EE2029 Introduction to Electrical Energy Systems

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Learning Outcomes

Upon completion of this module, students should be able to :

- analyse ac circuits using phasor and impedance
- explain active, reactive, complex power, and power factor – its impact on losses and need for power factor correction.
- examine power in single-phase and three-phase balanced systems.
- model key components of power systems including generator, transmission line, transformer and induction motor load.
- analyse the working of a complete power system from generation to load.

Syllabus

1. Review of AC circuit analysis (3 hours)
   - Use of phasor and impedance in AC circuit analysis.
2. Structure of Electrical Power Systems (3 hours)
   - Introduction to power generation, transmission and distribution systems.
3. Three-Phase systems (6 hours)
   - Revise active power, reactive power and apparent power. Concept of harmonics and how it influences power factor. Introduction to phasor diagrams and complex power. Balanced three-phase systems and their single-phase equivalents. Power factor correction. Relationship between phase and line quantities Concept of regulation.
4. Generating sources (3 hours)

   Gas Turbine: basic energy conversion model, IEC symbol, and conversion efficiencies, and concept of rotating prime mover applied to other similar sources. Photovoltaic array: basic model, and conversion efficiencies.

Syllabus

4. Transmission System (6 hours)

   Three-phase-four-wire system, three-phase-three-wire system, and three-phase circuit analysis. Modelling and sizing of cables. Circuit breaker and its sizing. Grounding and earth followed by safety and earthing.

5. Transformers (6 hours)

   Ideal transformer, Magnetic circuits, magnetizing current and saturation, real transformers. Equivalent circuits with short-circuit and open circuit. Phasor diagram, regulation (applied to transformer) and efficiency. Three-phase transformer connections, including with wye and delta connections.

6. Loads (6 hours)

   Static loads: Lighting, heating, resistive, and inductive. Three-phase induction machine: Operating principle, equivalent circuits, torque-speed characteristics, losses and efficiency.

Assessment

- Laboratory work: (10%)
- Continuous Assessment: Quizzes and Test (40%)
- Final Examination: 50%

Part1

- Weekly quizzes 15% (3% each)
- Midterm quiz 10%

Part2

- Lab 10%
- Midterm quiz 15%

Schedule for EE2029 (First half) in Sem 1 AY2021/22

Week	Date	Time	Lecture	Topic
1	10 Aug 2021	16:00- 18:00	Lec1	Topic 1 AC Fundamentals
	13 Aug 2021	12:00-14:00	Tutorial 1	Tutorial 1 AC Fundamentals
2	17 Aug 2021	16:00- 18:00	Lec2	Topic 2 AC Power
	20 Aug 2021	12:00-14:00	Tutorial 2	Tutorial 2 AC Power
3	24 Aug 2021	16:00- 18:00	Lec3	Topic 3 Three phase analysis
	27 Aug 2021	12:00-14:00	Tutorial 3	Tutorial 3 Three phase analysis
4	31 Aug 2021	16:00- 18:00	Lec4	Topic 4 Generation
	3 Sep 2021	12:00-14:00	Tutorial 4	Tutorial 4 – Generation
5	7 Sep 2021	16:00- 18:00	Lec5	Topic 5 Renewable generation
	10 Sep 2021	12:00-14:00	Tutorial 5	Tutorial 5 – Renewable generation
6	14 Sep 2021	16:00- 18:00	Summary	Doubt clearing
	17 Sep 2021	12:00-14:00		Midterm Quiz 1

Introduction

Importance of Energy

- Energy is defined as the capacity to do any activity in nature.
- Over the millennia, human beings have been improving their ability to harness energy from nature to improve their lifestyles.
- Early human beings burnt fuelwood for giving them warmth, protection, and cooking food.
- In the 19th century, steam engines were developed to convert heat energy into motion which in turn led to the industrial revolution in Europe.
- In the late 1850s, internal combustion engine was invented which are used in the majority of vehicles today.
- In the late 1800s, Thomas Alva Edison developed an electric light bulb.

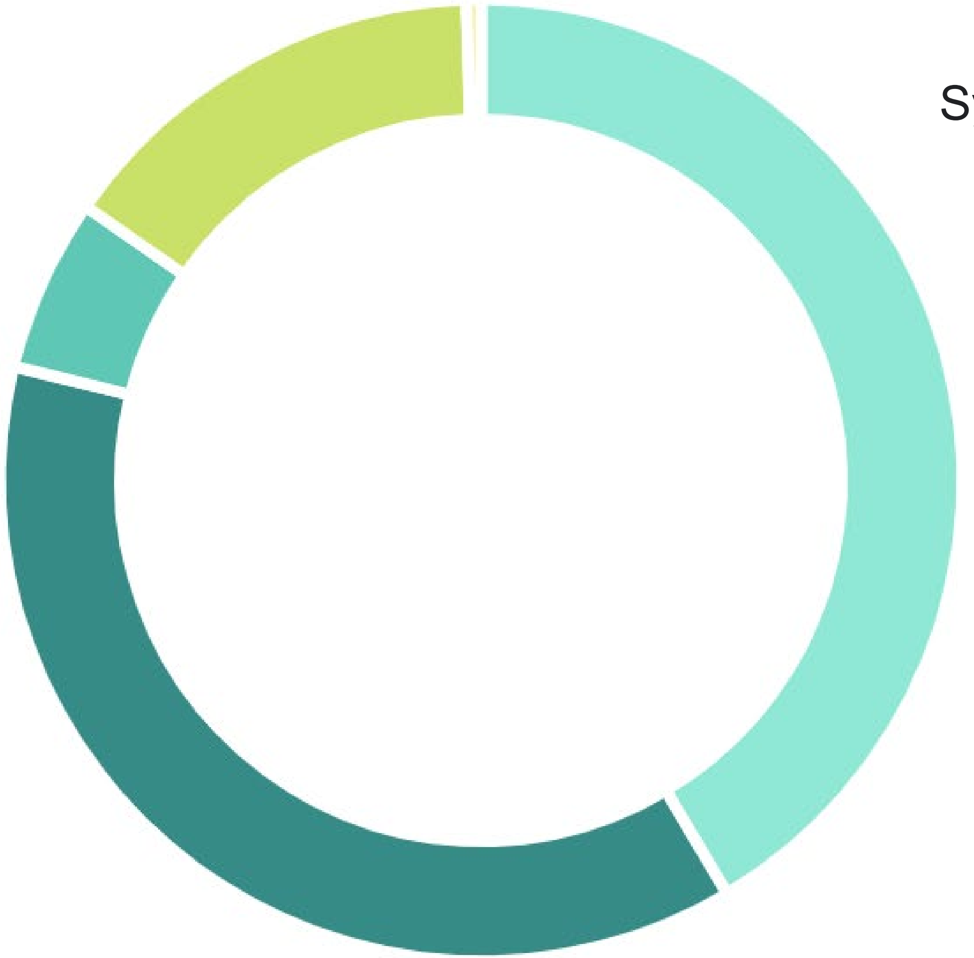
The world is lighted up using electricity

Home appliances and ICT gadgets

Electric transportation

Singapore's electricity use in 2019

- Industrial-related
- Commerce and Services-related
- Transport-related
- Households
- Others



System peak demand **7,404 MW**

Overall Electricity Consumption:

51.7 TWh in 2019

Source: EMA

Food and water in Singapore

- Indoor vertical farms
  - Singapore imports 90% of its food and allocates less than one per cent of land for agriculture
  - In land-scarce Singapore, vertical farms can be used with indoor lighting
  - Vertical farms need lots of electricity

- Water desalination
  - There is plenty of sea water around Singapore
  - Desalination plants are installed to produce drinking water
  - This is an energy-intensive technology

Singapore’s electricity generation

- Currently, 95% of Singapore’s electricity is produced using natural gas, while the rest is produced by coal, oil, municipal waste, and solar.
- <u>Energy reset in Green Plan 2030</u>

> “We will **quadruple our solar energy deployment by 2025, including covering the roof tops of** our **HDB** (public housing) **blocks with solar panels.** By 2030, solar energy deployed will be five times that of today. With at least 2 gigawatt-peak, it can power about 350,000 households a year. We are also looking to **tap green energy sources from the ASEAN region and beyond**, through electricity imports and hydrogen.”

