

Computer Networking and Energy Systems

Introduction

WS 2014/2015

Prof. Dr. Herman de Meer (hermann.demeer@uni-passau.de)

Ammar Alyousef (ammar.alyousef@uni-passau.de)

Zhiyuan “Leo” Sui (suizhiyu@fim.uni-passau.de)

Ali Alshawish (ali.alshawish@uni-passau.de)



Timetables

- Lecture
 - Tuesday, 10.00 – 12.00, weekly
 - Room ITZ SR 001
 - Prof. Dr. Herman de Meer
 - First lecture on 07.10.2014
- Two tutorials
 - Monday, 16:00 - 18:00, weekly
 - Room ITZ SR 004
 - Thursday, 10:00-12:00, weekly
 - Room ITZ SR 002



Table of Contents

- Electric Power Systems
 - Ch01: The Physics of Electricity
 - Ch02: Basic Circuit Analysis
 - Ch03: AC Power
 - Ch04: Generators
 - Ch05: Loads
 - Ch06: Transmission and Distribution
 - Ch07: Power Flow Analysis
 - Ch08: System Performance
 - Ch09: System Operation, Management, and New Technology
 - Ch10: Smart Grid



Objectives

- Understand electric power systems basics to be able to identify where and how apply computer science techniques in energy management and in designing and building smart grids
- Understand smart grid concepts and components
- Understand energy efficiency concepts
 - Energy saving vs. Energy efficiency
 - ICT for energy efficiency vs. Energy-efficient ICT
 - Power vs. Energy



Major Literature

- **Alexandra von Meier:** *Electric Power Systems – A Conceptual Introduction*. IEEE Press. ISBN-13: 978-0-471-17859-0, ISBN-10: 0-471-17859-4
- **James Momoh:** *Smart Grid – Fundamentals of Design and Analysis*. IEEE Press. ISBN: 978-0-470-88939-8
- NIST Framework and Roadmap for Smart Grid Interoperability Standards U.S. Department of Commerce, Office of the National Coordinator for Smart Grid Interoperability, NIST Special Publication 1108, Release 1.0
Published Jan. 2010



Further Readings

- **J. Glover, M. S. Sarma, T. J. Overbye:** *Power System Analysis and Design*. ISBN-13: 978-1-111-42579-1, ISBN-10: 1-111-42579-5.
Edition: 5th
- International Electrotechnical Commission
<http://www.iec.ch/smartgrid/background/explained.htm>
- European technology platform for the electricity networks of the future
<http://www.smartgrids.eu/FAQ#12>
- (US) National Institute of Standards and Technology
<http://www.nist.gov/el/smartgrid/sgprogram.cfm>



Electric Power System

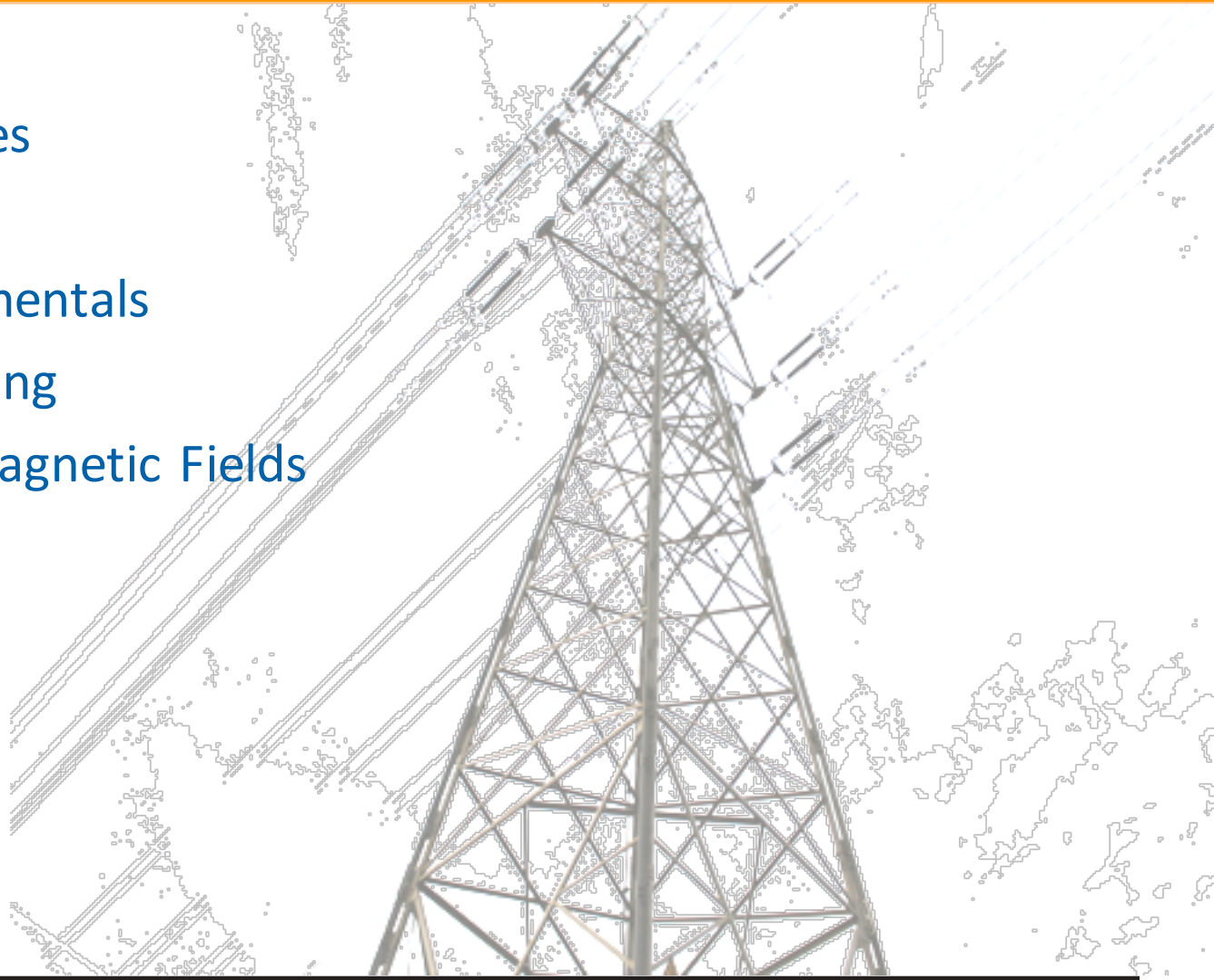
Chapter 01: The Physics of Electricity



1. The Physics of Electricity

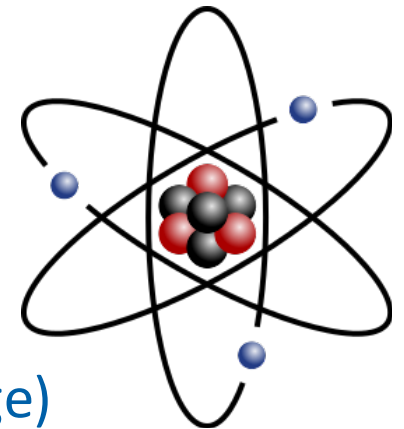
■ Contents

- 1) Basic Quantities
- 2) Ohm's law
- 3) Circuit Fundamentals
- 4) Resistive Heating
- 5) Electric and Magnetic Fields
- 6) Summary



1.1 Basic Quantities (1)

- Charge:
 - Positive & negative charge
 - Like charges repel each other
 - Opposite charges attract each other
 - Atom: electrons (-), protons (+), neutrons (no charge)
 - Charged versus uncharged particles
 - Positively charged: number of protons $>$ number of electrons
 - Negatively charged: number of protons $<$ number of electrons
 - Electrically neutral: number of protons = number of electrons

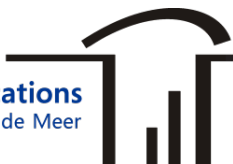


Source: <http://commons.wikimedia.org>



1.1 Basic Quantities (2)

- Charge:
 - Ion: naturally charged atoms or molecules (group of atoms)
 - Imbalanced number of protons and electrons
 - Unit of charge
 - coulomb (C)
 - Charge of 6.25×10^{18} protons
 - Proton charge: 1.6×10^{-19} C
 - Electron charge: -1.6×10^{-19} C
 - Symbol of charge
 - Q or q



1.1 Basic Quantities (3)

■ Potential or Voltage

- The potential energy held by a charge in a particular location, relative to a reference location, divided by the amount of its charge
- The required work to move the charge (to / from) that location

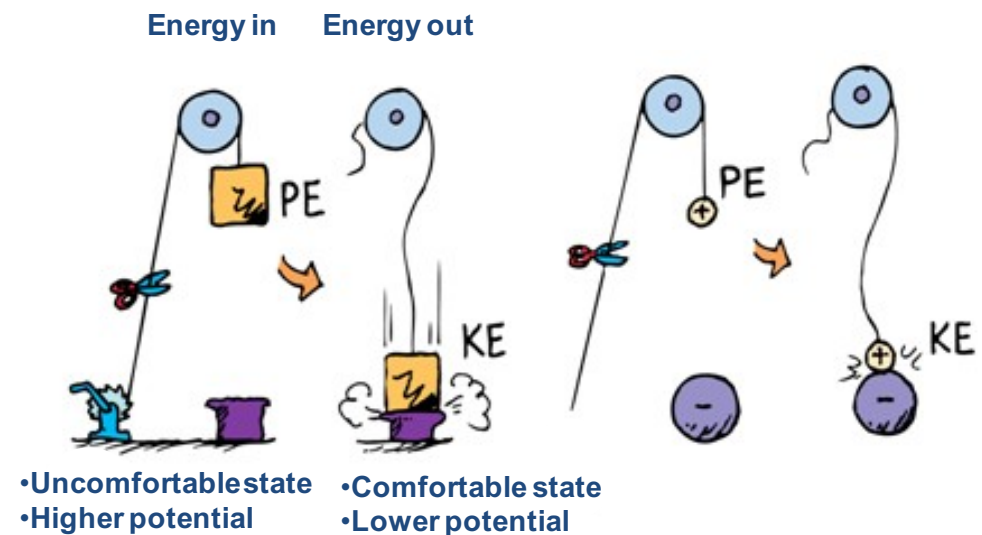
- Can be positive or negative

■ Unit

- volt (V)
- 1 volt = 1 joule per coulomb

■ Symbol

- E, e, V, or v



Source: <http://slideplayer.us> (33 Electric Fields and Potential)

1.1 Basic Quantities (4)

- Ground
 - Electrically neutral place
 - Able to absorb excesses of either positive or negative charge
 - Synonym: *earth*



Signal
ground



Chassis
ground



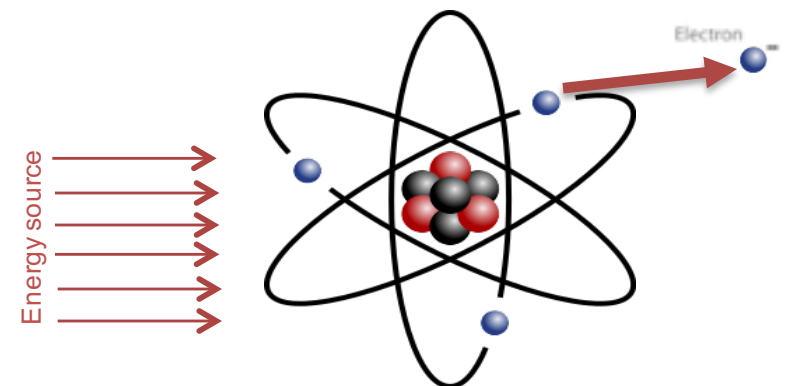
Earth
ground



1.1 Basic Quantities (5)

■ Conductivity

- The material is able to conduct electricity if it has number electrons that are always free to travel
- Conducting materials: metals, water (with dissolved ions)
- Ionization: a process by which electrically neutral atoms or molecules are converted to electrically charged atoms or molecules (ions)
 - Heat
- Superconducting
 - Very low temperature



Source: <http://commons.wikimedia.org>



1.1 Basic Quantities (6)

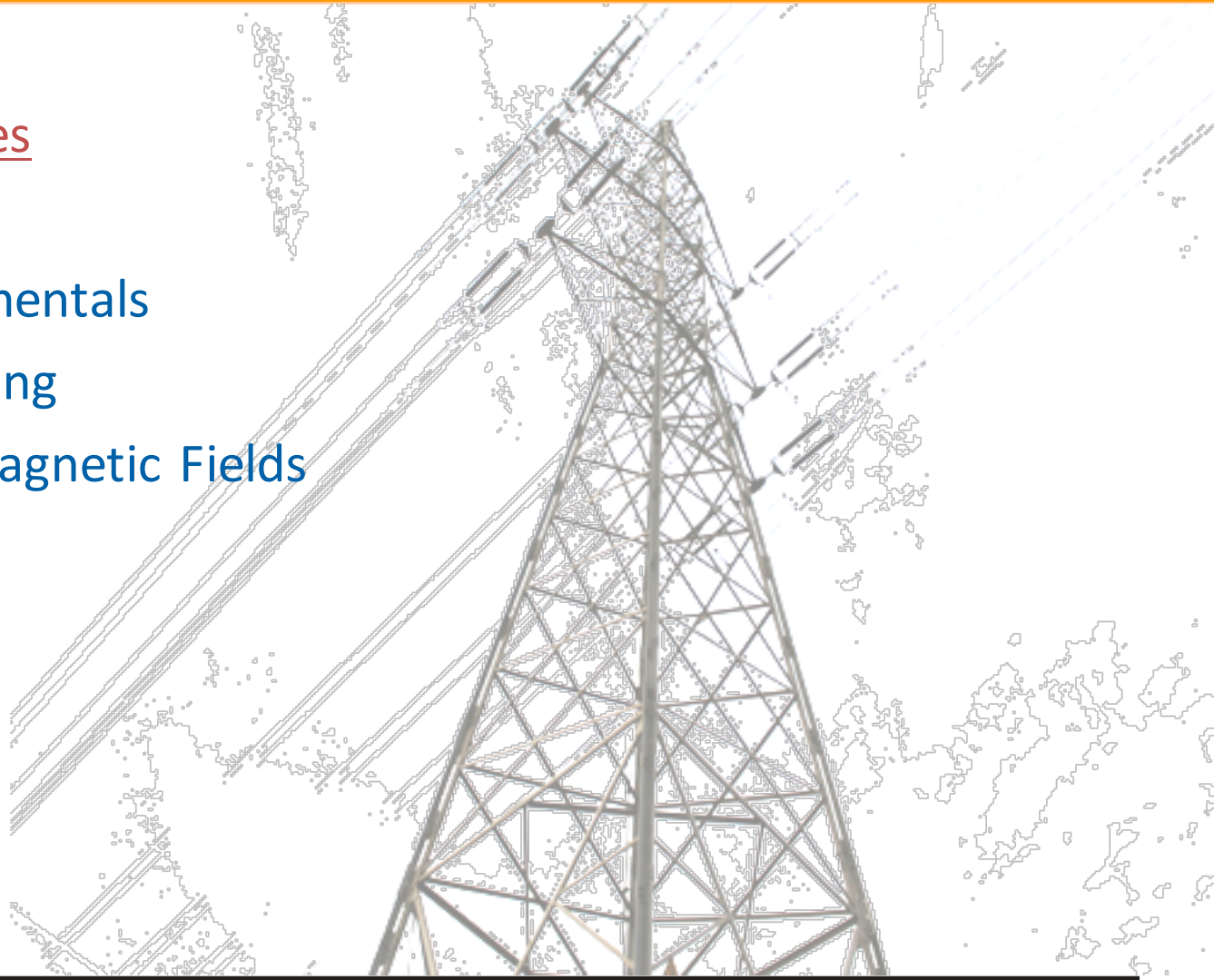
- Current
 - The movement of electric charge
 - Flow rate of charge
 - Positive or negative
 - DC or AC
 - Unit
 - amperes (A)
 - 1 ampere = 1 coulomb per second
 - Symbol
 - I or i



1. The Physics of Electricity

■ Contents

- 1) Basic Quantities
- 2) Ohm's law
- 3) Circuit Fundamentals
- 4) Resistive Heating
- 5) Electric and Magnetic Fields
- 6) Summary

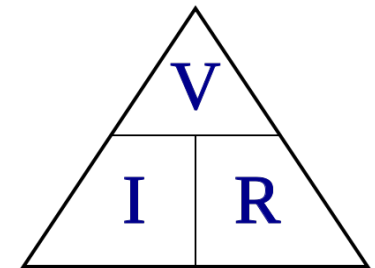


1.2 Ohm's law (1)

■ OHM's Law

- Intuitively, voltage and current are related, e.g. if the potential difference between two ends of a wire is increased, a greater current to flow would be expected.
- OHM's Law expresses the linear relationship between voltage and current

$$V = IR$$



- V is the voltage
- I is the current
- R is the proportionality constant called resistance



1.2 Ohm's law (2)

■ Resistance

- It is usually a fixed, unchanging property of the object with respect to current and voltage
- It depends on an object's material composition and its shape
 - Length l (*meter*): *resistance increases with length*
 - Cross-sectional area A (*square meter*): *resistance decreases with cross-sectional area*
 - Resistivity ρ (*ohm*meter*): an intrinsic material property that quantifies how strongly a given material impedes the flow of electric current.

- $$R = \frac{\rho l}{A}$$



1.2 Ohm's law (3)

■ Resistance

- Resistance also tends to vary with temperature
 - E.g. the resistance of a copper wire increases as it heats up

■ Unit:

- ohm (Ω)
- By rearranging Ohm's law, we see $R = V/I$
 - 1 ohm = 1 volt per ampere ($\Omega = V/A$)
- The unit of resistivity are ohm*meter ($\Omega*m$), which can be reconstructed through the preceding formula:
 - $\rho = RA / l = \Omega*m^2/m = \Omega*m$



1.2 Ohm's law (4)

■ Conductance

- Conductivity is the inverse of resistivity $\sigma = 1 / \rho$ (mho/m)
- Conductance is the reciprocal of resistance $G = 1 / R$
- The conductance is related to the conductivity by:

$$G = \frac{\sigma A}{l} = \frac{1}{R}$$

■ Unit

- mho
- $1 \text{ mho} = 1 / \Omega$



1.2 Ohm's law (5)

- Insulation
 - Aims to keep current from flowing where it is not desired
 - Insulators have an infinite resistance or zero conductance, so that zero current flows through it



Source: <http://www.answers.com>



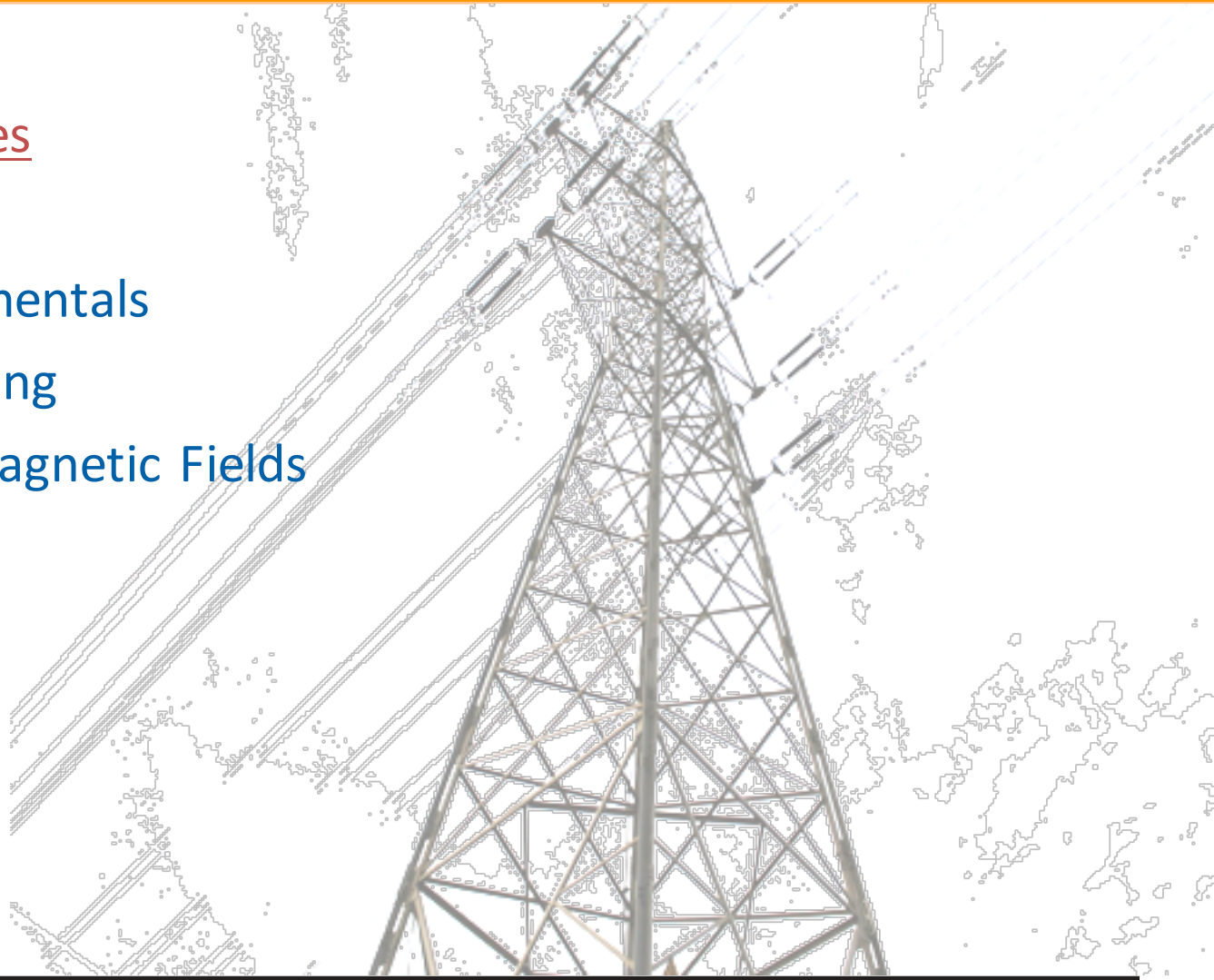
Source: <http://commons.wikimedia.org>



1. The Physics of Electricity

■ Contents

- 1) Basic Quantities
- 2) Ohm's law
- 3) Circuit Fundamentals
- 4) Resistive Heating
- 5) Electric and Magnetic Fields
- 6) Summary



1.3 Circuit Fundamentals (1)

- **Static Charge** is accumulation of charge in one place due to lack of a conducting pathway that enables it to move towards its opposite charge.



Source: <http://commons.wikimedia.org>

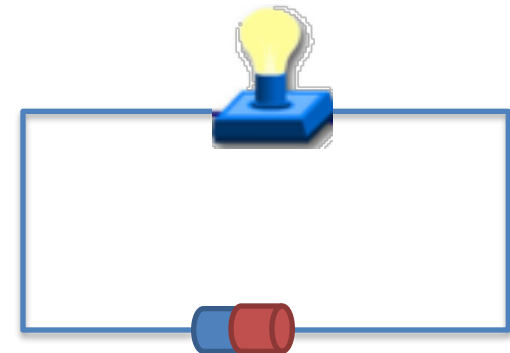


Source: www.freeimages.com



1.3 Circuit Fundamentals (2)

- **Electric Circuit** is a pathway to recycle charge to its origin to maintain potential difference, in order to produce a sustained flow of current
 - **Electromotive force (*emf*)** refers to the mechanism that force the charge to return to the less “comfortable” potential.



1.3 Circuit Fundamentals (3)

- **Voltage Drop** is the difference in voltage between two points in a circuit as the electric current flows
 - As in Ohm's law $V = IR$, voltage drop is proportional to the current flowing through the component and its resistance
- **Electric shock** is the reaction or injury caused by electric current flowing through an object.

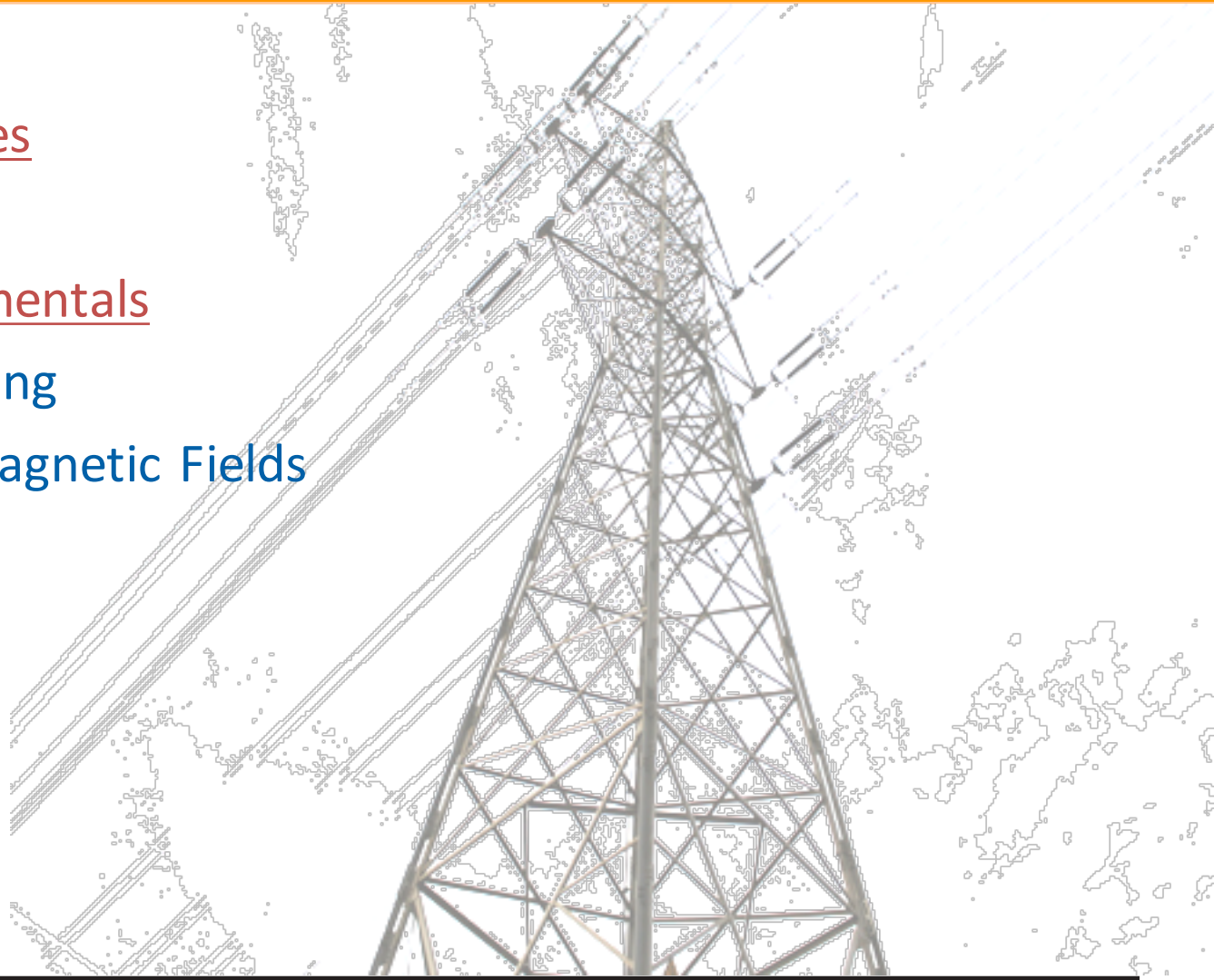


Source: www.coolquiz.com

1. The Physics of Electricity

■ Contents

- 1) Basic Quantities
- 2) Ohm's law
- 3) Circuit Fundamentals
- 4) Resistive Heating
- 5) Electric and Magnetic Fields
- 6) Summary



1.4 Resistive Heating (1)

- Calculating Resistive Heating
 - The process of generating heat due to flow electric current through a conductor that has some resistance.
 - Desirable (e.g. in any heating appliance)
 - Undesirable: resistive losses (e.g. power lines)
 - This heat is measured in terms of **power**
 - $P = IV = \frac{\text{Charge}}{\text{Time}} \cdot \frac{\text{Energy}}{\text{Charge}} = \frac{\text{Energy}}{\text{Time}}$
 - $P = I^2 R$
 - Unit
 - watt (W) = amperes x volts
 - $W = A^2 \times \Omega$



1.4 Resistive Heating (2)

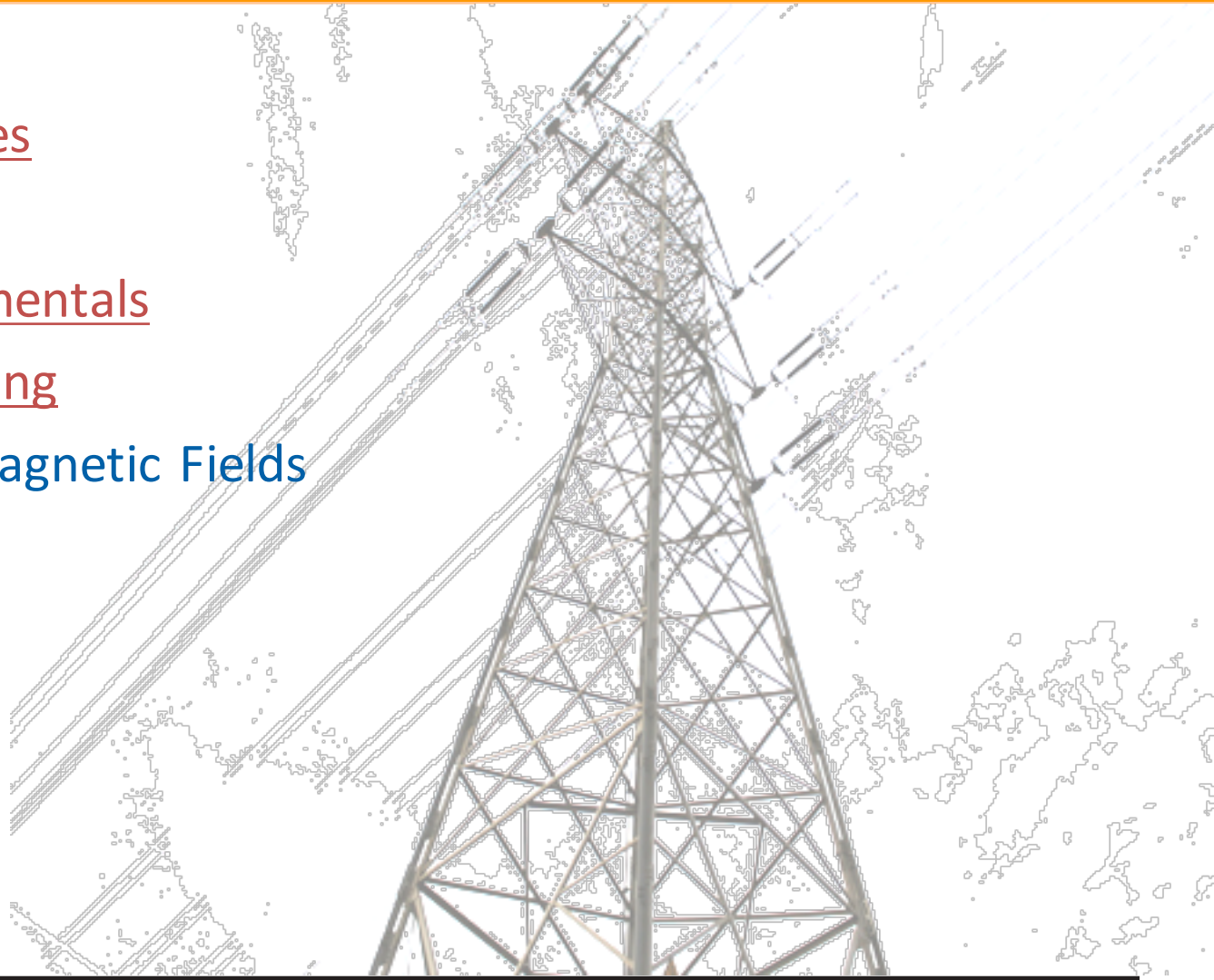
- Transmission Voltage and Resistive Losses
 - High level voltage are used for power transmission lines
 - Acc. to $P = IV$, a high level voltage implies less current needs to flow in order to transmit the same amount of power
 - Acc. To $P = I^2R$, reducing the current result in reducing the line losses
 - Reducing the power losses by reducing the resistance of the conductors
 - Only at the expense of making them thicker and heavier



1. The Physics of Electricity

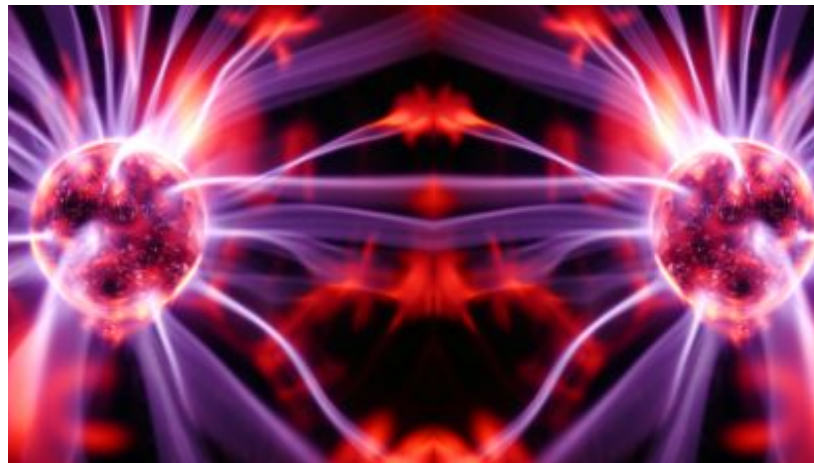
■ Contents

- 1) Basic Quantities
- 2) Ohm's law
- 3) Circuit Fundamentals
- 4) Resistive Heating
- 5) Electric and Magnetic Fields
- 6) Summary



1.5 Electric and Magnetic Fields (1)

- A *field* is an abstraction developed in physics to explain how tangible objects exert forces on each other at a distance, by invisible means

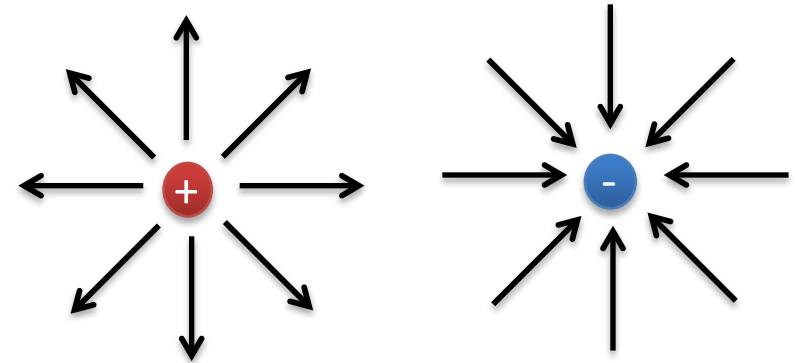


Source: www.freeimages.com

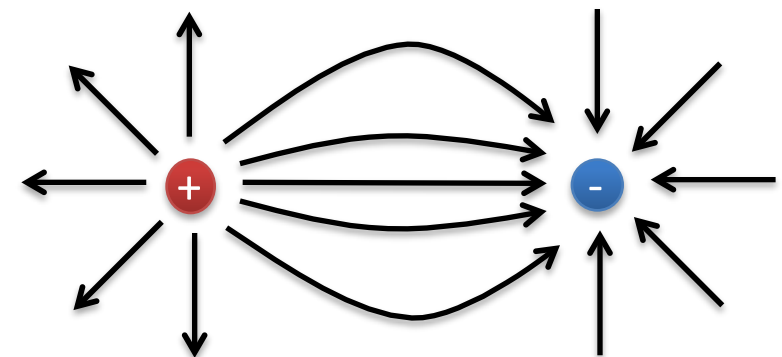


1.5 Electric and Magnetic Fields (2)

- **Electric Field** is a map of electric force experienced by a charge at any location
 - This invisible field of force is represented by field lines indicating the direction of movement of positive charge
 - The electric force drops off at rate proportional to the square of the distance



Electric field of single charges



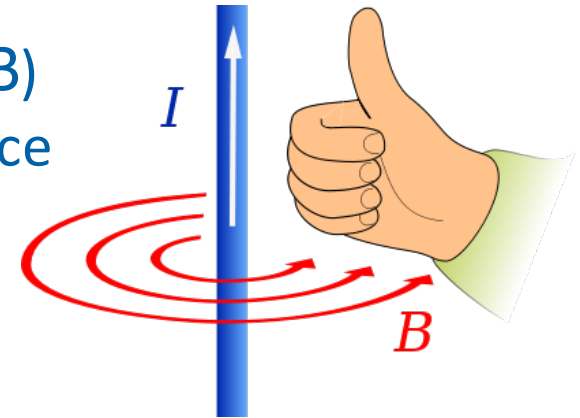
Electric field of two opposite charges



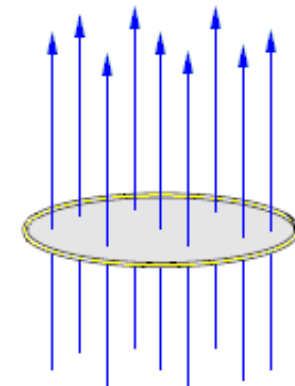
1.5 Electric and Magnetic Fields (3)

■ Magnetic field

- Electric current produce a magnetic field (B)
→ A **magnetic field** is the magnetic influence of electric currents and magnetic materials
- Right-hand rule to specify the direction
- Unit of magnetic field:
 - tesla (T) or gauss (G)
- Magnetic flux (Φ) is the amount of magnetic field passing through a surface
 - It is measured in units of weber (Wb)
- Magnetic field = Magnetic flux density
 - → 1 tesla = 1 weber per square meter



Source: <http://commons.wikimedia.org>



Source: <http://commons.wikimedia.org>

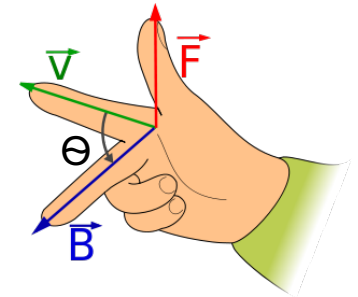
1.5 Electric and Magnetic Fields (4)

■ Electromagnetic Induction:

- A process of exerting a force on the charge, accelerating them in one direction along the wire and causing a current to flow
- This force is caused by a varying magnetic field
 - Changing intensity of **B**
 - Relative motion between the charge and **B**

■ Lorentz equation: $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$

- **F** :magnetic force (vector: magnitude and direction)
- **q** :particle's charge (determine the direction)
- **B** :magnetic field (vector: magnitude and direction)
- **v** :velocity (vector: magnitude and direction)
- When θ is 90° the maximum force is possible

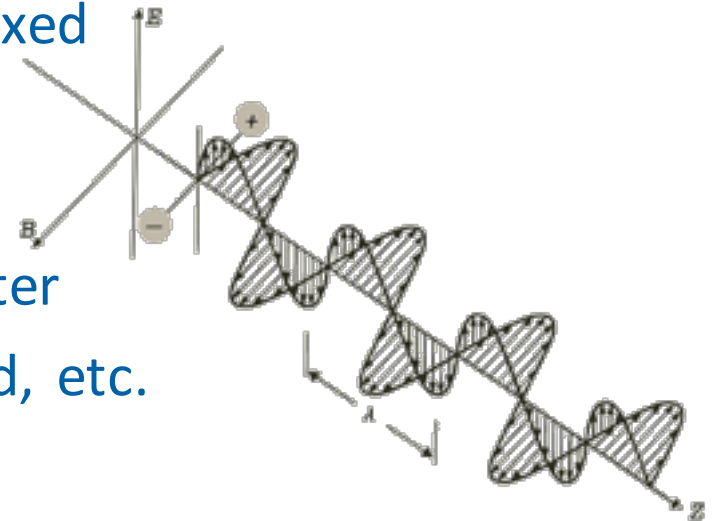


Source: <http://commons.wikimedia.org>



1.5 Electric and Magnetic Fields (5)

- Electromagnetic Radiation (EMR)
 - A self-propagating oscillating wave of electric and magnetic fields
 - The propagation speed of the wave is fixed
 - Speed of light = 3×10^8
 - EMR carries energy
 - Electrons are used to interact with matter
 - Light, radio waves, microwaves, infrared, etc.



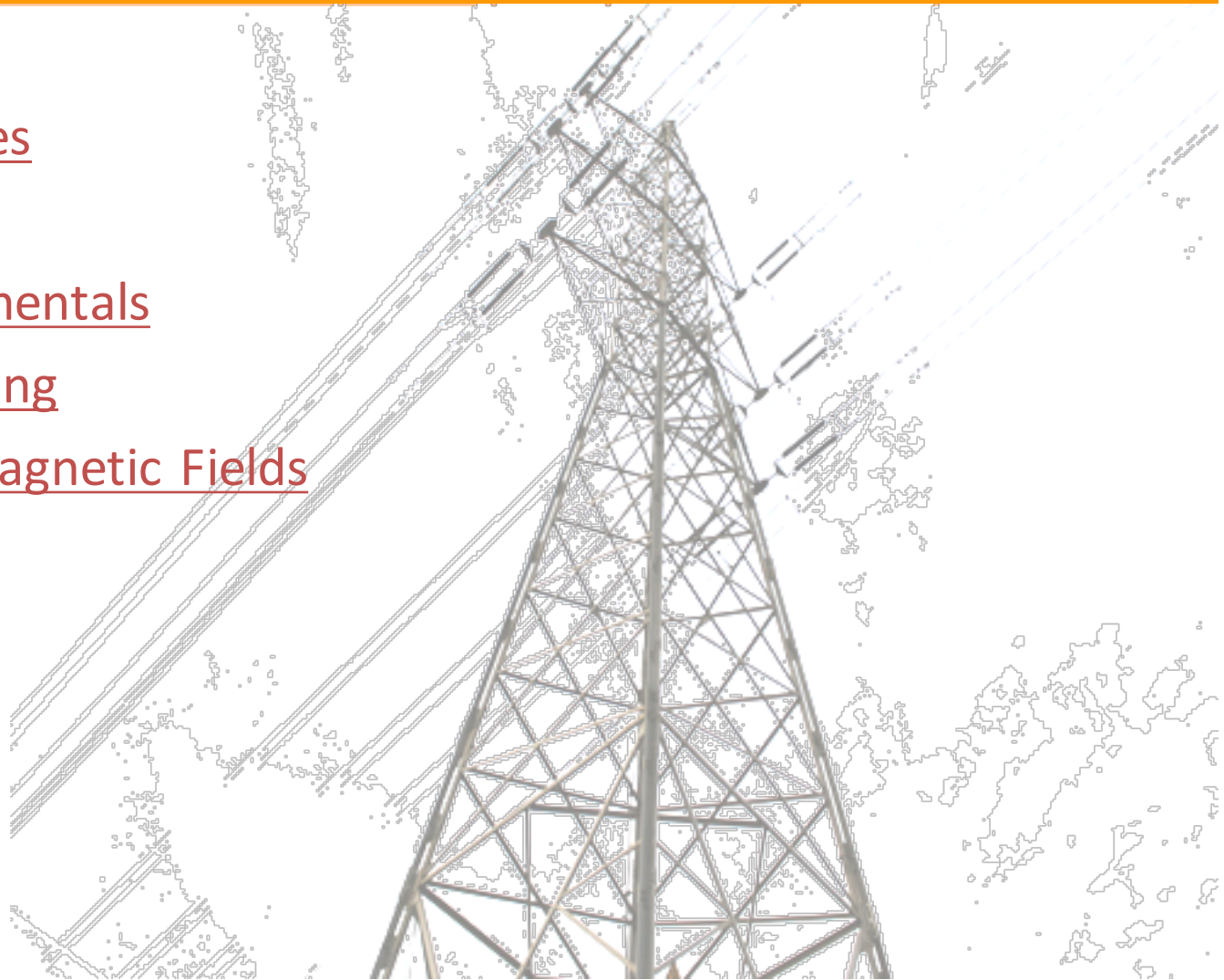
Source: <http://commons.wikimedia.org>



1. The Physics of Electricity

■ Contents

- 1) Basic Quantities
- 2) Ohm's law
- 3) Circuit Fundamentals
- 4) Resistive Heating
- 5) Electric and Magnetic Fields
- 6) Summary



1.6 Summary

- Mobile charge carriers (electrons and ions) provide conductivity
- Voltage refers to the difference of electric potential energy between two points
- Current refers to the flow of electric charge (carried by moving electrons and ions)
- OHM's Law states the relationship between the voltage (V), resistance (R), and current (I)
- Whenever an electric current flows through a material that has some resistance, it generates heat.
- Electromagnetic Induction refers to the induction of an electromotive force in a circuit by a varying magnetic field



Electric Power System

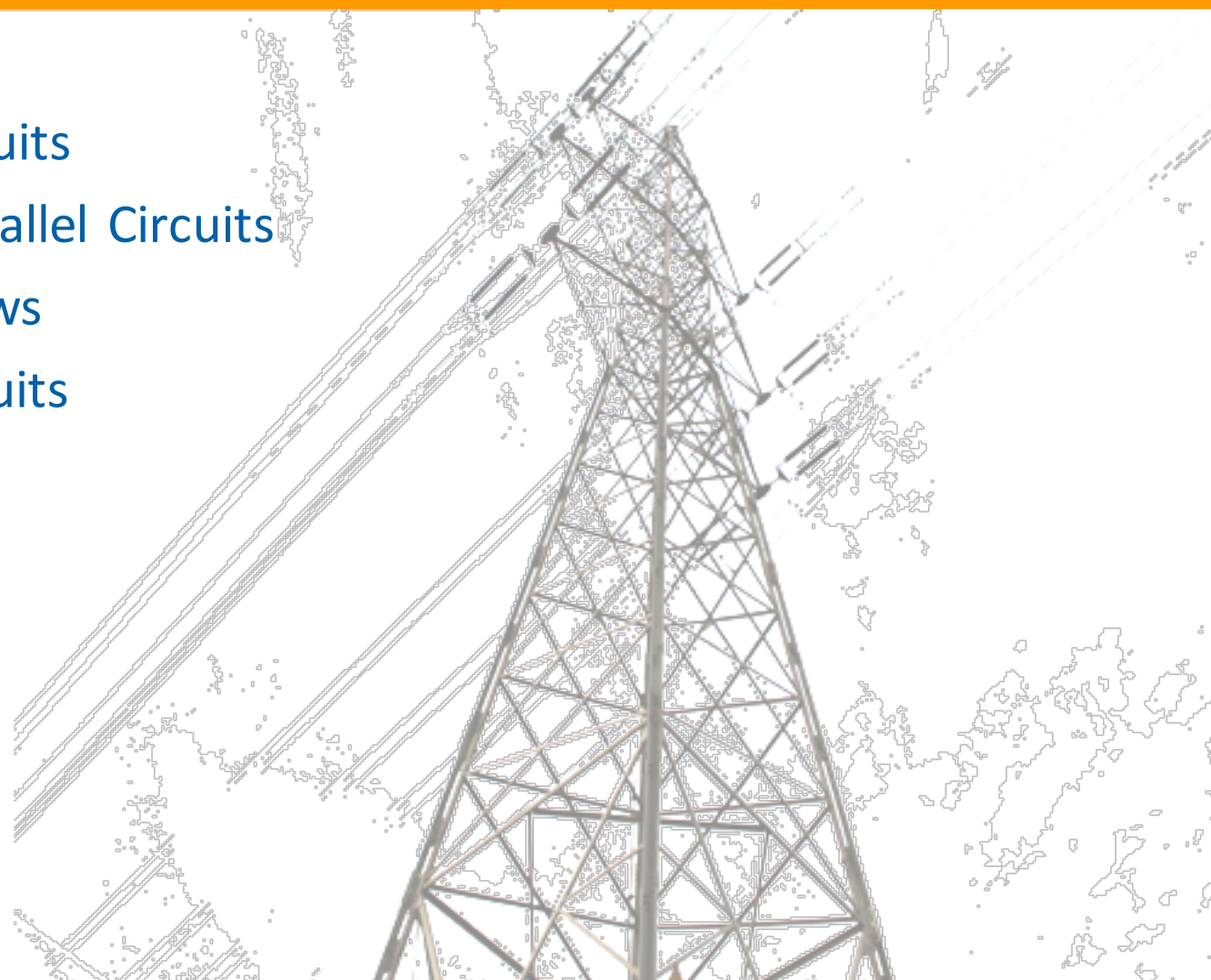
Chapter 02: Basic Circuit Analysis



2. Basic Circuit Analysis

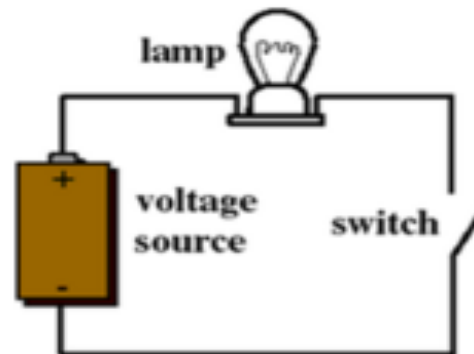
■ Contents

- 1) Modeling Circuits
- 2) Series and Parallel Circuits
- 3) Kirchhoff's Laws
- 4) Magnetic Circuits
- 5) Summary



2.1 Modeling Circuits (1)

- Electric circuit:
 - An interconnection of electric elements
 - Power source (battery, wall outlet, or generator)
 - Conductor:
 - Negligible or zero resistance
 - Drawn as lines, of arbitrary length and shape
 - Load in which the electric power is being utilized (e.g. light)



commons.wikimedia.org



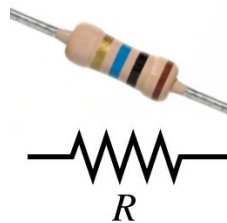
2.1 Modeling Circuits (2)

- Circuit elements:

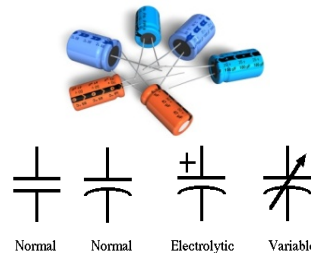
- Linear elements:

- Exhibit linear relationships between voltage and current or their rates of change

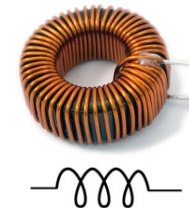
Resistors



Capacitors



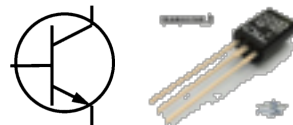
Inductors



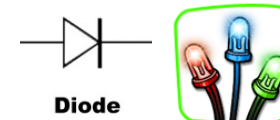
- Non linear elements

- Does not have a linear relationship between current and voltage

Transistors



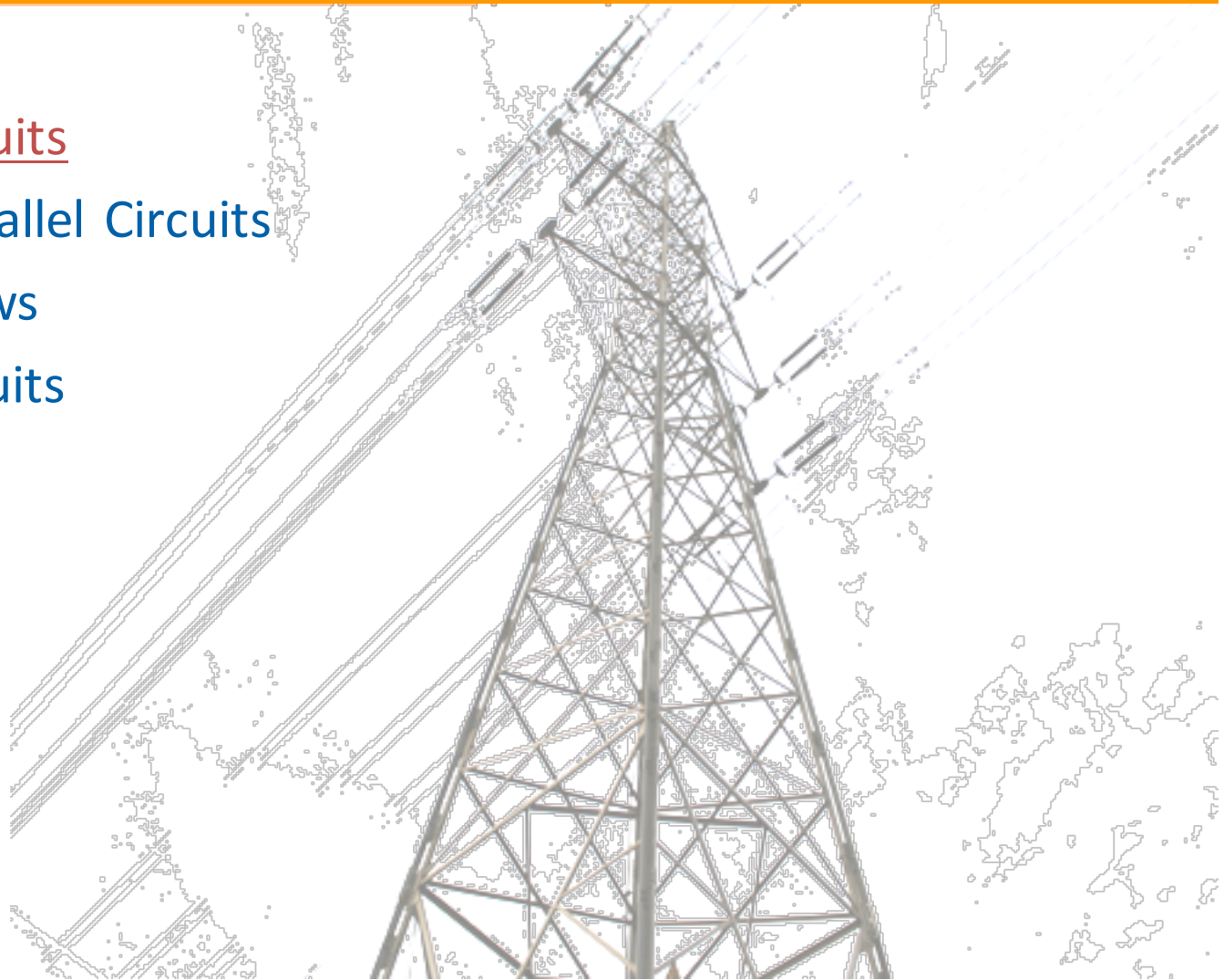
Diodes



2. Basic Circuit Analysis

■ Contents

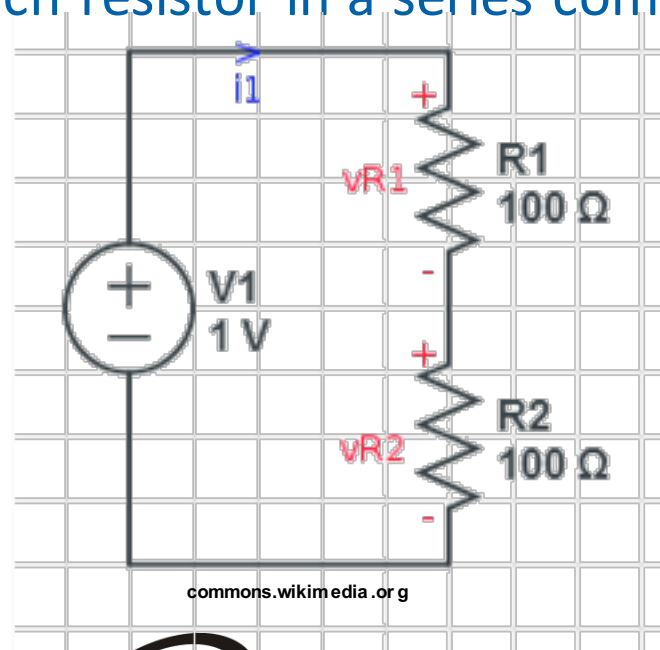
- 1) Modeling Circuits
- 2) Series and Parallel Circuits
- 3) Kirchhoff's Laws
- 4) Magnetic Circuits
- 5) Summary



