Single Phase AC Circuits

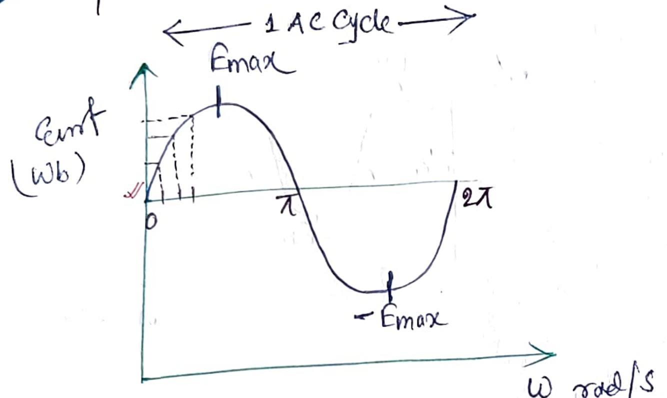
(changes mag. as well as dir. peridocally)

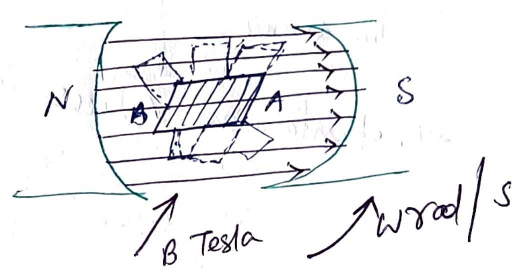
Introduction of Single Phase AC

- Generation of single phase AC
- Basic Termed used
- Emf equ^n for 1ϕ AC

① Generation of Single Phase AC,

$$\boxed{e = -\frac{N\,d\phi}{dt}}$$





② Basic Termed used:-

① Circuits
(ii) Alternating Current (AC)
(iii) Cycle
(iv) frequency for AC = 50 Hz, for DC = 0
(v) Phase difference
(vi) Leading Phase
(vii) Lagging Phase

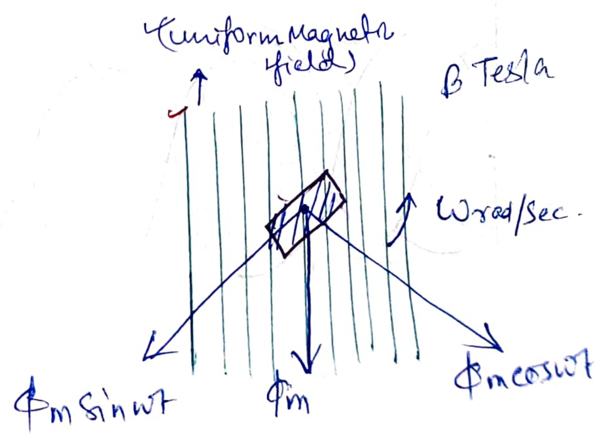
* $\boxed{T = \frac{1}{f}}$
* $\boxed{\omega T = 2\pi}$

$\omega t \rightarrow \theta$

③ Emf equation for Single Phase AC:-

$$\boxed{e = -N \cdot \frac{d\phi}{dt}} \quad \text{--- ①}$$

for the given cond^n



PTO

$\boxed{\phi = \phi_m \cos \omega t}$ (⊥ component)

$\frac{d\phi}{dt} = -\phi_m \sin \omega t \cdot \omega$

$\therefore \quad e = -N \cdot \frac{d\phi}{dt}$

$= N\omega\phi_m \sin \omega t$

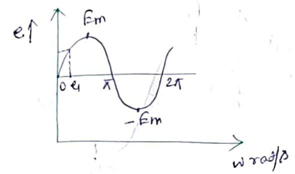
$\boxed{e = N\omega\phi_m \sin \omega t}$

$\boxed{E_m = N\omega\phi_m}$ → (maxi. value)

$\boxed{e = E_m \sin \omega t}$

$\boxed{\begin{array}{l} V = V_m \sin \omega t \\ i = i_m \sin \omega t \end{array}}$