Industry Track under Power and Energy

- EE2029 Introduction to Electrical Energy System
- EE4501 Power System Management & Protection
- EE4502 Electric Drives and Control
- EE4503 Power Electronics for Sustainable Energy Technologies
- EE4505 Power Semiconductors Devices & ICs
- EE4511 Renewable Generation and Smart Grid
- EE4513 Electric Vehicles and their Grid Integration

Revision of Complex numbers

We need to use complex number algebra in analysis of AC power systems.

- Definition
- Algebraic properties
- Argand diagram
- Euler’s formula
- Complex number as vector

Complex number definition

- $z = a + jb$
  - z : $complex\ number$
  - a, b: $both\ real\ numbers; a = Real\ part\ of\ z, \quad b = Imaginary\ part\ of\ z$
  - $j^2 = -1\ or\ j = \sqrt{-1}$
  - Examples
    - $z_1 = 4$
    - $z_2 = j5$
    - $z_3 = -j6$
    - $z_4 = 3 + j4$
    - $z_5 = 5 - j8$
- $z^* = a - jb$ is known as the complex conjugate of z

Algebraic properties of complex numbers

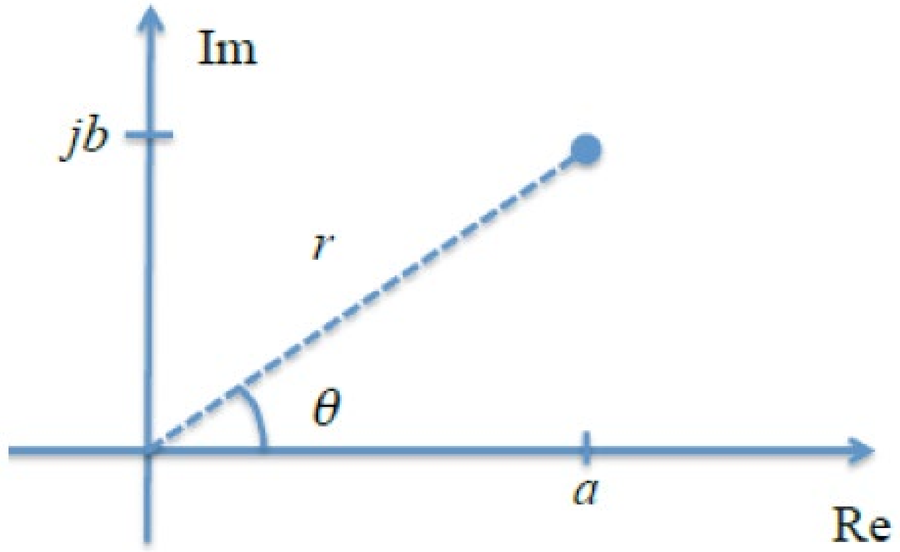
- Addition/Subtraction:
  - $z_1 + z_2 = (a_1 + jb_1) + (a_2 + jb_2) = (a_1 + a_2) + j(b_1 + b_2)$
  - $z_1 - z_2 = (a_1 + jb_1) - (a_2 + jb_2) = (a_1 - a_2) + j(b_1 - b_2)$
- Multiplication:
  - $z_1 z_2 = (a_1 + jb_1)(a_2 + jb_2) =$

  $= a_1 a_2 + j a_1 b_2 + j a_2 b_1 + j^2 b_1 b_2 = (a_1 a_2 - b_1 b_2) + j(a_1 b_2 + a_2 b_1)$

  $as\, j^2 = -1$
- Division:
  - $\frac{z_1}{z_2} = \frac{a_1 + jb_1}{a_2 + jb_2} = \frac{(a_1 + jb_1)(a_2 - jb_2)}{(a_2 + jb_2)(a_2 - jb_2)} = \frac{(a_1 a_2 + b_1 b_2) + j(a_2 b_1 - a_1 b_2)}{a_2^2 + b_2^2}$

Multiplication and division are easier to do in polar form or exponential form of complex number.

Argand Diagram for $z = a + jb$



Magnitude of z : $r = |z| = \sqrt{a^2 + b^2}$

Argument of z : $\theta = \arg(z) = tan^{-1}\left(\frac{b}{a}\right)$

These two new parameters allow us to represent complex numbers in another form:

$r\angle\theta$ known as polar form.

$a + jb$ is known as rectangular form.

$$a = r\,cos\theta, b = r\,sin\theta$$

Euler's Formula

- Euler's formula allows us to form a link between complex numbers and trigonometric functions:

$$e^{j\theta} = cos\theta + jsin\theta$$

- If we multiply Euler's formula by a constant, r > 0:

$$z = re^{j\theta} = r\cos\theta + j\,r\sin\theta = r\angle\theta$$

- Multiplication, division is much easier in polar form :

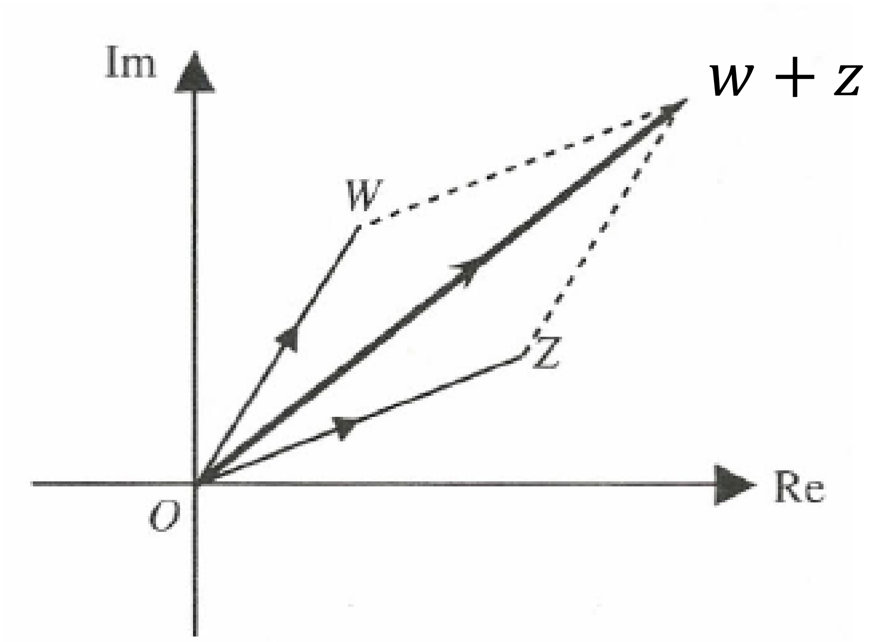
$$z_1 z_2 = r_1 e^{j\theta_1} r_2 e^{j\theta_2} = r_1 r_2 e^{j(\theta_1+\theta_2)}$$

$$\frac{z_1}{z_2} = \frac{r_1 e^{j\theta_1}}{r_2 e^{j\theta_2}} = \frac{r_1}{r_2} e^{j(\theta_1-\theta_2)}$$

Exercises

- Convert the following complex exponentials from polar to rectangular form
  - $5e^{j\frac{\pi}{4}}$
  - $e^{-\frac{3\pi}{2}}$
  - $e^{j\frac{3\pi}{2}}$
- Simplify the following expressions
  - $5e^{j\frac{\pi}{4}} + 4e^{j\frac{3\pi}{2}}$
  - $5e^{j\frac{\pi}{4}} \times 4e^{j\frac{3\pi}{2}}$
  - $(4 + j3)(1 - j)$
  - $\frac{5+j12}{1+j}$

Complex numbers as vectors



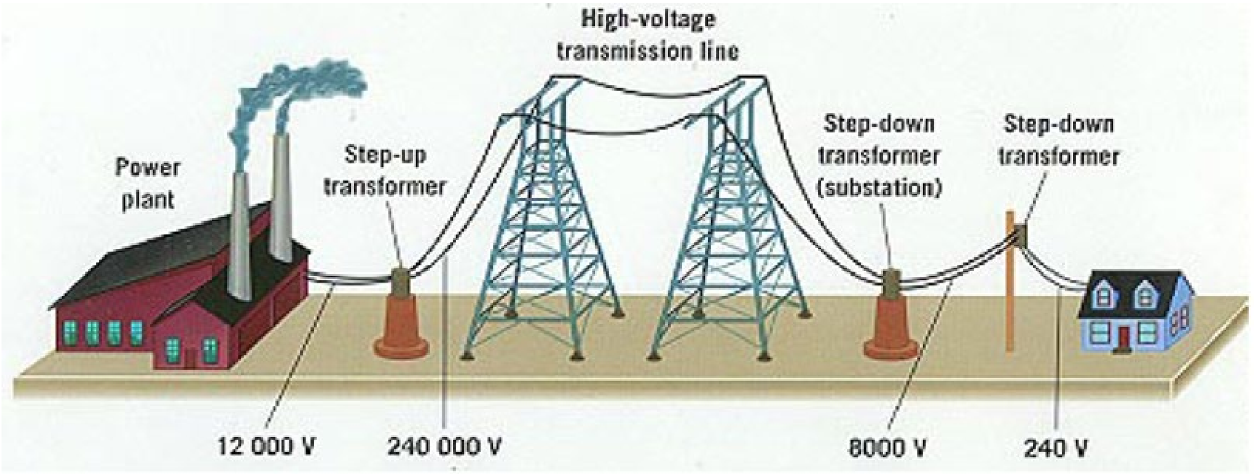
AC Systems Fundamentals

Most of power system is AC

- Why AC and not DC ?
- Why a sinusoidal alternating voltage ?
- Why 50 Hz (or 60 HZ) ?