2.2 Series and Parallel Circuits (1)

■ Resistance in Series

- Resistance of a series combination of resistors = The sum of their individual resistances
- A voltage drop proportional to each resistance will be across each resistor in a series combination



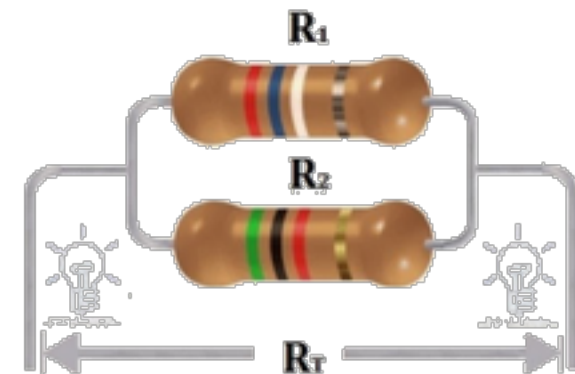
Combined (series) resistance
 $R = R_1 + R_2 = 200 \Omega$

2.2 Series and Parallel Circuits (2)

- Resistance in Parallel
 - Decreasing the overall resistance of the combination
 - “Alleviates” the current flow through each branch
 - Consider resistors in terms of **conductance** ($G=1/R$)
 - The total resistance will always be less than any of the individual resistances

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$$

Where **R** is the combined Resistance



Parallel Resistor Calculator
Copyright © www.electronicsbooksgang.com

2.2 Series and Parallel Circuits (3)

- Series vs. Parallel

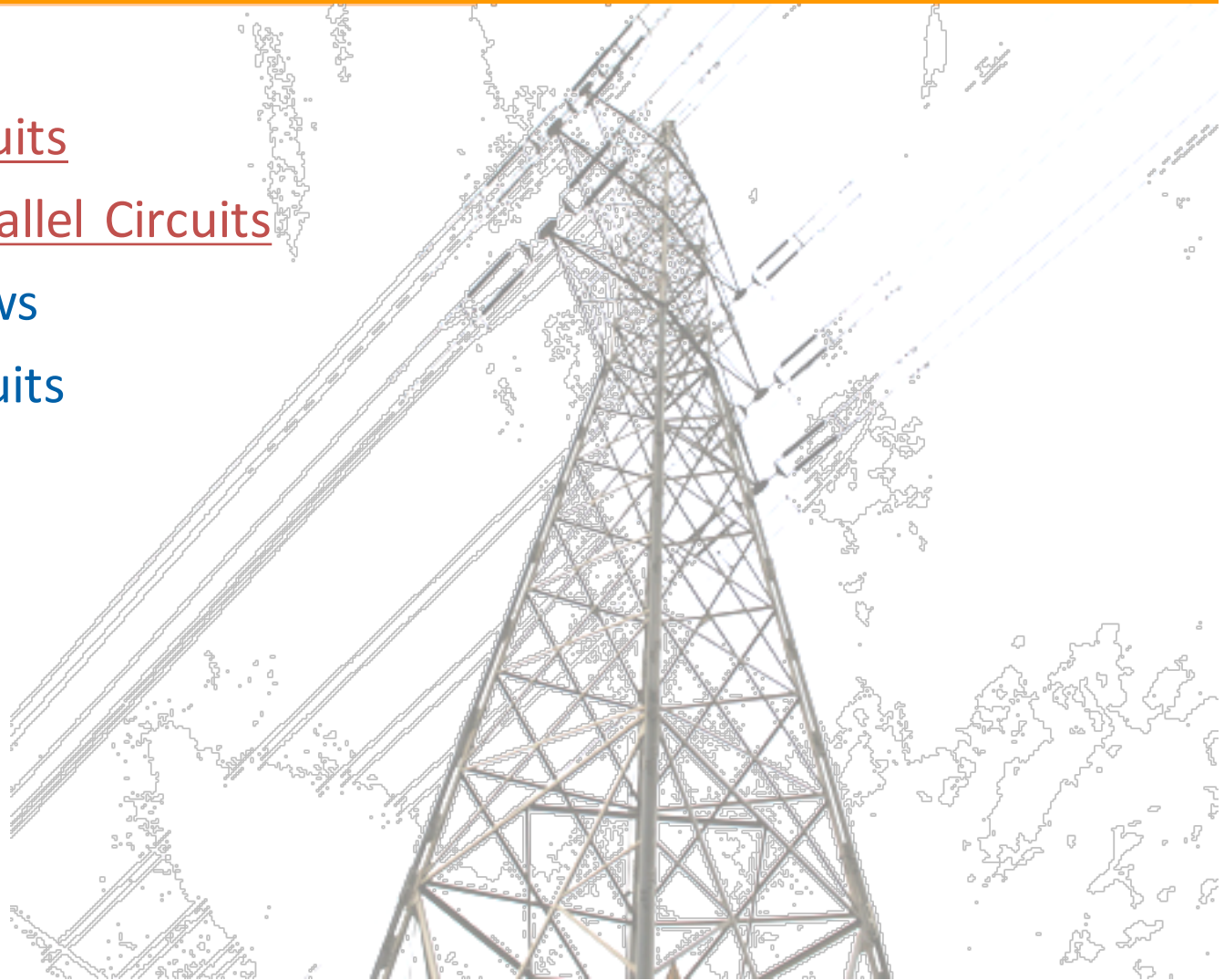
Resistance	Current	Voltage drops
Series	The same	Vary
Parallel	Vary	The same



2. Basic Circuit Analysis

■ Contents

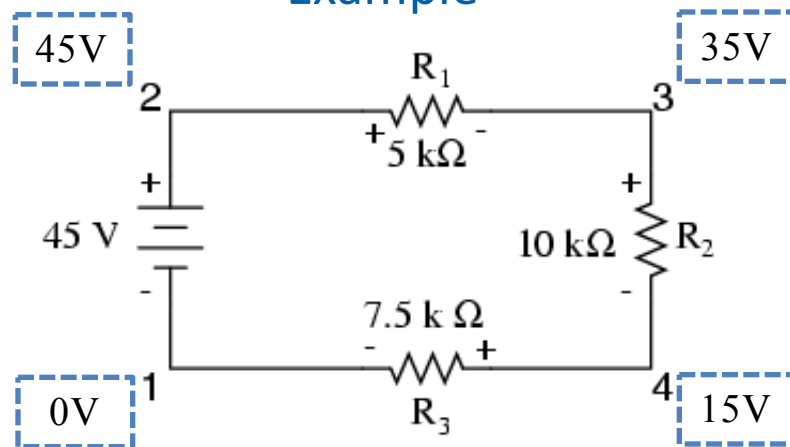
- 1) Modeling Circuits
- 2) Series and Parallel Circuits
- 3) Kirchhoff's Laws
- 4) Magnetic Circuits
- 5) Summary



2.3 Kirchhoff's Laws (1)

- Kirchhoff's Voltage Law (KVL)
 - The sum of voltages around any closed loop in a circuit must be zero
 - The polarity of the voltage is very important

■ Example



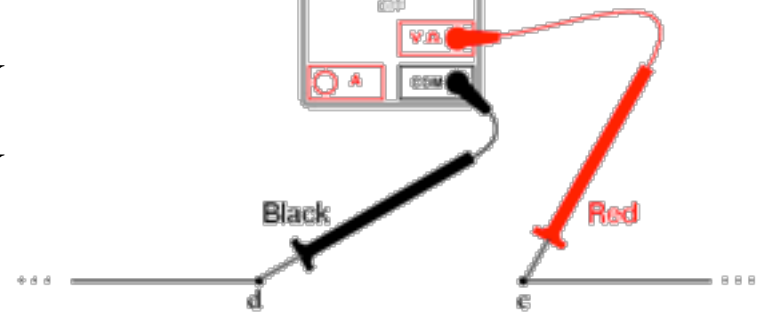
$$E_{2-1} = +45V$$

$$E_{3-2} = -10V$$

$$E_{4-3} = -20V$$

$$E_{1-4} = -15V$$

The meaning of E_{cd}



www.allaboutcircuits.com

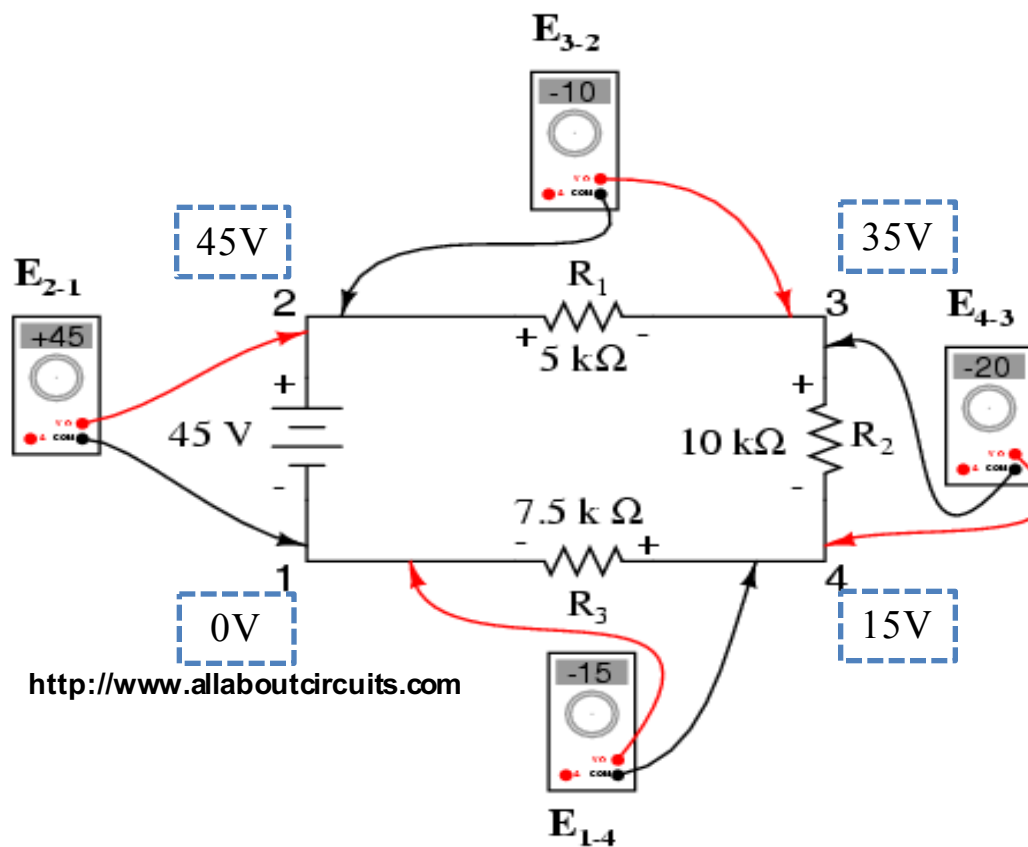
$$E_{2-1} = E_2 - E_1$$

The voltage at "2" in reference to "1"

2.3 Kirchhoff's Laws (2)

■ Kirchhoff's Voltage Law (KVL)

■ Example



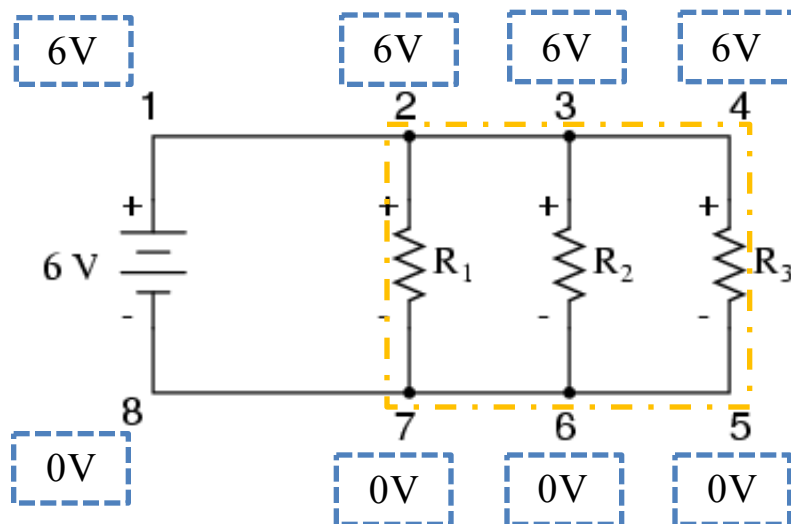
$$\begin{array}{ll}
 E_{2-1} = +45 \text{ V} & \text{voltage from point 2 to point 1} \\
 E_{3-2} = -10 \text{ V} & \text{voltage from point 3 to point 2} \\
 E_{4-3} = -20 \text{ V} & \text{voltage from point 4 to point 3} \\
 + E_{1-4} = -15 \text{ V} & \text{voltage from point 1 to point 4} \\
 \hline
 & 0 \text{ V}
 \end{array}$$

$$\begin{array}{ll}
 E_{2-3} = +10 \text{ V} & \text{voltage from point 2 to point 3} \\
 E_{1-2} = -45 \text{ V} & \text{voltage from point 1 to point 2} \\
 E_{4-1} = +15 \text{ V} & \text{voltage from point 4 to point 1} \\
 + E_{3-4} = +20 \text{ V} & \text{voltage from point 3 to point 4} \\
 \hline
 & 0 \text{ V}
 \end{array}$$

<http://www.allaboutcircuits.com>

2.3 Kirchhoff's Laws (3)

- Kirchhoff's Voltage Law (KVL)
 - Work for any circuit configuration, not just simple series
 - Example
 - Circuit (2,3,4,5,6,7) ; The branch (3,6) is not considered

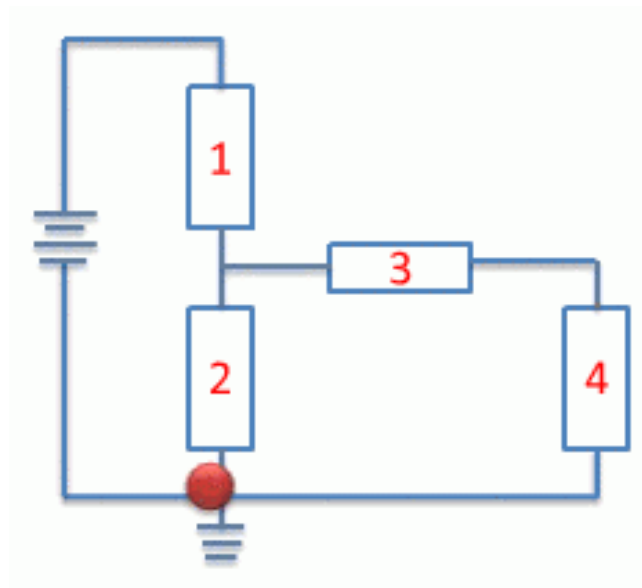


$E_{3-2} = 0 \text{ V}$	<i>voltage from point 3 to point 2</i>
$E_{4-3} = 0 \text{ V}$	<i>voltage from point 4 to point 3</i>
$E_{5-4} = -6 \text{ V}$	<i>voltage from point 5 to point 4</i>
$E_{6-5} = 0 \text{ V}$	<i>voltage from point 6 to point 5</i>
$E_{7-6} = 0 \text{ V}$	<i>voltage from point 7 to point 6</i>
$+ E_{2-7} = +6 \text{ V}$	<i>voltage from point 2 to point 7</i>
$E_{2-2} = 0 \text{ V}$	

<http://www.allaboutcircuits.com>

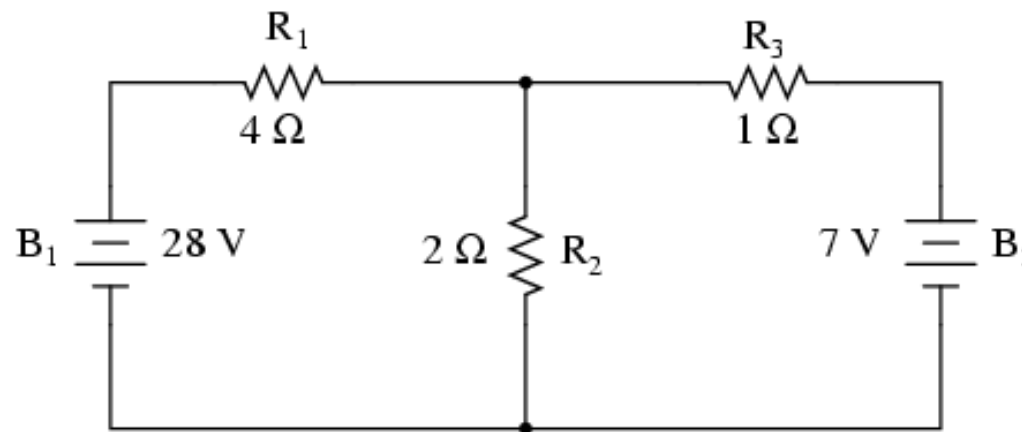
2.3 Kirchhoff's Laws (4)

- Kirchhoff's Current Law (KCL)
 - The currents entering and leaving any branch point or node in the circuit must add up to zero
 - Work for any circuit configuration, not just simple series



2.3 Kirchhoff's Laws (5)

- The Superposition Principle
 - For circuits with more than one voltage or current source
 - The combined effect—that is, the voltages and currents at various locations in the circuits—from the several sources is the same as the sum of individual effects
 - Example



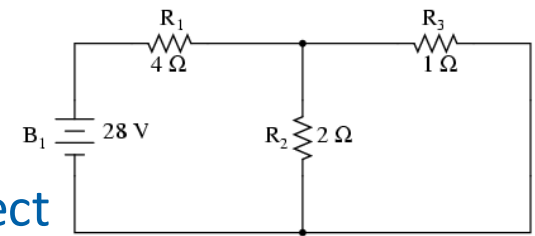
www.allaboutcircuits.com

2.3 Kirchhoff's Laws (6)

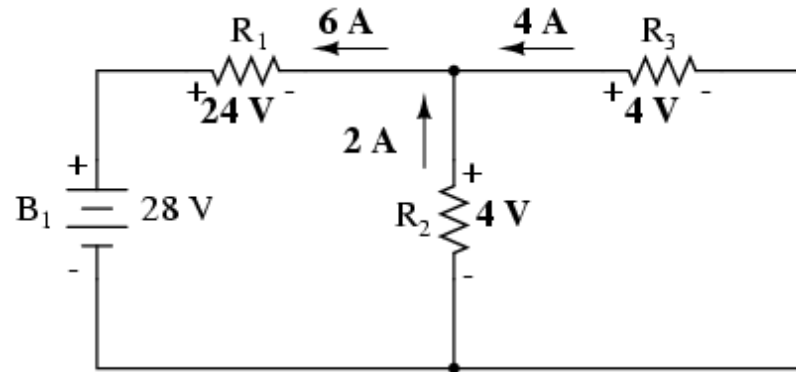
- The Superposition Principle

- Example

- The circuit with only the 28 volt battery in effect



	R_1	R_2	R_3	$R_2 // R_3$	$R_1 + R_2 // R_3$	
E	24	4	4	4	28	Volts
I	6	2	4	6	6	Amps
R	4	2	1	0,667	4,667	Ohms

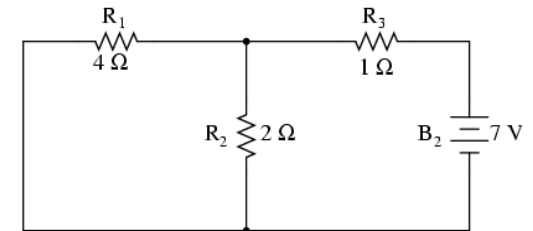


2.3 Kirchhoff's Laws (7)

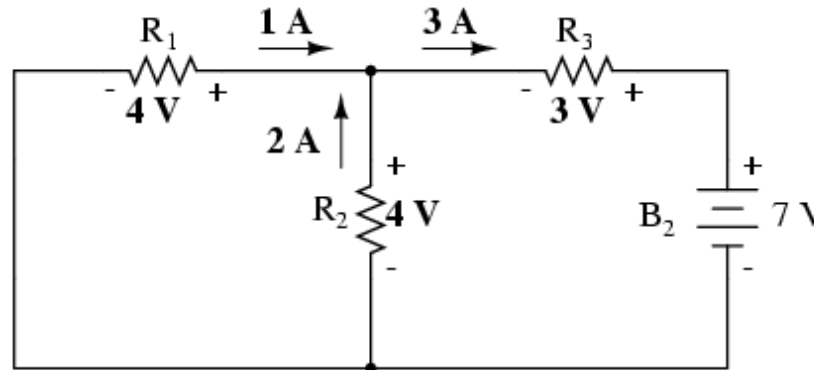
- The Superposition Principle

- Example

- The circuit with only the 7 volt battery in effect



	R_1	R_2	R_3	$R_2//R_3$	$R_1+R_2//R_3$	
E	4	4	3	4	7	Volts
I	1	2	3	3	3	Amps
R	4	2	1	1.333	2.333	Ohms

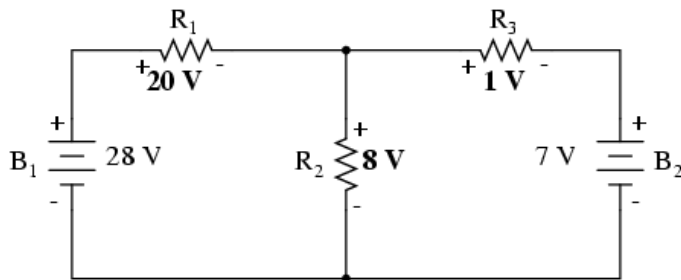





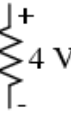
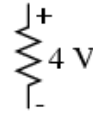
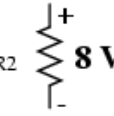
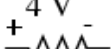
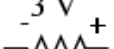

2.3 Kirchhoff's Laws (8)

- The Superposition Principle

- Example

- When superimposing these values of voltage



<i>With 28 V battery</i>	<i>With 7 V battery</i>	<i>With both batteries</i>
24 V  E_{R1}	4 V  E_{R1}	20 V  E_{R1} $24\text{ V} - 4\text{ V} = 20\text{ V}$
 E_{R2}	 E_{R2}	 E_{R2} $4\text{ V} + 4\text{ V} = 8\text{ V}$
4 V  E_{R3}	3 V  E_{R3}	1 V  E_{R3} $4\text{ V} - 3\text{ V} = 1\text{ V}$

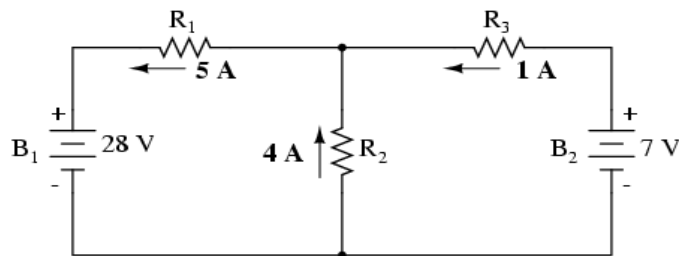




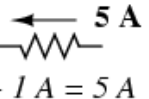
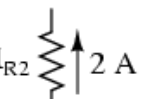
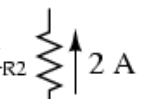
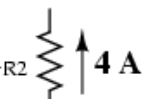
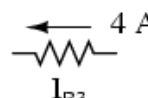
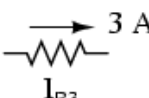
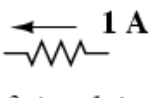
2.3 Kirchhoff's Laws (9)

- The Superposition Principle

- Example

- When superimposing these values of current



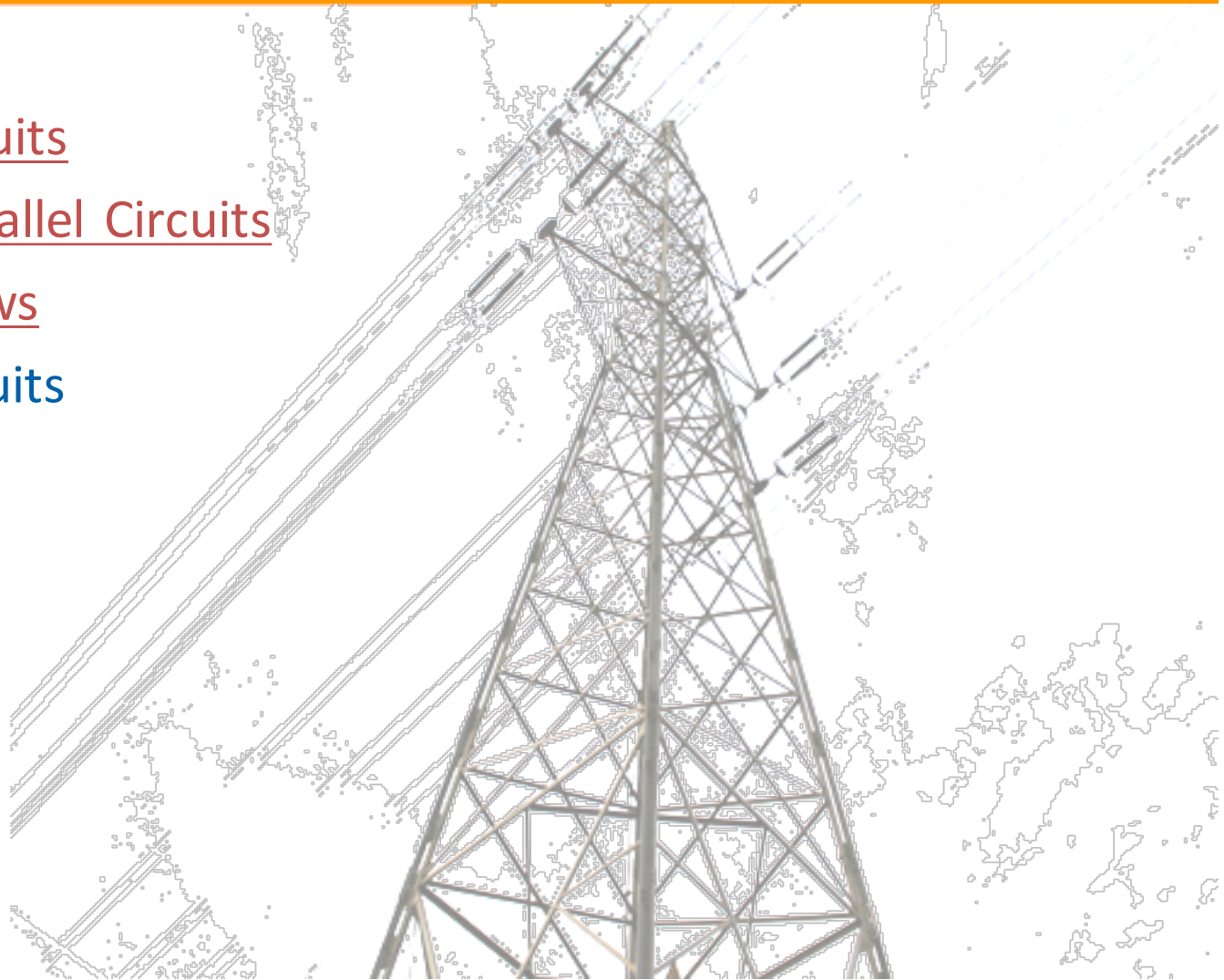
With 28 V battery	With 7 V battery	With both batteries
 I_{R1}	 I_{R1}	 I_{R1} $6 A - 1 A = 5 A$
 I_{R2}	 I_{R2}	 I_{R2} $2 A + 2 A = 4 A$
 I_{R3}	 I_{R3}	 I_{R3} $4 A - 3 A = 1 A$



2. Basic Circuit Analysis

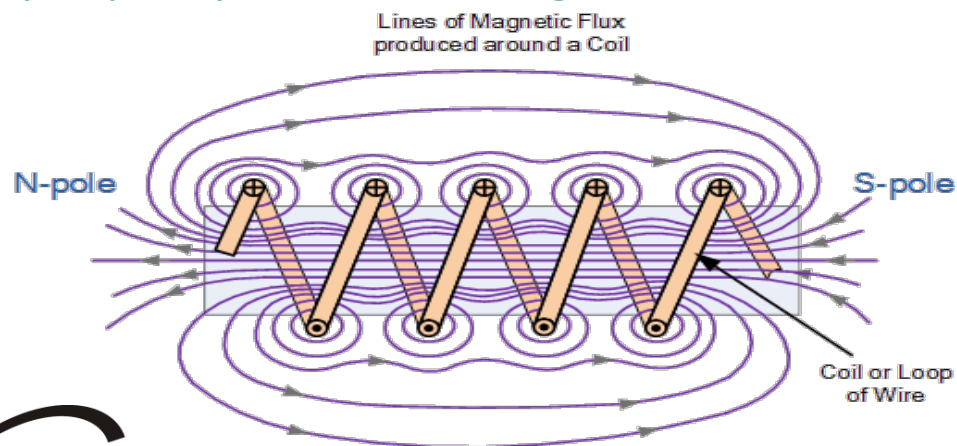
■ Contents

- 1) Modeling Circuits
- 2) Series and Parallel Circuits
- 3) Kirchhoff's Laws
- 4) Magnetic Circuits
- 5) Summary



2.4 Magnetic Circuits (1)

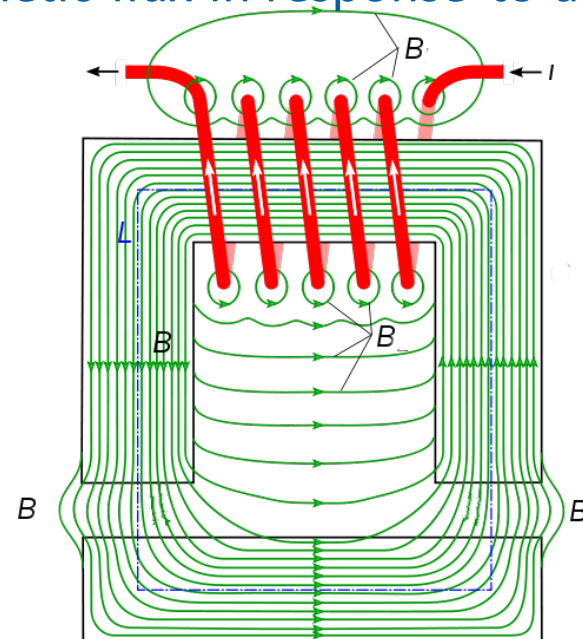
- The magnetic flux ϕ representation:
 - Two poles (north, south)
 - Always continuous
 - Flux lines neither begin nor end anywhere
 - Travel around in closed loops
 - Analogous to an electric current traveling through a closed circuit
 - Has the property that “what goes in must come out”



www.electronics-tutorials.ws

2.4 Magnetic Circuits (2)

- This analogy extends in such a way that we can speak of magnetic circuits that obey similar rules as electric circuits
 - Magnetic permeability μ
 - Analogous to electrical conductivity
 - Material's propensity to carry magnetic flux in response to an externally applied magnetic field
 - The permeability of a vacuum μ_0
 - Is not negligible
 - Called the *permeability constant*



commons.wikimedia.org

2.4 Magnetic Circuits (3)

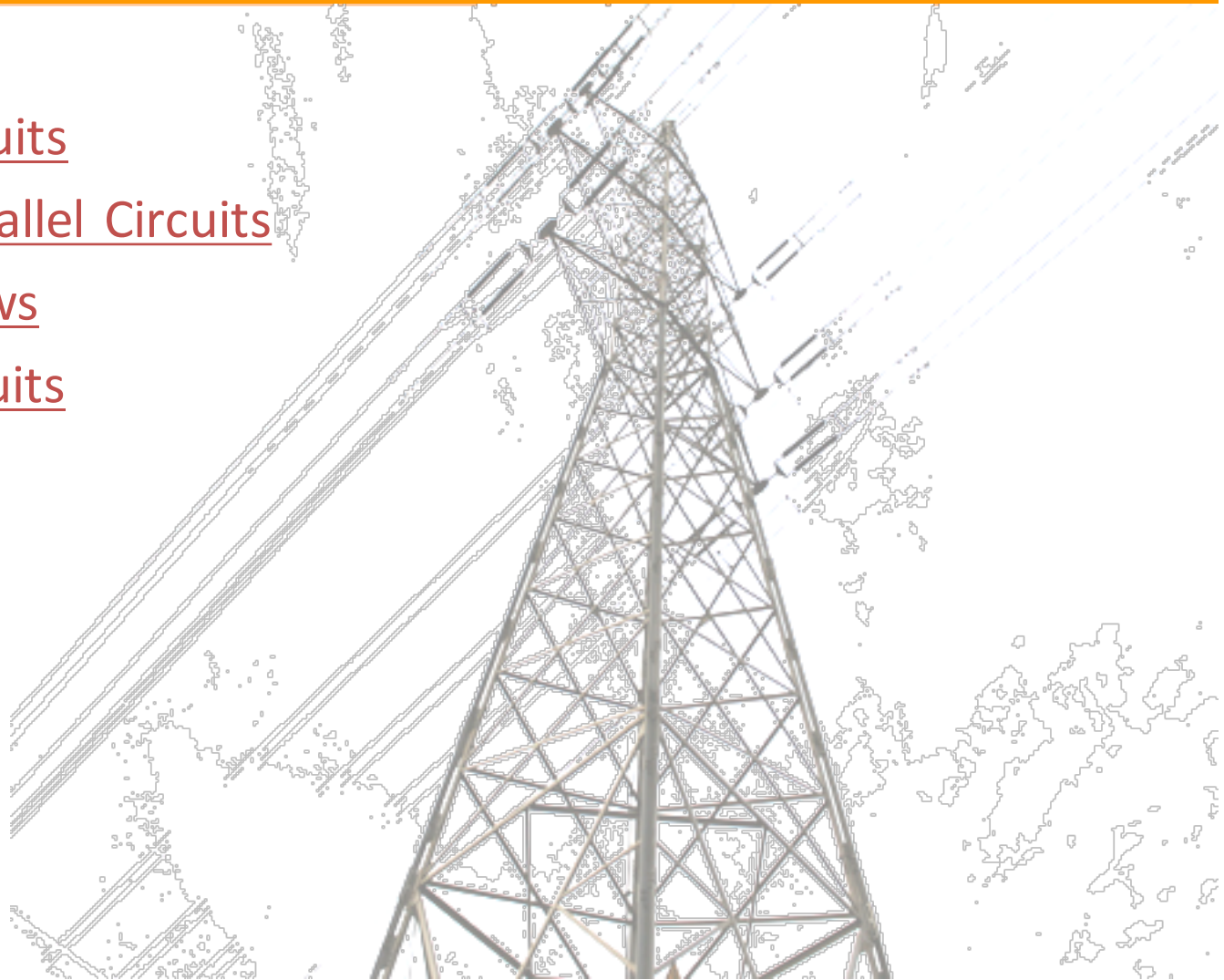
- This analogy extends in such a way that we can speak of magnetic circuits that obey similar rules as electric circuits
 - Reluctance R
 - Analogous to the electrical resistance
 - The relative difficulty or ease with which the magnetic flux may traverse an element within a magnetic circuit
 - The reluctance of a magnetic circuit element $R = \ell / \mu A$; ℓ : The length, A the cross-sectional area of the element



2. Basic Circuit Analysis

■ Contents

- 1) Modeling Circuits
- 2) Series and Parallel Circuits
- 3) Kirchhoff's Laws
- 4) Magnetic Circuits
- 5) Summary



2.5 Summary

- The current flow at any element in a DC circuit can be determined using KCL
- The voltage at any point in a DC circuit can be determined using KVL
- The equivalent resistance of series and parallel combinations of elements can be used to simplify DC circuit analysis
- Magnetic circuit is made up of one or more closed loop paths containing a magnetic flux



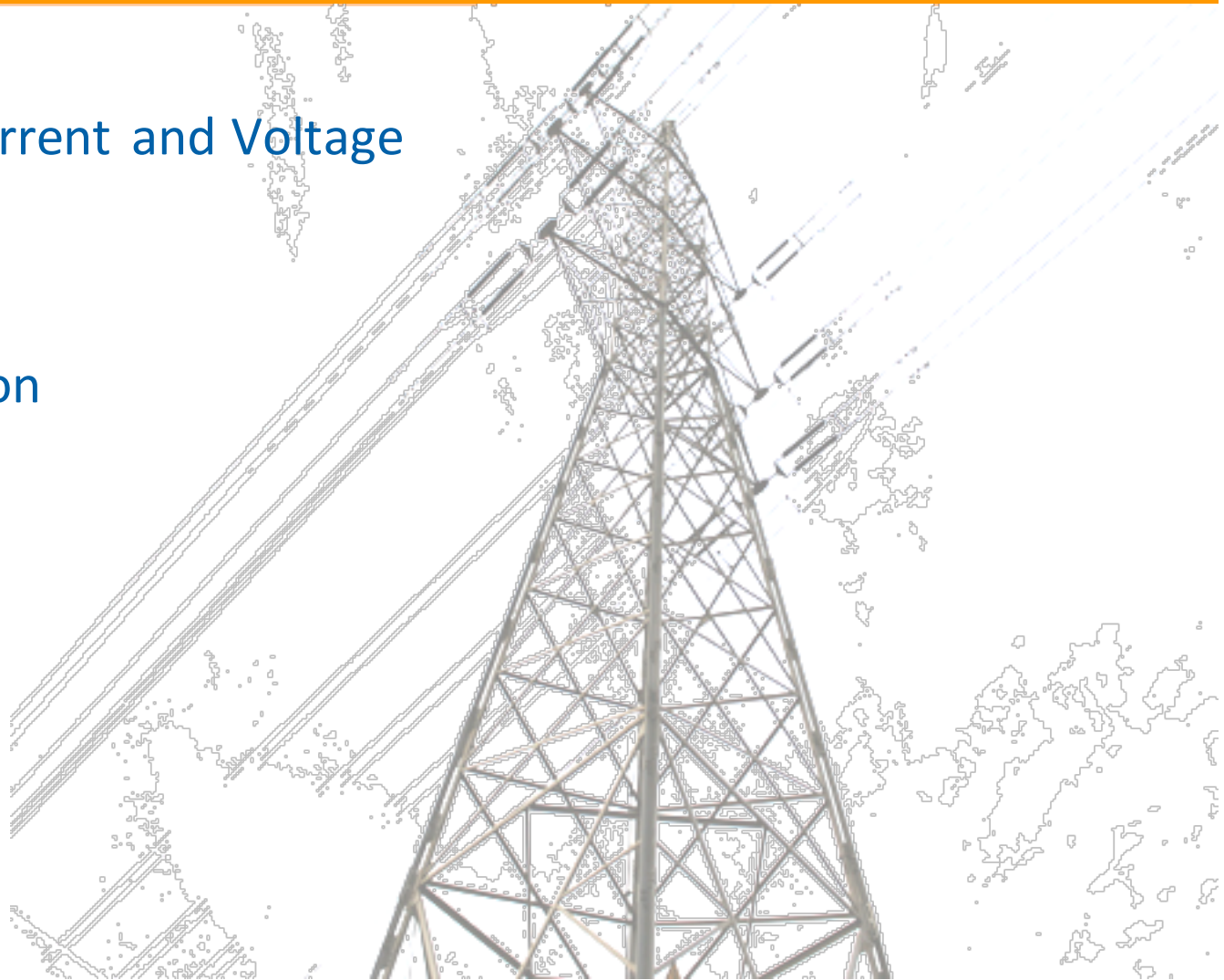
Electric Power System

Chapter 03: AC Power



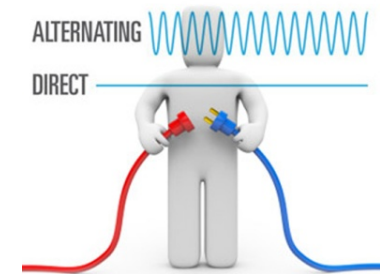
3. AC Power

- Contents
 - 1) Alternating Current and Voltage
 - 2) Reactance
 - 3) Power
 - 4) Phasor Notation
 - 5) Summary

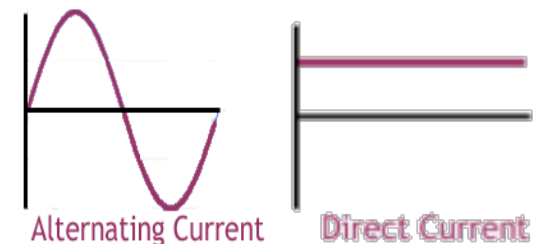


3.1 Alternating Current & Voltage (1)

- Direct current (d.c.) circuits
 - Polarity always remains the same
 - The current always flows in the same direction
- Alternating current (a.c.) circuits
 - The polarity reverses and oscillates very rapidly
 - a.c. frequency is measured by hertz (Hz) or cycles per second
 - In USA : 60 Hz
 - In Germany : 50 Hz
 - The direction of voltage and current are reversed, and reversed back again, (60,50) times every second



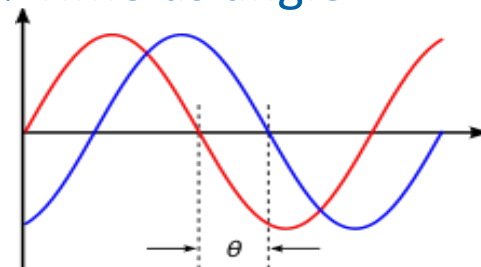
Source: abbaustralia.com.au



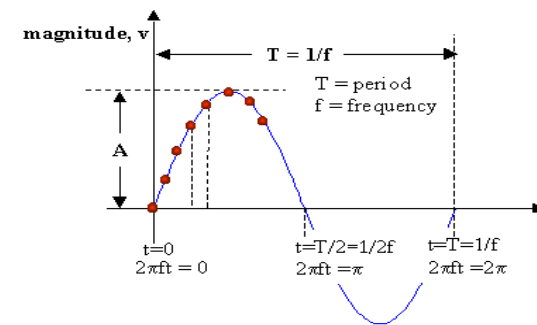
3.1 Alternating Current & Voltage (2)

■ Mathematical description

- Sinusoidal function is used to model the oscillation of voltage and current
- A sinusoidal function is specified by three parameters:
 - Amplitude A : The maximum value or height of the curve
 - Frequency F : The number of complete oscillations per unit time
 - Period T : Inverse of frequency; Duration of one complete cycle
 - Phase ϕ : Shift of the entire curve to the left or right
 - Angle ωt : Time as angle



Source: <http://commons.wikimedia.org>



3.1 Alternating Current & Voltage (3)

■ Mathematical description

■ Time as angle

- A fraction of the complete oscillation

- Unit: Radians (rad)

- Refer to arc described by an angle.

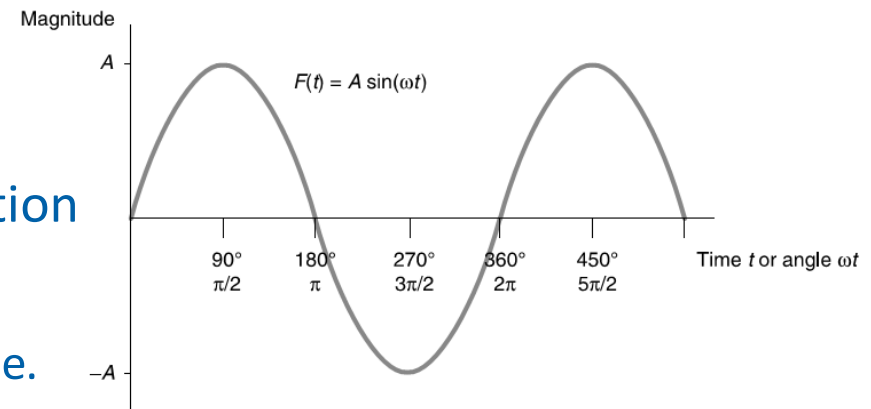
- π rad = one half cycle (180°)

- The period of which would be 1/60th of a second for 60 Hz, is taken to correspond to a full circle of 360 degrees.

■ Angular frequency ω

- radians per second

- $\omega = 60 \text{ cycles/s} \cdot 2\pi \text{ radians/cycle} = 377 \text{ rad/s}$



Copyright John Wiley & Sons



3.1 Alternating Current & Voltage (4)

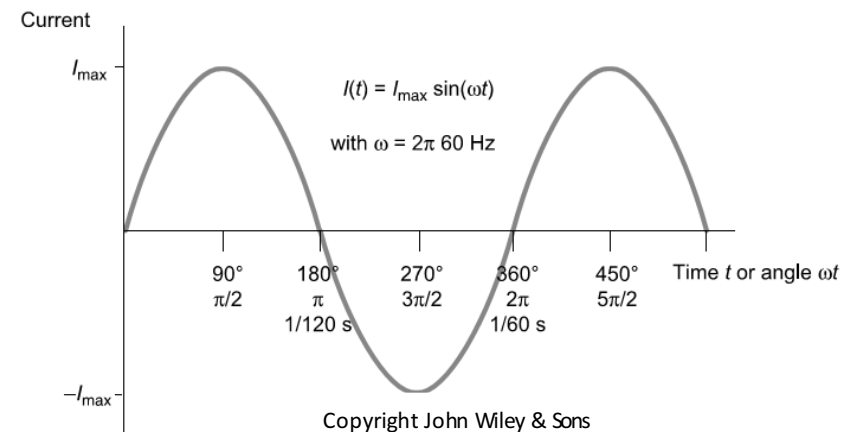
■ Mathematical description

■ An alternating current as a function of time

- $I(t) = I_{\max} \sin(\omega t + \phi_I)$
- I_{\max} : The maximum value or amplitude of the current
- $-I_{\max} \leq I(t) \leq +I_{\max}$
- ϕ_I : Phase shift

■ An alternating voltage as a function of time

- $V(t) = V_{\max} \sin(\omega t + \phi_V)$



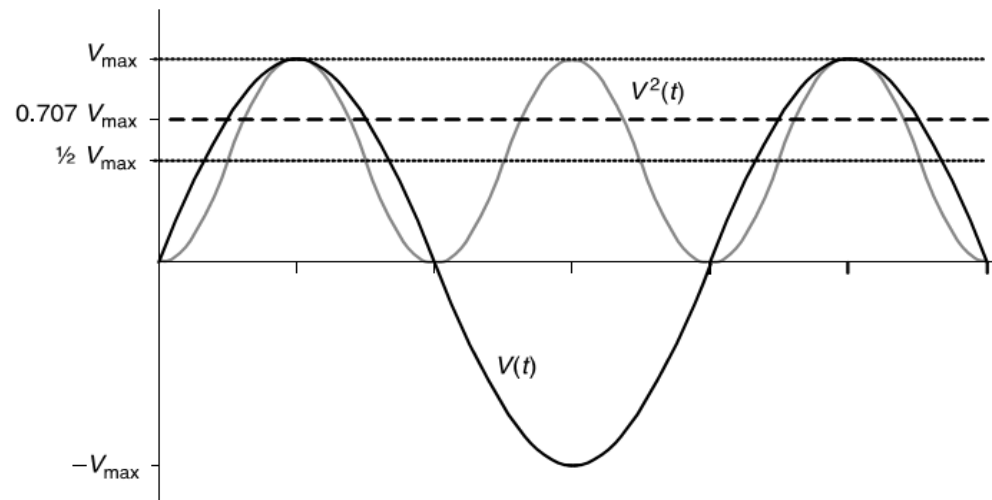
3.1 Alternating Current & Voltage (5)

- The *root mean square* (rms) Value
 - Determining the overall magnitude of a.c. Sinusoidal function
 - Indicate the amplitude of the sine wave
 - Most of the time, the actual value is much less than the maximum
 - Simple arithmetic average or mean
 - Zero, sine wave is positive half the time and negative the other half
 - Contains no useful information
 - Meaningful physical measure equivalent to a d.c. value
 - Calculation
 - i. Squaring the entire function
 - ii. Taking the average (mean)
 - iii. Taking the square root of this mean



3.1 Alternating Current & Voltage (6)

- The *root mean square* (rms) Value
 - The rms value of a sine curve = 0,707 the original amplitude
 - Utility voltages and currents are almost always given as rms values
 - 120 V is the rms voltage for a residential outlet

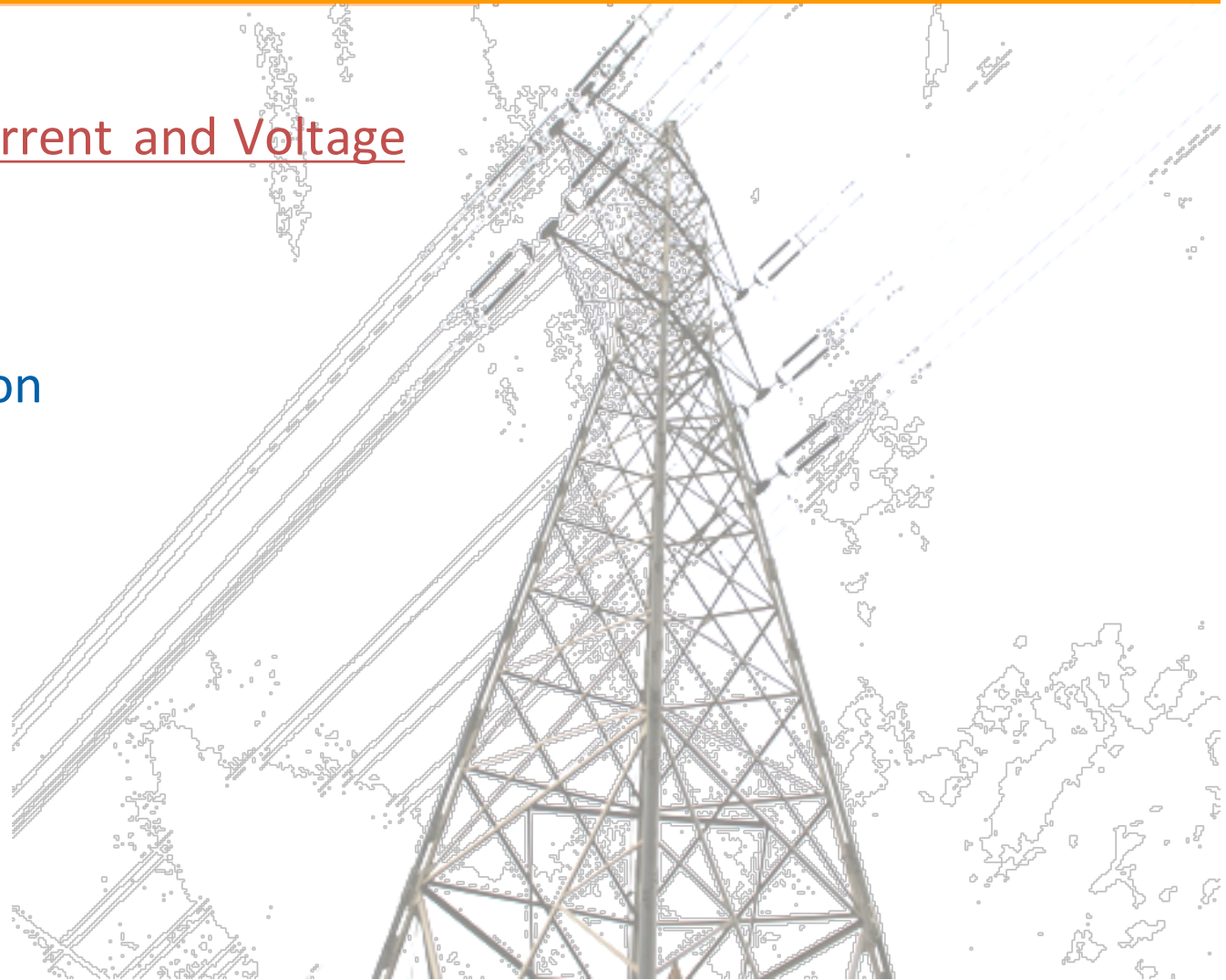


Copyright John Wiley & Sons

3. AC Power

■ Contents

- 1) Alternating Current and Voltage
- 2) Reactance
- 3) Power
- 4) Phasor Notation
- 5) Summary



3.2 Reactance (1)

- The property of a device to influence the relative timing of an alternating voltage and current.
- Depending on the frequency
- Related to the internal geometry of a device
- physically unrelated to the resistance
- Two types of reactance
 - Inductive reactance : based on inductance
 - Capacitive reactance : based on capacitance
- Impedance
 - Both resistance and reactance
- Units of impedance, reactance and resistance : Ohm Ω

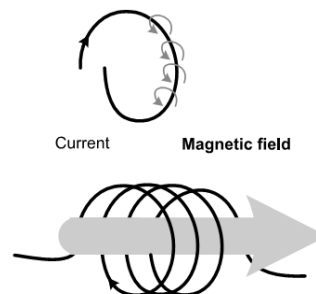


3.2 Reactance (2)

■ Inductance

■ Inductor or solenoid:

