Review

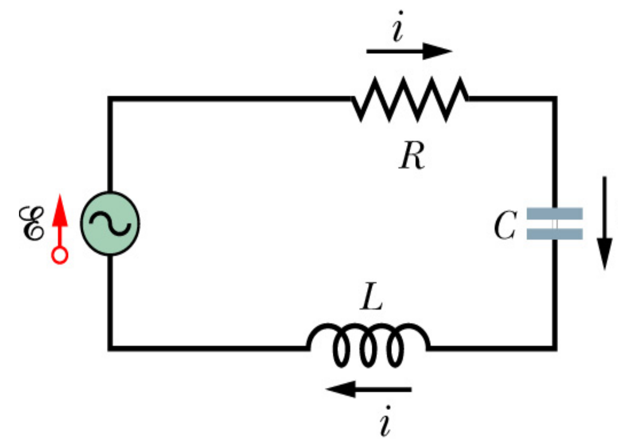
- Characterized ideal LC circuit
  - Charge, current and voltage vary sinusoidally
- Added resistance to LC circuit
  - Oscillations become damped
  - Charge, current and voltage still vary sinusoidally but decay exponentially
- Added ac generator to circuits with just a
  - Resistor
  - Capacitor
  - Inductor

Review

Element	Reactance/ Resistance	Phase of Current	Phase angle ϕ	Amplitude Relation
Resistor	R	In phase	0°	$V_R=I_RR$
Capacitor	$X_C= 1/\omega_dC$	Leads v_C	-90°	$V_C=I_CX_C$
Inductor	$X_L=\omega_dL$	Lags v_L	+90°	$V_L=I_LX_L$

EM Oscillations

- RLC circuit – resistor, capacitor and inductor in series
- Apply alternating emf



$$\mathcal{E} = \mathcal{E}_m \sin \omega_d t$$

- Elements are in series so same current is driven through each

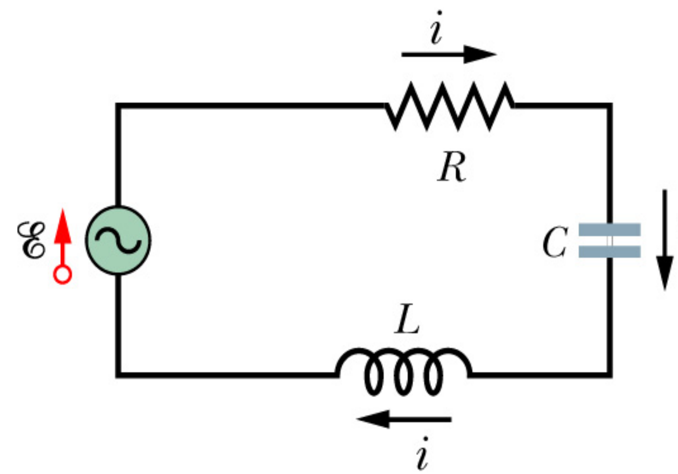
$$i = I \sin(\omega_d t - \phi)$$

- From the loop rule, at any time *t*, the sum of the voltages across the elements must equal the applied emf