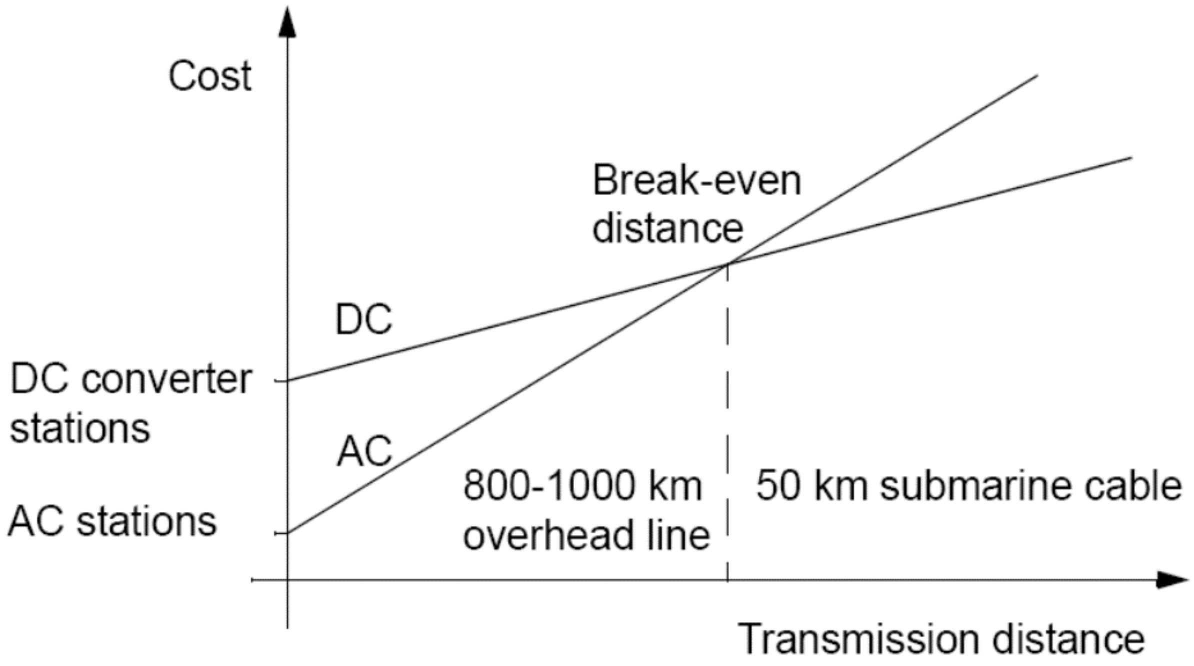
AC vs DC

- First generator was DC built by Thomas Edison. However, it could supply power only in local area as there would be huge resistive power loss (I^2R) over longer distance.
- Tesla introduced AC system. Transformer in AC system could step-up the voltage and reduce the current. Thus, power could be sent over longer distance. AC was preferred over DC to build larger system.

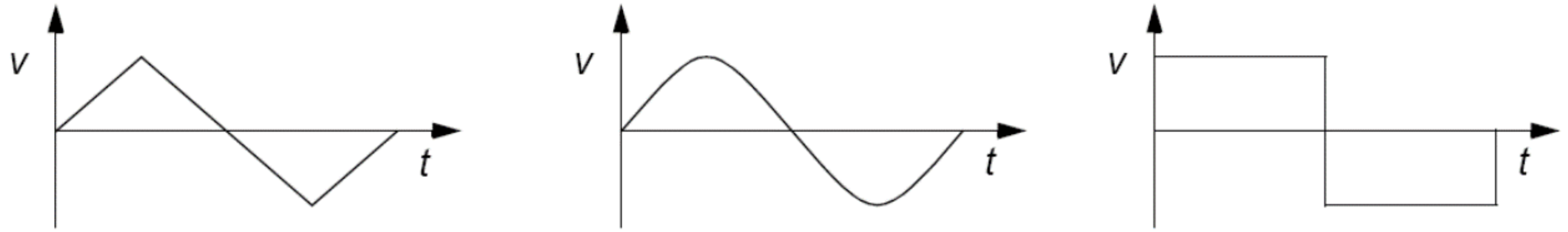


AC vs DC system

These days, with power electronic converters, DC also can be stepped-up and HVDC systems are becoming popular for power transfer over very long distance.



Why a Sinusoidal Alternating Voltage ?



Triangular, sinusoidal and square-wave signals

- In the power system, inductor and capacitor voltage-current relationship involves differentiation and integration, etc.
- Differentiation and integration of sinusoidal waveforms result in sinusoidal waveforms only. This is not true for other waveforms.
- Only for sinusoidal source voltage, the current will be sinusoidal and vice-versa.

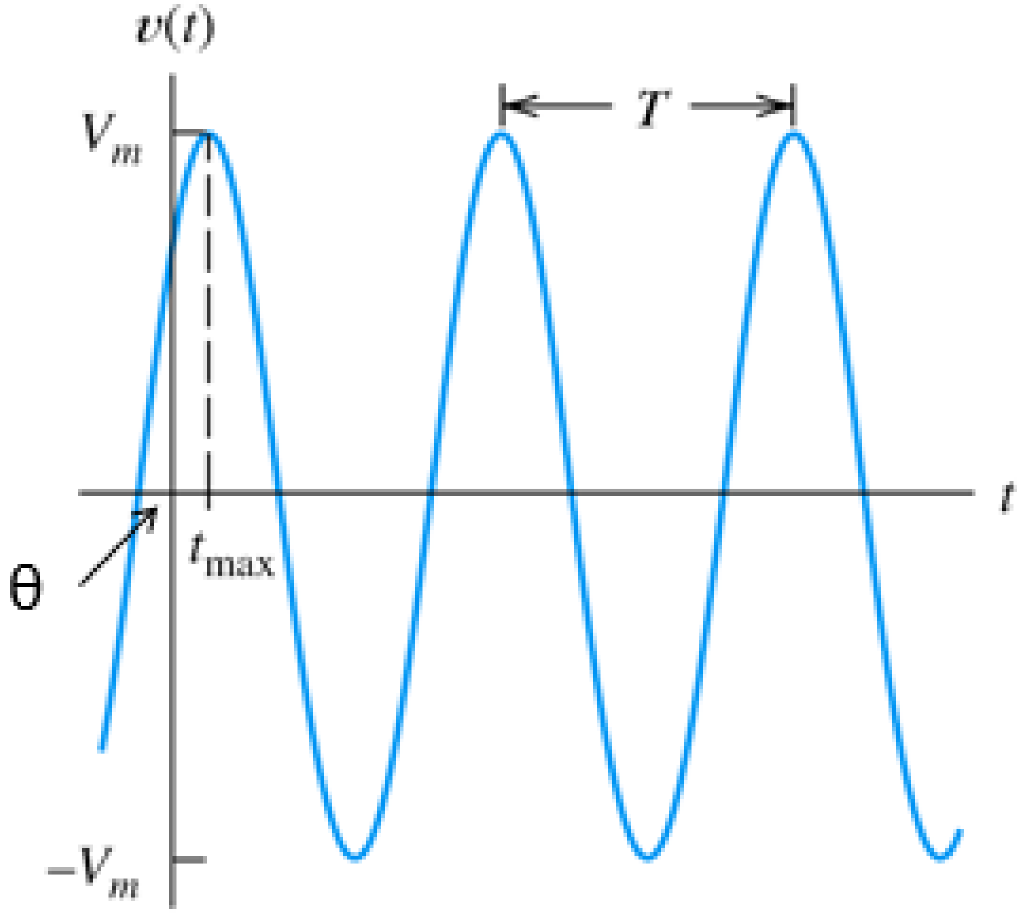
Choice of frequency for power systems

- A too low frequency, like 10 or 20 Hz causes perceptible flicker in incandescent bulbs. Hence, it should be higher than this.
- A too high frequency:
  - Increases the hysteresis losses:
    - $P_{loss,hysteresis} \propto f\psi^{1.5-2.5}$
  - Increases the eddy current losses:
    - $P_{loss,hysteresis} \propto f^2\psi^2$
  - Increases the cable and line impedance

$$\mathrm{Z} = \mathrm{R} + \mathrm{j}X = R + j2\pi f L$$

- Usually 50 Hz (Singapore, UK, etc.) or 60 Hz (USA, Japan, etc.)

