency → alternating pointer
- Higher frequencies → pointer is not moved.
- AC/DC converter is needed.





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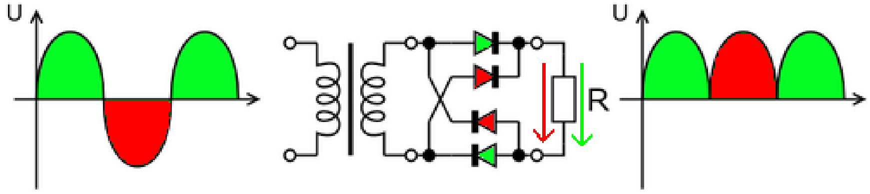
AC/DC Converter

- Full-wave rectifier circuit using bridge diodes
- Current flows only in one direction, anode to cathode, when diodes are forward biased.
- Inertia of moving coil → average value



- R → Galvanometer (G)

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AC Calibration

Actually, AC meter responses to an average value of half-cycle wave. It can show root-mean-square values of sinusoidal wave by calibrating the scale by multiplying with form factor constant.

$$I_{rms} = FF \times I_{+\text{ half cycle}}$$
$$= 1.11 \times I_{+\text{ half cycle}}$$

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Error for Other-Form Wave

- If the input signal is not a sinusoidal wave form ($FF \neq 1.11$), a reading error is,

$$\text{Error} = (1.11 - FF) / FF \quad \times 100\%$$

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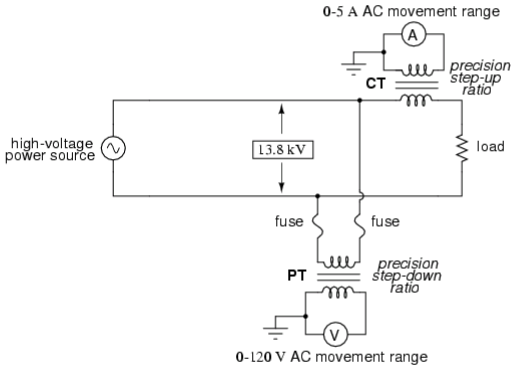
Full-Scale-Deflection for AC Meter

- Current transformer scales current down.
- Potential transformer scales voltage down.
- Each points in transformer can be tapped.



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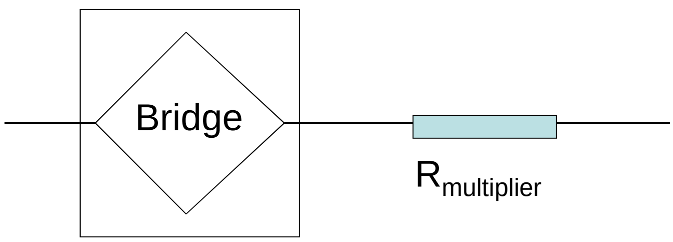
AC Ammeter and Voltmeter

- Shunt resistor connected in parallel or
- Multiplier resistance connected in series to the bridge



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Sensitivity: AC Vs DC

<u>Ex</u>

if the AC input is 10 V_{rms}

$$V_{peak} = 1.414 \times 10\ V$$
$$= 14.14\ V$$
$$V_{avg} = 0.636 \times 14.14\ V$$
$$= 9\ V$$

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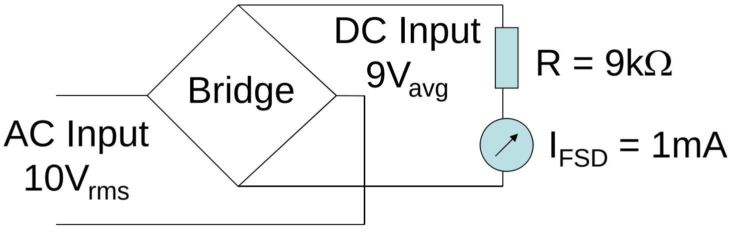
<u>Ex</u> (Cont'd)

$$\text{Sensitivity} = V_{DC} / V_{AC} \times 100\%$$
$$= V_{avg} / V_{rms} \times 100\%$$
$$= 90\%$$



