Theory of AC and DC Meter Testing

Prepared by Tom Lawton, TESCO

For North Carolina Electric Meter School
Advanced
Tuesday, June 15, 2021 at 9:30 a.m.

A Little History

- **1800** Volta
  - First electric battery
- **1830-31** Faraday and Henry
  - Changing magnetic field can induce an electric current. Build first very crude electric motors in lab.
- **1832** Pixii
  - First crude generation of an AC current.
- **1856** Siemens
  - First really practical electric motor
- **1860s** Varley, Siemens and Wheatstone
  - Each develop electric dynamos (DC Generators).

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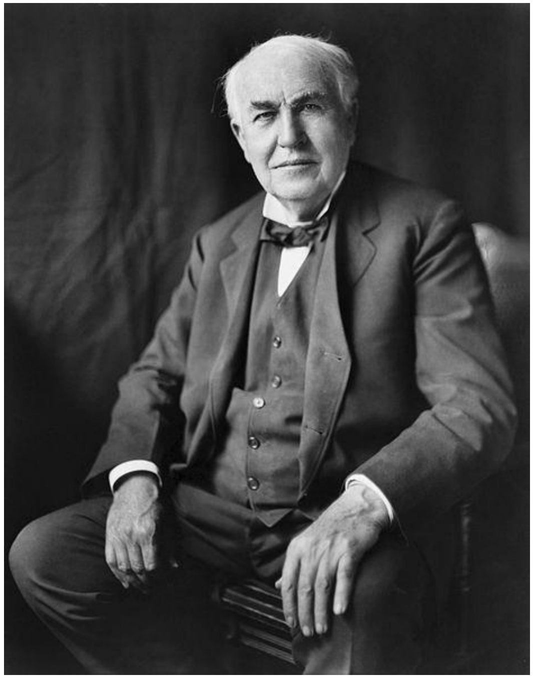
A Little History

- **1870s**
  - First electric railroad and street lights in Berlin (DC).
- **1880**
  - First electric elevator (DC).
- **1885-88** Thomson, Ferraris, Tesla
  - Each develop AC electric induction motors.
  - Tesla is granted a US patent for induction motor in 1888.
- **1890** Dolivo-Dobrovolsky
  - First three phase generator, motor and transformer

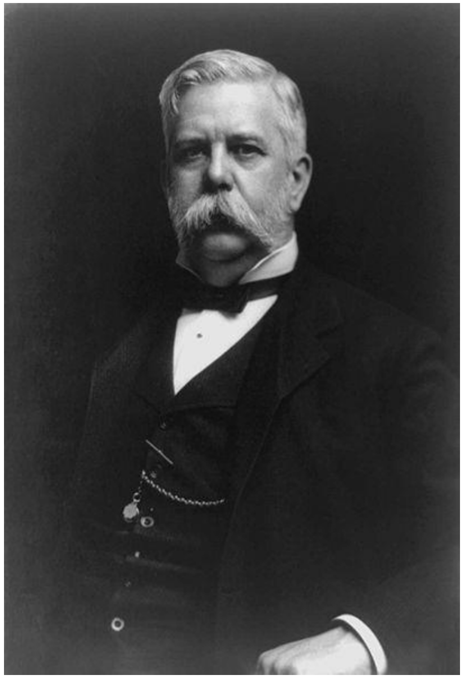
A Little History

- Edison and Westinghouse
  - Edison favored DC power distribution, Westinghouse championed AC distribution.
  - The first US commercial electric systems were Edison’s DC systems.
- First AC system was in 1893 in Redlands, CA. Developed by Almirian Decker it used 10,000 volt, three phase primary distribution.
- Siemens, Gauland and Steinmetz were other pioneers.

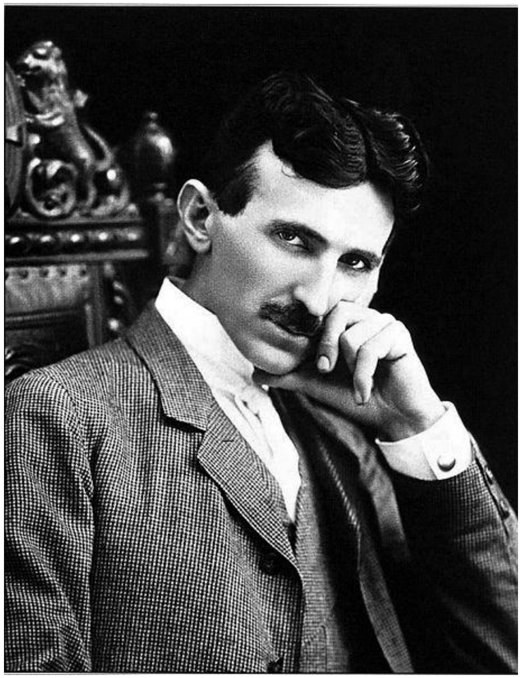
War of the Currents



Thomas Edison



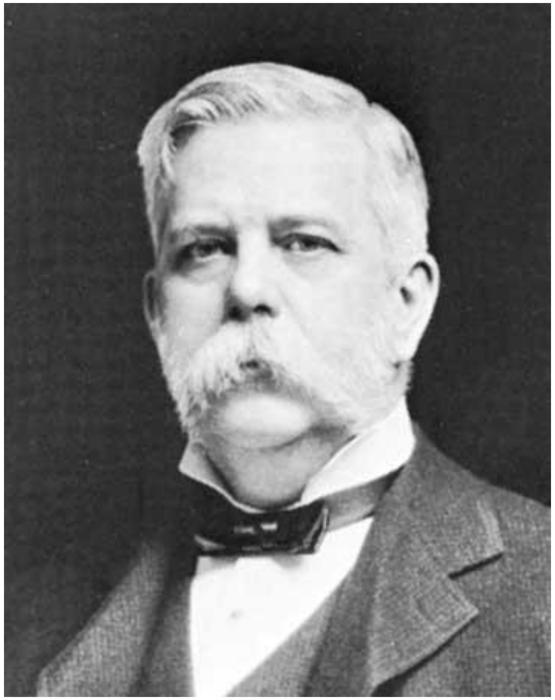
George Westinghouse



Nikola Tesla

Westinghouse

- 1884 – George Westinghouse establishes the Union Switch & Signal Co. in Pittsburgh, PA
- Buys the U.S. rights to a transformer patented in Europe
- The company reorganizes as the Westinghouse Electric and Manufacturing Company
- William Stanley joins the company as the chief electrical engineer and Oliver B. Shallenberger resigns as an officer in the U.S. Navy to work under him as the chief electrician.

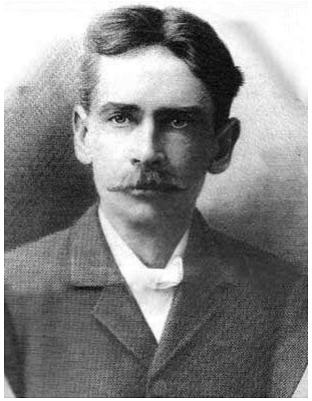


George Westinghouse

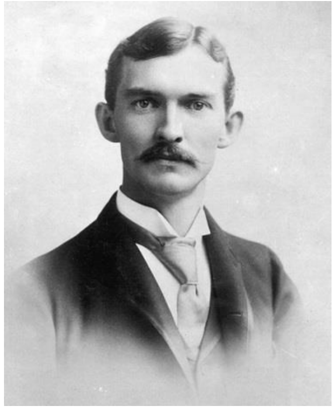
AC Starts to Win

- Stanley and Schallenberger: They refine the transformer design and in 1886 Stanley demonstrates the first complete system of high voltage AC transmissions including generators, transformers, and high voltage transmission lines.

- AC had none of the issues of DC (voltage drop in long lines and a lack of an easy way to increase or decrease the voltage). However there was no meter that could accurately record the usage of electricity on AC circuits.



William Stanley, Jr.



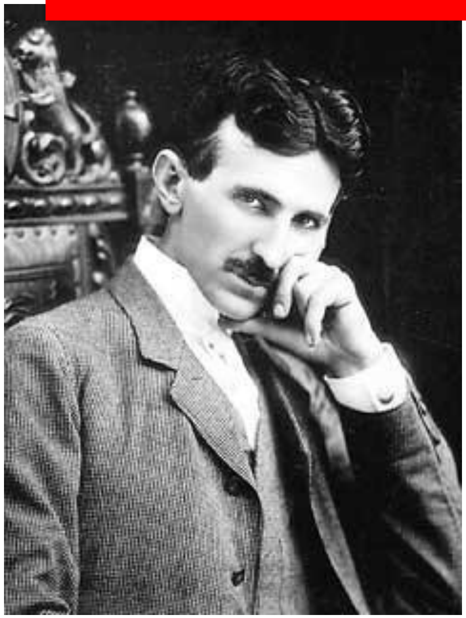
Oliver Schallenberger

Thomas Edison - 1889

"Fooling around with alternating current is just a waste of time. Nobody will use it, ever."

- Thomas Edison, 1889

1888: A Young Serb Named Никола Тесла (Nicola Tesla) Meets George Westinghouse



Nicola Tesla,
"The Wizard of
The West"

1893: World's Fair Chicago lighted by Westinghouse / Tesla

1882: Induction Motor

1888: Westinghouse, American entrepreneur and engineer meets Tesla

1893: Westinghouse Awarded the Contract for Powerhouse at Niagara Falls

Edward Dean Adams power station at Niagara, with ten 5,000-horsepower Tesla/Westinghouse AC generators — the culmination of Tesla's dream. **(Courtesy Smithsonian Institution)**

AC Theory - History

- By 1900 AC power systems had won the battle for power distribution.
  - Transformers allowed more efficient distribution of power over large areas.
  - AC motors were cheaper and easier to build.
  - AC electric generators were easier to build.

