ELECTRICAL MACHINES

Elective Course – EPM332

Course Grading System

100 Marks

70
Final Exam

30
Semester Work
- 15 Mid-term
- 10 Quizzes
- 5 Assignments

Course Schedule

- Lecture: Tuesday 12:15 - 1:45 pm
- Office Hours: Tuesday 2-3 pm
- Quizzes: W6 – W12
- Mid-term: W8 (29 March-3 April)
- Email: tamer.m.abdo@gmail.com
- Scholar page: https://goo.gl/ymLdIl

Course ILOs

1. **Explain the construction, types, principle of operation, equivalent circuit and tests of the 1-phase transformer**
2. **Define the principle of pulsating and rotating fields**
3. **Explain the construction, types, principle of operation and equivalent circuit of the 3-phase induction machines.**
4. **Explain the theory of operation of single-phase induction motor**
5. **Discuss the different types of 1-phase induction motors and their performance**
6. **Calculate the basic quantities concerning the operation of the transformer and induction machines.**
7. **Solve performance problems of transformer and induction machines**
8. **Compare different types of single-phase induction motors and different starting methods**
9. **Explain the construction, types and theory of operation of the stepper motor.**

Course Contents

- Basic Principles
- Transformers
- Induction Machines

1. Three-phase induction motors.
2. Two-phase induction motors (AC Servo).
3. Single-phase induction motors.

- Stepper Motors

Revision: Basic Principles

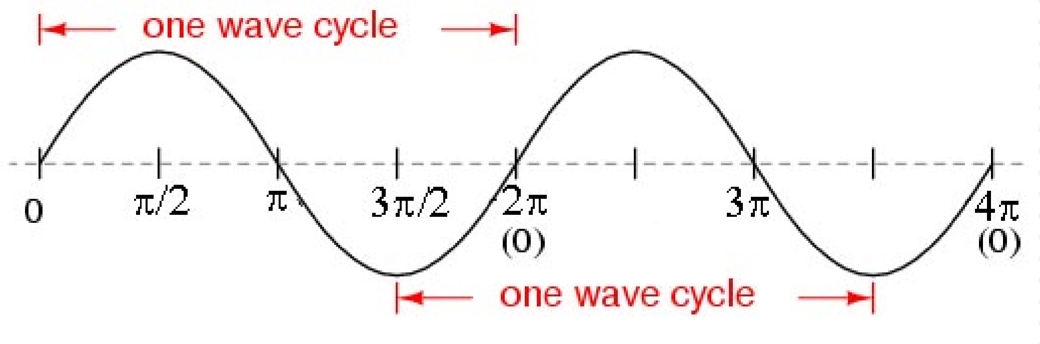
- AC Circuits
- Three-phase Circuits
- Magnetic Fields
- Time-varying Fields: Faraday's Law
- Magnetic Circuits

Revision: Basic Principles

AC Circuits

Sinusoidal Voltage Supply

$$v = V_m \sin(\omega t)$$



Time of one cycle = Period = T

$$2\pi = \omega T$$ → $$T = \frac{2\pi}{\omega}$$ (sec) → $$f = \frac{\omega}{2\pi}$$ (Hz) → $$\omega = 2\pi f$$ (rad/sec)

No. of cycles/sec = Frequency = 1/T

Revision: Basic Principles

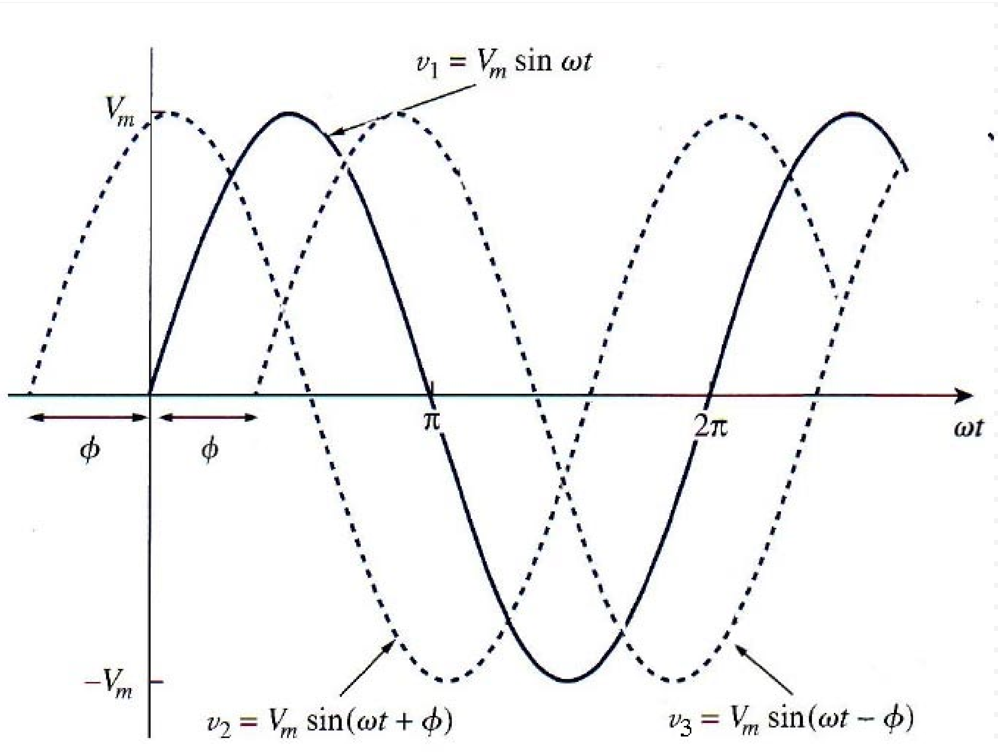
AC Circuits

Phase Shift

$$v_1 = V_m \sin(\omega t)$$

$$v_2 = V_m \sin(\omega t + \phi)$$

$$v_3 = V_m \sin(\omega t - \phi)$$



v_1 lags v_2 but leads v_3

v_3 lags v_1 and lags v_2

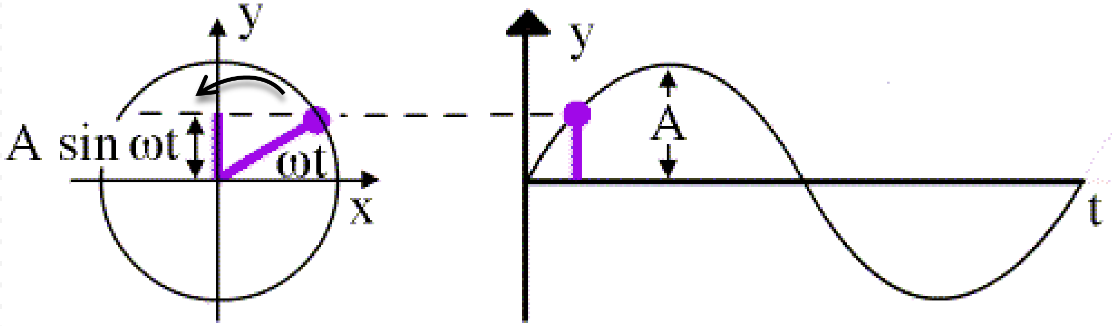
*The terms lag and lead are used to describe phase shift between sinusoidal waveforms of **same frequency***