Sinusoidal waveform



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

V_m is the peak value

ω is the angular frequency in radians/sec

θ is the phase angle

T is the time period

Power in AC - Root-mean-square (RMS) value

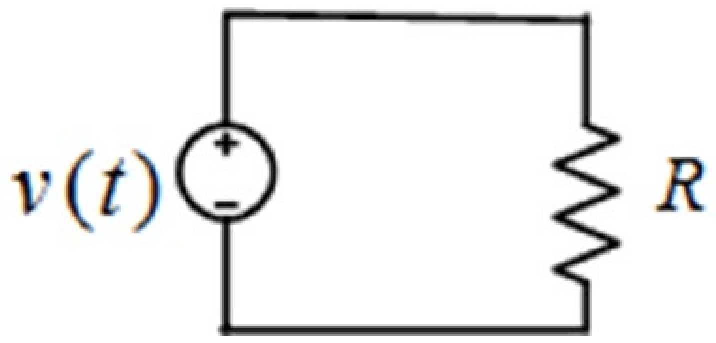
$$p(t) = \frac{v^2(t)}{R}$$

$$P_{avg} = \frac{E_T}{T} = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T \frac{v^2(t)}{R}dt = \frac{\frac{1}{T}\int_0^T v^2(t)dt}{R}$$

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

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

$$P_{avg} = \frac{V_{rms}^2}{R}$$



Using RMS value in AC is convenient for calculating average power as the formula becomes similar to the DC power: $P_{DC} = \frac{V^2}{R}$.

Average and Root-Mean-Square Values for sinusoidal waveform

- Instantaneous voltage is $v(t)$

- Average voltage : $\frac{1}{T}\int_0^T v(t)dt = \frac{1}{T}\int_0^T V_m \sin(\omega t + \theta)dt = 0$

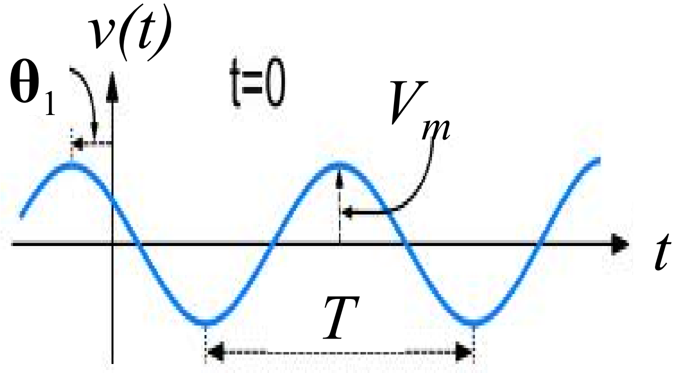
- RMS voltage : $\sqrt{\frac{1}{T}\int_0^T v(t)dt} = \sqrt{\frac{1}{T}\int_0^T V_m^2 sin^2(\omega t + \theta)dt} = \frac{V_m}{\sqrt{2}}$

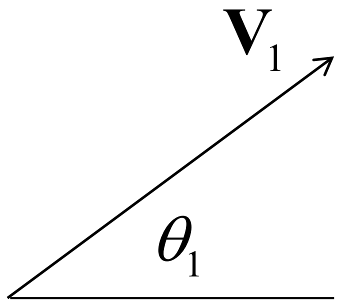
AC circuit analysis

Phasor and impedance

AC circuit analysis using Phasor for sinusoids

Time function : $v_1(t) = V_m \cos(\omega t + \theta_1)$





Phasor : $\mathbf{V}_1 = V_1 \angle \theta_1$

- Phasor is a complex number. It has magnitude and argument.
- Phasor captures the RMS value and the phase angle of the signal.

Where V_1 is the RMS value of voltage : $V_1 = \frac{V_m}{\sqrt{2}}$

Example 1: Converting sinusoidal time-domain expression to phasor form

$$v(t) = \sqrt{2}.20\cos\left(\omega t - 45\right)$$

$$V_{rms} = \frac{V_m}{\sqrt{2}} = 20$$

$$\mathbf{V}_1 = 20\angle -45^{\circ}$$

Using Phasors to Add Sinusoids

$$v_1(t) = \sqrt{2}.20\cos(\omega t - 45)$$

$$v_2(t) = \sqrt{2}.10\cos(\omega t - 30)$$

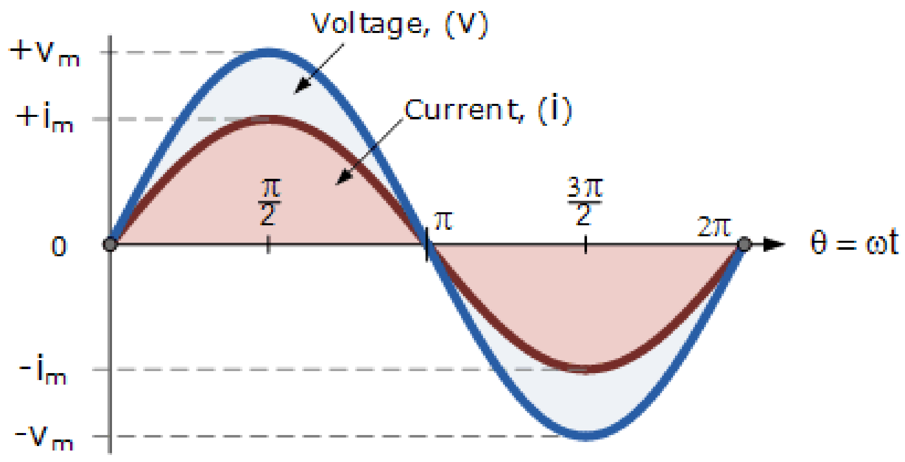
$$\mathbf{V}_1 = 20\angle -45^\circ$$

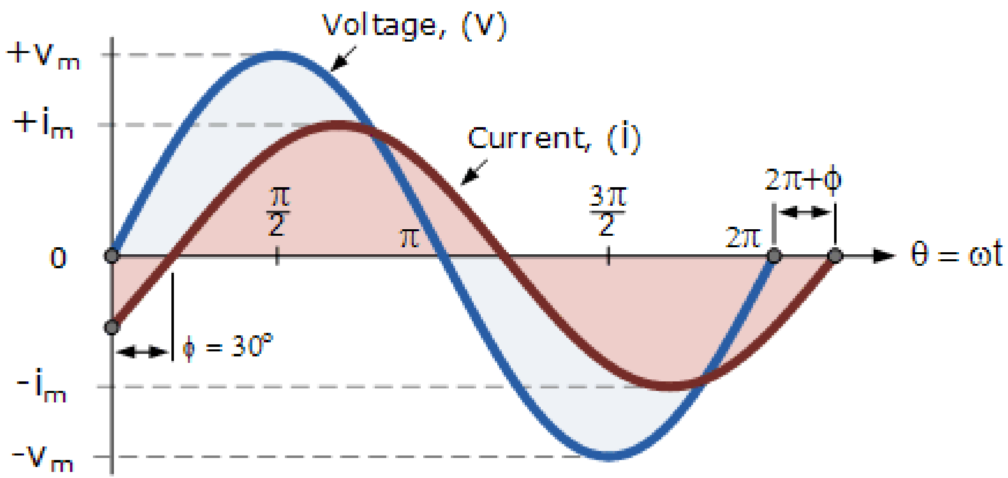
$$\mathbf{V}_2 = 10\angle -30^\circ$$

$$\begin{aligned}\mathbf{V}_s &= \mathbf{V}_1 + \mathbf{V}_2 \\ &= 20\angle -45^\circ + 10\angle -30^\circ \\ &= 14.14 - j14.14 + 8.660 - j5 \\ &= 23.06 - j19.14 \\ &= 29.97\angle -39.7^\circ\end{aligned}$$