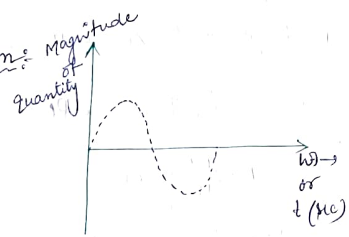
Instantaneous Values

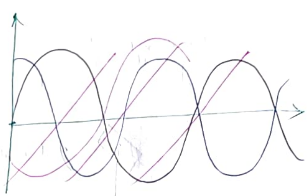


Representation of Single Phase AC

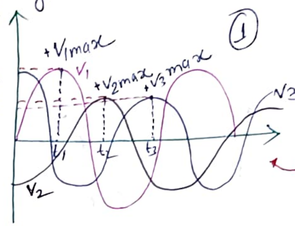
- Graphical form
- Magnitude form
- Mathematical form

① Graphical form: ① Wave form:



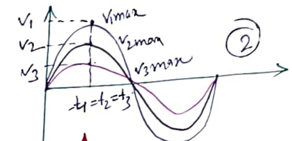


(for tracing) freq. of all the quantities should be same.



3 signals are (out of phase)

Lead / Lag Condn



Same phase (No phase diff.)

* but have same freq. and T

Between ① & ② Graph, Only Graph ① show phasor difference and leading & lagging Condn along with different different time.

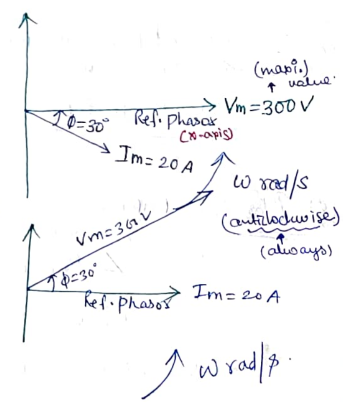
① Phasor Form: (2D) (same freq.)

V = 30° leading from Current I.

$V_m = 300V$

$I_m = 20A$

* maxi. value pata honi chaiye.
* ∅, phase diff. and sath mein kaun lead/ lag kar raha hai woh pata hoga chaiye.



ω rad/s.

② Mathematical form of representation of AC.

(1) Rectangular form:- $a \pm jb$

a = Constant part,

b = Fluctuating part

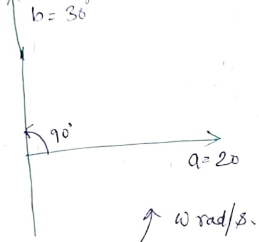
$j = \sqrt{-1}$, phase shift of 90°

+ → leading Condn.

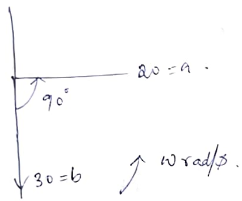
− → lagging Condn.

$a = 20, \quad b = 30$

$a + jb = 20 + j30$



$20 - j30$



$$\boxed{\text{Phasor angle } (\phi) = \tan^{-1}\frac{b}{a} \Rightarrow \tan\phi = b/a.}$$

(b) Trignometrical Form :- (NOT IMP*)
(derivation wostare)

$$\boxed{a\cos\theta \pm jb\sin\theta}$$

(c) Polar Form :- (IMP NUM.)

$V = |\bar{V}| \angle \pm \theta$ (magnitude; phase angle)

$V = 20\angle{-30°}$ V — magnitude is = 20 and lagging by 30°

$V = 20\angle{+30°}$ V — magnitude = 20 and leading by 30°

(3) Magnitude Form :-

(i) Instantaneous Values

(ii) Peak or Maximum Value / Amplitude

(iii) Average Value representation

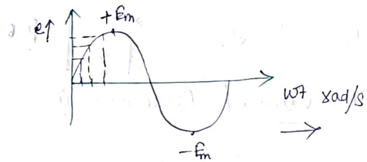
(iv) RMS Value (Root Mean Square Value) Representation.

(i) Instantaneous Values :-

$e = E_m \sin\omega t$

$V = V_m \sin\omega t$

$i = I_m \sin\omega t$



$V = 200 \sin 35t$ V

$V = V_m \sin\omega t$.

