First Course on POWER SYSTEMS

MNPERE

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Course Objective #3

Review Elements of Basic Electric Circuit Theory Essential in Learning Power Systems

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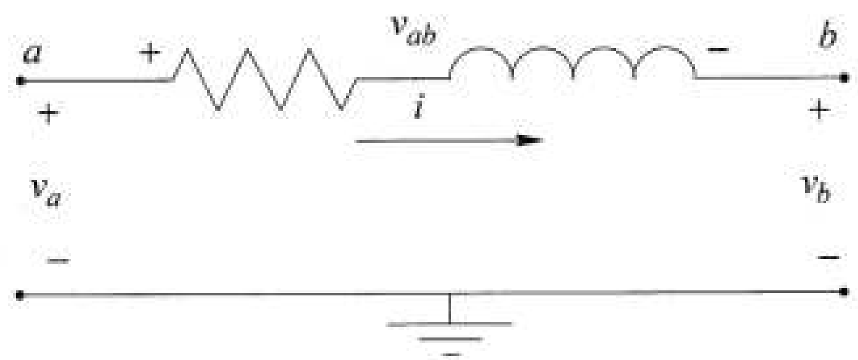
Outline

- General use of phasors for analysis of electric circuits in sinusoidal steady-state
- Instantaneous, average, and reactive powers
- Power factor
- Analysis of 3-phase circuits
- Power flow in ac circuits
- Per-unit quantities

Symbols and Conventions

- Use of MKS (SI) units, and IEEE standard letters and symbols
- Current direction, voltage polarities
- Passive sign convention



Convention for voltages and currents

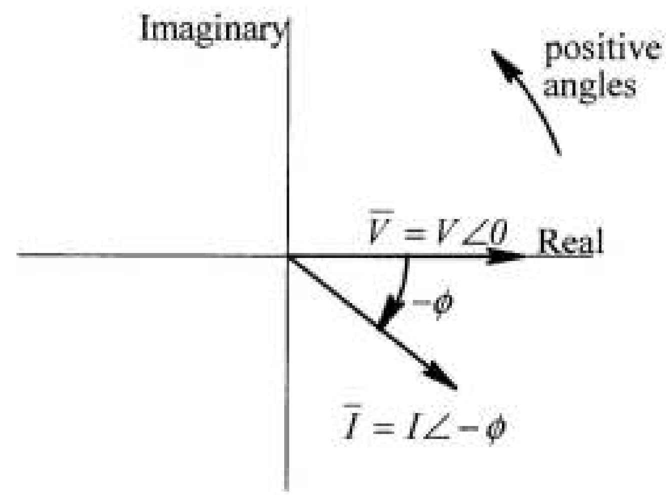
❖Note: $v_{ab} = v_a - v_b$

Phasor Representation in Sinusoidal Steady State

- Voltages and currents applied for a long time, with $f = \omega/(2\pi)$
- Simplified circuit calculations by means of phasor-domain analysis
- Use of *rms* values for V and I as magnitudes of complex variables

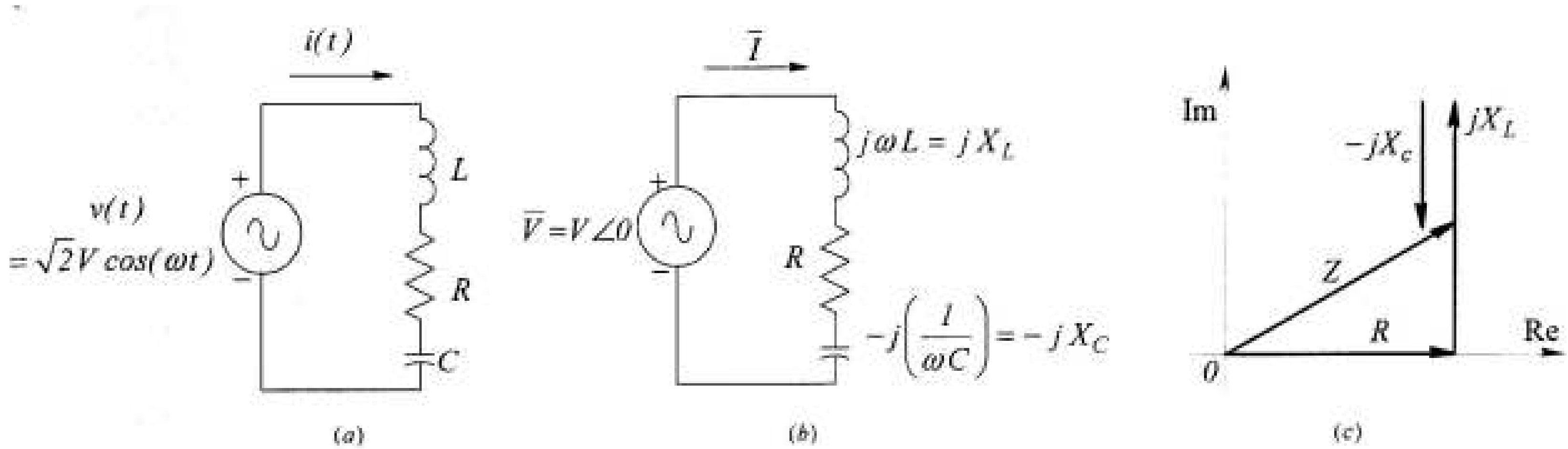
$v(t) = \sqrt{2}V\cos(\omega t)$

$i(t) = \sqrt{2}I\cos(\omega t - \Phi)$



Phasor diagram

Phasor-Domain Analysis



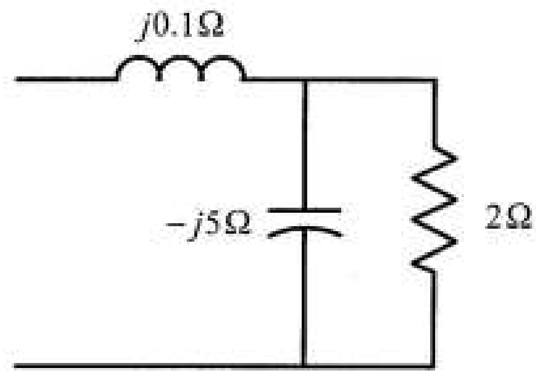
A circuit in sinusoidal steady-state
(a) in time-domain, and (b) in phasor-domain; (c) impedance triangle