$$v_s(t) = 42.38\cos(\omega t - 39.7)volts$$

Phase Relationships





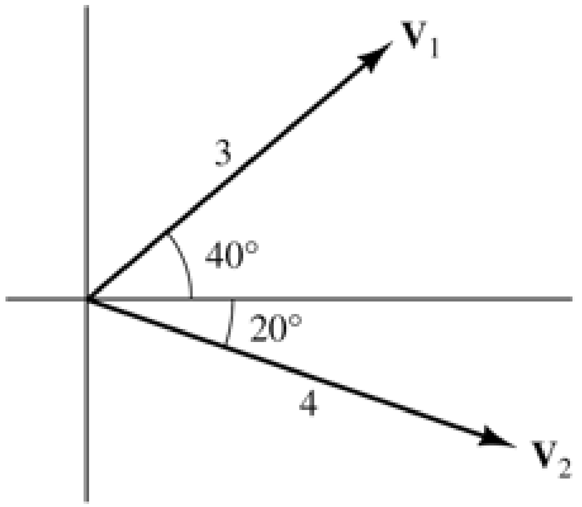
Left: voltage and current are in-phase.

Right: voltage is leading current by 30^o.

Phase Relationships – Phasor diagram

$$V_1 = 3\angle 40^o$$

$$V_2 = 4\angle 20^o$$

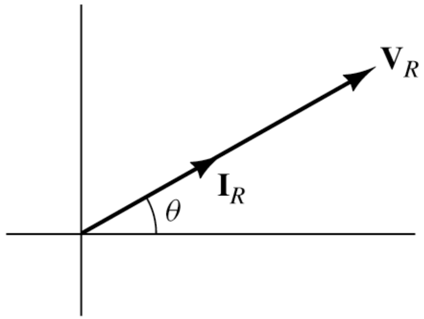


- Phasor diagram shows the phasors in the complex plane.
- It is useful to read the relative phase angles of various voltage and currents in the system.

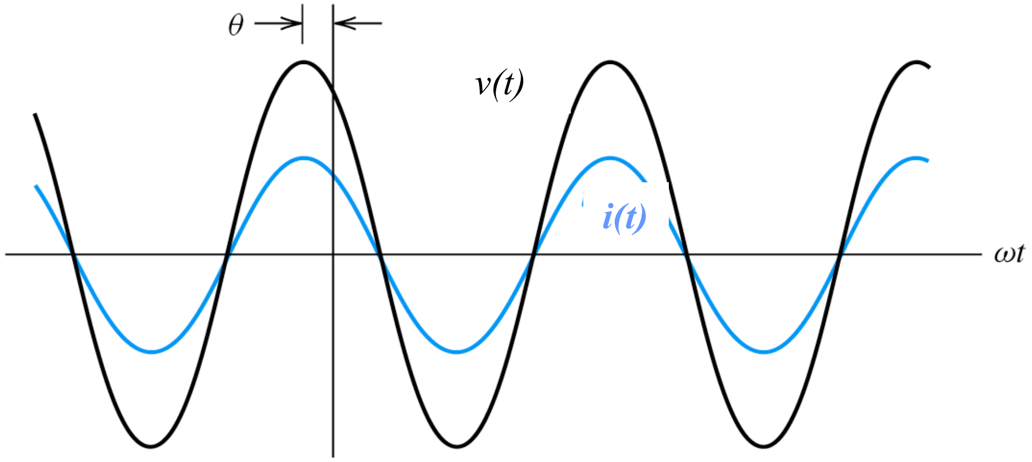
Impedance for R, L and C

- Impedance is a complex number also known as complex resistance
- DC circuit resistance is the ratio of voltage to current.
- Similarly, impedance in AC circuit is the ratio of voltage phasor to current phasor.
- We shall see that impedance for resistance(R) is real: just R. But the impedance for inductance(L) and capacitance(C) are imaginary numbers: $Z_L = j\omega L, Z_C = \frac{1}{j\omega C}$.
- AC circuit analysis is similar to DC circuit, except that we need to deal with complex numbers.

Voltage and current in a Resistance



(a) Phasor diagram

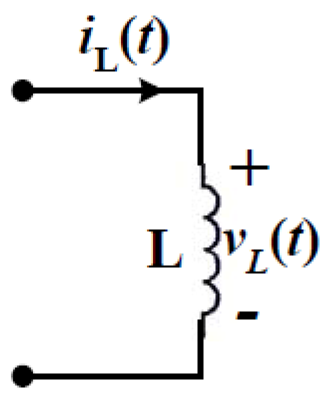


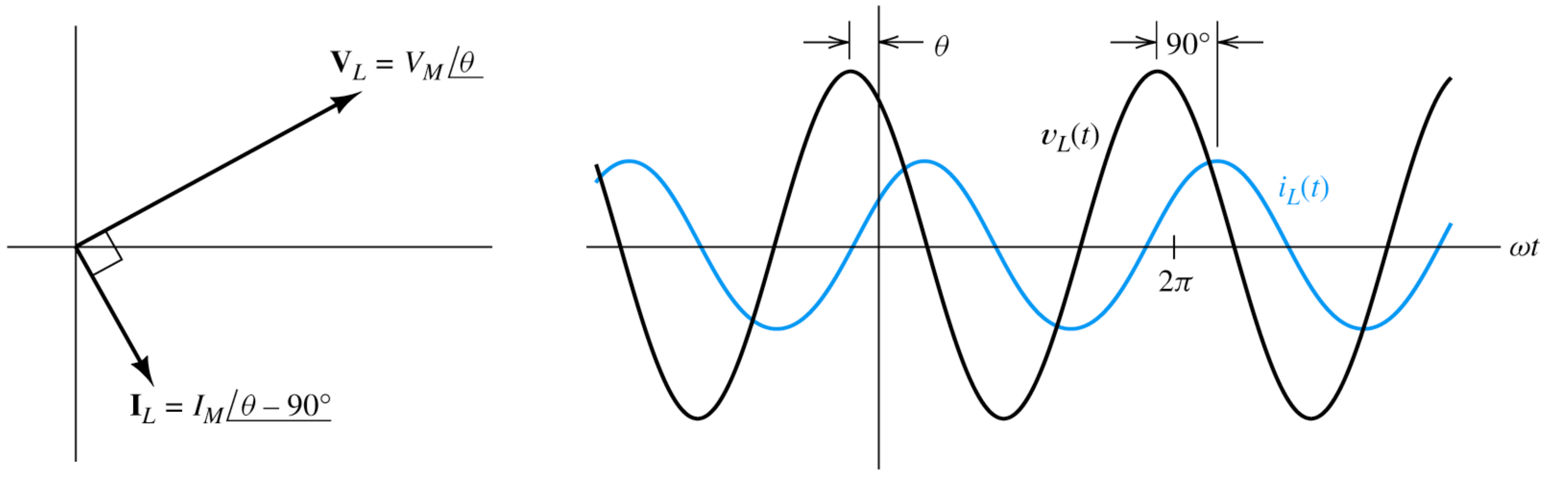
(b) Current and voltage versus time

For a pure resistance, current and voltage are in phase.

$$v(t) = R \cdot i(t) \qquad V_R = I_R R \qquad Z_R = \frac{V_R}{I_R} = R$$

Voltage and current in an Inductor





(a) Phasor diagram

(b) Current and voltage versus time

Current lags voltage by $90°$ in a pure inductance.