Revision: Basic Principles

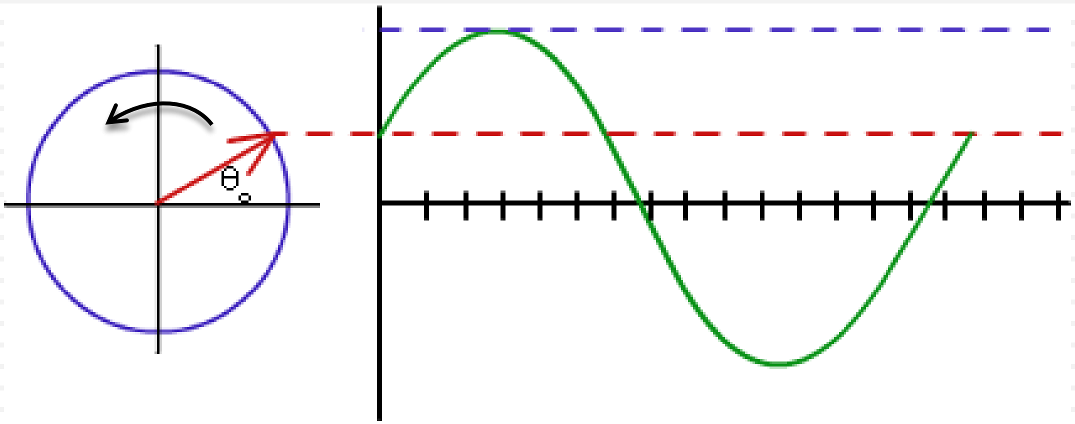
AC Circuits

Phasor Representation

$$v_1 = V_m \sin(\omega t)$$



$$v_2 = V_m \sin(\omega t + \theta_o)$$

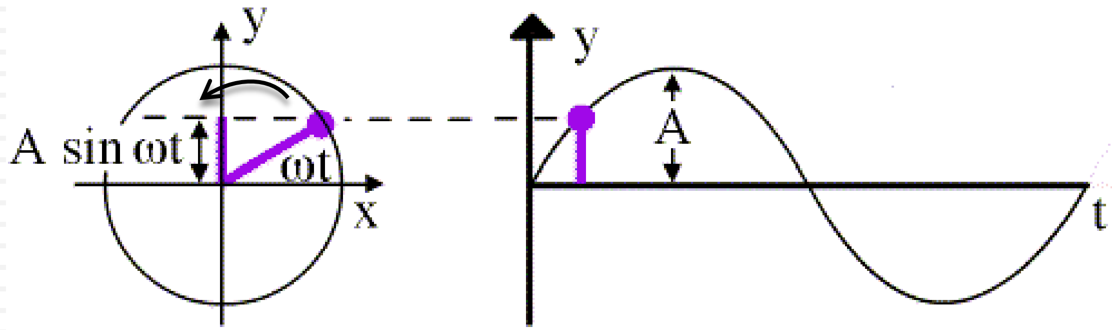


Revision: Basic Principles

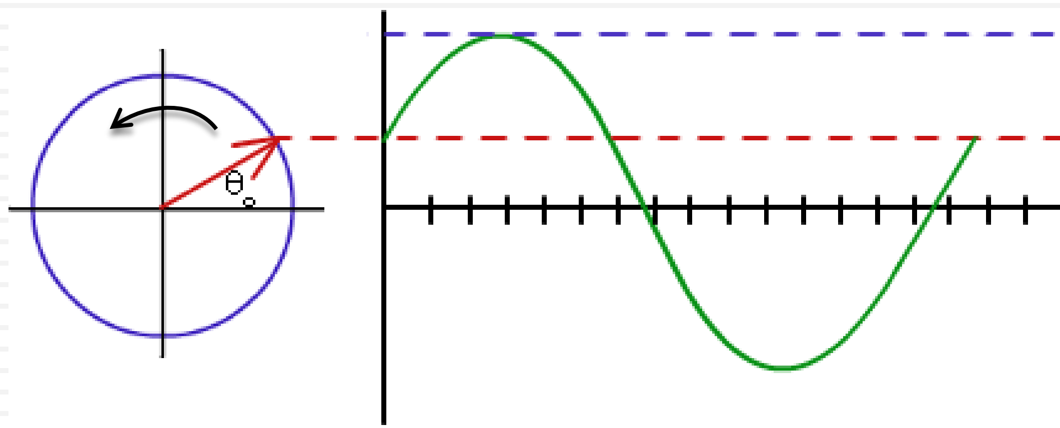
AC Circuits

Phasor Representation

$$V_1 = V_{rms} \angle 0$$



$$V_2 = V_{rms} \angle \theta_o$$



$$V_{rms} = \frac{V_m}{\sqrt{2}}$$

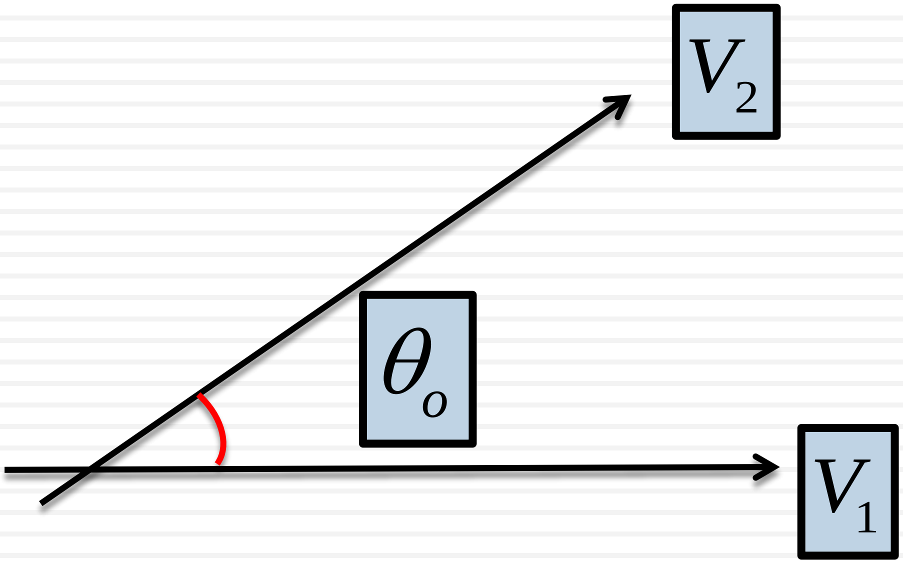
Revision: Basic Principles

AC Circuits

Phasor Representation

$$V_1 = V_1 \angle 0$$

$$V_2 = V_2 \angle \theta_o$$



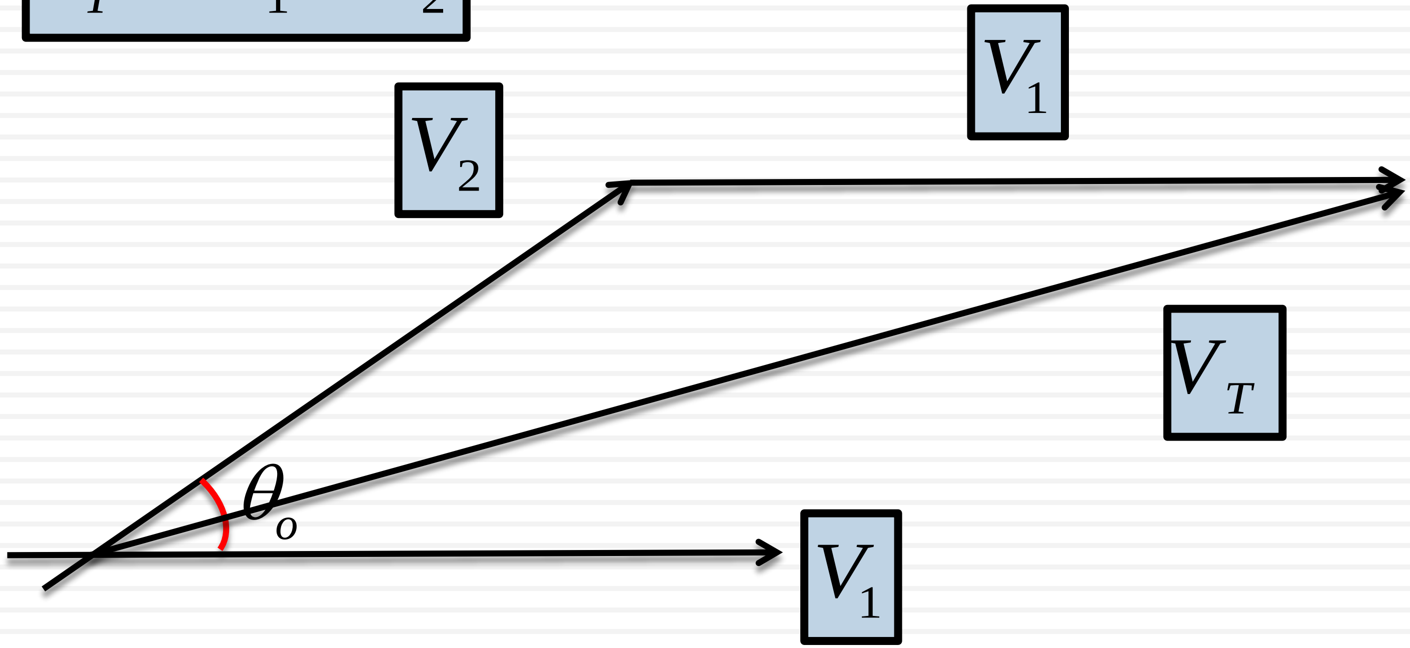
Phasor Diagram

Revision: Basic Principles

AC Circuits

Phasor Representation

$$V_T = V_1 + V_2$$



Revision: Basic Principles

AC Circuits

Phasor Representation

Polar form

$$V = |V| \angle \theta_o$$

$$V = A + jB$$

Rectangular form

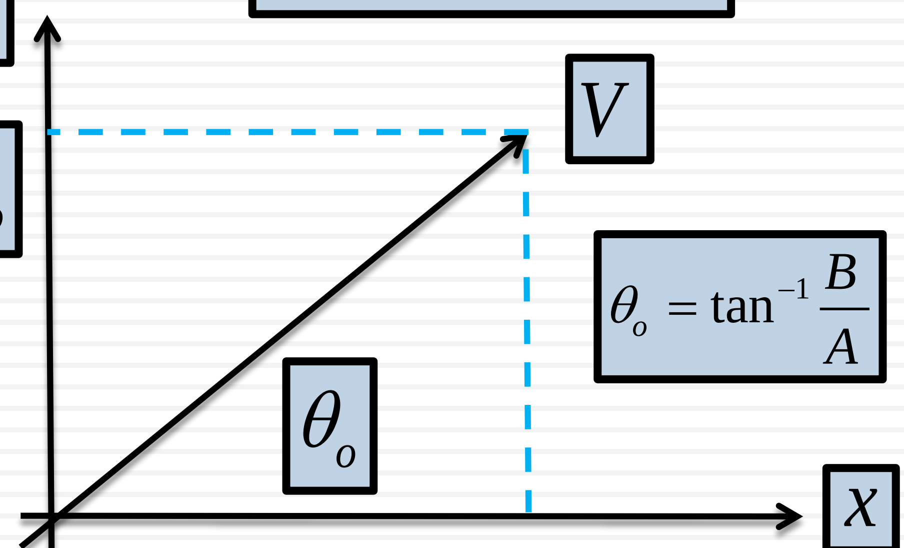
$$B = V \sin \theta_o$$

$$|V| = \sqrt{A^2 + B^2}$$

$$\theta_o = \tan^{-1} \frac{B}{A}$$

$$A = V \cos \theta_o$$

Img y



Real

Revision: Basic Principles

AC Circuits

Phasor Representation

$$V_1 = A_1 + jB_1 \Leftrightarrow V_1 = |V_1|\angle\theta_1$$

$$V_2 = A_2 + jB_2 \Leftrightarrow V_2 = |V_2|\angle\theta_2$$

$$V_T = V_1 \pm V_2$$

$$V_T = (A_1 \pm A_2) + j(B_1 \pm B_2)$$

$$V_T = |V_T|\angle\theta_T$$

$$|V_T| = \sqrt{(A_1 \pm A_2)^2 + (B_1 \pm B_2)^2}$$

$$\theta_T = \tan^{-1}\frac{B_1 \pm B_2}{A_1 \pm A_2}$$

Revision: Basic Principles

AC Circuits

Phasor Representation

$$V_1 = A_1 + jB_1 \Leftrightarrow V_1 = |V_1|\angle\theta_1$$

$$V_2 = A_2 + jB_2 \Leftrightarrow V_2 = |V_2|\angle\theta_2$$

$$V_T = V_1 \times V_2$$

$$V_T = [|V_1|\angle\theta_1] \times or \div [|V_2|\angle\theta_2]$$

$$V_T = |V_1| \times or \div |V_2| \angle\theta_1 \pm \theta_2$$

$$V_T = |V_T|\angle\theta_T$$

$$|V_T| = |V_1| \times or \div |V_2|$$

$$\theta_T = \theta_1 \pm \theta_2$$

Revision: Basic Principles

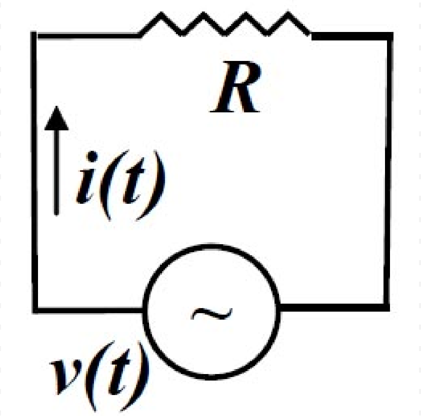
AC Circuits

Loads: Resistive Load

