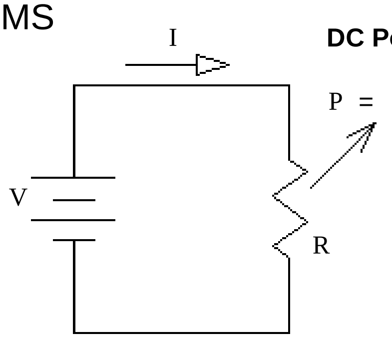
ECE 3600 Lecture 3 & 4 notes Introduction to AC Power, RMS

A. Stolp
3/31/09,
2/20/10,
8/29/11
4/15/20

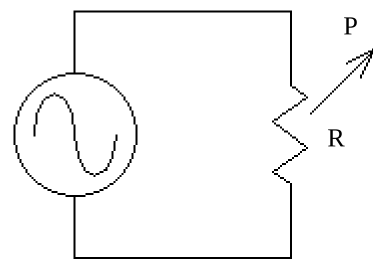
RMS

DC Power

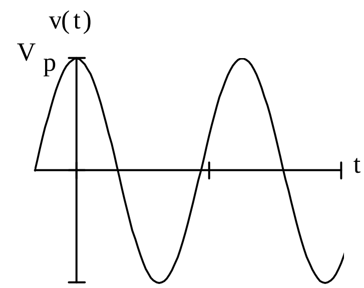


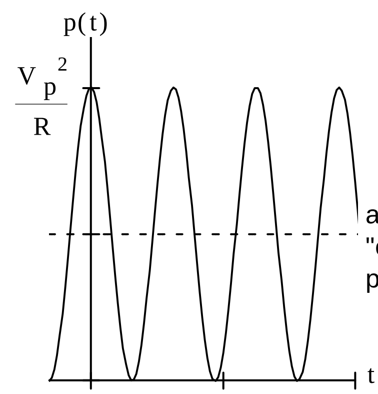
$$P = V \cdot I = \frac{V^2}{R} = I^2 \cdot R$$

AC Power



$$v(t) = V_p \cdot \cos(\omega \cdot t)$$





average or "effective" power = $\dfrac{\left(\dfrac{V_p^{\,2}}{R}\right)}{2}$

Couldn't we define an "effective" voltage that would allow us to use the same relationships for AC power as used for DC power?

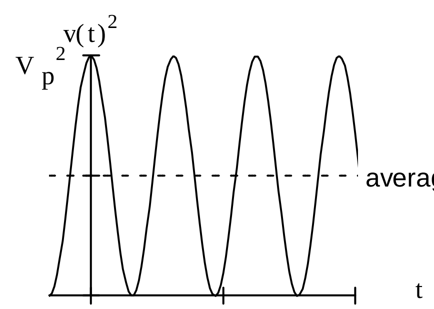
$$P_{ave} = \frac{\left(\frac{V_p^{\,2}}{R}\right)}{2} = \frac{\left(\frac{V_p^{\,2}}{2}\right)}{R} = \frac{\left(\frac{V_p}{\sqrt{2}}\right)^2}{R}$$

$$V_{eff} = \sqrt{\left(\frac{V_p}{\sqrt{2}}\right)^2} = \frac{V_p}{\sqrt{2}} = V_{rms} = \sqrt{\frac{1}{T}\cdot\int_0^T (v(t))^2\,dt}$$

Square

Mean (average)

Root



average = $\dfrac{V_p^{\,2}}{2}$

RMS **R**oot of the **M**ean of the **S**quare

Use RMS in power calculations

Sinusoids

$$V_{rms} = \sqrt{\frac{1}{T}\cdot\int_0^T (v(t))^2\,dt} = \sqrt{\frac{1}{T}\cdot\int_0^T \left(V_p\cdot\cos(\omega\cdot t)\right)^2 dt} = \sqrt{\frac{1}{T}\cdot\int_0^T V_p^{\,2}\cdot\left(\frac{1}{2}+\frac{1}{2}\cdot\cos(2\cdot\omega\cdot t)\right) dt}$$

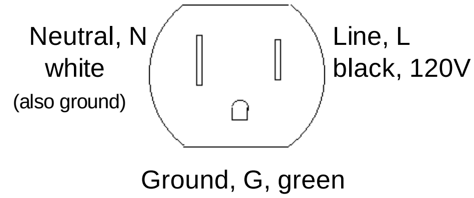
$$= \frac{V_p}{\sqrt{2}}\cdot\sqrt{\frac{1}{T}\cdot\int_0^T (1)\,dt + \frac{1}{T}\cdot\int_0^T \cos(2\cdot\omega\cdot t)\,dt} = \frac{V_p}{\sqrt{2}}\cdot\sqrt{1+0}$$

Common household power

$$f = 60 \cdot Hz$$

$$\omega = 377 \cdot \frac{rad}{sec}$$

$$T = 16.67 \cdot ms$$

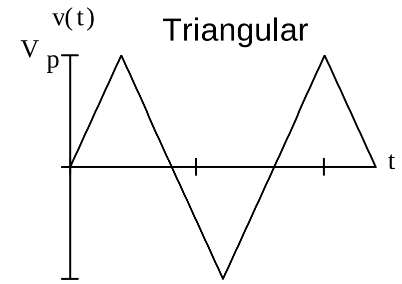


$$V_{rms} := 120 \cdot V$$

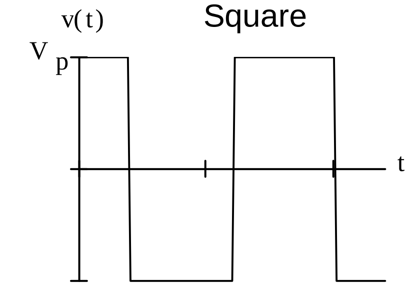
$$V_p = V_{rms} \cdot \sqrt{2} = 170 \cdot V$$

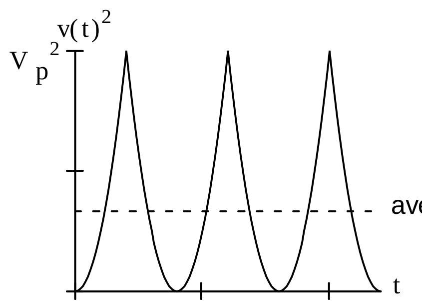
What about other wave shapes??

Triangular

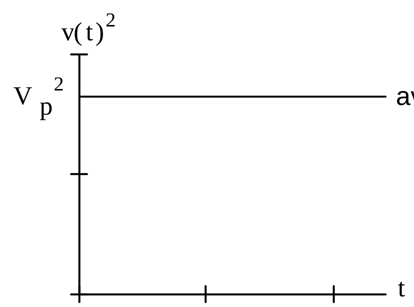


Square





average = $\frac{V_p^2}{3}$



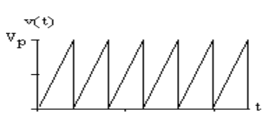
average = V_p^2

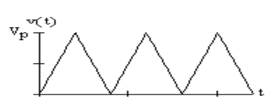
$$V_{rms} = \frac{V_p}{\sqrt{3}}$$

$$V_{rms} = V_p$$

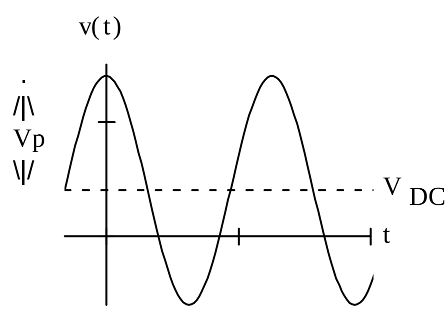
Works for all types of triangular and sawtooth waveforms

Same for DC





How about AC + DC ?



$$V_{rms} = \sqrt{\frac{1}{T} \cdot \int_0^T (v(t))^2 \, dt}$$

$$= \sqrt{\frac{1}{T} \cdot \int_0^T \left(V_p \cdot \cos(\omega \cdot t) + V_{DC}\right)^2 dt}$$

$$= \sqrt{\frac{1}{T} \cdot \int_0^T \left[\left(V_p \cdot \cos(\omega \cdot t)\right)^2 + 2 \cdot \left(V_p \cdot \cos(\omega \cdot t)\right) \cdot V_{DC} + V_{DC}^2\right] dt}$$

$$= \sqrt{\frac{1}{T} \cdot \int_0^T \left(V_p \cdot \cos(\omega \cdot t)\right)^2 dt + \frac{1}{T} \cdot \int_0^T 2 \cdot \left(V_p \cdot \cos(\omega \cdot t)\right) \cdot V_{DC} \, dt + \frac{1}{T} \cdot \int_0^T V_{DC}^2 \, dt}$$