$$\mathcal{E} = v_R + v_C + v_L$$

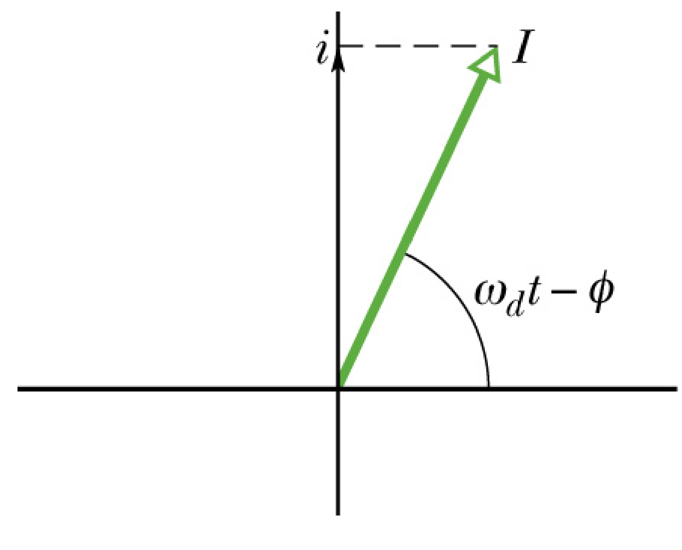
EM Oscillations

- Want to find amplitude I and the phase constant ϕ



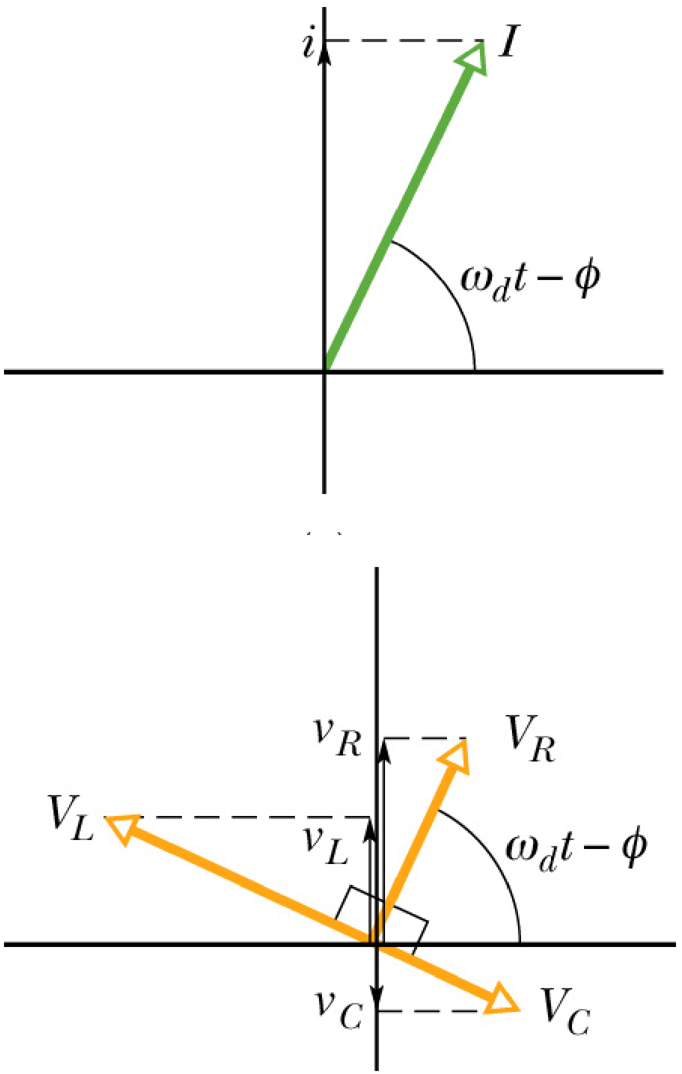
- Using phasors, represent the current at time t
  - Length is amplitude I
  - Projection on vertical axis is current i at time t
  - Angle of rotation is the phase at time t

$$\omega_d t - \phi$$



EM Oscillations

- Draw phasors for voltages of *R, C* and *L* at same time *t*
- Orient V_R, V_L, & V_C phasors relative to current phasor
- Resistor – V_R and I are in phase
- Inductor – V_L is ahead of I by 90°
- Capacitor – I is ahead of V_C by 90°
- v_R, v_C, & v_L are projections