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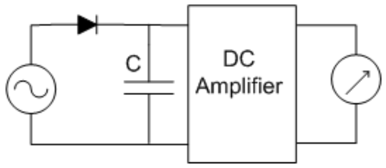
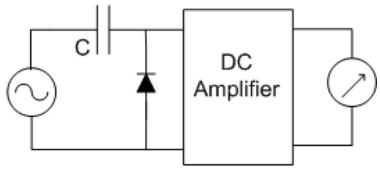
Peak Responding AC Voltmeter

- The difference to mean responding meters is the use of storage capacitors with the half-wave rectifying diode. The capacitor charges to peak value of the applied voltage, $V_c = Q/C$ and the meter then response to it.
- The capacitor discharges very slowly through the high input impedance of DC amplifier, so that a negligible small amount of current supplied by the circuit under test.
- The scale is then calibrated in RMS values.





True RMS Converter

- A correct conversion or the measurement of non-sinusoidal values requires a more complex and costly converter, known as a true RMS converter.

Multimeter type	Response to sine wave	Response to square wave	Response to single phase diode rectifier	Response to 3 ∅ diode rectifier
Average responding	Correct	10 % high	40 % low	5 % to 30 % low
True-rms	Correct	Correct	Correct	Correct

True RMS Converter: Thermal Converter

- The RMS value of an alternating current is also known as its heating value, as it is a voltage which is equivalent to the direct current value that would be required to get the same heating effect.
- For example, if we applied 120 V AC RMS to a resistive heating element it would heat up by exactly the same amount as if we had applied 120V DC.

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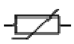
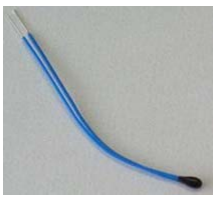
True RMS Converter: Thermal Converter (Cont'd)

- The AC signal would be applied to a small heating element that was matched with a *thermistor*, a resistor whose resistance is dependent on temperature, which could be used in a DC measuring circuit.
- The technique is not very precise but it will measure any waveform at any frequency.

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True RMS Converter: Thermal Converter (Cont'd)

- A big drawback is that it is low-impedance, that the power used to heat the thermistor comes from the circuit being measured.
- If the circuit being measured can support the heating current, then it is possible to make a post-measurement calculation to correct the effect, as the impedance of the heating element is known.
- If the signal is small then a pre-amplifier is necessary, and the measuring capabilities of the instrument will be limited by this pre-amplifier.

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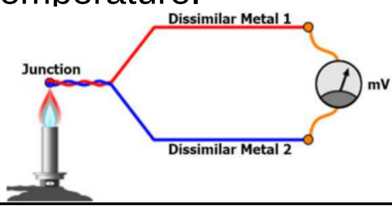
True RMS Converter: Thermal Converter (Cont'd)

- The heating power can be measured by amplifying and feeding it to a *thermocouple*, whose output voltages is then proportional to the V_{rms}.
- A thermocouple is an electrical device consisting of two dissimilar electrical conductors forming electrical junctions at differing temperatures to produce a temperature-dependent voltage as a result of the thermoelectric effect, and this voltage can be interpreted to measure temperature.



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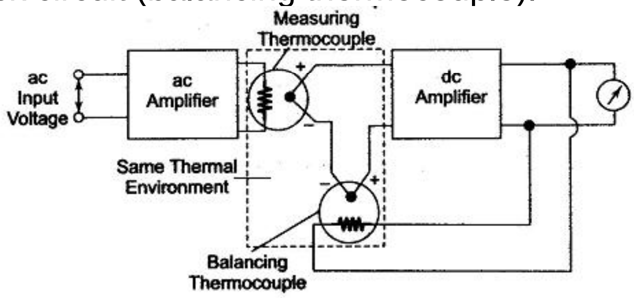
True RMS Converter: Thermal Converter (Cont'd)

- However, thermocouples are non-linear devices. This difficulty can be overcome in some instruments by placing two thermocouples in the same thermal environment.
- The effect of non-linear behavior of the thermocouple in the input circuit (measuring thermocouple) is cancelled by similar non-linear effects of the thermocouple in the feedback circuit (balancing thermocouple).