- Coil of wire
- Electric current produces a magnetic field around it
- Direction of the field : right-hand rule
- Wire is coiled up, it effectively amplifies this magnetic field
- Great in the center, pointing along the central axis the coil
- Electromagnet
 - Coil + Material of high magnetic permeability (iron)



Copyright John Wiley & Sons



3.2 Reactance (3)

■ Inductance

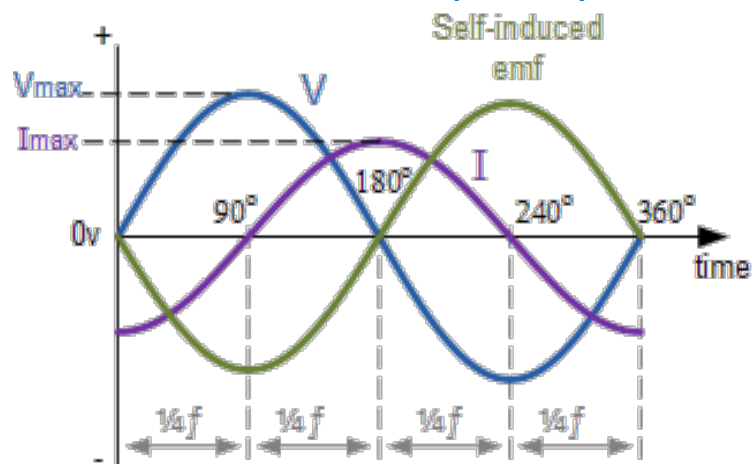
- **Principle** : Changing magnetic field in the vicinity of a conducting wire induces an electric current to flow through this wire
- In a.c. circuit
 - The current oscillates back and forth, so does the magnetic field
 - Other current induce in coil
 - Because of continuously changing of magnetic field
 - Proportional to the rate of change of the magnetic field
 - Exerts an opposing effect on the change in current flow that is responsible for producing the magnetic field
 - Lead to delay or phase shift of the alternating current with respect to the alternating voltage (*90° with ideal inductor*)



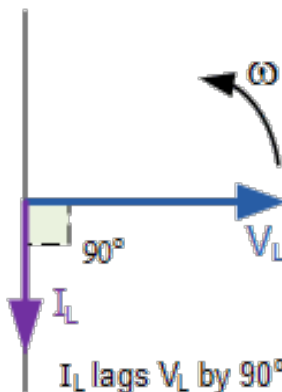
3.2 Reactance (4)

■ Inductance

- D.C. corresponds to case of zero Frequency
- Frequency of the applied alternating current is important
 - The higher the frequency, the greater the induced current
 - The lower frequency, the current pass through the inductor easier



Source: www.electronics-tutorials.ws



$$V(t) = V_{\max} \sin(\omega t)$$

$$I(t) = I_{\max} \sin(\omega t - \pi / 2)$$

Current lagging voltage by 90° with ideal inductor



3.2 Reactance (5)

■ Inductance

■ The inductive reactance X_L

■ $X_L = \omega L$

■ ω : Angular a.c. frequency

■ L : The inductance depends on

- The physical shape of the inductor
- Measured in units of henrys (H)

■ In the context of power systems

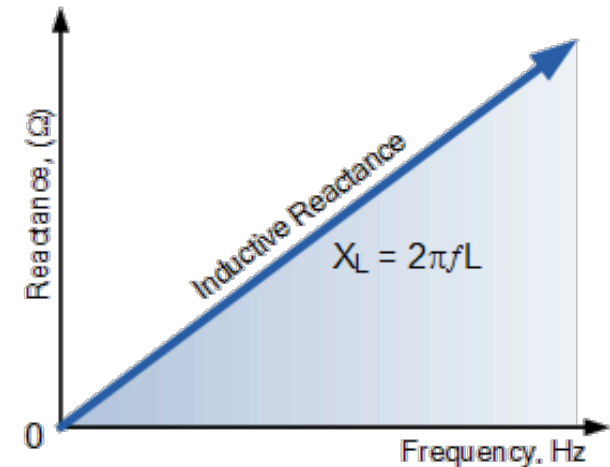
■ Frequency is always the same

■ Reactance is treated as if it were a constant property

■ Inductor as a thing that resists any changes in current

■ $V = L (dI/dt)$;

■ V : The voltage drop across an inductor



Source: www.electronics-tutorials.ws

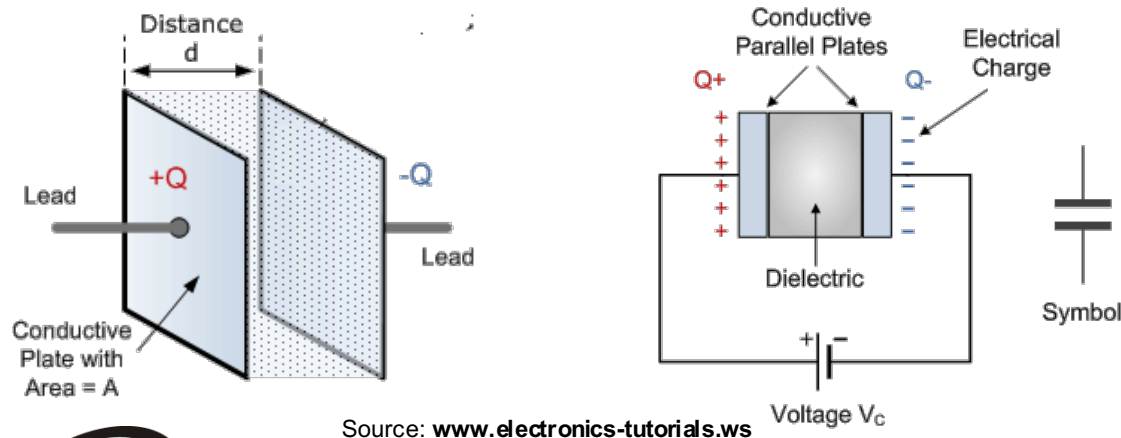


3.2 Reactance (6)

- Capacitance

- Capacitor

- Two conducting surfaces or plates that face each other and are separated by a small gap
 - These plates can carry an opposite electric charge
 - Electric field across the gap
 - Coaxial cables : capacitors with unideal shapes

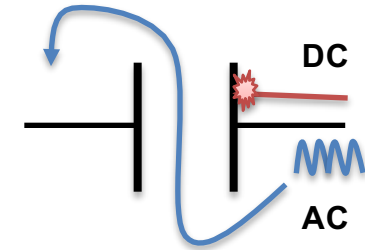


3.2 Reactance (7)

■ Capacitance

■ Capacitor

- In d.c. circuits
 - acts as an open circuit, and no current will flow
- In a.c. circuits
 - a.c. current can get across the capacitor
 - Impulses of electrons can be transmitted across the gap by means of the electric field
 - This transmission only remains effective as long as the voltage keeps changing
 - Current flow across a capacitor proportional to
 - The rate of change of the electric field
 - The rate of change of the voltage across the capacitor



3.2 Reactance (8)

■ Capacitance

■ Capacitance C

- Unit: farad (F)

- Increases with

 - The area of the plates

 - Decreasing separation between plates (except zero)

■ The capacitive reactance X_C

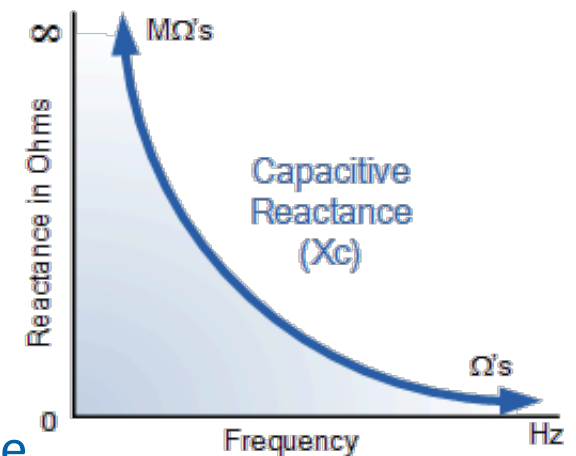
- $X_C = - 1/ \omega C$

- Increases with

 - Decreasing angular frequency ω

 - Decreasing capacitance

- Effect is opposite that of inductive reactance



Source: www.electronics-tutorials.ws



3.2 Reactance (9)

- Capacitance

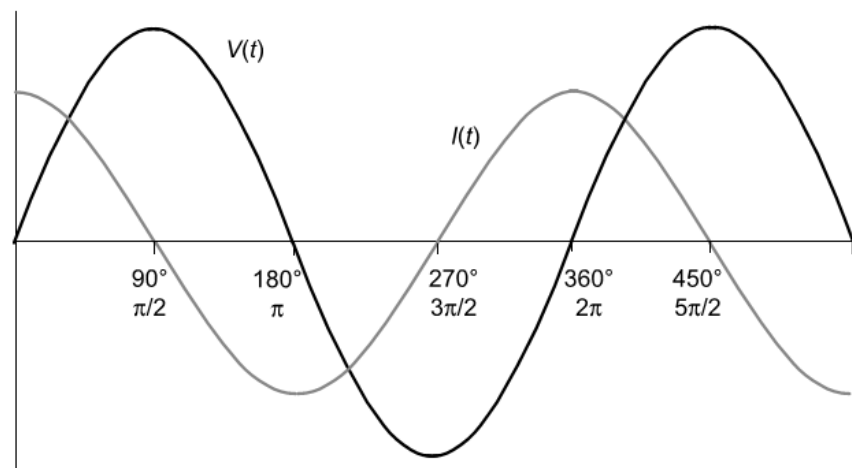
- The capacitive reactance

- Capacitor stores and releases energy during different parts of the cycle (as inductor does)
 - This energy resides in the electric field between the plates
 - The storage and release of energy by a capacitor occurs at time intervals opposite to those of an inductor in the same circuit
 - A capacitor and an inductor can therefore exchange energy between them in an alternating fashion
 - Capacitor as a thing that resists changes in voltage
 - $I = C (dV/dt)$
 - I : The current through the capacitor



3.2 Reactance (10)

- Capacitance
 - The capacitive reactance
 - Causes a phase shift between current and voltage
 - Opposite direction: The current lead the voltage by 90°



Copyright John Wiley & Sons

Current leading voltage by 90° with a pure capacitance



3.2 Reactance (11)

- Complex representation
 - Complex numbers
 - Concise way to mathematically represent two aspects of a physical system at the same time (e.g. impedance)
 - Contain
 - A real part
 - Ordinary number
 - Directly corresponds to a measurable physical quantity
 - An imaginary part
 - A sort of intangible quantity
 - When projected onto physical reality, represents oscillatory behavior
 - Multiple of the imaginary unit quantity $j = \sqrt{-1}$
 - The complex number $C = a + jb$



3.2 Reactance (12)

- Complex representation

 - Complex numbers

 - The complex number $C = a + jb$

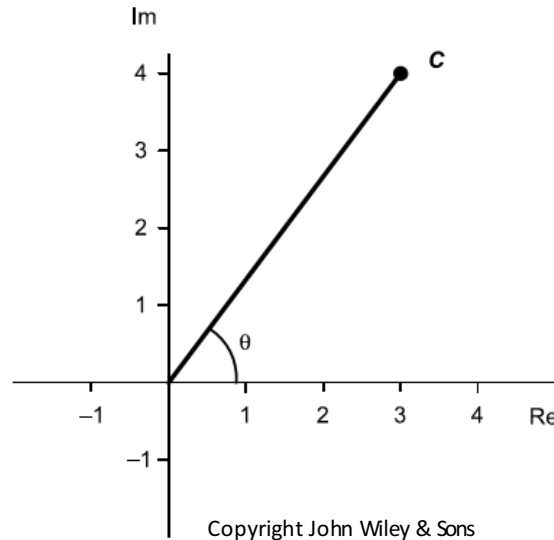
 - Refers to the point a units to the right of the origin and b units above

$$|C|^2 = a^2 + b^2$$

$$\sin \theta = b/C$$

$$\cos \theta = a/C$$

$$\tan \theta = b/a$$



$$C_1 + C_2 = (a_1 + a_2) + j(b_1 + b_2)$$

$$C_1 - C_2 = (a_1 - a_2) + j(b_1 - b_2)$$

$$C_1 \cdot C_2 = (a_1 \cdot b_1 - a_2 \cdot b_2) + j(a_1 \cdot b_2 + a_2 \cdot b_1)$$

The number $C = 3 + j4 =$



3.2 Reactance (13)

- Complex representation

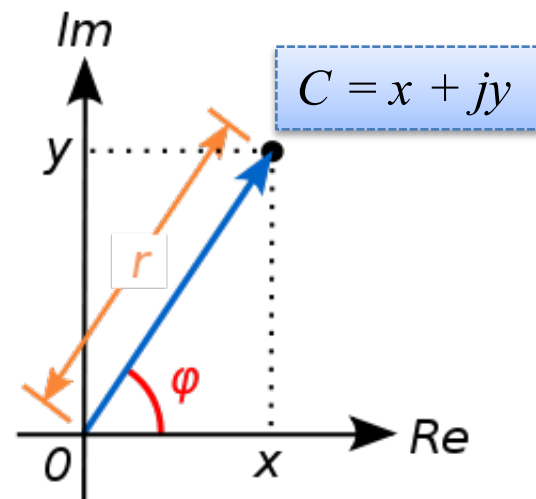
- Polar form

- $C = |C|(\cos \varphi + j \sin \varphi)$

- $C = |C|e^{i\varphi}$

- $C_1 \cdot C_2 = |C_1| \cdot |C_2| e^{i\varphi_1 + \varphi_2}$

- $C_1 / C_2 = |C_1| / |C_2| e^{i\varphi_1 - \varphi_2}$



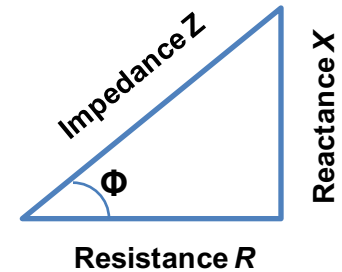
Source: <http://en.wikipedia.org>



3.2 Reactance (14)

■ Impedance Z

- Combination of reactance X and resistance R
- Vector sum of R and X in the complex plane
 - $Z = R + jX$
- Any device found in an electric power system has it
- Combined according to the same rules for series and parallel
- The angle Φ
 - Shift between current and voltage
 - Positive when reactance is inductive
 - Negative when reactance is capacitive



3.2 Reactance (15)

■ Impedance Z

■ Example

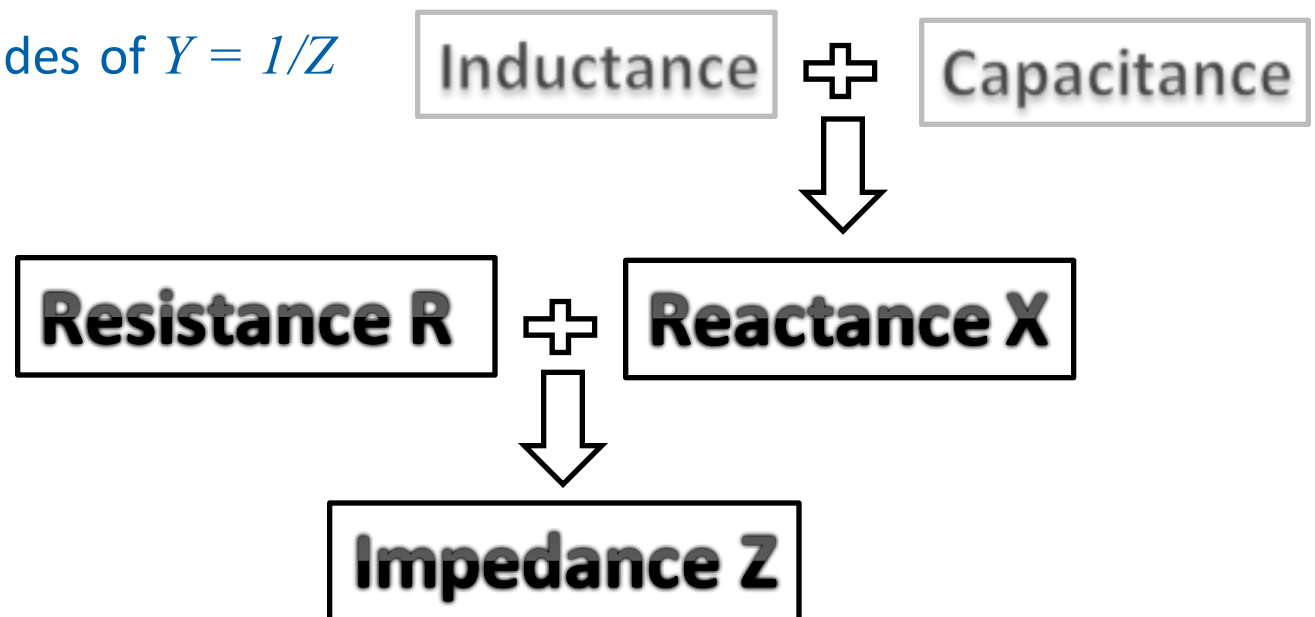
■ *An electrical device contains a resistance, an inductance, and a capacitance, all connected in series. Their values are $R=1\Omega$, $L=0,01H$ and $C=0,001F$, respectively. At an a.c. frequency of 60 cycles, what is the impedance of the device?*

- The inductive reactance $X_L = \omega L = 377 \text{ rad/s} \cdot 0,01H = 3,77 \Omega$
- The capacitive reactance $X_C = -1/\omega C = -1/377 \text{ rad/s} \cdot 0,001F = -2,65 \Omega$
- The reactances are in series
 - $X = X_L + X_C = 3,77 - 2,65 = 1,12 \Omega$
- The impedance $Z = 1 \Omega + j 1,12 \Omega$
 - In the polar form $|Z| = 1,5 \Omega$, $\varphi = 48,2^\circ$
 - This impedance would simply be referred to as $1,5 \Omega$



3.2 Reactance (16)

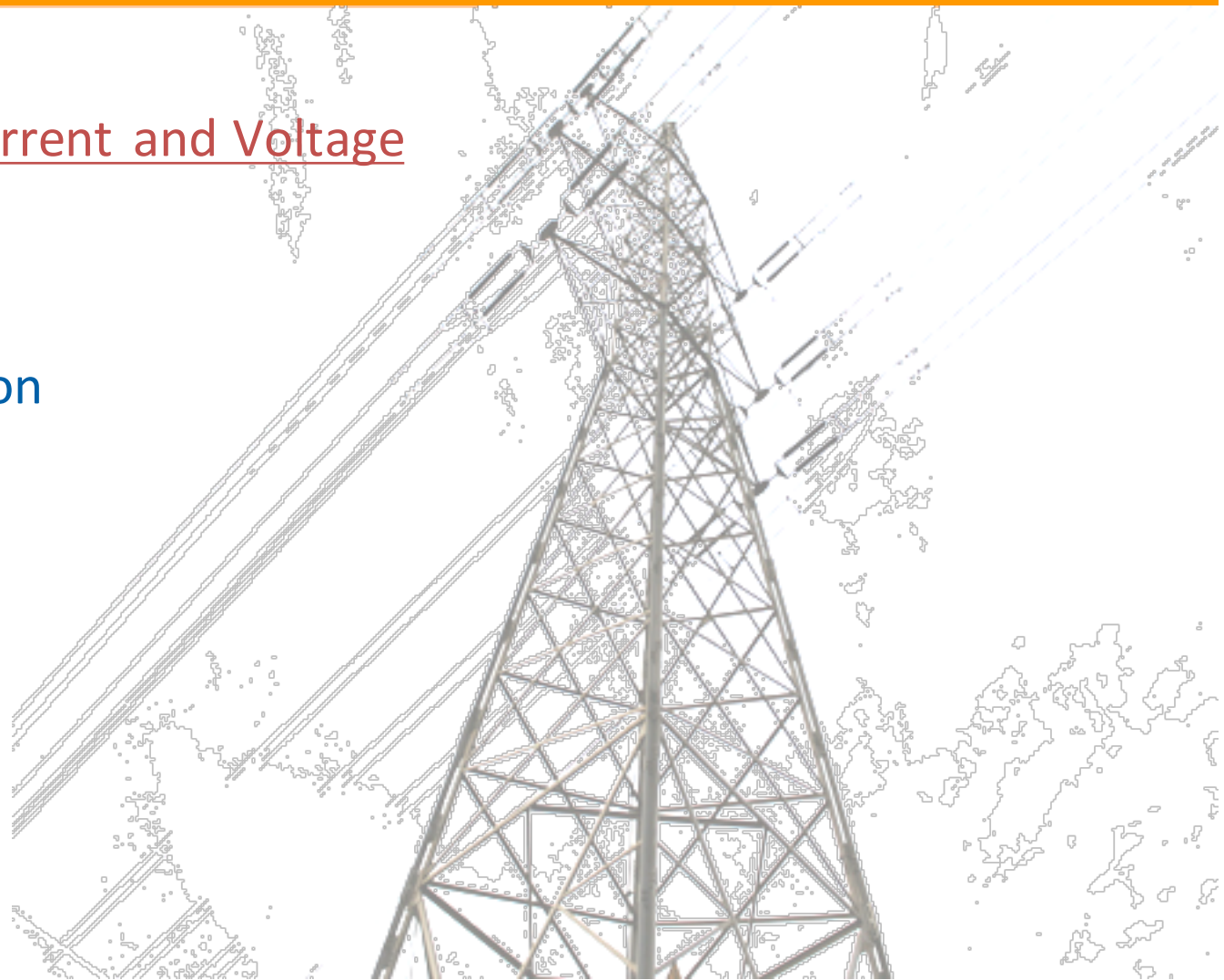
- Admittance Y
 - Inverse of the complex impedance $Y=1/Z$
 - Combination of conductance G and susceptance B (the inverse of X)
 - $Y = G + j B$
 - Y, Z are complex (vector) quantities
 - The magnitudes of $Y = 1/Z$
 - $G = R/Z^2$
 - $B = - X/Z^2$



3. AC Power

■ Contents

- 1) Alternating Current and Voltage
- 2) Reactance
- 3) Power
- 4) Phasor Notation
- 5) Summary



3.3 Power (1)

- Definition of Electric Power
 - Measure of energy per unit time
 - Rate of energy consumption or production
 - The units for power are generally Watt(W)
 - P : Power dissipated by a circuit element
 - $P = I^2R = IV$; R : resistance, I : current, V : voltage
 - Converted to heat
 - Maybe part of the appliance's intended function
 - Considered as a loss (transmission lines)



3.3 Power (2)

- Definition of Electric Power
 - In transmission lines two types of power
 - The dissipated power : “ I^2R losses”
 - $P = IV$: less convenient for two reasons
 - Power line as not just a resistive wire; has a significant reactance
 - Multiplying I and V will be more complicated due to phase shift
 - Which V to use?
 - line drop : (Voltage difference between two ends)
 - A few percent of the line voltage
 - Not known precisely
 - Line voltage : specifies the line voltage with respect to ground
 - Power transmitted by the line
 - $P = IV = \text{Charge/Time} \cdot \text{Energy/Charge} = \text{Energy/Time}$
 - V : The line voltage (line is considered as extended terminals)



3.3 Power (3)

■ Complex Power

■ I and V vary in time :

■ Instantaneous conditions $P(t) = I(t)V(t)$

■ Need an expression for power as averaged over entire cycles

■ Purely resistive load : Voltage and current are in phase

$$\blacksquare P_{ave} = I_{rms} V_{rms}$$

■ Load with reactance

■ The relative timing of voltage and current has been shifted

■ The average power is clearly less than it was in the resistive case

$$\blacksquare P_{ave} = I_{rms} V_{rms} \cos \phi = \frac{1}{2} I_{max} V_{max} \cos \phi; I_{rms} = \frac{1}{\sqrt{2}} I_{max} \ \& \ V_{rms} = \frac{1}{\sqrt{2}} V_{max}$$

■ Power factor p.f. = $\cos \phi$

■ Average power (*Wirkleistung*) : (Watt) Real power, active power

■ Apparent power S (*Scheinleistung*) : (volt-amperes VA)

$$\blacksquare \text{Regardless of phase shift} = I_{rms} V_{rms}$$



3.3 Power (4)

■ Complex Power

■ I and V vary in time :

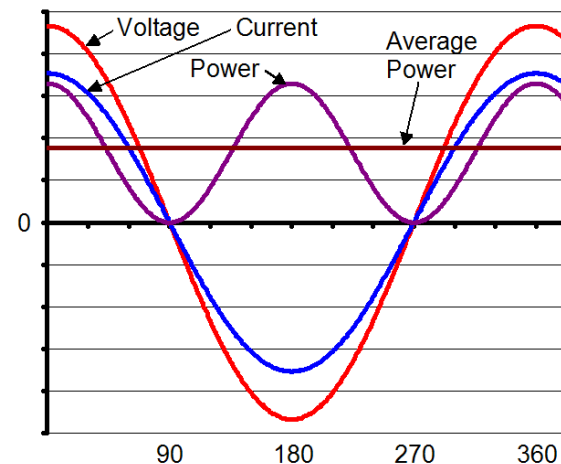
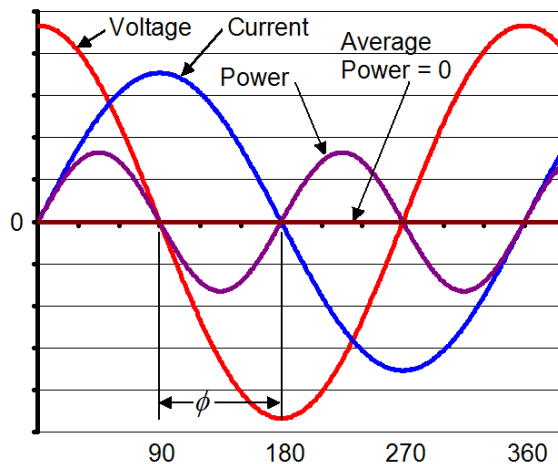
■ Need an expression for power as averaged over entire cycles

■ Purely resistive load : Voltage and current are in phase

$$P_{ave} = I_{rms} V_{rms}$$

■ Load with reactance

$$P_{ave} = I_{rms} V_{rms} \cos \phi$$



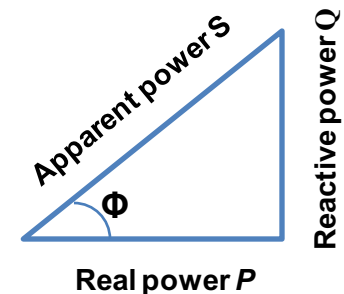
Source: <http://slideplayer.us>



3.3 Power (5)

■ Complex Power

- Average power (*Wirkleistung*) (Watt **W**): real power, active power
 - The power actually transmitted or consumed by the load
- Apparent power S (*Scheinleistung*) (volt-amperes **VA**):
 - The product of current and voltage, regardless of their phase shift
- Reactive power Q (*Blindleistung*) (**VAR** volt-ampere reactive)
 - Oscillates back and forth through the lines
 - Not getting dissipated
 - Exchanged between electric-magnetic fields
 - $Q = I_{rms} V_{rms} \sin \phi$
 - Inductive loads “consume” reactive power,
 - Capacitive loads “supply” reactive power



3.3 Power (6)

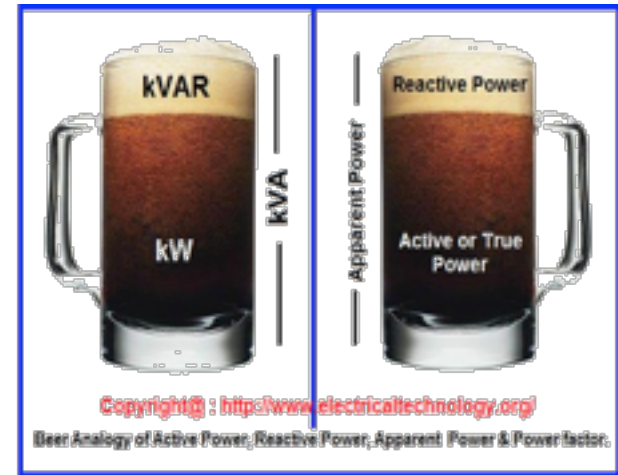
- The Significance of Reactive Power

- The cholesterol of power lines

- Doing no useful work
 - Causes the utility to incur costs
 - Additional losses
 - Greater capacity requirements

- Reactive losses (*VAR* volt-ampere reactive)

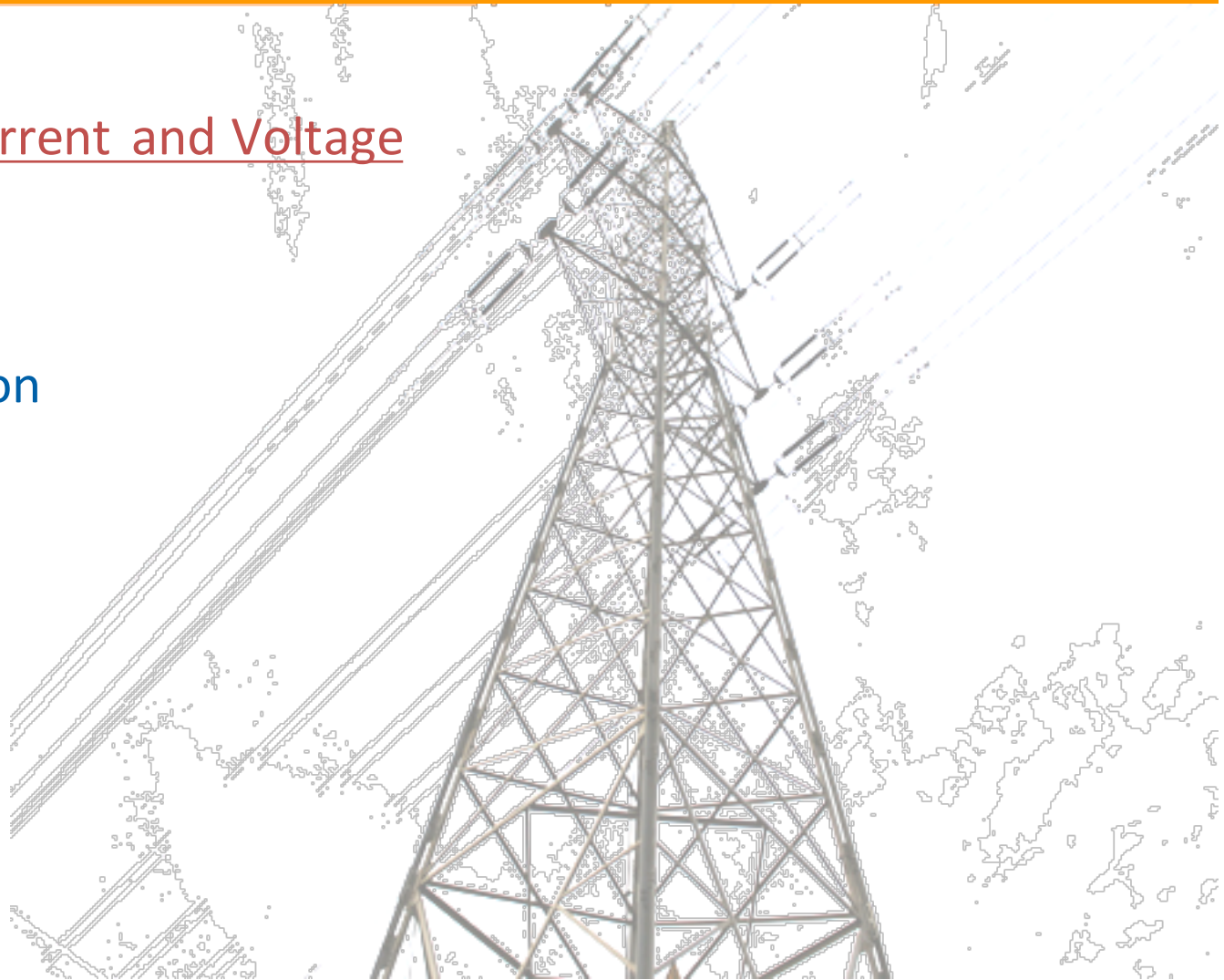
- The difference between the reactive power supplied by generators and that consumed by loads
 - Important in the context of planning and scheduling reactive power generation



3. AC Power

■ Contents

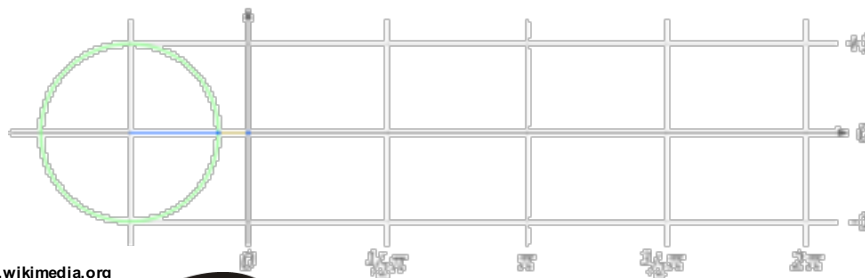
- 1) Alternating Current and Voltage
- 2) Reactance
- 3) Power
- 4) Phasor Notation
- 5) Summary



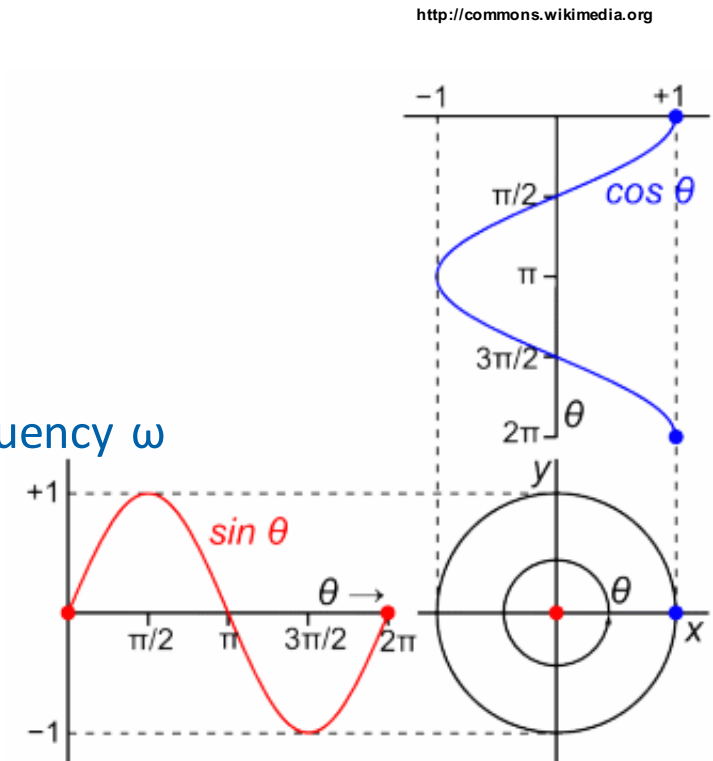
3.4 Phasor Notation (1)

■ Phasors as Graphics

- A way to characterize a sine wave, specifying its magnitude
- Map the sine wave onto a circle (*phasor diagram*)
 - The vertical axis : Physical quantity
 - The horizontal axis : Time
 - The voltage as an arrow (*voltage phasor*)
 - Constant length : Maximum or *rms* value
 - Spins around the circle counterclockwise
 - Spinning speed is constant : Angular frequency ω



Source: <http://commons.wikimedia.org>



3.4 Phasor Notation (2)

■ Phasors as Exponentials

■ The voltage phasor

■ $Ve^{j\phi}$

- V : The magnitude of the voltage
- ϕ : The voltage phase angle

■ $V\angle\phi$

- \angle : Symbol means “angle.”

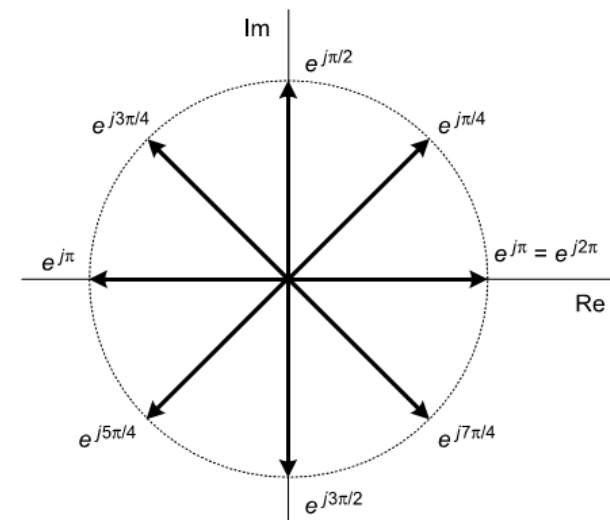
■ The current phasor

■ $Ie^{j\phi}$

- I : The magnitude of the current
- ϕ : The current phase angle

■ $I\angle\phi$

- \angle : Symbol means “angle.”



Copyright John Wiley & Sons



3.4 Phasor Notation (3)

■ Phasors as Graphics

■ The impedance $\mathbf{Z} = Z \angle \theta$

- θ : Means a ratio of components ,not a time
- θ : Physically determines the time lag of current with respect to voltage

■ $\mathbf{V} = \mathbf{I}\mathbf{Z}$

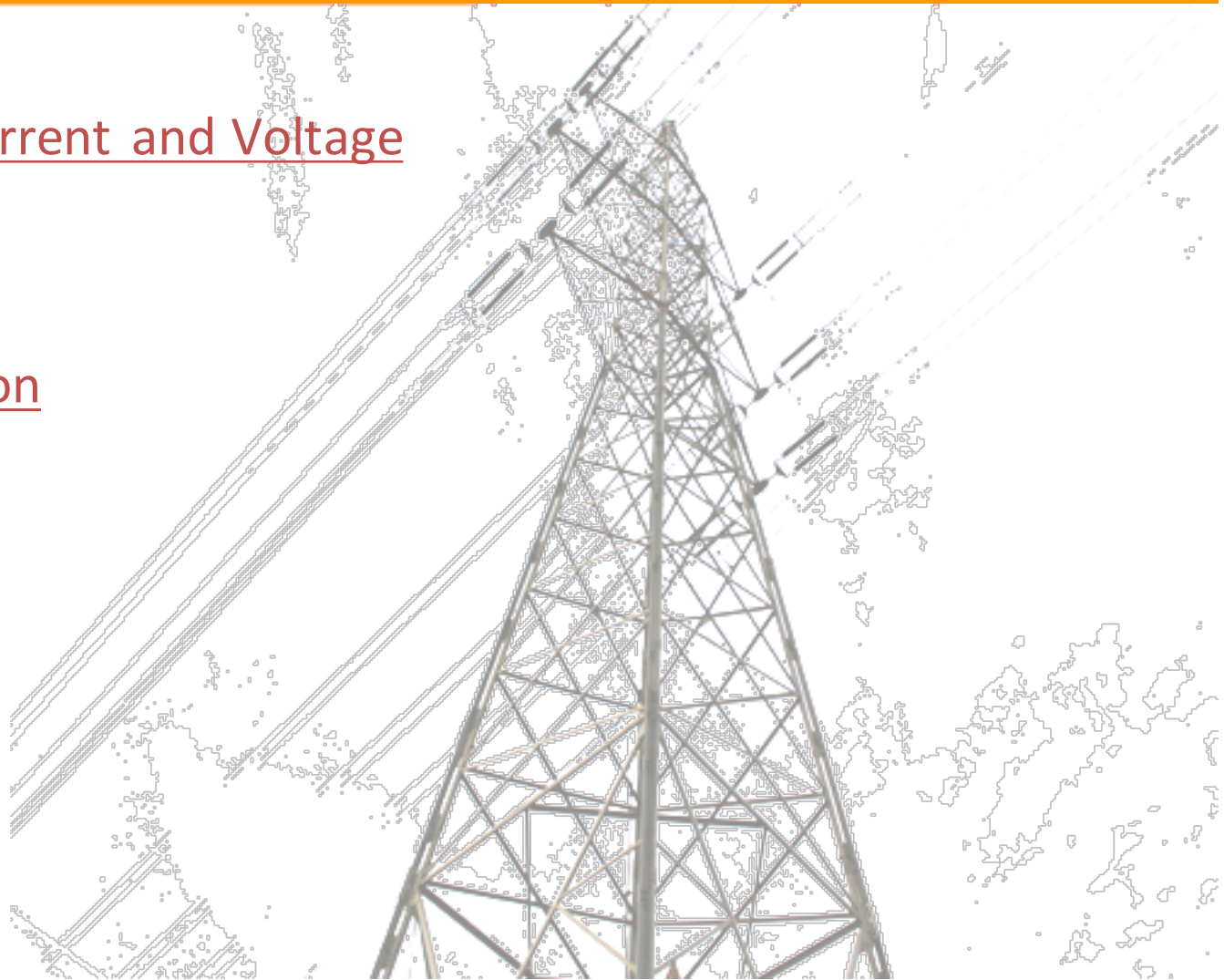
- $V \angle 0^\circ = I \angle -\theta \cdot Z \angle \theta$
- $V e^{j \theta_v} = I e^{j \theta_I} Z e^{j \theta_Z} = I Z e^{j (\theta_I + \theta_Z)}$



3. AC Power

■ Contents

- 1) Alternating Current and Voltage
- 2) Reactance
- 3) Power
- 4) Phasor Notation
- 5) Summary



3.5 Summary

- Two types of current
 - Alternating current (a.c.)
 - Direct current (d.c.)
- Reactance Vs Resistance
- Reactive power Vs Real power
- Phasor notation
 - Used to know what happens over the course of many cycles, not within a single cycle



Electric Power System

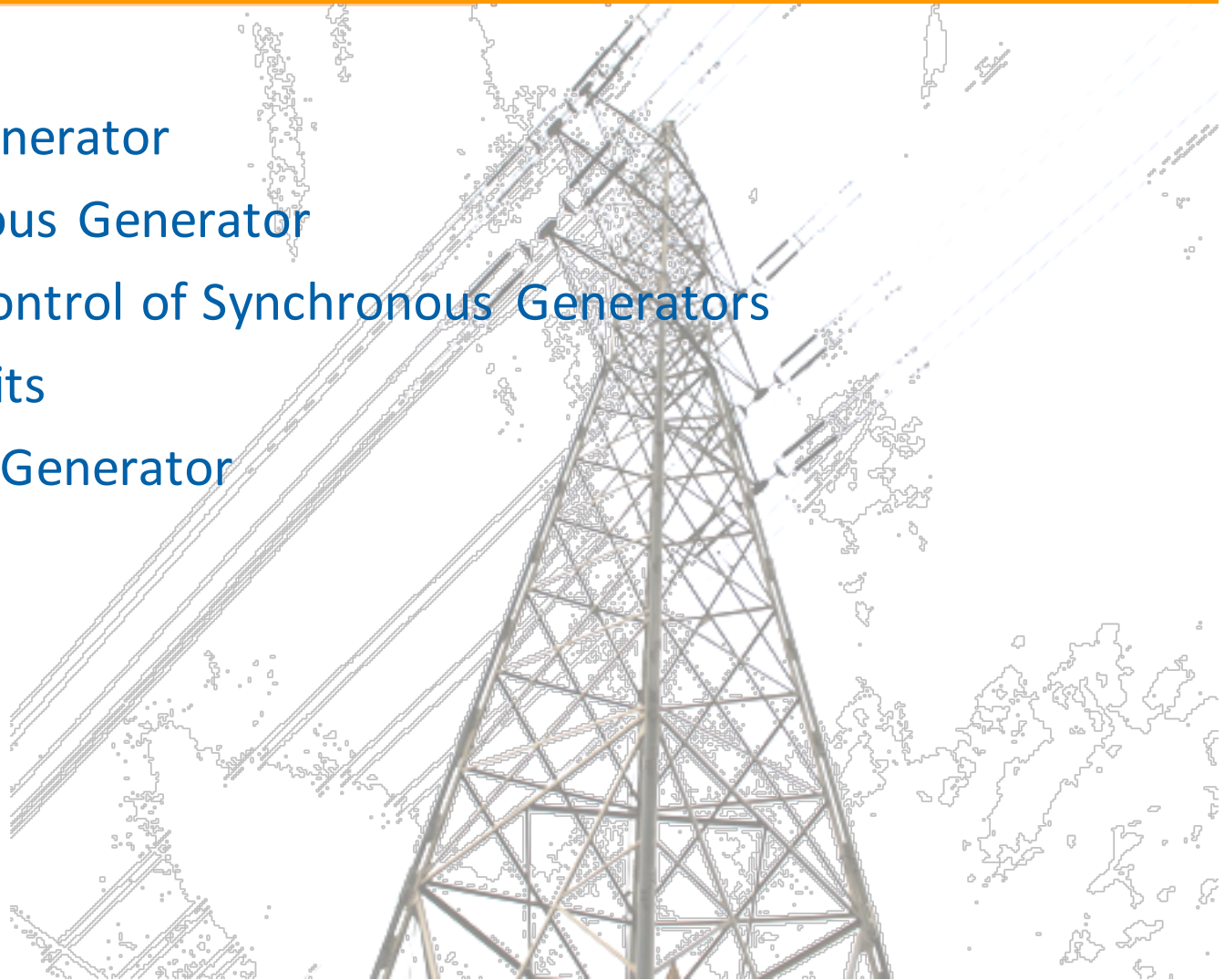
Chapter 4: Generator



4. Generator

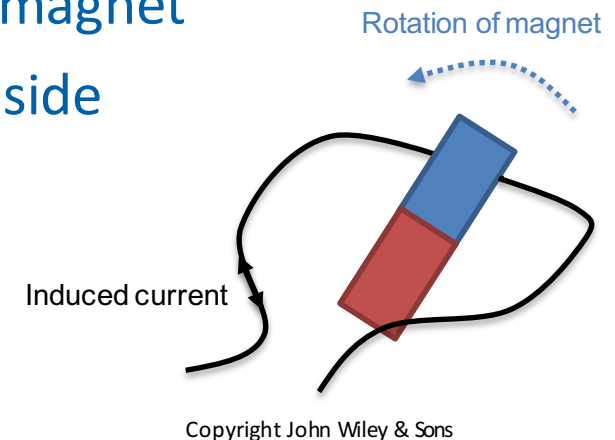
■ Contents

- 1) The Simple Generator
- 2) The Synchronous Generator
- 3) Operational Control of Synchronous Generators
- 4) Operating Limits
- 5) The Induction Generator
- 6) Inverters
- 7) Summary



4.1 The Simple Generator (1)

- An electric generator is a device designed to convert movement into electricity based on *electromagnetic induction*
- A generator converts mechanical energy of motion into electrical energy, whereas the electrical motor accomplishes just the reverse
- Simple generator:
 - consists of a loop of wire surrounding a bar magnet
 - Induces a current by rotating the magnet inside the loop (or by rotating the loop around it)



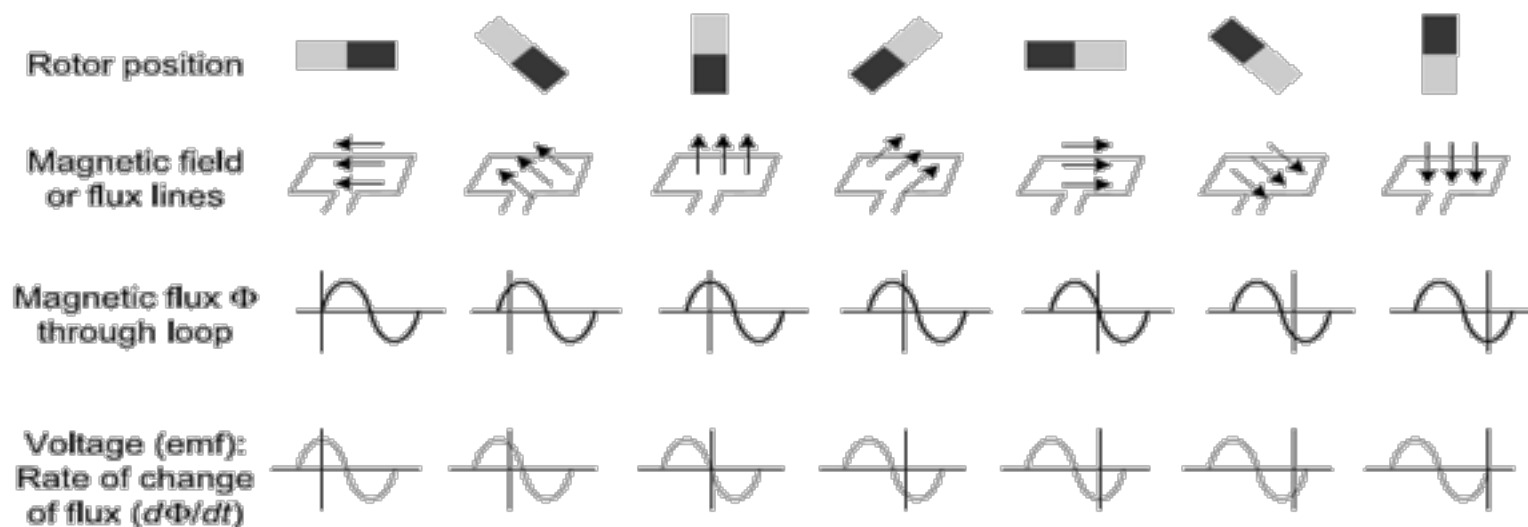
4.1 The Simple Generator (2)

- What is the effect of rotating magnetic field?
 - The rotation results in a magnetic field or flux that changes over time
 - With continued function, the flux over time could be plotted out as oscillating function (sine or cosine wave)
 - The amount of the current induced in the loop of wire will be directly proportional to the rate of the magnetic flux linking it (i.e. alternating current)
 - The induced current will have a direction so as to oppose, not enhance, the changing magnetic field that create it (energy conservation)



4.1 The Simple Generator (3)

- What is the effect of rotating magnetic field?
 - The induced voltage and its resulting current resembles also the sine or cosine wave, but offset from flux wave
 - Derivative of the sine is a cosine, or a curve of the same shape, only shifted by 90°



Copyright John Wiley & Sons



4.1 The Simple Generator (4)

- Where does the carried energy in the wire come from?
 - The energy is put into the generator by an external source of mechanical energy
 - Prime mover
 - An external force spins the magnet (e.g. steam turbine)
 - Renewable or non-renewable energy
 - High-pressure steam, fissioning atoms, etc.