AC vs DC

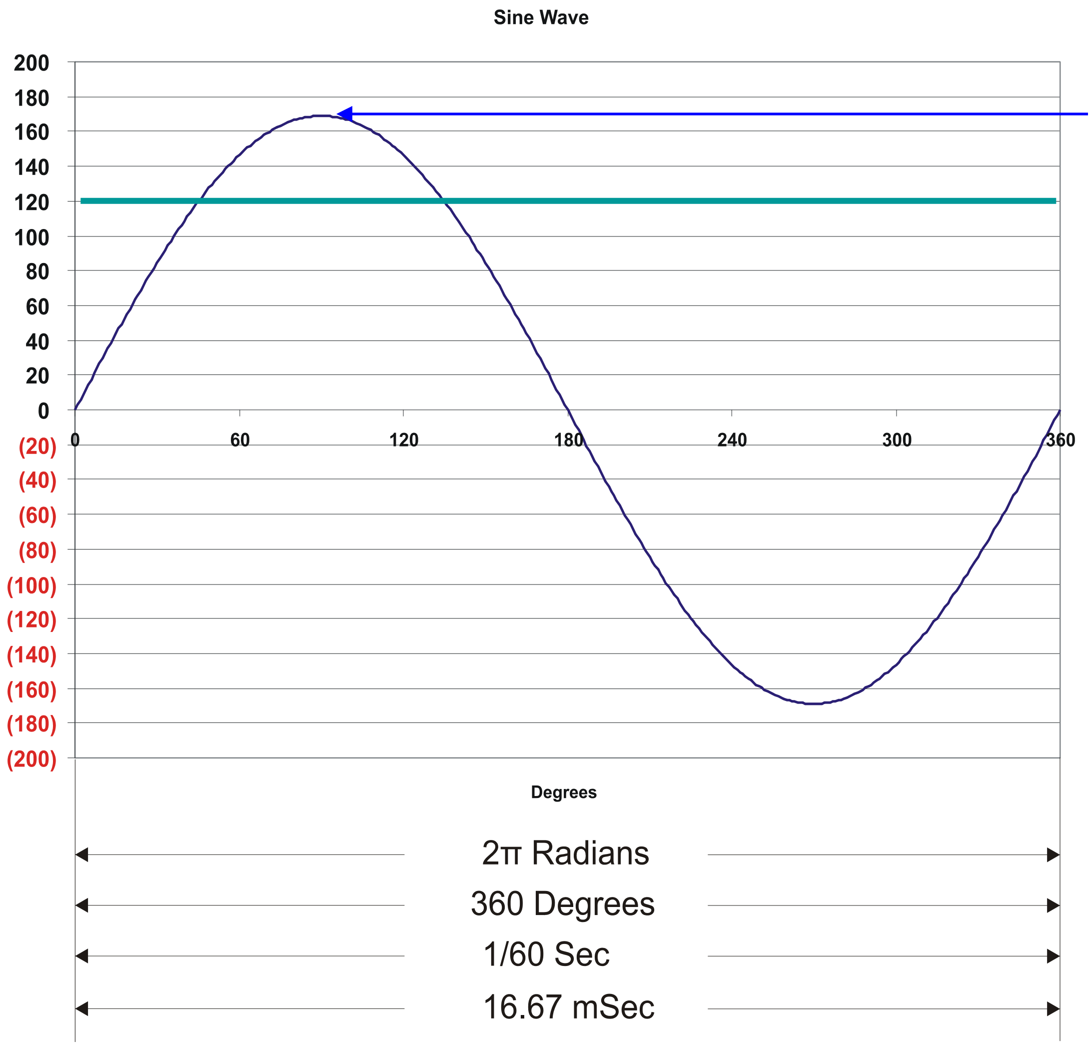
- **Direct Current (DC)** – an electric current that flows in one direction.(IEEE100)

- **Alternating Current (AC)** – an electric current that reverses direction at regularly recurring intervals of time. (IEEE100)

AC Circuits

- An AC circuit has three general characteristics
  - Value
  - Frequency
  - Phase
- In the US, the household value is 120 Volts with other common voltages being 208, 240, 277 and 480 Volts. The frequency is 60 Hertz (cycles per second).

AC Theory – Sine Wave



$$V = V_{pk}\sin(2\pi ft - \theta)$$

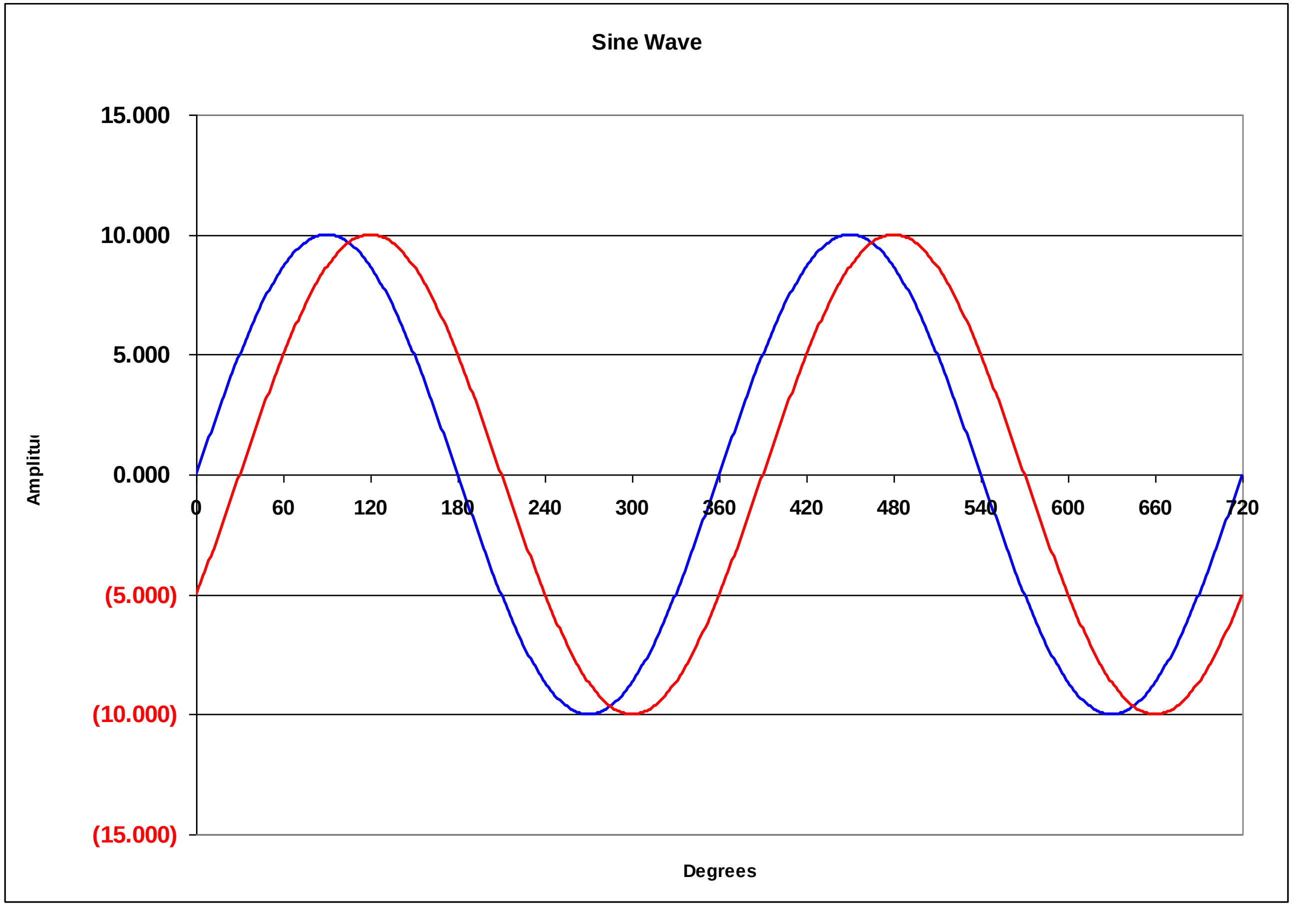
$$V = \sqrt{2}V_{rms}\sin(2\pi ft - \theta)$$

$$V_{rms} = 120$$

$$V_{pk} = 169$$

$$\theta = 0$$

AC Theory - Phase



$$V = 10\sin(2\pi f t)$$

$$I = 10\sin(2\pi f t - 30)$$

Here current LAGS voltage.

AC vs DC

- In DC theory we learned
  - Ohm's Law
    - **Voltage = Current x Resistance**
    - **$V = IR$**
  - Power
    - **$P = I^2R = V^2/R$**
- For AC we would like the same equations to apply.
  - Specifically we want to be able to say that a DC voltage of 10 Volts applied to a resistor of value R produces the same power dissipation as an AC voltage of 10 volts applied to the same resistor.