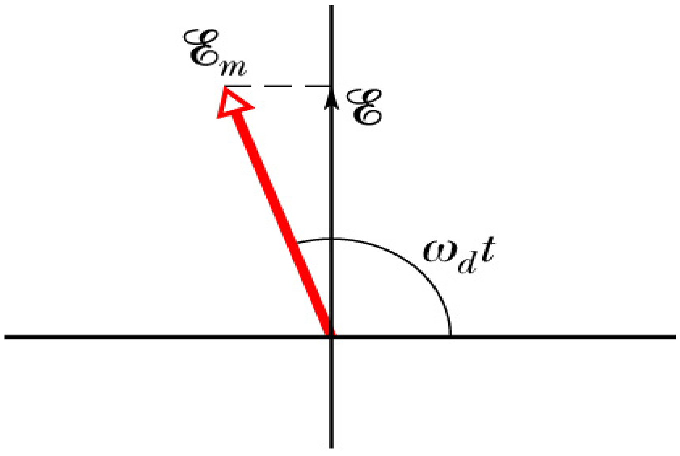
EM Oscillations

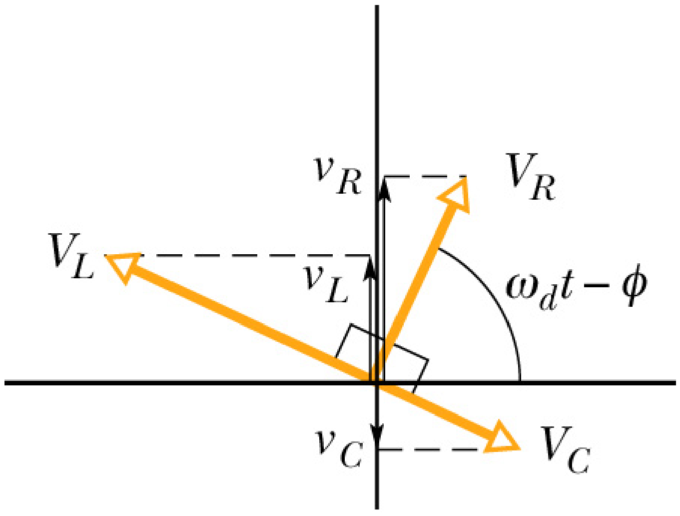
- Draw phasor for applied emf

$$\mathcal{E} = \mathcal{E}_m \sin \omega_d t$$

- Length is amplitude $\mathcal{E}_m$
- Projection is $\mathcal{E}$ at time t
- Angle is phase of emf $\omega_d t$
- From loop rule the projection $\mathcal{E}$ = the algebraic sum of projections v_R, v_L & v_C

$$\mathcal{E} = v_R + v_C + v_L$$





EM Oscillations

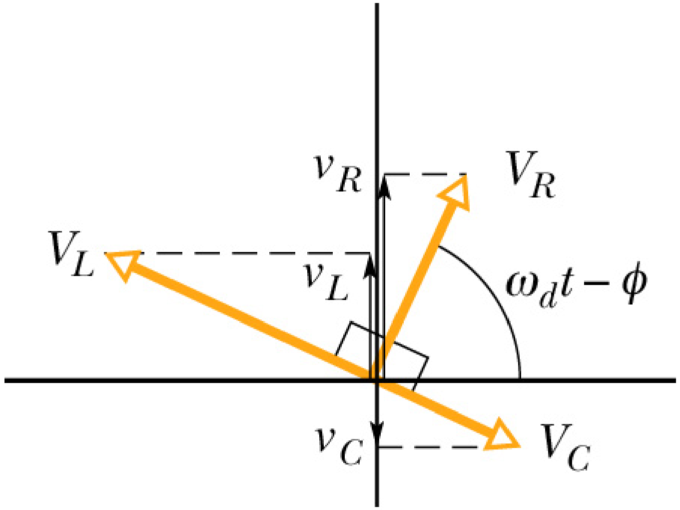
$$\mathcal{E} = v_R + v_C + v_L$$

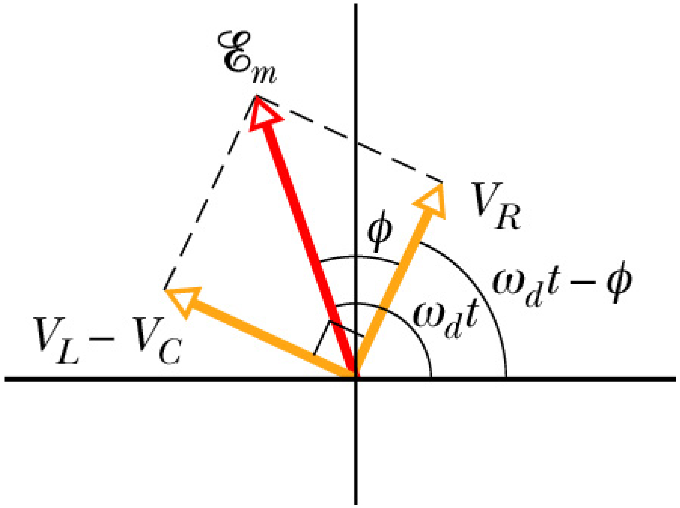
- Phasors rotate together so equality always holds
- Phasor $\mathcal{E}_m$ = vector sum of voltage phasors

$$\vec{\mathcal{E}}_m = \vec{V}_R + \vec{V}_C + \vec{V}_L$$

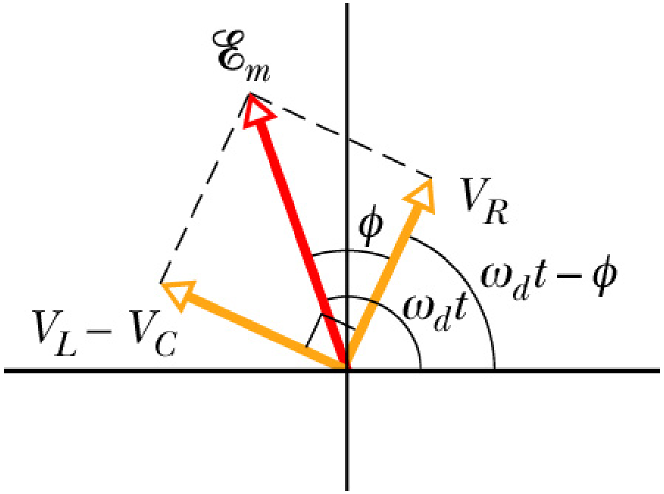
- Combine V_L & V_C to form single phasor