$$v(t) = V_m \sin(\omega t) = \sqrt{2} V \sin(\omega t)$$

$$V = V \angle 0$$

$$i(t) = \frac{v(t)}{R} = \sqrt{2} \frac{V}{R} \sin(\omega t)$$



$$i(t) = \sqrt{2} I \sin(\omega t)$$

$$I = I \angle 0$$

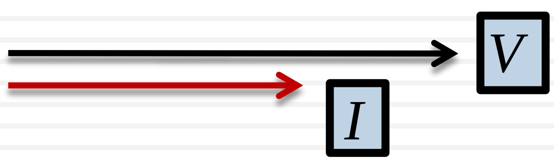
$$V = IR$$

Revision: Basic Principles

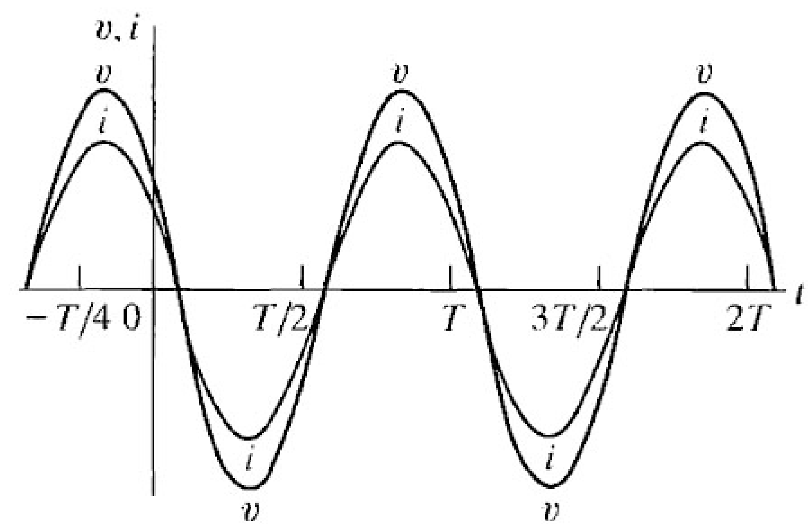
AC Circuits

<u>Loads:</u> *Resistive Load*

$$V = IR$$



Phasor Diagram



Voltage and current are in-phase

Revision: Basic Principles

AC Circuits

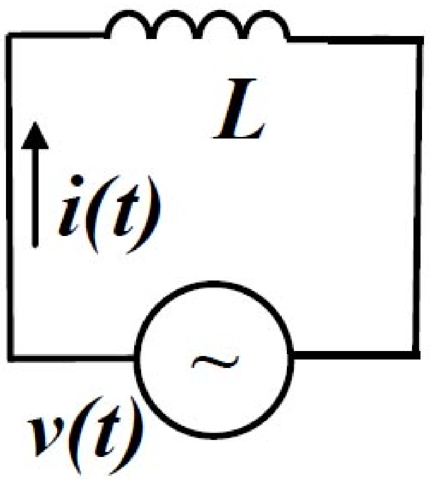
Loads: Inductive Load

$$v = N\frac{d\phi}{dt} = L\frac{di}{dt}$$

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

$$i(t) = \frac{1}{L}\int v(t)dt = -\sqrt{2}\frac{V}{\omega L}\cos(\omega t)$$

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



Revision: Basic Principles

AC Circuits

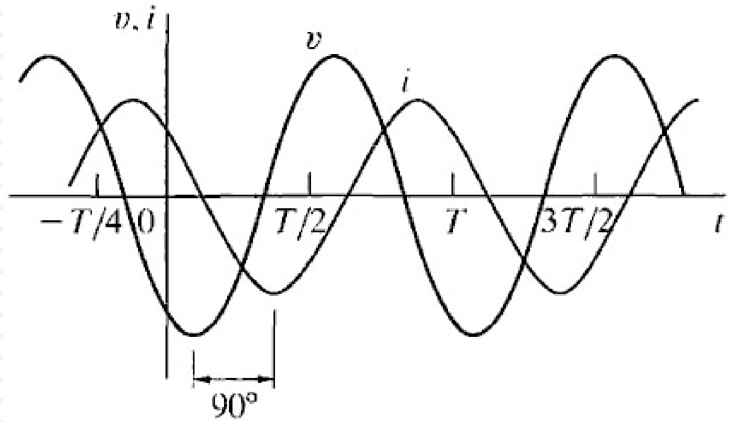
Loads: *Inductive Load*

$$I = -j\frac{V}{\omega L}$$

$$V = j(\omega L)I$$

$$V = jX_L I$$

Inductive reactance (Ω)



current **lags** voltage by 90°

Revision: Basic Principles

AC Circuits

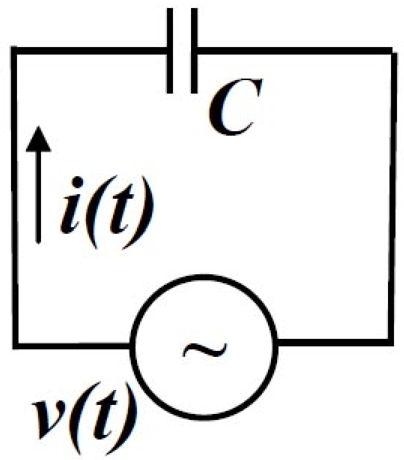
Loads: Capacitive Load

$$i = C\frac{dv}{dt}$$

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

$$i(t) = \sqrt{2}\omega CV\cos(\omega t)$$

$$i(t) = \sqrt{2}\omega CV\sin(\omega t + \frac{\pi}{2})$$



Revision: Basic Principles

AC Circuits

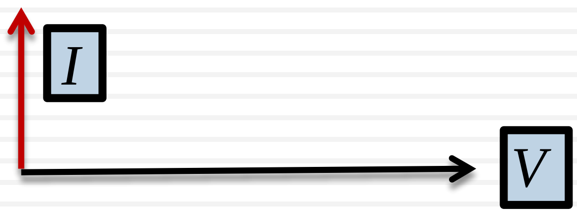
Loads: Capacitive Load

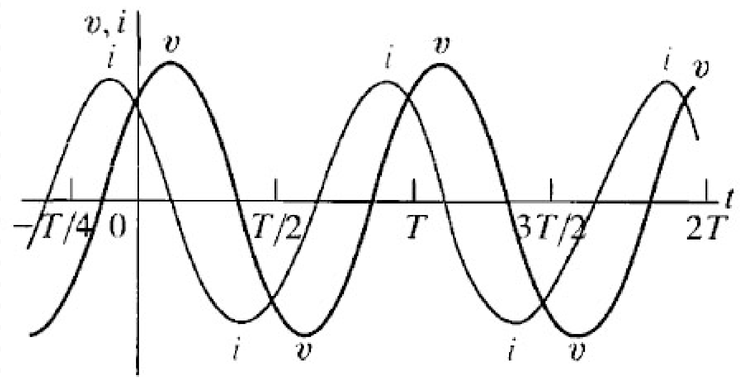
$$I = j(\omega C)V$$

$$V = -j\left(\frac{1}{\omega C}\right)I$$

$$V = -jX_C I$$

Capacitive reactance (Ω)





current **leads** voltage by 90°

Revision: Basic Principles

AC Circuits

Loads: R-L Load

$$V = I(R + j\omega L)$$

$$V = I(R + jX_L)$$

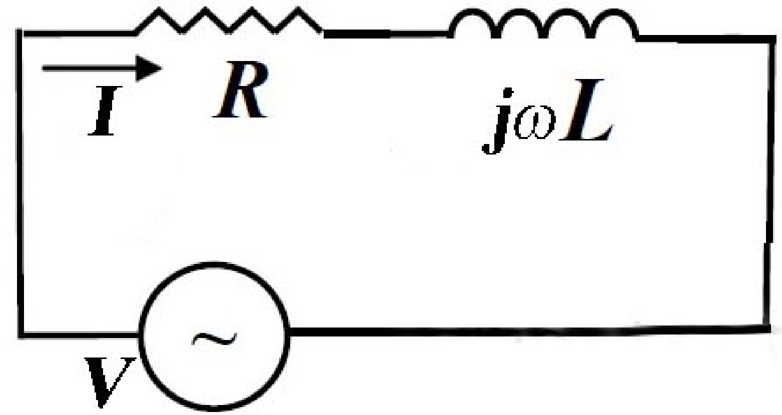
$$V = IZ$$

Impedance

$$Z = R + jX_L = Z\angle\Phi$$

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

$$\Phi = \tan^{-1}\frac{\omega L}{R}$$



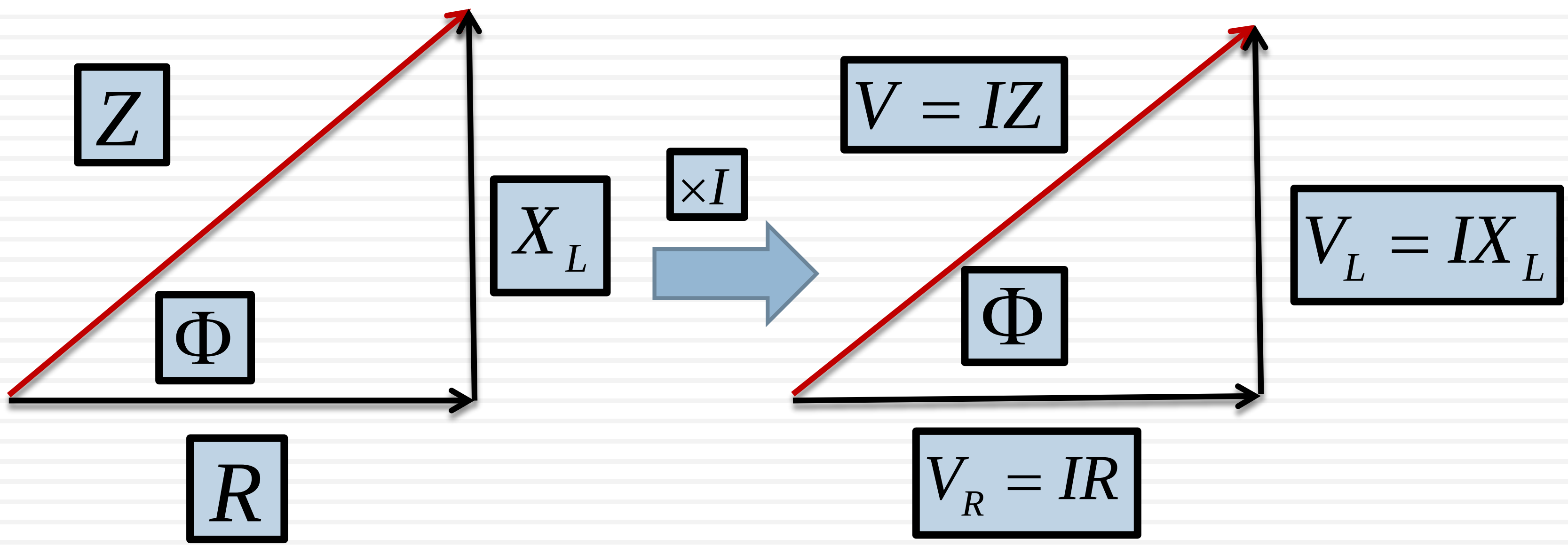
$$I = \frac{V\angle 0}{Z\angle\Phi} = \frac{V}{Z}\angle -\Phi$$