- - - zero over one period - - -

$$= \sqrt{V_{rmsAC}^2 + 0 + V_{DC}^2} \qquad = \sqrt{V_{rmsAC}^2 + V_{DC}^2}$$

sinusoid: $V_{rms} = \dfrac{V_p}{\sqrt{2}}$ $\quad I_{rms} = \dfrac{I_p}{\sqrt{2}}$

triangular: $V_{rms} = \dfrac{V_p}{\sqrt{3}}$ $\quad I_{rms} = \dfrac{I_p}{\sqrt{3}}$

square: $V_{rms} = V_p$ $\quad I_{rms} = I_p$

waveform + DC $\quad V_{rms} = \sqrt{V_{rmsAC}^2 + V_{DC}^2}$

<u>rectified average</u> $\quad V_{ra} = \dfrac{1}{T}\cdot\displaystyle\int_0^T |v(t)|\, dt$

$V_{ra} = \dfrac{2}{\pi}\cdot V_p$ $\quad I_{ra} = \dfrac{2}{\pi}\cdot I_p$

$V_{ra} = \dfrac{1}{2}\cdot V_p$ $\quad I_{ra} = \dfrac{1}{2}\cdot I_p$

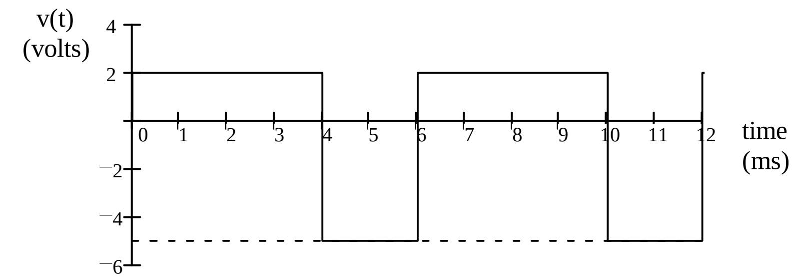
$V_{ra} = V_{rms} = V_p$ $\quad I_{ra} = I_{rms} = I_p$

Most AC meters don't measure true RMS. Instead, they measure V_{ra} , display $1.11V_{ra}$, and call it RMS. That works for sine waves but not for any other waveform.

Use RMS in power calculations

Some waveforms don't fall into these forms, then you have to perform the math from scratch

For waveform shown

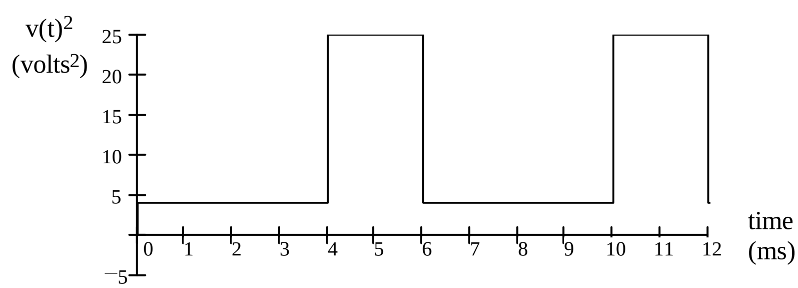


The average DC (V_{DC}) value

$$\frac{2\cdot V\cdot(4\cdot ms) + (-5\cdot V)\cdot(2\cdot ms)}{6\cdot ms} = -0.333\cdot V$$

The RMS (effective) value

Graphical way



$$\frac{4\cdot V^2\cdot(4\cdot ms) + 25\cdot V^2\cdot(2\cdot ms)}{6\cdot ms} = 11\cdot V^2$$

$V_{RMS} := \sqrt{11\cdot V^2}$ $\qquad V_{RMS} = 3.32\cdot V$

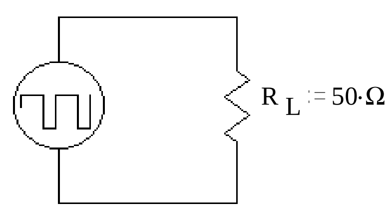
OR...

$$V_{RMS} = \sqrt{\frac{1}{T}\cdot\int_0^T (v(t))^2\, dt}$$

$$= \sqrt{\frac{1}{6\cdot ms}\cdot\left[\int_{0\cdot ms}^{4\cdot ms}(2\cdot V)^2\, dt + \int_{4\cdot ms}^{6\cdot ms}(-5\cdot V)^2\, dt\right]} = \sqrt{\frac{1}{6\cdot ms}\cdot\left[4\cdot ms\cdot(2\cdot V)^2 + 2\cdot ms\cdot(-5\cdot V)^2\right]} = 3.32\cdot V$$

The voltage is hooked to a resistor, as shown, for 6 seconds.

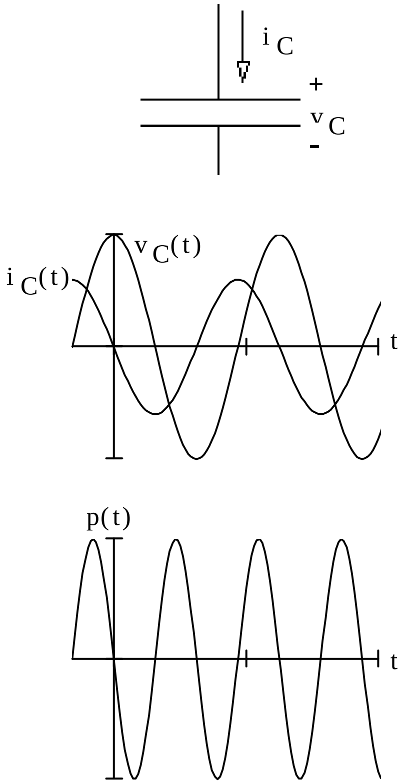
The energy is transferred to the resistor during that 6 seconds:

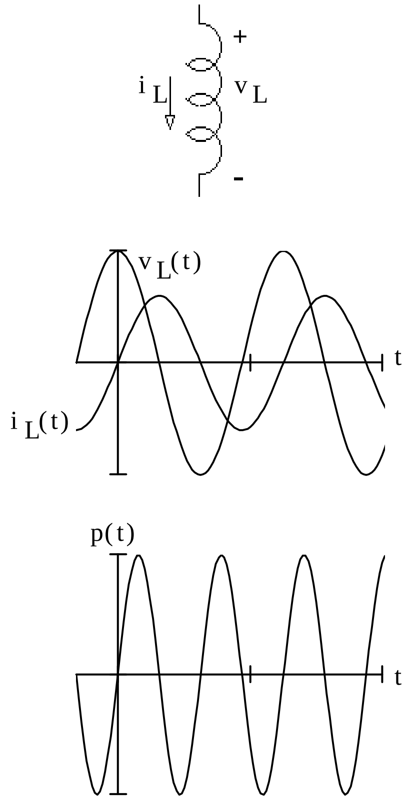


$P_L := \dfrac{V_{RMS}^{\ 2}}{R_L}$ $\qquad P_L = 0.22\cdot W$

$W_L := P_L\cdot 6\cdot sec$ $\qquad W_L = 1.32\cdot joule$ All converted to heat

Capacitors and Inductors





Average power is ZERO $P = 0$

Average power is ZERO $P = 0$

Capacitors and Inductors DO NOT dissipate (real) average power.

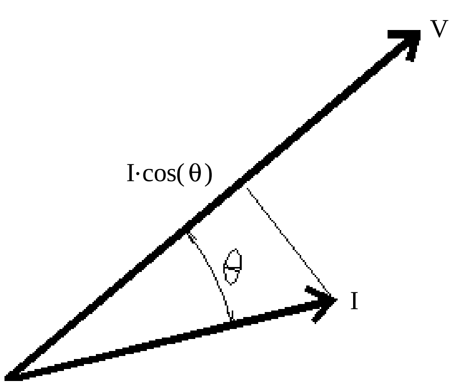
Reactive power is negative

$$Q_C = -I_{Crms} \cdot V_{Crms} = -I_{Crms}^2 \cdot \frac{1}{\omega \cdot C} = -V_{Crms}^2 \cdot \omega \cdot C$$

Reactive power is positive

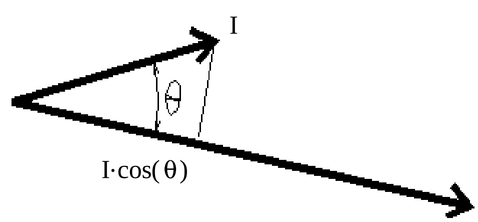
$$Q_L = I_{Lrms} \cdot V_{Lrms} = I_{Lrms}^2 \cdot \omega \cdot L = \frac{V_{Lrms}^2}{\omega \cdot L}$$

If current and voltage are not in phase, only the in-phase part of the current matters for the power-- DOT PRODUCT



"Lagging" power

Inductor dominates



"Leading" Power

Capacitor dominates

All voltages and currents shown are RMS

BOLD is a complex number

Real Power

$$P = V \cdot I \cdot \cos(\theta) = I^2 \cdot |\mathbf{Z}| \cdot \cos(\theta) = \frac{V^2}{|\mathbf{Z}|} \cdot \cos(\theta)$$

P = "Real" Power (average) = $V \cdot I \cdot pf = I^2 \cdot |\mathbf{Z}| \cdot pf = \frac{V^2}{|\mathbf{Z}|} \cdot pf$ units: watts, kW, MW, etc.