$$V_L - V_C$$





EM Oscillations



- Using Pythagorean theorem

$$\mathcal{E}_m^2 = V_R^2 + (V_L - V_C)^2$$

- From amplitude relations replace voltages with

$$V_R = IR \qquad V_L = IX_L \qquad V_C = IX_C$$

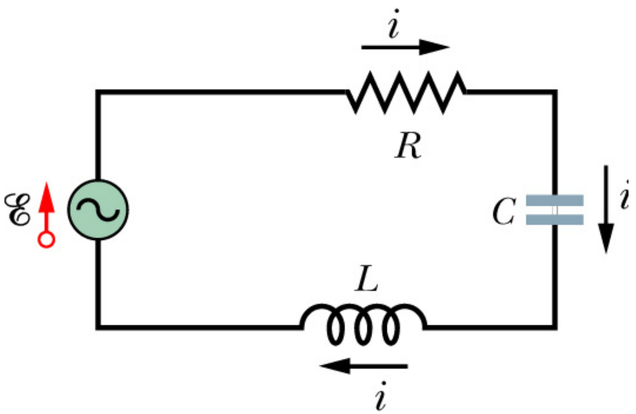
$$\mathcal{E}_m^2 = (IR)^2 + (IX_L - IX_C)^2$$

- Rearrange to find amplitude I

$$I = \frac{\mathcal{E}_m}{\sqrt{R^2 + (X_L - X_C)^2}}$$

EM Oscillations

$$I = \frac{\mathcal{E}_m}{\sqrt{R^2 + (X_L - X_C)^2}}$$



- Define impedance, Z to be

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

- Using reactances rewrite current as

$$X_L = \omega_d L$$

$$X_C = \frac{1}{\omega_d C}$$

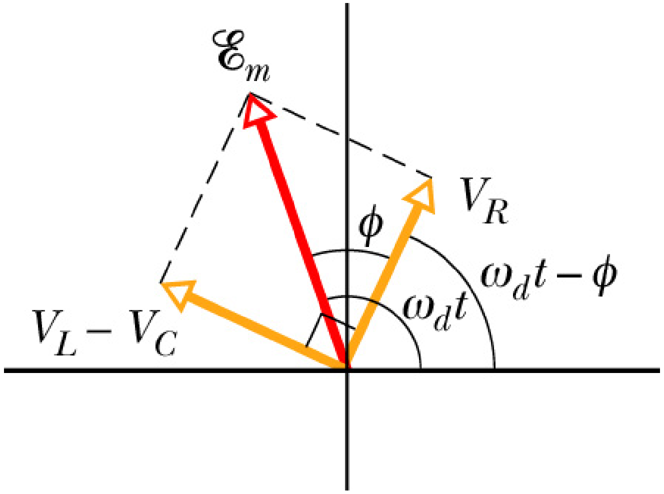
$$I = \frac{\mathcal{E}_m}{\sqrt{R^2 + (\omega_d L - 1/\omega_d C)^2}}$$