❖ Discussion question:

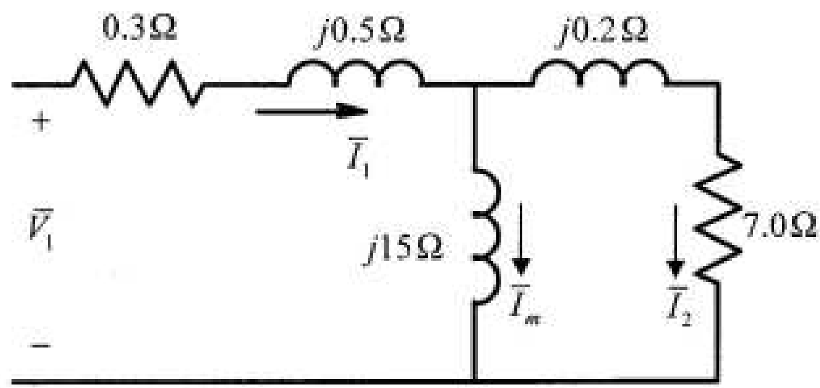
Do we want to include, eventually, the minus sign for $X_c = - 1/(\omega C)$?

Examples of Impedance Calculation

- calculate the equivalent impedance



- Given V_1 and frequency f, calculate I_1



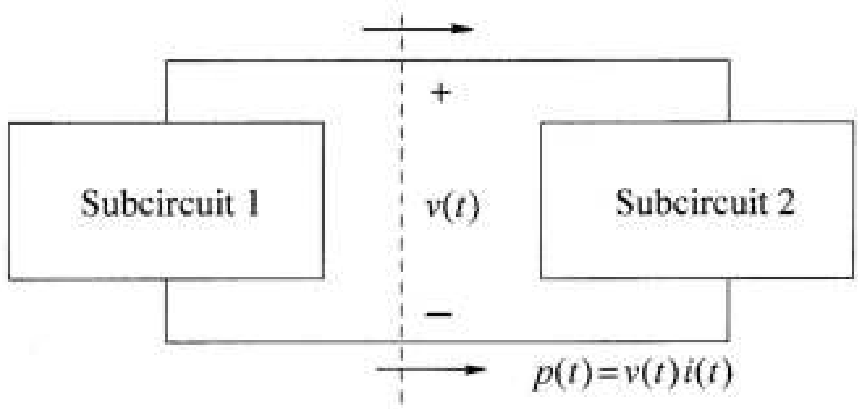
❖Note: Impedance Z, and admittance Y = 1/Z, are complex quantities and not phasors.

Power Flow

- each subcircuit may consist of passive elements and active voltage and/or current sources

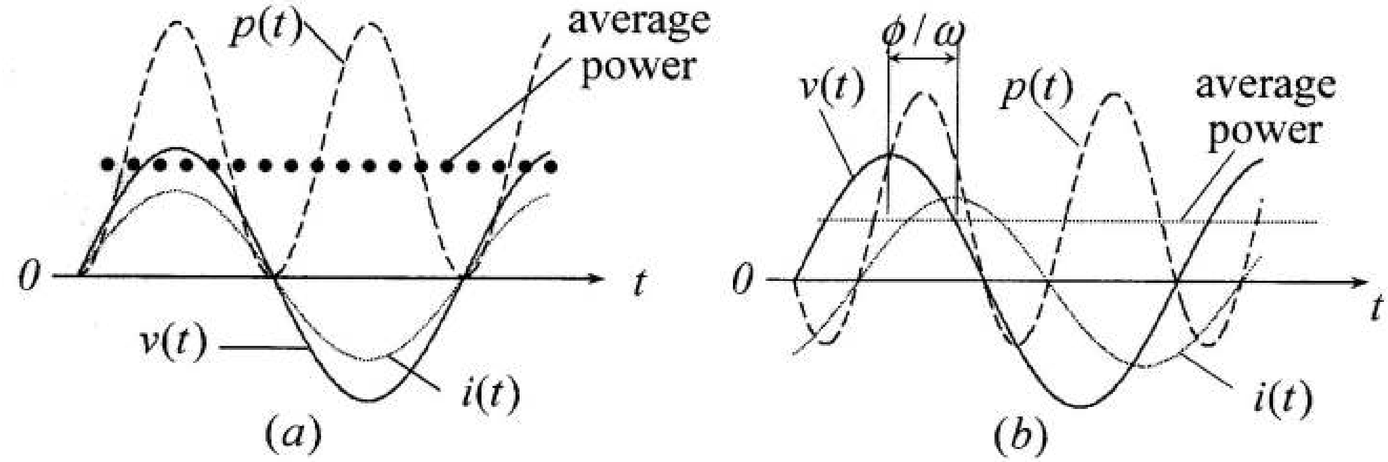
- arbitrary v, and i

- a negative value of p(t) reverses the assumed roles of both subcircuits.



A generic circuit divided into two sub-circuits

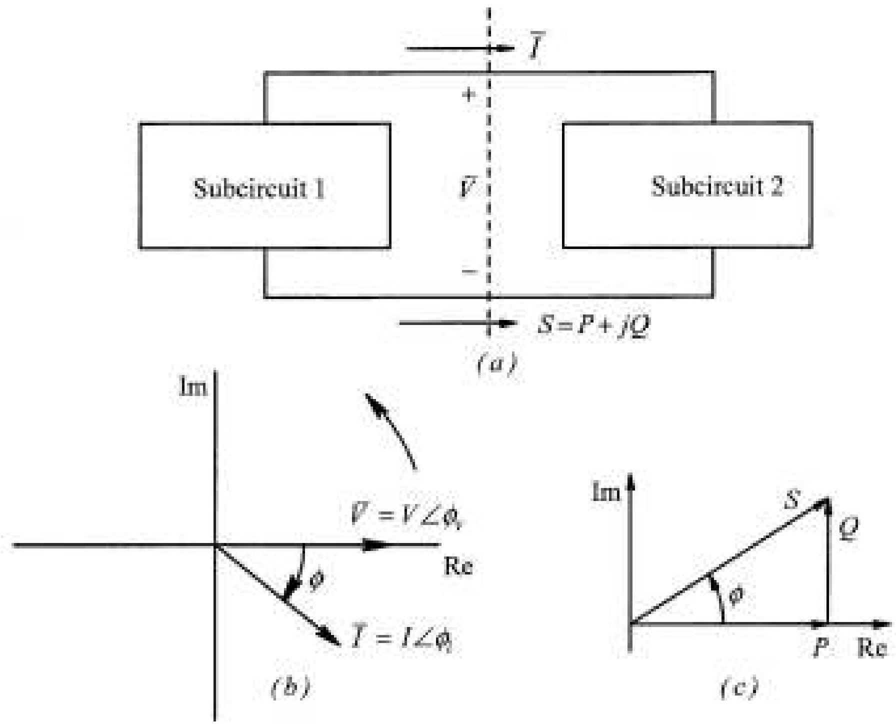
Instantaneous and Average Power



Instantaneous power with sinusoidal currents and voltages

(a)v and i are in phase, p(t) ≥ 0, always, and average is P=VI
(b)i lags behind v by Φ(t), when p(t) < 0 power flows in the opposite direction, and average is P=VIcosΦ