current **lags** voltage

Revision: Basic Principles

AC Circuits

Loads: ***R-L Load***



Revision: Basic Principles

AC Circuits

Loads: R-C Load

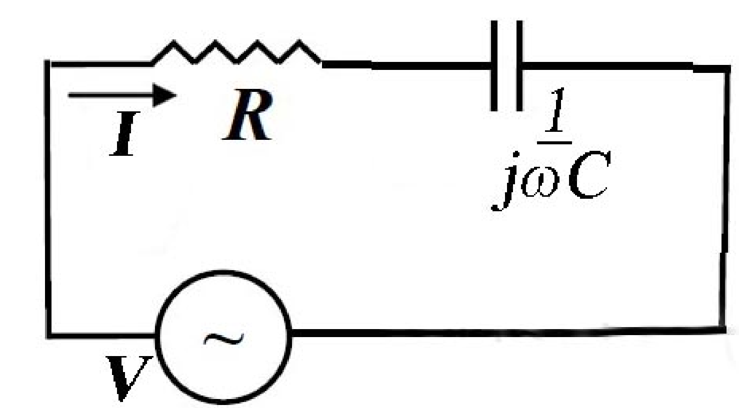
$$V = I(R - j\frac{1}{\omega C})$$

$$V = I(R - j X_C)$$

$$Z = R - j X_C = Z\angle -\Phi$$

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

$$\Phi = \tan^{-1}\frac{1/\omega C}{R}$$



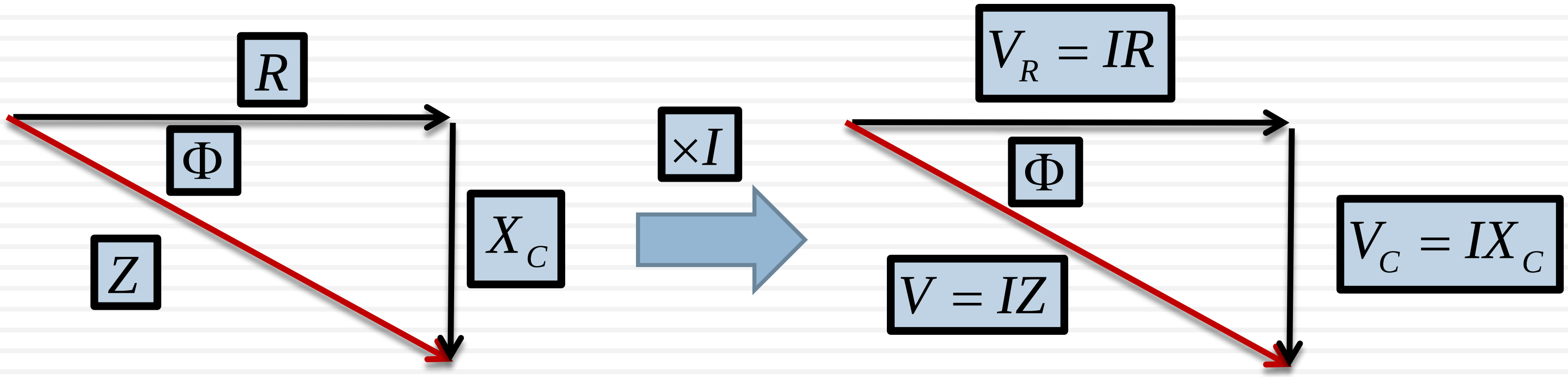
$$I = \frac{V\angle 0}{Z\angle -\Phi} = \frac{V}{Z}\angle \Phi$$

current **leads** voltage

Revision: Basic Principles

AC Circuits

Loads: *R-C Load*



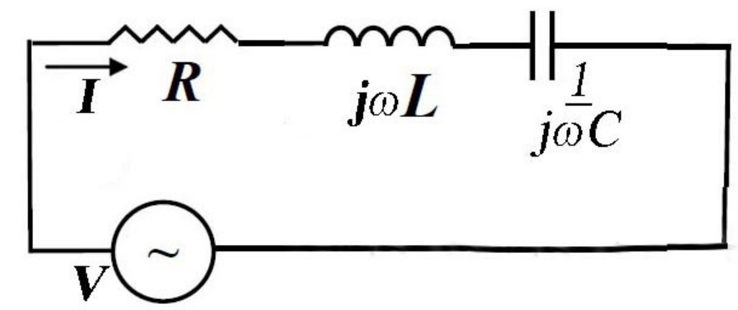
Revision: Basic Principles

AC Circuits

Loads: R-L-C Load

$$V = I\,[R + j(X_L - X_C)]$$

$$Z = R + j(X_L - X_C) = Z\angle\Phi$$



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

$$\Phi = \tan^{-1}\frac{X_L - X_C}{R}$$

$X_L > X_C$ $\quad \Phi = +ve$

inductive load

$X_L < X_C$ $\quad \Phi = -ve$

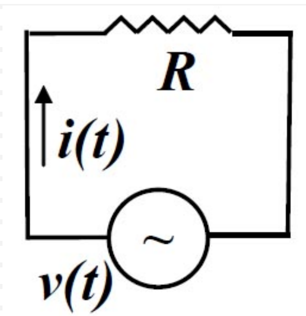
capacitive load

$$I = \frac{V\angle 0}{Z\angle \pm\Phi} = \frac{V}{Z}\angle\mp\Phi$$

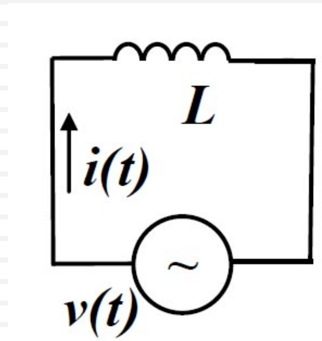
Revision: Basic Principles

AC Circuits

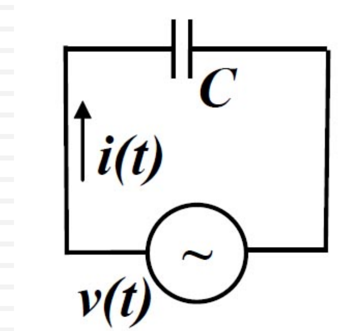
Loads



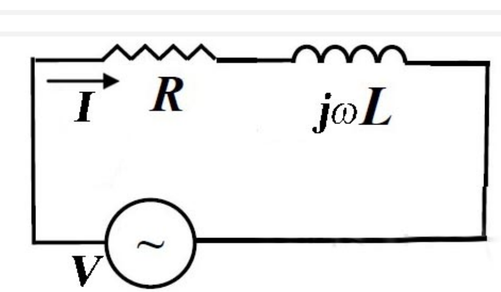
Resistive load



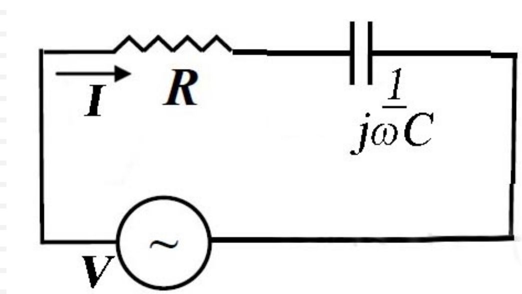
Pure inductive load



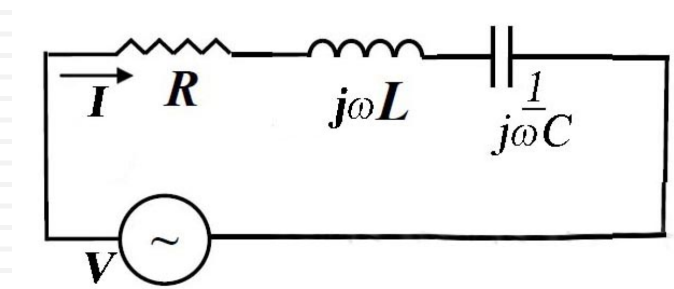
Pure capacitive load



inductive load



capacitive load



$X_L > X_C$ inductive load

$X_L < X_C$ capacitive load

Revision: Basic Principles

AC Circuits

AC Power

$$p(t) = v(t) \times i(t)$$

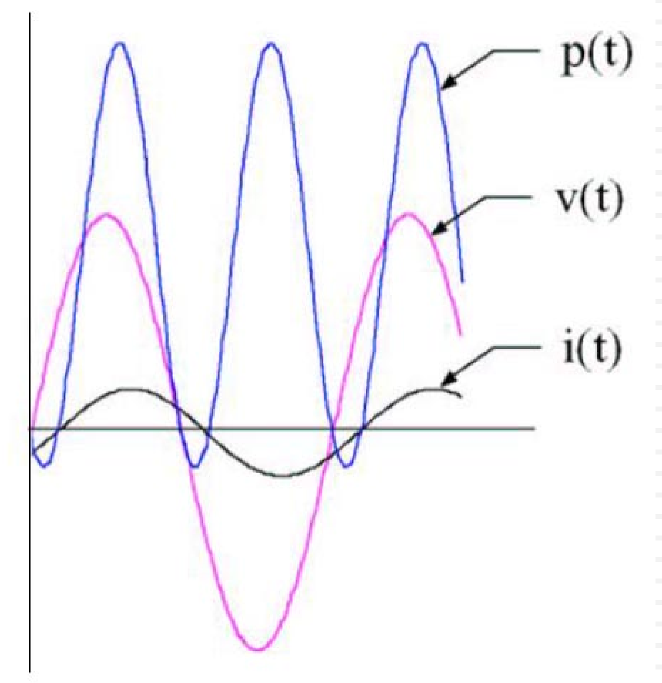
$$v(t) = \sqrt{2}V \sin(\omega t)$$

$$i(t) = \sqrt{2}I \sin(\omega t \pm \Phi)$$

$$p(t) = VI[\cos(\Phi) - \cos(2\omega t \pm \Phi)]$$

$$P_{avg} = VI \cos \Phi$$

Active Power (W)



Revision: Basic Principles

AC Circuits

Active and Reactive Power

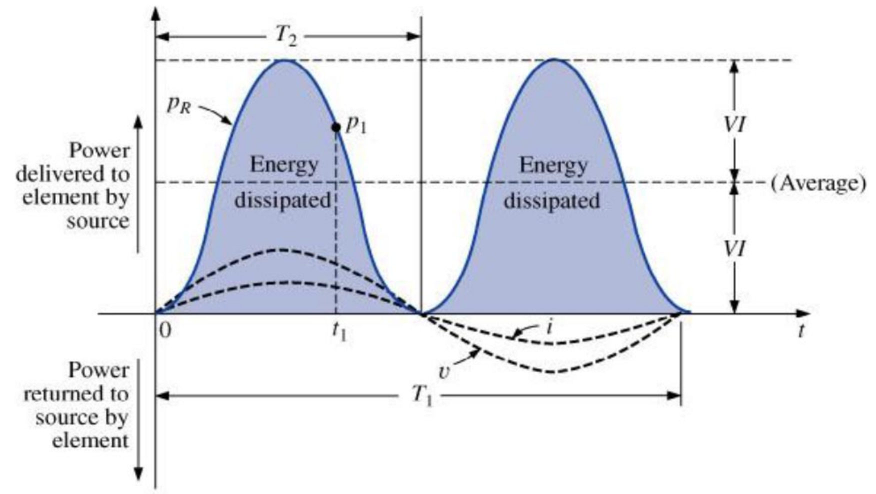
$$p(t) = VI[\cos(\Phi) - \cos(2\omega t \pm \Phi)]$$