$pf = \cos(\theta)$ = power factor

otherwise....

I_R, V_R for resistors only part that uses real average power $P = I_R^2 \cdot R = \frac{V_R^2}{R}$

Reactive Power

Q = Reactive "power" = $V \cdot I \cdot \sin(\theta)$ units: VAR, kVAR, etc. "volt-amp-reactive"

otherwise....

I_C, V_C capacitors -> - Q $Q_C = I_C^2 \cdot X_C = \frac{V_C^2}{X_C}$ $X_C = -\frac{1}{\omega \cdot C}$ and is a negative number

I_L, V_L inductors -> + Q $Q_L = I_L^2 \cdot X_L = \frac{V_L^2}{X_L}$ $X_L = \omega \cdot L$ and is a positive number

Complex and Apparent Power

complex conjugate

$\mathbf{S}$ = Complex "power" = $P + jQ = VI\,\underline{/\theta} = \mathbf{V} \cdot \overline{\mathbf{I}} = I^2 \cdot \mathbf{Z}$ units: VA, kVA, etc. "volt-amp"

NOT $\mathbf{V} \cdot \mathbf{I}$ **NOR** $\frac{V^2}{\mathbf{Z}}$

S = Apparent "power" = $|\mathbf{S}| = \sqrt{P^2 + Q^2} = V \cdot I$ units: VA, kVA, etc. "volt-amp"

Power factor

$pf = \cos(\theta)$ = power factor (sometimes expressed in %) $0 \le pf \le 1$

θ is the **phase angle** between the voltage and the current or the phase angle of the impedance. $\theta = \theta_Z$

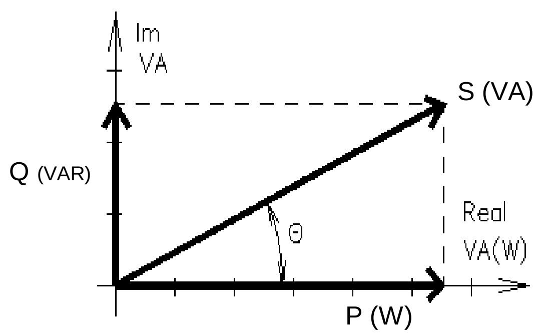
$\theta < 0$ Load is "Capacitive", power factor is "leading". This condition is very rare

$\theta > 0$ Load is "Inductive", power factor is "lagging". This condition is so common you can assume any power factor given is lagging unless specified otherwise. Transformers and motors make most loads inductive.

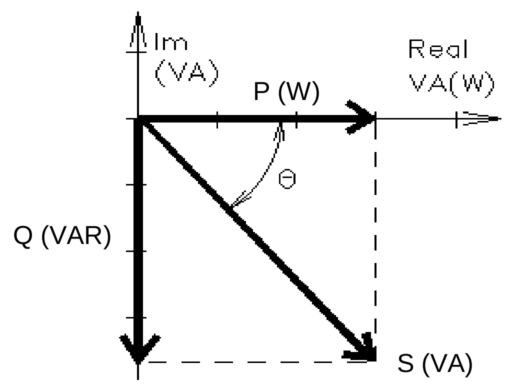
Industrial users are charged for the reactive power that they use, so power factor < 1 is a bad thing.

Power factor < 1 is also bad for the power company. To deliver the same power to the load, they have more line current (and thus more line losses).

Power factors are "corrected" by adding capacitors (or capacitve loads) in parallel with the inductive loads which cause the problems. (In the rare case that the load is capacitive, the pf would be corrected by an inductor.)



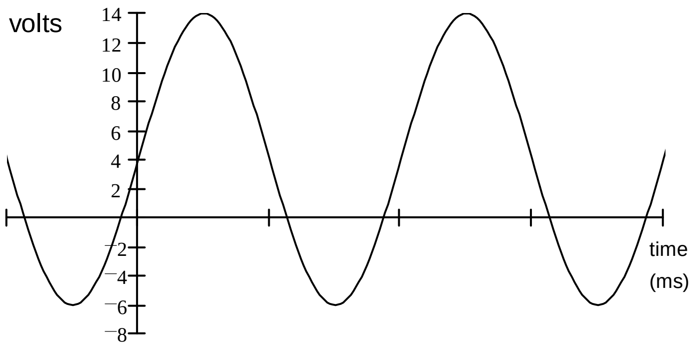
"Lagging" power



"Leading" Power

ECE 3600 RMS Examples

Ex. 1 Find the DC and RMS of the following waveform



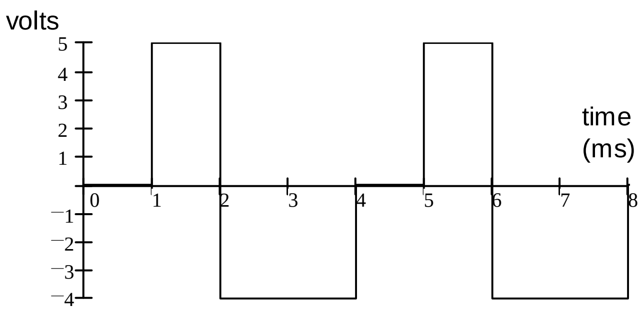
$$V_{DC} := \frac{14\cdot V + -6\cdot V}{2} \qquad V_{DC} = 4\cdot V$$

$$V_{pp} := 14\cdot V - -6\cdot V \qquad V_{pp} = 20\cdot V$$

$$V_{RMS} := \sqrt{\left(\frac{V_{pp}}{2\cdot\sqrt{2}}\right)^2 + V_{DC}^{\,2}}$$

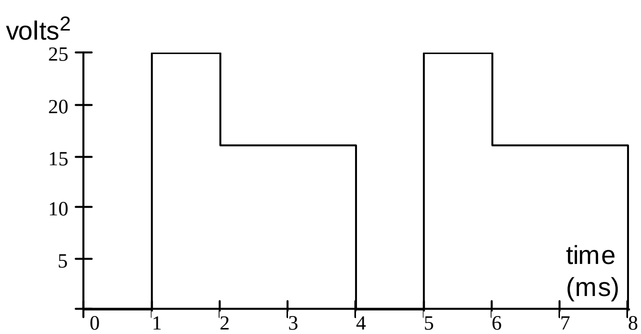
$$V_{RMS} = 8.12\cdot V$$

Ex. 2 Find the DC, rectified average and RMS of the following waveform



$$V_{DC} = \frac{0\cdot V\cdot(1\cdot ms) + 5\cdot V\cdot(1\cdot ms) + (-4\cdot V)\cdot(2\cdot ms)}{4\cdot ms} = -0.75\cdot V$$

$$V_{RA} = \frac{0\cdot V\cdot(1\cdot ms) + 5\cdot V\cdot(1\cdot ms) + \left|-4\cdot V\right|\cdot(2\cdot ms)}{4\cdot ms} = 3.25\cdot V$$



RMS (effective) value

Graphical way

$$\frac{(0\cdot V)^2\cdot(1\cdot ms) + (5\cdot V)^2\cdot(1\cdot ms) + (-4\cdot V)^2\cdot(2\cdot ms)}{4\cdot ms} = 14.25\cdot V^2$$

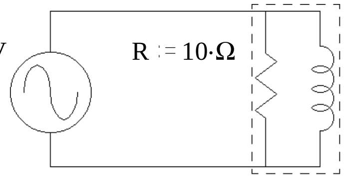
$$V_{RMS} = \sqrt{14.25\cdot V^2} = 3.77\cdot V$$

AC Power Examples

A.Stolp
11/06/02
rev 8/28/20

Ex. 1 R & L together are the load. Find the real power P, the reactive power Q, the complex power **S**, the apparent power |**S**|, & the power factor pf. Draw phasor diagram for the power.