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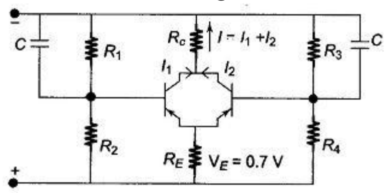
True RMS Converter: Analog Electronic Converters

- An analog multiplier in a specific configuration which multiplies the input signal by itself (squares it), averages the result with a capacitor, and then calculates the square root of the value (via a multiplier/squarer circuit in the feedback loop of an operational amplifier), or
- Squaring device that the ac component of the voltage developed across the common collector resistors of two transistors that are connected in parallel, and between the bases of which a small ac voltage is applied, is proportional to the square of the applied input voltage. The scale of the true rms meter is then calibrated in terms of the square roots of the indicated values, or



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True RMS Converter: Analog Electronic Converters (Cont'd)

- A full-wave precision rectifier circuit to create the absolute value of the input signal, which is fed into an operational amplifier arranged to give an exponential transfer function, then doubled in voltage and fed to a log amplifier as a means of deriving the square-law transfer function, before time-averaging and calculating the square root of the voltage, similar to above, or
- A field-effect transistor may be used to directly create the square-law transfer function, before time-averaging.
- Unlike thermal converters they are subject to bandwidth limitations.

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True RMS Converter: Digital RMS Converters

- Most digital and PC-based oscilloscopes include a function to give the RMS value of a waveform.
- If a waveform has been digitized, the correct RMS value may be calculated directly.
- The precision and the bandwidth of the conversion is entirely dependent on the analog to digital conversion.
- In most cases, true RMS measurements are made on repetitive waveforms, and under such conditions digital oscilloscopes are able to achieve very high bandwidths as they sample at a fraction of the signal frequency to obtain a stroboscopic effect.

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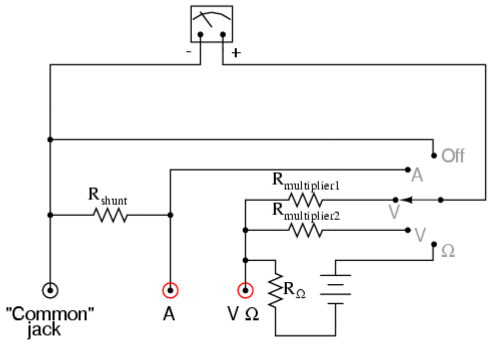
PMMC Analog Multimeter

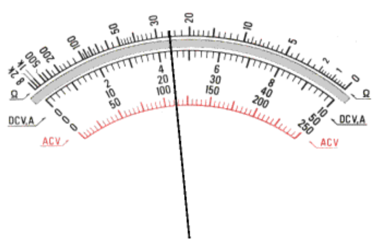
Combination of

- Appropriate shunts for direct current ranges,
  50 μA - 10 A
- Multipliers for direct voltage ranges,
  100 mV - 3000 V
- Rectifier for alternating currents designed for sine wave, 10 mA - 10 A and 3 V - 3000 V (RMS)
- Ohmmeter with 1.5 V, 3 V, 9 V battery,
  2 kΩ - 20 MΩ
- Accuracy,
  about ±1%FSD (DC), ±2%FSD (AC),
  ±3% Mid-Scale Ω

PMMC Analog Multimeter (Cont'd)

- With all three fundamental functions available, DCA, ACV/ACV and Ω, this multimeter may also be known as a volt-ohm-milliammeter (VOM).
- Multimeters may also have other functions, such as diode and continuity tests.





e.g. Sanwa YX-360TRF Multitester

Analog Display

Battery
AA 1.5V×2

Setting
Selector

Test Lead +

Test Lead –COM

- Note that your multimeter should come with some basic instructions. Read and understand the user manual before operating the meter. 45

Parallax Error

- Because the pointer of the meter is usually a small distance above the scale of the meter, parallax error can occur when the operator attempts to read the scale line that lines up with the pointer.
- To counter this, some meters include a mirror along the markings of the principal scale. It is improved by reading the scale so that the pointer and the reflection of the pointer are aligned.