AC Theory – RMS

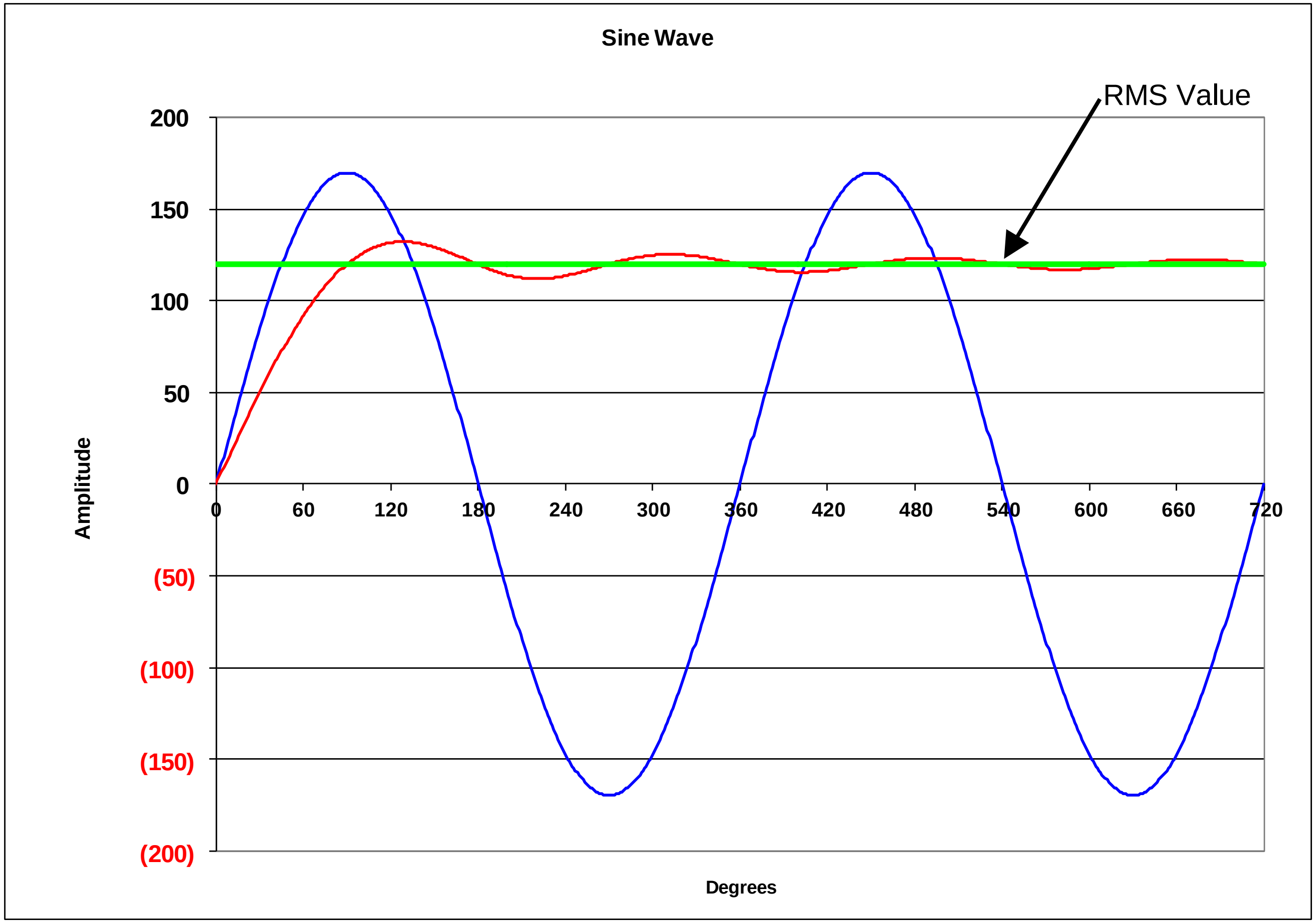
- For DC voltage to equal AC voltage we need

$$\frac{V_{dc}^2}{R} = \int \frac{1}{R} V_0^2 \sin^2(2\pi ft - \theta)dt$$

$$\frac{V_{dc}^2}{R} = \frac{V_0^2}{2R}$$

$$V_0 = \sqrt{2} V_{DC}$$

AC Theory - RMS



$$V = 120\sqrt{2}\sin(\omega t) = 169.68\sin(\omega t)$$

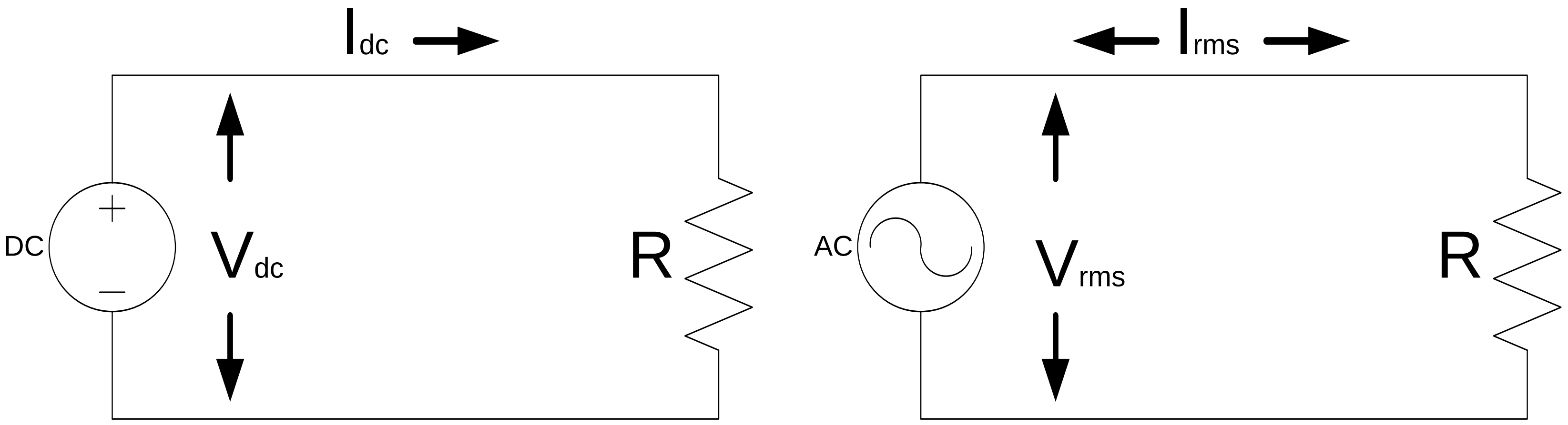
AC Theory – RMS

- So if we want to have the V in our equation for an AC signal represent the same value as the its DC counterpart we have

$$V(t) = \sqrt{2}V_{DC}\sin(2\pi ft - \theta)$$

- By convention in AC theory we refer to V_{DC} as the RMS (Root Mean Squared) voltage.
- When we talk about AC values we always mean the RMS value not the peak value unless we say so specifically