Complex, Average (Real), Reactive, and Apparent Power

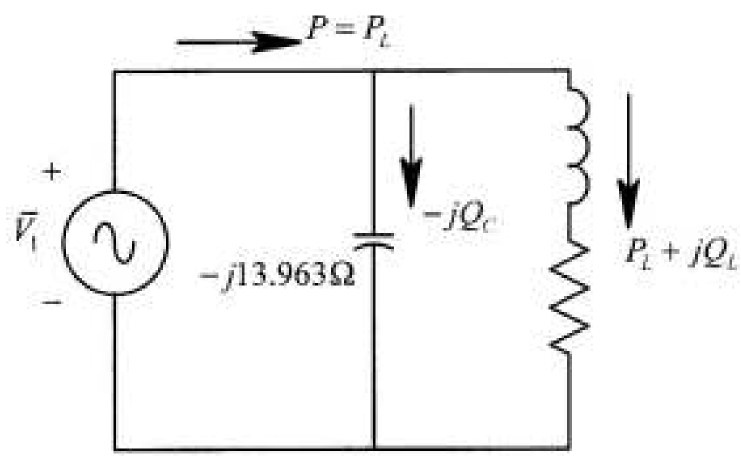


(a) Circuit in phasor-domain; (b) phasor diagram;
(c) power triangle

❖Note: Power balance for the total average and reactive supplied powers

Example
Power Factor Correction

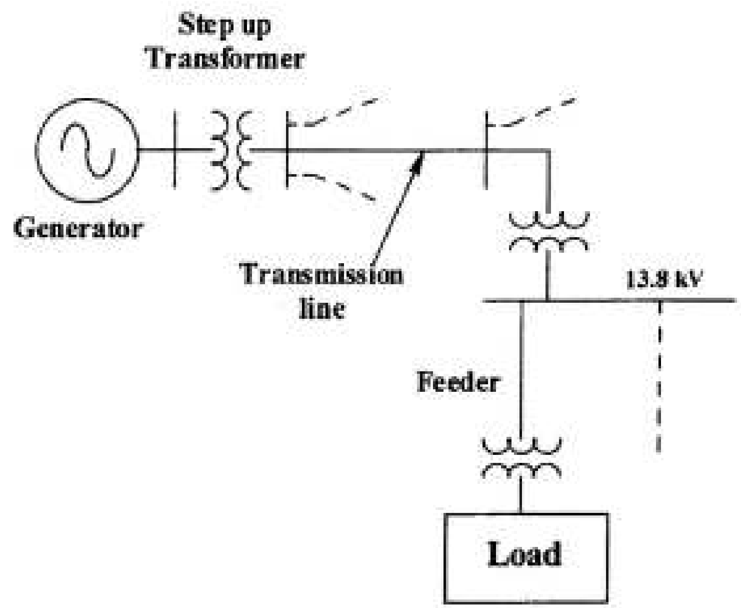
- Calculate the reactance in parallel with the load that will result in the overall pf = 1 (or close) as seen from the voltage source



Power factor correction

- Note: derive a practical formula of the required capacitance for the power factor improvement ($\cos\Phi_{old} < \cos\Phi_{new}$)