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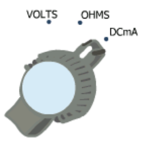
DC Ammeter Precautions

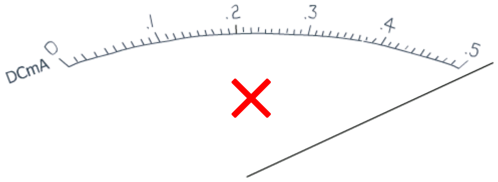
- Never connect an ammeter across a source of EMF (electromotive force) because its low resistance would draw a high current and destroy the movement. Fuse is needed.
- Observe the correct polarity. Reverse current causes the meter to deflect against the mechanic stopper, which may damage the pointer movement.
- If the polarity is not known, insert the test leads momentarily. If the pointer goes down scale, remove immediately and reverse the polarity.

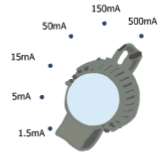
DC Ammeter Usage

- Set a function selector to the “DCmA” position.



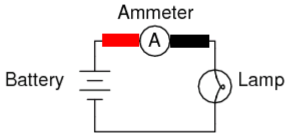
- Set the range to the maximum current, i.e. 500 mA, to avoid pegging the meter or the pointer goes beyond the right of the scale.





DC Ammeter Usage (Cont'd)

- Turn off the circuit power.
- Open the circuit and reconnect it by placing the ammeter in series between the two points the circuit broken.
- The red lead (+) should be placed on the side current enters the meter and the black lead (–) is for the current exits the meter.



- Turn the power on and re-energize the circuit.

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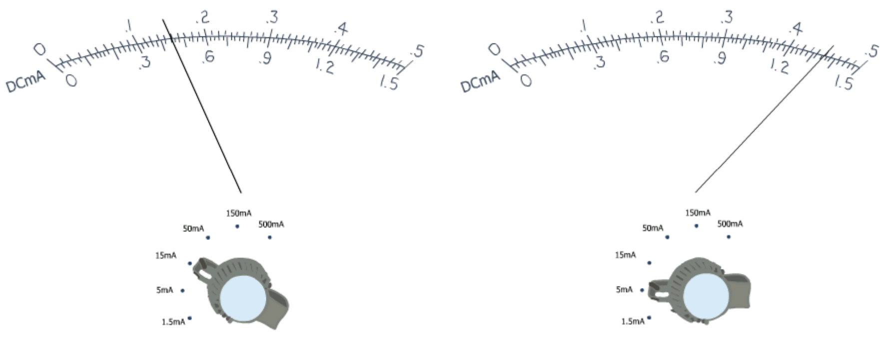
DC Ammeter Usage (Cont'd)

- Adjust the range so that the pointer is as close to the farthest position to the right, i.e. 0.5 mA range should be selected.



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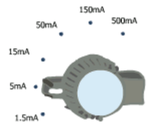
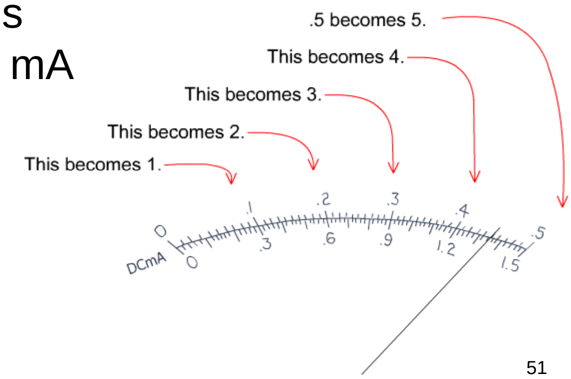
DC Ammeter Usage (Cont'd)

- Read the linear scale with the range you selected, e.g. the maximum value is 5 mA.
- Multiply the reading on 0.5 mA range by 10 and the answer is $0.450 \times 10 = 4.50$ mA
- Tolerance $\pm$e%FSD (DC)





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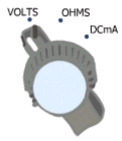
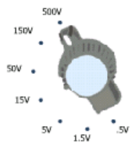
DC Voltmeter Usage

- Set a function selector to the "Volts" position.