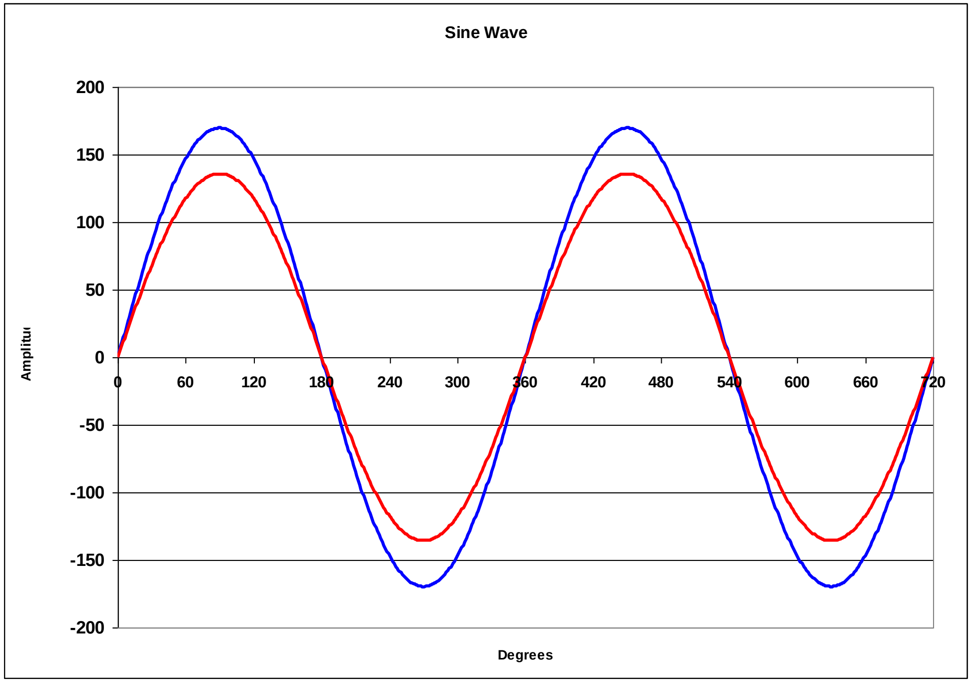
AC vs DC

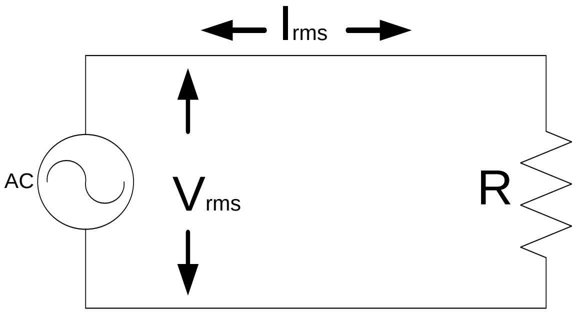


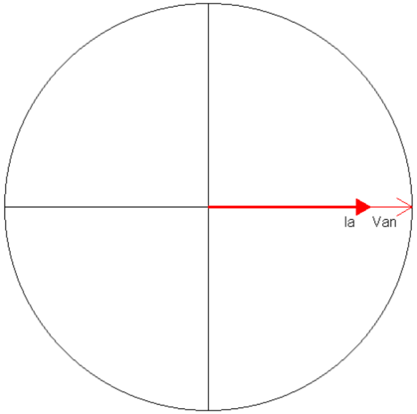
$$V = IR$$

$$P = VI = I^2R = V^2/R$$

AC Theory – Resistive Load

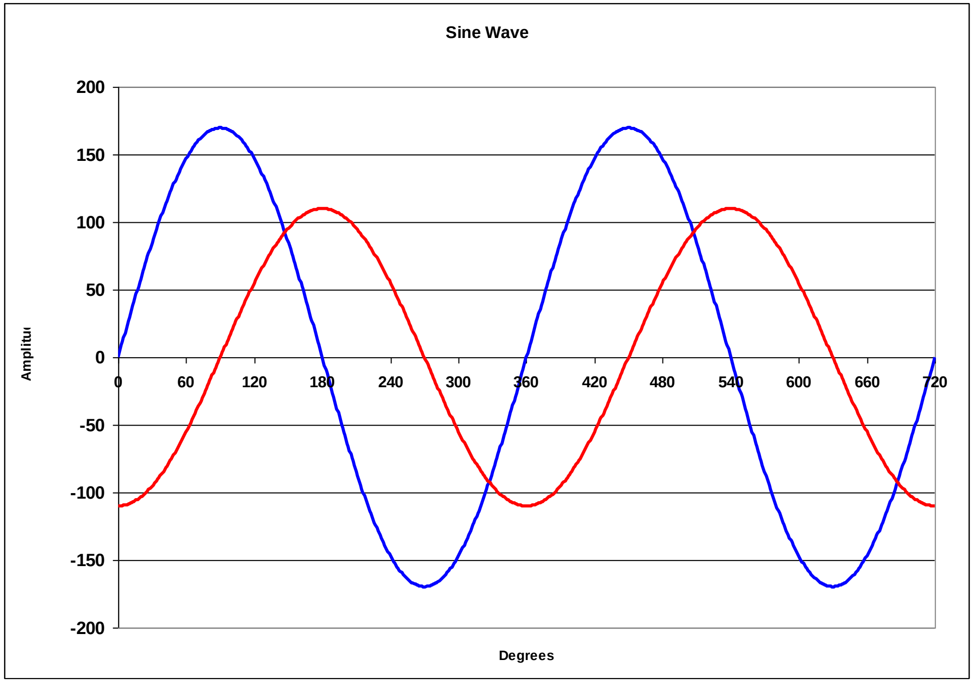


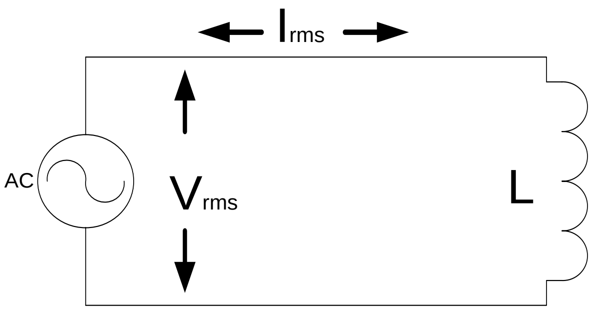


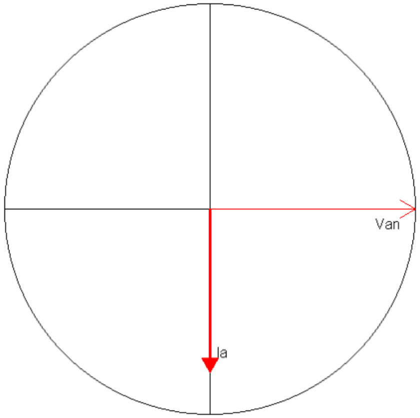


Resistors are measured in Ohms. When an AC voltage is applied to a resistor, the current is in degrees. A resistive load is considered a “linear” load because when the voltage is sinusoidal the current is sinusoidal.

AC Theory – Inductive Load

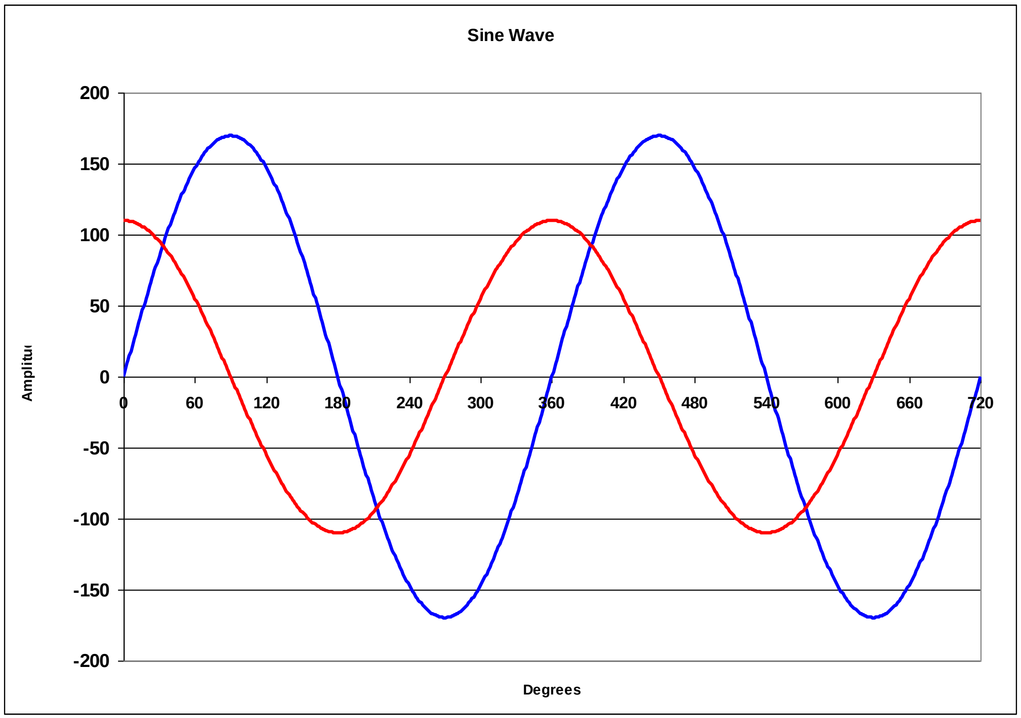


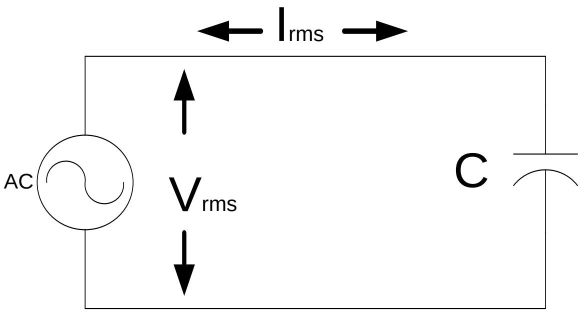


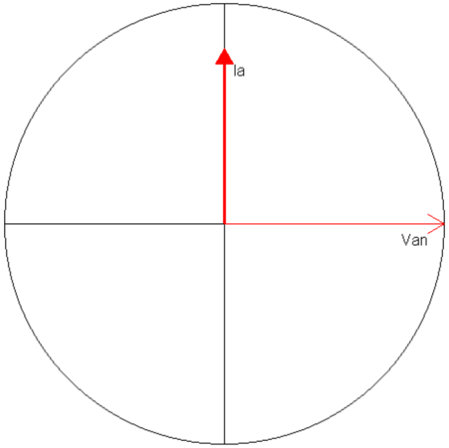


Inductors are measured in Henrys. When an AC voltage is applied to an inductor, the current is 90 degrees out of phase. We say the current "lags" the voltage. A inductive load is considered a "linear" load because when the voltage is sinusoidal the current is sinusoidal.

AC Theory – Capacitive Load







Capacitors are measured in Farads. When an AC voltage is applied to a capacitor, the current is 90 degrees out of phase. We say the current “leads” the voltage. A capacitive load is considered a “linear” load because when the voltage is sinusoidal the current is sinusoidal.

AC Theory – Active Power

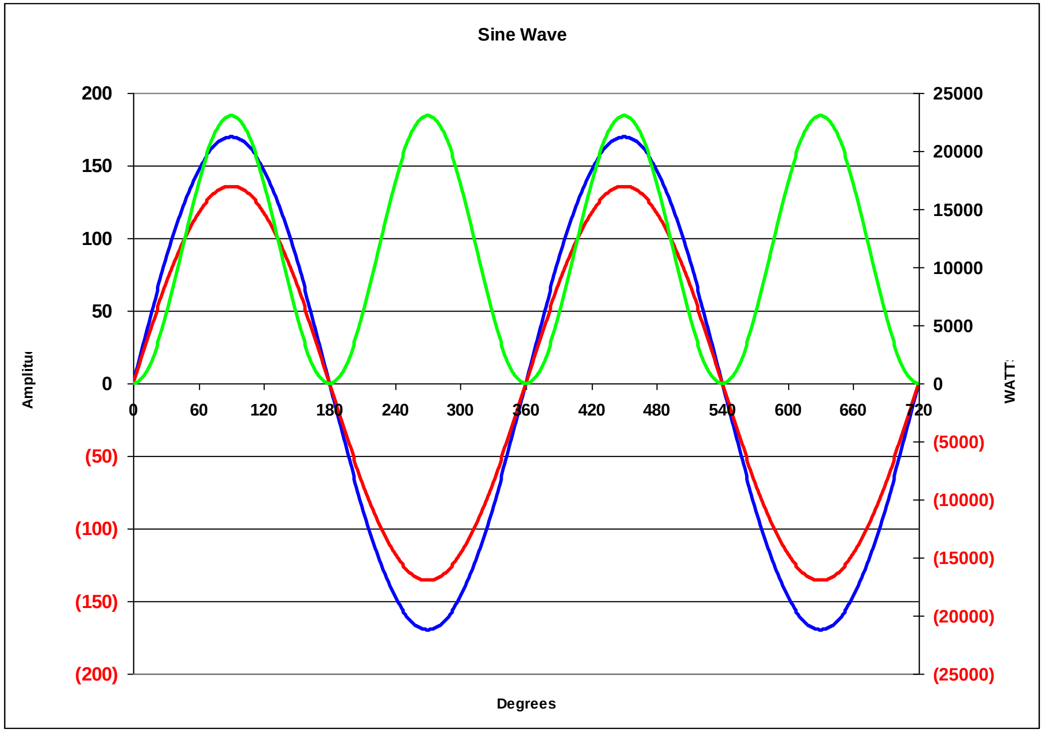
- **Active Power** is defined as   P = VI
- Power is a rate, i.e. Energy per unit time.
- The Watt is the unit for Power
  - 1 Watt = 1000 Joules/sec
- Since the voltage and current at every point in time for an AC signal is different, we have to distinguish between **instantaneous power** and **average power**.
- Generally when we say “power” we mean average power.