$\mathbf{V}_{in} := 110 \cdot V$ $\quad \omega := 377 \cdot \frac{rad}{sec}$



$R := 10 \cdot \Omega$ $\quad L := 25 \cdot mH$ $\quad$ load

$$\mathbf{Z} := \frac{1}{\left(\frac{1}{R} + \frac{1}{j \cdot \omega \cdot L}\right)} = \frac{1}{0.1458 \cdot \frac{1}{\Omega} \cdot e^{-j \cdot 46.7 \cdot deg}}$$

$\mathbf{Z} = 4.704 + 4.991j \ \cdot \Omega$ $\quad |\mathbf{Z}| = 6.859 \cdot \Omega$ $\quad \theta := \arg(\mathbf{Z})$ $\quad \theta = 46.7 \cdot deg$ $\quad pf := \cos(\theta)$ $\quad pf = 0.686$

$\mathbf{I} := \frac{\mathbf{V}_{in}}{\mathbf{Z}}$ $\quad \mathbf{I} = 11 - 11.671j \ \cdot A$ $\quad |\mathbf{I}| = 16.038 \cdot A$ $\quad \arg(\mathbf{I}) = -46.7 \cdot deg$

$P := |\mathbf{V}_{in}| \cdot |\mathbf{I}| \cdot pf$ $\quad P = 1.21 \cdot kW$

$Q := |\mathbf{V}_{in}| \cdot |\mathbf{I}| \cdot \sin(\theta)$ $\quad Q = 1.284 \cdot kVAR$ $\quad$ OR... $\quad Q := |\mathbf{V}_{in}| \cdot |\mathbf{I}| \cdot \sqrt{1^2 - pf^2}$ $\quad Q = 1.284 \cdot kVAR$

$\mathbf{S} := \mathbf{V}_{in} \cdot \overline{\mathbf{I}}$ OR.. $\mathbf{S} := P + j \cdot Q$ $\quad \mathbf{S} = 1.21 + 1.284j \ \cdot kVA$ $\quad S := \sqrt{\mathrm{Re}(\mathbf{S})^2 + \mathrm{Im}(\mathbf{S})^2} = |\mathbf{S}| = 1.764 \cdot kVA$

$\mathrm{atan}\left(\frac{\mathrm{Im}(\mathbf{S})}{\mathrm{Re}(\mathbf{S})}\right) = 46.696 \cdot deg$

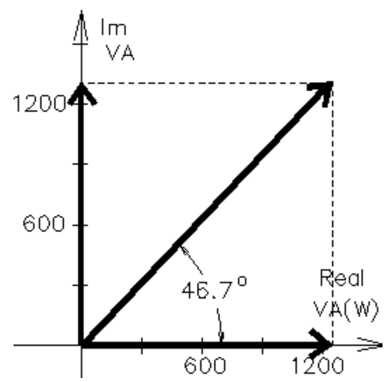
S = 1.764kVA $\underline{/46.7^o}$

OR, since we know that the voltage across each element of the load is V_{in} ...
Real power is dissipated only by resistors

$P := \frac{(|\mathbf{V}_{in}|)^2}{R}$ $\quad P = 1.21 \cdot kW$ $\quad Q := \frac{(|\mathbf{V}_{in}|)^2}{\omega \cdot L}$ $\quad Q = 1.284 \cdot kVAR$

$\mathbf{S} := P + j \cdot Q$

$S = |\mathbf{S}| = \sqrt{P^2 + Q^2} = 1.764 \cdot kVA$ $\quad pf = \frac{P}{|\mathbf{S}|} = 0.686$



What value of C in parallel with R & L would make pf = 1 (Q = 0) ?

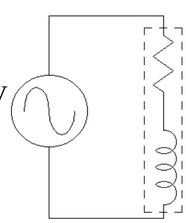
$\mathrm{Im}(\mathbf{I}) = -11.671 \cdot A$ $\quad X_C := \frac{\mathbf{V}_{in}}{\mathrm{Im}(\mathbf{I})}$ $\quad X_C = -9.425 \cdot \Omega = \frac{-1}{\omega \cdot C}$

$\frac{1}{|X_C| \cdot \omega} = 281 \cdot \mu F$ $\quad$ OR.. $\quad \omega = \frac{1}{\sqrt{L \cdot C}}$ $\quad C := \frac{1}{L \cdot \omega^2}$ $\quad C = 281 \cdot \mu F$

Ex. 2 R & L together are the load. Find the real power P, the reactive power Q, the complex power **S**, the apparent power |**S**|, & the power factor pf. Draw phasor diagram for the power.

Series R & L

$\mathbf{V}_{in} := 110 \cdot V$ $\quad \omega := 377 \cdot \frac{rad}{sec}$



$R := 10 \cdot \Omega$ $\quad$ load $\quad L := 25 \cdot mH$

$\mathbf{Z} := R + j \cdot \omega \cdot L$

$\mathbf{Z} = 10 + 9.425j \ \cdot \Omega$ $\quad |\mathbf{Z}| = 13.742 \cdot \Omega$

$\theta := \arg(\mathbf{Z})$ $\quad \theta = 43.304 \cdot deg$ $\quad pf := \cos(\theta)$ $\quad pf = 0.728$

$\mathbf{I} := \frac{\mathbf{V}_{in}}{\mathbf{Z}}$ $\quad \mathbf{I} = 5.825 - 5.49j \ \cdot A$

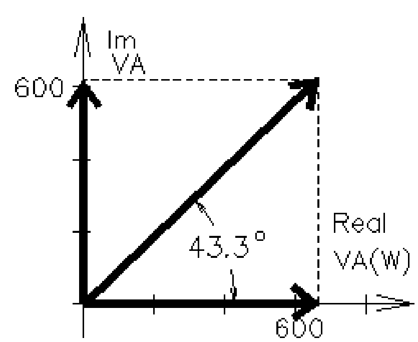
$|\mathbf{I}| = 8.005 \cdot A$ $\quad \arg(\mathbf{I}) = -43.304 \cdot deg$

$P := |\mathbf{V}_{in}| \cdot |\mathbf{I}| \cdot pf$ $\quad P = 0.641 \cdot kW$

$Q := |\mathbf{V}_{in}| \cdot |\mathbf{I}| \cdot \sin(\theta)$ $\quad Q = 0.604 \cdot kVAR$

$\mathbf{S} := \mathbf{V}_{in} \cdot \overline{\mathbf{I}}$ $\quad \mathbf{S} = 0.641 + 0.604j \ \cdot kVA$

$|\mathbf{S}| = 0.881 \cdot kVA$ $\quad \arg(\mathbf{S}) = 43.304 \cdot deg$ $\quad$ **S** = 881VA$\underline{/43.3^o}$



OR, if we first find the magnitude of the current which flows through each element of the load...

$$|\mathbf{I}| = \frac{\mathbf{V_{in}}}{\sqrt{R^2 + (\omega \cdot L)^2}} = 8.005 \cdot A$$

$P := (|\mathbf{I}|)^2 \cdot R$ $\quad P = 0.641 \cdot kW$ $\quad Q := (|\mathbf{I}|)^2 \cdot (\omega \cdot L)$ $\quad Q = 0.604 \cdot kVAR$

$\mathbf{S} := P + j \cdot Q$ $\quad |\mathbf{S}| = \sqrt{P^2 + Q^2} = 0.881 \cdot kVA$ $\quad pf = \frac{P}{|\mathbf{S}|} = 0.728$

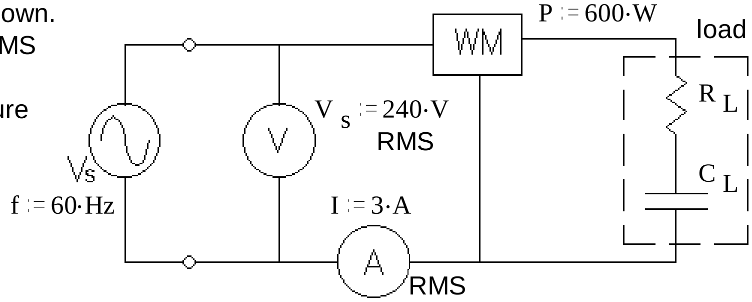
What value of C in parallel with R & L would make $pf = 1$ $(Q = 0)$?