$V_m = 200$ V, $\quad \omega = 35$ rad/s

(ii) Peak or Max^m Value Representation :-

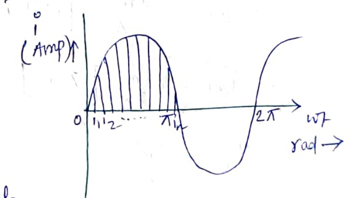
emf ⇒ E_0, E_m, E

Voltage ⇒ V_0, V_m, V

Current → I_0, I_m, I

(iii) Average value Representation :-

$$Avg = \frac{\text{Sum of all values}}{\text{no. of values}}$$



~~$I_{av} = I_1 + I_2 + I_3 + \dots + I_n$~~

* Only half cycle avg. nikala jata hai (+ve) half.
(1 complete cycle ka avg. nhi nikala jata hai)

* avg. → sinewave
1T → 0

(half part of cycle)

Taking the area of alternation of $0-\pi$ and dividing it into all possible divisions.

$$I_{av} = \int_0^{\pi} \frac{I_m \sin\omega t}{\pi - 0}\, d\omega t$$

$$\Rightarrow I_{av} = \frac{I_m}{\pi}\int_0^{\pi} \sin\omega t\, d\omega t$$

$$\Rightarrow I_{av} = \frac{I_m}{\pi}(-\cos\omega t)_0^{\pi}$$

$$\Rightarrow I_{av} = \frac{I_m}{\pi}\times(1+1) = \boxed{\frac{2I_m}{\pi}} \Rightarrow \boxed{0.637\, I_m}$$

(iv) RMS Value of Representation:-

$$I = I_m \sin\omega t$$

Squaring both sides

$$i^2 = I_m^2 \sin^2\omega t$$

$$\Rightarrow i^2 = I_m^2\left(\frac{1-\cos 2\omega t}{2}\right)$$

Taking avg of given value.

$$\Rightarrow i^2_{avg} = \frac{I_m^2}{2}\int_0^{\pi} \frac{(1-\cos 2\omega t)}{\pi-0}\, d\omega t$$

$$\Rightarrow i^2_{av} = \frac{I_m^2}{2\pi}\int_0^{\pi} (1-\cos 2\omega t)\, d\omega t$$

$$\Rightarrow i^2_{av} = \frac{I_m^2}{2\pi}\left[(\omega t)_0^{\pi} - \left(\frac{\sin 2\omega t}{2}\right)_0^{\pi}\right]$$

$$\Rightarrow i^2_{av} = \frac{I_m^2}{2\pi}[\pi - 0]$$

$$\Rightarrow i^2_{av} = \frac{I_m^2}{2}$$

Square rooting both sides.

$$\cancel{\Rightarrow i_{av} = \frac{I_m}{\sqrt{2}}}$$

$$i_{rms} = \sqrt{\frac{I_m^2}{2}}$$

(impo)

$$\Rightarrow \boxed{i_{rms} = \frac{I_m}{\sqrt{2}}} \quad \boxed{V_{rms} = \frac{V_m}{\sqrt{2}}} \quad \boxed{E_{rms} = \frac{E_m}{\sqrt{2}}}$$

By default, numerical mein V, I → rms value hote hai.

* peak factor $K_p = \boxed{\frac{\text{Maximum}}{\text{rms}}}$
* form factor $f.f. = \boxed{\frac{\text{rms.}}{\text{avg.}}}$

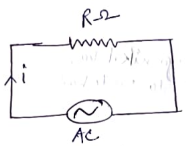
Analysis of Single phase AC

- Resistive Load R
- Inductive Load L
- Capacitive Load C

(a) Relation b/w V and I due to that load

(b) Power dissipated

AC circuit Containing purely Resistive load:-



$V = V_m \sin\omega t$

Let us assumed that a purely Resistive Load RΩ is Connected across a supply of

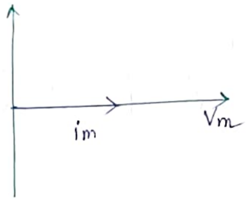
$$V = V_m \sin\omega t \quad —(1)$$

$$i = \frac{V}{R} \quad \text{[By using ohm's law]}$$

Putting the value of V from eq (1).