AC Theory – Energy

- Energy is power integrated over a period of time.
- The units of Energy are:
  - Watt-Hour (abbreviated Wh)
  - Kilowatt-Hour (abbreviated kWh)
- A Wh is the total energy consumed when a load draws one Watt for one hour.

AC Theory – Instantaneous Power

For a resistive load: $p = vi = 2VI\sin^2(\omega t) = VI(1-\cos(2\omega t))$



$V = 120\sqrt{2}\sin(2\pi ft)$

$I = 96\sqrt{2}\sin(2\pi ft)$

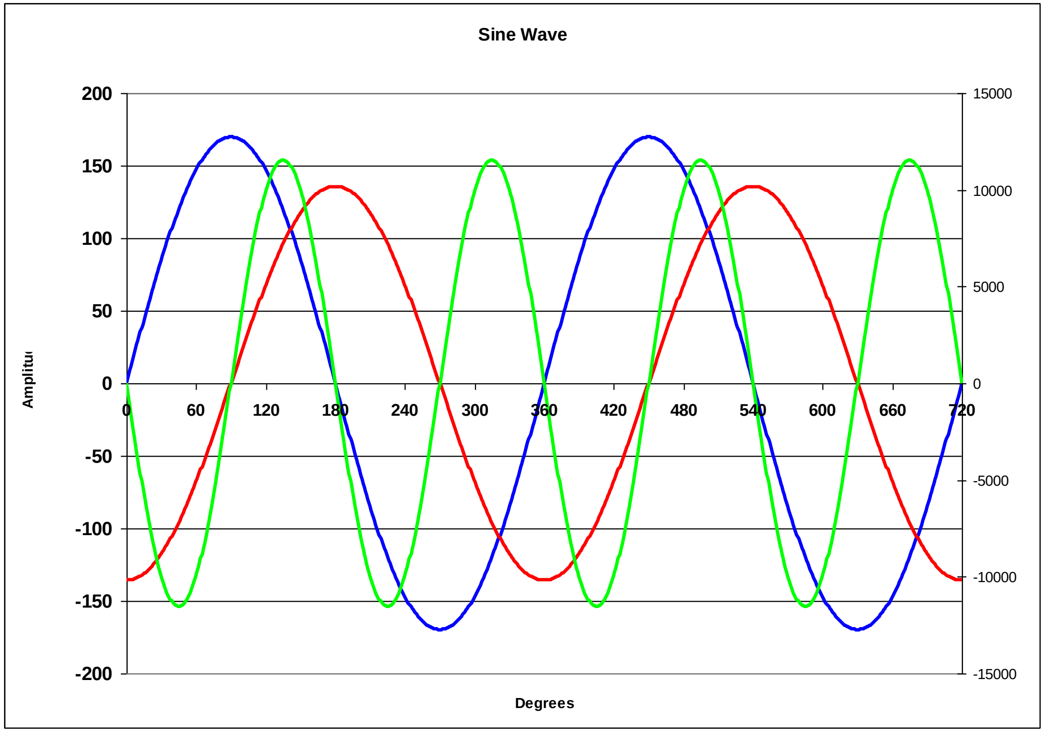
$P = 23040\sin^2(2\pi ft)$

P = 11520 Watts

AC Theory – Instantaneous Power

For an inductive load:

$$p = vi = 2VI\sin(\omega t)\sin(\omega t - 90) = -VI\sin(2\omega t)$$



$V = 120\sqrt{2}\sin(2\pi f t)$

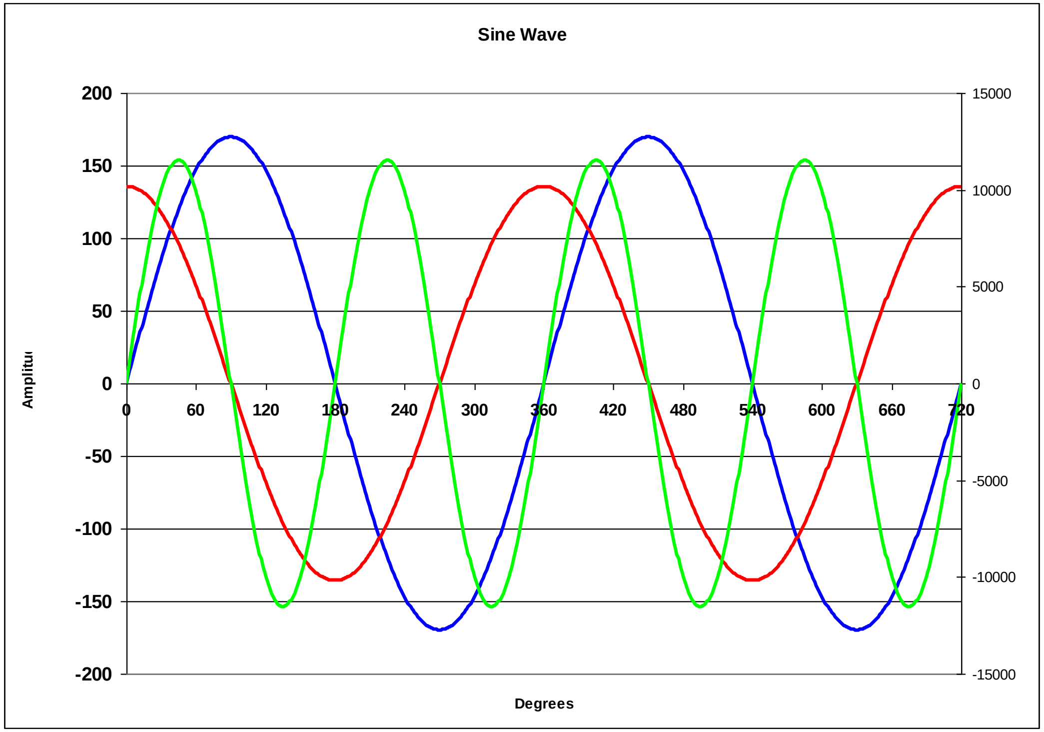
$I = 96\sqrt{2}\sin(2\pi f t - 90)$

$P = -11520\sin(2\pi f t)$

P = 0 Watts

AC Theory – Instantaneous Power

For an capacitive load: $p = vi = 2VISin(\omega t)Sin(\omega t + 90) = VISin(2\omega t)$



$V = 120\sqrt{2}\sin(2\pi ft)$

$I = 96\sqrt{2}\sin(2\pi ft + 90)$

$P = 11520\sin(2\pi ft)$

P = 0 Watts

AC Theory – Complex Circuits

- Impedance – The equivalent to the concept of resistance for an AC circuit. It is also measured in Ohms. Designated by the symbol X.
- In AC circuits non-resistive impedance affects both the amplitude and phase of the current.
- A resistor R has an impedance which is frequency independent. There is no phase shift.
- An inductor has an impedance which is proportional the frequency, $X_L = 2\pi fL$. The phase is shifted by 90 degrees lagging.
- A capacitor has an impedance which is inversely proportional the frequency, $X_C = 1/2\pi fC$. The phase is shifted by 90 degrees leading.