For pure resistive load:

$$\Phi = 0$$

$$p(t) = VI[1 - \cos(2\omega t)]$$

$$P_{avg} = VI$$



AC Circuits

Active and Reactive Power

$$p(t) = VI[\cos(\Phi) - \cos(2\omega t \pm \Phi)]$$

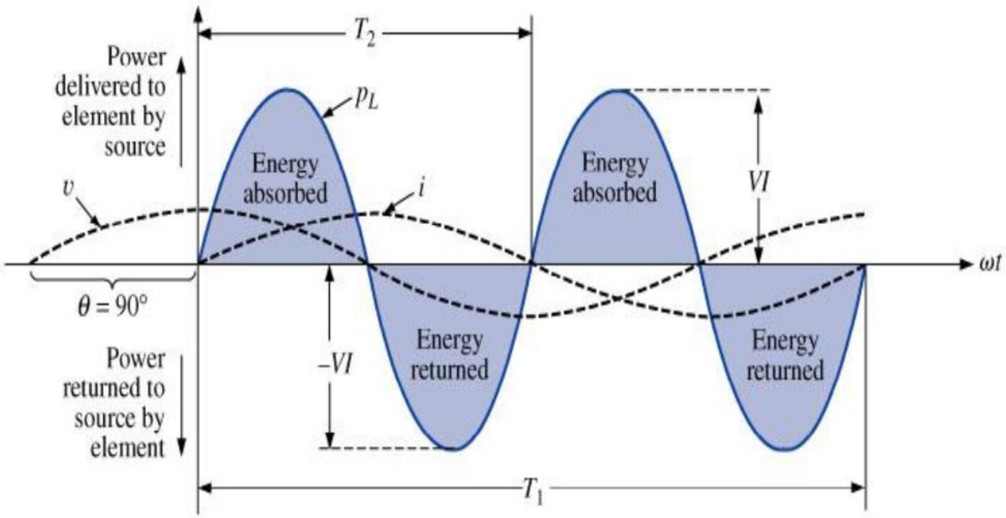
For pure inductive load:

$$\Phi = -90^o$$

$$p(t) = VI\cos(2\omega t - 90^o)$$

$$p(t) = VI\sin(2\omega t)$$

$$P_{avg} = zero$$



Revision: Basic Principles

AC Circuits

Active and Reactive Power

$$p(t) = VI[\cos(\Phi) - \cos(2\omega t \pm \Phi)]$$

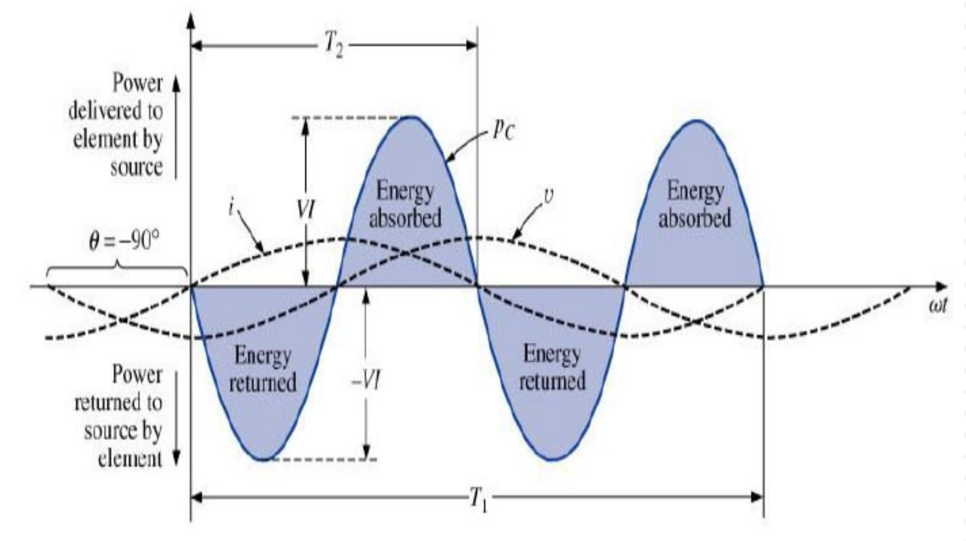
For pure capacitive load:

$$\Phi = 90^o$$

$$p(t) = VI\cos(2\omega t + 90^o)$$

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

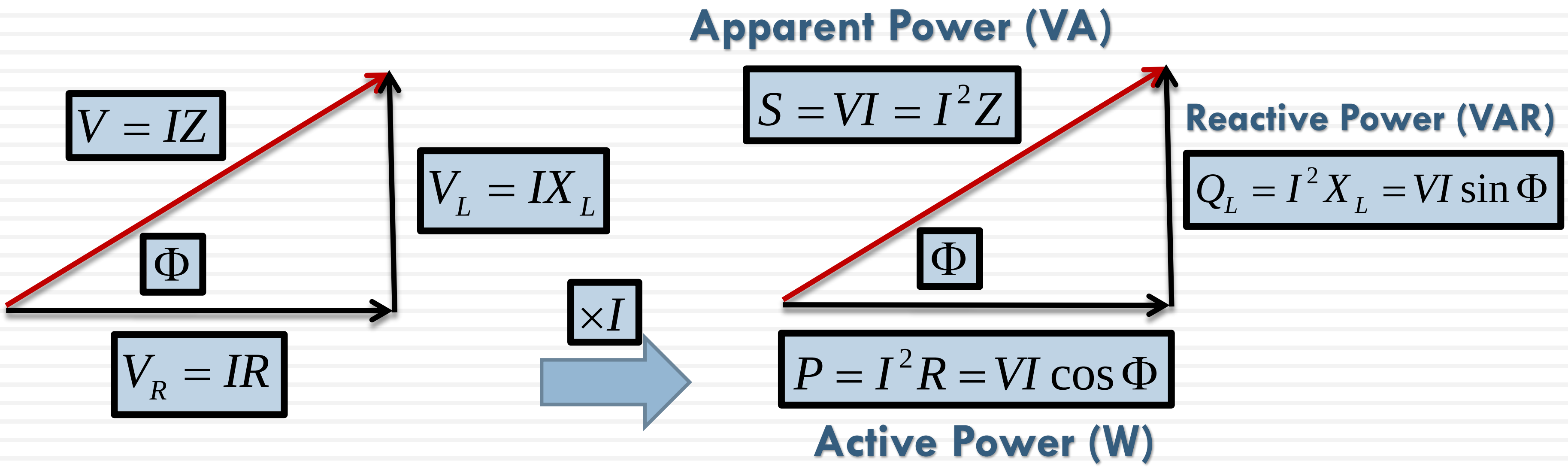
$$P_{avg} = zero$$



Revision: Basic Principles

AC Circuits

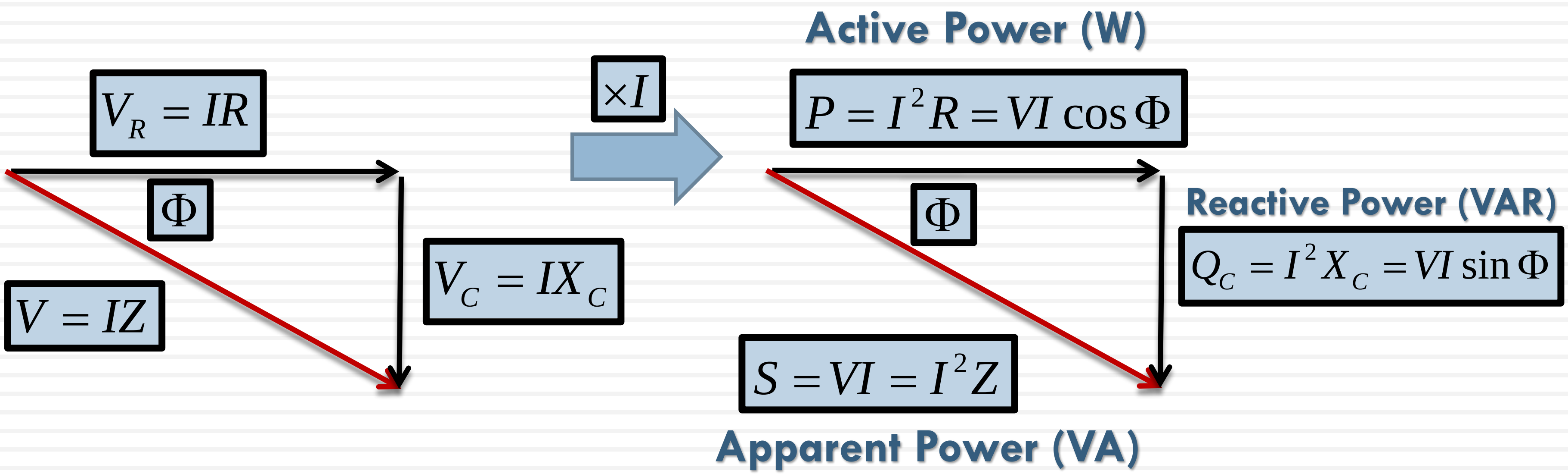
AC Power: Inductive Load



Revision: Basic Principles

AC Circuits

AC Power: Capacitive Load



Revision: Basic Principles

AC Circuits

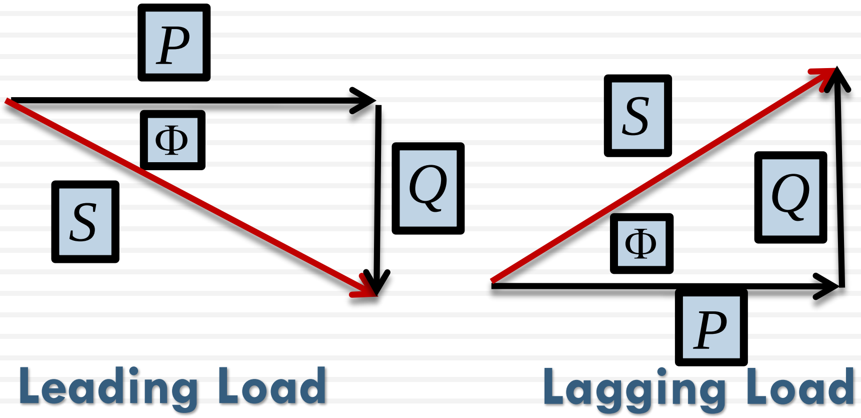
Complex Power & Power Factor

$$S = P \pm jQ = VI^*$$

$$I^* = (I\angle \mp \Phi)^* = I\angle \pm \Phi$$

$$S = VI\cos\phi \pm jVI\sin\phi$$

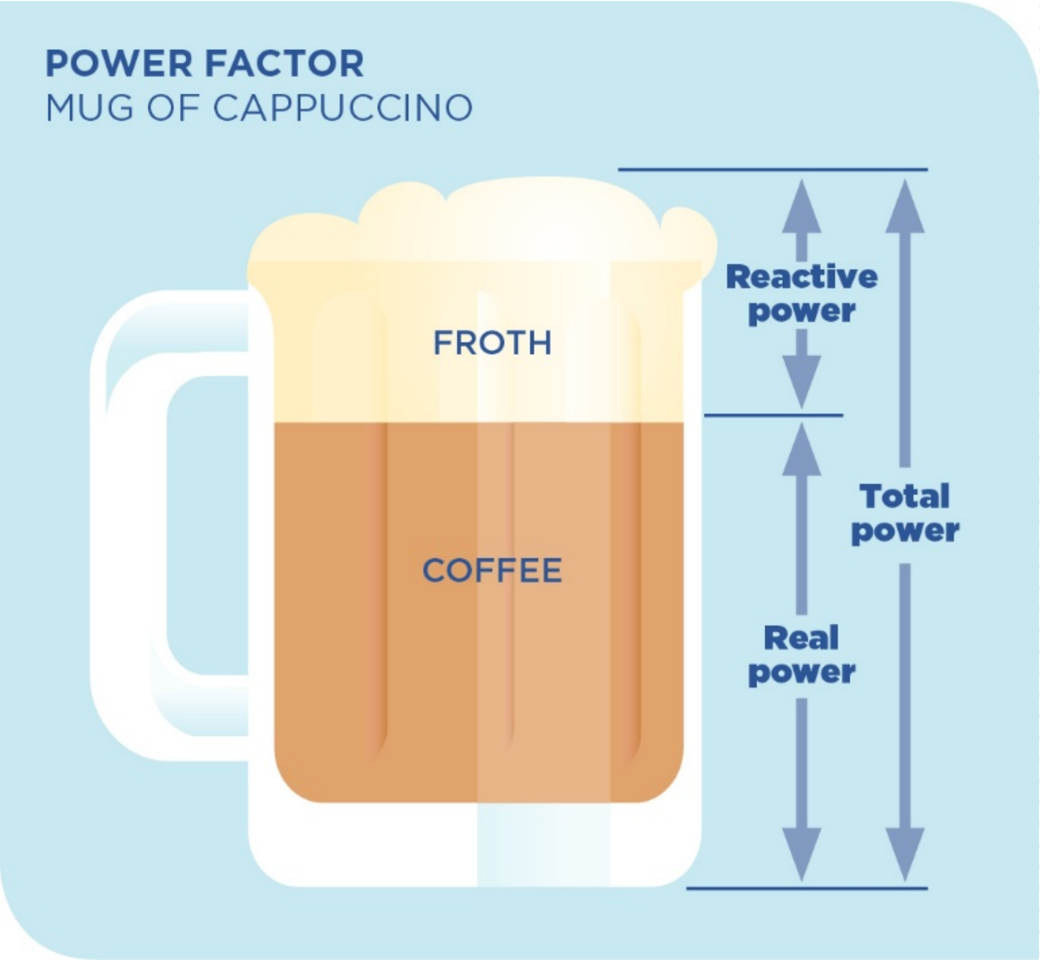
$$power\ \ factor = \frac{P}{S} = \cos\Phi$$