$$v_L(t) = L\frac{di_L(t)}{dt}$$

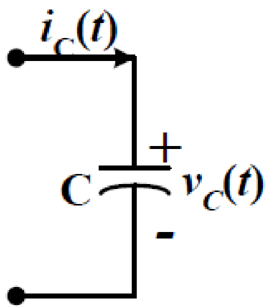
$$V_L = j\omega L \cdot I_L$$

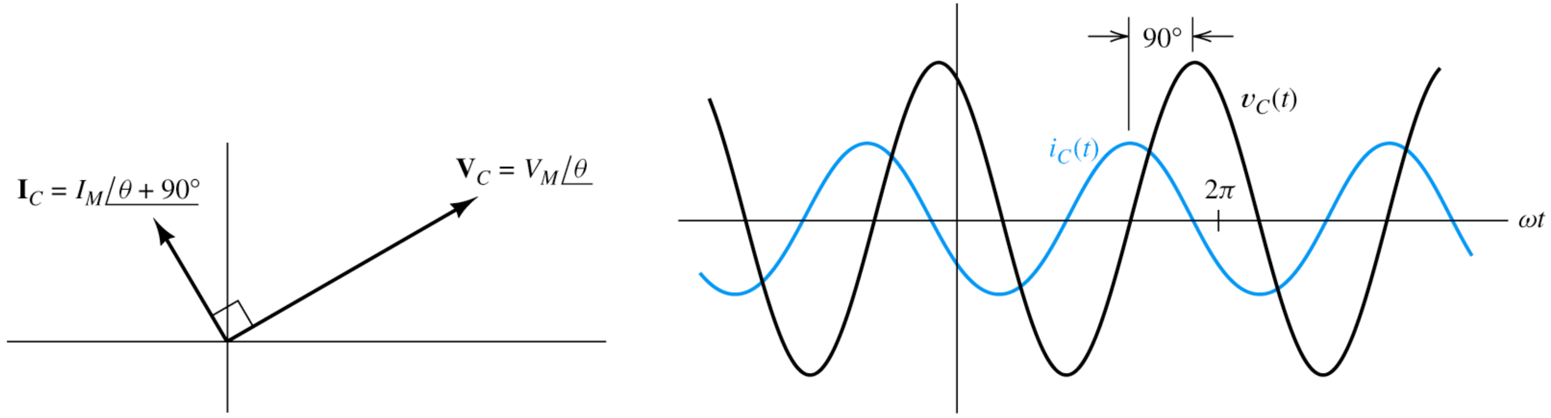
$$Z_L = \frac{V_L}{I_L} = j\omega L$$

Time derivative of sinusoids causes phase advance of 90^o and also results in multiplication by ω.

Impedance of pure inductance is also known as Inductive reactance, $X_L = \omega L$

Voltage and current in a Capacitor





(a) Phasor diagram

(b) Current and voltage versus time

Current leads voltage by 90° in a pure capacitance.

$$v_c(t) = \frac{\int i_C(t)dt}{C}$$

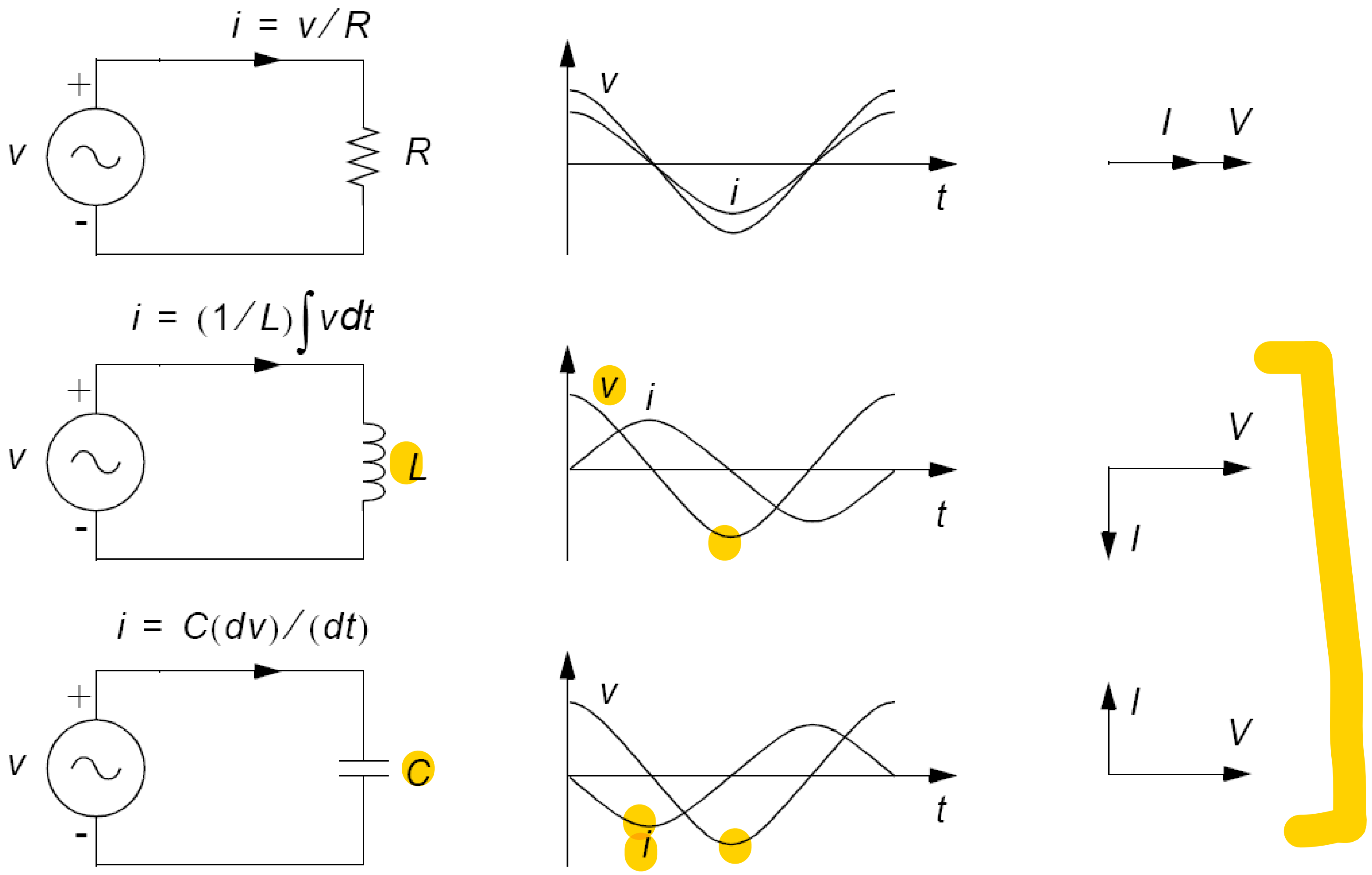
$$V_C = \frac{1}{j\omega C} I_c$$

$$Z_C = \frac{1}{j\omega C} = -\mathrm{j}\frac{1}{\omega C}$$

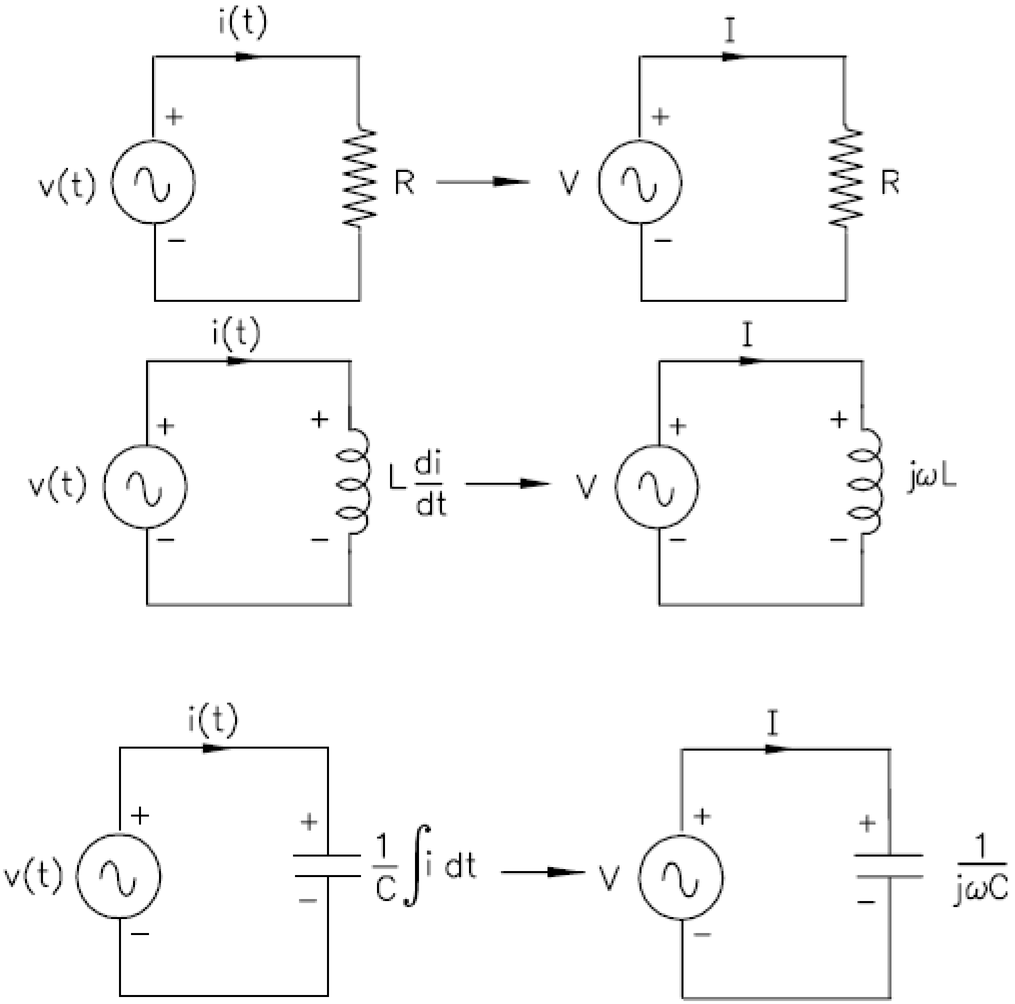
Time integration of sinusoids causes phase lag of 90^o and also results in division by ω.