$Q = 603.9 \cdot VAR$ so we need: $Q_C := -Q$ $\quad Q_C = -603.9 \cdot VAR = \frac{V_{in}^2}{X_C}$

$X_C := \frac{\mathbf{V_{in}}^2}{Q_C}$ $\quad X_C = -20.035 \cdot \Omega = \frac{-1}{\omega \cdot C}$ $\quad C := \frac{1}{|X_C| \cdot \omega}$ $\quad C = 132 \cdot \mu F$

Check: $\frac{1}{\frac{1}{R + j \cdot \omega \cdot L} + j \cdot \omega \cdot C} = 18.883 \cdot \Omega$ No j term, so $\theta = 0^o$

Ex. 3 R, & C together are the load in the circuit shown. The RMS voltmeter measures 240 V, the RMS ammeter measures 3 A, and the wattmeter measures 600 W. Find the following: Be sure to show the correct units for each value.



a) The value of the load resistor. R_L = ?

$P = I^2 \cdot R_L$

$R_L := \frac{P}{I^2}$ $\quad R_L = 66.7 \cdot \Omega$

b) The apparent power. |**S**| = ? $\quad S := V_s \cdot I$ $\quad S = 720 \cdot VA$

c) The reactive power. Q = ? $\quad Q := -\sqrt{S^2 - P^2}$ $\quad Q = -398 \cdot VAR$

d) The complex power. **S** = ? $\quad \mathbf{S} := P + j \cdot Q$ $\quad \mathbf{S} = 600 - 398i \cdot VA$

e) The power factor. pf = ? $\quad pf := \frac{P}{V_s \cdot I}$ $\quad pf = 0.833$

f) The power factor is leading or lagging? leading (load is capacitive, Q is negative)

g) The two components of the load are in a box which cannot be opened. Add (draw it) another component to the circuit above which can correct the power factor (make pf = 1). Show the correct component in the correct place and <u>find its value</u>. This component should not affect the real power consumption of the load.

$f = 60 \cdot Hz$ $\quad \omega := 2 \cdot \pi \cdot f$ $\quad \omega = 376.991 \cdot \frac{rad}{sec}$

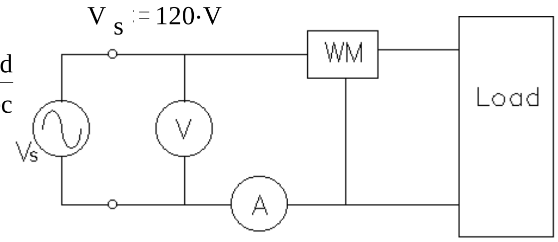
Add an inductor in parallel with load

$Q = -398 \cdot VAR$ so we need: $Q_L := -Q$ $\quad Q_L = 398 \cdot VAR = \frac{V_s^2}{X_L}$

$X_L := \frac{V_s^2}{Q_L}$ $\quad X_L = 144.725 \cdot \Omega = \omega \cdot L$ $\quad L := \frac{|X_L|}{\omega}$ $\quad L = 384 \cdot mH$

Ex. 4 For the 60 Hz load shown in the figure, the RMS voltmeter measures 120 V. The phasor diagram for the power is also shown. Find the following:

$\omega := 377\cdot\frac{rad}{sec}$

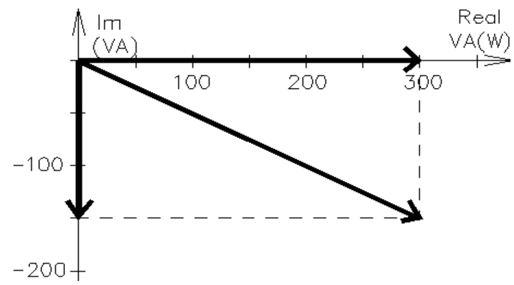


a) The complex power. **S** = ?

$P := 300\cdot W$ $\qquad Q := -150\cdot VA$

$\mathbf{S} := P + j\cdot Q$ $\qquad \mathbf{S} = (300 - 150j)\cdot VA$

b) The apparent power. |**S**| = ? $\quad |\mathbf{S}| = \sqrt{P^2 + Q^2} = 335.4\cdot VA$



c) The power factor. pf = ? $\quad pf := \frac{P}{|\mathbf{S}|}$ $\qquad pf = 0.894$

d) The item marked "WM" in the figure is a wattmeter, what does it read? (give a number) $\quad P = 300\cdot W$

e) The item marked "A" in the figure is an RMS ammeter, what does it read? (give a number)

$I := \frac{|\mathbf{S}|}{V_s}$ $\qquad I = 2.795\cdot A$ $\qquad I = 2.8\cdot A$

f) The power factor is leading or lagging? leading (Q is negative)

g) The 3 components of the load are in a box which cannot be opened. Add another component to the circuit above which can correct the power factor (make pf = 1). Show the correct component in the correct place and <u>find its value</u>. This component should not affect the real power consumption of the load.

Add an inductor in parallel with load

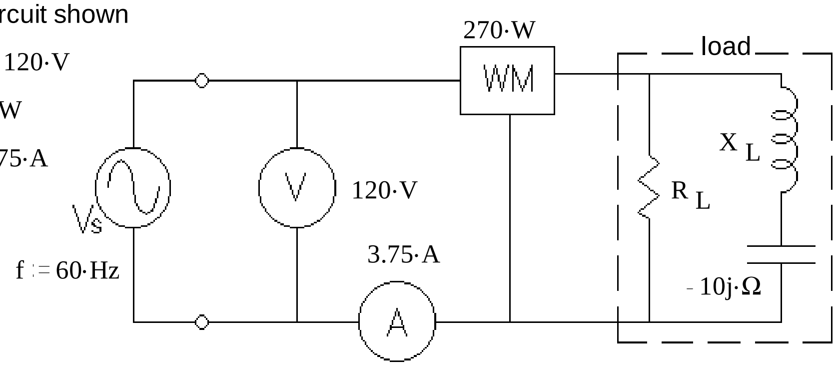
$Q = -150\cdot VAR$ $\qquad$ need: $Q_L := -Q$ $\qquad Q_L = 150\cdot VAR = \frac{V_s^2}{\omega\cdot L}$ $\qquad L := \frac{V_s^2}{\omega\cdot Q_L}$ $\qquad L = 255\cdot mH$

Ex. 5 R, L, & C together are the load in the circuit shown

The RMS voltmeter measures 120 V. $\quad V_s := 120\cdot V$

The wattmeter measures 270 W. $\quad P := 270\cdot W$

The RMS ammeter measures 3.75 A. $\quad I := 3.75\cdot A$



Find the following: Be sure to show the correct units for each value.

a) The value of the load resistor. R_L = ?

$P = \frac{V_s^2}{R_L}$ $\qquad R_L := \frac{V_s^2}{P}$ $\qquad R_L = 53.3\cdot\Omega$

b) The magnitude of the impedance of the load inductor (reactance) . $|\mathbf{Z_L}| = X_L$ = ?

$I_R := \frac{V_s}{R_L}$ $\qquad I_R = 2.25\cdot A$ $\qquad I_L := \sqrt{I^2 - I_R^2}$ $\qquad I_L = 3\cdot A$ $\qquad X := \frac{V_s}{I_L}$ $\qquad X = 40\cdot\Omega$

$X_C := -10\cdot\Omega$ $\qquad X_L := X - X_C$ $\qquad X_L = 50\cdot\Omega$

c) The reactive power. Q = ? $\quad Q := \sqrt{(V_s\cdot I)^2 - P^2}$ $\qquad Q = 360\cdot VAR$ $\quad$ positive, because the load is primarily inductive

d) The power factor is leading or lagging? lagging (load is inductive, Q is positive)

e) The 3 components of the load are in a box which cannot be opened. Add another component to the circuit above which can correct the power factor (make pf = 1). Show the correct component in the correct place and <u>find its value</u>. This component should not affect the real power consumption of the load.

Add a capacitor in parallel with load

$f = 60 \cdot Hz \qquad \omega := 2 \cdot \pi \cdot f \qquad \omega = 376.991 \cdot \frac{rad}{sec}$

$Q = 360 \cdot VAR$ so we need: $Q_C := -Q \qquad Q_C = -360 \cdot VAR = -\frac{V_s^2}{\frac{1}{\omega \cdot C}} = -\omega \cdot C \cdot V_s^2$

$C := \frac{Q_C}{-\omega \cdot V_s^2} \qquad C = 66.3 \cdot \mu F$

Ex. 6 An inductor is used to completely correct the power factor of a load.

Find the following:

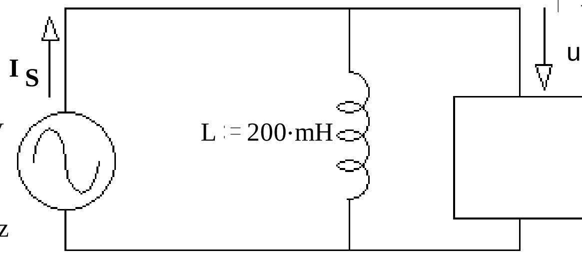
a) The power consumed by the load. P_L = ?