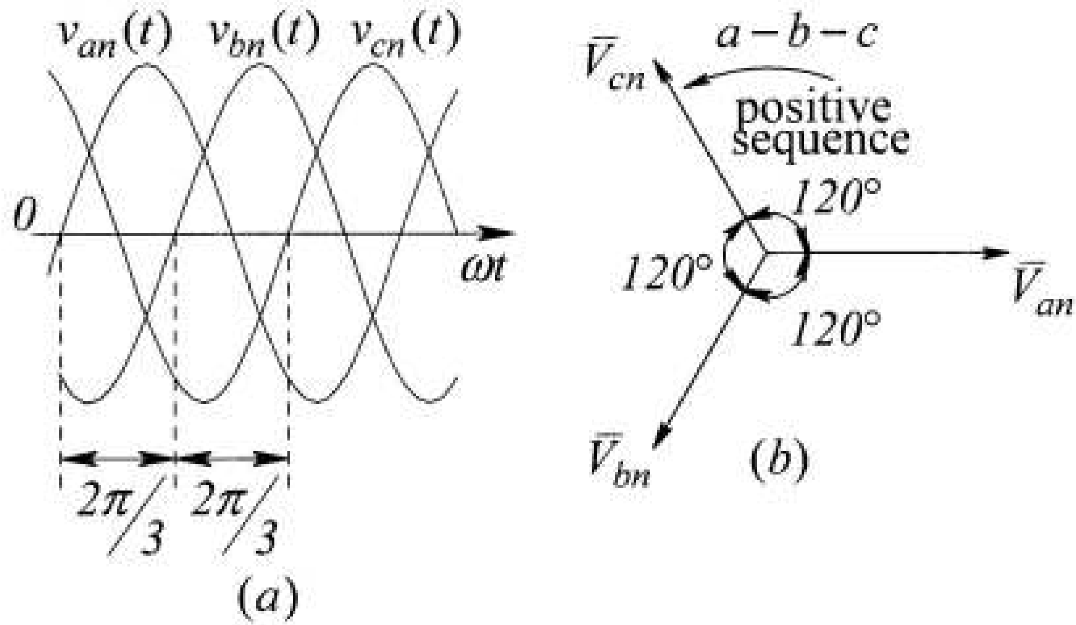
Three-Phase Circuits



One-line diagram of a three-phase transmission and distribution system

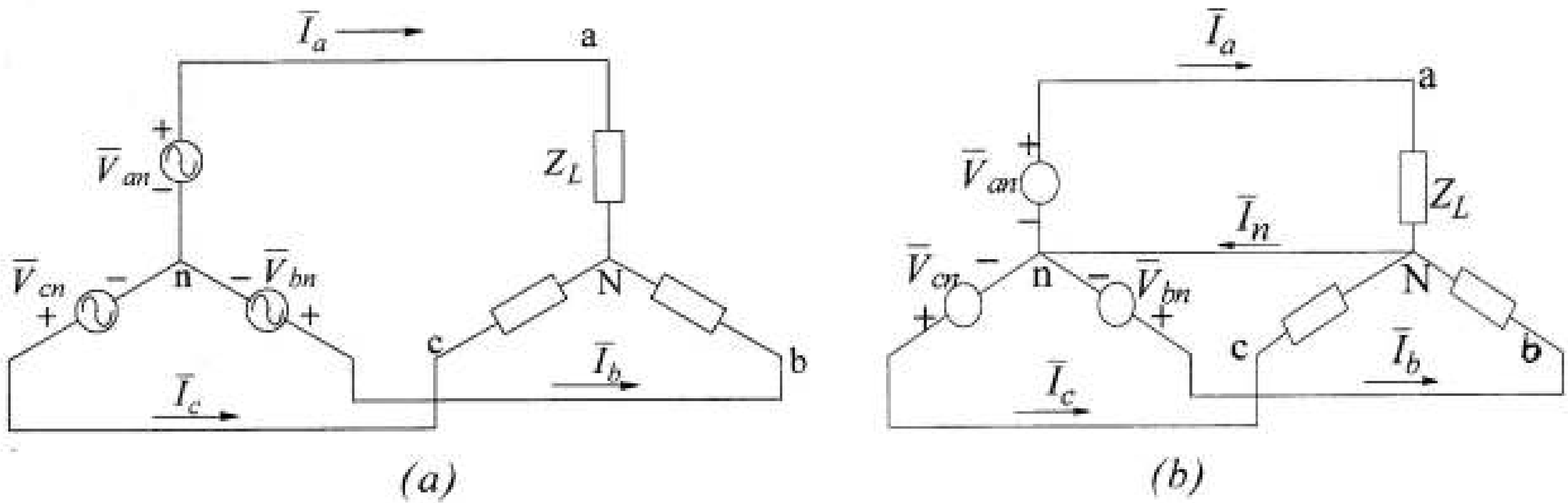
- Most of electric generators are ac 3-phase generators (usually < 25 kV)