- Set the range to the maximum voltage, i.e. 500 V, to avoid the condition the pointer goes beyond the right of the scale.



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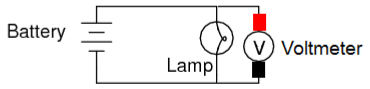
DC Voltmeter Usage (Cont'd)

- Turn off the circuit power.
- Connect the voltmeter in parallel to two terminals of the component we want to measure the voltage dropped across it.
- The red lead (+) should be placed on the side current enters the meter and the black lead (–) is for the current exits the meter.

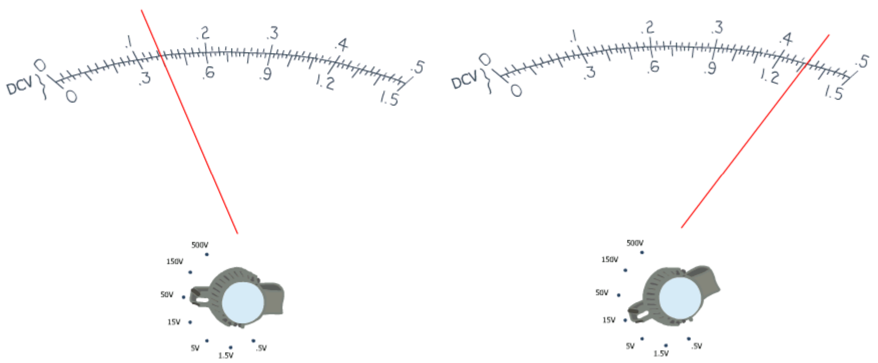


- Turn the power on and re-energize the circuit.

53

DC Voltmeter Usage (Cont'd)

- Adjust the range so that the pointer is as close to the farthest position to the right, i.e. 15 V range should be selected.



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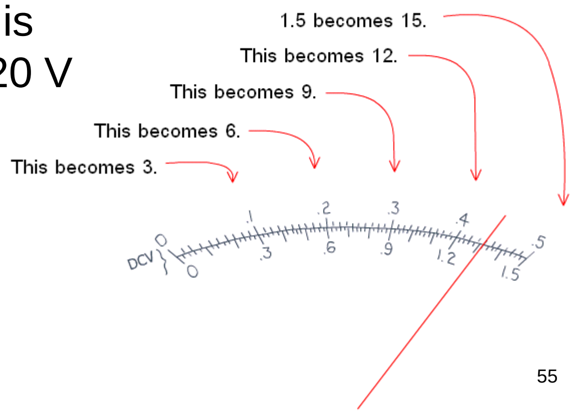
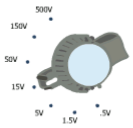
DC Voltmeter Usage (Cont'd)

- Read the linear scale with the range you selected, e.g. the maximum value is 15 V.
- Multiply the reading on 1.5 V range by 10 and the answer is 1.320×10 = 13.20 V
- Tolerance ±e%FSD (DC)





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AC Voltmeter Usage

- Connect the meter across the circuit as same as DC voltmeter usage but it does not require correct application of the polarity .
- If the voltage range is unknown get the estimate value by setting the knob at the highest range at 1000 V, then lower the range until you could read it conveniently.
- The reading is in RMS value.