$|\mathbf{I_L}| = 4 \cdot A$ unknown phase

$\mathbf{I_S}$

$\mathbf{V_S} := 120 \cdot V$ <u>/ 0º</u> $60 \cdot Hz$

$L := 200 \cdot mH$



$I_L := 4 \cdot A \qquad \omega = 376.991 \cdot \frac{rad}{sec}$

$Q_L := \frac{-(|\mathbf{V_S}|)^2}{\omega \cdot L} \qquad Q_L = -190.986 \cdot VAR \qquad Q_{load} := -Q_L$

$S_L := |\mathbf{V_S}| \cdot I_L \qquad S_L = 480 \cdot VA \qquad P_L := \sqrt{S_L^2 - Q_{load}^2} \qquad P_L = 440.4 \cdot W$

b) The power supplied by the source. $P_S = P_L = 440 \cdot W$

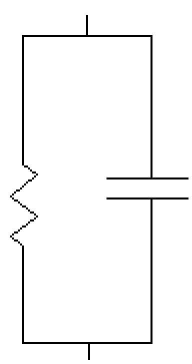
c) The source current (magnitude and phase). $\mathbf{I_S} := \frac{P_L}{\mathbf{V_S}} \qquad \mathbf{I_S} = 3.67 \cdot A$ <u>/ 0º</u>

because the source sees a pf = 1

d) The load can be modeled as 2 parts in parallel. Draw the model and find the values of the parts.

$P = \frac{V^2}{R}$

$R_L := \frac{(|\mathbf{V_S}|)^2}{P_L} \qquad R_L = 32.7 \cdot \Omega$



$Q_C = V^2 \cdot (\omega \cdot C)$

$C_L := \frac{Q_{load}}{\omega \cdot (|\mathbf{V_S}|)^2}$

$C_L = 35.181 \cdot \mu F$

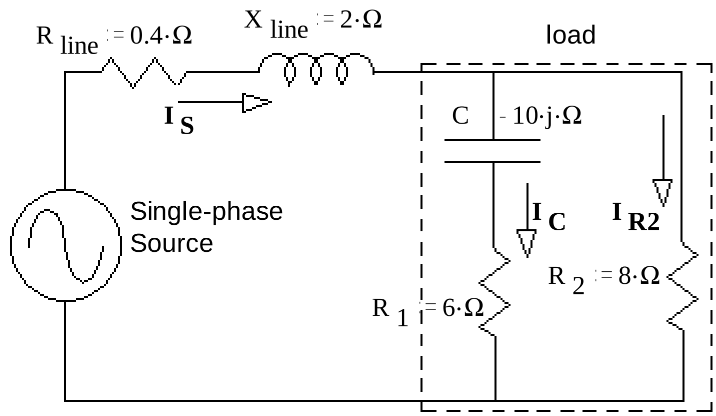
e) The inductor, L, is replaced with a 50 mH inductor.

circle one

i) The **new** source current $|\mathbf{I_S}|$ is **greater** than that calculated in part c). <-- Answer

ii) The **new** source current $|\mathbf{I_S}|$ is **the same** as that calculated in part c).

iii) The **new** source current $|\mathbf{I_S}|$ is **less** than that calculated in part c).



Ex. 7 C, R_1, & R_2 together are the load (in dotted box). The reactive power used by the load is

$Q_{load} := -600 \cdot VAR$ Find:

a) The real power used by the load. $P_{load} = ?$

$X_C := -10 \cdot \Omega$

$\mathbf{I_C} = I_C := \sqrt{\dfrac{Q_{load}}{X_C}}$ $\quad I_C = 7.746 \cdot A$

$V_{load} := I_C \cdot \sqrt{R_1^{\,2} + X_C^{\,2}}$ $\quad V_{load} = 90.333 \cdot V$

$P_{load} := I_C^{\,2} \cdot R_1 + \dfrac{V_{load}^{\,2}}{R_2}$ $\quad P_{load} = 1.38 \cdot kW$

b) The apparent power of the load. $|\mathbf{S}| = S := \sqrt{P_{load}^{\,2} + Q_{load}^{\,2}}$ $\quad S = 1.505 \cdot kVA$

c) The power factor of the load. $pf := \dfrac{P_{load}}{S}$ $\quad pf = 0.917$

d) This power factor is: i) leading ii) lagging Leading, capacitor

e) The voltage at the load (magnitude). $V_{load} = 90.333 \cdot V$ found above

f) The magnitudes of the three currents. $|\mathbf{I_C}| = ?$ $\quad |\mathbf{I_{R2}}| = ?$ $\quad |\mathbf{I_S}| = ?$

$|\mathbf{I_C}| = I_C = 7.746 \cdot A$ found above

$|\mathbf{I_{R2}}| = I_{R2} = \dfrac{V_{load}}{R_2} = 11.292 \cdot A$

$|\mathbf{I_S}| = I_S := \dfrac{S}{V_{load}}$ $\quad I_S = 16.658 \cdot A$

g) The source voltage (magnitude). $V_S = ?$

$P_{Line} := I_S^{\,2} \cdot R_{line}$ $\quad P_{Line} = 111 \cdot W$

$Q_{Line} := I_S^{\,2} \cdot X_{line}$ $\quad Q_{Line} = 555 \cdot VAR$

$|\mathbf{S_S}| = S_S := \sqrt{(P_{load} + P_{Line})^2 + (Q_{load} + Q_{Line})^2}$ $\quad S_S = 1.492 \cdot kVA$

$V_S := \dfrac{S_S}{I_S}$ $\quad V_S = 89.546 \cdot V$

h) Is there something weird about this voltage? If so, what? V_S is less than V_{Load}

Why? Because the Q of the line partially cancels the Q of the load

OR Partial resonance between the inductance in the line and the capacitance of the load.

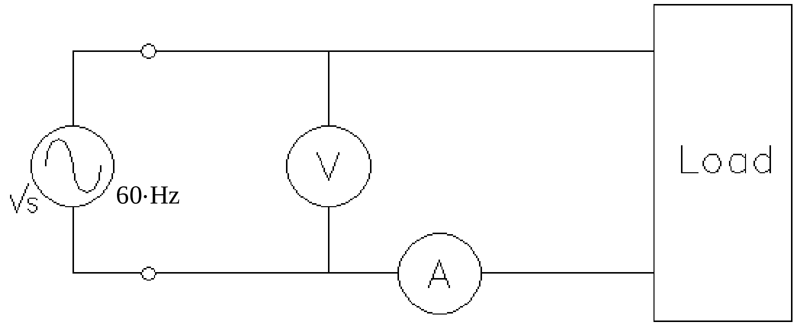
i) The efficiency. $\eta = ?$

When asked for efficiency, assume the power used by R_{line} is a loss and P_{load} is the output power.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{P_{load}}{P_{load} + P_{Line}} = 92.56 \cdot \%$$

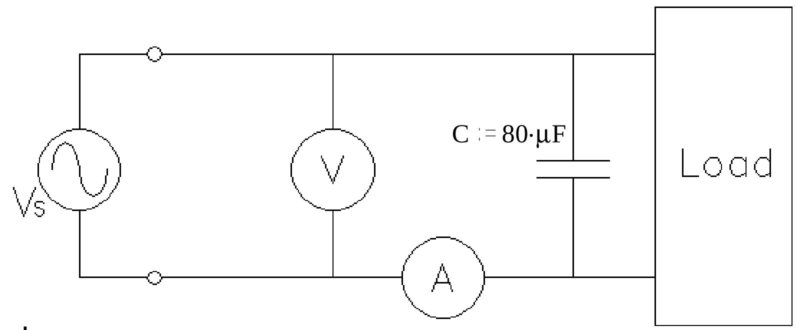
Ex. 8 In the circuit shown, the ideal voltmeter, V, reads 120V and ideal ammeter, A, reads 5A.