Three-Phase Voltages



Three-phase voltages (a) in time domain and (b) phasor domain

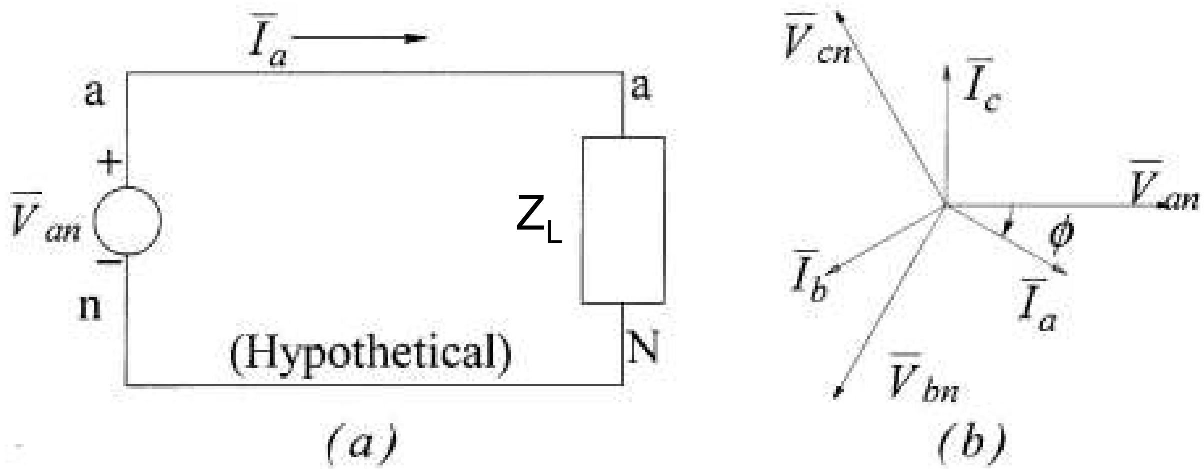
Balanced Three-Phase Circuit Analysis



A balanced wye-connected, three-phase circuit

- Use of the 4th wire ($V_{nN} = 0$) leads to per-phase circuit analysis

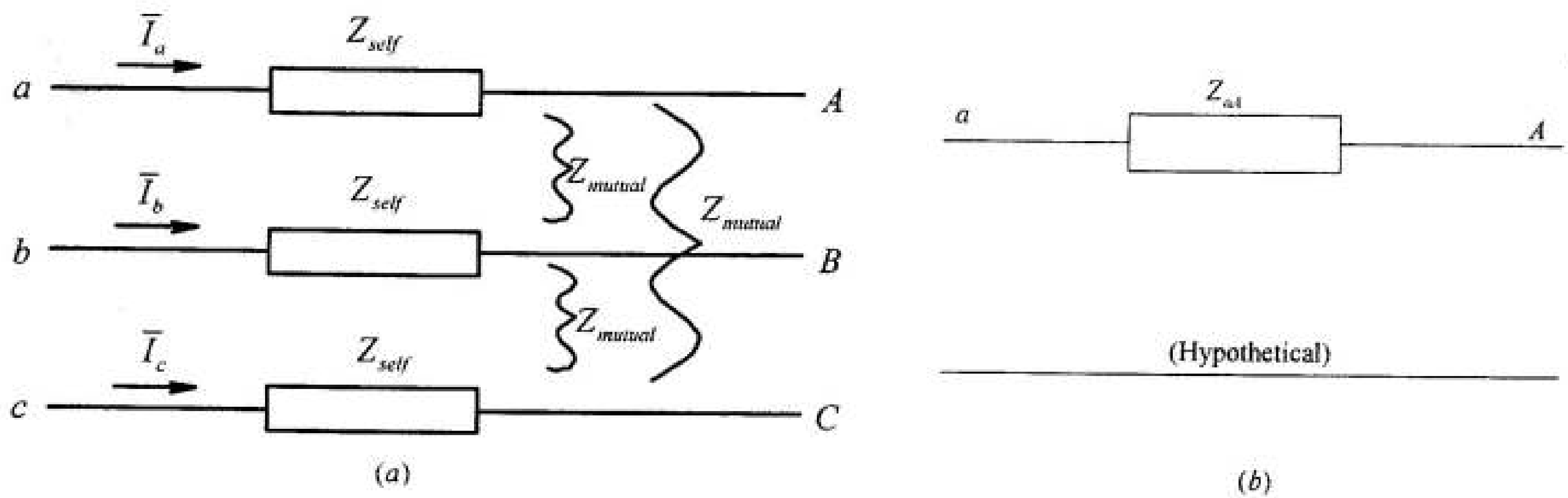
Per-Phase Analysis



Per-phase circuit and the corresponding phasor diagram

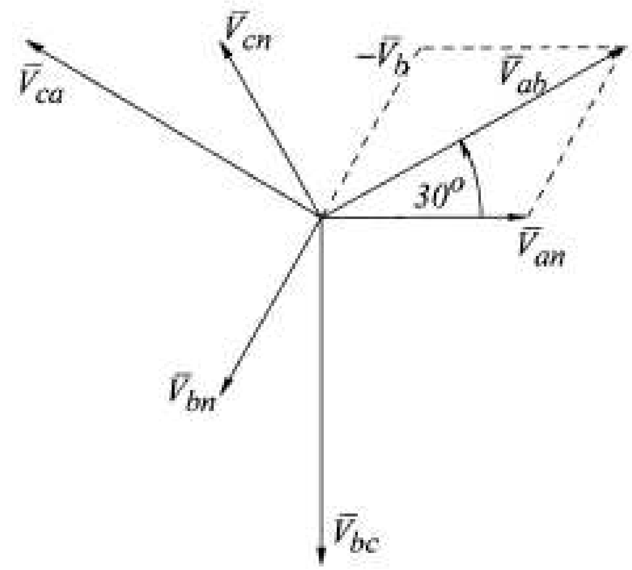
- The total power factor is the same as its per-phase value
- The total powers $P_T = 3P_{ph}$; $Q_T = 3Q_{ph}$

Balanced Three-Phase Circuits Including Mutual Coupling



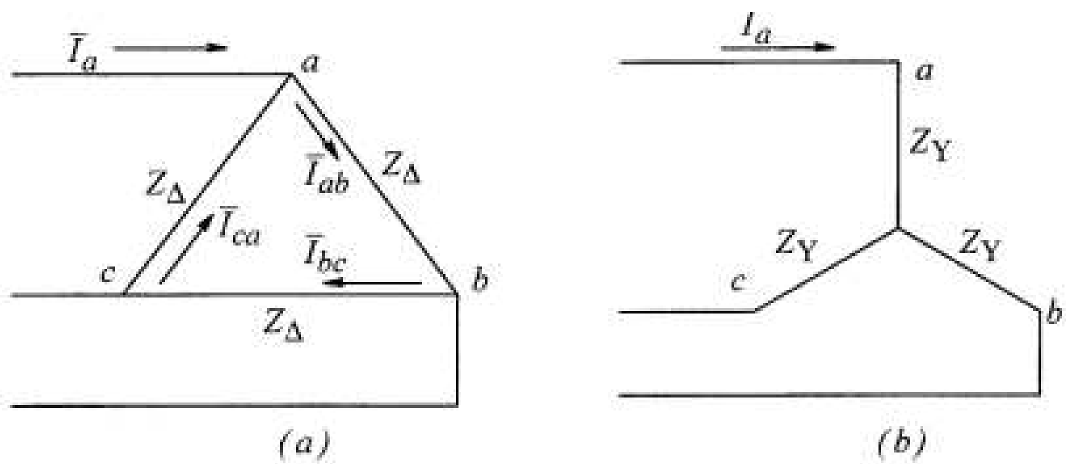
- Example: in a 3-phase synchronous generator the flux lines produced by a phase current link not only that phase winding but the other two phase windings as well

Line-to-Line Voltages



Line-to-line voltages in a three-phase Y connected circuit – phasor diagram

Delta Connected Loads



Delta-to-wye transformation of a three-phase load

- Example: the windings in 3-phase ac motor drives, or transformers
- Under balanced conditions determine $Z_Y = Z_\Delta/3$, an then apply a single phase equivalent analysis

Powers in Three-Phase Circuits

The total average (real) and reactive powers in a 3-phase circuit are

$P_{3\text{-}phase} = 3\text{x}P_{per\text{-}phase} = 3VI\cos\varphi$

$Q_{3\text{-}phase} = 3\text{x}Q_{per\text{-}phase} = 3VI\sin\varphi$

where $V = V_{ph}$ and $I = I_{ph}$ represent per-phase *rms* values

The total apparent power in a 3-phase circuit is

$|S|_{3\text{-}phase} = 3\text{x}|S_{per\text{-}phase}| = 3VI$

Powers in Three-Phase Circuits

The power factor in a three-phase circuit is the same as the per-phase power factor

$$pf = P_{3\text{-}phase} \,/\, |S|_{3\text{-}phase} = 3VI\cos\varphi \,/\, (3VI) = \cos\varphi$$

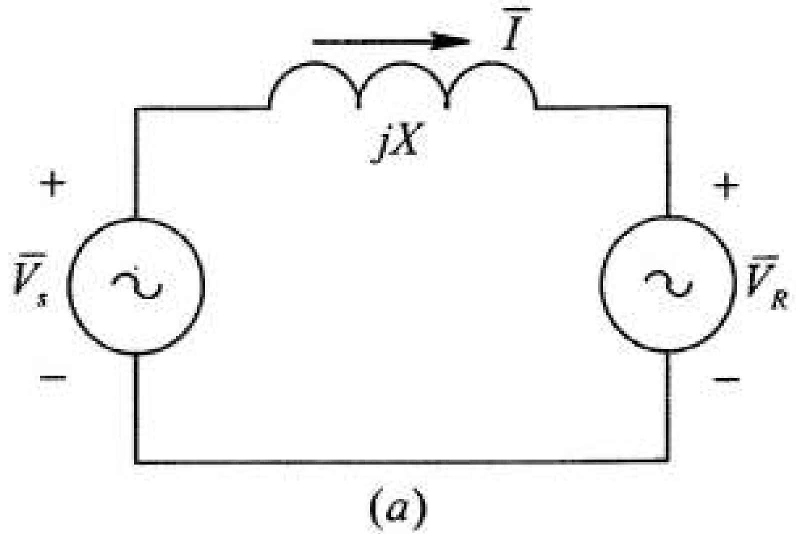
Specific to 3-phase circuits is the total (combined) instantaneous power in steady-state which is constant (non-pulsating), and equal to its average value