$$I = \frac{\mathcal{E}_m}{Z}$$

EM Oscillations

- Using trig find the phase constant ϕ

$$\tan\phi = \frac{V_L - V_C}{V_R}$$



- Using amplitude relations

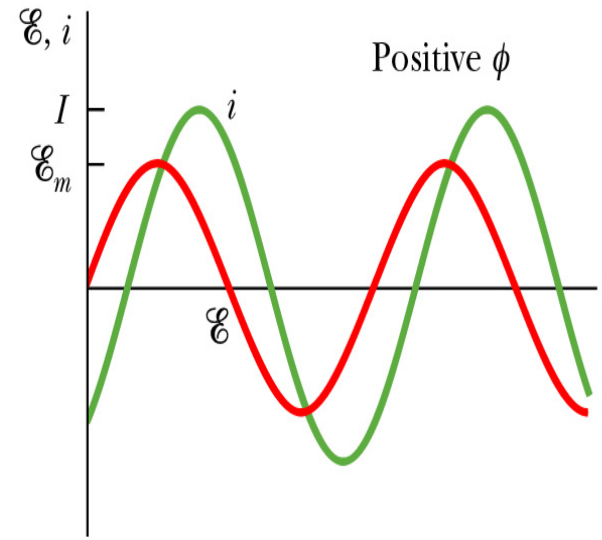
$$\tan\phi = \frac{IX_L - IX_C}{IR}$$

$$\tan\phi = \frac{X_L - X_C}{R}$$

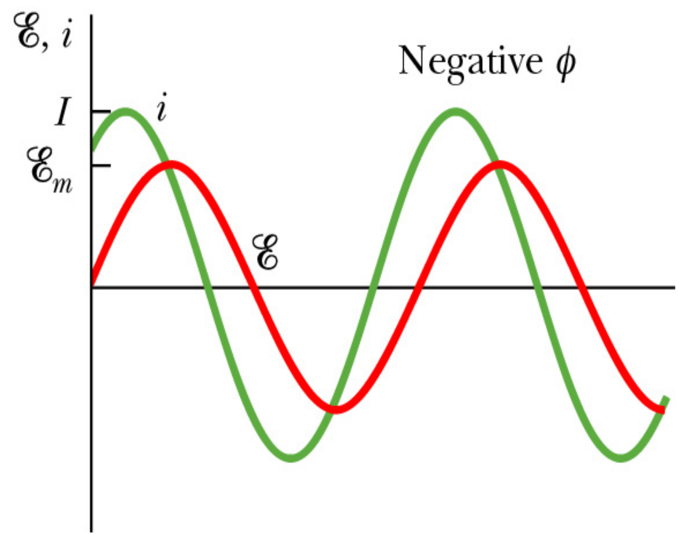
- Examine 3 cases:
  - $X_L > X_C$
  - $X_L < X_C$
  - $X_L = X_C$

EM Oscillations

$$\tan\phi = \frac{X_L - X_C}{R}$$

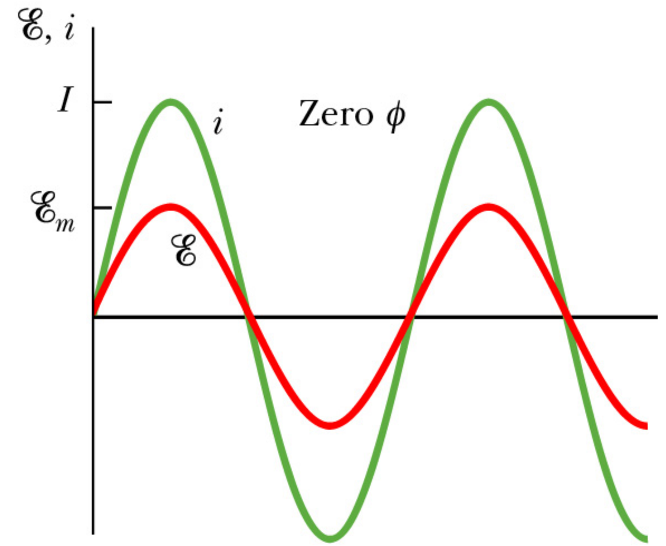


- If $X_L > X_C$ the circuit is more inductive than capacitive
  - ϕ is positive
  - Emf is before current
- If $X_L < X_C$ the circuit is more capacitive than inductive
  - ϕ is negative
  - Current is before emf



EM Oscillations

$$\tan\phi = \frac{X_L - X_C}{R}$$



- If $X_L = X_C$ the circuit is in resonance – emf and current are in phase
- Current amplitude I is max when impedance, Z is min

$$X_L - X_C = 0$$

$$Z = R$$

$$I = \frac{\mathcal{E}_m}{Z} = \frac{\mathcal{E}_m}{\sqrt{R^2 + (X_L - X_C)^2}} = \frac{\mathcal{E}_m}{R}$$