$S_{load} := 120 \cdot V \cdot 5 \cdot A \qquad S_{load} = 600 \cdot VA$



a) You add a capacitor, C, and the ammeter reading changes to 5.3A. Find the following:

$P_{load} = ? \qquad Q_{load} = ?$



I_C is **NOT** 0.3A, That's <u>subtracting magnitudes</u>

$S_{load} := 120 \cdot V \cdot 5 \cdot A \qquad S_{load} = 600 \cdot VA = \sqrt{P_{load}^2 + Q_{load}^2}$

OR $\quad (600 \cdot VA)^2 = P_{load}^2 + Q_{load}^2$

$P_{load}^2 = (600 \cdot VA)^2 - Q_{load}^2$

$$Q_C := \frac{(120 \cdot V)^2}{\left(-\frac{1}{\omega \cdot C}\right)} = -(120 \cdot V)^2 \cdot \omega \cdot C \qquad Q_C = -434.294 \cdot VAR$$

With Capacitor:

$S_S := 120 \cdot V \cdot 5.3 \cdot A \qquad S_S = 636 \cdot VA = \sqrt{P_{load}^2 + \left(Q_{load} + Q_C\right)^2}$

OR $\quad (636 \cdot VA)^2 = P_{load}^2 + \left(Q_{load} + Q_C\right)^2$

Substitute in $\quad (636 \cdot VA)^2 = \left[(600 \cdot VA)^2 - Q_{load}^2\right] + \left(Q_{load} + Q_C\right)^2$

$= \left[(600 \cdot VA)^2 - Q_{load}^2\right] + \left(Q_{load}^2 + 2 \cdot Q_C \cdot Q_{load} + Q_C^2\right)$

$= (600 \cdot VA)^2 + 2 \cdot Q_C \cdot Q_{load} + Q_C^2$

$$Q_{load} := \frac{(636 \cdot VA)^2 - (600 \cdot VA)^2 - Q_C^2}{2 \cdot Q_C} \qquad Q_{load} = 165.919 \cdot VAR$$

$$P_{load} := \sqrt{S_{load}^2 - Q_{load}^2} \qquad P_{load} = 576.603 \cdot W$$

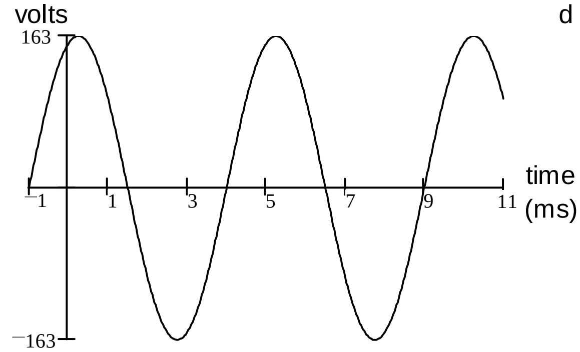
Double Check: $\quad S_S = \sqrt{P_{load}^2 + \left(Q_{load} + Q_C\right)^2} = 636 \cdot VA$

The power factor was way over corrected by $C = 80 \cdot \mu F$

ECE 3600 Homework # 3A **Due: Fri, 9/2/22**

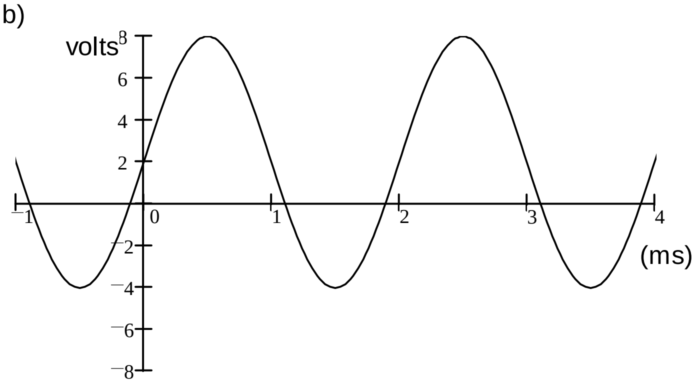
1. For each of the following waveforms, find:
   1) Average DC (V_{DC}, or I_{DC}) value
   2) RMS (effective) value

1a)

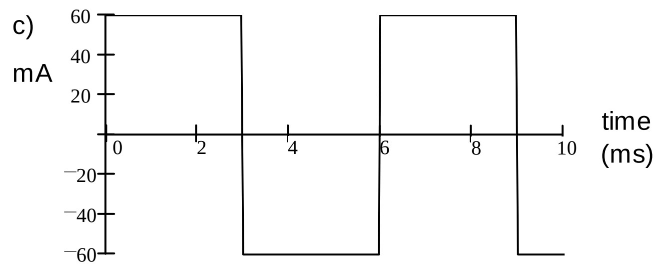


d

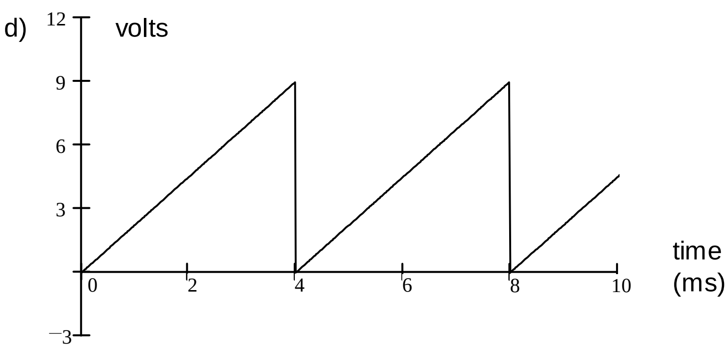
b)



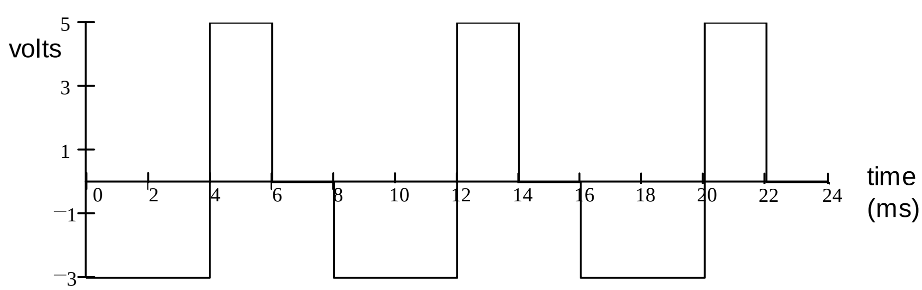
c)



d)



2. For waveform shown, find:
   a) Rectified average (V_{RA}) value
   b) RMS (effective) value



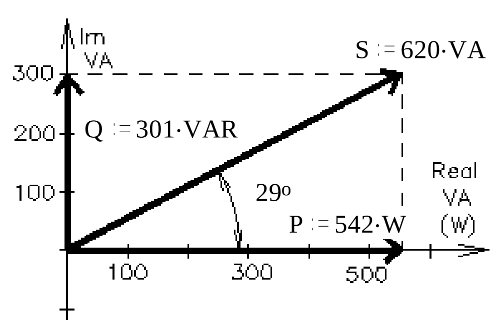
3. Compute the power factor for an inductive load consisting of $L := 20 \cdot mH$ and $R := 6 \cdot \Omega$ in series. $\omega := 377 \cdot \frac{rad}{s}$

4. The complex power consumed by a load is $620\ \underline{/29^o}\ VA$. Find:
   a) Apparent power (as always, give the correct units). b) Real power. c) Reactive power. d) Power factor.
   e) Is the power factor leading or lagging? f) Draw a phasor diagram.

Answers

1. a) $0 \cdot V$ $115 \cdot V$ b) $2 \cdot V$ $4.69 \cdot V$
   c) $0 \cdot mA$ $60 \cdot mA$ d) $4.5 \cdot V$ $5.2 \cdot V$
2. a) $2.75 \cdot V$ b) $3.28 \cdot V$
3. $pf := 0.623$

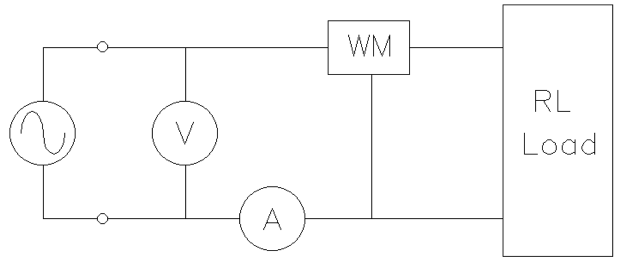
4. a) $620 \cdot VA$
   b) $542 \cdot W$
   c) $301 \cdot VAR$
   d) 0.875
   e) lagging
   f) ------->



ECE 3600 Homework # 3A

ECE 3600 Homework # 3B **Due: Wed, 9/7/22** e

1. In the circuit shown, the voltmeter measures 120V and the ammeter measures 6.3A (recall that AC meters read RMS). The wattmeter measures 560W. The load consists of a resistor and an inductor. The frequency is 60Hz. Find the following:



   a) Power factor

   b) Leading or lagging?

   c) Real power.

   d) Apparent power.