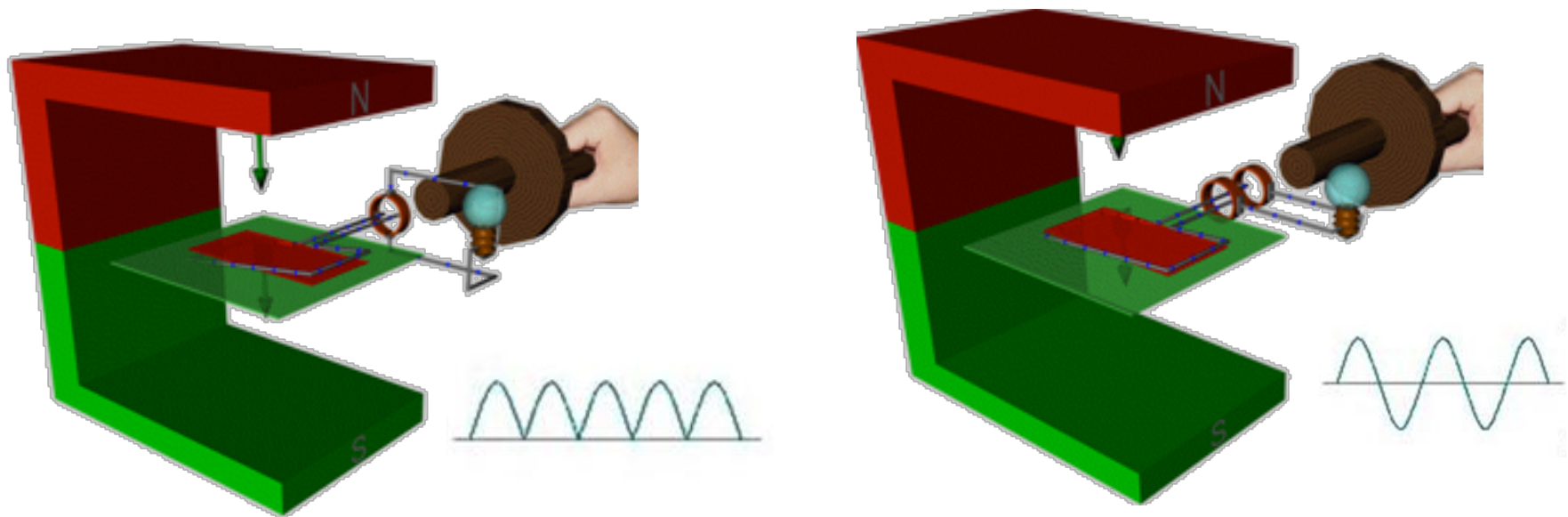
4.1 The Simple Generator (5)

- Must the magnet offer some resistance to being spun?
 - If the magnet offered no resistance to being spun, it would be impossible to exert a force on it, and therefore impossible for it to do any work
 - In physics, the mechanical work done equals the force applied by the distance an object is being pushed
- Where does this resistance come from?
 - The rotating magnet is pushing against a second magnetic field that is a result of the induced current in the wire (**armature reaction**)



4.1 The Simple Generator (6)

- How to produce direct current?
 - Hold the magnet stationary while the wire rotates
 - Use sliding contact for rectifying
 - reverse the connection each half turn

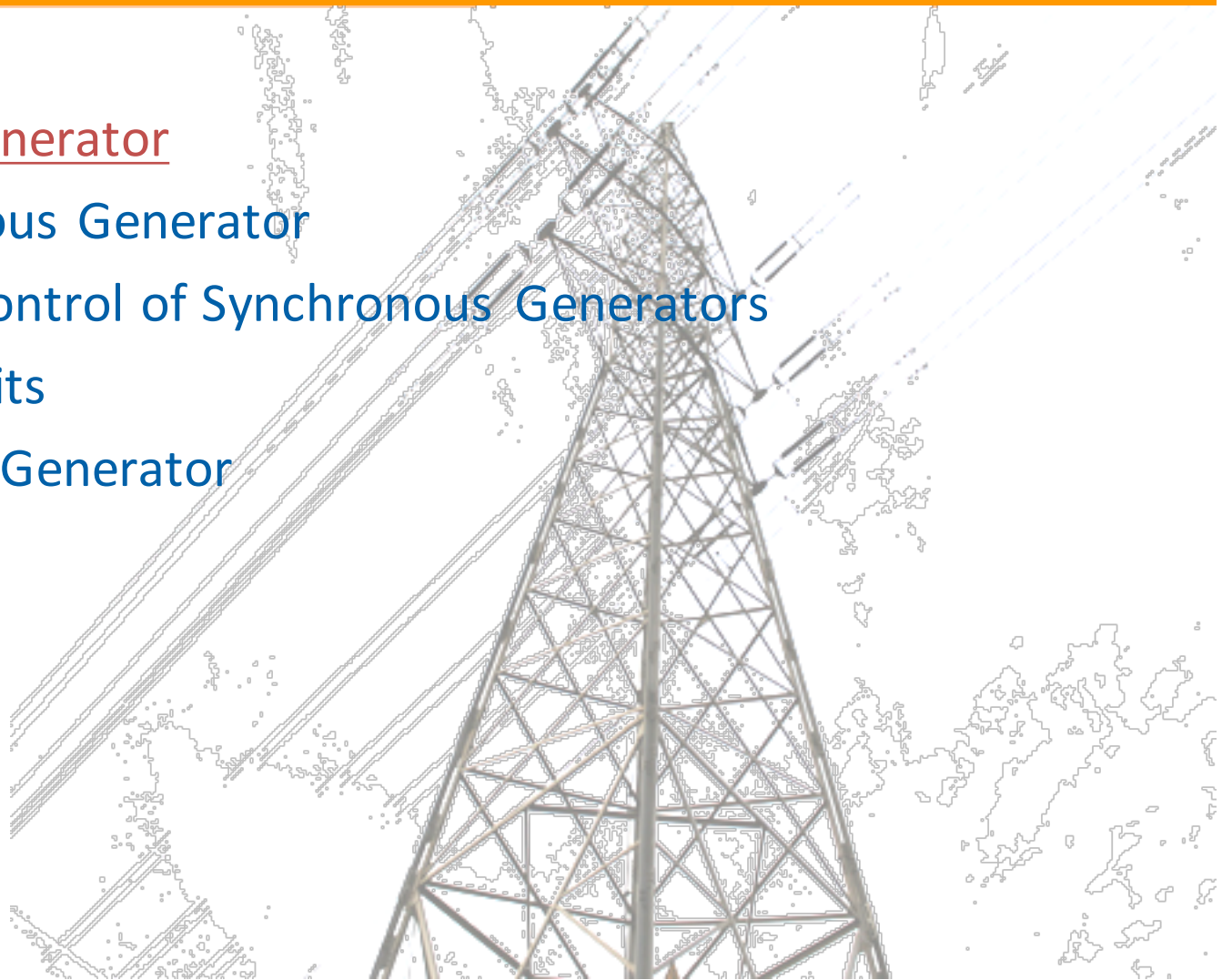


Source: www.wikimedia.com (Physik3D.de)

4. Generator

■ Contents

- 1) The Simple Generator
- 2) The Synchronous Generator
- 3) Operational Control of Synchronous Generators
- 4) Operating Limits
- 5) The Induction Generator
- 6) Inverters
- 7) Summary

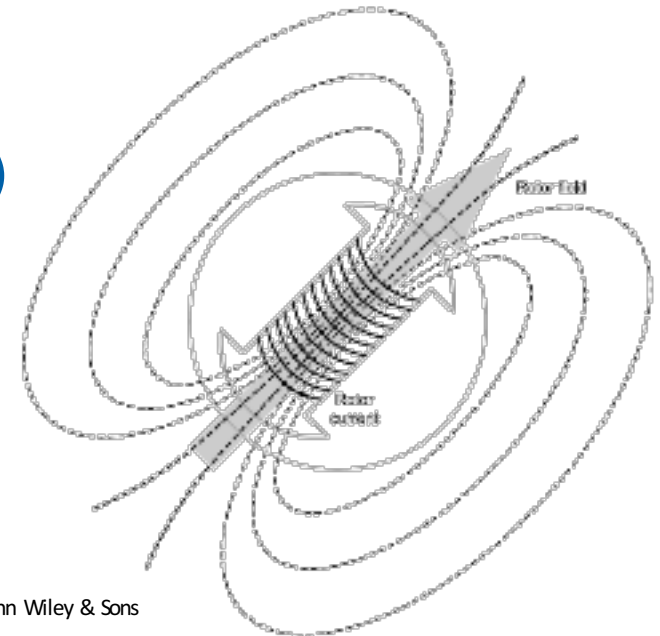


4.2 The Synchronous Generator (1)

■ Basic Components and Functioning

■ Rotor

- The rotating assembly in the center of the generator
- Contains the magnet
 - Rotor winding : electromagnet (coil of wire wound around an core of high permeability)
 - Rotor magnetic field is provided by an external dc current supplier (exciter)



Copyright John Wiley & Sons

4.2 The Synchronous Generator (2)

- Basic Components and Functioning
 - Stator
 - The stationary part of the generator
 - Contains the armature where the current is induced and is electrically connected to the load
 - Stator winding (single conductor (1 phase), three conductors (3 phases))
 - In the three phase design the phases are wound such that they are 120° spatially on the stator
 - Each phase carries an alternating voltage and current shifted in time from the others by one-third of a cycle

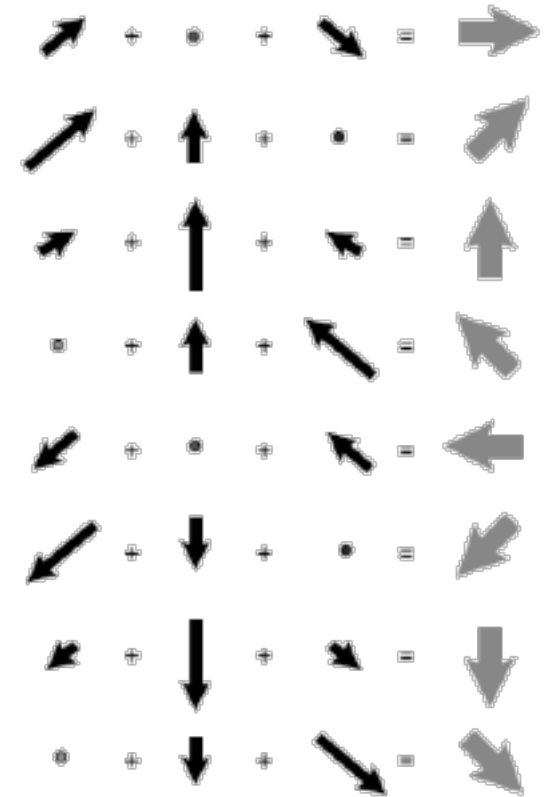


4.2 The Synchronous Generator (3)

■ Basic Components and Functioning

- In single phase generator the force between the magnetic fields pulsed during the rotation
- Three phase generator provide a uniform force or torque on the rotor for a much smoother conversion of the energy
- Because the magnetic fields resulting from the three induced currents of the stator are combined together to resemble the magnetic field of a single, rotating magnet

Phase A + Phase B + Phase C = Total armature



Copyright John Wiley & Sons



4.2 The Synchronous Generator (4)

- Basic Components and Functioning
 - The stator field (armature reaction) spins at the same frequency as the rotor field (move in synchronicity)



4.2 The Synchronous Generator (5)

■ Basic Components and Functioning

- Rotor rotation (revolutions per minute (rpm)) = frequency of alternating current (hertz (cycle per second))
- 60 Hz = 3600 rpm (rotor with two magnetic poles)
- Rotor with more poles need less revolutions to still produce an a.c. frequency of 60 Hz

- $f = \frac{np}{120}$; f: the a.c. frequency in Hz; n: the rotational rate of the rotor in rpm; p: the number of magnetic poles (2,4,8,32)

■ Cooling system is very important

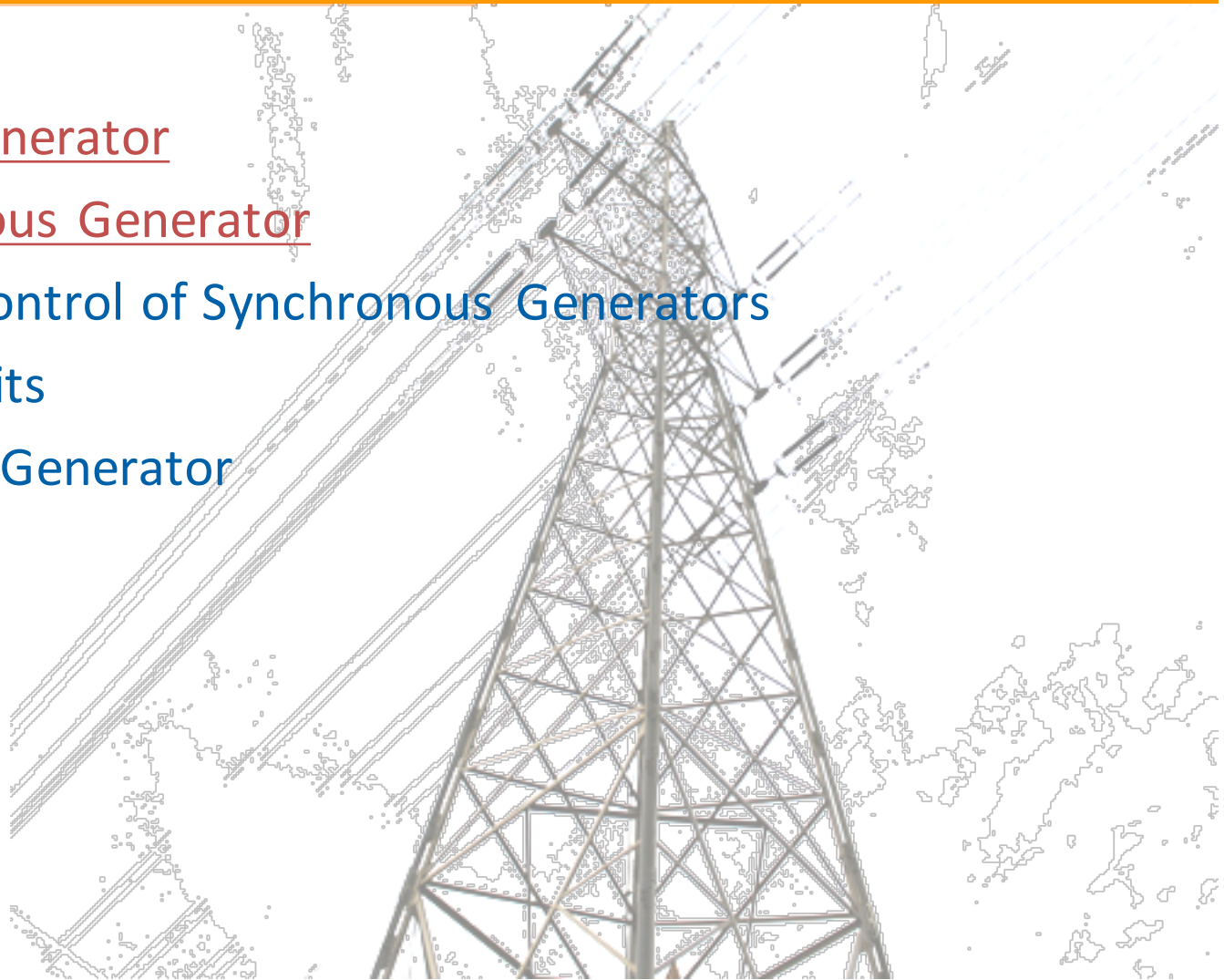
- 100 MW generator with an efficiency of 99% releases continuously 1 MW of heat into its environment



4. Generator

■ Contents

- 1) The Simple Generator
- 2) The Synchronous Generator
- 3) Operational Control of Synchronous Generators
- 4) Operating Limits
- 5) The Induction Generator
- 6) Inverters
- 7) Summary



4.3 Operational Control (1)

- There are two control variables (two dimensions) to adjust the generator's behavior
 - Rotational frequency of the generator
 - Related to the real power it supplies
 - Voltage at its terminal (the generator bus voltage)
 - Related to the reactive power it supplies
- A bus/busbar is a metal bar to which all the incoming and outgoing conductors are connected
 - A reference point for measurements of voltage, current, and power flow
 - A definitive measure of how the generator is interacting with the grid



4.3 Operational Control (2)

- Single generator: Real Power
 - Controlled through the force exerted by the prime mover
 - Rate of rotation of the rotor
 - First operating model called “On the governor”
 - As load-following generator which must respond to load fluctuations
 - Continually monitors the generator frequency (e.g. set point 3600 rpm)
 - Uses a governor valve to adjust the supplied force
 - Second operating model called “on the load limit”
 - Generators are operated at a fixed level of power output
 - Corresponding to its maximum load
 - Used for base-load plants



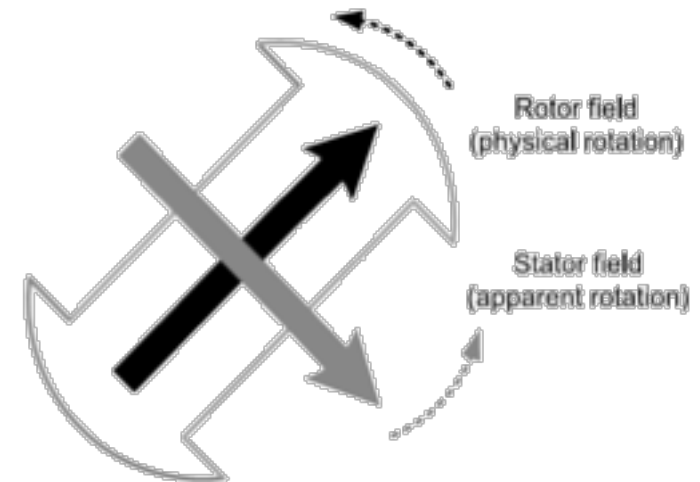
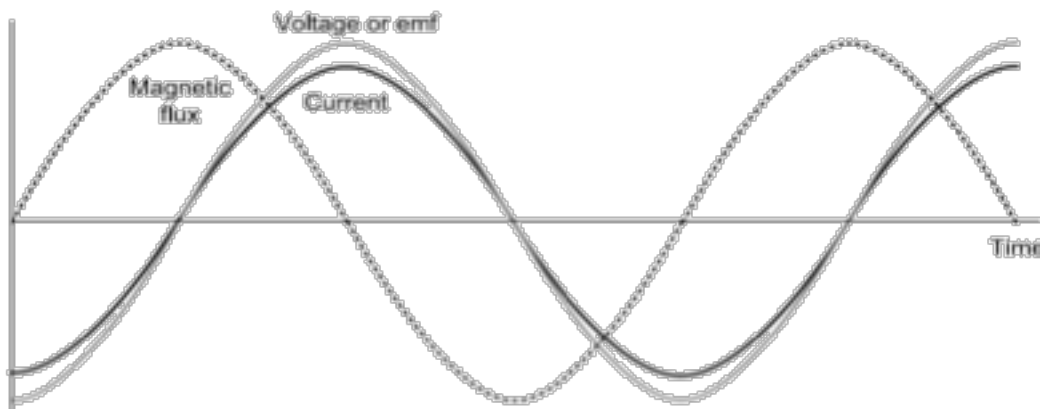
4.3 Operational Control (3)

- Single generator: reactive power
 - Controlled by the current provided to the rotor windings by the exciter
 - Increasing d.c. current → Increasing rotor magnetic field → Increasing *emf* in the armature's windings
 - This emf manifests as a voltage difference between the generator's terminals (*bus*)
 - **The magnitude of the rotor field determine the induced *emf* in the armature, and thus the generator bus voltage**



4.3 Operational Control (4)

- Single generator: reactive power
 - Unity power factor
 - The angle between the stator field and the rotor field is 90°

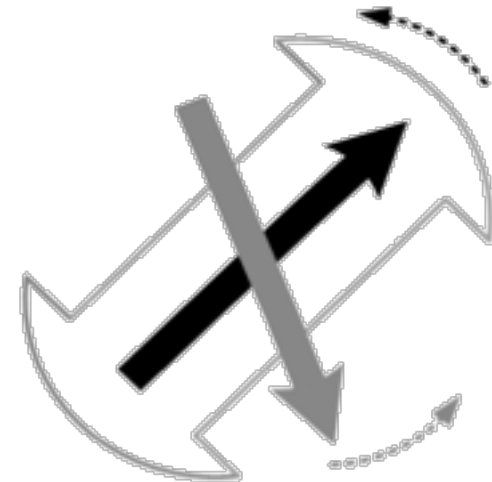
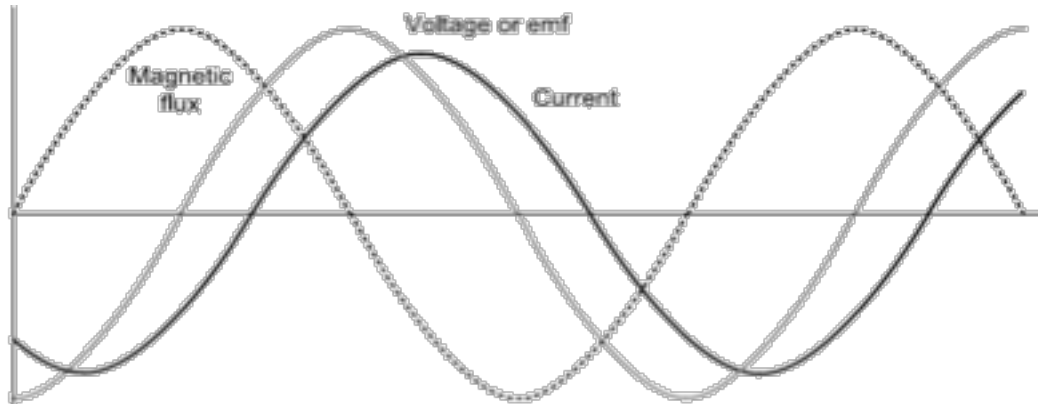


Copyright John Wiley & Sons



4.3 Operational Control (5)

- Single generator: reactive power
 - Lagging power factor
 - The angle between the stator field and the rotor field is longer than 90°

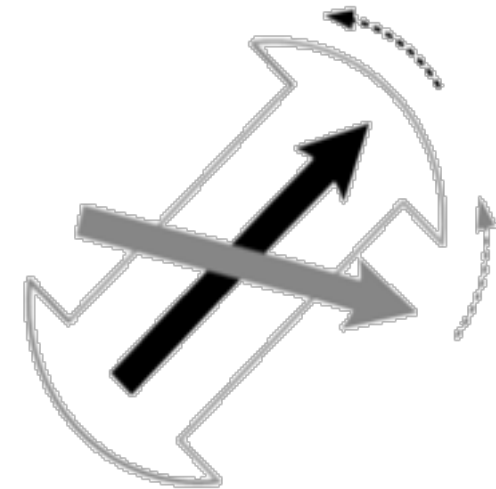
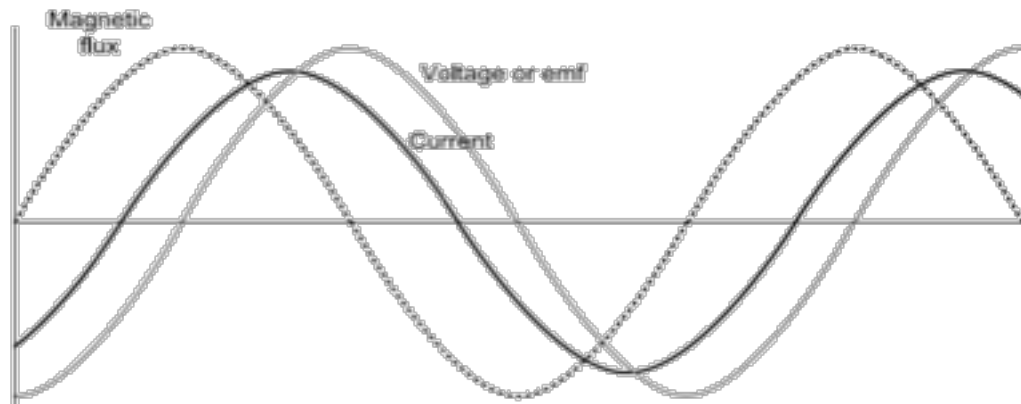


Copyright John Wiley & Sons



4.3 Operational Control (6)

- Single generator: reactive power
 - Leading power factor
 - The angle between the stator field and the rotor field is shorter than 90°

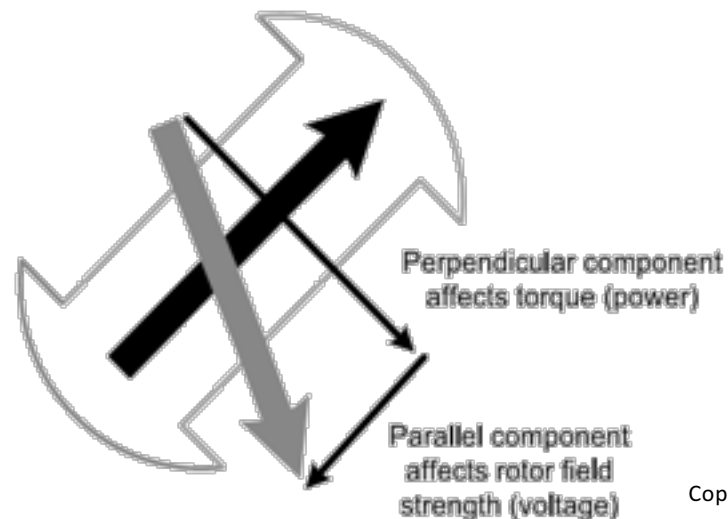


Copyright John Wiley & Sons



4.3 Operational Control (7)

- Single generator: reactive power
 - Decomposition of the stator field into two components
 - Perpendicular to the rotor field affects the torque
 - Parallel to the rotor field affects the rotor fields



Copyright John Wiley & Sons

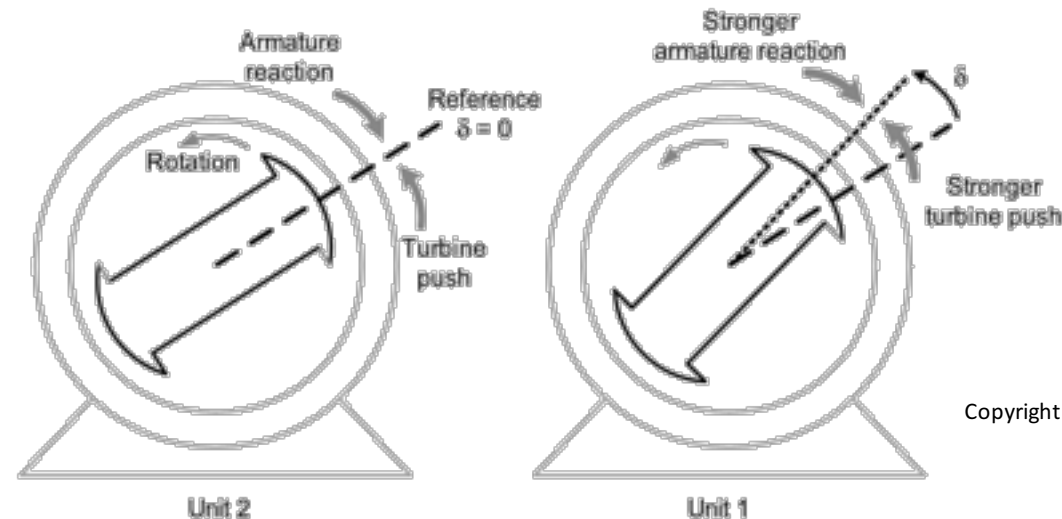
4.3 Operational Control (8)

- Single generator: reactive power
 - Load → producing reactive power → change in rotor field → change in generator voltage → change in real power supplied to the load
 - Voltage-control mechanism
 - Maintains the bus voltage constant
 - By continually varying the field current as required by the load



4.3 Operational Control (9)

- Multiple generators: Real power
 - Relationship between interconnected sync generators
 - Rotating exactly at the same frequency
 - Coincident timing of all produced alternating voltages (in step)
 - Power angle (δ) is the variation of the precise timing among voltages as supplied by different generators



Copyright John Wiley & Sons

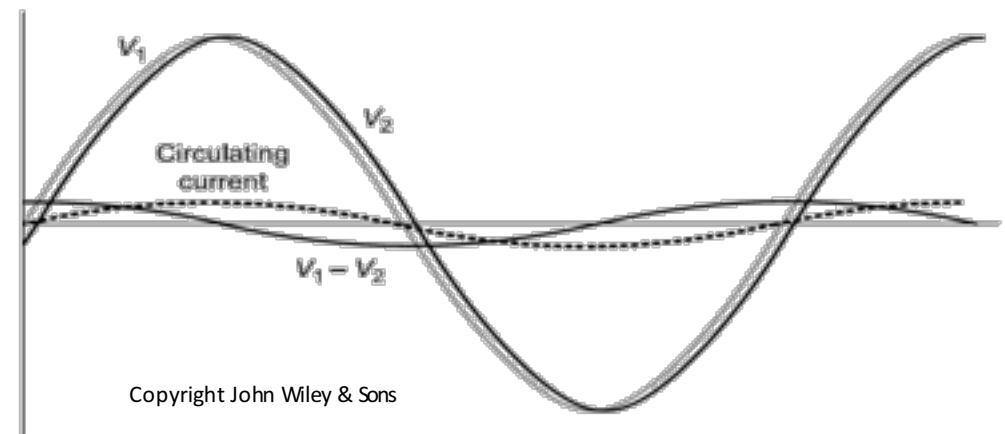
4.3 Operational Control (10)

- Multiple generators: Real power
 - The more ahead the power angle, the more power the generator is producing compared to the others
 - This result in a stronger armature reaction and greater restraining torque on the turbine
 - → slowing down the generator until an equilibrium is reached
 - Conversely, if one generator slows down to fall behind the others, this will reduce its load while increasing that of the others
 - This relieving the torque on its turbine
 - → allowing it to speed up until equilibrium is again reestablished



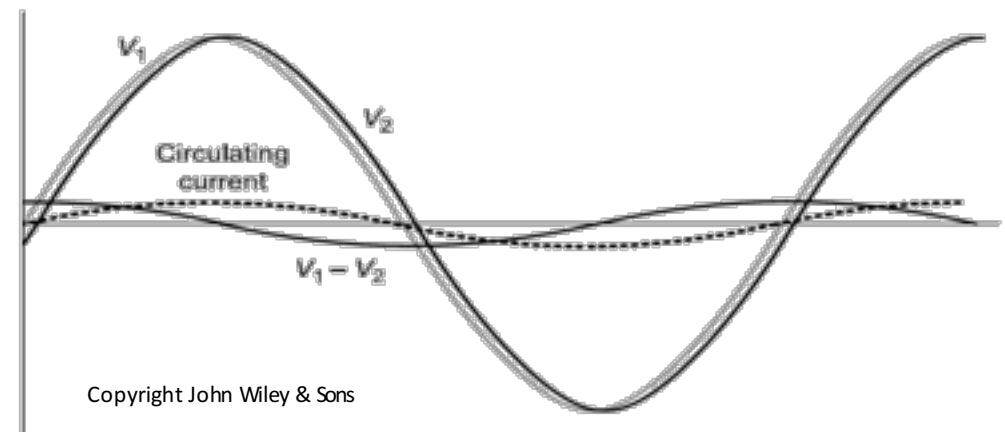
4.3 Operational Control (11)

- Multiple generators: Real power
 - Increasing forward torque at unit 1 \rightarrow rotor 1 moves ahead of rotor 2 \rightarrow V_1 occurs in each phase slightly ahead of V_2
 - Difference voltage ($V_1 - V_2$) is approx. 90° out of phase with both
 - Units 1 and 2 have opposite perspective
 - Circulating current is associated with difference and flows between the two generators



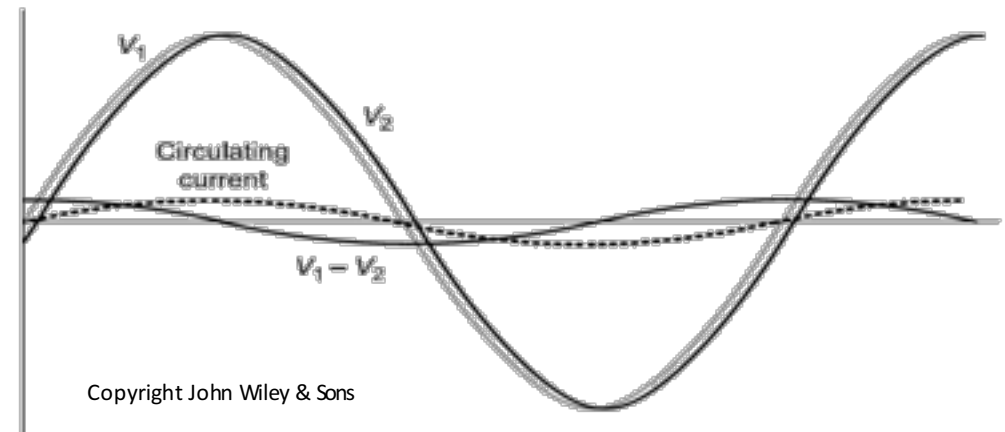
4.3 Operational Control (12)

- Multiple generators: Real power
 - Circulating current is associated with difference and flows between the two generators
 - This current lag by almost 90° the difference voltage
 - Inductive reactance
 - → The circulating current is in phase with current generated by unit 1 (addition), but approx. 180° out of phase with current at unit 2 (subtraction)



4.3 Operational Control (13)

- Multiple generators: Real power
 - → The real power output of unit 1 increases, while the power output of unit 2 decreases
 - Load reduction will be shared among all the generators in the system → these generator will speed up



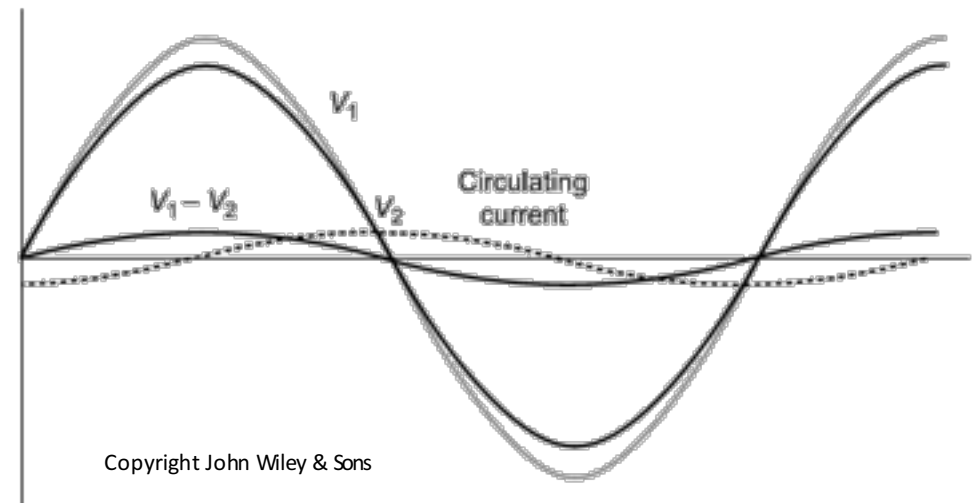
4.3 Operational Control (14)

- Multiple generators: Reactive power
 - The allocation of reactive power among interconnected generators can be controlled by the magnitude of the supplied voltage (rotor field current)
 - All generators have the same bus voltage → their reactive power output would be in the same proportion to the generating real power
 - Why may it be desirable to change this balance?
 - Maintaining voltage profile throughout the system
 - Minimizing cost
 - Avoiding loss of real power



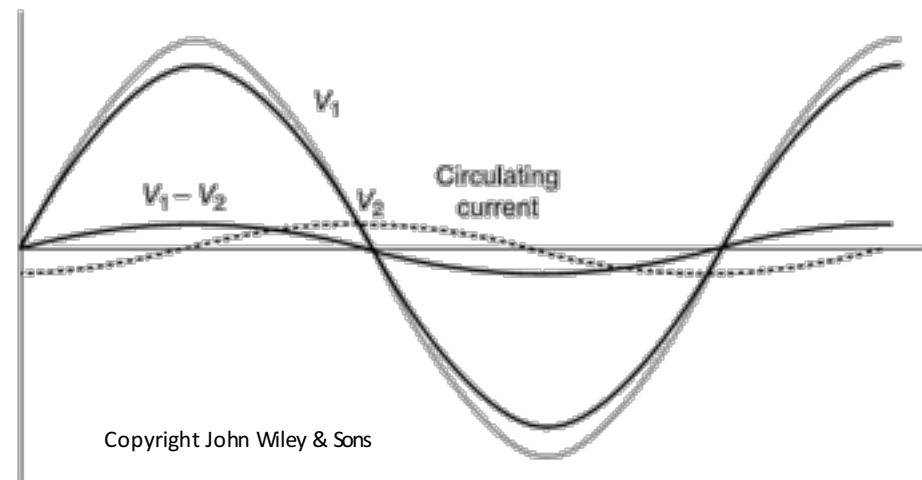
4.3 Operational Control (15)

- Multiple generators: Reactive power
 - Increasing the voltage set point of unit 1 → increasing rotor field current of unit 1 → increasing reactive power contribution
 - Voltage difference is in phase with the normal voltage
 - Circulating current lag by almost 90° the difference voltage
 - Inductive reactance



4.3 Operational Control (16)

- Multiple generators: Reactive power
 - At unit 1 lagging circulating current coincides with lagging current associated with reactive power supplied to the load
 - Increased reactive load → Weakening the rotor field
 - At unit 2 the circulating current is observed as leading
 - Decreased reactive load → Strengthening the rotor field



4.3 Operational Control (17)

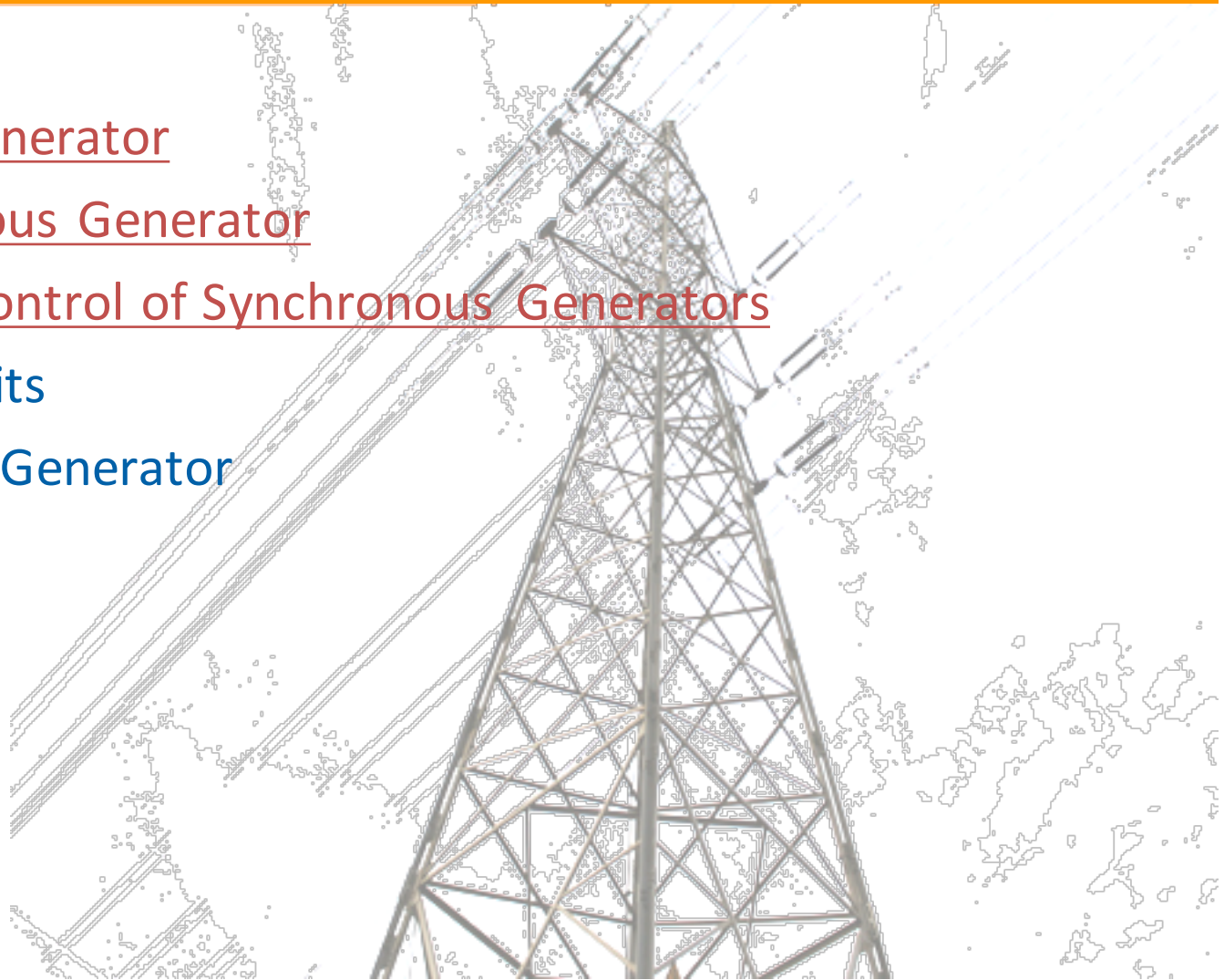
- Multiple generators:
 - The circulating current, as an electrical interaction between generators, has the effect of equalizing:
 - The voltages
 - Rotational frequencies



4. Generator

■ Contents

- 1) The Simple Generator
- 2) The Synchronous Generator
- 3) Operational Control of Synchronous Generators
- 4) Operating Limits
- 5) The Induction Generator
- 6) Inverters
- 7) Summary



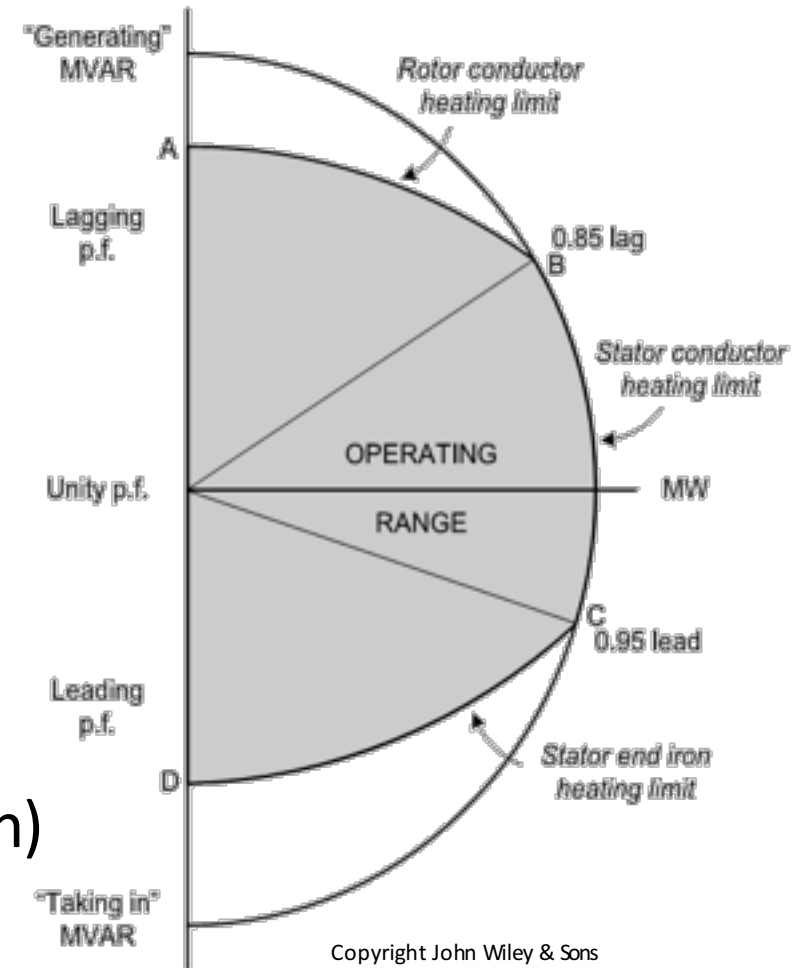
4.4 Operating Limits (1)

- The appropriate measure of generating capacity is in units of apparent power (KVA or MVA)
- Overloading means primarily overheating
 - Insulation damage
 - Thermal expansion between winding conductors and the core
- Operating limits assure the integrity of the equipment
 - Reactive capability curve
- Automatics control are used to assist the operator that these limit are not exceeded



4.4 Operating Limits (2)

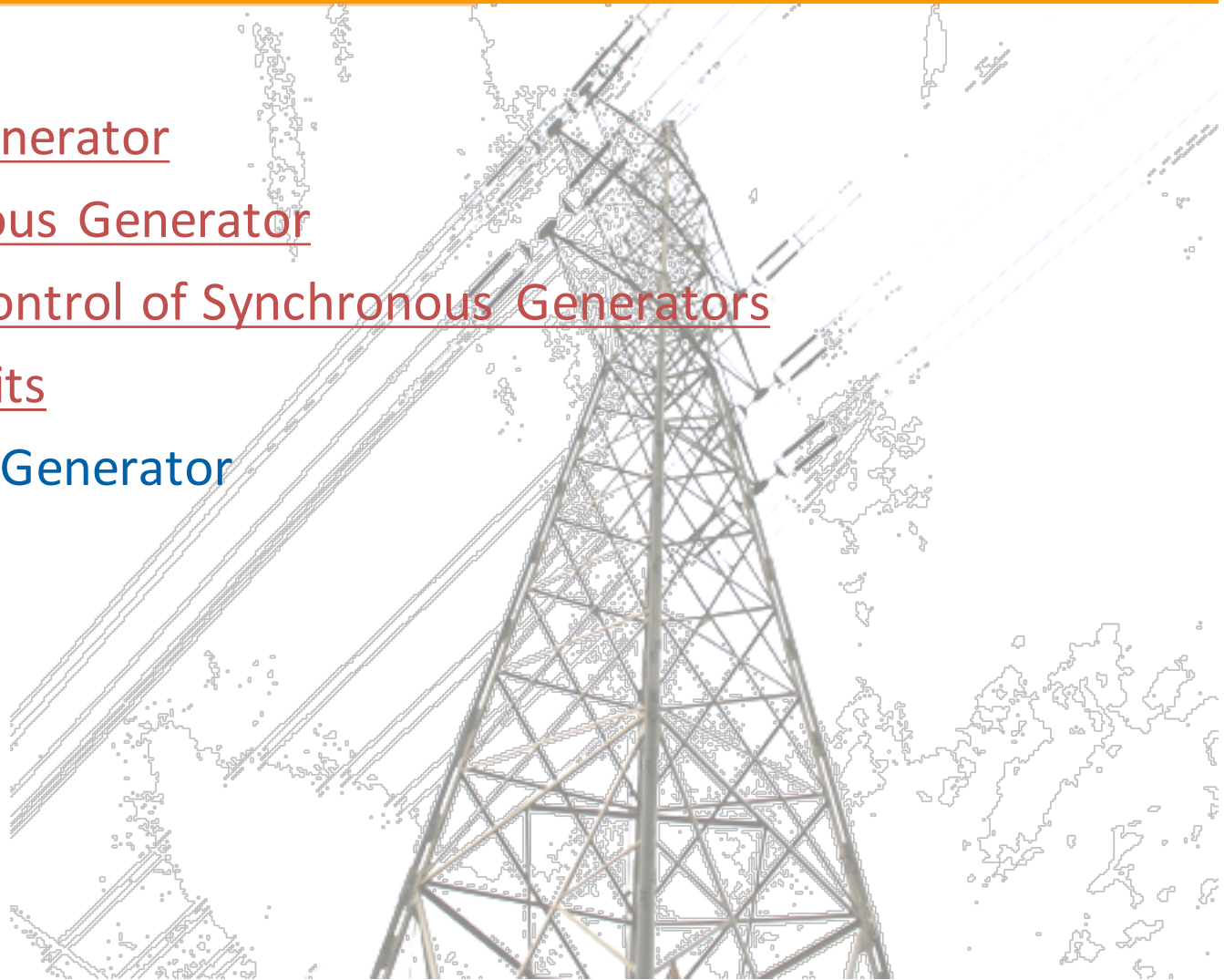
- Reactive capability curve
 - A boundary on permissible combinations of real and reactive power output
- Normal operating range:
 - Operating limit imposed by heating of stator conductor (BC)
- lagging power factor (overexcitation)
 - Heating of the rotor conductor (BA)
- leading power factor (underexcitation)
 - Heating of the stator core iron (CD)



4. Generator

■ Contents

- 1) The Simple Generator
- 2) The Synchronous Generator
- 3) Operational Control of Synchronous Generators
- 4) Operating Limits
- 5) The Induction Generator
- 6) Inverters
- 7) Summary



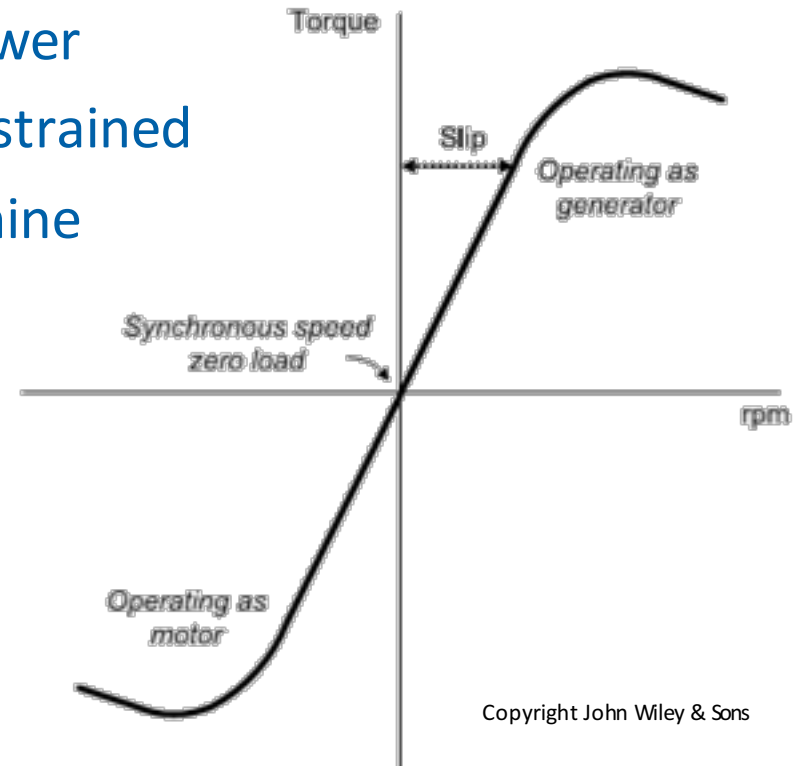
4.5 The Induction Generator (1)

- General Characteristics of asynchronous generator
 - Without an independent excitation for rotor
 - Armature is connected to a live a.c. system (electrical grid)
 - Rotor field current is obtained by electromagnetic induction from the rotating stator field
 - Not fixed rotation rate
 - Synchronous speed is the speed of rotation of stator's field
 - Corresponding to the electrical grid
 - Syn. speed = 1800 rpm for 60 Hz and 2 magnetic poles
 - Slip speed is the difference between the rotor speed and the synchronous speed



4.5 The Induction Generator (2)

- General Characteristics of asynchronous generator
 - Zero Slip represent equilibrium state, it delivers no power
 - Exerting forward torque (by a turbine) would accelerate beyond syn. speed and generate electric power
 - Spinning slower than syn. Speed (restrained by mechanical load) , then the machine is operating as a motor!



4.5 The Induction Generator (3)

- Electromagnetic characteristic
 - Stator field rotates corresponding to the a.c. frequency
 - Rotating stator field induces an a.c. current to flow in the rotor
 - As a result, a torque is exerted on the rotor to accelerate it in the rotation direction of the stator field
 - The rate of change of the flux through the rotor depends on
 - A.c. frequency in the stator
 - Slip speed
 - Exerting external torque on the rotor → rotor revolve faster than stator field → inducing emf in the armature winding, which acts to strengthen the potential difference at the generator terminal → flowing current to load and transmitting power



4.5 The Induction Generator (4)

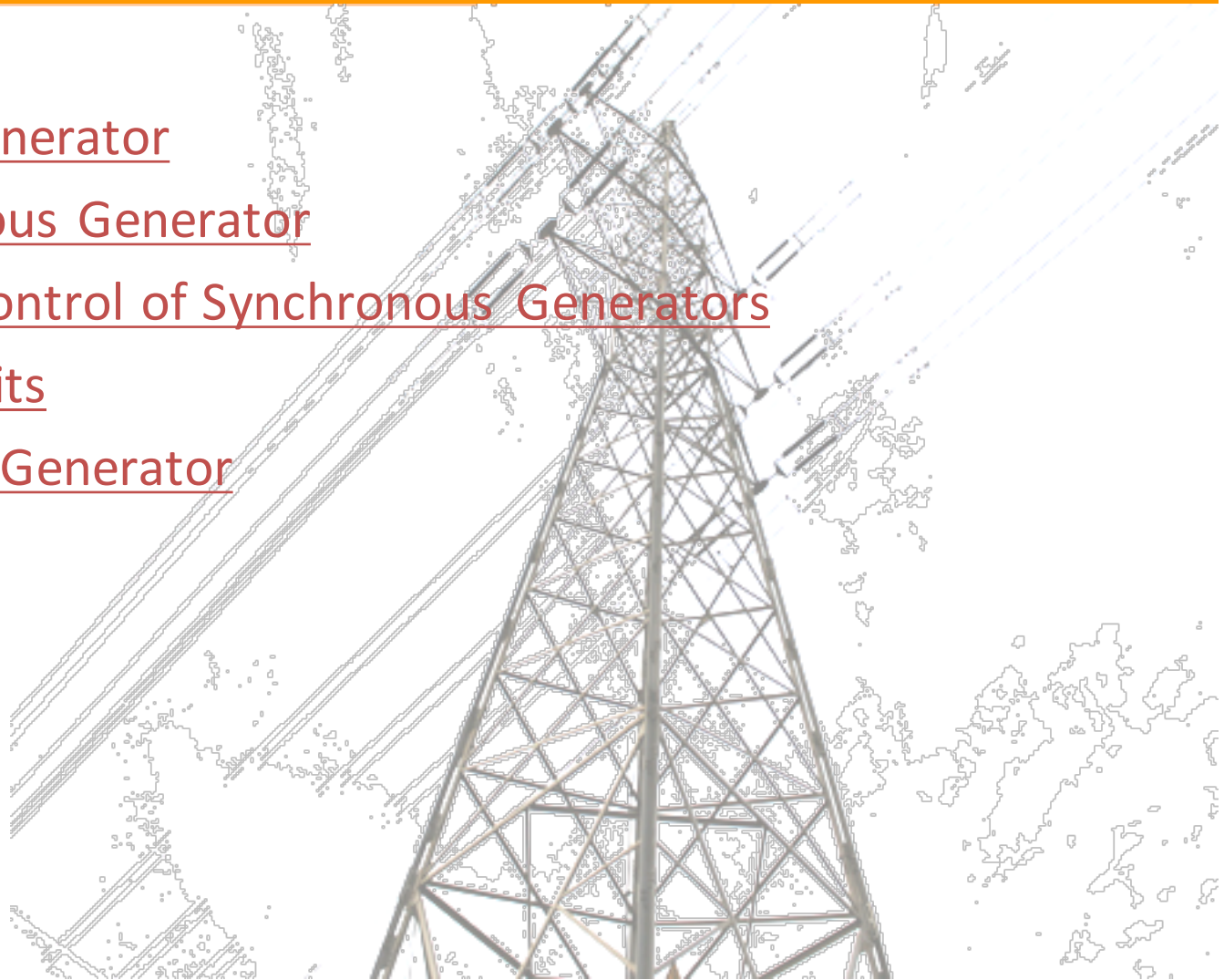
- Electromagnetic characteristic
 - When the machine is operated as a motor, with mechanical force holding the rotor back, the rotor current lags 90° behind the stator field
 - As a generator, with a mechanical force accelerating the rotor beyond sync speed, the rotors current leads the stators field by 90°
 - Inductive generator can only generate at leading power factor
 - It consumes reactive power



4. Generator

■ Contents

- 1) The Simple Generator
- 2) The Synchronous Generator
- 3) Operational Control of Synchronous Generators
- 4) Operating Limits
- 5) The Induction Generator
- 6) Inverters
- 7) Summary



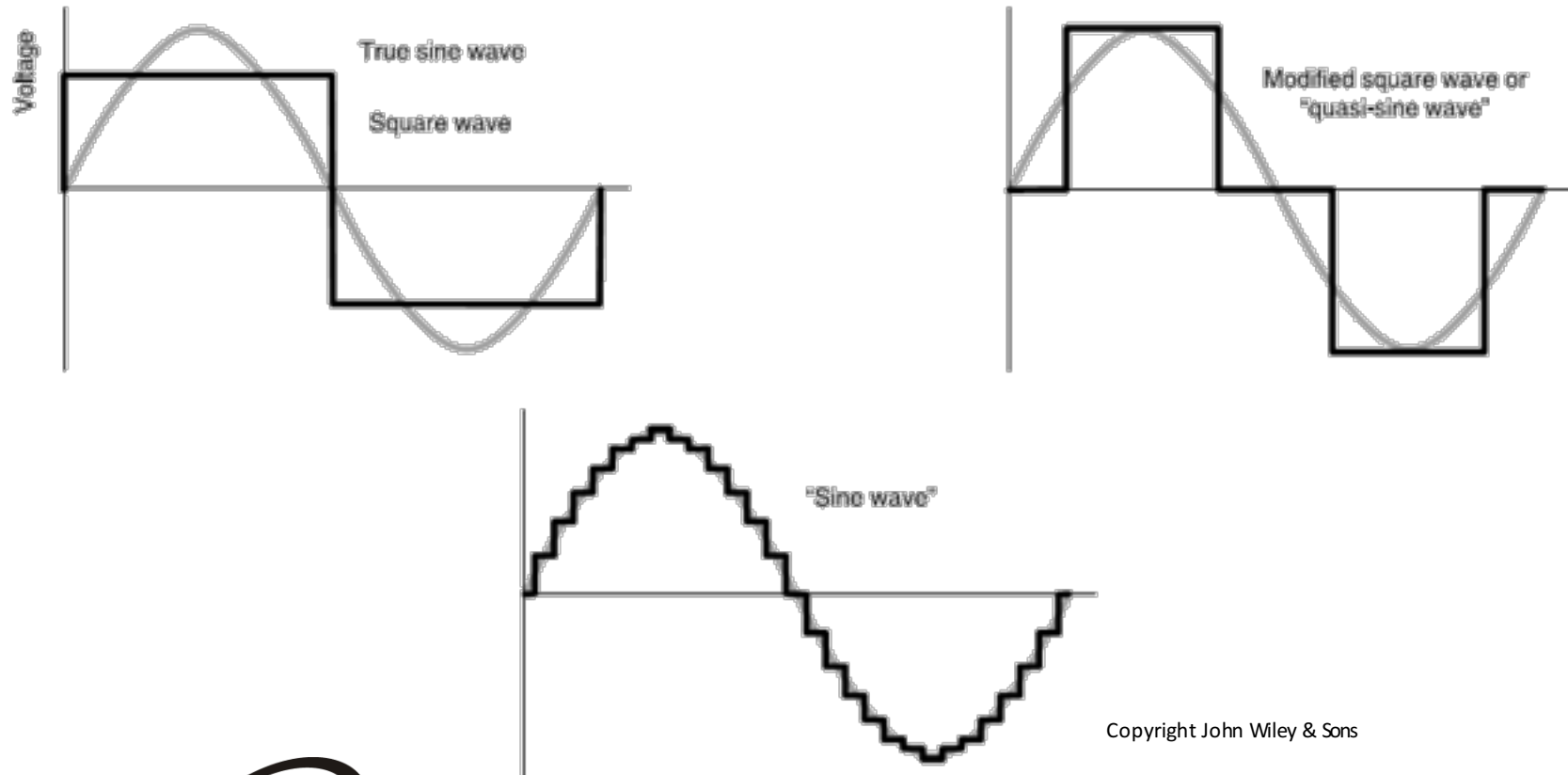
4.6 Inverters (1)

- Is a device that changes d.c. into a.c.
- To obtain a.c. power from d.c. electrical source
 - In Power generation systems
 - E.g. to inject power into grid from photovoltaic module
 - In battery powered devices
- As a part of the conversion process of a.c. frequencies to a steady 60 Hz
 - a.c. output from a variable-speed wind turbine
- Rotary inverter: a d.c. motor powers an a.c. generator
- Electronic inverter: rapidly switching electronic circuit
- The key performance criterion of inverter is the waveform



4.6 Inverters (2)

■ Waveforms

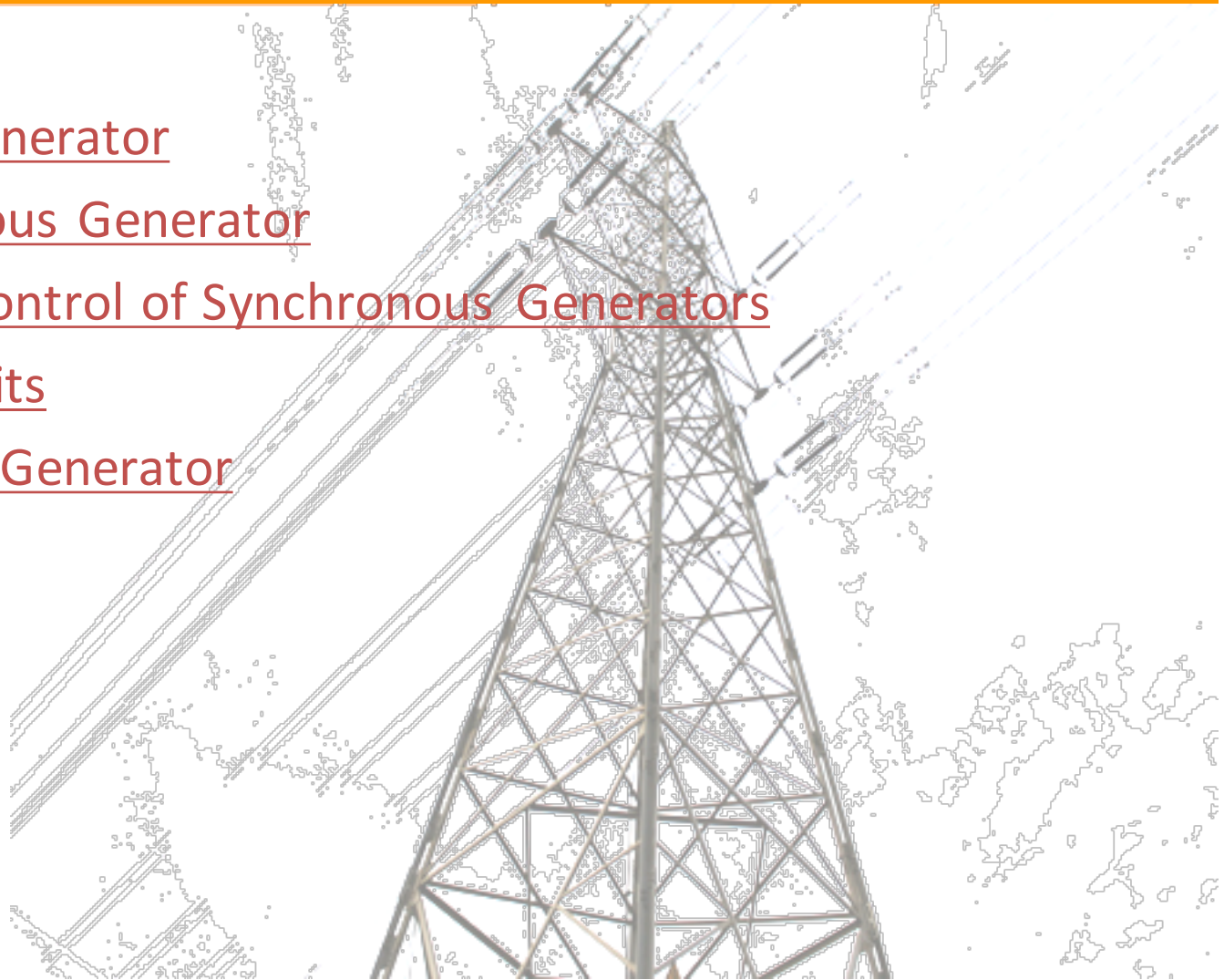


Copyright John Wiley & Sons

4. Generator

■ Contents

- 1) [The Simple Generator](#)
- 2) [The Synchronous Generator](#)
- 3) [Operational Control of Synchronous Generators](#)
- 4) [Operating Limits](#)
- 5) [The Induction Generator](#)
- 6) [Inverters](#)
- 7) Summary



4.7 Summary

- An electric generator is a device designed to convert movement into electricity based on *electromagnetic induction*
- In the synchronous generator the stator field (armature reaction) spins at the same frequency as the rotor field
- Requires an external d.c. current
- An induction (asynchronous) generator operates without an independent source for its rotor field current
- The inverter is a device that changes d.c. into a.c.