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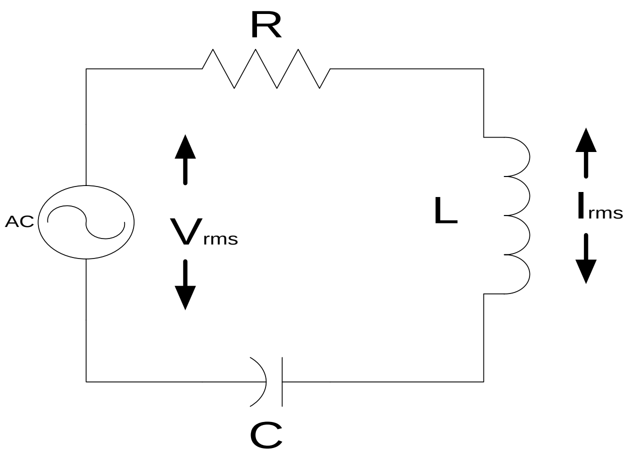
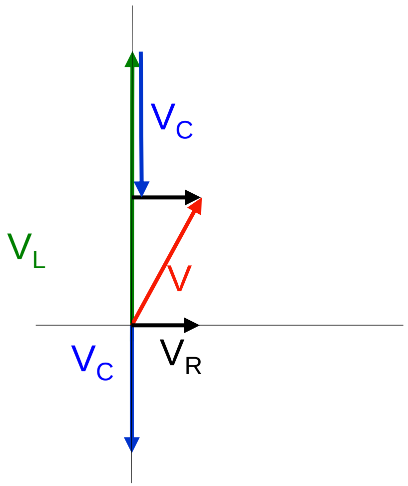
AC Theory – Complex Circuits



Amplitude (Current)

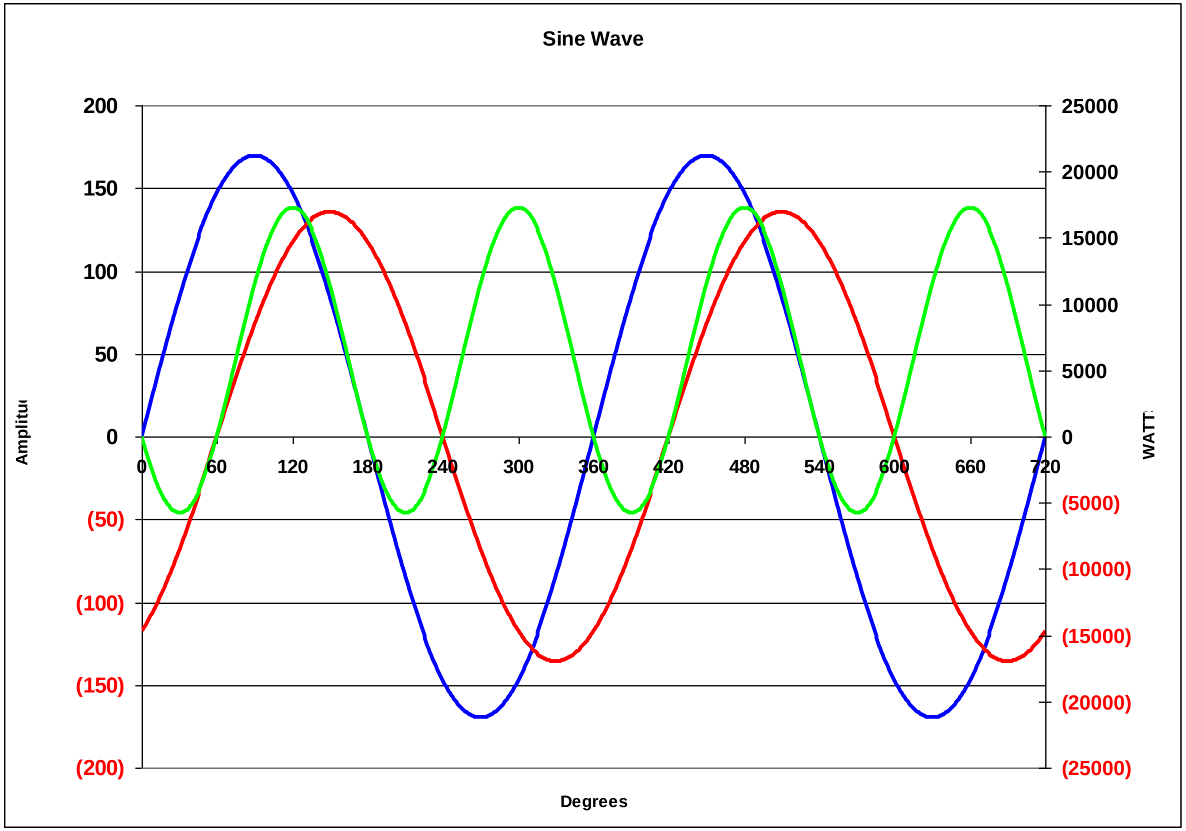
$$I = \frac{V}{\sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2}}$$



Phase (Current)

$$\varphi = \arctan\left[\frac{(\omega L - \frac{1}{\omega C})}{R}\right]$$

AC Theory – Instantaneous Power



$$V = 120\sqrt{2}\sin(2\pi ft)$$

$$I = 96\sqrt{2}\sin(2\pi ft - 60)$$

$$P = VI = 23040(\cos(60°) + \cos(4\pi ft - 60°)) = 19953 - 23040\cos(4\pi ft - 60°)$$

Time Out for Trig

(Right Triangles)

The Right Triangle:

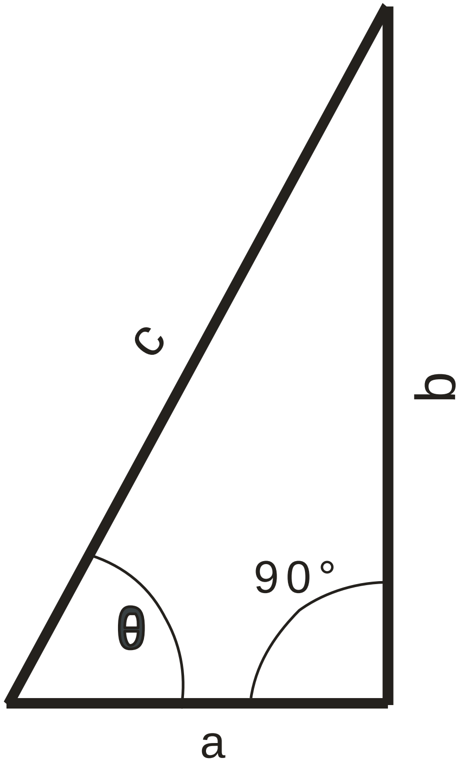
The Pythagorean theory

$$c^2 = a^2 + b^2$$

$$\sin(\theta) = \frac{b}{c}$$

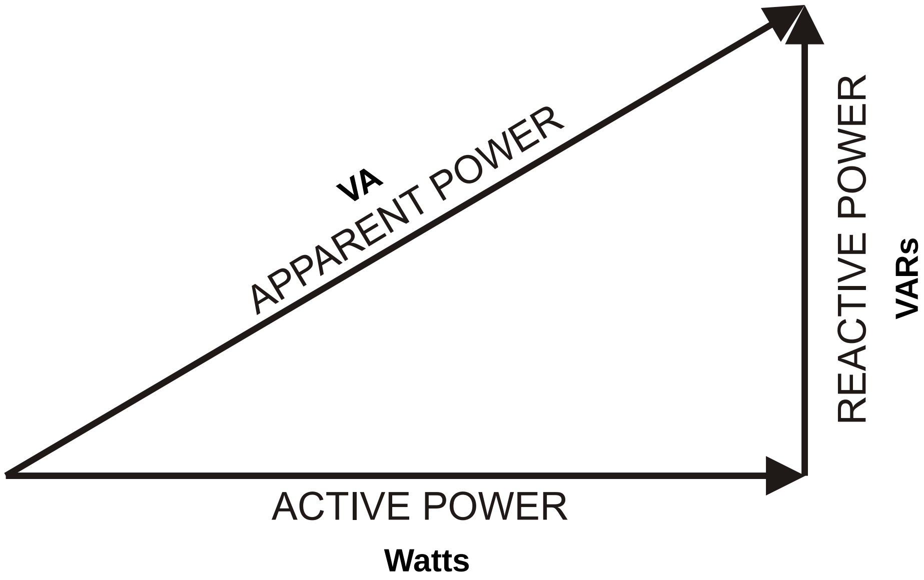
$$\cos(\theta) = \frac{a}{c}$$

$$\tan(\theta) = \frac{b}{a}$$



AC Theory – Power Triangle

(Sinusoidal Waveforms)



If V = sin(ωt) and I = sin(ωt - θ) (and the load is linear) then

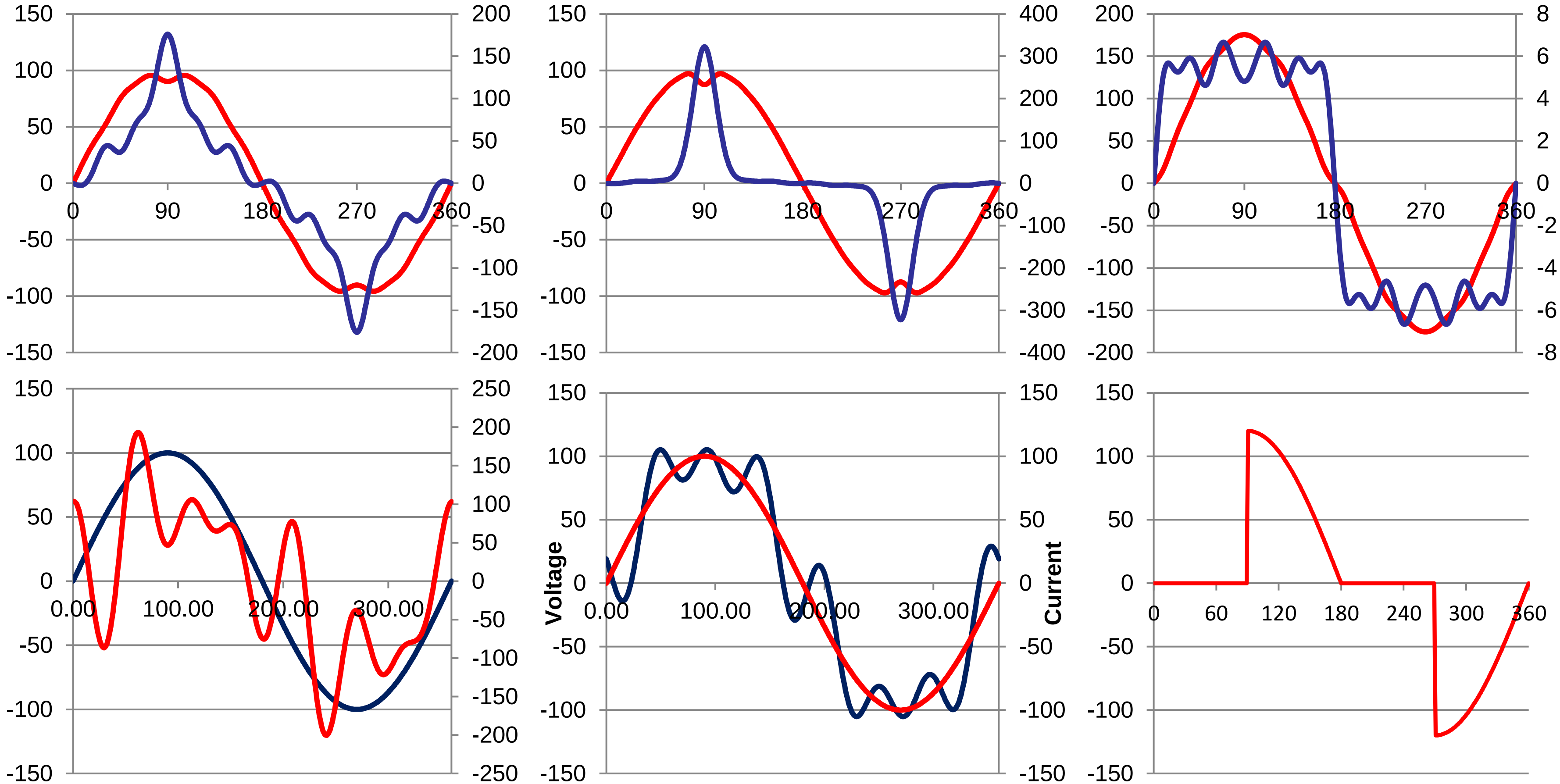
Active Power =	VI*cos*(θ)	Watts
Reactive Power =	VI*sin*(θ)	VARs
Apparent Power =	VI	VA
Power Factor =	Active/Apparent =	*cos*(θ)