Revision: Basic Principles

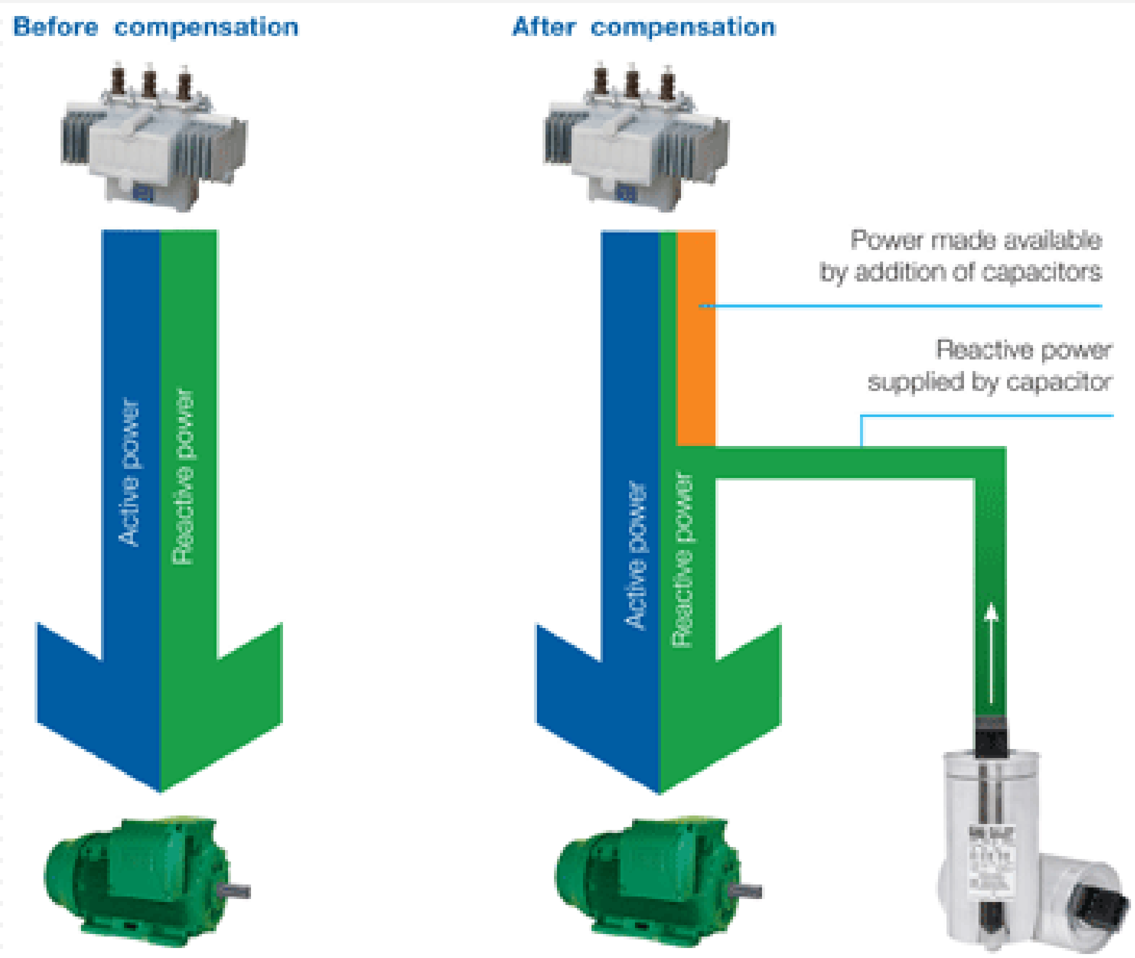
AC Circuits

$$Power\ Factor = \frac{P}{S}$$



Revision: Basic Principles

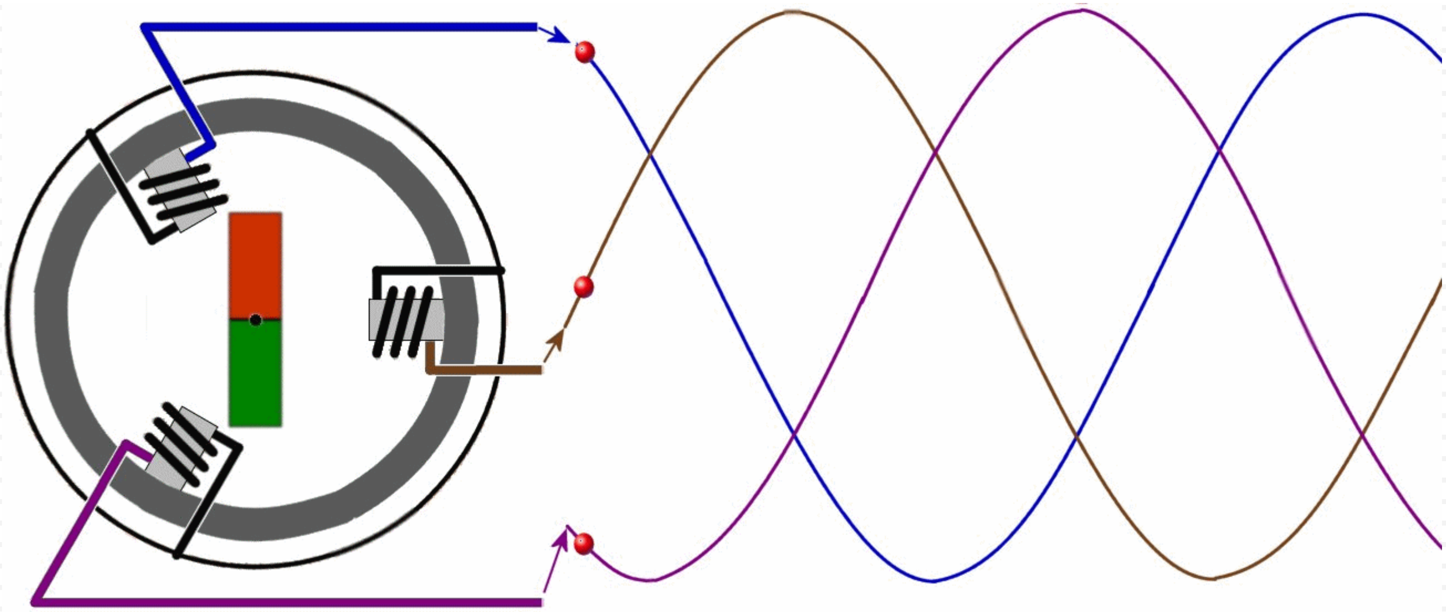
AC Circuits



Revision: Basic Principles

3-phase AC Circuits

3-phase AC Supply



Revision: Basic Principles

3-phase AC Circuits

The three-phases are called: A-B-C or R-S-T or R-Y-B

$$v_a = V_m \sin(\omega t)$$

$$V_a = V\angle 0$$

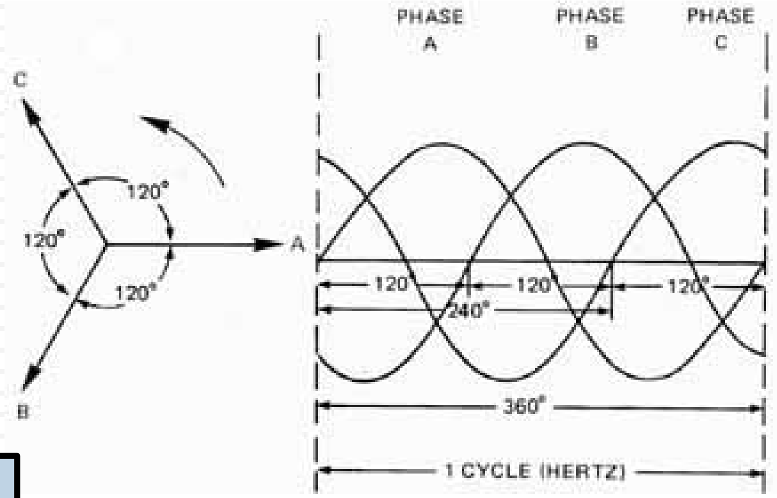
$$v_b = V_m \sin(\omega t - 120^o)$$

$$V_b = V\angle -120$$

$$v_c = V_m \sin(\omega t - 240^o)$$

$$v_c = V_m \sin(\omega t + 120^o)$$

$$V_c = V\angle 120$$

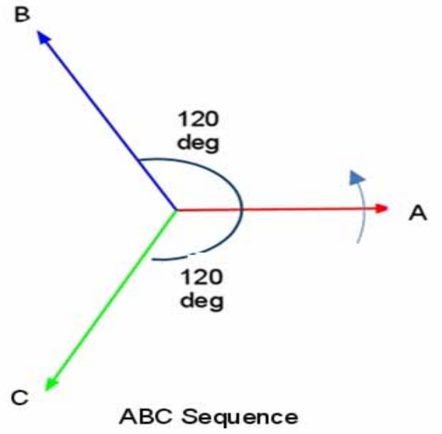


Balanced 3-phase supply: the three voltages are equal in magnitude and are 120o out of phase.

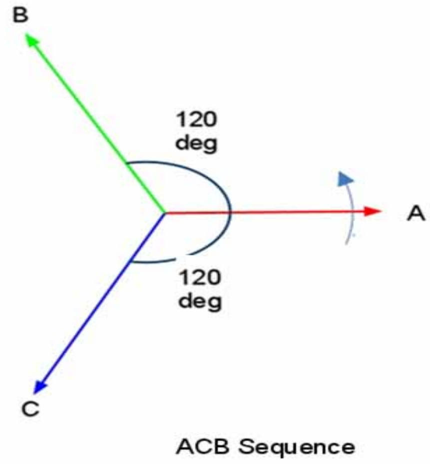
Revision: Basic Principles

3-phase AC Circuits

A-B-C



A-C-B



Positive sequence

$$V_a = V\angle 0$$

$$V_b = V\angle -120$$

$$V_c = V\angle 120$$

Negative sequence

$$V_a = V\angle 0$$

$$V_b = V\angle 120$$

$$V_c = V\angle -120$$

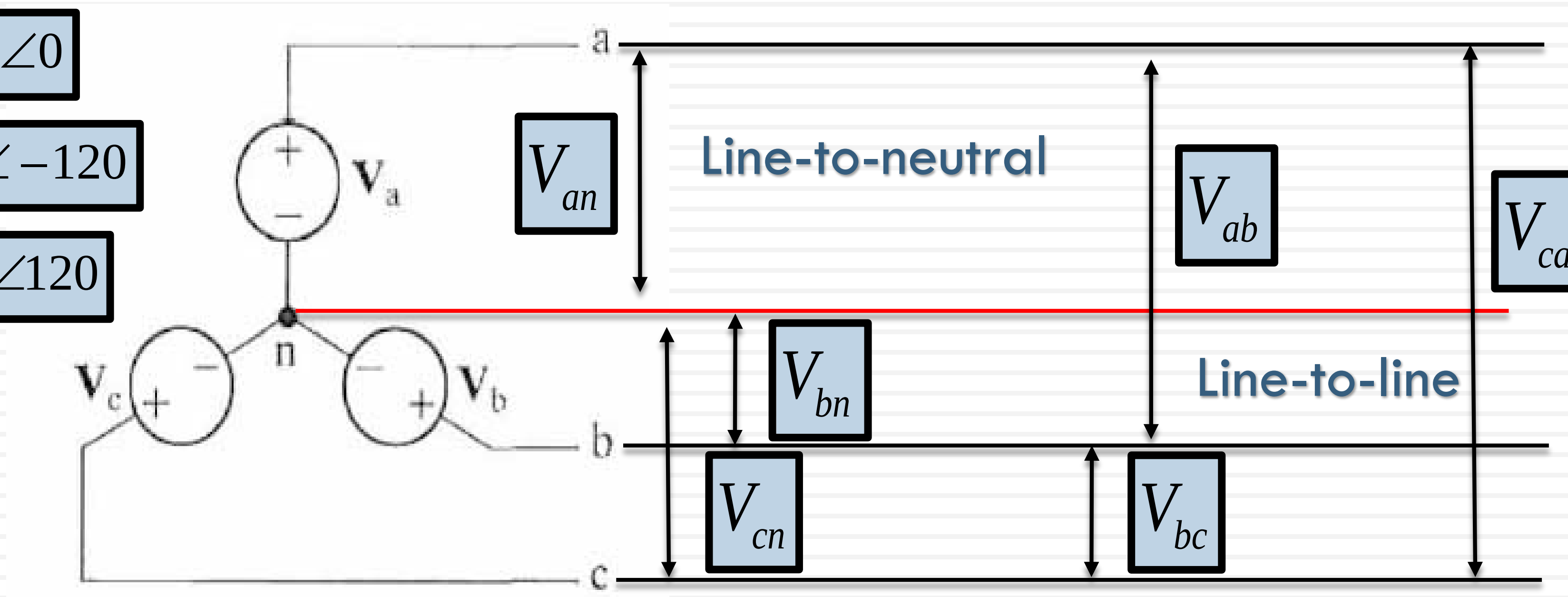
Revision: Basic Principles

3-phase AC Circuits

$$V_{an} = V\angle 0$$

$$V_{bn} = V\angle -120$$

$$V_{cn} = V\angle 120$$



$$V_{ab} = V_{an} - V_{bn}$$

$$V_{bc} = V_{bn} - V_{cn}$$

$$V_{ca} = V_{cn} - V_{an}$$

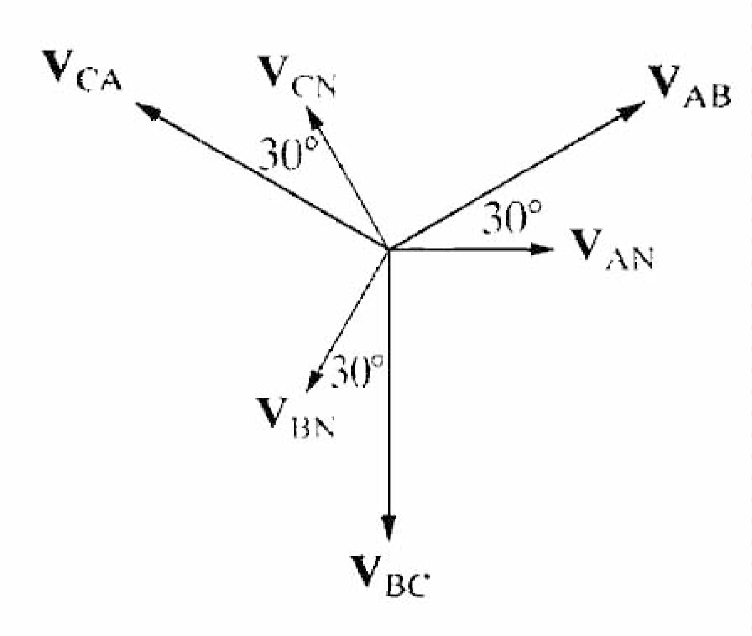
Revision: Basic Principles

3-phase AC Circuits

$$V_{ab} = V_{an} - V_{bn} = \sqrt{3}V\angle 30$$

$$V_{bc} = V_{bn} - V_{cn} = \sqrt{3}V\angle -90$$

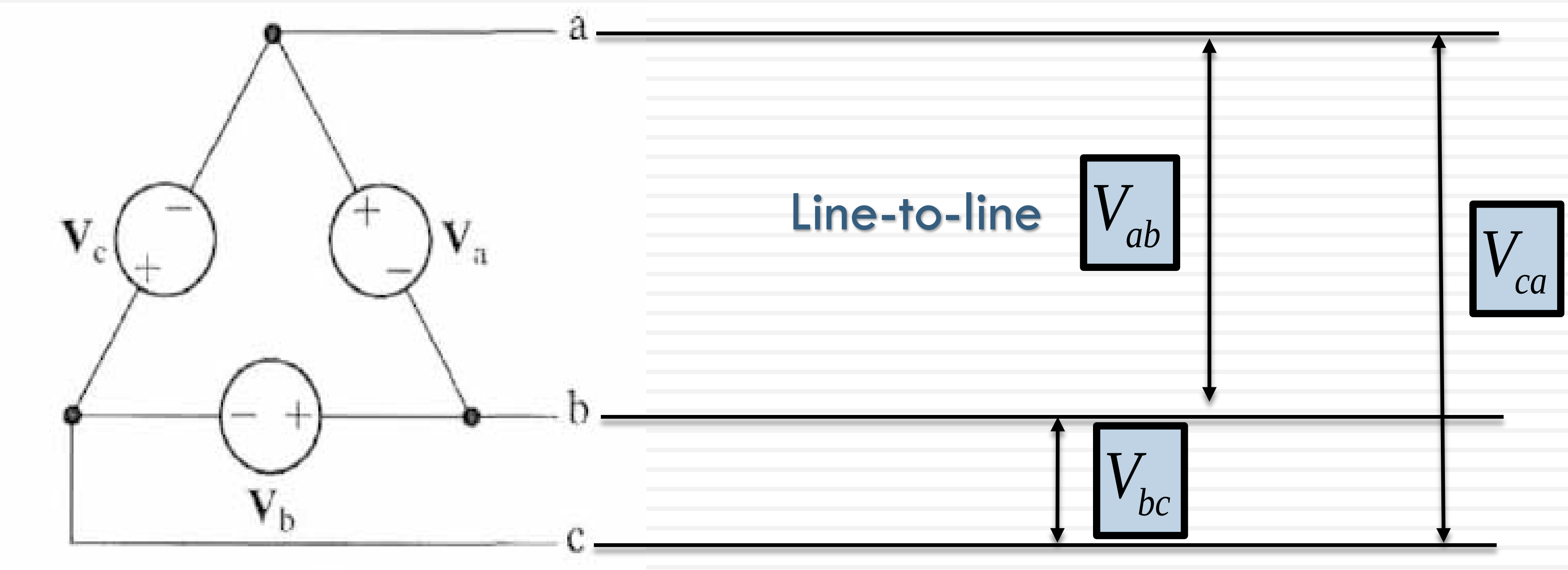
$$V_{ca} = V_{cn} - V_{an} = \sqrt{3}V\angle 150$$