Electric Power System

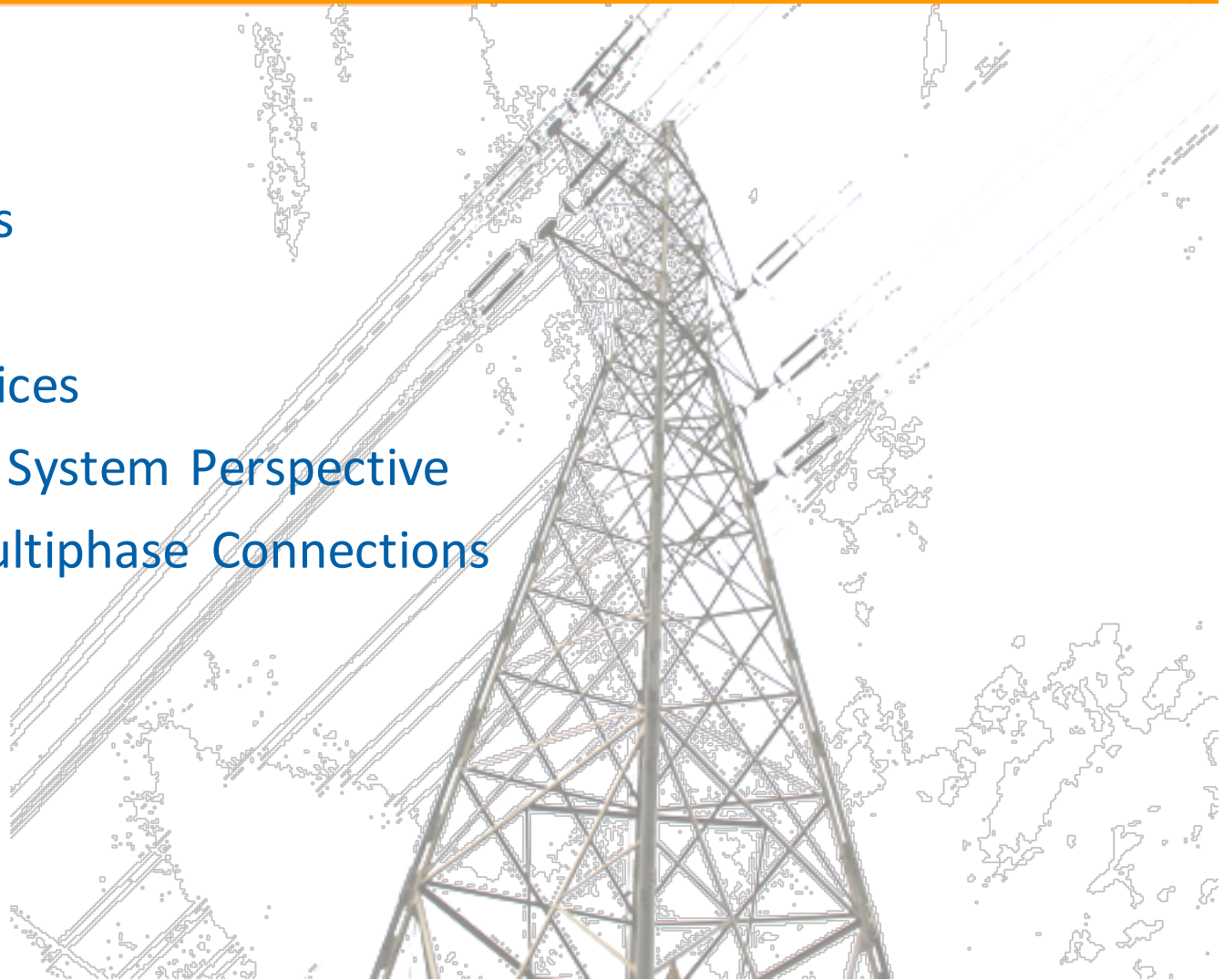
Chapter 05: Loads



5. Loads

■ Contents

- 1) Introduction
- 2) Resistive Loads
- 3) Motors
- 4) Electronic Devices
- 5) Load from the System Perspective
- 6) Single- and Multiphase Connections
- 7) Summary



5.1 Introduction (1)

- Load refers to any device in which power is being consumed
 - Individual appliances (e.g. light bulb)
 - Aggregated system (e.g. city block)
- The load is defined mainly by
 - Impedance (resistance and reactance)
 - Aggregated behavior (e.g. timing of demand)
 - Type of electric power (d.c. or a.c.)
- Theoretically there are three types of loads acc. to impedance
 - Resistive loads
 - Inductive loads (motors)
 - Capacitive loads (electronics devices)



5.1 Introduction (2)

■ Types of loads

Type of loads	Examples
Pure resistive loads	Incandescent lamps Heaters (toaster, iron)
Motors	Pumps Fans Household appliances Power tools Large commercial three-phase motors
Electronics	Power supplies for computers and other electronics Transformers (adapters, battery chargers) Microwave ovens Fluorescent lamps

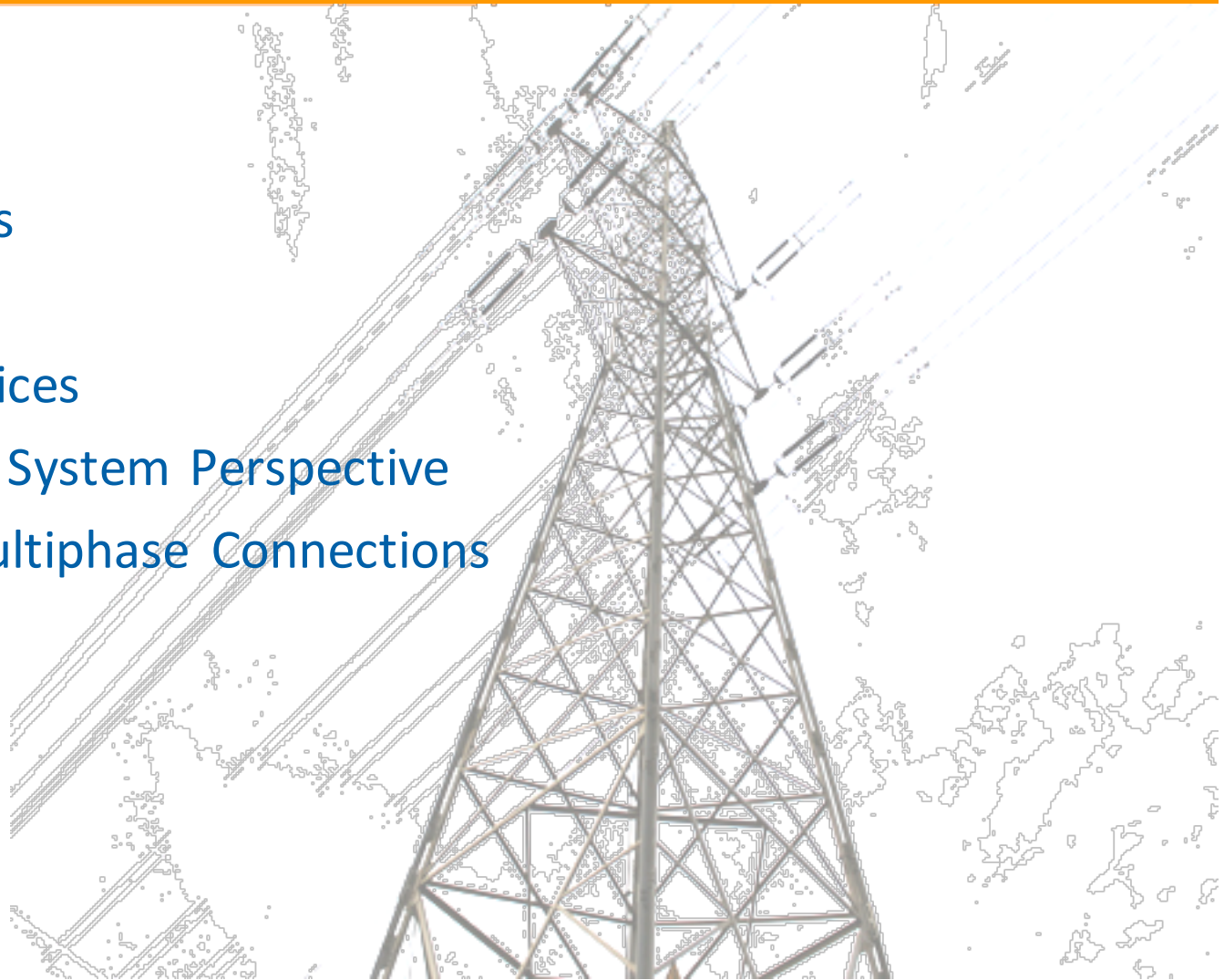
Copyright John Wiley & Sons



5. Loads

■ Contents

- 1) Introduction
- 2) Resistive Loads
- 3) Motors
- 4) Electronic Devices
- 5) Load from the System Perspective
- 6) Single- and Multiphase Connections
- 7) Summary



5.2 Resistive loads (1)

- This type of load is a purely resistive load without capacitive or inductive reactance
- Power factor of such a load is 1.0
- The heating element dissipates power according to:
 - $P = I^2R = IV = V^2/R$
- According to $P = V^2/R$ the strongest heaters are those with the lowest resistance
- Resistance is usually a fixed property of a device
- Resistive load are the most tolerant of variation in power quality, such as variation in voltage or in a.c. frequency



5.2 Resistive loads (2)

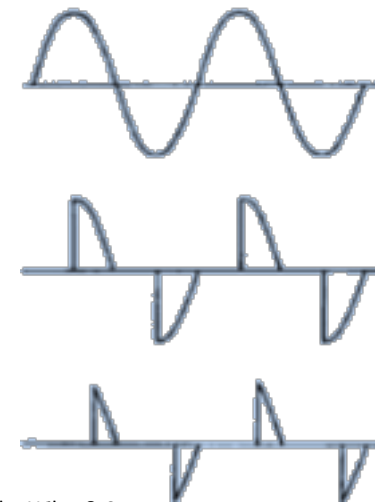
- resistive device can be damaged by excessively high voltage
 - Overheat
- Low voltage causes no physical damage, but the heat or the light output will be reduced
- The resistive loads are indifferent to the a.c. frequency
 - The performance of an incandescent lamp at a.c and d.c is indistinguishable by human eyes
- What happens to loads and their power consumption when voltage changes?
 - $P = V^2/R$



5.2 Resistive loads (3)

■ Dimmer

- Dimmer is used to control the brightness of a light by reducing the effective root-mean-square (rms) voltage across the lamp
- Dimmer selectively turns the voltage on and off for a certain fraction for each cycle, producing a jagged voltage curve
 - No problem; resistive loads are indifferent to a.c. waveform
- As a result, the overall brightness is diminished in relation to the average amount of power dissipated by the load, which in turn given by the average voltage



Copyright John Wiley & Sons



5.2 Resistive loads (4)

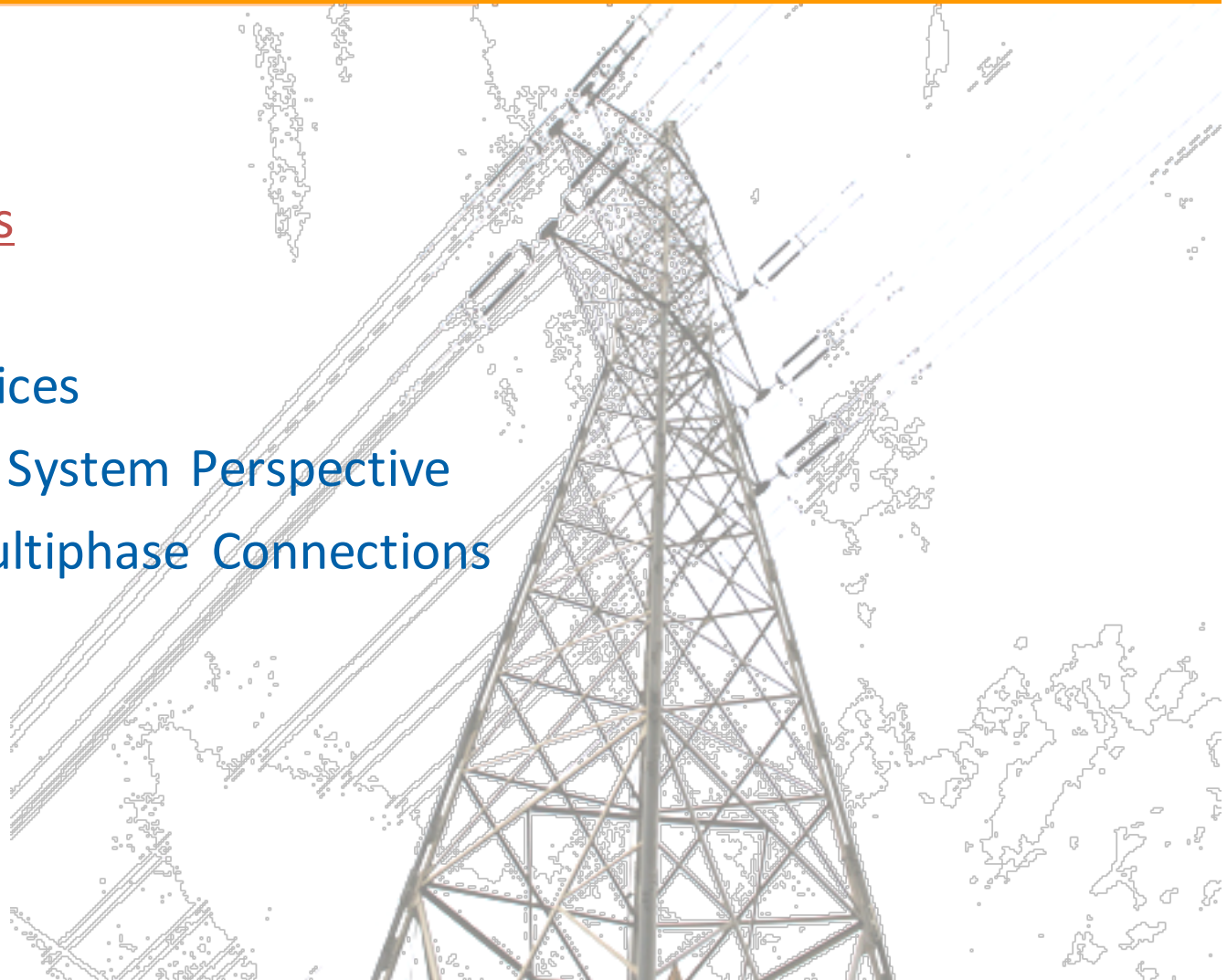
- Dimmer
 - Dimmer switches should only be installed in appropriate circuits
 - The majority of fluorescent lamps are not dimmable
 - They are not resistive load, therefore reducing the voltage may damage them
 - Rheostat refers to the process of reducing the voltage by inserting a variable resistance in series with light bulb
 - Splitting the voltage between the light bulb and the rheostat
 - Dissipating less power by the light bulb (dimming)
 - But, rheostat dissipates also a significant amount of the power
 - →no savings from reduced lightning energy use
 - →risk of meltdown and fire



5. Loads

■ Contents

- 1) Introduction
- 2) Resistive Loads
- 3) Motors
- 4) Electronic Devices
- 5) Load from the System Perspective
- 6) Single- and Multiphase Connections
- 7) Summary



5.3 Motors (1)

- Motors refer to the inductive loads
- Motor loads comprise anything electric that moves, such as fans, pumps of all kinds, power tools and even electric cars
- The motor is essentially as a generator operated backwards
- The mechanical power output of a motor is expressed in units of horsepower (hp)
 - 1 hp = 0.746 kW
- There are three main types of motors
 - Induction
 - Synchronous
 - D.c.



5.3 Motors (2)

- Induction motor
 - Similar to induction generator
 - No independent source of magnetization for the rotor
 - Induced rotor current (a.c. frequency and slip)
 - Inrush current refers to the drawn current by a motor when first switched on and before establishing the rotor field
 - Maximum drawn current by the motor (very little impedance)
 - Starting current refers to the drawn current after establishing the rotor field until the motor reaches its operating speed
 - Several times greater than the current under full load
 - Power factor less than unity



5.3 Motors (3)

- Synchronous motors
 - An independent source of magnetization for the rotor
 - Permanent magnet
 - Electromagnet (excitation)
 - Operating at synchronous a.c. speed regardless of load
 - More complicated and expensive than induction motors
 - Used in industrial application, especially those requiring high power force and constant speed



5.3 Motors (4)

- d.c. motors
 - An independent magnetization
 - Require commutation
 - Brushed motor: commutator rings and brushes
 - Brushless motor: electronic commutation (stepper motors)
 - Distinguished by:
 - High starting torque
 - Convenient speed control (varying directly with voltage)
 - → Useful in application such as accelerating vehicles from rest



5.3 Motors (4)

- Three phase motors
 - Only a.c. motors
 - Constant torque afforded by three separate windings
 - Staggered in space and time
 - Operating more smoothly and much more efficiently than single-phase motor
 - High performance, high horsepower and high efficiency
 - Used for large industrial and commercial applications
 - More expensive



5.3 Motors (5)

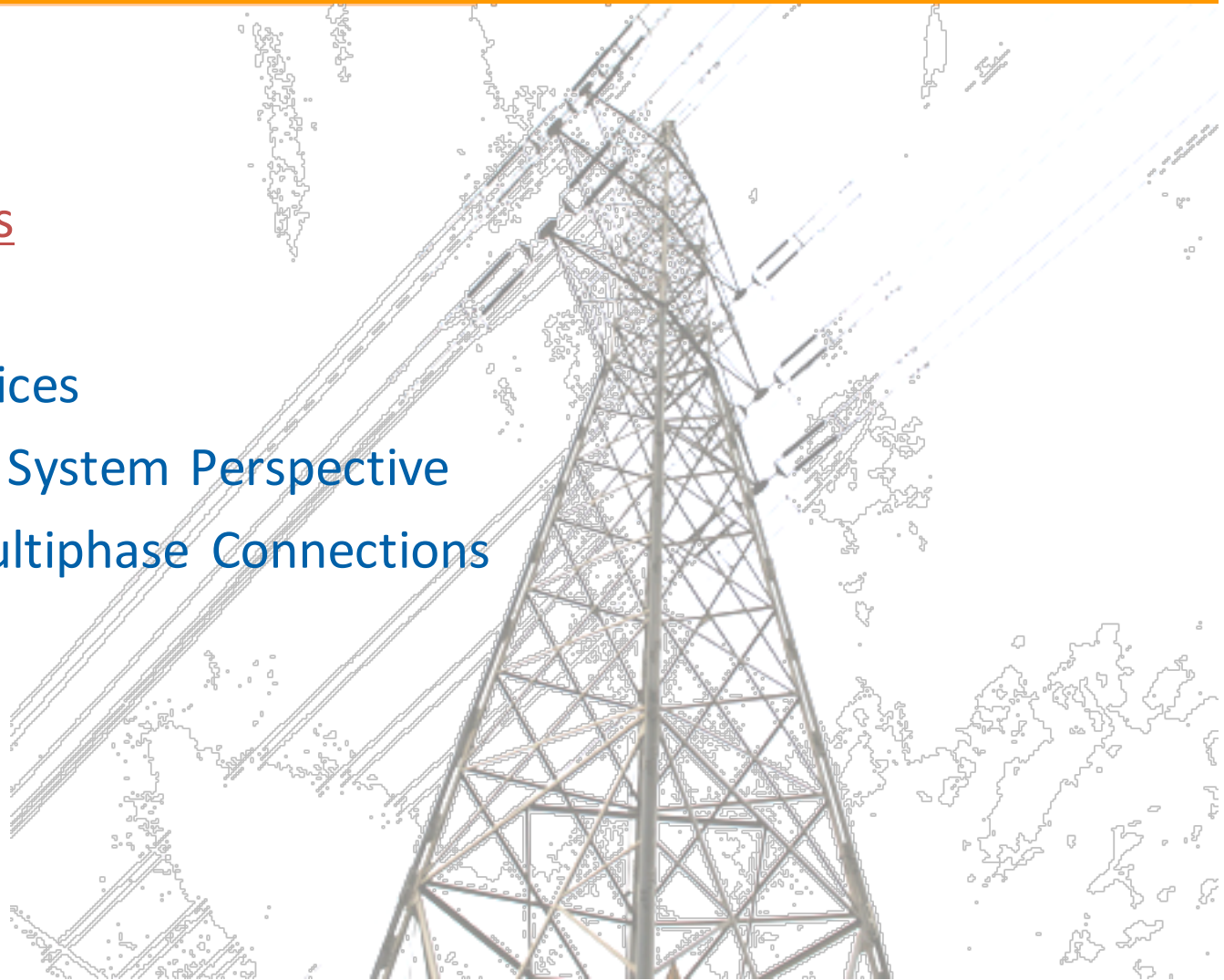
- Motors account for a large portion of our society's energy consumption
 - They represent a significant opportunity for energy saving
 - Increasing motor efficiency
 - Motor design
 - Speed controls
- Unlike resistive loads. Electric motors are sensitive to power quality
 - Voltage, frequency, harmonic content and phase imbalance
 - Causing excessive heating and energy and performance losses



5. Loads

■ Contents

- 1) Introduction
- 2) Resistive Loads
- 3) Motors
- 4) Electronic Devices
- 5) Load from the System Perspective
- 6) Single- and Multiphase Connections
- 7) Summary



5.4 Electronic devices (1)

- Electronic devices refer to capacitive loads
- Electronics are powered by a low-voltage d.c.
 - By batteries
 - Through a power supply
- They are not designed to do any real physical work, but to relay information by switching tiny circuits “on” or “off” in some pattern
- Pure electronic devices
 - Require a very small current
 - E.g. pocket calculator or digital wristwatches



5.4 Electronic devices (2)

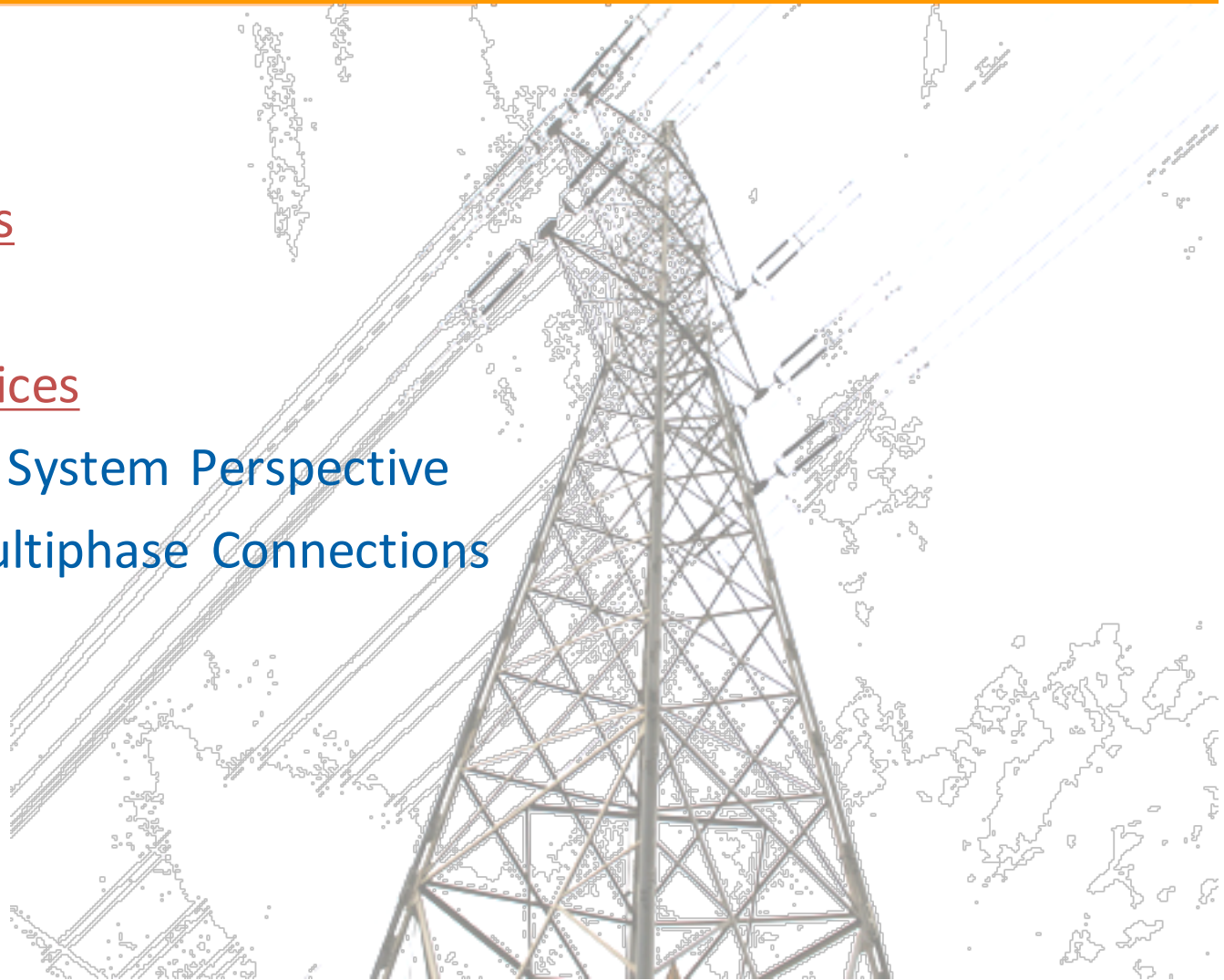
- Standby power refers to the consumed power by electronic devices (requiring physical work to operate) whenever they are plugged in and ready to respond
 - Can be recognized as a warmth on the back of the appliance
 - For a household, standby appliances consume annually hundreds of kWh
- Mixed electronic and power appliances appear as resistive or inductive loads, depending on the feature that dominates energy consumption
- Heat producing electronics represent a double energy load
 - Requiring cooling systems to protect them from overheating



5. Loads

■ Contents

- 1) Introduction
- 2) Resistive Loads
- 3) Motors
- 4) Electronic Devices
- 5) Load from the System Perspective
- 6) Single- and Multiphase Connections
- 7) Summary



5.5 Load from the system perspective (1)

- Demand refers to a physical quantity of power demanded at any given time
- Central challenge in designing and operating power systems is serving the instantaneous demand under diverse circumstances
- The historical service philosophy considers demand as the independent variable that is to be met by supply at any costs
 - Customers freely determine how much power they want
 - Power system operators have to accommodate this demand
 - Because of the consideration: “load is a variable beyond control”



5.5 Load from the system perspective (2)

- Recently, new philosophy has appeared by which customers vary their demand according to the electricity prices
 - Making demand more responsive
 - Using remote-controlled and automated devices
- Load forecasting refers to the process of predicting the demand at a given future time
 - Based on statistics of past demand behavior and other factors



5.5 Load from the system perspective (3)

- Coincident and noncoincident demand
 - Coincident demand refers to the amount of combined power demand that could normally be expected from a given set of customers
 - Noncoincident is the total drawn power by these customers if all their appliances were operating at the same time
 - E.g. suppose each of 10 residences had a 600 W refrigerator
 - The noncoincident demand would be 6000 W
 - As the compressor in each refrigerator goes on and off on a duty cycle and as these cycles will be at random in relation to each other, so we could expect at any given time only one in five is operating
 - → The coincident demand in this case would be 20% of 6000W (1200 W)



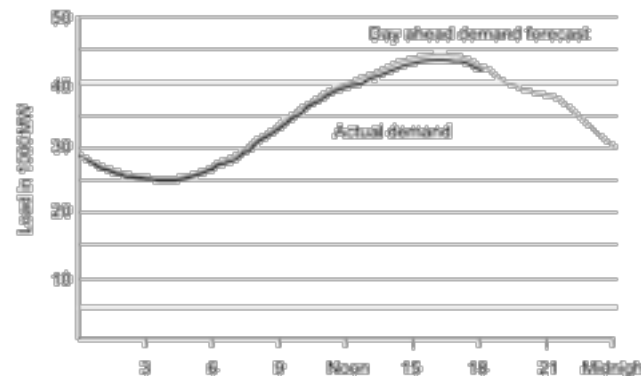
5.5 Load from the system perspective (4)

- Coincident and noncoincident demand
 - Power system operator must be prepared to face noncoincident demand under certain circumstances
 - E.g. after a power outage
 - In addition to the simultaneous operation of normal loads after an outage, the inrush currents of electric motors as they turn on and establish their internal magnetic field can overload the grid



5.5 Load from the system perspective (5)

- Load profiles and load duration curve
 - Load profile represents the instantaneous demand variation over the course of a day
 - At any level of aggregation: individual user, distribution feeder or entire grid
 - An actual day, or a statistical average over typical days in a given month or season
 - Peak demand refers to the maximum demand

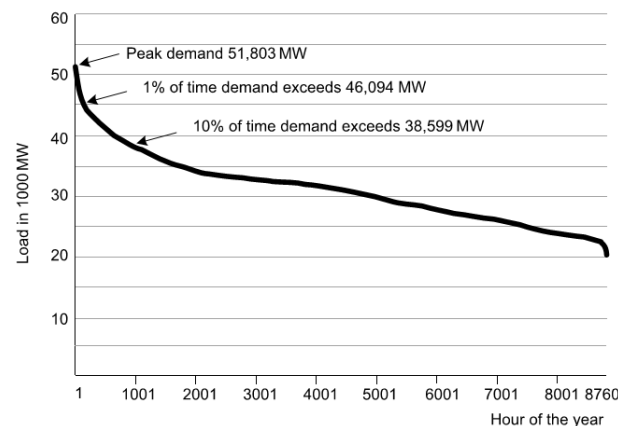


Load profile for an August day in California
(www.caiso.com)

Copyright John Wiley & Sons

5.5 Load from the system perspective (6)

- Load profiles and load duration curve
 - Load duration curve depicts instantaneous demand at various time (generally in one-hour intervals), but the hours are sorted not in temporal sequence but according to the demand in each hour
 - The highest demand hour of the year is the first hour
 - The shape of this curve is a useful to characterize the pattern of demand



Load duration curve for California
(www.energy.ca.gov)

Copyright John Wiley & Sons

5.5 Load from the system perspective (7)

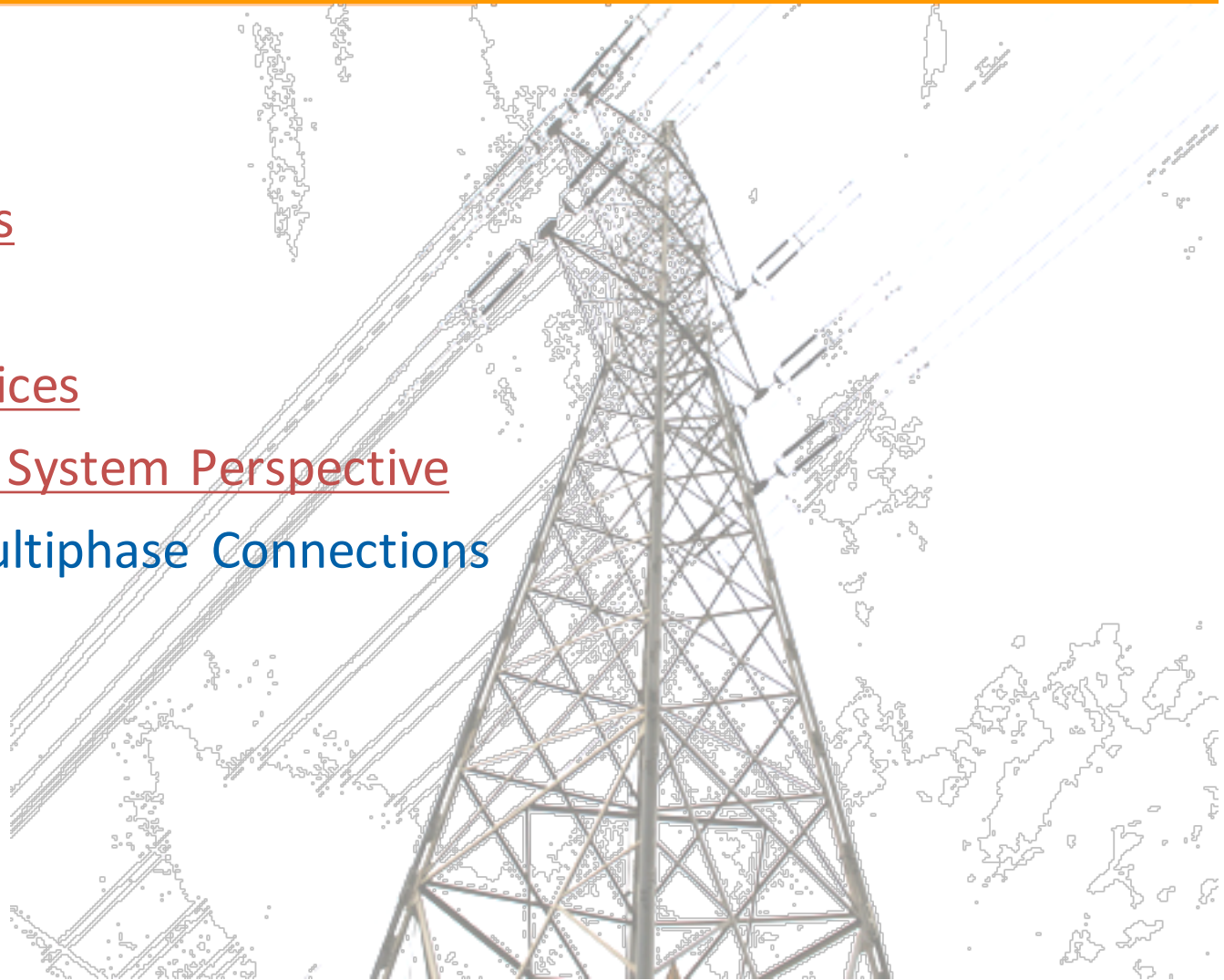
- Load profiles and load duration curve
 - Load factor is the ratio between average and peak demand
 - For utilities a relatively flat load duration curve with a high load factor is desirable, because:
 - The cost of providing service is related to peak capacity
 - Whereas, revenues are related to total energy consumed (i.e. average demand)
 - Load factor can be improved through increased load diversity, which refers to the diversity within the customer base
 - Commercial loads, residential loads



5. Loads

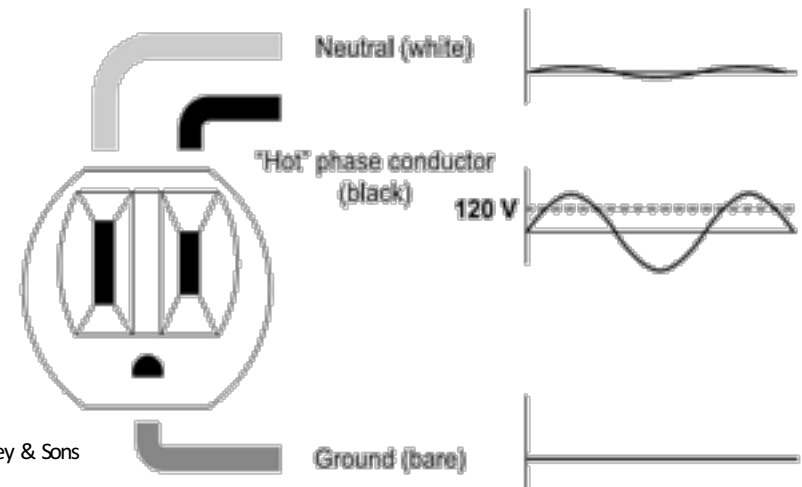
■ Contents

- 1) Introduction
- 2) Resistive Loads
- 3) Motors
- 4) Electronic Devices
- 5) Load from the System Perspective
- 6) Single- and Multiphase Connections
- 7) Summary



5.6 Single- and multiphase connections (1)

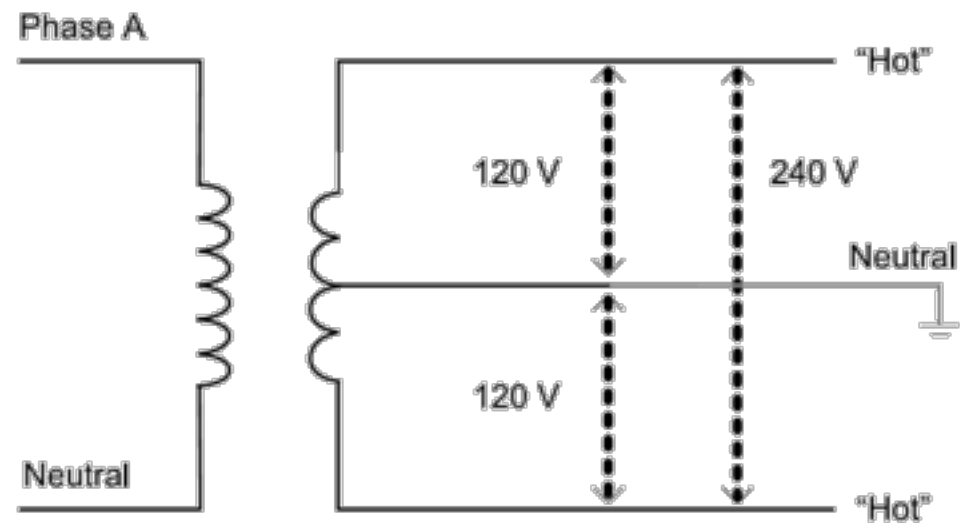
- 120 V Standard outlet has three terminals:
 - Hot: phase supplies an alternative voltage with an rms value of $120\text{ V} \pm 5\%$ between it and the neutral terminal
 - Neutral: its voltage between zero and a few volts
 - Balanced loads in the neighborhood between the three phases
 - Distance to the physically grounded neutral terminal
 - Safety ground



Copyright John Wiley & Sons

5.6 Single- and multiphase connections (2)

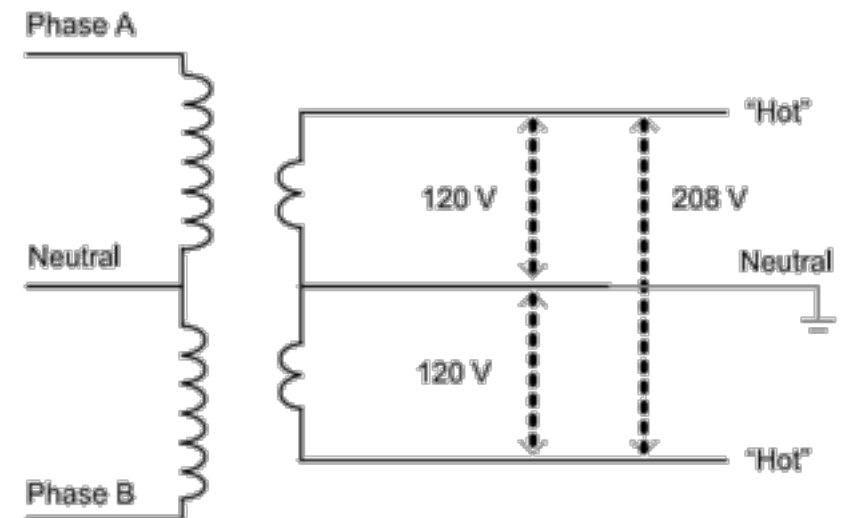
- 120/240 multiphase outlet
 - Consists of one neutral and two phase conductors
 - Both 120 and 240 are coming from the same phase (A, B or C)



Copyright John Wiley & Sons

5.6 Single- and multiphase connections (3)

- 120/208 multiphase outlet
 - Uses two different phase combination (A und B)
 - Phase-to-ground voltage between one phase and the neutral terminal is 120 V
 - Phase-to-phase voltage between two different phases is 208 V
 - 208 V corresponds to the difference between two sine curves of equal magnitude and shifted by 120 degrees
 $= 120\sqrt{3}$

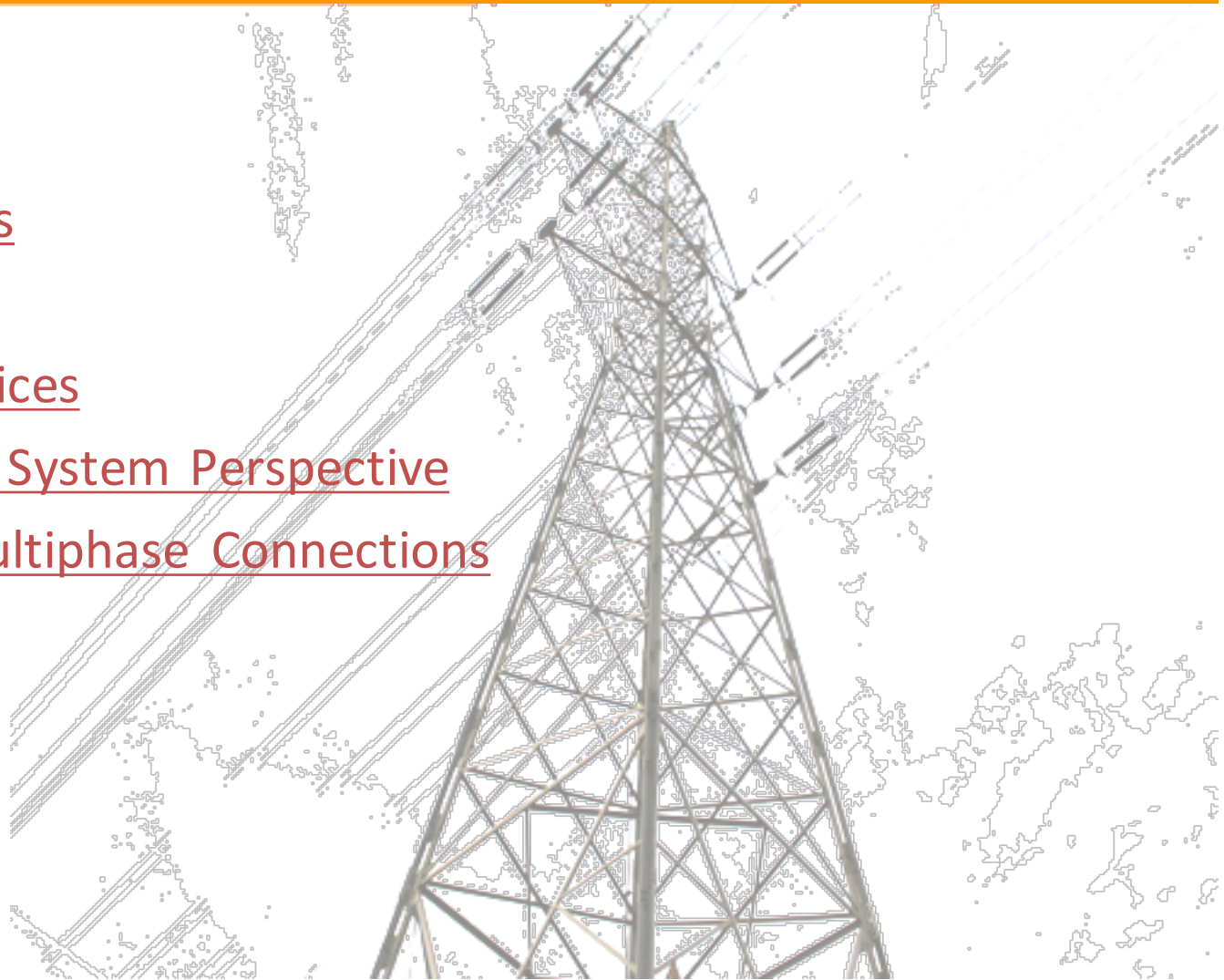


Copyright John Wiley & Sons

5. Loads

■ Contents

- 1) Introduction
- 2) Resistive Loads
- 3) Motors
- 4) Electronic Devices
- 5) Load from the System Perspective
- 6) Single- and Multiphase Connections
- 7) Summary



5.7 Summary

- Load refers to any device in which power is being consumed
- Theoretically there are three types of loads acc. to impedance
 - Resistive loads
 - Inductive loads (motors)
 - Capacitive loads (electronics devices)
- Central challenge in designing and operating power systems is serving the instantaneous demand under diverse circumstances
 - Load following power plant
 - Smart grid: demand response



Electric Power System

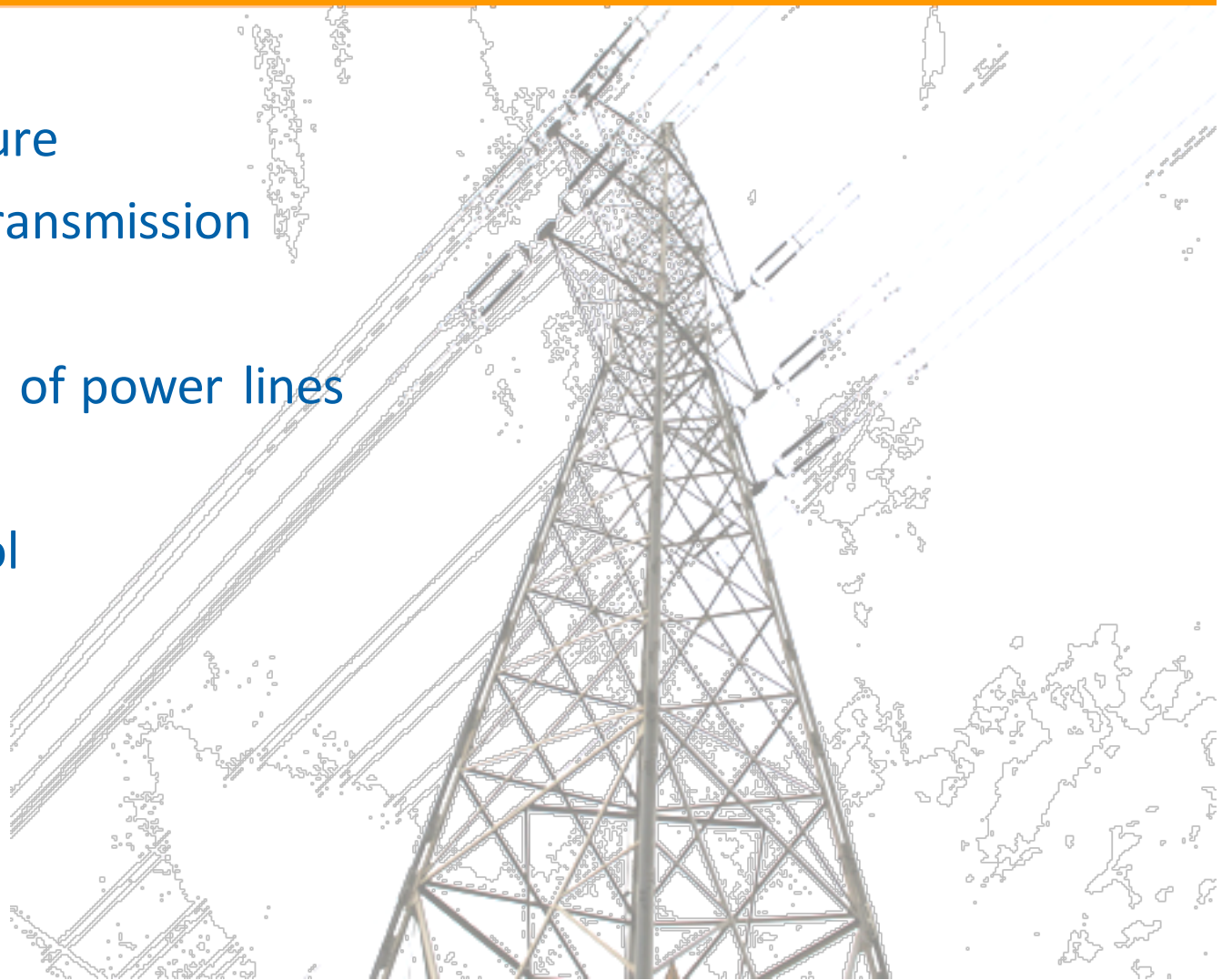
Chapter 6: Transmission and Distribution