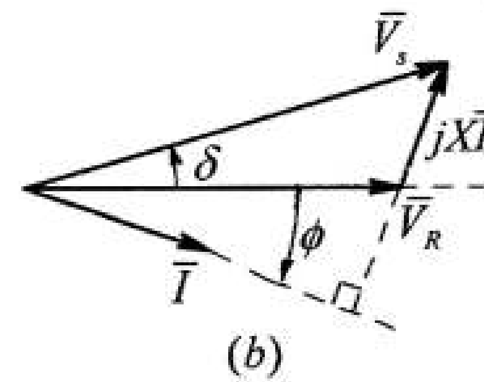
$$p_{3\text{-}phase}(t) = p_a(t) + p_b(t) + p_c(t)$$

$$= 3VI\cos\varphi = P_{3\text{-}phase}$$

- *The non-pulsating $p_{3\text{-}phase}$ results in non-pulsating torque in 3-phase motors and generators*

Power Flow in AC Systems

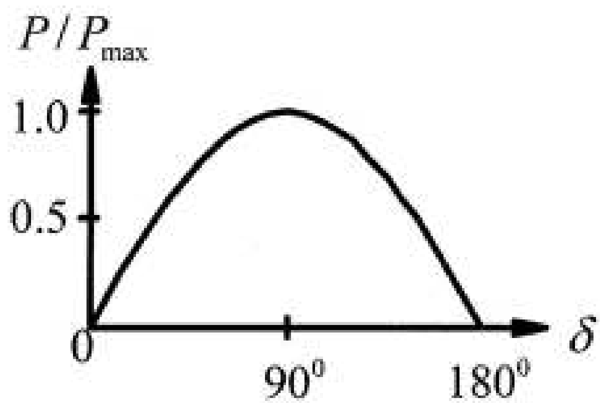


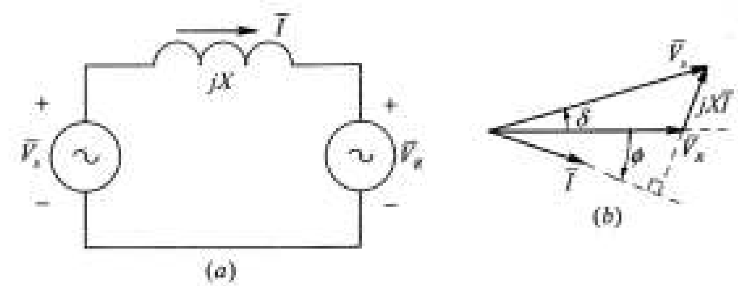


Power transfer between two ac systems
in a simplified representation

- $S_R = P_R + j\, Q_R = V_R I^*$

Power-Angle Diagram





Power as a function of the phase angle (of the V_s voltage)

- $P_R = (V_S V_R \sin\delta)/X$; $Q_R = (V_S V_R \cos\delta)/X - V_R V_R/X$
- At $\sin\delta = 0$, $\delta = 0$, and then $Q_R = V_R/X(V_S - V_R)$

Base Values and Per Unit Quantities

$$R_{base}, X_{base}, Z_{base} = \frac{V_{base}}{I_{base}} \qquad \text{(in } \Omega\text{)}$$

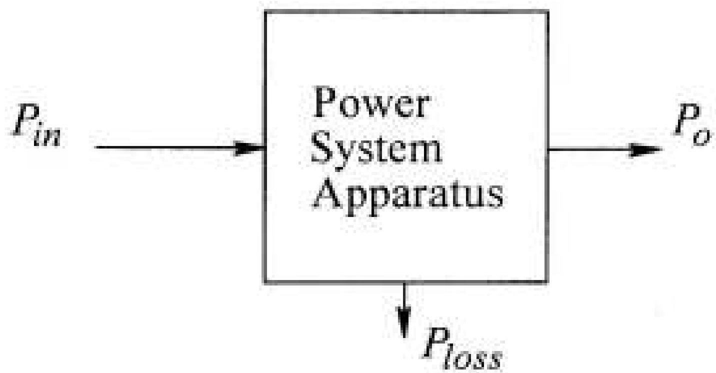
$$G_{base}, B_{base}, Y_{base} = \frac{I_{base}}{V_{base}} \qquad \text{(in ℧)}$$

$$P_{base}, Q_{base}, (VA)_{base} = V_{base} I_{base} \qquad \text{(in Watt, VAR, or VA)}$$