Impedance of pure capacitance is also known as capacitive reactance, $X_C = -\frac{1}{\omega C}$

Summary: Time domain and Phasor diagram

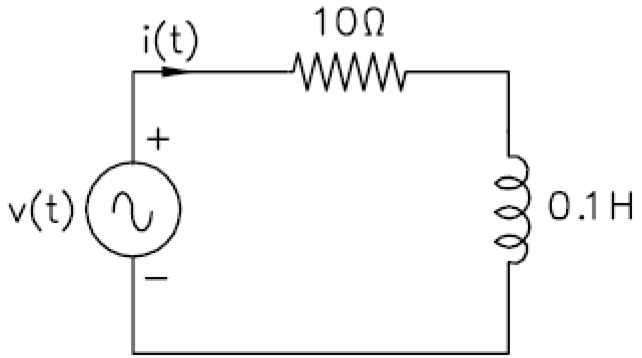


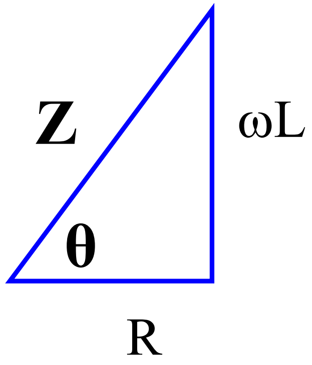
Summary: time domain and complex domain

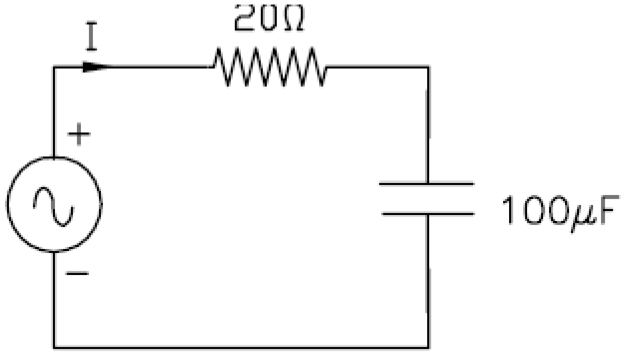


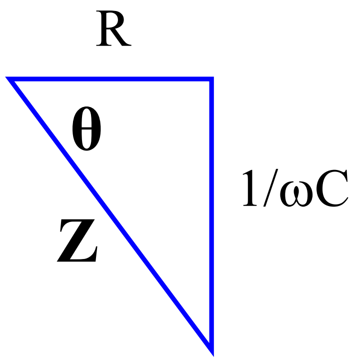
Element	Voltage	Current	Impedance
R	$\|V\|\angle 0^\circ$	$\frac{\|V\|\angle 0^\circ}{R}$	R
L	$\omega L\|I\|\angle 90^\circ$	$\|I\|\angle 0^\circ$	$j\omega L$
C	$\|V\|\angle 0^\circ$	$\omega C\|V\|\angle 90^\circ$	$\frac{1}{j\omega C}$

Complex Impedance





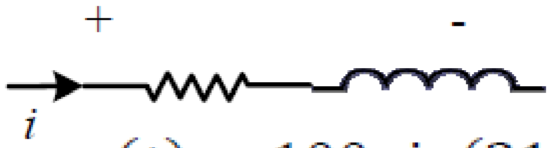




Example

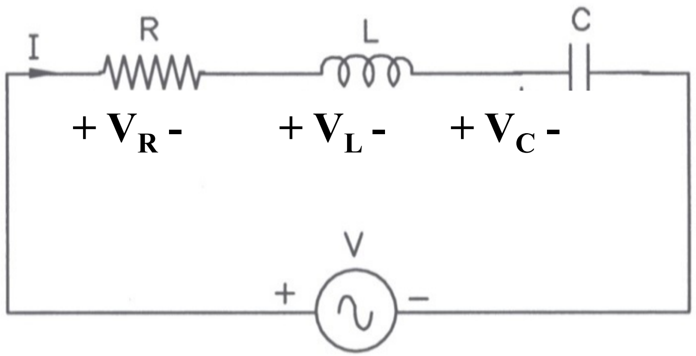
A time-varying voltage v(t) is applied across a series combination of 100Ω resistor and 0.1 H inductor.

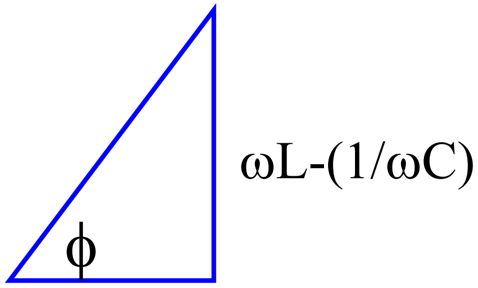
Find the peak amplitude of the resulting current waveform.



$$v(t) = 100\sin(314t)$$

RLC series circuit





Impedance:

$$Z = R + j\omega L - \frac{j}{\omega C} = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

$$= |Z|\angle\phi$$

$$|Z| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \qquad \tan\phi = \frac{\omega L - \frac{1}{\omega C}}{R}$$

Magnitude and phase angle of current:

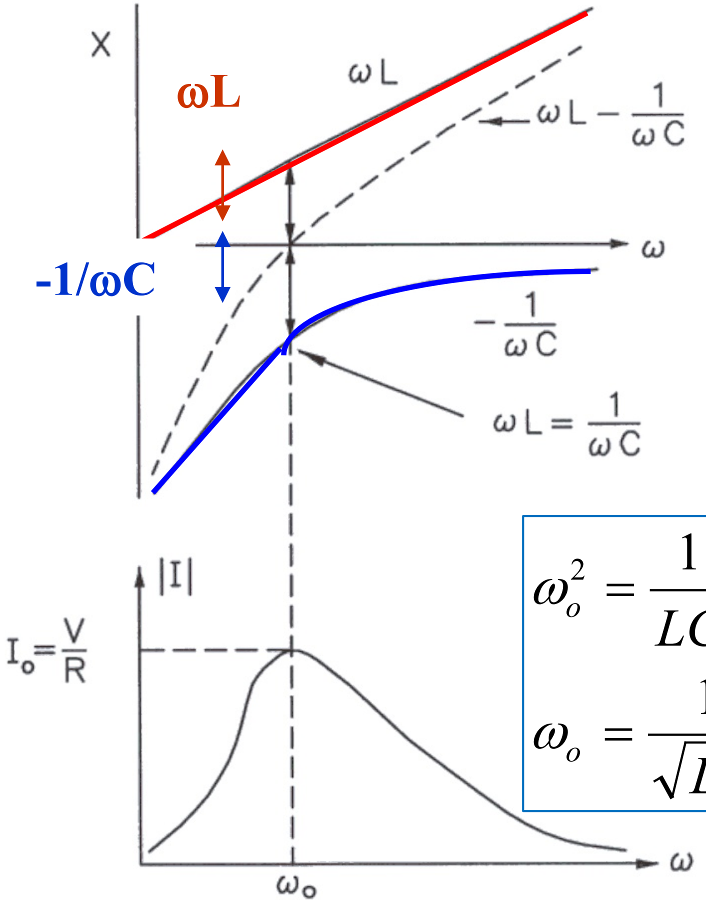
$$I = \frac{V}{R + j\omega L - \frac{j}{\omega C}}$$