6. Transmission and Distribution

■ Contents

- 1) System structure
- 2) Three phase transmission
- 3) Transformers
- 4) Characteristics of power lines
- 5) Loading
- 6) Voltage control
- 7) Protection
- 8) Summary



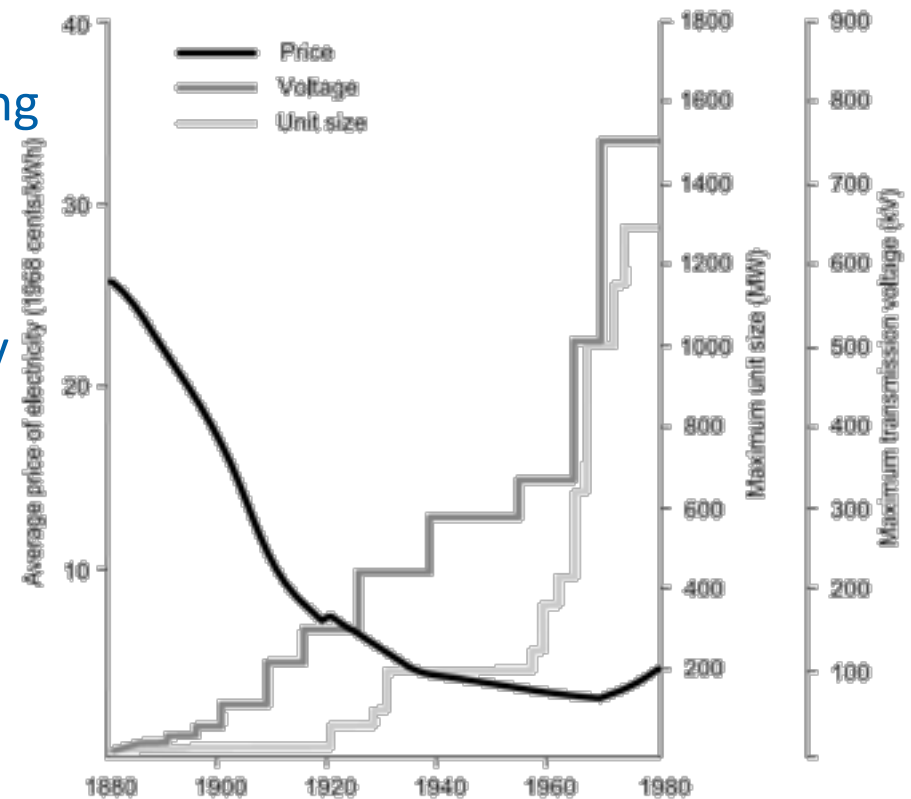
6.1 System Structure (1)

- Earlier, the standard power system consisted of an individual generator connected to an appropriately matched load
- Then, these isolated systems had begun to interconnect with each other, and to expand geographically to capture an increasing number of customers
- The technical justifications for expansion and interconnection of power systems are:
 - Economy of scale
 - Improvement of the load factor
 - Enhancement of reliability by pooling generating reserves



6.1 System Structure (2)

- Economy of scale
 - It is less expensive to build and operate one larger generator than several smaller ones
 - Construction costs and operating costs in aspects such as labor, maintenance and operational support are not depending very much on the unit's capacity



Copyright John Wiley & Sons

Historical growth of generation unit size and transmission voltage

6.1 System Structure (3)

- Load factor
 - It is the ratio of a load's actual energy consumption over a period of time (revenues) to the maximum amount of power it demands at any one instant (infrastructure investment)
 - Ideal customers would be demanding a constant amount of power 24 hours a day
 - Aggregating loads by combining a larger set and different types of customers within the same supply system whose demand times do not coincide
 - The greater the geographical expansion and interconnection, the larger the number of customers with different types of needs



6.1 System Structure (4)

- Service reliability
 - Generating reserve refers to the reserve margin of generation maintained by utilities for unexpected power losses or outages
 - When the generator is unavailable for any reason, the load can be served from another one elsewhere
 - The larger the number of interconnected utilities, the smaller the probability of their reserves being needed simultaneously
- This interconnection allows for managing and utilizing resources for power supply in the most economic way
 - More options in choosing the least expensive generators
 - More options for selling the electricity of a surplus of inexpensive generating capacity

6.1 System Structure (5)

- On the other side, the transmission voltages have to be increased to reduce current flow and therefore resistive losses in the lines
- Long transmission lines introduce the problem of stability
- The more the interdependence among areas, the greater the vulnerability to disturbances far away
 - Including voltage and frequency fluctuations



6.1 System Structure (6)

- Structural features
 - In the design of power delivery systems, the greater energy efficiency of high voltage and low current must be weighed against safety and capital cost
 - Transformers allow to operate different parts of the system at different voltages
 - Therefore, power delivery systems are divided into two general tiers:
 - A transmission system that spans long distances at high voltages
 - Hundreds of kilovolts (kV)
 - Local distribution system at intermediate voltages
 - Tens of kV



6.1 System Structure (7)





- Structural features
 - Primary distribution systems
 - Tens of kV
 - Connect large commercial and industrial customers
 - Secondary distribution systems
 - At voltage in 100 V range
 - Connect most domestic and small commercial customers
- → the entire power delivery system is referred to as *the transmission and distribution (T&D) system*
 - Division is defined in terms of voltage level
 - In general, “distribution” means below 60 or 70 kV
 - Physically, the boundary is demarcated by transformers

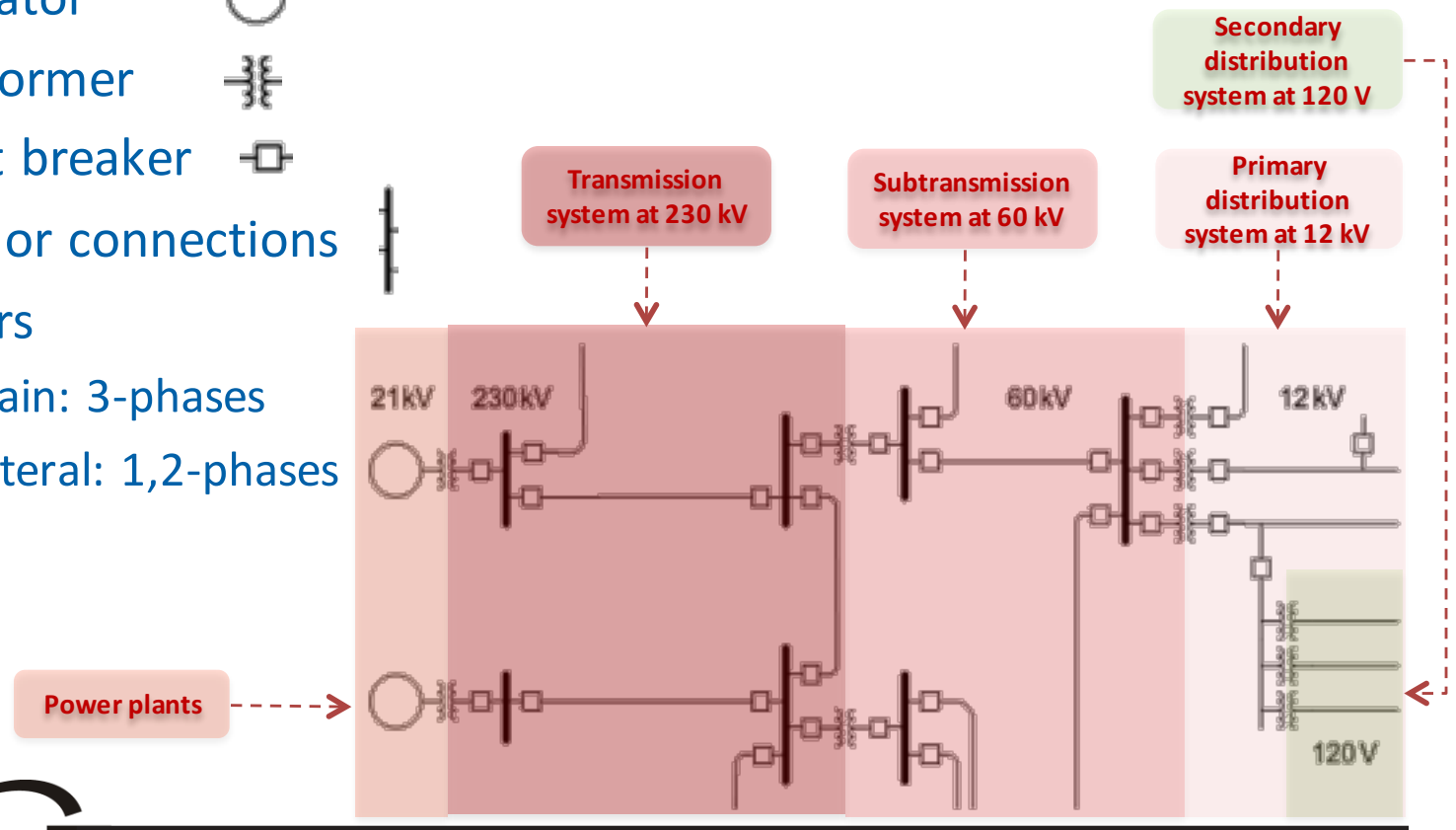


6.1 System Structure (8)

■ Sample diagram (one-line diagram)

■ Basic components

- Generator 
- Transformer 
- Circuit breaker 
- Buses or connections 
- Feeders
 - Main: 3-phases
 - Lateral: 1,2-phases



Copyright John Wiley & Sons

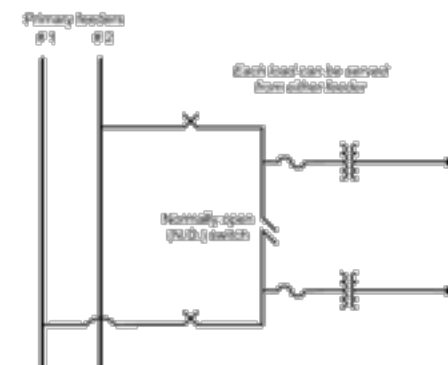
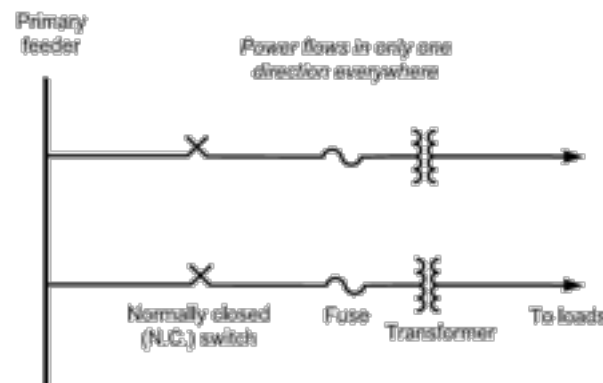
6.1 System Structure (9)

- Topology
 - It refers to how the transmission and distribution lines are connected
 - Radial configuration where lines branch out sequentially and power flows strictly in one direction
 - Network configuration where the lines are more interconnected and some lines form loops so that any two points are usually connected by more than one path
 - Transmission systems are generally networks
 - Redundancy



6.1 System Structure (10)

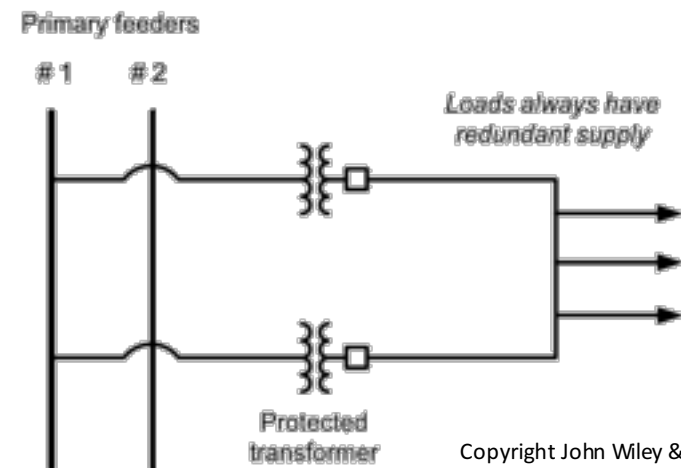
- Topology
 - Radial system
 - A strict hierarchy: power flows in one direction
 - Any component can be energized from one direction
 - Upstream and downstream
 - Fault can readily be isolated
 - Normally open (N.O.) loops can be used to improve the reliability



Copyright John Wiley & Sons

6.1 System Structure (11)

- Topology
 - Network system
 - No hierarchy
 - More reliable because of built-in redundancy
 - More expensive than a simple radial system
 - Larger number of lines
 - Equipment for switching and protection
 - Complex fault isolation



Copyright John Wiley & Sons

6.1 System Structure (12)

- Topology
 - Power island refers to an energized section of circuits separate from the larger system
 - One or more local generators continue to power a location during a service interruption
 - Rooftop photovoltaic, fuel cells
 - Reasons for anti-islanding
 - Safety concerns: jeopardizing the safety of line crews
 - Liability: different power quality can damage customer equipment which the utility may then be held liable



6.1 System Structure (13)

- Loop flow
 - It can arise whenever there are multiple paths between two points in the system
 - The problem is that the current cannot be directed along any particular branch in the network, but determined by:
 - Kirchhoff's laws
 - Relative impedance of the links
 - Power flow through the network becomes critically important when there is congestion or overloading of transmission lines
 - Effectively adjusting of generator output

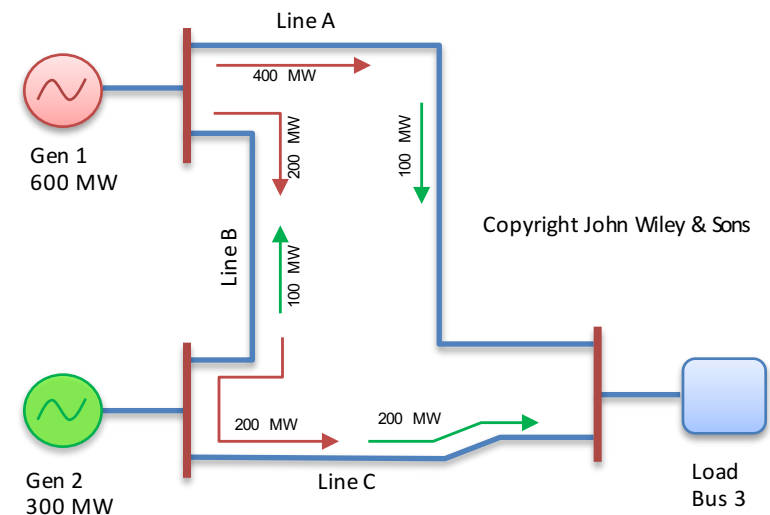


6.1 System Structure (14)

■ Loop flow

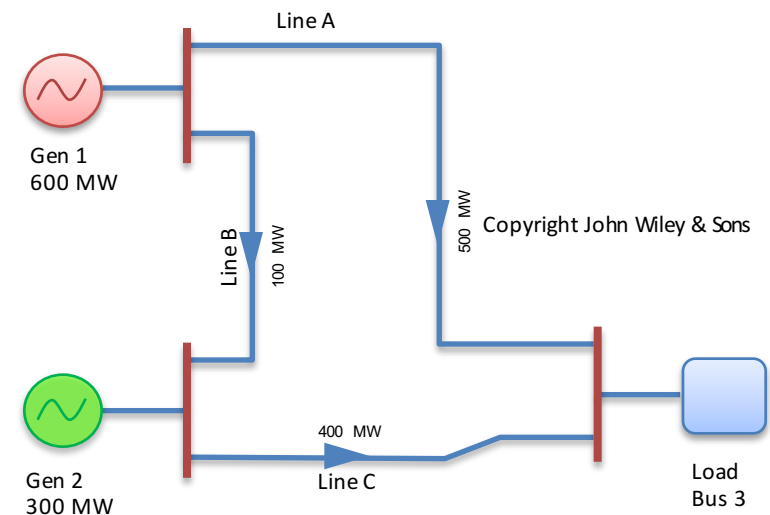
■ Example

- One load at bus 3 of 900 MW
- Two generators supply 600 MW and 300 MW
- Three transmission lines A, B, C
 - The impedances are exactly the same
- Power flows
 - From Gen1 to load3 through
 - Path 1 = line A
 - Path 2 = line B + line C
 - From Gen2 to load3 through
 - Path 1 = line C
 - Path 2 = line B + line A



6.1 System Structure (15)

- Loop flow
 - Example
 - Power flows by superposition principle
 - Line A = 400 MW + 100 MW = 500 MW
 - Line B = 200 MW - 100 MW = 100 MW
 - Line C = 200 MW + 200 MW = 400 MW
 - The more paths connecting to the buses, the more complicated the power flow calculation
 - The effect of one generator's output may be to reduce rather than to increase the flow on a given link



6.1 System Structure (16)

- Stations and substations
 - Represent an interface between different levels or sections of the power system, with the capability to switch or reconfigure the connections among various lines
 - Largest scale: a transmission substation would be the meeting place for different high voltage transmission circuits
 - Intermediate scale: a large distribution station would receive high-voltage transmission on one side and provide power to a set of primary distribution circuits. They include control room from which operations are coordinated
 - Smaller scale: a smaller distribution substation receives high-voltage power and send out a number of distribution feeders at lower voltage. It serves limited area and is usually unstaffed



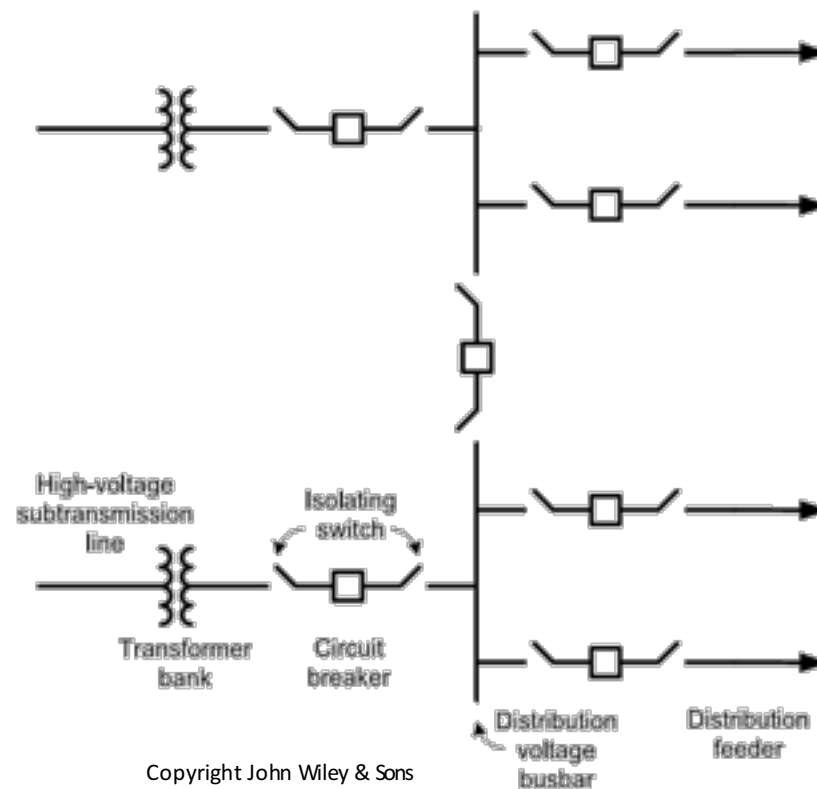
6.1 System Structure (17)

- Stations and substations
 - Transformer (bank): represents a central component as it provide an interface between high- and low-voltage system parts
 - Circuit switches: control devices that can be opened or closed deliberately to establish or break a connection.
 - Operable under normal current
 - Circuit breakers: protective devices that open automatically in the event of a fault, that is, when a protective relay indicates excessive current due to some abnormal condition
 - Capacitor bank: to provide voltage support



6.1 System Structure (18)

- Stations and substations
 - Distribution substation layout



6.1 System Structure (19)

- Reconfiguring the system
 - Switching operations
 - Remotely through a supervisory control and data-acquisition (SCADA)
 - Manually by field crews per telephone instructions from operators
 - Switching reasons
 - Contingencies: isolation of faulty line and redistribution the load among the other connection
 - Work clearance: maintenance or replacement of a line or system component requires isolating of this component
 - Service restoration after an outage
 - Managing overloads
 - Enhancing system efficiency



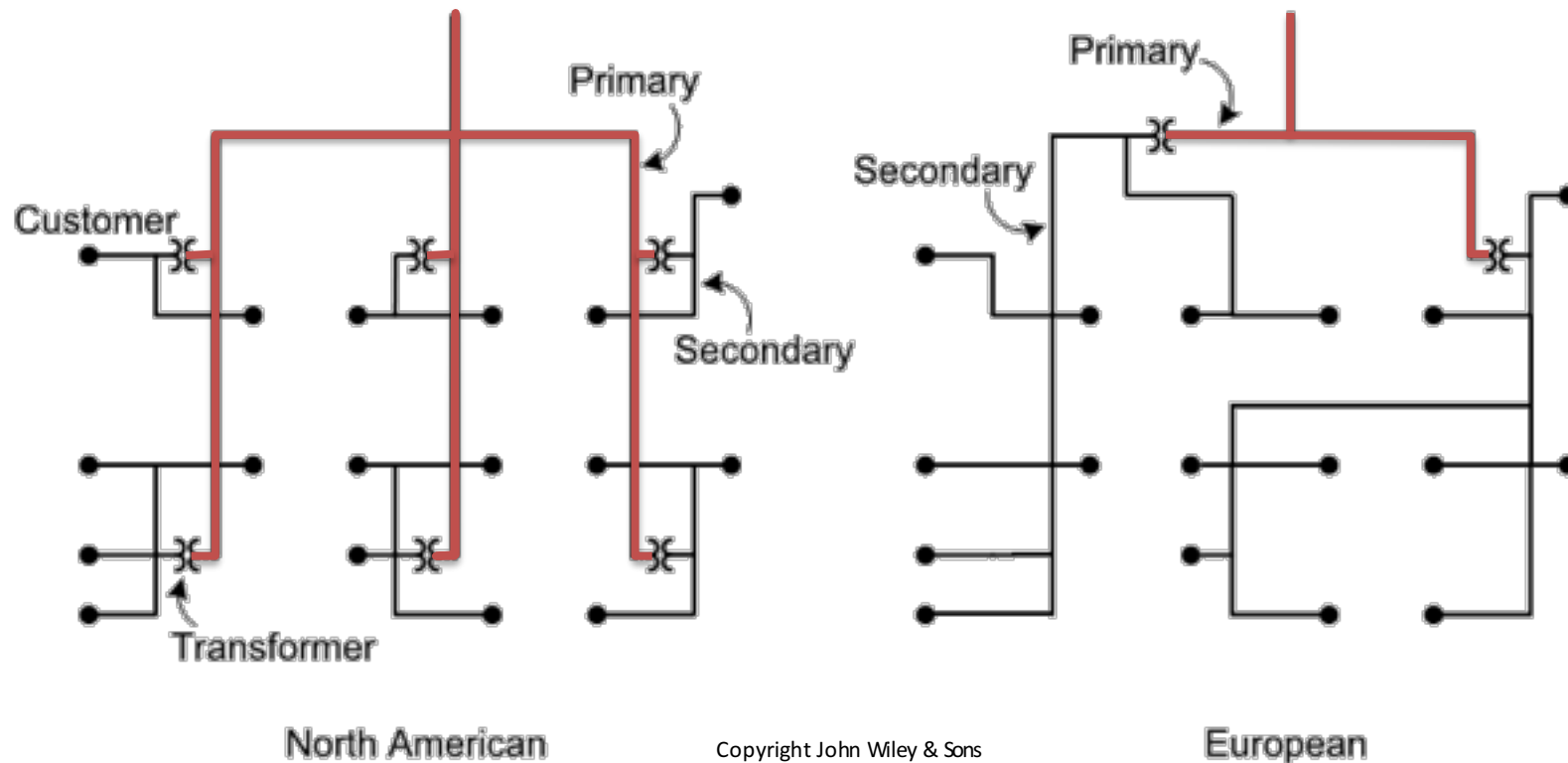
6.1 System Structure (20)

- International differences in distribution system design
 - In Europe
 - Standard secondary voltage is 220 V
 - There are fewer and larger transformer
 - Transformer are hidden in vaults
 - Inexpensive secondary (low-voltage) lines represent the larger part of the distribution system (undergrounded)
 - In United States
 - Standard secondary voltage is 120 V
 - A distribution transformer for every few customers
 - Distribution transformers are mounted on poles
 - Expensive primary (medium-voltage) lines makes up the larger part of the distribution system



6.1 System Structure (21)

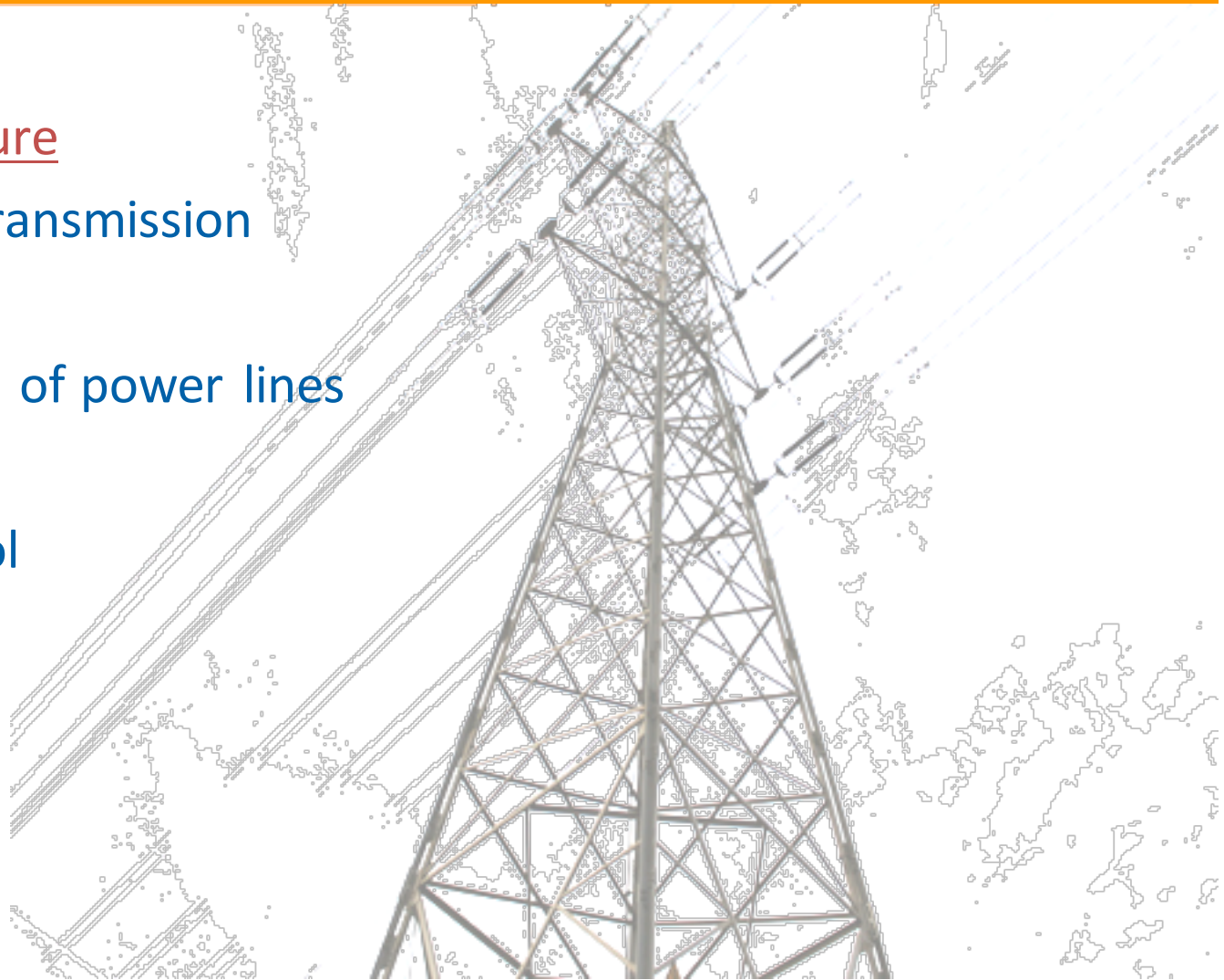
- International differences in distribution system design



6. Transmission and Distribution

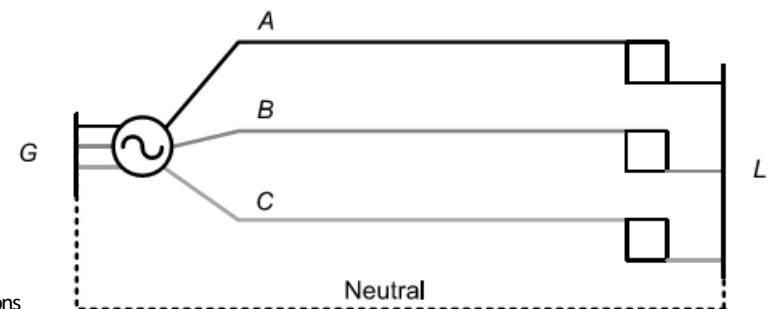
■ Contents

- 1) System structure
- 2) Three phase transmission
- 3) Transformers
- 4) Characteristics of power lines
- 5) Loading
- 6) Voltage control
- 7) Protection
- 8) Summary



6.2 Three-phase Transmission (1)

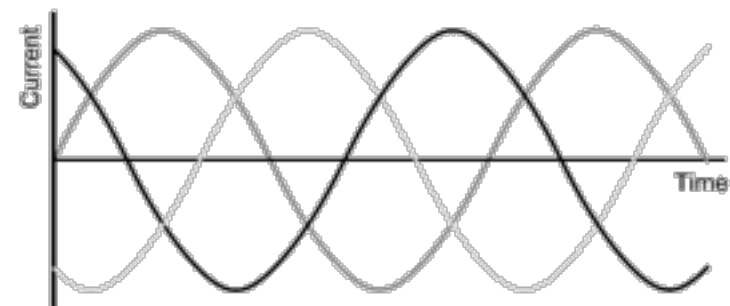
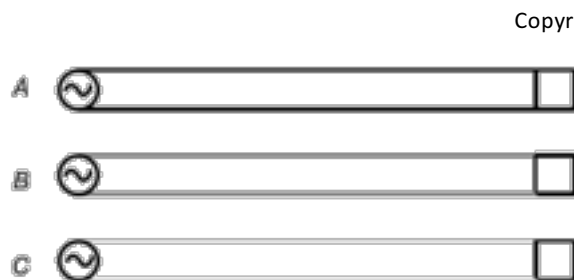
- Rationale for three phases
 - Smooth power generating
 - A constant torque (uniform force) on the rotor as opposed to the pulsating torque that appears in single-or two-phase machine
 - Economy of transmission
 - Fewer wires and less conductor capacity
 - One combined return conductor for the three phases



Copyright John Wiley & Sons

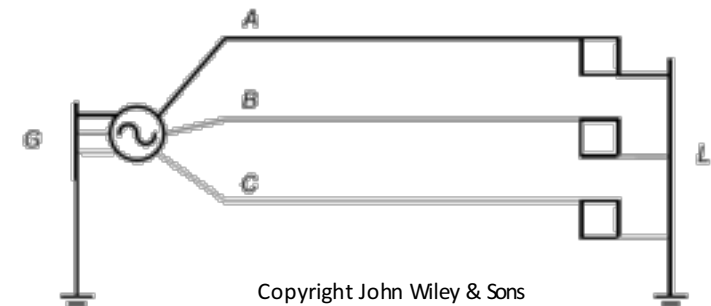
6.2 Three-phase Transmission (2)

- Rationale for three phases
 - Economy of transmission
 - What would be the combined current in the wire?
 - If the three phases are exactly 120° apart and have the same amplitude, then
 - Always $I_A(t) + I_B(t) + I_C(t) = 0$



6.2 Three-phase Transmission (3)

- Rationale for three phases
 - Economy of transmission
 - What would be the voltage at the source point G (at generator) and L (at load)?
 - The sum of the three generated sinusoidal waves remains also zero at all times, assuming that all three loads are identical
 - →no potential difference between G and L →no return current → the wire can be simply eliminated
 - In reality, loads may not be balanced → flowing of some return current → G and L are both grounded



6.2 Three-phase Transmission

(4)

- Rationale for three phases
 - Why three phases is the global standard?
 - Only two phases means a greater vulnerability to imbalance in the loading of two circuits
 - More phases can absorb the difference
 - More than three phases
 - Expensive and complicated
 - E.g. transmission and distribution lines should consists of more separate conductors
 - For the same amount of total power, the capacity of each component could be smaller, whereas the total cost would be greater



6.2 Three-phase Transmission

(5)

- Balancing loads
 - Eliminating of the return conductor is based on the assumption that “the total load connected to each phase is identical”
 - Certain loads such as large commercial motors connected to all phases draw power equally from all of them
 - But, Combined loads from small commercial and residential customers have to be distributed as evenly as possible between the three phases
 - Balancing loads is an approximate procedure
 - Limited precision: loads come in chunks
 - Fluctuating balance: switching on and off of devices



6.2 Three-phase Transmission (6)

■ Delta and wye connections

- A wye (Y) connection refers to the arrangement, where three loads are connected one phase each and ground

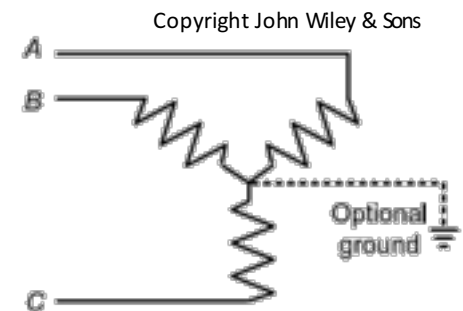
- Phase-to-ground voltage

- E.g. 120 V

- For each load voltages and current are 120° apart

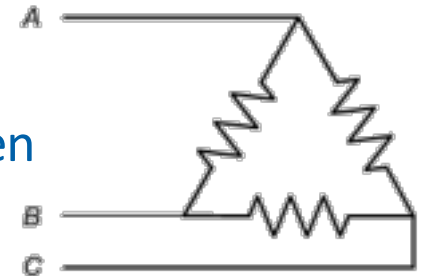
- Another single ground anywhere else in the system will cause a fault and the breakers will be opened

- Typically used on generators, main transformer banks and transmission lines

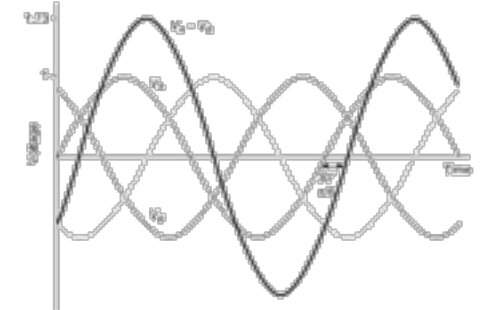


6.2 Three-phase Transmission (7)

- Delta and wye connections
 - A delta connection (Δ) refers to the arrangement, in which three loads are connected between one pair of phases
 - Phase-to-phase voltage
 - The voltage across a load is the difference between the voltages on both sides
 - Phase-to-phase voltage = $\sqrt{3}$ Phase-to-ground voltage
 - Phase current = line current $/\sqrt{3}$
 - If any part of the circuit accidentally gets grounded, the delta connection can continue to operate
 - \rightarrow more reliable
 - Used on auxiliary equipment in power plants, or on smaller transformer



Copyright John Wiley & Sons



6.2 Three-phase Transmission

(8)

- Three-phase power
 - Transmitted apparent power $S = 3 \times (\text{voltage} \times \text{current (for each phase)})$
 - V_{rms} refers to the phase-to-phase voltage
 - I_{rms} refers to flowing current in each conductor
 - In case of wye connection: voltage seen by the load is the line-to-ground $\rightarrow \text{voltage} = V_{\text{rms}} / \sqrt{3}$
 - $\rightarrow S = 3 I_{\text{rms}} (V_{\text{rms}} / \sqrt{3})$
 - In case of delta connection: the current through each conductor contributes to two phase pairs \rightarrow for each load the credited current is only $1/\sqrt{3}$ of the line current
 - $\rightarrow \text{current} = I_{\text{rms}} / \sqrt{3} \rightarrow S = 3 (I_{\text{rms}} / \sqrt{3}) V_{\text{rms}}$



6.2 Three-phase Transmission (9)

- Three-phase power
 - → Transmitted apparent power

$$S = \sqrt{3} I_{\text{rms}} V_{\text{rms}}$$

regardless of how the load is connected

- For real and reactive power need to include $\cos\Phi$ and $\sin\Phi$ respectively, depending on load power factor (p.f.).



6.2 Three-phase Transmission (10)

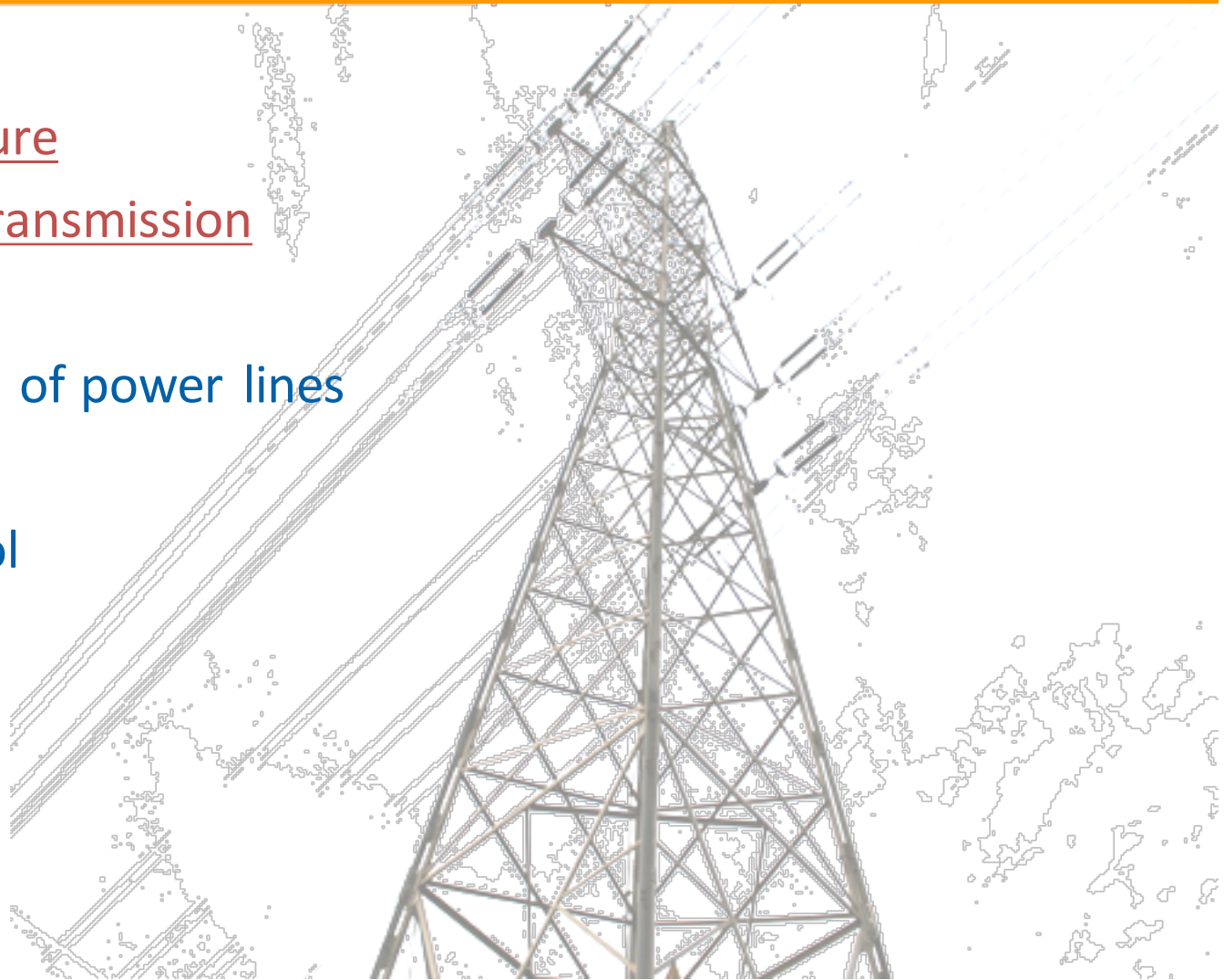
- D.C. transmission
 - Power has to be converted both at the beginning and the end of the d.c. line
 - Using costly solid-state devices (thyristors)
 - d.c. transmission is worthwhile
 - No stability limit because reactance is irrelevant for d.c.
 - May carry very high voltages and is therefore highly efficient
 - Provide intertie between two a.c. systems that are not in sync
 - Not vulnerable to frequency-related disturbances
 - Have a thermal limit (determined by the line resistance)



6. Transmission and Distribution

■ Contents

- 1) System structure
- 2) Three phase transmission
- 3) Transformers
- 4) Characteristics of power lines
- 5) Loading
- 6) Voltage control
- 7) Protection
- 8) Summary



6.3 Transformers (1)

■ General properties

- A transformer is a device for changing the voltage in an a.c. circuit

- Consists of two conductor coils with different number of turns or loops in each coil

- Primary winding (n_1)

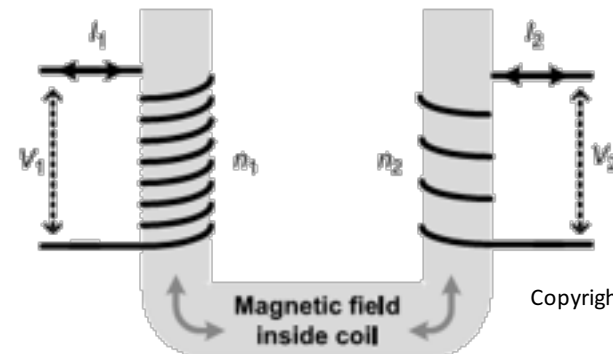
- Power source connection

- Secondary winding (n_2)

- Load connection

- The two coils are not connected electrically but through magnetic flux

- Ideally, the same amount of power goes into the transformer as goes out



Copyright John Wiley & Sons



6.3 Transformers (2)

- General properties

- Transformer coils are wound (with n turns) around a core of magnetically susceptible material (e.g. iron) with a low magnetic reluctance \mathcal{R}

- In the primary winding:

- Magnetomotive force $\text{mmf} = nI$
- Produced magnetic flux $\Phi = \text{mmf} / \mathcal{R}$

- In the secondary winding:

- Inducing an electromotive force (emf)
- Current is determined by the connected impedance
- Emf is proportional to the number turns (n_2) and the flux change rate



6.3 Transformers (3)

■ General properties

- Changing the voltage is related to the turns ratio between primary and secondary windings

- $n_1 = n_2 \rightarrow$ no change

- $n_1 > n_2 \rightarrow$ step down the voltage

- $n_1 < n_2 \rightarrow$ step up the voltage

$$\frac{V_1}{V_2} = \frac{n_1}{n_2} = \frac{I_2}{I_1}$$

- Some transformers have a transformer tap, which is a movable connection between the secondary winding and the conductor.
- This tap adjust the voltage by moving up or down changing the effective turns ratio
 - Load tap changers (LTCs): used in distribution transformers to compensate changes in voltage level associated with changes in load

6.3 Transformers (4)

- Transformer heating
 - Refers to the power dissipated as a heat in a transformer
 - Copper losses: the power losses in the windings due to the electrical resistance of the conductor
 - Iron losses: the power losses from the transformer core
 - result from the rapid direction change of the magnetic field → friction due to continually realignment of the iron particles in the direction of the field
 - Smaller transformers are passively cooled by radiating heat away to their surrounding
 - Large transformers require the heat to be removed from the core and windings by active cooling
 - E.g. through circulating oil



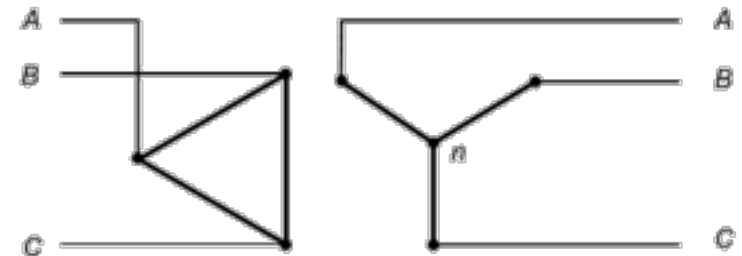
6.3 Transformers (5)

- Delta and wye transformers
 - Transforming three-phase power requires three transformers, one for each phase.
 - These transformers are magnetically separate
 - They don't share magnetic flux among their cores, because the three fluxes oscillate in different phases
 - Delta and wye connections are used
 - To connect a set of single-phase loads to three-phase system
 - To connect a set of transformers to three-phase system

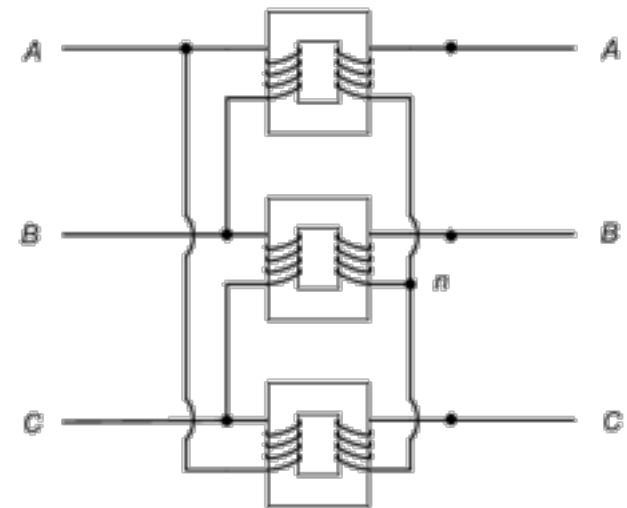


6.3 Transformers (6)

- Delta and wye transformers
 - In the wye connection
 - Each transformer winding connects between one phase and ground
 - In the delta connection
 - Each transformer winding connects between one phase and another
 - Because of electrical separation between the primary and secondary side, the type of connection on either side need not to be the same

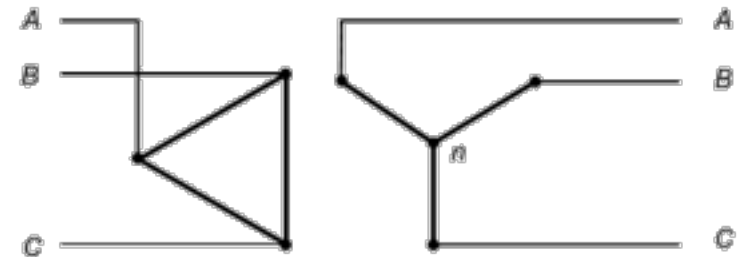


Copyright John Wiley & Sons

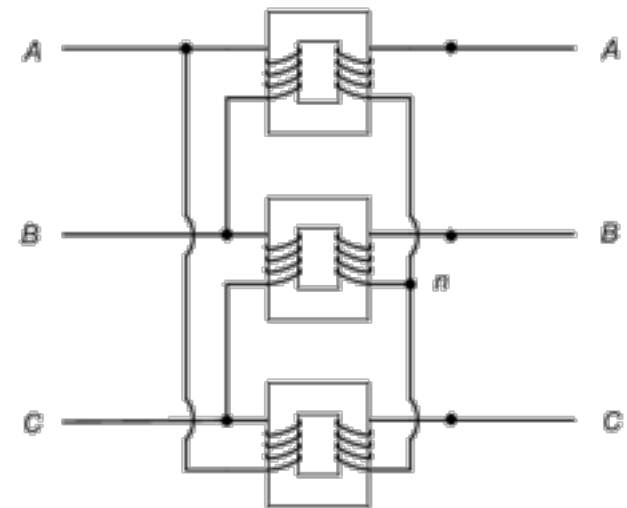


6.3 Transformers (7)

- Delta and wye transformers
 - → there are four possibilities for a three-phase transformer connection
 - $\Delta - \Delta, Y - Y, \Delta - Y, Y - \Delta$
 - Using the same connection on both sides
 - As in $\Delta - \Delta, Y - Y$
 - The voltage change from the primary to the secondary side is simply given by **the turns ratio**

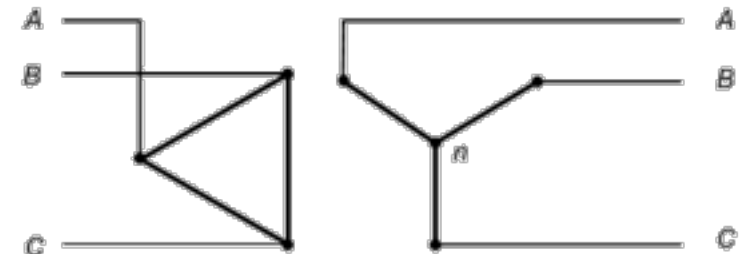


Copyright John Wiley & Sons

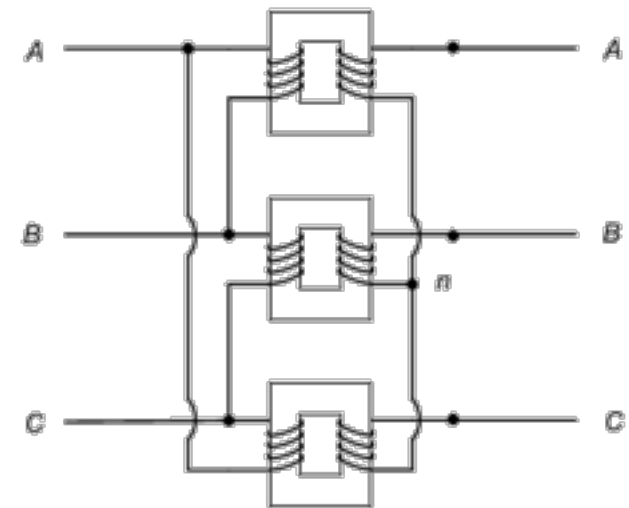


6.3 Transformers (8)

- Delta and wye transformers
 - Using different connection on either side
 - As in $\Delta - Y$, $Y - \Delta$
 - The voltage change is affected by
 - The turns ratio
 - The connection type
 - Phase-to-phase voltage = $\sqrt{3}$ ·Phase-to-ground voltage
 - $\Delta - Y$ transformer increases voltage by a factor $\sqrt{3}$
 - $Y - \Delta$ transformer decreases voltage by a factor $\sqrt{3}$



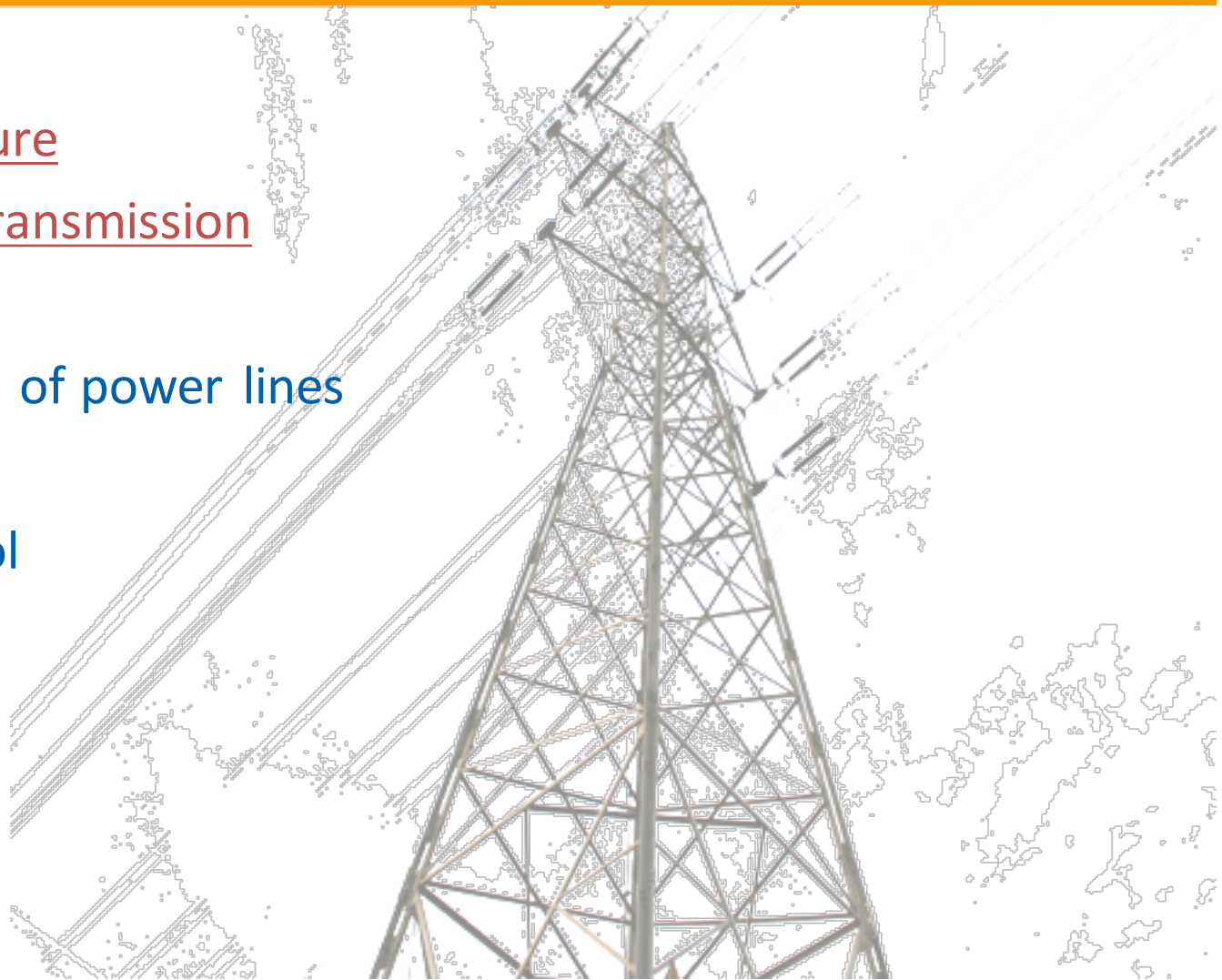
Copyright John Wiley & Sons



6. Transmission and Distribution

■ Contents

- 1) System structure
- 2) Three phase transmission
- 3) Transformers
- 4) Characteristics of power lines
- 5) Loading
- 6) Voltage control
- 7) Protection
- 8) Summary



6.4 Characteristics of power lines (1)

- Conductors
 - Overhead lines
 - Lightweight: Aluminum and reinforced with steel
 - Often stranded
 - Much easier to bend and manipulate
 - Underground cables
 - Heat dissipation
 - Copper
 - Low resistance to minimize energy losses
 - Line resistance increases linearly with distance and decreases with the conductor cross section, $R = \rho l/A$
 - Line resistance is critical in the context of line losses



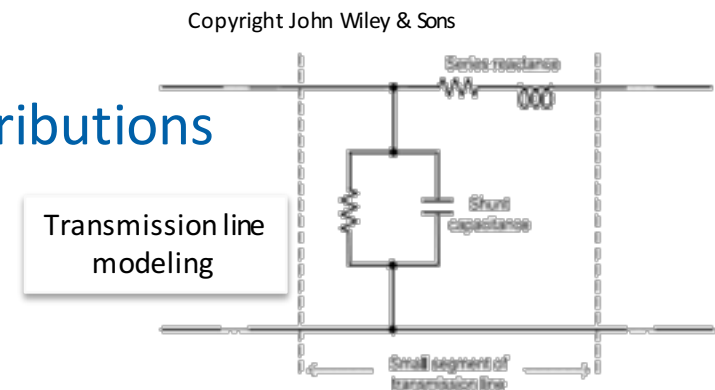
6.4 Characteristics of power lines (2)

- Conductors
 - Line inductance
 - The impedance of a line is dominated by its inductive reactance more than its resistance
 - Transmission and distribution lines have inductance
 - Since straight wire can be considered an infinitely large loop, and
 - the magnetic flux around the wire does link it
 - Magnetic effect is cumulative on per-unit-length basis → the effect increases with length of the conductor
 - There are two inductance contributions
 - Self inductance : as a part of large loop
 - Mutual inductance : between the conductors of the three different phases



6.4 Characteristics of power lines (3)

- Conductors
 - Line capacitance
 - Between two parallel lines with gap in between
 - Between a conductor and the ground
 - In coaxial cables where one conductor surrounds another with insulation in between
 - → in general, lines can be characterized in terms of an equivalent resistance, reactance and capacitance on a per-meter or per-mile basis
 - Summing up the line segments' contributions
 - → inductance, capacitance and resistance increase with line length



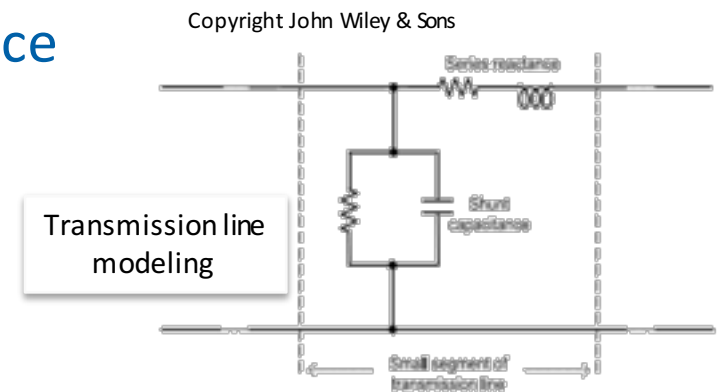
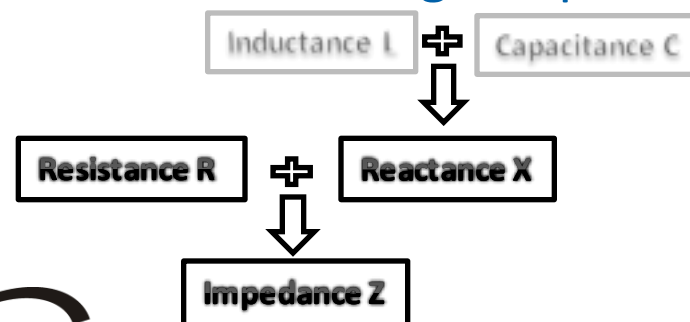
6.4 Characteristics of power lines (4)

■ Conductors

- **Characteristic impedance** is the ratio of series impedance (resistance and reactance) and shunt admittance (capacitance)
- **Surge impedance (SI)** is the square root of inductance to capacitance, in the case where resistance is negligible

- $SI = \sqrt{\frac{L}{C}}$

- In telecommunications: a voltage signal can be transmitted with minimal loss if the resistance connected at the line end is equal in magnitude to line's surge impedance



6.4 Characteristics of power lines (5)

- Conductors
 - For power lines: Surge impedance loading (SIL) states the amount of real power transmission where the line's inductive and capacitive properties are completely balanced
 - $SIL = V^2 / SI$
 - Measured in MW
 - If transmitted power along the line is less than SIL → the line appears as capacitance that injects reactive power (VARs) into the system
 - If the transmitted power exceeds SIL → the line appears as inductance that consumes VARs
 - SIL serves as benchmark to system operator



6.4 Characteristics of power lines (6)

- Conductors
 - Inductance → reactive power consumption
 - Is a function of the line current
 - $Q_{\text{loss}} = I^2 X_L$
 - $X_L = \omega L$
 - Capacitive → reactive power generating
 - Is a function of the line's energizing voltage
 - $Q_{\text{prod}} = V^2 / X_c$
 - $X_c = -1 / \omega C$
 - Balanced state:
 - $Q_{\text{prod}} = Q_{\text{loss}} \rightarrow X_L X_c = V^2 / I^2$



6.4 Characteristics of power lines (7)

- Conductors
 - Impedance is the ratio of voltage to current (Ohm's law)
 - Impedance = $\frac{V}{I} = \sqrt{L/C}$, which is the surge impedance
 - Then, the surge impedance loading is $SIL = \frac{V^2}{\sqrt{L/C}}$



6.4 Characteristics of power lines (8)

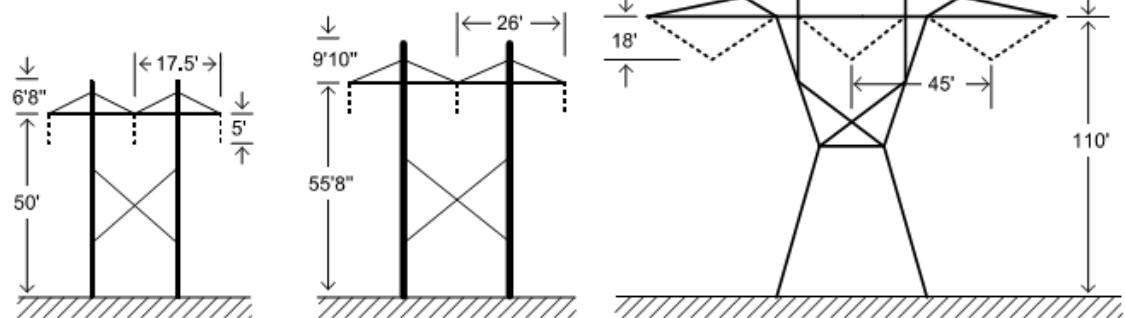
■ Conductors

■ Sample transmission line data

	Line Voltage (kV)		
	138	345	765
Conductors per phase	1	2	4
Number of strands aluminum/steel	54/7	45/7	54/19
Diameter (in.)	0.977	1.165	1.424
Conductor geometric mean radius (ft)	0.0329	0.0386	0.0479
Current-carrying capacity per conductor (A)	770	1010	1250
Geometric mean diameter phase spacing (ft)	22.05	32.76	56.7
Inductance ($H/m \times 10^{-7}$)	13.02	9.83	8.81
Inductive reactance X_L (Ohms/mi)	0.789	0.596	0.535
Capacitance ($F/m \times 10^{-12}$)	8.84	11.59	12.78
Capacitive reactance X_C (MOhms/mi)	0.186	0.142	0.129
Resistance (Ohms/mi)	0.1688	0.0564	0.0201
Surge impedance loading (MVA)	50	415	2268

Source: Bergen, Arthur R.; Vittal, Vijay, *Power Systems Analysis*, 2nd Edition, © 2000, p. 85. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.