In terms of these base quantities, the per-unit quantities can be specified as

$$\text{Per-Unit Value} = \frac{\text{actual value}}{\text{base value}}$$

Energy Efficiency of Power System Apparatus

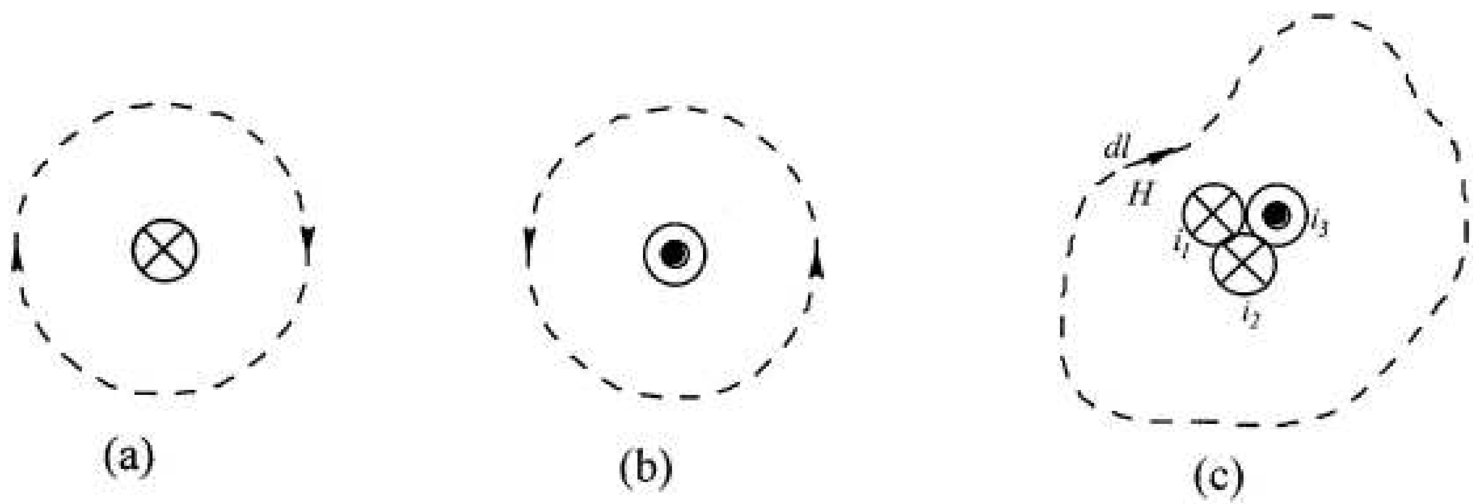


- Energy efficiency : $\eta = P_o / P_{in} = P_o / (P_o + P_{loss})$

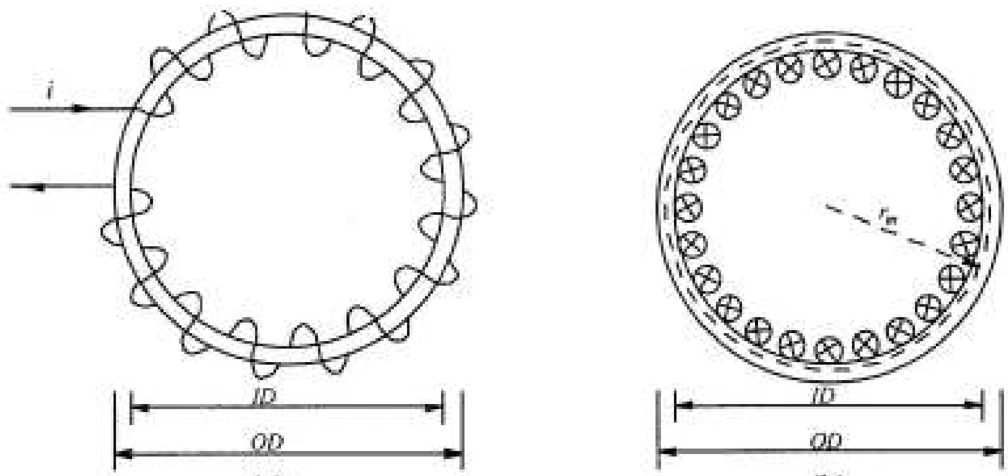
Thank You!

Discussion

Electromagnetic Concepts
Ampere's law

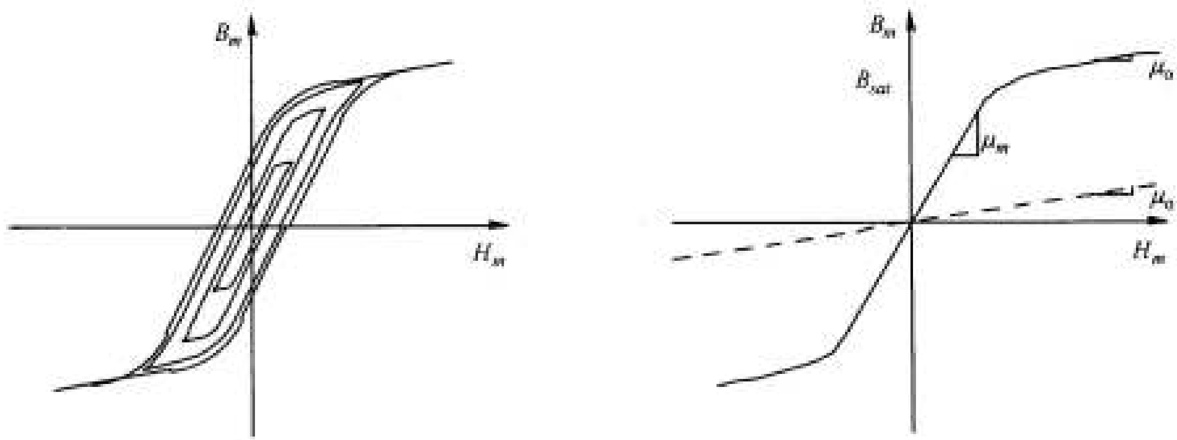


Example of a Toroid



(a) (b)

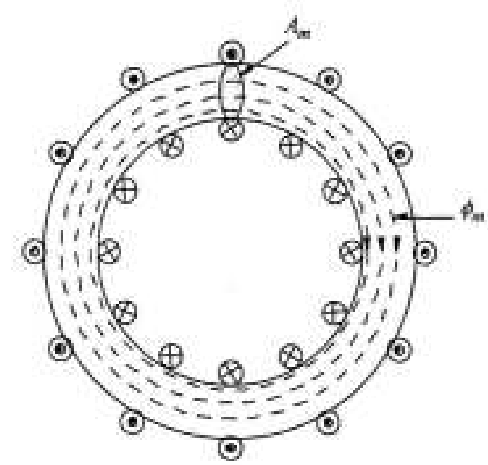
Ferromagnetic Materials
B-H Curves



(a) (b)

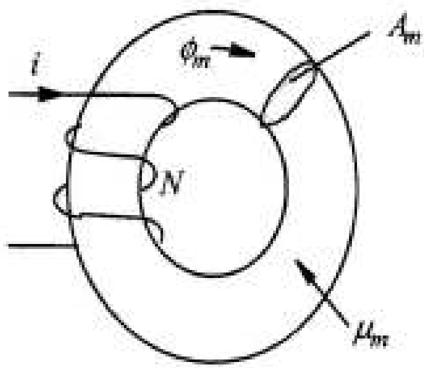
B-H characteristic off ferromagnetic materials