EM Oscillations

- When $X_L = X_C$ the driving frequency is

$$\omega_d L = \frac{1}{\omega_d C} \qquad \omega_d = \frac{1}{\sqrt{LC}}$$

- This is the same as the natural frequency, ω

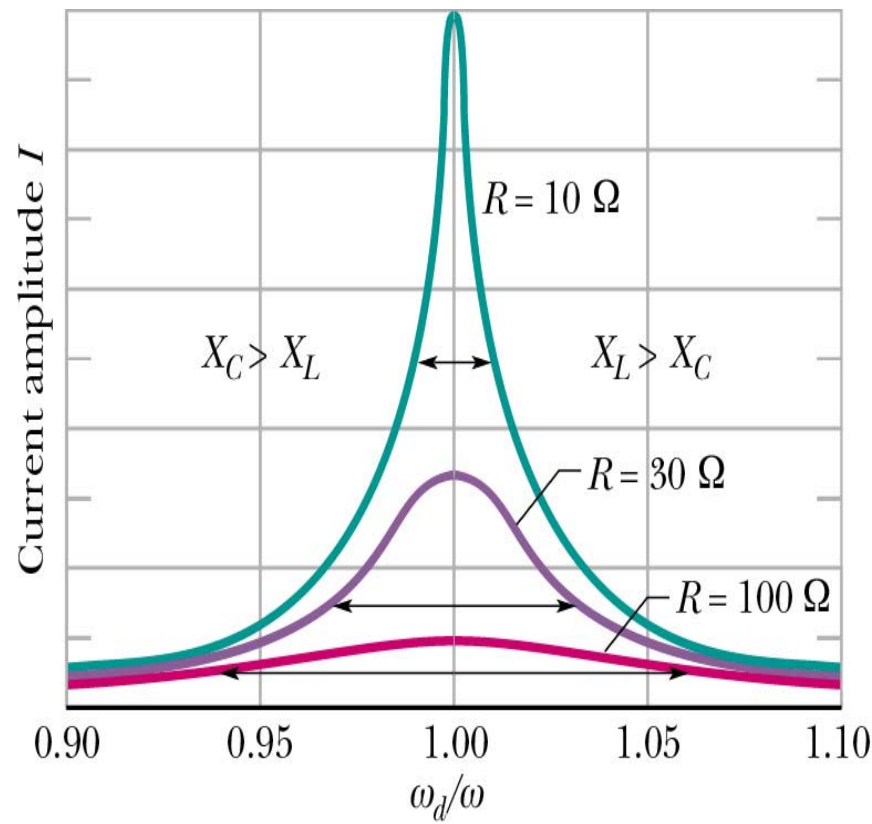
$$\omega_d = \omega = \frac{1}{\sqrt{LC}}$$

- For RLC circuit, resonance and the max current I occurs when $\omega_d = \omega$

EM Oscillations

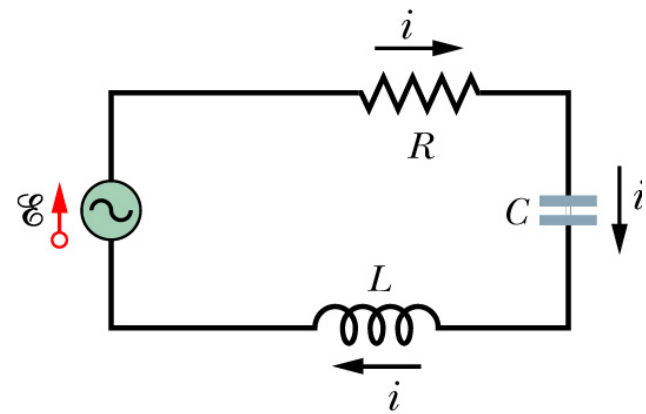
$$I = \frac{\mathcal{E}_m}{\sqrt{R^2 + (\omega_d L - 1/\omega_d C)^2}}$$

- For small driving frequency, $\omega_d < \omega$
  - X_L is small but X_C is large
  - Circuit capacitive
- For large driving frequency, $\omega_d > \omega$
  - X_C is small but X_L is large
  - Circuit inductive
- For $\omega_d = \omega$, circuit is in resonance



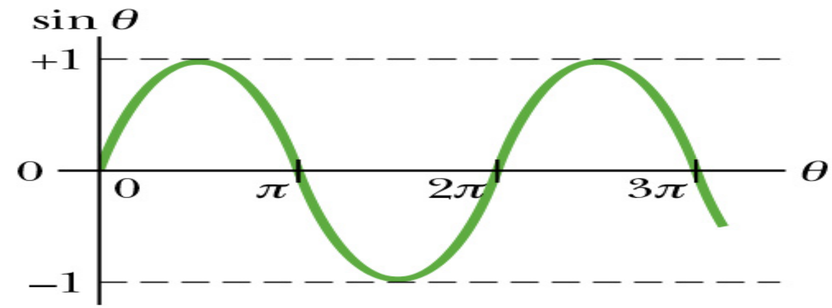
EM Oscillations

- Instantaneous rate which energy is dissipated in resistor is $P = i^2 R$



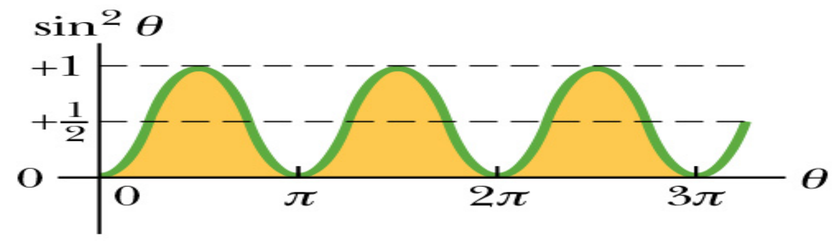
- But $i = I\sin(\omega_d t - \phi)$

$$P = I^2 R \sin^2(\omega_d t - \phi)$$



(a)