Copyright John Wiley & Sons



Copyright John Wiley & Sons

6.4 Characteristics of power lines (9)

- Conductors
 - Bundled conductor is composed of two, three or four wires a few inches apart, held together with connectors (conducting frames)
 - Such as high-voltage and high capacity transmission lines
 - Advantages
 - Increasing heat dissipation because of increasing the surface area of the conductors → more effectively radiate heat off into the surrounding environment



6.4 Characteristics of power lines (10)

■ Conductors

- Bundled conductor is composed of two, three or four wires a few inches apart, held together with connectors (conducting frames)
 - Such as high-voltage and high capacity transmission lines
 - Advantages
 - Increasing heat dissipation
 - Reducing corona losses
 - Corona discharge refers to the microscopic arcs occurring between the conductor surface at high potential and ionized air molecules in the vicinity (e.g. Tesla coil)
 - Increasing conductor's surface area → decreasing the surface charge density → reducing electrical field strength → reducing formation of arcs → reducing corona losses



6.4 Characteristics of power lines (11)

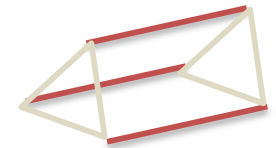
- Conductors
 - Bundled conductor is composed of two, three or four wires a few inches apart, held together with connectors (conducting frames)
 - Such as high-voltage and high capacity transmission lines
 - Advantages
 - Increasing heat dissipation
 - Reducing corona losses
 - Reducing line inductance
 - Inductance is less for a bigger wire diameter
 - Changing a single wire into a bundled conductors makes it resemble a wire of larger diameter (concerning magnetic fields)



6.4 Characteristics of power lines (12)

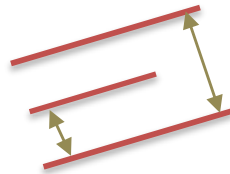
■ Conductors

- To keep mutual inductance about equal on all three phases, the three conductors should be arranged symmetrically as an equilateral triangle



- Over a long distance, it is not possible

- Wires are in a row



- Asymmetry

- Therefore, the wires are transposed every so often, allowing each phase to cover roughly the same distance in each of the three position



6.4 Characteristics of power lines (13)

- Towers, insulators and other components
 - Towers support overhead lines
 - Wood or metal (for larger towers)
 - Designing depends on
 - Line voltage, conductor size and weight, terrain, aesthetic preference and tradition
 - Safe clearance maintaining
 - Between conductors and the ground
 - Between conductors and the towers
 - Taking into account sagging of the lines due to thermal expansion



6.4 Characteristics of power lines (14)

- Towers, insulators and other components
 - Insulators serve to electrically separate the conductor from the tower
 - Consisting of one or several smooth and rounded bells
 - Providing more surface area for spreading out surface charge
 - Bells are made of a nonconducting ceramic or plastic
 - Number of bells is roughly proportional to the line voltage
 - Each bell contributes to insulate around 10kV



6.4 Characteristics of power lines (15)

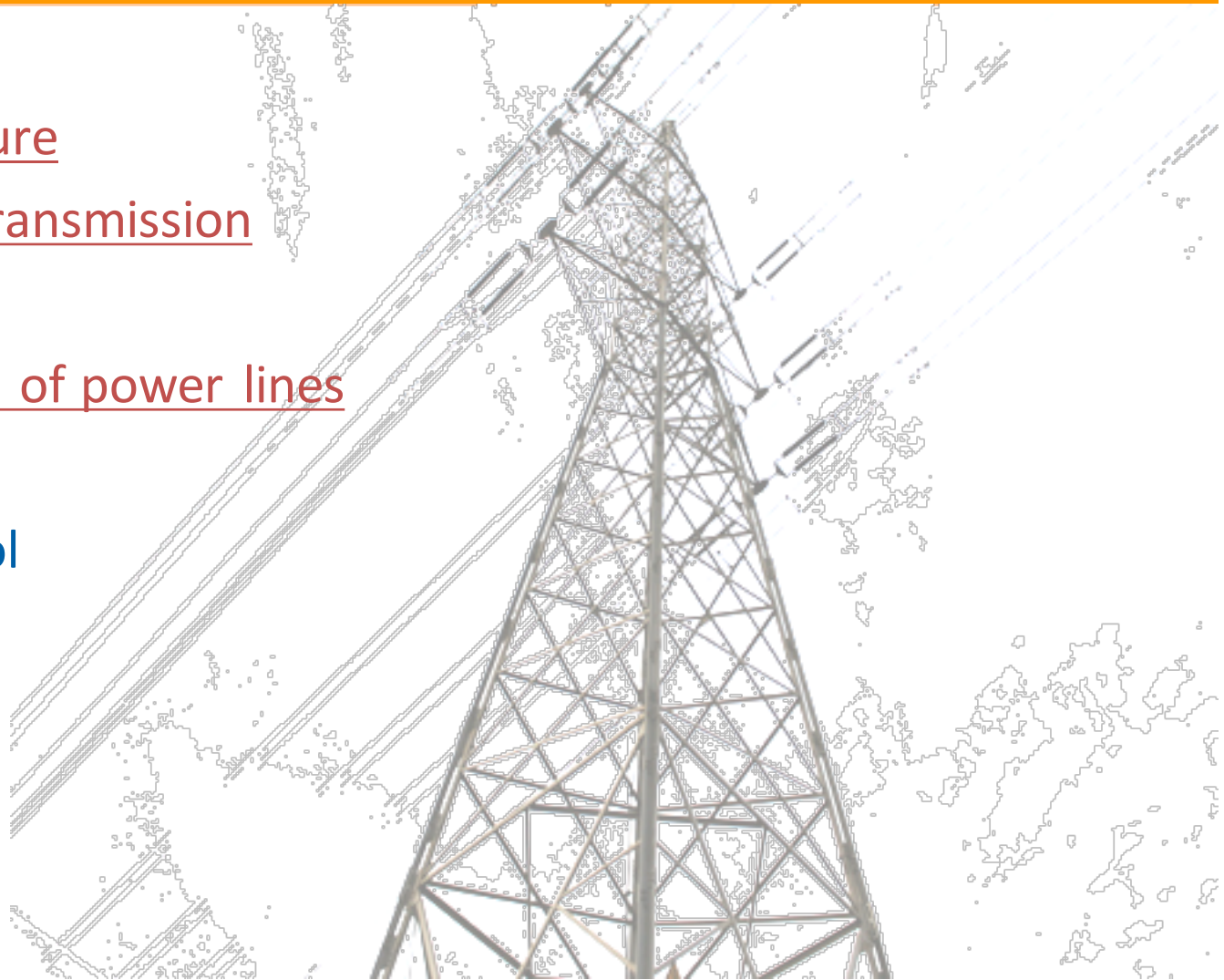
- Towers, insulators and other components
 - Metal lightning arresters are used to attract lightning and direct it to ground
 - Using small metallic objects to reduce the swinging and vibration of the conductor in the wind
 - There are large red and white plastic balls, intended for airplane and helicopter to see



6. Transmission and Distribution

■ Contents

- 1) System structure
- 2) Three phase transmission
- 3) Transformers
- 4) Characteristics of power lines
- 5) Loading
- 6) Voltage control
- 7) Protection
- 8) Summary



6.5 Loading (1)

- There are two important limits for power transmission and distribution
 - Thermal limit
 - Stability limit



6.5 Loading (2)

- Thermal limits
 - The resistive heating of the lines limits their capacity to transmit power
 - Thermal limit \rightarrow magnitude of the current \rightarrow limiting the loading
 - Line ratings are generally expressed in ampacity, which refers to current-carrying capacity in amperes
 - Environmental conditions
 - Temperature, wind and rain
 - Loading history of the line
 - Thermal limits are given in terms of current (amp) or apparent power volt-amperes (AV)
 - Heating also limits the operation of transformers at high-current



6.5 Loading (3)

■ Stability limit

- Maintaining the feedback between generators on either end of the line that keep them locked in synchronicity
- Sending generator pushes harder than the receiving generator
- Sending generator has a power angle δ that is somewhat ahead of the receiving one
- The amount of real power transmitted on an ideal, lossless line

$$P = \frac{V_1 V_2}{X} \sin \delta_{12}$$

- δ_{12} is the power angle difference, X is the line reactance
- → It is necessary to increase the angle difference (but less than the maximum permissible difference) to transmit a large amount of power on a given line



6.5 Loading (4)

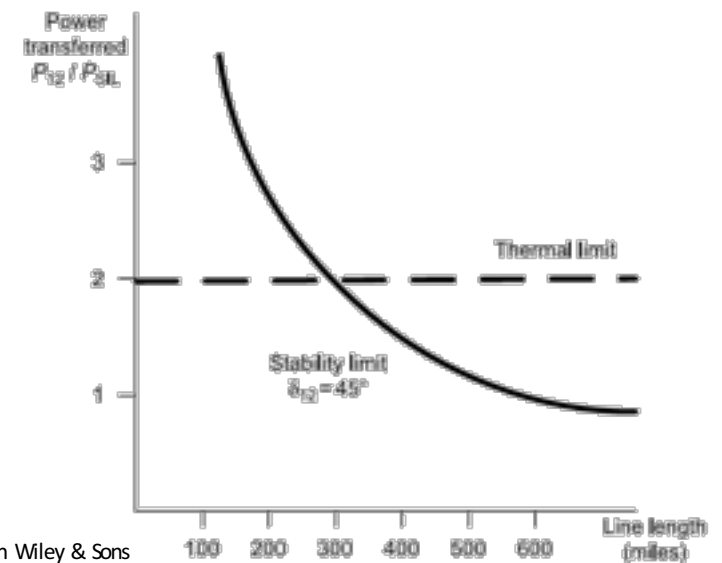
■ Stability limit

- $P = \frac{V_1 V_2}{X} \sin \delta_{12}$
- For short lines, the reactance X is usually small → a small δ_{12} still results in a large amount of power transmitted
 - → risk of exceeding the line's thermal capacity before reaching the maximum permissible δ_{12}
- For long lines, the reactance X is more significant
 - → risk of reaching dangerous δ_{12} before reaching the thermal limit of the line
- The stability limit is given in terms of real power (MW)



6.5 Loading (5)

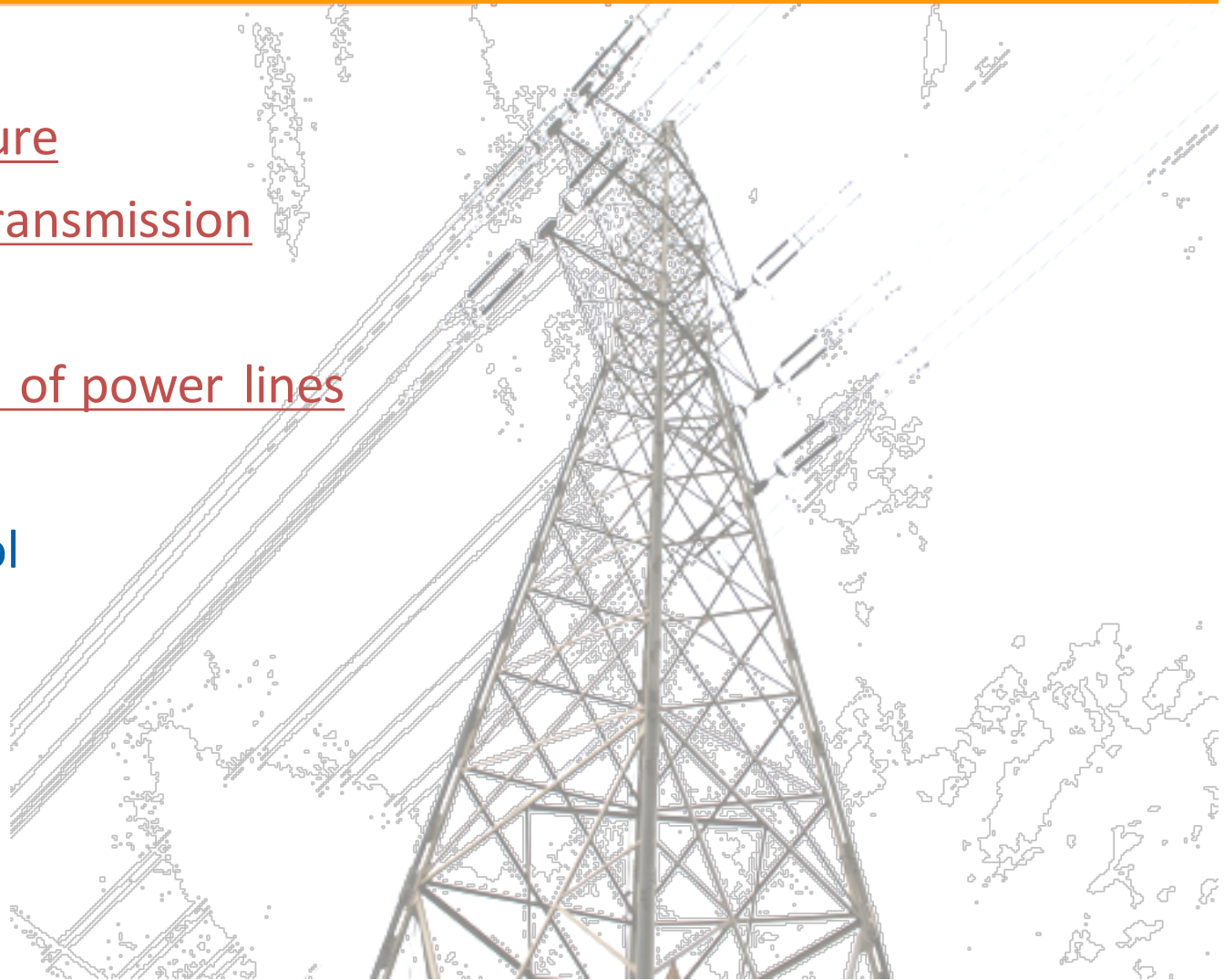
- Thermal and stability limits
 - Limits as a function of line length
 - P_{12}/P_{SIL} is a measure of the real power transmitted between two ends of the line, expressed as a ratio of the actual power in watts and the surge impedance loading
 - $\delta_{12} = 45^\circ$ is the maximum permissible phase separation between the two line ends before synchronicity is lost



6. Transmission and Distribution

■ Contents

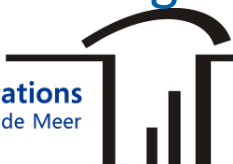
- 1) System structure
- 2) Three phase transmission
- 3) Transformers
- 4) Characteristics of power lines
- 5) Loading
- 6) Voltage control
- 7) Protection
- 8) Summary



6.6 Voltage control (1)

- Voltage in power systems is controlled both
 - At generator (bus voltage)
 - By the excitation or the rotor field current
 - Throughout the transmission and distribution system
 - By using transformers

- At any location the exact voltage level depends on
 - The reactive power generated or consumed in the vicinity
 - Generator voltage is directly linked to reactive power generation
 - The two variables cannot be controlled independently of each other
 - The voltage drop associated with resistive losses



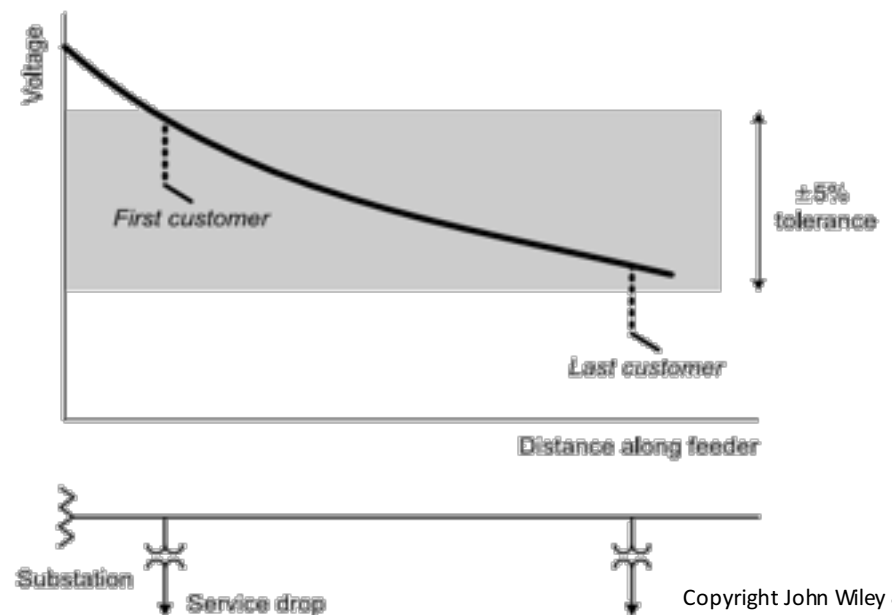
6.6 Voltage control (2)

- Controlling line drop
 - Line drop refers to the voltage decreasing as one moves from the power source to the end of a distribution feeder
 - Voltage difference $V = IZ$, I is the current and Z is the line's impedance
 - The drop depends on the drawn current, which in turn depends on the power demand (i.e. connected load)
 - → maintaining a perfectly flat voltage profile is physically impossible
 - Thus, a window of tolerance of the nominal voltage is expected
 - In US, the tolerance is $\pm 5\%$ of the nominal voltage



6.6 Voltage control (3)

- Controlling line drop
 - When customer nominally receiving 120 V, should expect voltage between 114 and 126 V
 - For very long feeder, voltage boosting is necessary to maintain a permissible voltage level along the entire feeder



Copyright John Wiley & Sons

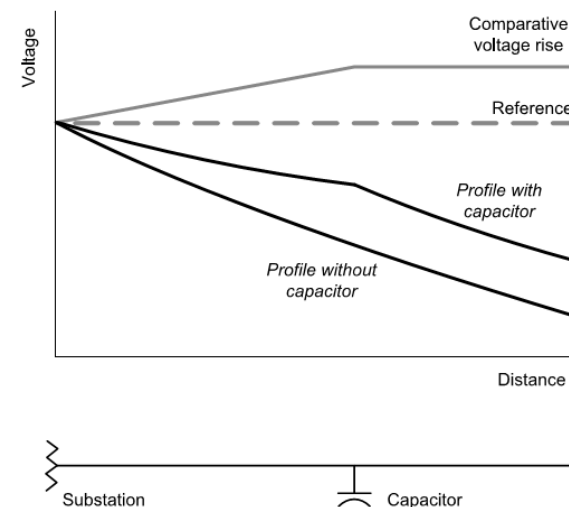
6.6 Voltage control (4)

- Controlling line drop
 - Load tap charger (LTC) refers to the process of changing the effective number of the turns of the transformer winding
 - Voltage regulator looks like transformer between two segments of the same line
 - The regulator's turns ratio is adjusted to boost the voltage just enough to compensate for line voltage drop



6.6 Voltage control (5)

- Controlling reactive power
 - Boosting the local voltage level by injecting reactive power into the system provided by capacitive reactance
 - There are three devices, which provide capacitive reactance
 - Static VAR compensators (SVCs)
 - Synchronous condensers (sync generators operating at zero real power output)
 - Capacitors



Copyright John Wiley & Sons

6.6 Voltage control (6)

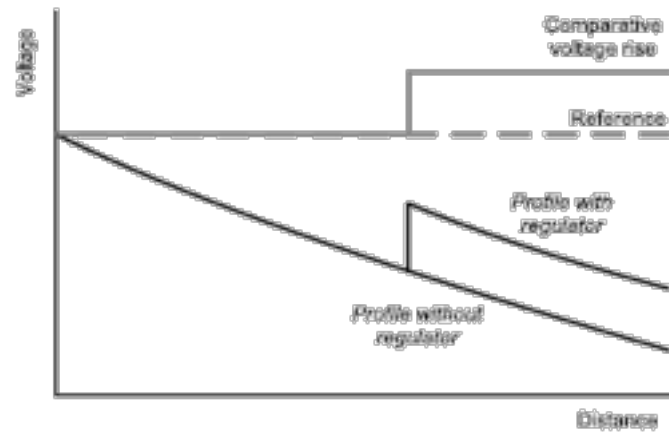
- Controlling reactive power
 - Capacitors are the simplest and most common at the distribution level
 - Capacitive devices are usually connected in parallel with load
 - Series capacitance is used in some specific applications, mostly on transmission lines
 - → the inductive load can be compensated by capacitance, which in turn brings the power factor of the load area closer to unity
 - → smaller apparent power is needed to deliver the real power
 - → reduction in the current
 - → reduction in the voltage drop (Ohm's law)



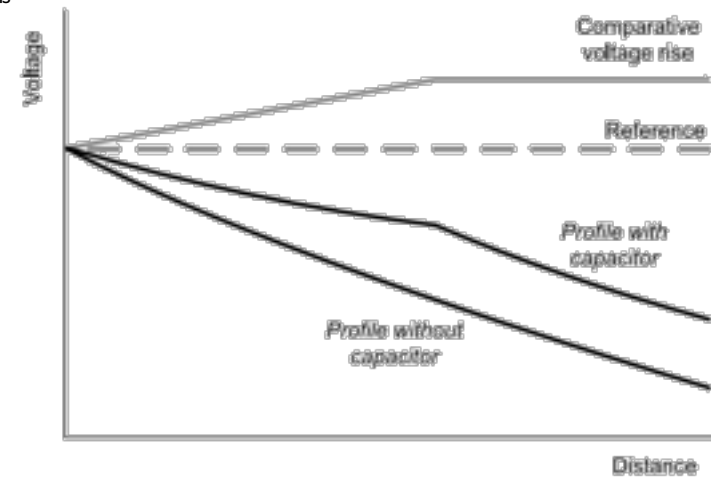
6.6 Voltage control (7)

- Controlling reactive power

Copyright John Wiley & Sons



Effect of voltage regulator



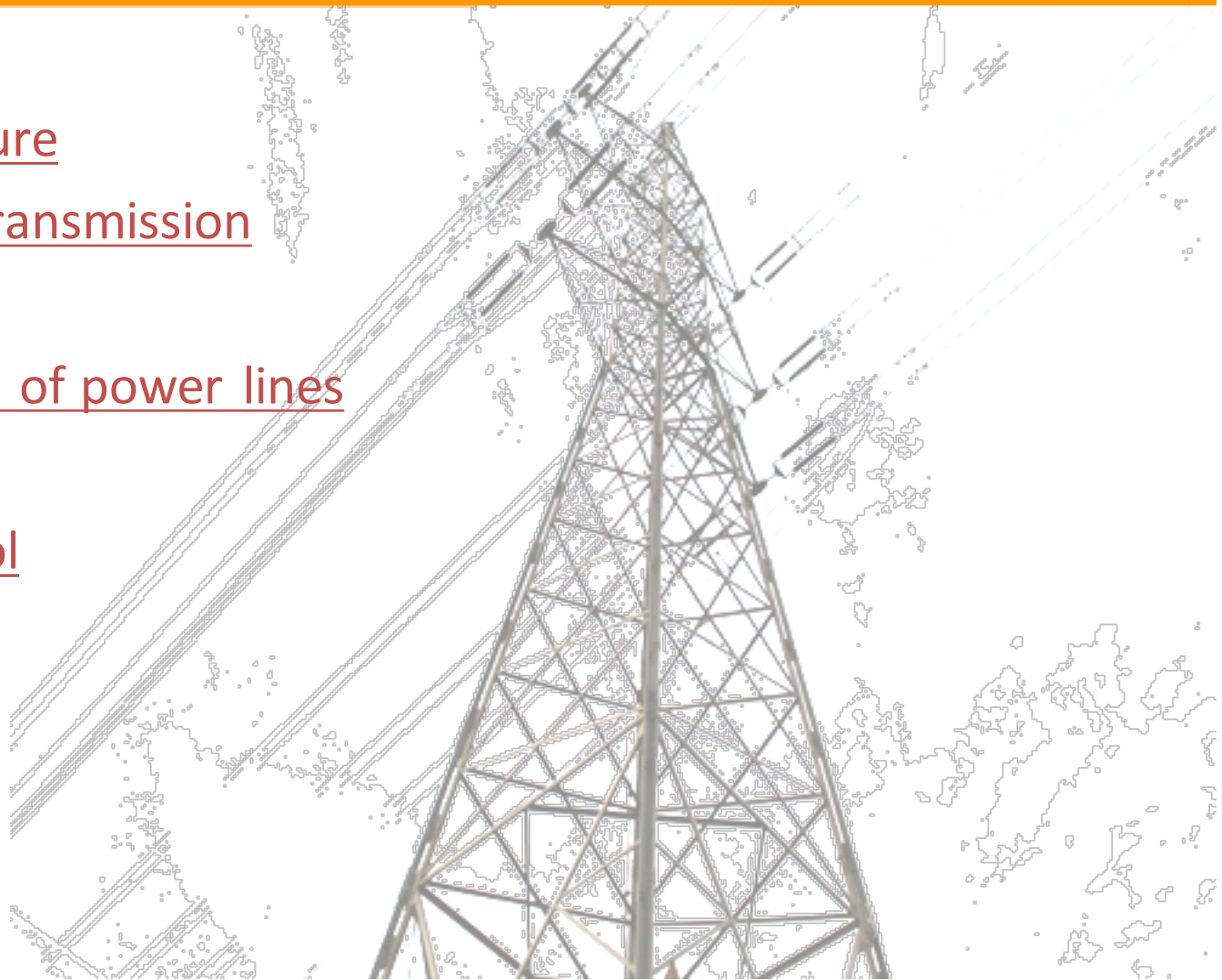
Effect of capacitor



6. Transmission and Distribution

■ Contents

- 1) System structure
- 2) Three phase transmission
- 3) Transformers
- 4) Characteristics of power lines
- 5) Loading
- 6) Voltage control
- 7) Protection
- 8) Summary



6.7 Protection (1)

- Basic protection and protective devices
 - Circuit protection refers to the scheme for disconnecting sections or components of an electrical circuit in the event of a fault
 - A fault means that an inadvertent electrical connection is made between an energized component and something at a different potential
 - Directly touching of two conductors
 - The basic types of faults
 - Phase-to-ground faults
 - Phase-to-phase faults



6.7 Protection (2)

- Basic protection and protective devices
 - The basic types of faults
 - Phase-to-ground faults
 - One or more conductors make electrical connect with the ground
 - Or point of zero-volt potential
 - E.g. tree conduct the current of a line into the ground because of its moisture
 - Phase-to-phase faults
 - Two different phases come into direct or indirect contact with each other
 - E.g. bird touches two conductors simultaneously



6.7 Protection (3)

- Basic protection and protective devices
 - Fault current (wasteful current flow) is determined by
 - Impedance of the connecting object
 - Ability of the power source to sustain the voltage during flowing of an abnormally current
 - The objective of the circuit protection is to detect the fault and to interrupt the power flow to it
 - Fault detection
 - Overcurrent (fuse, breaker)
 - Phase imbalance
 - Unusual voltage differences



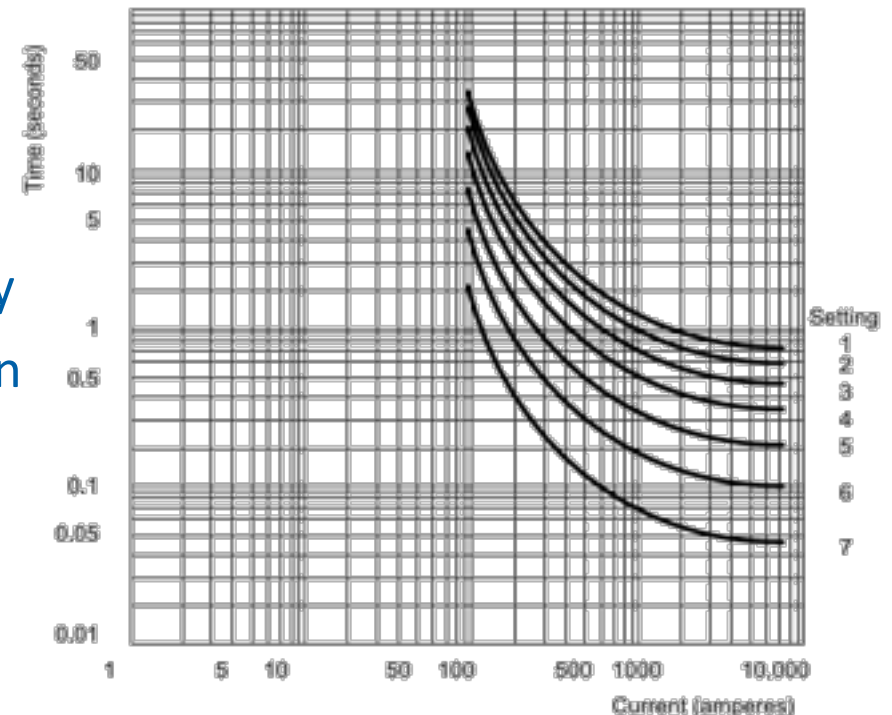
6.7 Protection (4)

- Basic protection and protective devices
 - A fuse consists of a thin wire that simply melts when the current is too high
 - Reliable, but
 - Delayed fault clearing (time for heating up und melting)
 - Time delay for connection restoring
 - Nonreusable
 - Fixed sensitivity



6.7 Protection (5)

- Basic protection and protective devices
 - A circuit breaker has movable contacts that can open or close the circuit according to a signal triggered by relay, which measures the current
 - More quickly
 - Reusable
 - Multiple settings for sensitivity
 - Fault clearing time depends on the current magnitude (inversely-related)



Copyright John Wiley & Sons

Time-current characteristic of a relay

6.7 Protection (6)

- Basic protection and protective devices
 - Then, a prerequisite for a fuse or a relay is a high fault current
 - High-impedance faults refer to the situation, in which the fault current is undistinguishable from a high load current
 - A differential relay detects the small fault current by comparing the currents on the different phases, or between a phase and a return flow
 - Used in transmission and distribution systems
 - In ground-fault circuit interrupters (GFCIs)
 - Outlet are close to water
 - In kitchens
 - Very sensitive and very quick



6.7 Protection (7)

- Basic protection and protective devices
 - Regular switches, in contrast to circuit breakers, serve the purposes of deliberately isolation individual pieces of the system
 - E.g. for maintenance
 - Switchgears consist of switches and circuit breakers, serving for deliberately and automatically isolating portion of the system
 - Key design challenge of switchgear
 - Ionization of the medium between the contacts, with results in arcs (plasma arc)
 - Immersing the contacts in a nonconducting fluid such as transformer oil or gas as sulfur hexafluoride SF₆
 - Placing the contacts in a vacuum



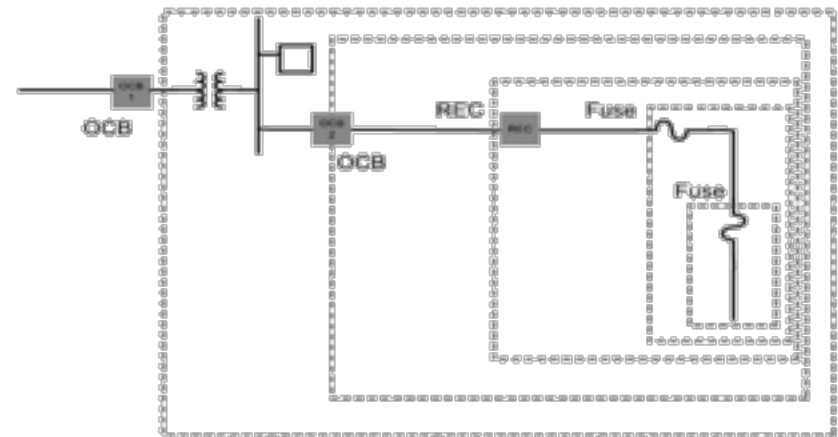
6.7 Protection (8)

- Basic protection and protective devices
 - Reclosing breaker (recloser REC) refers to the breaker that opens when the fault is detected, but then, after passing some time, closes again to see if the fault is still there
 - Useful in the event of transient faults
 - Lightning strike, momentarily contacting of power lines in the wind
 - Customers experience a very brief interruption
 - Two parameters
 - Reclosing time
 - Number of attempts



6.7 Protection (9)

- Protection coordination
 - Two main considerations:
 - Minimum interruption of service
 - Protection interrupts the circuit as close as possible to the fault location
 - Protection redundancy
 - → Protection coordination refers that for any given fault, the nearest breaker will trip first
 - protection zones
 - Each protection device
 - Primary protection for its zone
 - Backup protection for another
 - Less sensitive

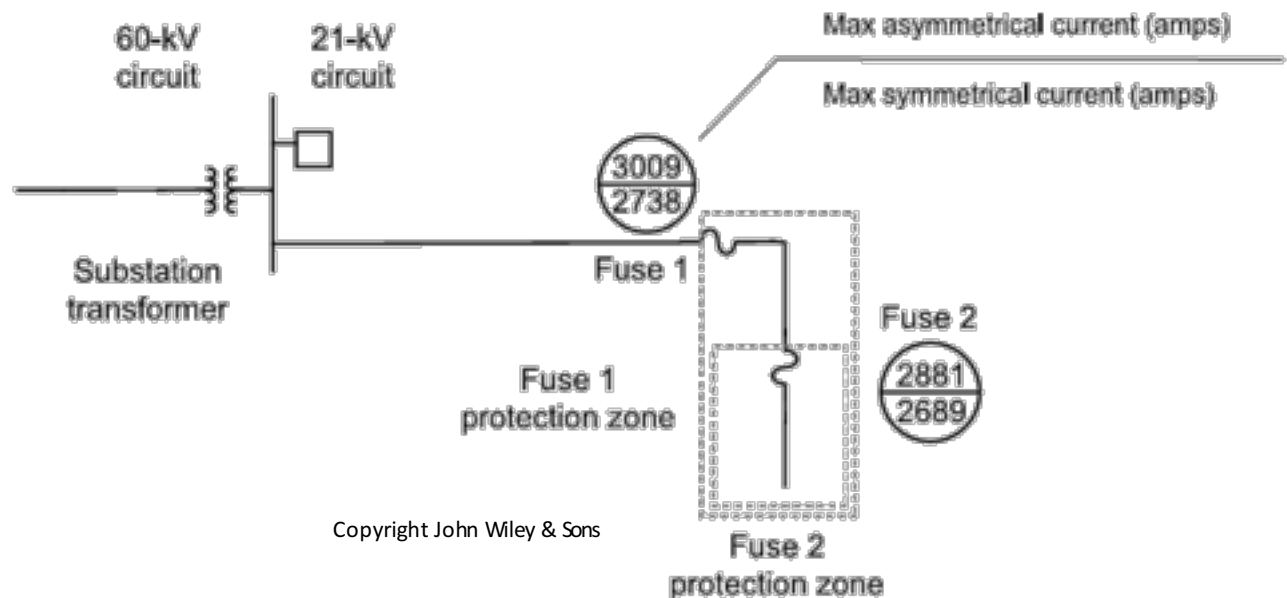


Copyright John Wiley & Sons

OCB=Oil Circuit Breaker, REC=Recloser

6.7 Protection (10)

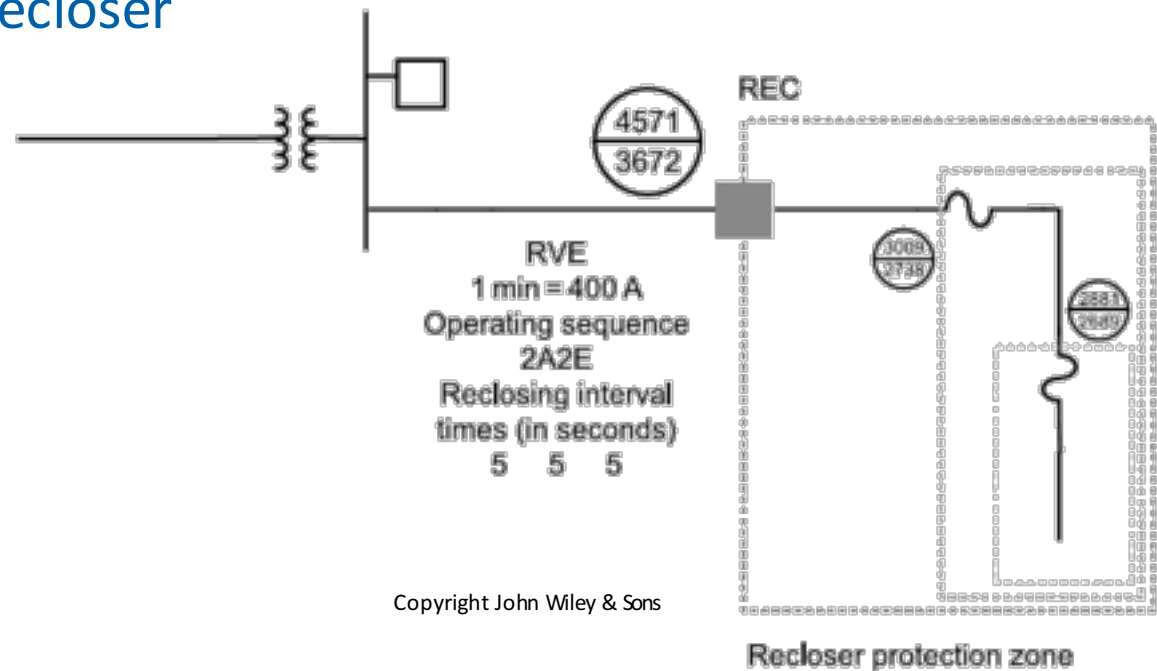
- Protection coordination
 - Primary protection device must be more sensitive than any other backup protection devices
 - As depicted in the figure, the fault current of Fuse 2 is less than the fault current of Fuse 1



6.7 Protection (11)

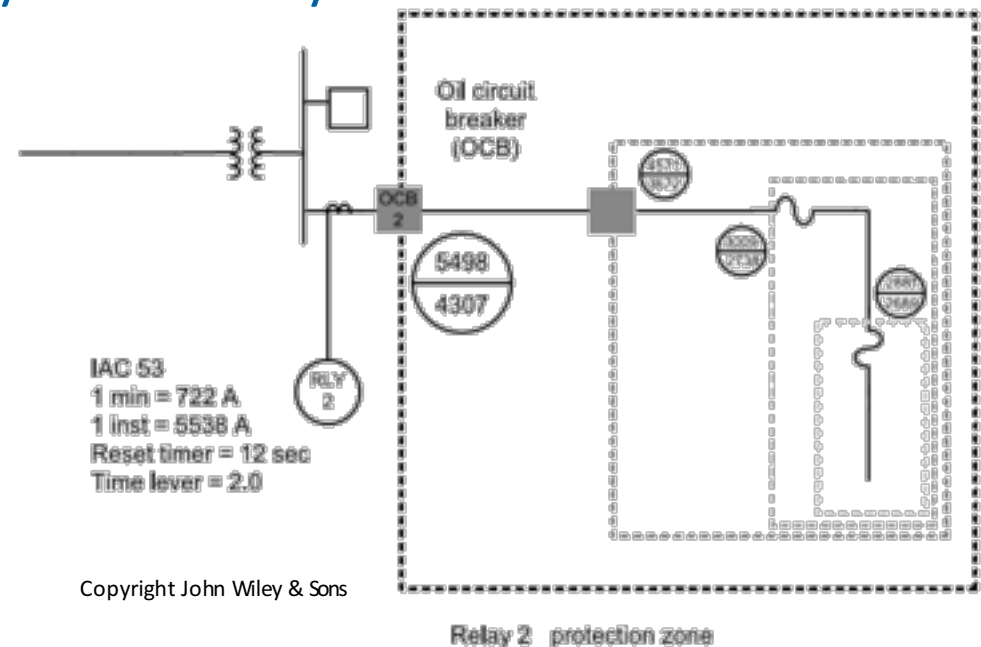
- Protection coordination

- Primary protection device must be more sensitive than any other backup protection devices
- As depicted in the figure, the fault current of Fuse 1 is less than the fault current the recloser



6.7 Protection (12)

- Protection coordination
 - Protection coordination involves location, current magnitude, individual phases and time.
 - All of which must be combined into a scheme that can be expected to perform safely and reliably

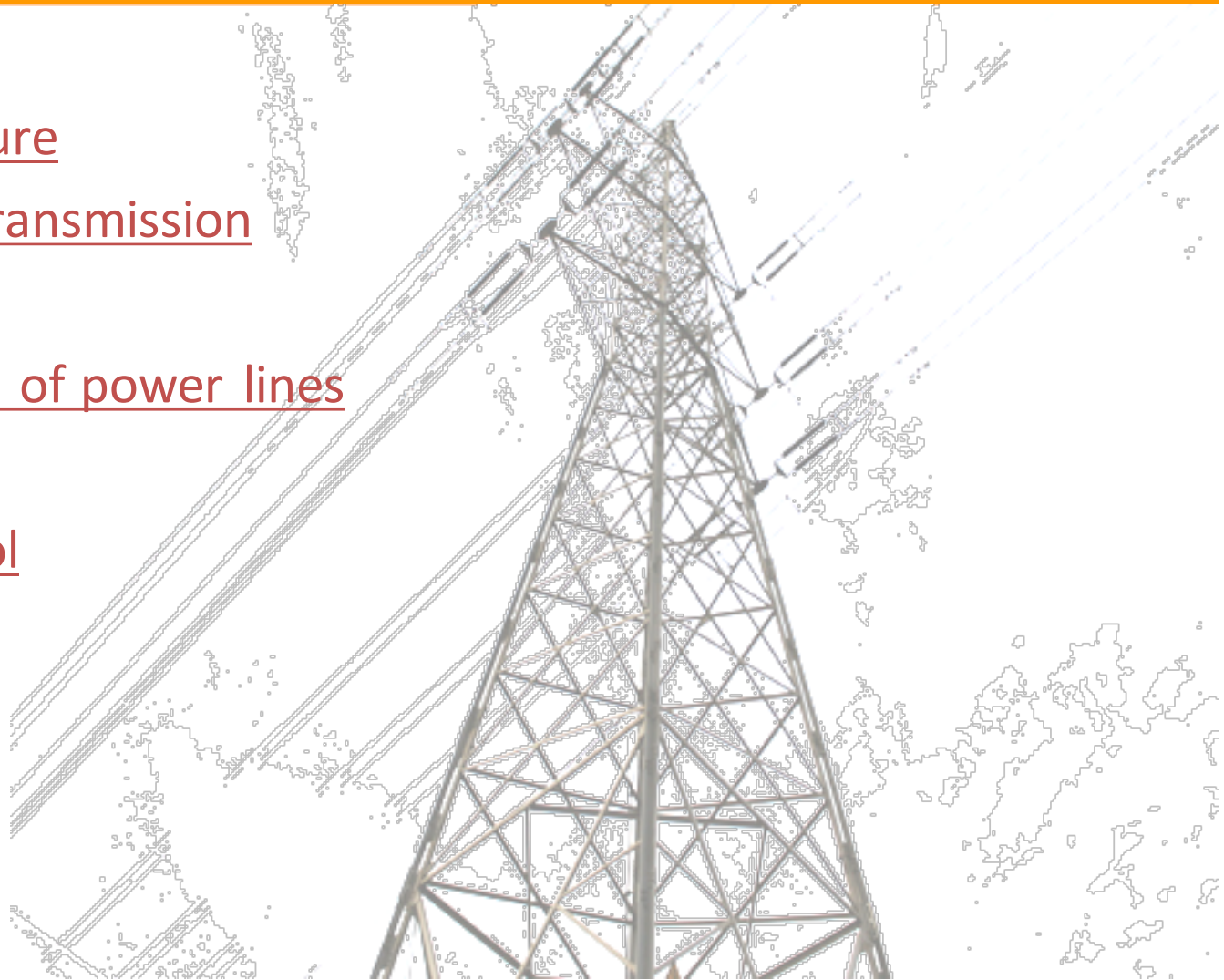


Copyright John Wiley & Sons

6. Transmission and Distribution

■ Contents

- 1) System structure
- 2) Three phase transmission
- 3) Transformers
- 4) Characteristics of power lines
- 5) Loading
- 6) Voltage control
- 7) Protection
- 8) Summary



6.8 Summary

- Transmission and Distribution system (T&D) refers to the entire power delivery system, which operates at different voltage levels
- Transformers are in charge of changing the voltage in an a.c. circuit
- Three phases in a.c. power system is a global standard
 - Less than three is heavily vulnerable to unbalanced load
 - More than three become increasingly complicated and expensive
- Power transmission is limited by thermal and stability limits
- The two methods for controlling or supporting voltage in the T&D system are transformer taps and reactive power injection
- Circuit protection refers to a scheme for disconnecting sections of an electric circuit in the event of a fault



Electric Power System

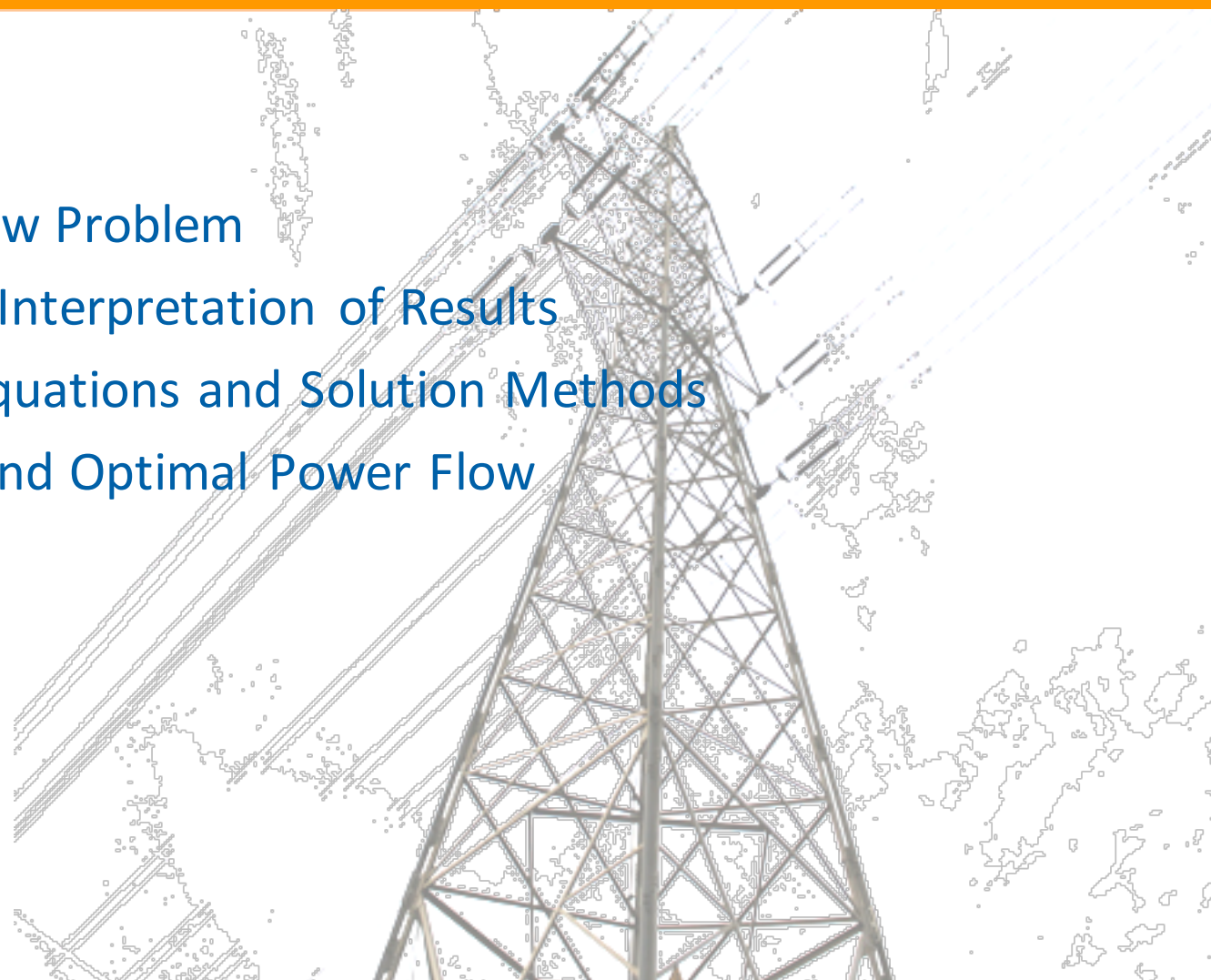
Chapter 07: Power Flow Analysis



7. Power Flow Analysis

■ Contents

- 1) Introduction
- 2) The Power Flow Problem
- 3) Example with Interpretation of Results
- 4) Power Flow Equations and Solution Methods
- 5) Applications and Optimal Power Flow
- 6) Summary