Harmonics
Curse of the Modern World

- Every thing discussed so far was based on "Linear" loads.
  - For linear loads the current is always a simple sine wave. Everything we have discussed is true.
- For nearly a century after AC power was in use ALL loads were linear.
- Today, many loads are NON-LINEAR.

Harmonic Load Waveforms

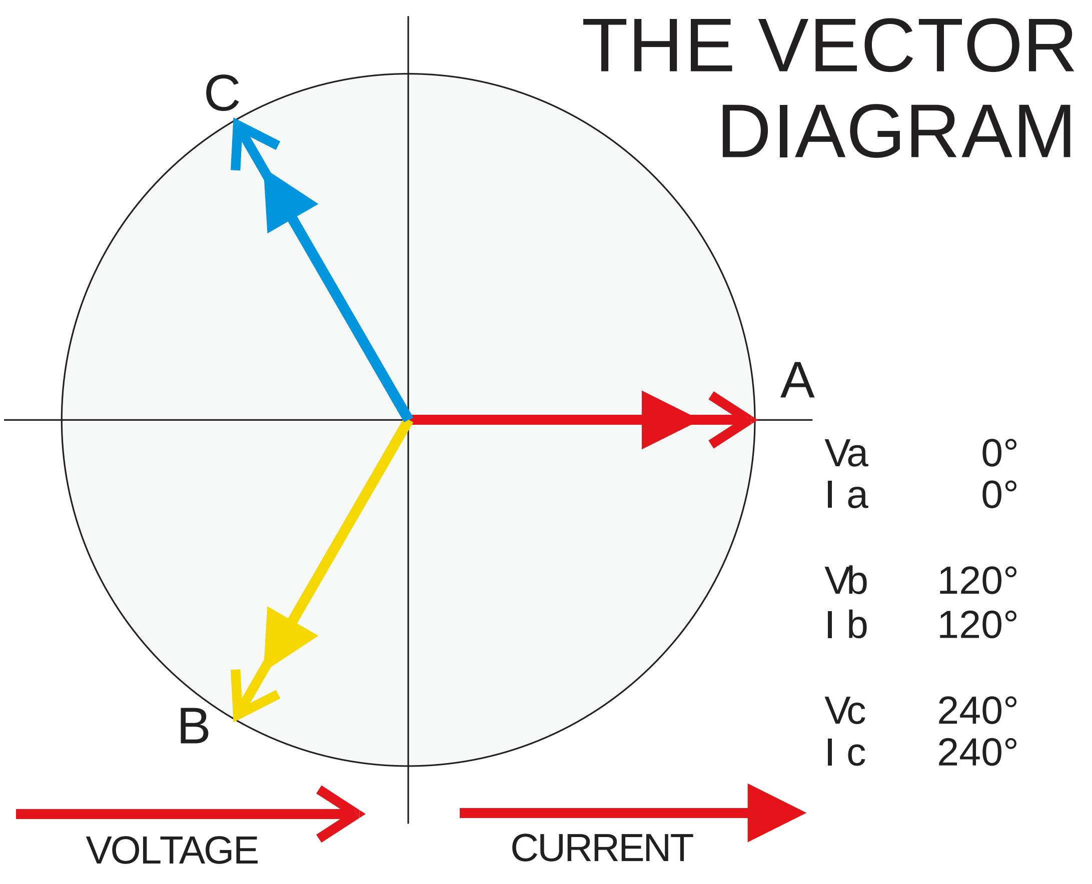
ANSI C12.20 now addresses harmonic waveforms as well as sinusoidal.



Test waveforms being proposed for ANSI C12.20.

AC Theory - Phasors

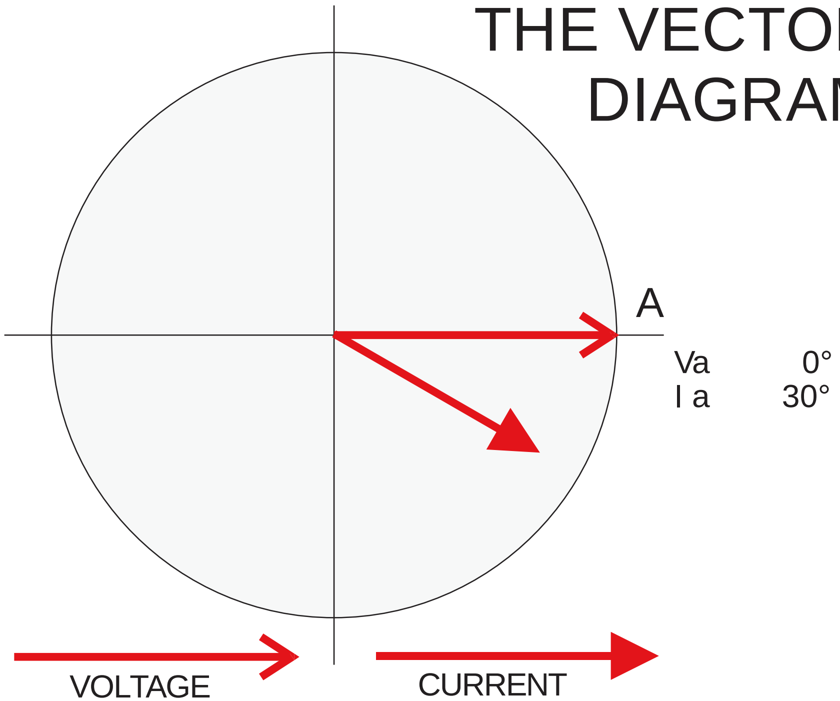
- An easier way to view AC data



AC Theory - Phasors

- The length of the phasor is proportional to the value of the quantity
- The angle of the phasor (by convention phase A is drawn as horizontal) shows the phase of the quantity relative to phase A voltage.
- Here the current “lags” the voltage by 30 degrees.