$$i = \frac{V_m \sin \omega t}{R}$$

$$\boxed{\Rightarrow i = i_m \sin \omega t} \quad \text{— (2)}$$



Comparing eq(1) & eq(11)
Voltage and current are in same phase (in phase)

$$\boxed{\phi = 0}$$

power dissipated in purely resistive load:-

$$P = vi$$

$$\Rightarrow P = V_m \sin \omega t \times I_m \sin \omega t$$

$$\Rightarrow P = V_m I_m \sin^2 \omega t$$

$$\Rightarrow P = V_m I_m \left(1 - \frac{\cos 2\omega t}{2}\right)$$

$$\Rightarrow P = \frac{V_m I_m}{2} - \frac{V_m I_m \cos 2\omega t}{2}$$

neglecting the fluctuating part or avg nikal kar ye la sakte hai

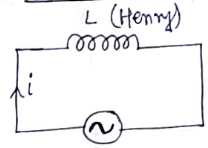
$$P = \frac{V_m I_m}{2} - 0$$

$$\Rightarrow P = \frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}}$$

$$\boxed{\Rightarrow P = V_{rms} \cdot I_{rms}}$$

AC Circuit Containing purely Inductive Load:-

(inductor → coil manoge)



$$V = V_m \sin \omega t \ \text{V}$$

Let us assumed, a purely inductive load to be connected across a supply of

$$V = V_m \sin \omega t \quad \text{— (1)}$$

emf induced in coil (inductor) is given as

$$\boxed{e = -N\frac{d\phi}{dt}}$$

$e = (-v)$ (∵ emf :- equivalent voltage)

$N = L$ (No. of turns = inductance) $N \uparrow L \uparrow$ symmetrical

$\frac{d\phi}{dt}$ (rate of ring flux) $= \frac{di}{dt}$ (rate of change of flow of supply current)

$$-V = -L \cdot \frac{di}{dt}$$

$$\Rightarrow V = L \cdot \frac{di}{dt}$$

from eq(1) $\quad V_m \sin \omega t = L \cdot \frac{di}{dt}$

$$\Rightarrow \int di = \int \frac{V_m}{L} \cdot \sin \omega t \, dt$$

$$\Rightarrow i = \frac{V_m}{L} \cdot \left[-\frac{\cos \omega t}{\omega}\right]$$

$$\Rightarrow i = -\frac{V_m}{\omega L} \cos \omega t$$

$$i = \frac{V_m}{\omega L} \sin(\omega t - \frac{\pi}{2})$$

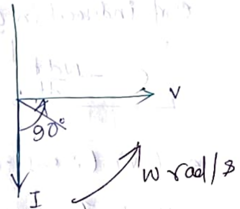
Comparing it with ohm's law:

$X_L = \omega L$ {By ohm's law}

$$i = \frac{V_m}{X_L} \sin(\omega t - \pi/2)$$

$\Rightarrow i = I_m \sin(\omega t - \pi/2)$ {By ohm's law} —(2)

for purely inductive Load, current lags by voltage by $90°$.



power in AC circuit for purely Inductive load:

$P = Vi$

$= V_m \sin\omega t \cdot I_m \sin(\omega t - \pi/2)$

$\Rightarrow P = -V_m I_m \sin\omega t \cos\omega t$

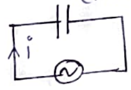
Multiplying and dividing with 2.

$\Rightarrow P = -\frac{V_m I_m}{2} \times 2 \sin\omega t \cos\omega t$

$\Rightarrow P = -\frac{V_m I_m}{2} \sin 2\omega t$. {neglecting fluctuating part}

$\Rightarrow \boxed{P_H = 0}$

AC circuit Containing purely Capacitive Load:-



Let us assumed that a purely capacitive load of C farads is connected across a supply of

$V = V_m \sin\omega t$ —(1)

The charge stored by a capacitor is given as

$q = CV$

$$i = \frac{dq}{dt}$$

$$\Rightarrow i = \frac{d}{dt}(CV)$$

$\Rightarrow i = C \cdot \frac{dV}{dt}$ $\Rightarrow i = C \cdot \frac{d}{dt} V_m \sin\omega t$