Series Resonance

Variation of inductive and capacitive reactance with respect to frequency

$$|I| = \frac{|V|}{|Z|} = \frac{V}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}$$

Variation of current with respect to frequency

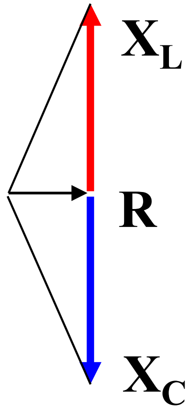


$$Z = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

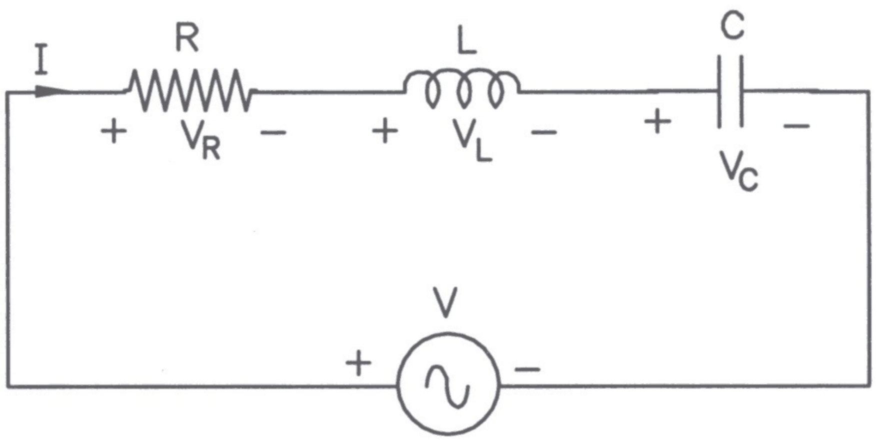
$$\omega_o^2 = \frac{1}{LC}$$

$$\omega_o = \frac{1}{\sqrt{LC}}$$

The resonant frequency (ω_o) is defined to be the frequency at which the circuit impedance is purely resistive (i.e. total reactance is zero).



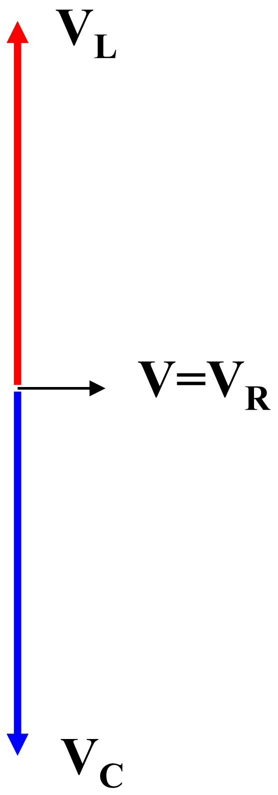
Phasor diagram at resonance



$$|V_L| = |I|\omega_0 L = \frac{V}{R}\frac{1}{\sqrt{LC}}L = V\frac{\sqrt{L/C}}{R}$$

$$|V_C| = |I|\frac{1}{\omega_0 C} = \frac{V}{R}\frac{1}{\frac{1}{\sqrt{Lc}}C} = V\frac{\sqrt{L/C}}{R}$$

$$|V_L| = |V_C|$$

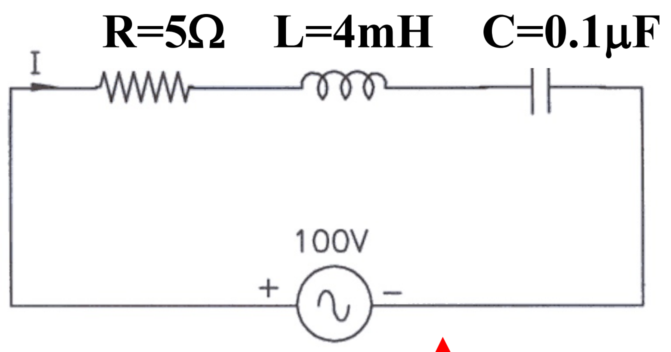


- The voltage across the inductor or capacitor can be much higher than the source voltage.
- This can be a problem in power systems if voltage goes above rated voltage.

Example

For the circuit shown below, determine the frequency at which resonance occurs. What is the current flow in the circuit at that frequency?

Also, determine the ratio of voltage across the inductor to that across the resistor.



$$\omega_o = \frac{1}{\sqrt{LC}} = 5\times10^4 \, rad/s$$

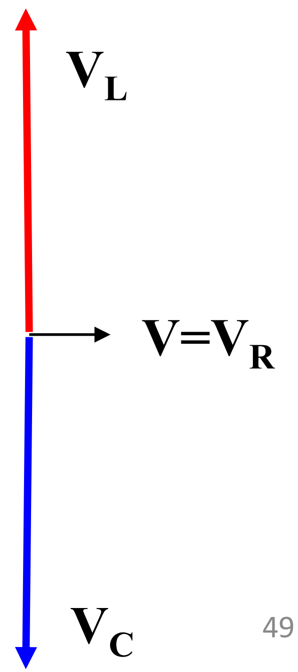
$$f_o = \frac{\omega_o}{2\pi} = 7.958kHz$$

$$I_o = \frac{V}{R} = \frac{100}{5} = 20A$$

$$|V_L| = \omega_o L I_o = 4000V$$

$$|V_C| = \frac{I_o}{\omega_o C} = 4000V$$

$$\frac{|V_L|}{|V_R|} = \frac{\omega_o L I_o}{R I_o} = \frac{\omega_o L}{R} = \frac{200}{5} = 40$$



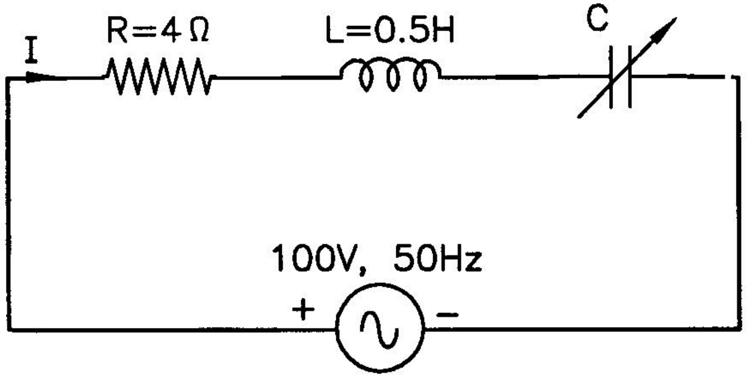
Example

A circuit, having a resisance of 4Ω, an inductance of 0.5H and a variable capacitor in series, is connected across a 100V, 50Hz supply. Calculate

(a) capacitance to give resonance,

(b) the voltage across the inductance and capacitance and

(c) the ratio of voltage across the inductor to that across the resistor.



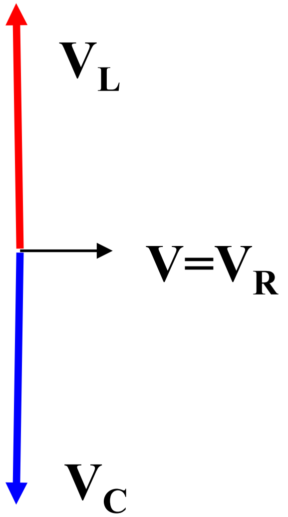
(a)For resonance $$2\pi fL = \frac{1}{2\pi fC}$$

$$C = \frac{1}{(2\pi \times 50)^2 \times 0.5} = 20.3\mu F$$

(b) At resonance $$I = \frac{V}{R} = \frac{100}{4} = 25A$$

$$|V_L| = 2\pi fLI = 2 \times 3.14 \times 50 \times 0.5 \times 25 = 3925V$$

$$|V_C| = |V_L| = 3925V$$



(c)Ratio $|V_L|$ to $|V_R|$ $$\frac{|V_L|}{|V_R|} = \frac{2\pi \times 50 \times 0.5}{4} = 39.25$$