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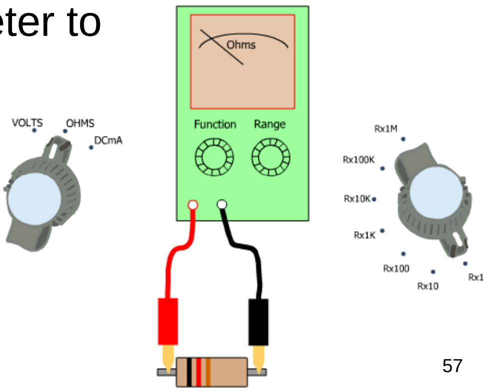
Ohmmeter Usage

- Set a function selector to the “Ohms” position.
- Set the range to the smallest multiplier, i.e. R×1.
- Connect the ohmmeter to the component being measured.



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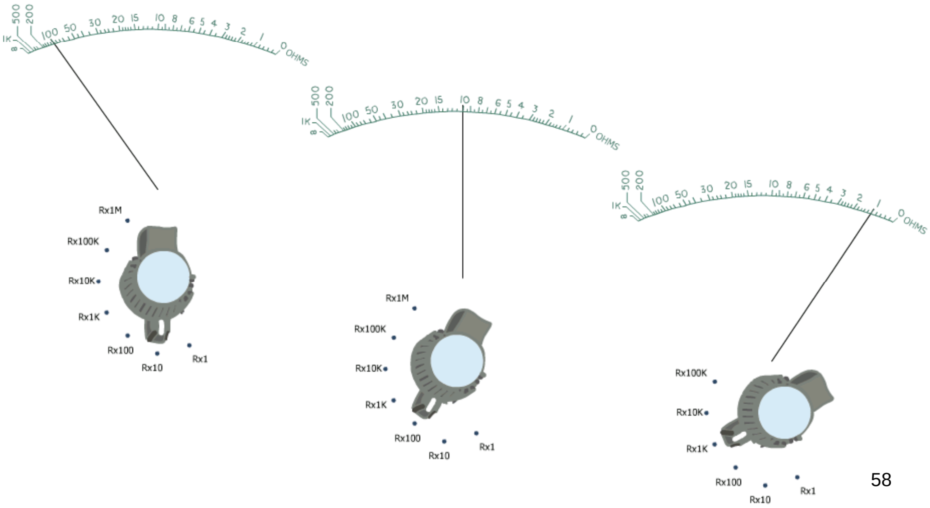
Ohmmeter Usage (Cont’d)

- Adjust the range so that the pointer is as close to the mid scale as possible, i.e. R×100.



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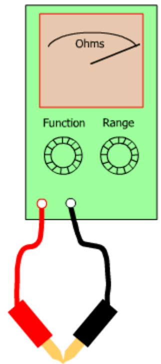
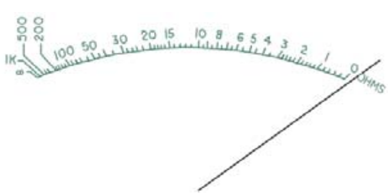
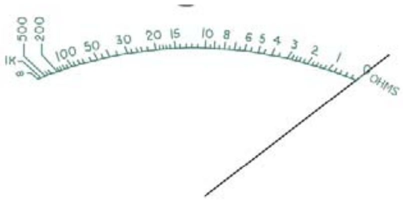
Ohmmeter Usage (Cont’d)

- Remove the component and touch the test leads together. If the pointer is not at the zero line, turn 0-Ω adjust knob so that it becomes properly aligned.





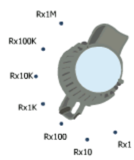


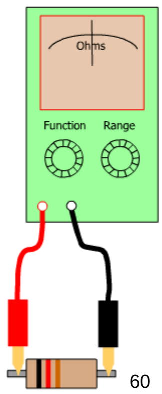
Ohmmeter Usage (Cont’d)

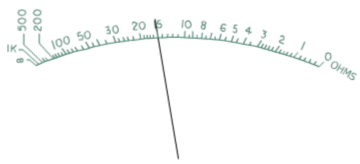
- The meter is now calibrated and ready to make an accurate measurement. Note that each time the different range is selected, the calibration needs to be repeated.
- e.g. multiply the reading by 100 and the answer is $15.00 \times 100\ \Omega$

  or $1.500\ \mathrm{k}\ \Omega$
- Tolerance

  $\pm$e% Mid-Scale







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