$\Rightarrow i = CV_m \cdot \frac{d}{dt} \sin\omega t$

$\Rightarrow i = V_m C \cdot \cos\omega t \cdot \omega$

$\Rightarrow i = V_m \omega C \cos\omega t$

$\Rightarrow i = V_m \omega C \cdot \sin(\omega t + \pi/2)$

$$\Rightarrow i = \frac{V_m \sin(\omega t + \pi/2)}{\left(\frac{1}{\omega C}\right)}$$

$$\Rightarrow i = \frac{V_m \sin(\omega t + \pi/2)}{X_C}$$

By comparing it to ohms law

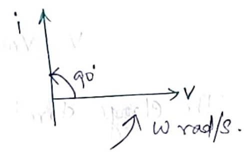
$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

$\Rightarrow i = I_m \sin(\omega t + \pi/2)$ {acc. to ohm's law} —(2)

By comparing eq(1) & eq(2)

I leads from Voltage by 90° for a purely capacitive load.

power in an AC circuit containing purely capacitive load.



$P = Vi$

$\Rightarrow P = V_m \sin\omega t \cdot I_m \sin(\omega t + \pi/2)$

$\Rightarrow P = V_m I_m \sin\omega t \cdot \cos\omega t$

$\Rightarrow P = \frac{V_m I_m}{2} \times \sin 2\omega t$

$\sin^2\omega t = \frac{1}{2}$
$\sin\omega t = 0$

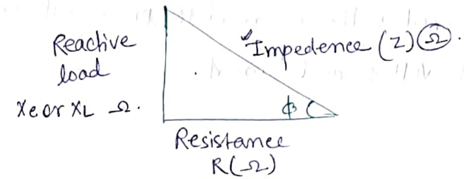
$\Rightarrow \boxed{P = 0.}$ {By neglecting fluctuating part}.

Components of Single Phase AC :-

1. Impedence Triangle :-
2. The power Triangle :-
3. Power Factor :-

P.T.O

Impedence Triangle :-



$R \rightarrow \phi = 0°$

$X_L \rightarrow I = I_m \sin(\omega t - \pi/2)$

$X_C \rightarrow I = I_m \sin(\omega t + \pi/2)$

$Z = \sqrt{(R)^2 + (X)^2}$

$Z = \sqrt{R^2 + (X_C - X_L)^2}$ if $X_C > X_L$

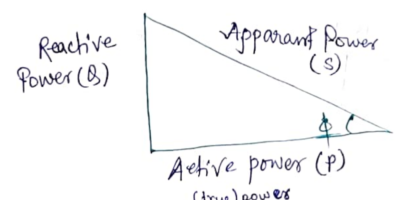
$Z = \sqrt{R^2 + (X_L - X_C)^2}$ if $X_L > X_C$

$Z = \sqrt{R^2} = R$ if $\boxed{X_L = X_C}$ (Resonance)

$\sin\phi = \frac{X}{Z}$

$\cos\phi = \frac{R}{Z}$

Power Triangle :-



1. Active power (P)
2. Reactive Power (Q)
3. Apparent power (S)

(Resistance)
$P = V_{rm} \cdot I_{rm} \cos\phi$ (watts)

(Cap and L)
$Q = V_{rm} \cdot I_{rm} \sin\phi$ (Volt-Amp Reactive) VAR

$S = V_{rm} \cdot I_{rm}$ (Volt Amp)
(resultant)

Power factor:- (factor on which true power depend)

A power factor is defined as the cosine of the phase difference angle between Supply Voltage and Current.

① $\cos\phi$

② $\cos\phi = \frac{R}{Z}$

③ $\cos\phi = \frac{\text{Active Power}}{\text{Apparant power}} = \frac{P}{S}$

Numericals on Series AC Circuit

Q Find an expression for current flowing and Calculate the power in a series R-L circuit of value $R = 50\Omega$ and $L = 0.159$ H when a Voltage of $V = 283 \sin 100t$ is applied.