THE VECTOR DIAGRAM

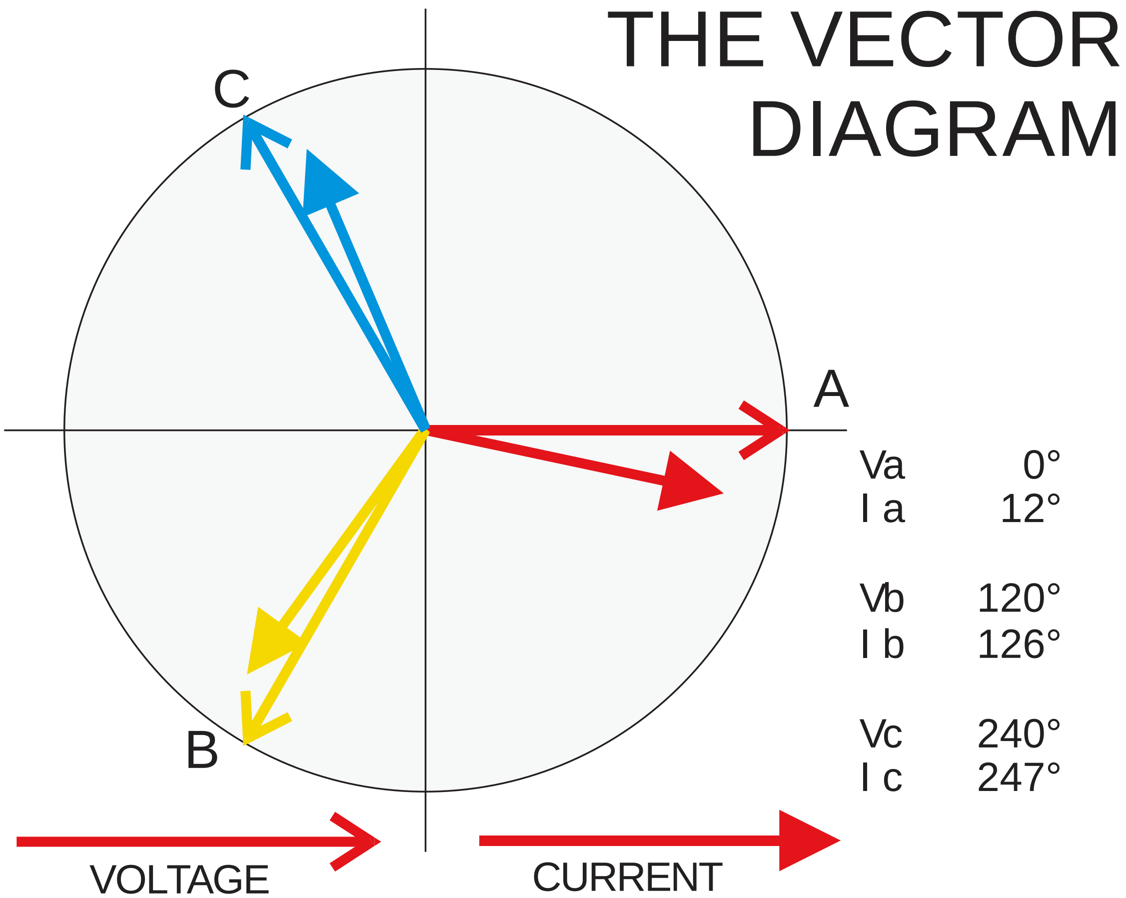


$$I = 2.5\sqrt{2}\sin(2\pi ft - 30)$$

$$V = 120\sqrt{2}\sin(2\pi ft - 0)$$

AC Theory - Phasors

Phasors are particularly useful in poly-phase situations



New Energy Definitions

- At the moment there is no non-sinusoidal definition for VA
- New ANSI Standard coming soon

C12.31

American National Standard

for Electricity Meters—
Measurement of VA and Power Factor

New Definitions

RMS Voltage

Eq. 4.1.4.1 $$V(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left(a_n \cos(n\omega_0 t) + b_n \sin(n\omega_0 t) \right)$$ Waveform

Eq. 4.2.4.1 $$V = \frac{1}{T} \int_0^T V^2(t) dt$$ Basic Definition

Eq. 4.2.4.2 $$V = \sqrt{\frac{1}{N} \sum_n V_n^2}$$ Time Domain

Eq. 4.2.4.3 $$V = \frac{1}{\sqrt{2}} \left[\sum_n (a_{vn}^2 + b_{vn}^2) \right]^{1/2}$$ Frequency Domain

New Definitions

RMS Current

Eq. 4.1.4.2 $$I(t) = \frac{c_0}{2} + \sum_{n=1}^{\infty} \left(c_n \cos(n\omega_0 t) + d_n \sin(n\omega_0 t) \right)$$ Waveform

Eq. 4.2.2.1 $$I = \frac{1}{T} \int_0^T I^2(t) dt$$ Basic Definition

Eq. 4.2.2.2 $$I = \sqrt{\frac{1}{N} \sum_n I_n^2}$$ Time Domain

Eq.4.2.2.3 $$I = \frac{1}{\sqrt{2}} \left[\sum_n (c_{vn}^2 + d_{vn}^2) \right]^{1/2}$$ Frequency Domain

New Definitions

Active Power

Eq. 4.2.3.1

$$P = \frac{1}{T}\int_0^T V(t)I(t)dt$$

Basic Definition

Eq. 4.2.3.2

$$P = \frac{1}{N}\sum\nolimits_{i=0}^{i=N-1} V_i I_i$$

Time Domain

Eq. 4.2.3.3

$$P = \frac{1}{2}\sum_n \left|\vec{V}_n \bullet \vec{I}_n\right| = \frac{1}{2}\sum_n (a_n c_n + b_n d_v)$$

$$= \frac{1}{2}\sum_n V_n I_n \cos(\theta_n)$$

Frequency Domain

New Definitions

Apparent Power

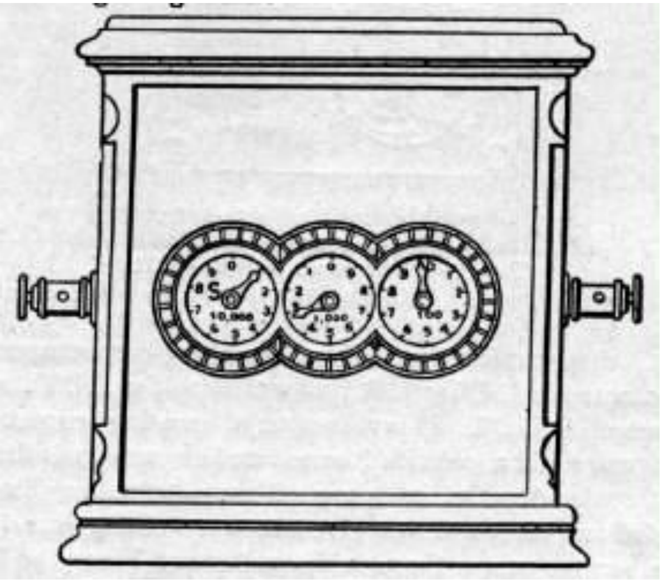
Eq. 4.2.3.1 $$S = \sqrt{\frac{1}{T}\int_0^T V^2(t)dt}\,\sqrt{\frac{1}{T}\int_0^T I^2(t)dt}$$ Basic Definition

Eq. 4.2.3.2 $$S = VA = \sqrt{\frac{1}{N}\sum_{i=0}^{i=N-1} V_i^2 \bullet \frac{1}{N}\sum_{i=0}^{i=N-1} I_i^2}$$ Time Domain

Eq. 4.2.3.3 $$S = \frac{1}{2}\left[\sum_n (a_n^2 + b_n^2)\sum_n (c_n^2 + d_n^2)\right]^{1/2}$$ Frequency Domain

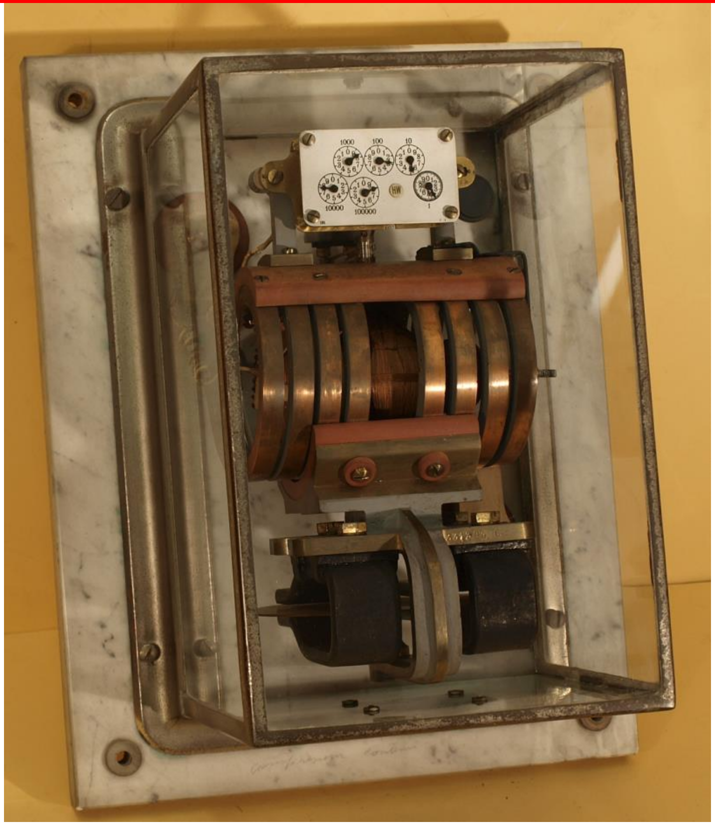
What about DC?

- We have had DC Metering since the 1870's.
- The first patented meter was a DC meter in 1872, six years before the first AC meter.



Elihu Thomson

- 1889 Thomson introduced his recording wattmeter (AC or DC – a commutator-type meter).
- This was the first true watthour meter, and it was an immediate commercial success, many utilities adopting it as their "standard" model.
- Although this meter was initially designed for use on AC circuits, it worked equally well with the DC circuits in use at the time.
- The introduction and rapid acceptance of induction-type watthour meters in the late 1890s relegated the use of this commutator-type meter to DC circuits.



DC Theory?

No need for new definitions. Power is simply VA. If we can measure the fundamental Volt and the fundamental Amp then we can create a Standard to measure against and can effectively test our DC meter.

What about DC?

- There are still a number of DC meters out on our systems, primarily in the larger, older urban areas such as San Francisco and New York City.
- There has been no effective way to test these legacy meters for some time. This is shortcoming was highlighted as new DC metering applications have begun to make an appearance on the grid and are demanding we find a solution (e.g. DC superchargers)
- Using labs with traceable Voltage sources and measurement capabilities and traceable Current sources and measurement capabilities we are now starting to do this.

ANSI C12.32

- As always, the theory is only the start. We now need to take this theory and create a practical process. For AC Meters we have been using ANSI C12.1 for many years to guide us on how to move from theory to practice.
- We have never had a comparable Standard for DC Metering
- ANSI Standard ANSI C12.32 for Electricity Meters for the Measurement of DC Energy has been developed over the past several years and is actively being balloted and is expected to be released in 2022.
- This Standard lays out the tests, the definitions, the acceptable performance levels for accuracy as well as functional testing.
- Definitions are given and the practical means of type testing as well as acceptance testing are given.

Questions and Discussion

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