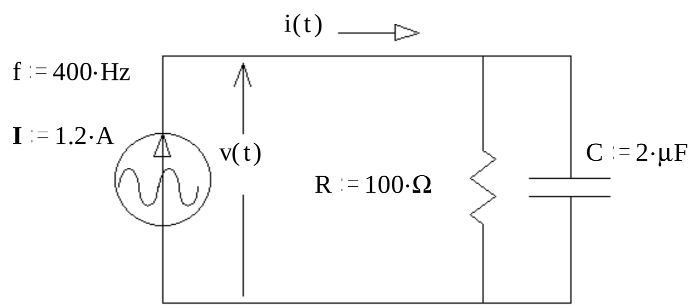
   e) Reactive power.

   f) Draw a phasor diagram.

   g) The load is in a box which cannot be opened. Add another component to the circuit above to correct the power factor (make pf = 1). Draw the correct component in the correct place and find its value. This component should not affect the real power consumption of the load.

   h) Find the new readings of voltmeter, ammeter, and wattmeter.

2. For the circuit shown, find the following:
   (as always, give the correct units)



   a) The complex power.

   b) Real power.

   c) Reactive power.

   d) Apparent power.

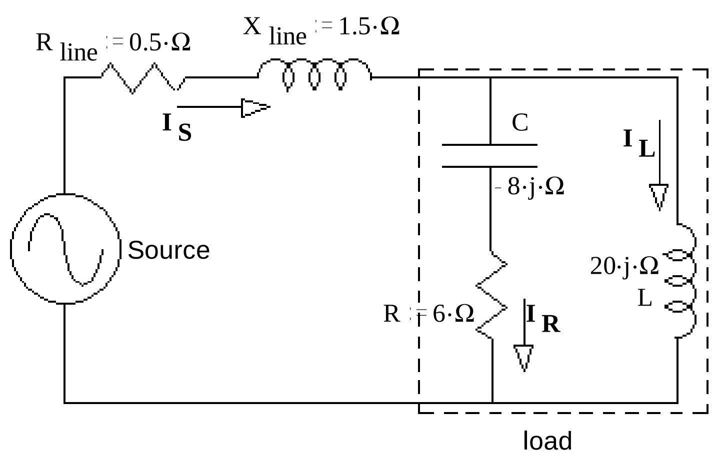
   e) Draw a power phasor diagram.

3. A load draws 12kVA at 0.8 pf, lagging when hooked to 480V. A capacitance is hooked in parallel with the load and the power factor is corrected to 0.9, lagging.

   a) Find the reactive power (VAR) of the capacitor. Draw a phasor diagram as part of the solution.

   b) Find the value of the capacitor assuming f = 60Hz.

4. R, L, & C together are the load (in dotted box). The power used by the load is $P_{Load} := 726 \cdot W$ Find:



   a) The reactive power used by the load.
      Q = ?

   If you can't find this Q, try parts e) and f) first and then come back to part a).

   b) The apparent power of the load. |**S**| = S = ?

   c) The power factor of the load. pf = ?

   d) Is the power factor i) leading? ii) lagging?

   e) The voltage at the load (magnitude). V_{Load} = ?

   f) The magnitudes of the three currents. $|\mathbf{I_R}|$ = ? $|\mathbf{I_L}|$ = ? $|\mathbf{I_S}|$ = ?

   g) The source voltage (magnitude). V_S = ?

   h) Is there something weird about this voltage? If so, what? Why?

   i) The efficiency. η = ?

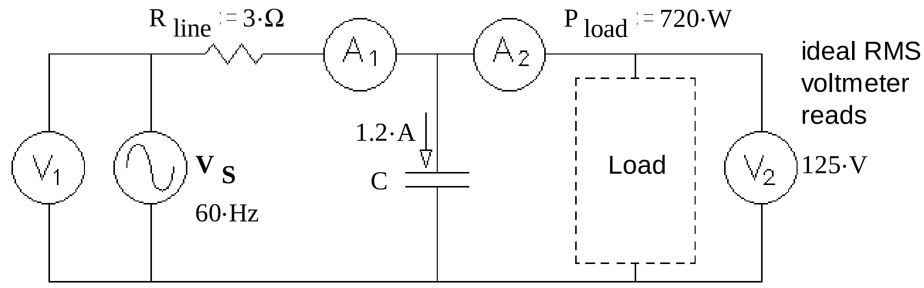
   When asked for efficiency, assume the power used by R_{line} is a loss and P_{load} is the output power.

5. (40 pts) A capacitor (C, shown below) is used to partially correct the power factor of a load to 0.9. A_1 and A_2 are ideal ammeters. V_1 and V_2 are ideal voltmeters. The load uses 720W. Find the following:

a) The RMS readings of the two ideal ammeters.

I_{A1} = ? I_{A2} = ?

Hint: there are a number of steps involved here. For A_1, do calculations on the load and cap together. For A_2 you'll need numbers for the load alone.



b) The load can be modeled as 2 parts in series. Draw the model and find the values of the parts.

$pf_{withCap} := 0.9$

c) The voltage measured by the ideal voltmeter, labeled V_1. V_1 = ?

d) The efficiency. η = ?
Assume the power used by R_{line} is loss and P_{load} is the output power.

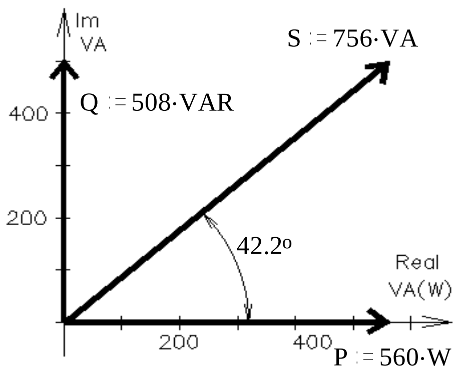
$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}}$$

e) Add an additional component to the drawing above in order to completely correct the power factor. Find the value of the component.

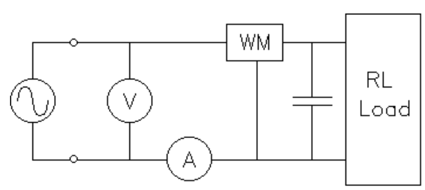
f) Without making any additional calculations, would the efficiency be better or worse with the added component of part e)? i) higher η ii) lower η iii) could be either iv) no difference

Answers

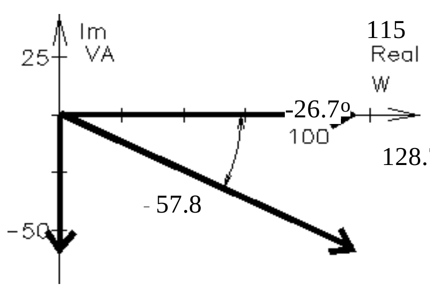
1. a) 0.741
   b) lagging
   c) 560·W
   d) 756·VA
   e) 508·VAR
   f) ------->
   g) 93.6·μF
   h) 120·V 4.67·A 560·W



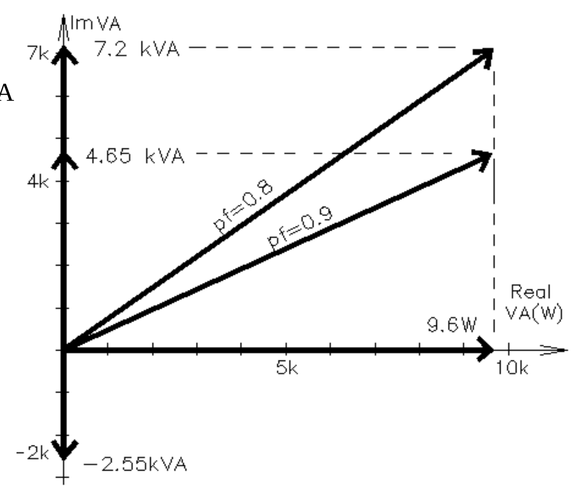
Draw a capacitor in parallel with load



2. a) $(115 - 57.8\cdot j)\cdot VA$
   b) 115·W
   c) -57.8·VAR
   d) 128.7·VA
   e) ------->



3. a) -2.55·kVA
   b) 29.4·μF



4. a) -363·VAR b) 812·VA c) 0.894 d) i) e) 110·V f) 11·A 5.5·A 7.38·A g) 109·V
   h) V_S is less than V_{Load} Because the Q of the line partially cancels the Q of the load i) 96.4·%

5. a) I_{A1} = 6.4·A I_{A2} = 7.01·A b) R = 14.67·Ω L = 26.9·mH c) 142.5·V
   d) 85.4·% e) 59.2·μF in parallel with existing C f) i)