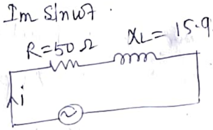
→ $V = 283 \sin 100t$

$V_m = 283\,V$, $\omega = 100$ rad/s.

$X_L = \omega L$
$= 100 \times 0.159$
$= 15.9\,\Omega$.

~~$I = \frac{V_m}{R} \sin 100t \Rightarrow I = \frac{283}{50} \sin 100t$~~.

$i = I_m \sin\omega t$



Always find rms values.

$\boxed{V_{rms}} = \frac{V_m}{\sqrt{2}} = \frac{283}{\sqrt{2}} = 200.11\,V$

$Z = \sqrt{R^2 + X_L^2}$

$= \sqrt{(50)^2 + (15.9)^2}$

$Z = 52.46\,\Omega$

$V = IZ$

$I_{rms} = \frac{V_{rms}}{Z_T}$

$I_{rms} = \frac{200.11}{52.46}$

$I_{rms} = 3.81\,A$.

$I_m = I_{rms} \times \sqrt{2}$

$= 3.81\sqrt{2}$

$= 5.39\,A$.

$\cos\phi = \frac{R}{Z}$

$\Rightarrow \cos\phi = \frac{50}{52.46}$

$\Rightarrow \phi = 17.63°$

$\boxed{i = 5.39 \sin(100t - 17.63°)\,A.}$

$P = V_{rms} I_{rms} \cos\phi$

$= 200.11 \times 3.81 \times \frac{50}{52.46}$ W

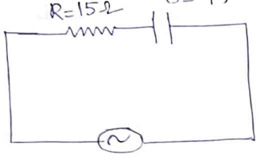
$= ~~7266~~ \; 726.6$ W

Q If a resistance of 15Ω and capacitor of $150\,\mu F$ are Connected in Series across 230 V, 50Hz Supply then Calculate

(a) Impedence
(b) Current
(c) Power factor
(d) Phase angle
(e) power consumed

→

$R = 15\Omega$ $\quad C = 150 \times 10^{-6}$ F



230V, 50 Hz.

→ $R = 15H$, $\quad C = 150 \times 10^{-6}$ F $\qquad V_{rms} = 230V$

$$\Rightarrow X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C} = \frac{10^6}{2\pi \times 50 \times 150}$$

$$= \frac{2 \times 10^4}{2\pi \times 150} = 21.23\,\Omega.$$

(I) Impedence $(Z) = \sqrt{(15)^2 + (21.23)^2}$

$$= \sqrt{225 + 454.96}$$

$$= 26.07\,\Omega.$$

(III) power factor $\cos\phi = \frac{R}{Z} = \frac{15}{26.07} = 0.53°$ (leading)

(IV) phase angle $\phi = 1.01°$

(V) power consumed $= V_{rms}\, I_{rms} \cos\phi$ $\qquad I_{rms} = \frac{V_{rms}}{Z} = 8.82$

$$= 230 \times 8.82 \times 0.53$$

$$= 1075.45\ W$$

(II) $I_{rms} = \frac{V_{rms}}{Z} = \frac{230}{26.07} = 8.82\ A.$

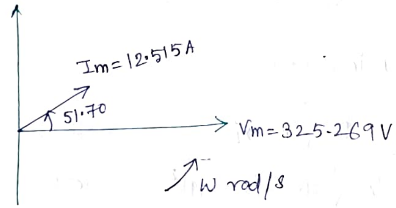
Phasor:-

$V_m = V_{rms} \times \sqrt{2} = 325.269\ V$

$I_m = I_{rms} \times \sqrt{2} = 12.515\ A$

$\phi = 51.70°$

* Agar L, C both ho toh X_L, X_C pe depend karta hai. (dominating) jo bhi hoga uske nature ka hoga circuit.



Numericals on Parallal AC Circuits:-

Q Two Branches A and B are Connected in parallel across a supply of 200V, 50 Hz, if A consist of a resistance of 10Ω and inductance of 0.12 H, B consist of a resistance of 20Ω and Capacitor of 40 μF, then calculate —

(I) Total Impedence
(II) Total current
(III) Current in each Branch
(IV) power factor
(V) phasor.