- Want average rate, P_{avg}
  - Average over complete cycle T $\sin^2\theta = 1/2$



EM Oscillations

- For alternating current circuits define root-mean-square or rms values for *i, V* and emf

$$I_{rms} = \frac{I}{\sqrt{2}} \qquad V_{rms} = \frac{V}{\sqrt{2}} \qquad \mathcal{E}_{rms} = \frac{\mathcal{E}}{\sqrt{2}}$$

- Ammeters, voltmeters - give rms values
- Write average power dissipated by resistor in an ac circuit is

$$P_{avg} = \frac{I^2 R}{2} = \left(\frac{I}{\sqrt{2}}\right)^2 R \qquad P_{avg} = I_{rms}^2 R$$

EM Oscillations

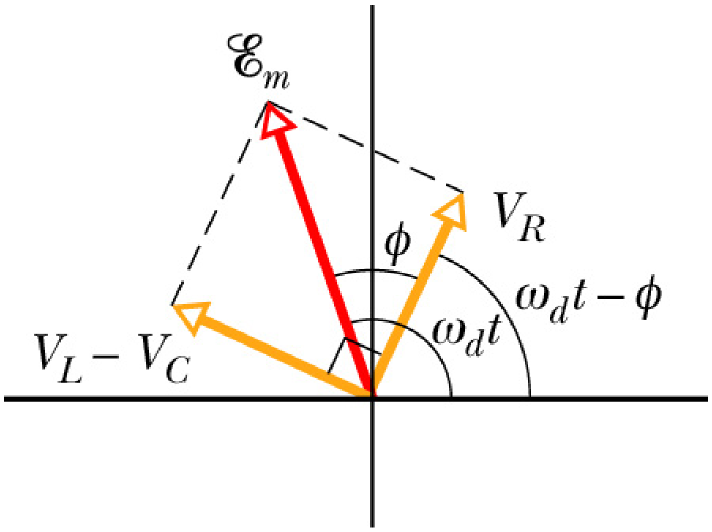
- Write average power in another form using

$$I_{rms} = \frac{\mathcal{E}_{rms}}{Z}$$

$$P_{avg} = I_{rms}^2 R = \frac{\mathcal{E}_{rms}}{Z} I_{rms} R = \mathcal{E}_{rms} I_{rms} \frac{R}{Z}$$

- Using phasor and amplitude relations

$$\cos\phi = \frac{V_R}{\mathcal{E}_m} = \frac{IR}{IZ} = \frac{R}{Z}$$



- Rewrite average power as

$$P_{avg} = \mathcal{E}_{rms} I_{rms} \cos\phi$$

EM Oscillations

- If ac circuit has only resistive load *R/Z = 1*

$$P_{avg} = \mathcal{E}_{rms} I_{rms} = I_{rms} V_{rms}$$

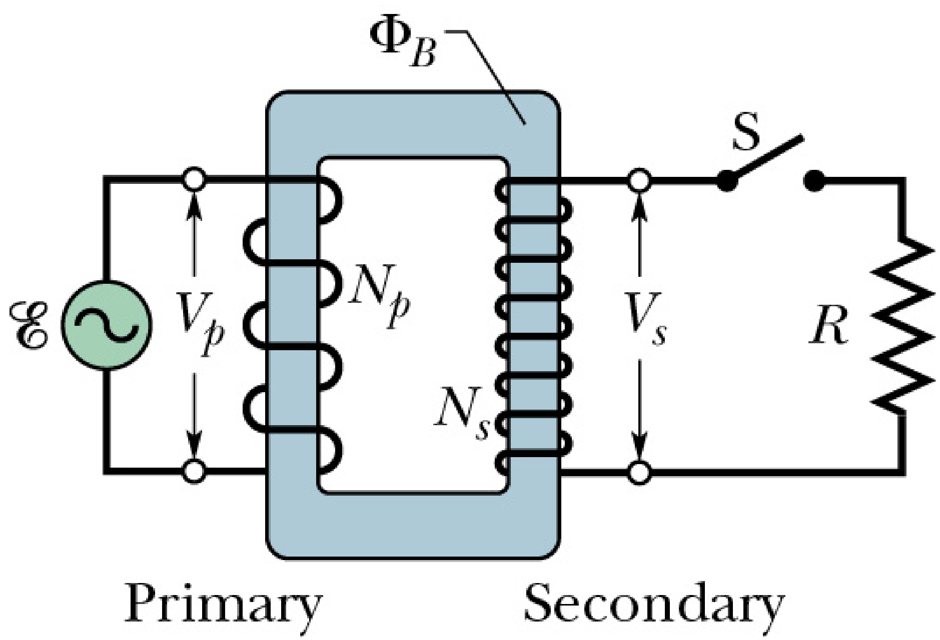
- Trade-off between current and voltage
  - For general use want low voltage
  - Means high current but

$$P_{avg} = I_{rms}^2 R$$

- General energy transmission rule: Transmit at the highest possible voltage and the lowest possible current