$$V_{LL} = \sqrt{3}V_{Ln}\angle(\theta + 30)$$

Revision: Basic Principles

3-phase AC Circuits



$$V_{ab} = V\angle 0$$

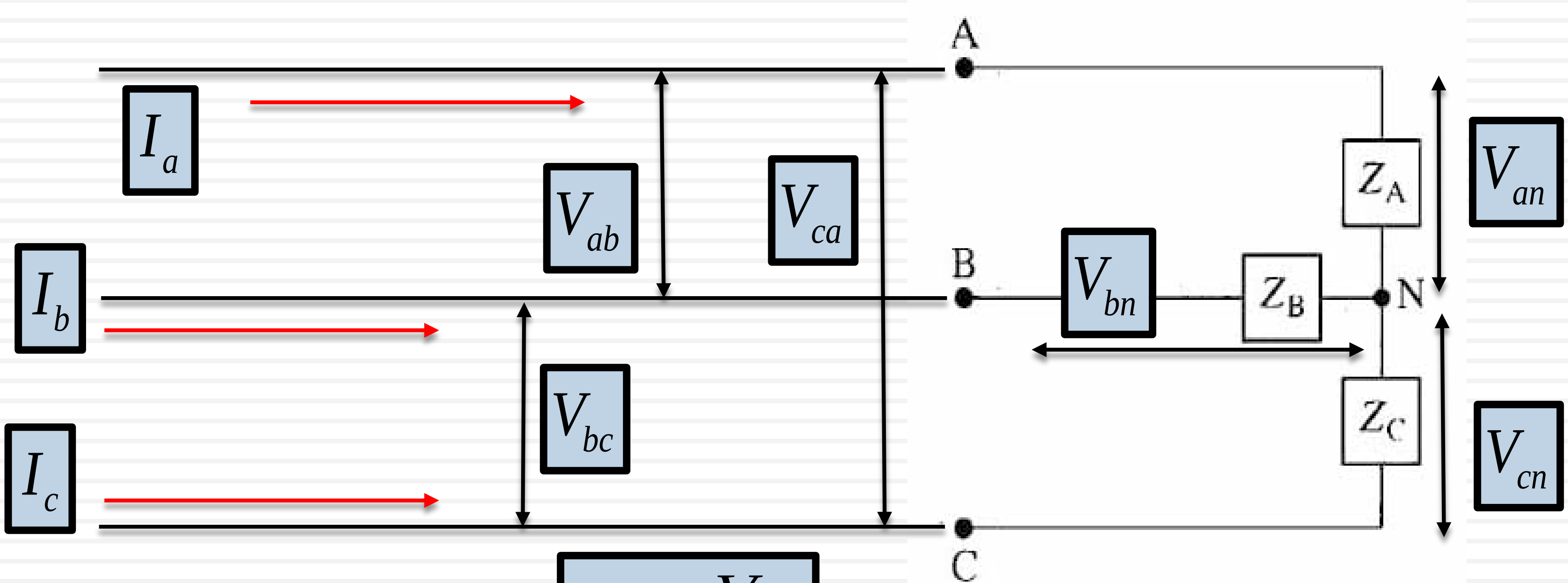
$$V_{bc} = V\angle -120$$

$$V_{ca} = V\angle 120$$

Revision: Basic Principles

3-phase AC Circuits

Balanced Star Load ($Z_A = Z_B = Z_C$)



$$|V_{ab}| = |V_{bc}| = |V_{ca}| = V_L$$

$$|I_a| = |I_b| = |I_c| = I_L$$

$$V_\phi = \frac{V_L}{\sqrt{3}}$$

$$I_\phi = I_L$$

$$|V_{an}| = |V_{bn}| = |V_{cn}| = V_\phi$$

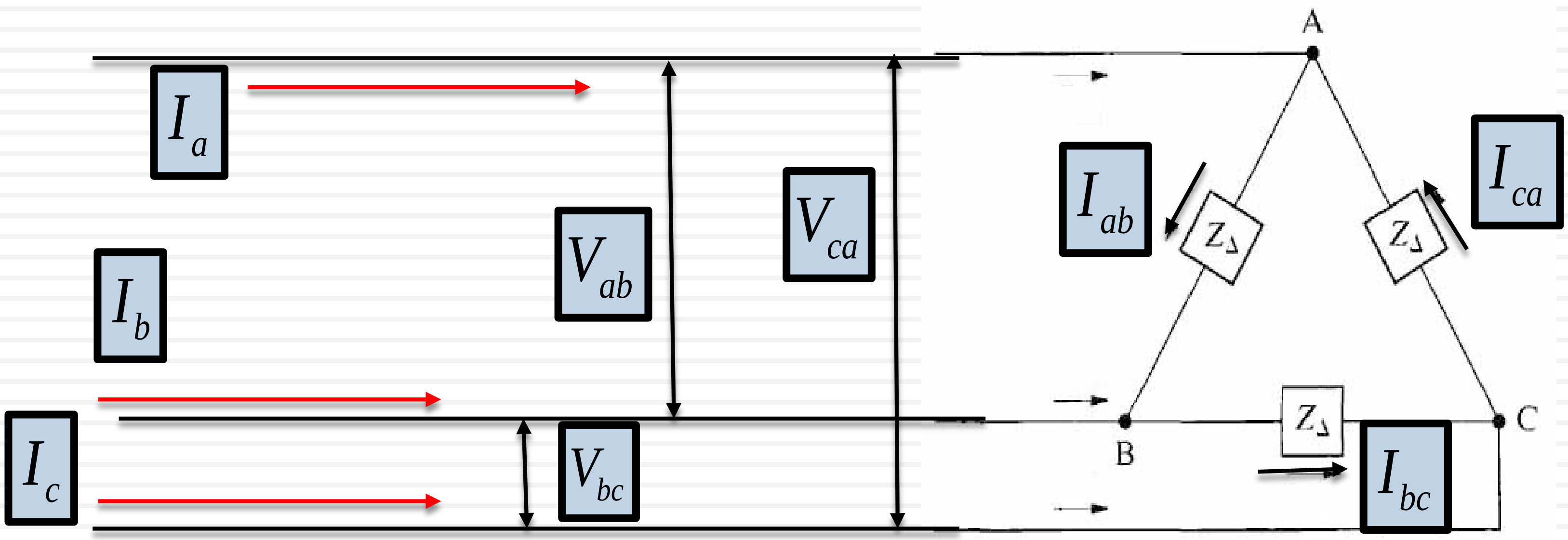
$$|I_{an}| = |I_{bn}| = |I_{cn}| = I_\phi$$

$$I_\phi = \frac{V_\phi}{Z_\phi}$$

Revision: Basic Principles

3-phase AC Circuits

Balanced Delta Load ($Z_A = Z_B = Z_C$)



$$|V_{ab}| = |V_{bc}| = |V_{ca}| = V_L$$

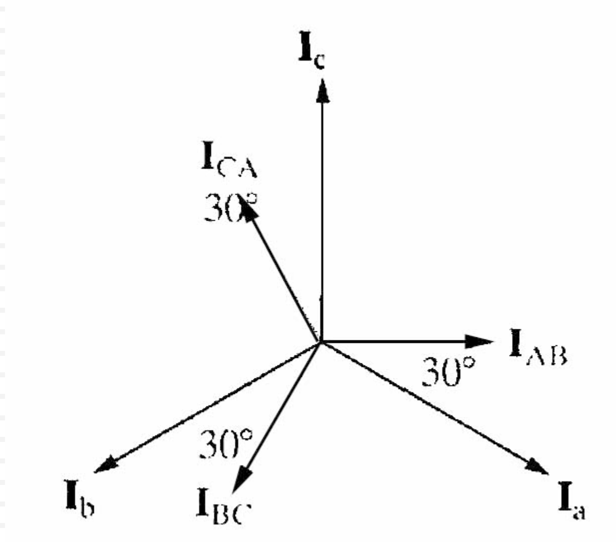
$$|I_a| = |I_b| = |I_c| = I_L$$

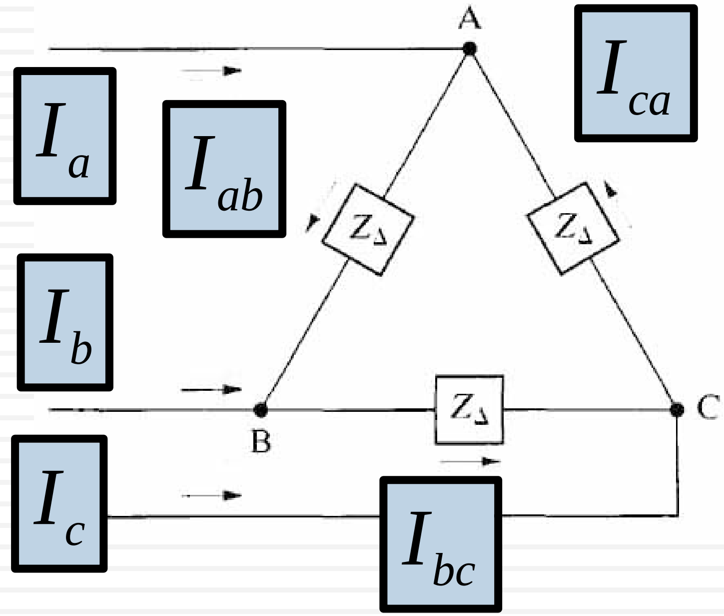
$$V_\phi = V_L$$

$$|I_{ab}| = |I_{bc}| = |I_{ca}| = I_\phi$$

Revision: Basic Principles

3-phase AC Circuits





$$I_a = I_{ab} - I_{ca} = \sqrt{3} I_\phi \angle -30$$

$$I_b = I_{bc} - I_{ab}$$

$$I_c = I_{ca} - I_{bc}$$

$$|I_{ab}| = |I_{bc}| = |I_{ca}| = I_\phi$$

$$|I_a| = |I_b| = |I_c| = I_L = \sqrt{3} I_\phi$$

Revision: Basic Principles

3-phase AC Circuits

Star $V_L = \sqrt{3} V_\phi$ $I_\phi = I_L$

Delta $V_L = V_\phi$ $I_L = \sqrt{3} I_\phi$

3-phase power = 3 x per phase power

$$P = 3 V_\phi I_\phi \cos \Phi = \sqrt{3} V_L I_L \cos \Phi$$

Active Power (W)

$$Q = 3 V_\phi I_\phi \sin \Phi = \sqrt{3} V_L I_L \sin \Phi$$

Reactive Power (VAR)

$$S = 3 V_\phi I_\phi = \sqrt{3} V_L I_L$$

Apparent Power (VA)

$$Power\ Factor = \frac{P}{S}$$