→ Branch A, $R = 10\Omega$, $L = 0.12H$, $X_L = \omega L = 2\pi f L$

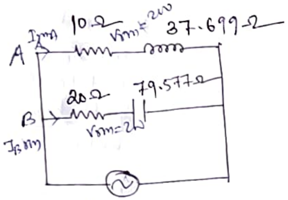
where $f = 50Hz$, $X_L = 2\pi \times 50 \times 0.12 = 37.699\,\Omega$

$V_{rms} = 200V$

Branch B, $R = 20\Omega$

$C = 40 \times 10^{-6}$ F

$X_C = \frac{1}{\omega C} = 79.577\,\Omega$



$V_{rm} = 200V,\ 50\,Hz.$

(i) Total impedence

$$Z = \sqrt{R^2 + X_L^2}$$

Branch wise, (series)

$$Z_A = \sqrt{(10)^2 + (37.699)^2} = 39.002\,\Omega$$

$$Z_B = \sqrt{R^2 + X_C^2} = \sqrt{(20)^2 + (79.577)^2}$$

$$= 82.051\,\Omega$$

(parallel)

$$Z_T = \boxed{\frac{Z_A \times Z_B}{Z_A + Z_B}} = 26.435\,\Omega.$$

(ii) Total supply current

$$I_{rms} = \frac{V_{rms}}{Z_T} = \frac{200}{26.435} = 7.565\,A.$$

(iii) (Branch wise)

$$I_{rms\,A} = \frac{200}{Z_A} = \frac{200}{39.002} = 5.127\,A.$$

$$I_{rm\,B} = \frac{200}{82.051} = 2.437\,A.$$

(iv) Power factor $(\cos\phi) = \frac{R}{Z} = \frac{6.67}{26.435}$ ** $\boxed{R_T} = \frac{10\times 20}{30} = \frac{20}{3} = 6.67$

$$= \boxed{0.252}$$

$\phi = \cos^{-1}(0.252) = 75.404°$

(v) Phasor:-

Branch A

$V_{mA} = 282.842\,V$

$I_{mA} = 7.250\,A$

$\phi_A = \frac{10}{39.002}$ ~~0.0256~~

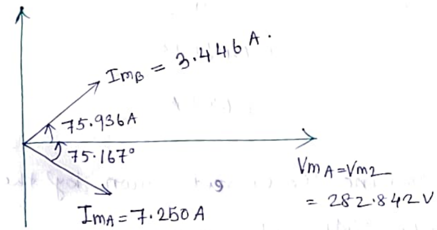
$= 75.167°$

Branch B

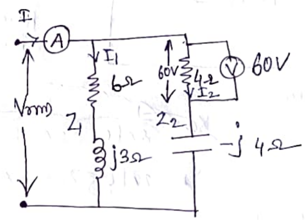
$V_{mB} = 282.842\,V$

$I_{mB} = 3.446\,A$

$\phi_B = 75.936°$



8 In the Given Circuit, if a Voltmeter reads 60V, Then find the reading of Ammeter.



$$Z_1 = \sqrt{6^2 + 3^2} = 6.708\,\Omega$$

$$Z_2 = \sqrt{4^2 + 4^2} = 5.656\,\Omega$$

$$I_{rms_2} = \frac{60}{4} = 15\,A$$

$$Z_2 = 5.656\,\Omega \qquad V_{rms_2} = 15 \times 5.656$$

$$= 84.84\,V$$

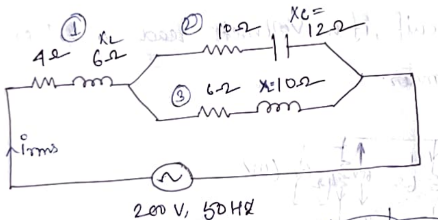
$V_{rms_1} = V_{rms_2} = 84.84\ V$

$Z_1 = 6.708\ \Omega$

$I_{rms_1} = \dfrac{84.84}{6.708} = 12.647\ A.$

$$I_{rms_T} = I_{rms_1} + I_{rms_2}$$
$$= 12.647 + 15$$
$$= 27.647\ A.$$

Q Determine the Current drawn by the given network at a Supply Voltage of 200V.