EM Oscillations

- Transformer – device used to raise (for transmission) and lower (for use) the ac voltage in a circuit, keeping *iV* constant
  - Has 2 coils (primary and secondary) wound on same iron core with different #s of turns

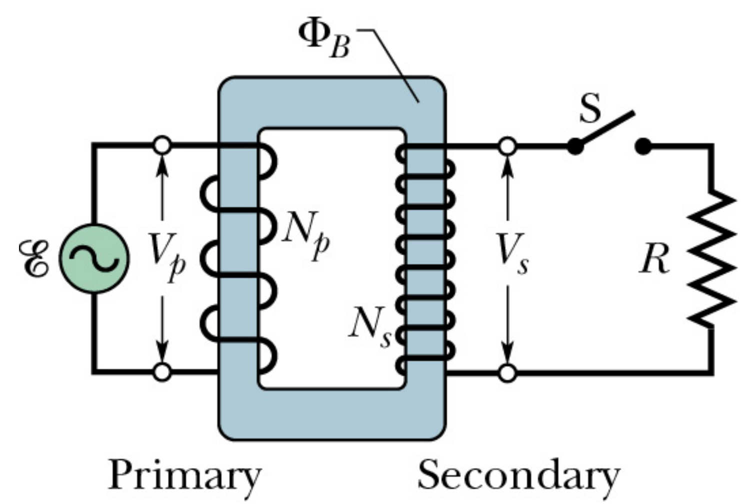


EM Oscillations

- Alternating primary current induces alternating magnetic flux in iron core
- Same core in both coils so induced flux also goes through the secondary coil
- Using Faraday's law

$$V_P = -N_P \frac{d\Phi B}{dt}$$

$$V_S = -N_S \frac{d\Phi B}{dt}$$

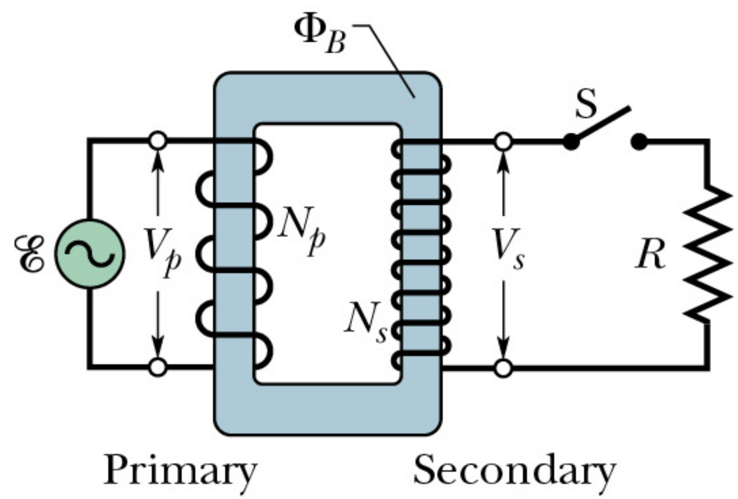


$$\frac{V_P}{N_P} = \frac{V_S}{N_S}$$

EM Oscillations

- Transformation of voltage is
- If $N_S > N_P$ called a step-up transformer
- If $N_S < N_P$ called a step-down transformer
- Conservation of energy

$$V_S = V_P \frac{N_S}{N_P}$$



$$I_P V_P = I_S V_S$$

$$I_S = I_P \frac{V_P}{V_S} = I_P \frac{N_P}{N_S}$$

EM Oscillations

- The current I_P appears in primary circuit due to R in secondary circuit.

$$I_P V_P = I_S V_S \qquad I_S = V_S / R$$

$$I_P = \frac{V_S}{R}\frac{V_S}{V_P} = \frac{1}{R}\frac{V_S^2}{V_P^2}V_P = \frac{1}{R}\left(\frac{N_S}{N_P}\right)^2 V_P$$

- Has for of IP = VP/Req where

$$R_{eq} = \left(\frac{N_P}{N_S}\right)^2 R$$