Magnetic Flux ϕ_m and Flux-Density B

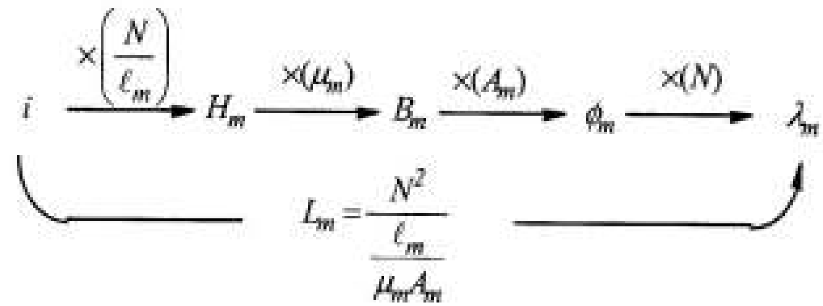


Toroid with flux φ_m

Flux Linkage and Magnetizing Inductance

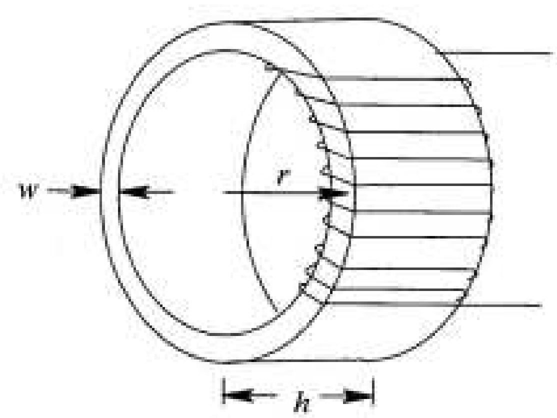


(a)



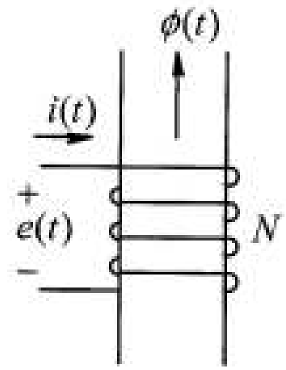
(b)

Example of a Toroid



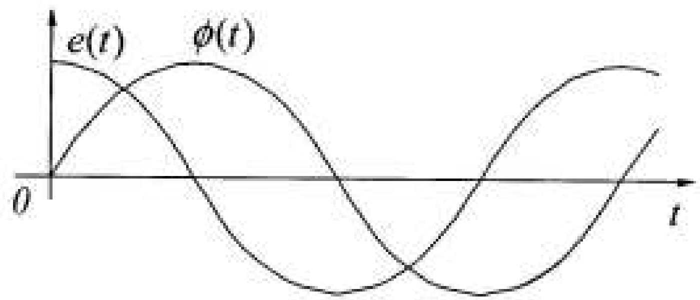
Rectangular toroid

Faraday's Law
Induced Voltage in a Coil

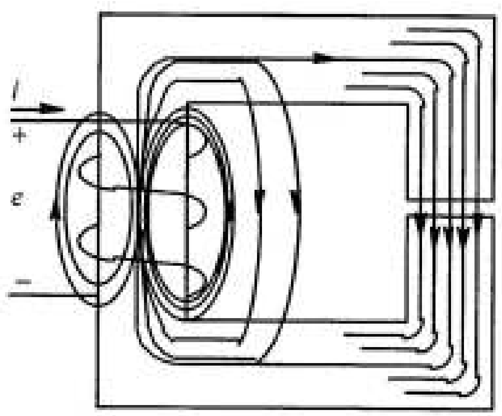


Voltage polarity and direction of flux and current

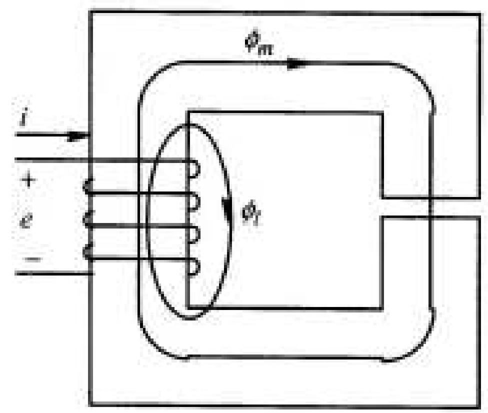
Plot of Time-Varying Flux and Induced Voltage



Leakage Flux ϕ_l



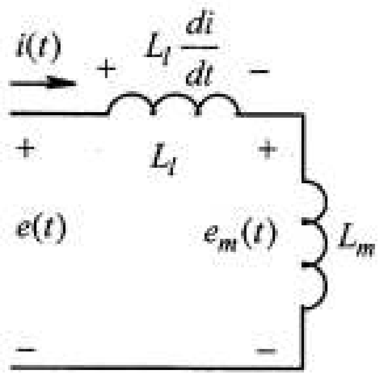
(a)



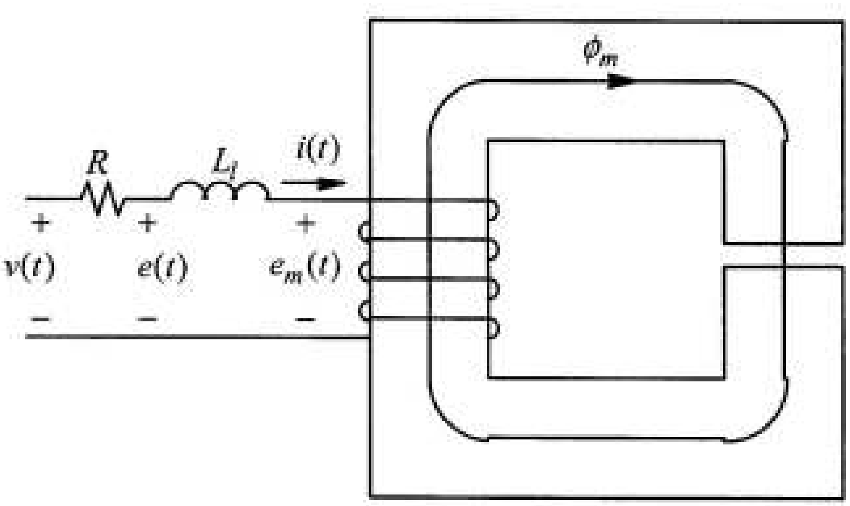
(b)

Magnetic field including leakage flux

Use of Leakage Inductance L_l to Represent the Leakage Flux ϕ_l



(a)



(b)

Analysis including the leakage flux

New Discussion