If capacitive, then unit will be in farad. Here unit Ω so it is X_L & X_C.

~~$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 50 \times 12} =$~~

~~$X_L = 2\pi f L = 2\pi \times 50 \times 6 =$~~

→ $V_{rms} = 200\ V$

$Z_1 = \sqrt{(4)^2 + (6)^2} = 7.211\ \Omega$

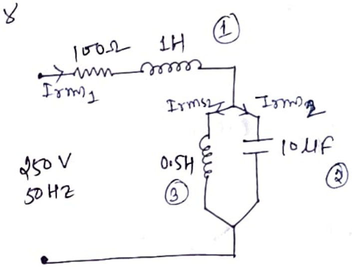
$Z_2 = \sqrt{(10)^2 + (12)^2} = 15.620\ \Omega$

$Z_3 = \sqrt{(6)^2 + (10)^2} = 11.661\ \Omega$

$Z_T = Z_1 + \dfrac{Z_2 \times Z_3}{Z_2 + Z_3} = 13.887\ \Omega$

$I_{rms} = \dfrac{200}{13.887} = 14.401\ A.$

Q With reference to the Network given below find:
(i) Z_T (ii) Branch Currents (iii) Power Factor (iv) power dissipated
(v) phasor



→ $L_1 = 1H, \quad X_{L_1} = 2\pi f L = 2\pi \times 50 \times 1 = 314.15\ \Omega$

$C = 10\mu F = X_C = \dfrac{1}{2\pi f C} = \dfrac{10^6}{2\pi \times 50 \times 10} = 318.3098\ \Omega.$

$X_{L_2} = 2\pi f \times 0.5 = 157.079\ \Omega$

$Z_1 = \sqrt{(100)^2 + (314.15)^2} = 3145.739\ \Omega$

$Z_2 = \sqrt{(3183.098)^2} = 3183.098\ \Omega$ ✗ $\boxed{318.3098\ \Omega}$

$Z_3 = \sqrt{(157.079)^2} = 157.079\ \Omega.$

(i). $Z_T = Z_1 + \dfrac{Z_2 \times Z_3}{Z_2 + Z_3} = 3295.399\ \Omega.$

(ii) $I_{rms} = \dfrac{250}{3295.399} = 0.075\ A.$ $\quad I_{rms_1} = I_{rms_T}.$

$Z_{parallel} = 149.660\ \Omega$

$I_{parallel} = I_{rms\,1} = 0.075.$

$V_{parallel} = 149.660 \times 0.075\ V$
$= 11.224\ V$

$V_{rms_2} = V_{rms_3} = 11.224\,V$

$\therefore I_{rms_2} = \dfrac{11.224}{3183.098} = 0.0035\,A$

$I_{rms_3} = \dfrac{11.224}{157.079} = 0.071\,A$

(iii) $\cos\phi = \dfrac{R_T}{Z} = \dfrac{100}{3295.399} = 0.030$

(iv) $P = V_{rms} I_{rms} \cos\phi$

$\Rightarrow P = 250 \times 0.075 \times 0.030 = 0.562\,W$

Branch (1)

(v) $V_{rms_1} = I_{rms_1} \times Z_1$

$\Rightarrow V_{rms_1} = 0.075 \times 3145.729 = 235.930\,V$

$V_{m_1} = 333.655\,V$

$I_{m_1} = 0.106\,A.$

$\cos\phi_1 = \dfrac{100}{3145.739} = 0.031$

$\phi_1 = \cos^{-1}(0.031) = 88.223^\circ$

Branch (3)

$V_{m_3} = 15.873\,V$

$I_{m_3} = 0.100\,A$

$\phi_3 = \cos^{-1} R/Z$

$\phi_3 = 90^\circ$

Branch (2)

$V_{m_2} = 15.873\,V$

$I_{m_2} = 0.004\,A$

$\cos\phi_2 = R/Z$

$\phi_2 = \cos^{-1}(R/Z) = 90^\circ$