7.1 Introduction

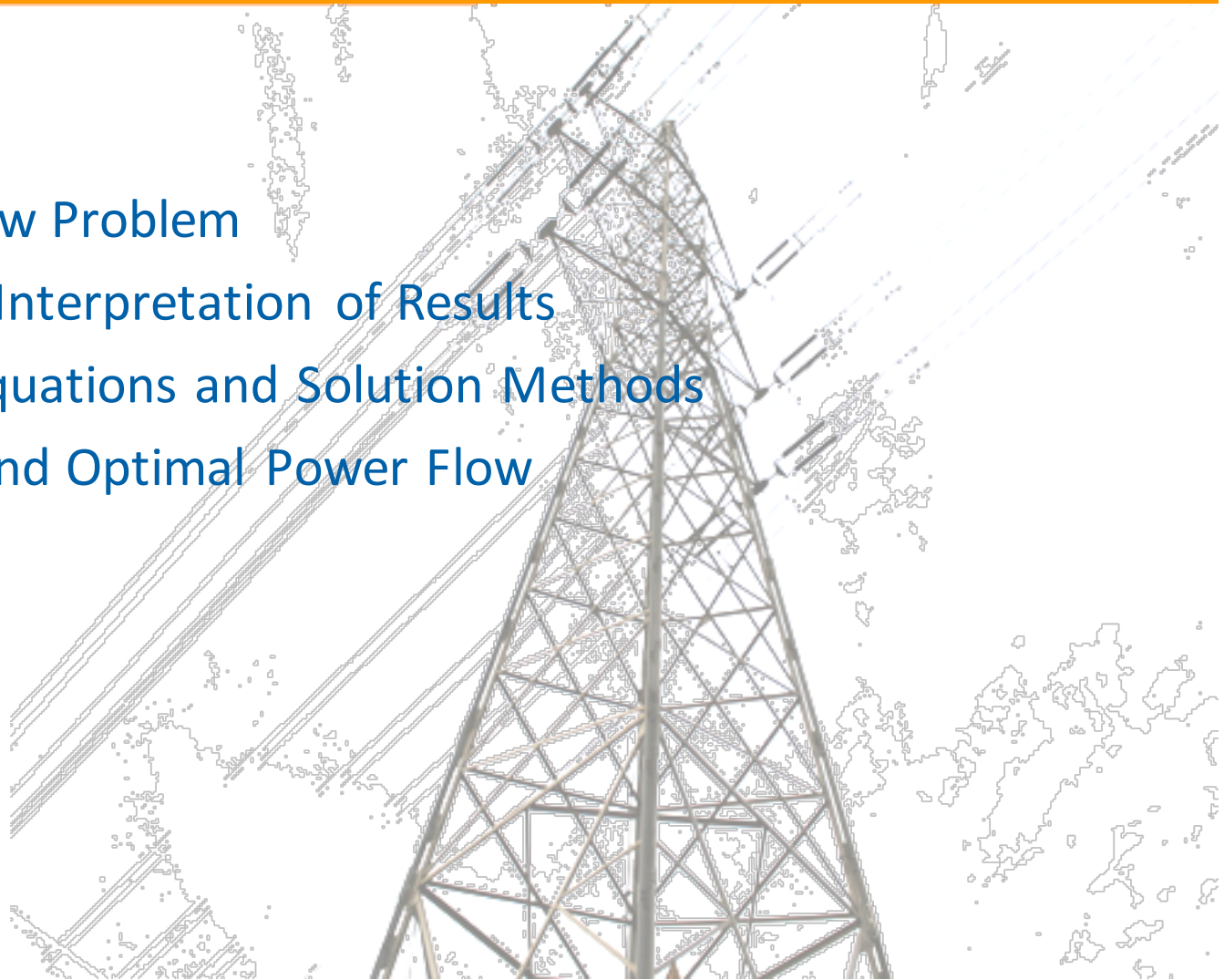
- Power flow or load flow
 - Given the amount of power delivered and where it comes from
- Power flow analysis
 - Describing the present operating state of an entire power system, given certain known quantities
 - To do:
 - A mathematical algorithm of successive approximation by iteration
 - The repeated application of calculation steps
 - Assuming one array of numbers for the entire system \mathbf{A}
 - While (\mathbf{A} isn't consistent with both physical law and the conditions stipulated by the user) do
 - Adjusting the numbers
 - Looks like a computer program



7. Power Flow Analysis

■ Contents

- 1) Introduction
- 2) The Power Flow Problem
- 3) Example with Interpretation of Results
- 4) Power Flow Equations and Solution Methods
- 5) Applications and Optimal Power Flow
- 6) Summary



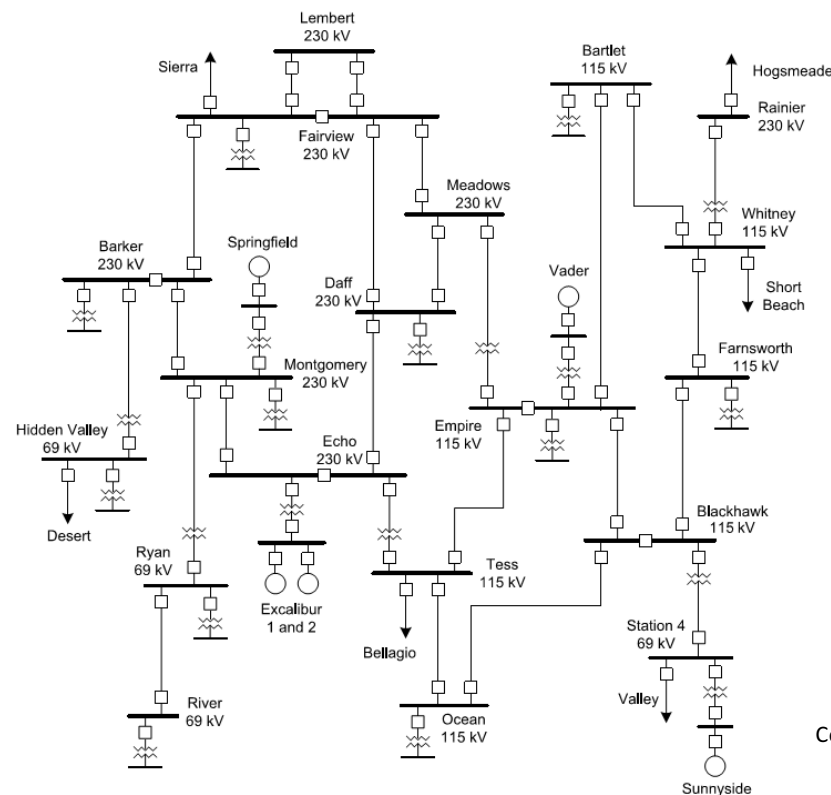
7.2 The Power Flow Problem (1)

- Network Representation
 - Nodes : The points that are electrically distinct
 - In power systems
 - Nodes are called buses
 - Marks the location of one of two things
 - A generator
 - A load
 - Represents aggregations of loads at the location where they connect to the high-voltage transmission system
 - The buses are connected by transmission lines
 - One-line diagram : does not generally distinguish among the three phases of an a.c. transmission
 - Impedance of the line : constant



7.2 The Power Flow Problem (2)

- Network Representation
 - Example
 - One-line Diagram for a power system



Copyright John Wiley & Sons

7.2 The Power Flow Problem

(3)

- Choice of Variables
 - In an a.c. circuit
 - To fully describe the voltage and current at any given node
 - Magnitude component : root-mean-squared (rms) value
 - Time component : phase angle
 - The amount of power transferred at any point
 - Real component
 - Reactive component
 - Two variables per node : determine everything in the system.
 - In practice:
 - Current is not known at all
 - Voltage is known explicitly for some buses but not for others
 - The amount of power going into or out of a bus is known



7.2 The Power Flow Problem

(4)

- Types of Buses
 - Load buses (P, Q buses)
 - The power consumption is given with two numbers
 - Real power referred to as P
 - Reactive power referred to as Q
 - Generator buses (P, V buses) except *slack bus*
 - Is given
 - Real power referred to as P
 - The generator bus voltage V



7.2 The Power Flow Problem (5)

- Variables for Balancing Real Power
 - Balancing the system
 - The generators in the system collectively must supply power in exactly the amount demanded by the load, plus the amount lost on transmission lines I^2R
 - No balancing : The system would lose synchronicity and crash
 - Difficult
 - To know ahead of time what the transmission losses will be
 - The exact amount will vary depending on
 - The different dispatch
 - Will result in a different distribution of current over the various transmission paths
 - Amount of power coming from each generator



7.2 The Power Flow Problem (6)

- Variables for Balancing Real Power
 - Mathematical way to deal with this situation
 - Assuming a typical percentage of losses (e. g. 5% of the total P demanded by the load)
 - Dispatch all the generators in the system in some way so that the sum of their output approximately matches what we expect the total real power demand (load plus losses) to be (105% of load demand)
 - Using slack bus (swing bus)
 - A generator whose output we allow to adjust, depending on the system's needs , generates
 - More power if system losses are greater than expected
 - Less if they are smaller



7.2 The Power Flow Problem

(7)

- Variables for Balancing Reactive Power
 - The total amount of reactive power generated throughout the system must match the amount of reactive power consumed by the loads
 - Mismatch of reactive power leads to voltage collapse
 - Reactive power losses I^2X
 - The difference between reactive power generated and reactive power consumed by the metered load
 - Does not refer to any physical measure of something lost
 - Positive or negative, depending on whether inductive or capacitive reactance plays a dominant role



7.2 The Power Flow Problem (8)

- Variables for Balancing Reactive Power
 - Power flow analysis
 - No need to know explicitly the total amount of Q
 - Specifying the voltage magnitude at a bus
 - Essentially equivalent to requiring a balanced Q
 - Could specify P and Q for each generator bus, except for one slack bus assigned the voltage regulation
 - Reactive slack bus
 - Specify voltage magnitude V instead of Q
 - Specify V instead of Q for all generator buses
 - voltage is the explicit operational control variable
 - Reactive slack
 - Shared between all generators



7.2 The Power Flow Problem

(9)

- The Slack Bus (*V buses*)
 - Real power balance
 - Manifests operationally as a steady frequency
 - Constant frequency is indicated by an unchanging voltage angle
 - Voltage angle known as the power angle at each generator
 - More power is consumed than generated
 - Generators' rotation slows down
 - Generators' electrical frequency drops
 - Generators' voltage angles fall farther and farther behind
 - Excess power is generated
 - Generators' frequency increases
 - The voltage angles move forward



7.2 The Power Flow Problem (10)

- The Slack Bus (*V buses*)
 - Load-following generator
 - Balance real power in real-time
 - Holding the generator frequency steady at a specified value
 - In power flow analysis
 - Slack bus is mathematically assigned to do the load following
 - The place of P will therefore be taken by the voltage angle
 - Voltage angle (θ)
 - The relative position of the slack bus voltage at time zero
 - The same thing that is elsewhere called the power angle δ
 - Actual numerical value has no physical meaning
 - Physical meaning: angle will not change as the system operates



7.2 The Power Flow Problem (11)

- The Slack bus (*V buses*)
 - In power flow analysis
 - Numerical value of voltage angle (θ)
 - Different (constant) value for each bus
 - Depending on its relative contribution to real power
 - Numerical values only have meaning in relation to a reference
 - Difference between the voltage angle at one bus and another
 - The difference in the precise timing of the voltage maximum
 - Systemwide reference for timing “zero”
 - At which the alternating voltage at the slack bus has its maximum
 - Any number between 0 and 360 degrees as the voltage angle
 - 0° is the simple and conventional choice



7.2 The Power Flow Problem (12)

■ Summary of Variables

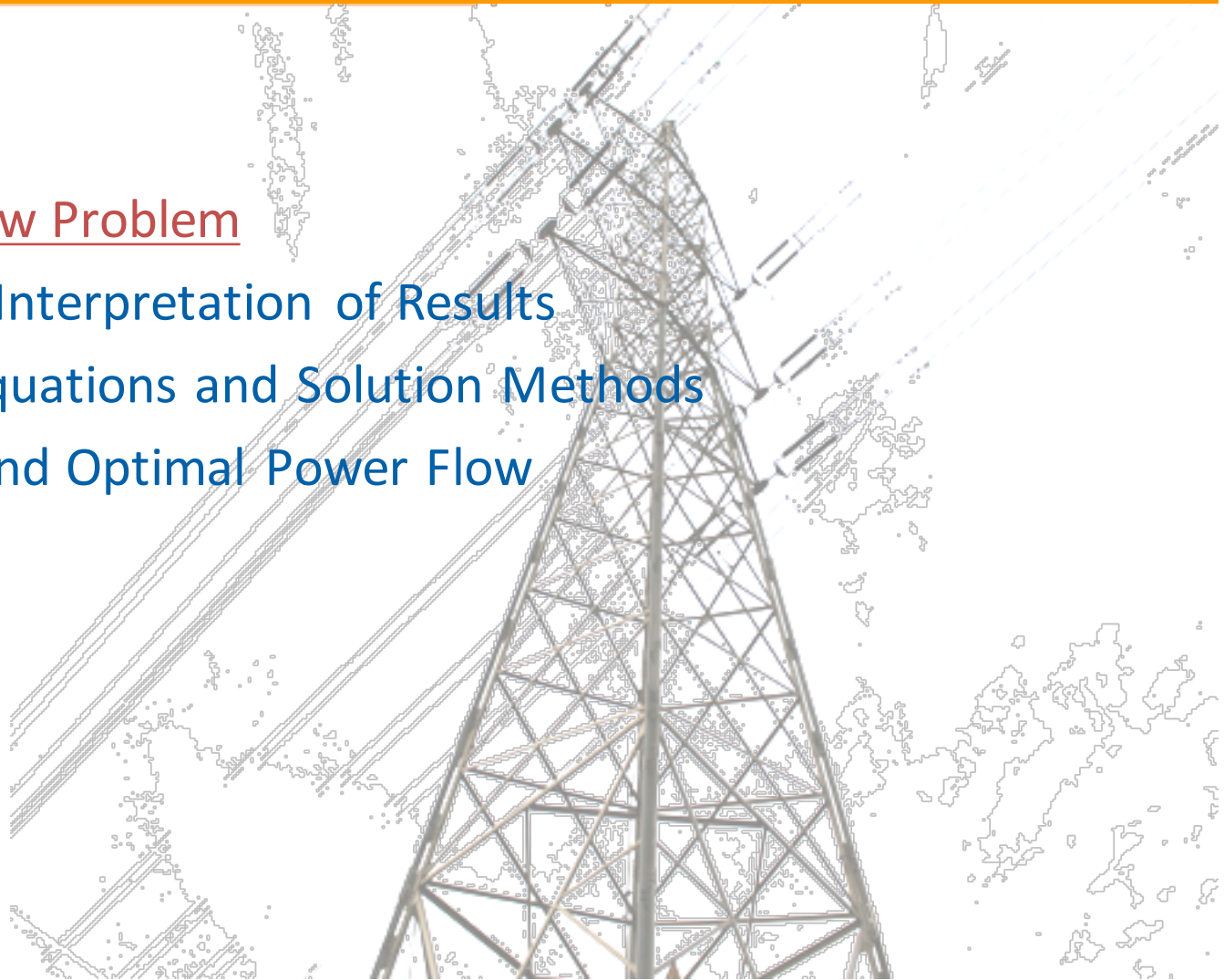
Type of Bus	Variables Given (Knowns)	Variables Found (Unknowns)
Generator	Real power (P)	Voltage angle (θ)
	Voltage magnitude (V)	Reactive power (Q)
Load or generator	Real power (P)	Voltage angle (θ)
	Reactive power (Q)	Voltage magnitude (V)
Slack	Voltage angle (θ)	Real power (P)
	Voltage magnitude (V)	Reactive power (Q)



7. Power Flow Analysis

■ Contents

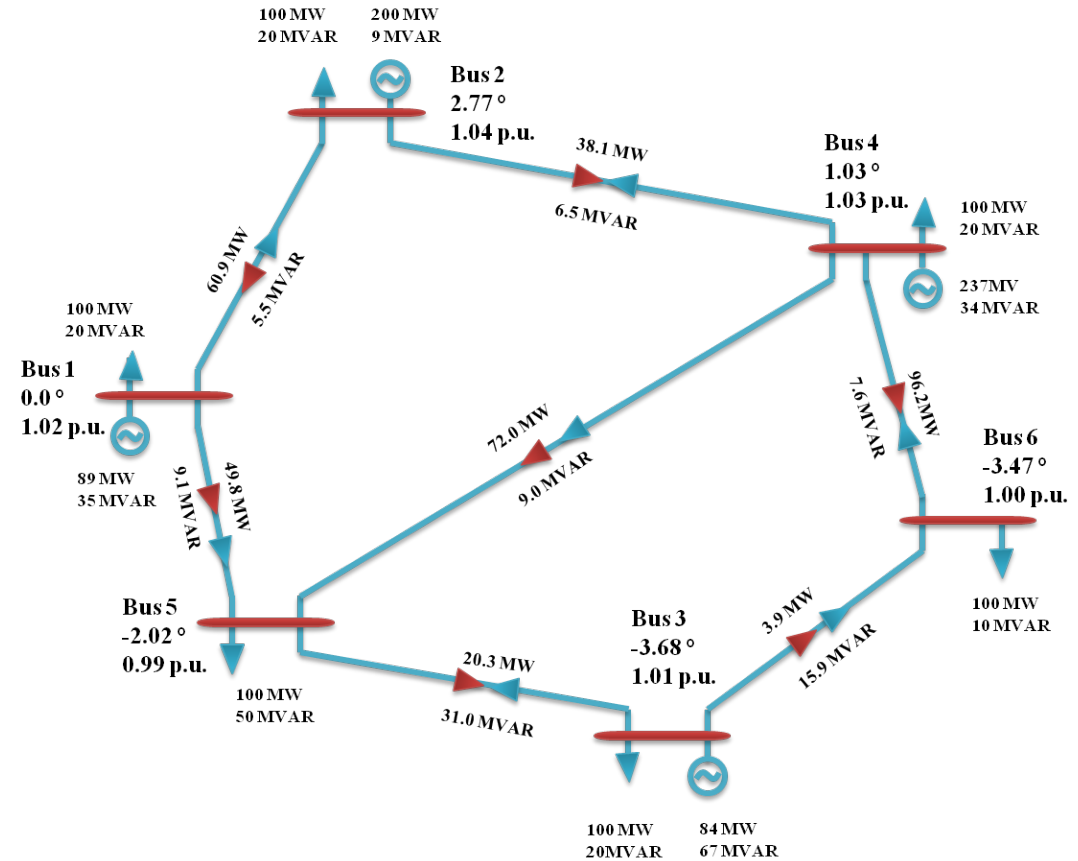
- 1) Introduction
- 2) The Power Flow Problem
- 3) Example with Interpretation of Results
- 4) Power Flow Equations and Solution Methods
- 5) Applications and Optimal Power Flow
- 6) Summary



7.3 Example With Interpretation Of Results (1)

■ Six-bus Example

- The six buses have a load
- Four of them also have generators (2,3,4)
- Slack bus (1)
- Buses have only loads (5,6)
- User specifies:
 - Real and reactive power of loads and the generation except the slack bus
 - Voltage magnitudes at each generator bus
- Max line capacity: 100 MW

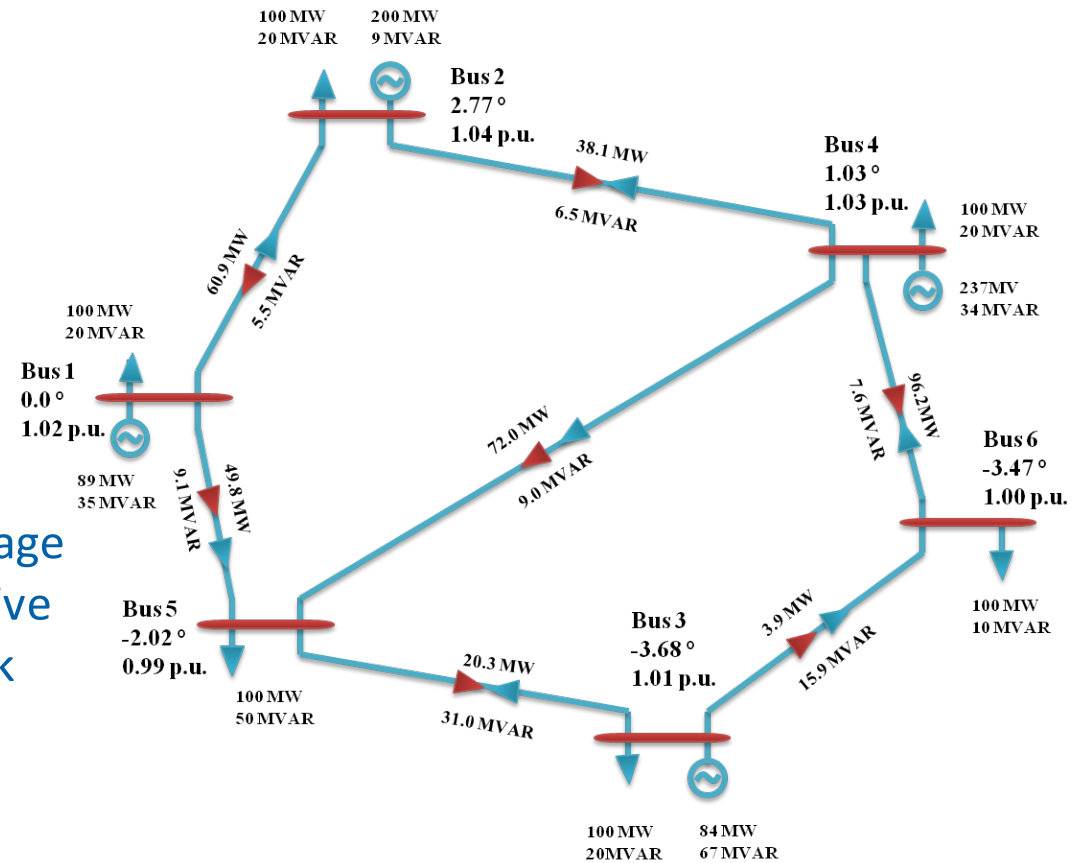


Copyright John Wiley & Sons

7.3 Example With Interpretation Of Results (2)

■ Six-bus Example

- Program (e.g. PowerWorld™) computes MVAR generation necessary to maintain this voltage at each bus.
- Voltage angle
 - At slack bus : 0.00 degrees
 - Program computes the voltage angle at each of the other five buses in relation to the slack bus



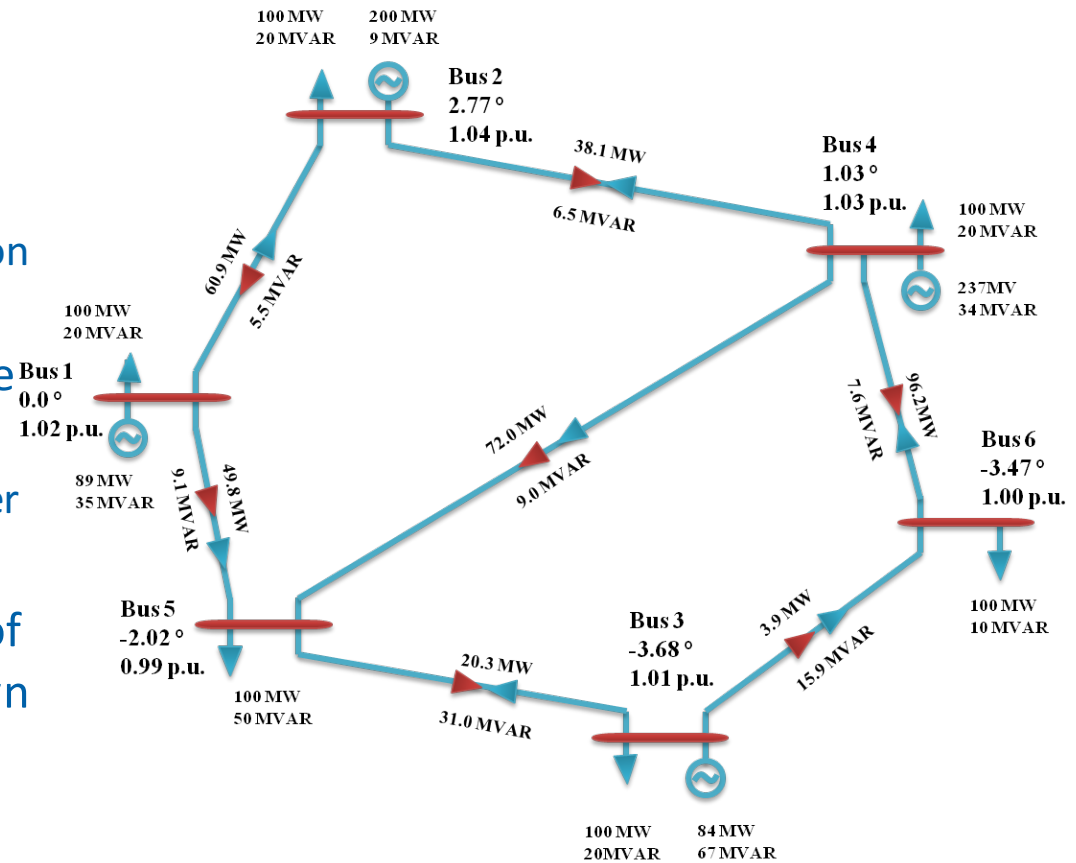
Copyright John Wiley & Sons

7.3 Example With Interpretation Of Results (3)

■ Six-bus Example

■ Voltage angle

- More positive voltage angle
 - Corresponds to an injection of power into the system
- More negative voltage angle
 - Corresponds to a consumption of real power
- Not in hierarchical order depending on the amount of power injected or withdrawn at each individual bus



Copyright John Wiley & Sons

7.3 Example With Interpretation Of Results (4)

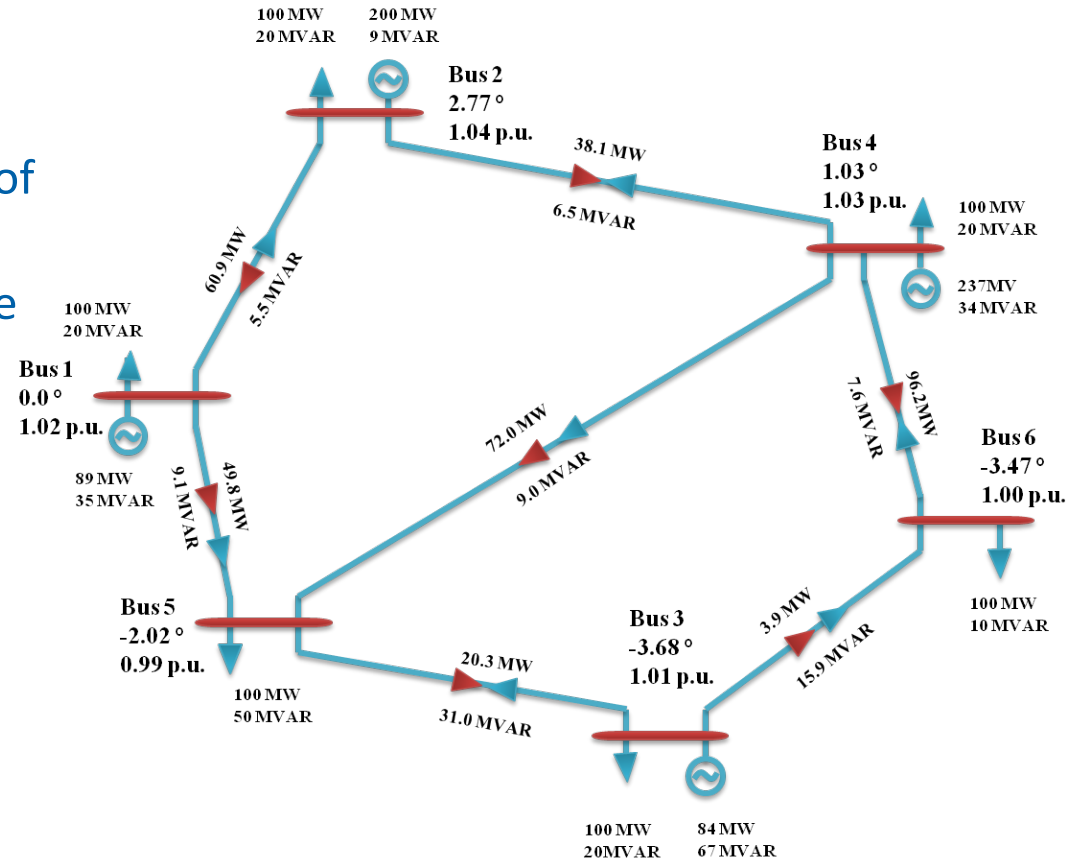
■ Six-bus Example

■ Voltage angle

- Must consider the location of each bus relative to the others in the system and the direction of power flow between them

■ Example

- Net generation at
 - Bus 4 is 137 MW
 - Bus 2 is 100 MW
- Voltage angle
 - at Bus 2 > at Bus 4



Copyright John Wiley & Sons

7.3 Example With Interpretation Of Results (5)

■ Six-bus Example

■ Voltage angle

■ Example

■ Voltage angle at Bus 2 > Voltage angle at Bus 4

- Real power is generally flowing from north to south
- From Bus 2 to the neighborhood of Buses 5, 3, and 6
- Where there is more load and less generation
- Power flows from a greater to a smaller voltage angle, the exception is Link 3–6
 - Power flow is very small
 - The difference in voltage angle is very small
 - A greater flow is associated with a greater angle difference

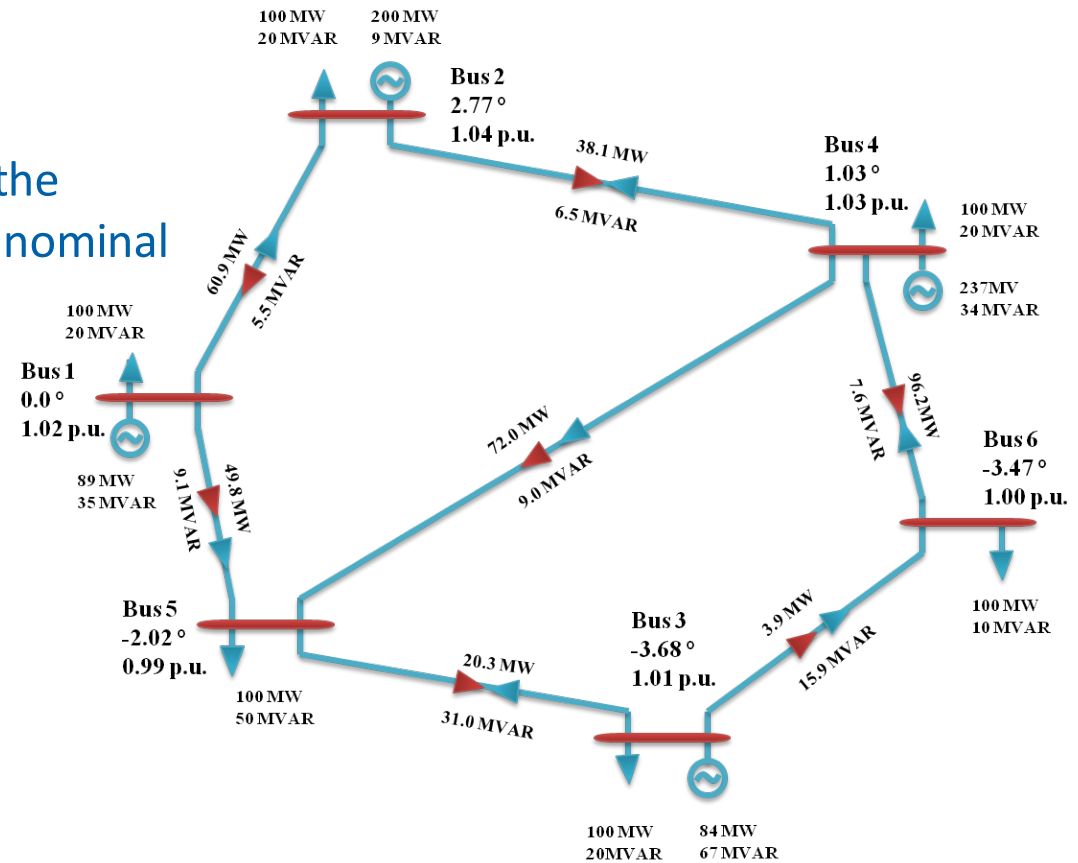


7.3 Example With Interpretation Of Results (6)

■ Six-bus Example

■ Per-unit (p.u.)

- Indicates the local value of the voltage as a multiple of the nominal value
- 138 kV equals 1.00 p.u.
- 141 kV equals 1.02 p.u.

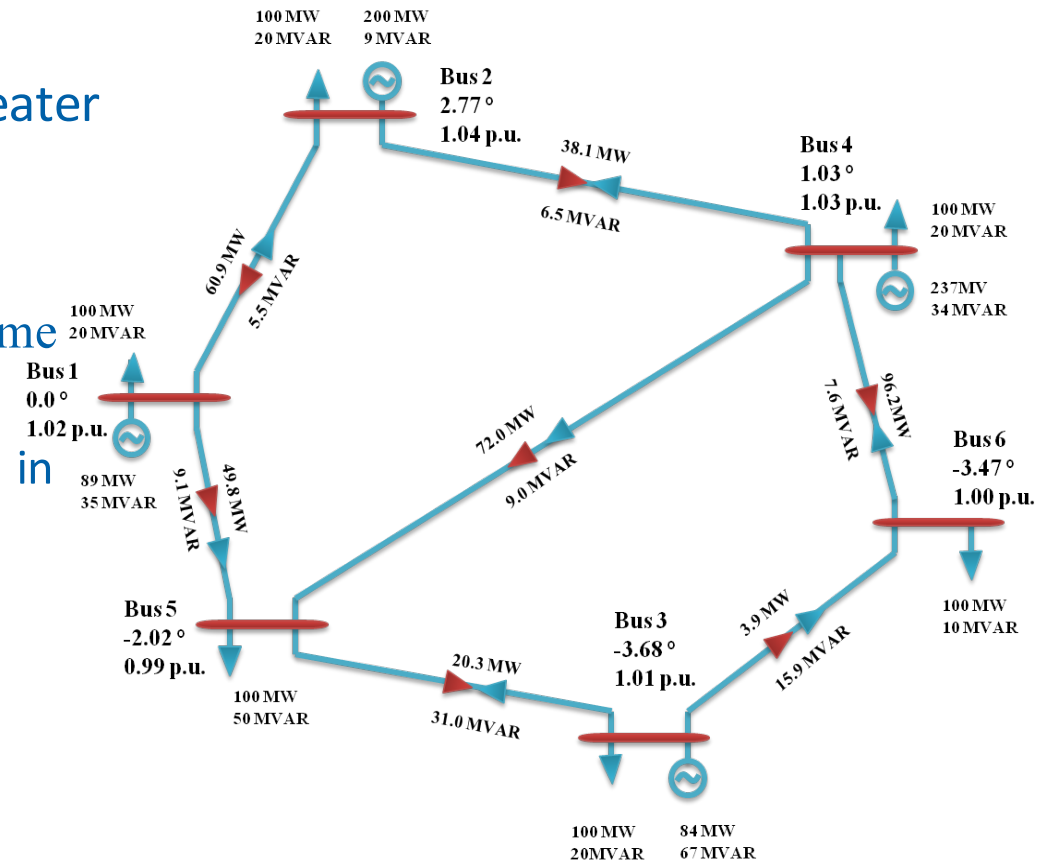


Copyright John Wiley & Sons

7.3 Example With Interpretation Of Results (7)

■ Six-bus Example

- Reactive power flows from greater to smaller voltage magnitude
- Real and reactive power
 - Not necessarily flow in the same direction on a given link
 - Imply no “relief” or reduction in current, $S^2 = P^2 + Q^2$

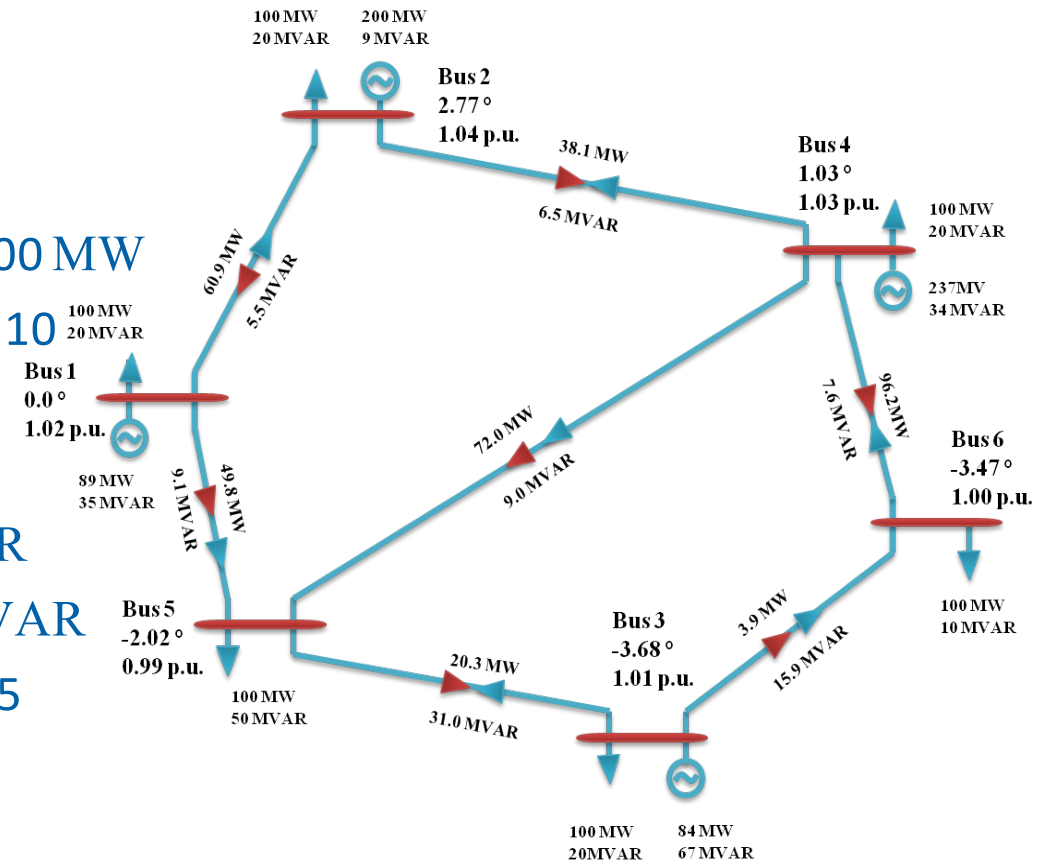


Copyright John Wiley & Sons

7.3 Example With Interpretation Of Results (8)

■ Six-bus Example

- The total real system losses
 - Generators supply 610 MW
 - Subtracting the six loads of 100 MW
 - The total real power losses is 10 MW
- The total reactive system loss
 - Generators supply 145 MVAR
 - Total reactive load is 140 MVAR
 - The system reactive losses is 5 MVAR



Copyright John Wiley & Sons

7.3 Example With Interpretation Of Results (9)

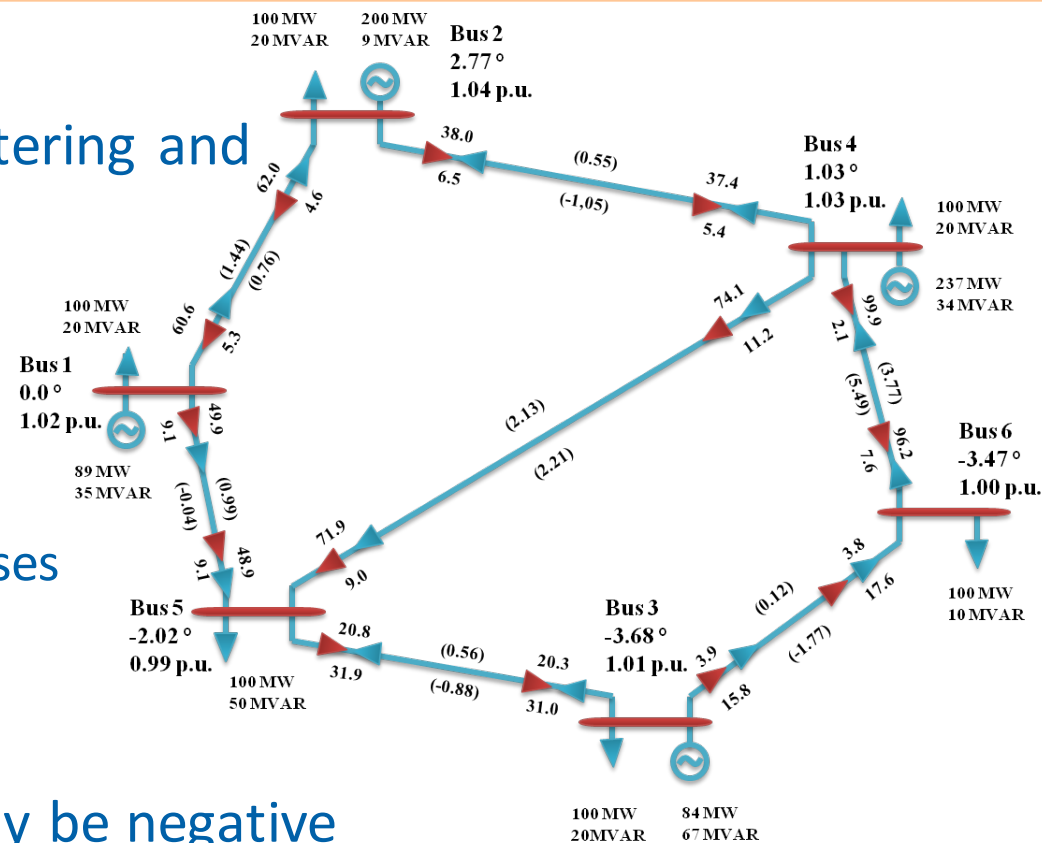
■ Six-bus Example

- Record both the power entering and exiting each link

- Real in red
- Reactive in blue

■ Losses

- The numbers in parentheses
- The real line losses
- All positive
- The reactive line losses may be negative
 - Typical for system reactive losses to be positive overall

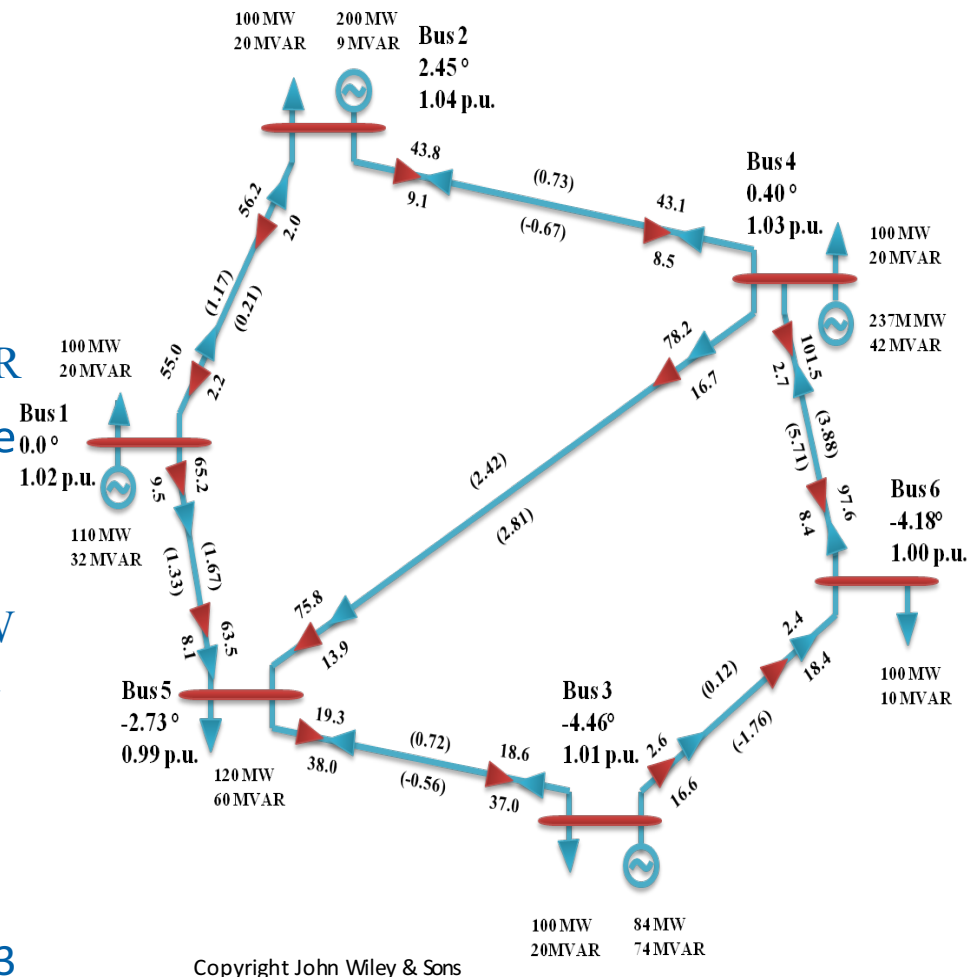


Copyright John Wiley & Sons

7.3 Example With Interpretation Of Results (10)

■ Tweaking the Case

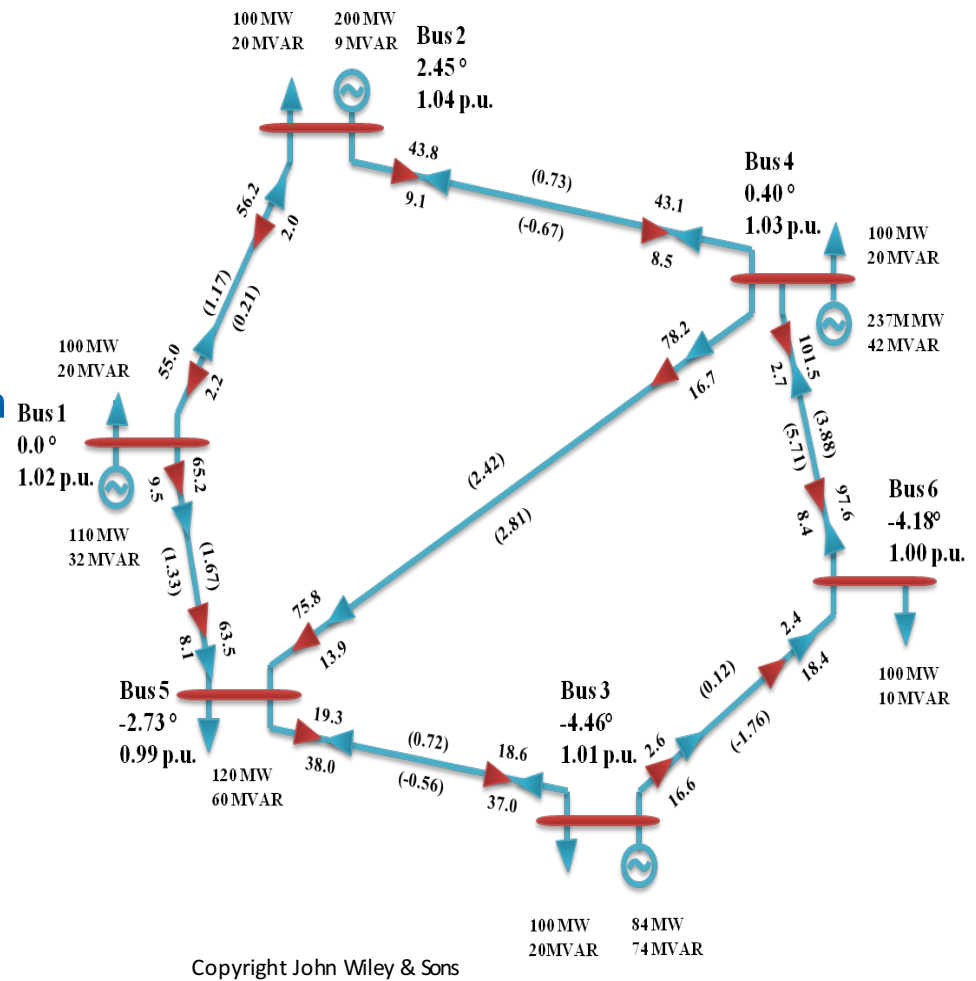
- Increase the load at bus 5 by 20%
- Power factor at bus 5: no change
 - Real power at bus 5 : 120 MW
 - Reactive power at bus 5 : 60 MVAR
 - This change is small enough for the generator at the slack bus to absorb.
 - The generation at Bus 1 : 110 MW
- The line flows to Bus 5 increase by a total of 20 MW
 - 14.5 MW comes from Bus 1
 - 4 MW from bus 4
 - Reduction of about 1.5 MW: Bus 3



7.3 Example With Interpretation Of Results (11)

■ Tweaking the Case

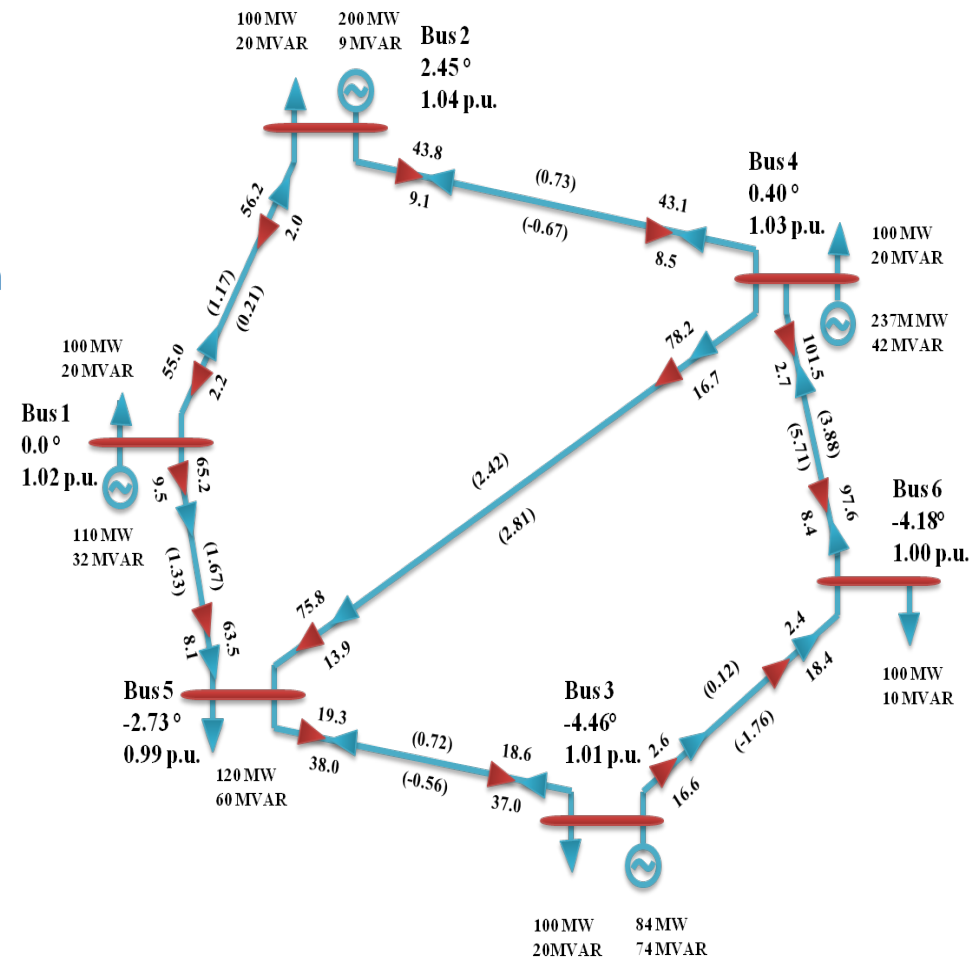
- Increase the load at bus 5 by 20%
 - Increasing reactive power at bus 4 and 3 and decreasing at slack bus
 - Voltage angles change as a result of the changed power flow pattern
 - The real power is fixed at all buses other than 1 and 5
 - Substantial increase in system reactive losses of 2.33 MVAR
 - Up almost 50% from 4.74 to 7.07 MVAR
 - Reactive power changed from 145 to 157 MVAR in total



7.3 Example With Interpretation Of Results (12)

■ Tweaking the Case

- Increase the load at bus 5 by 20%
 - The fully loaded link 4-6
 - Thermal limit of 100 MVA of each link
 - Carries after change 101,5 MVA
 - Becoming overloaded
 - In reality, proposed change is inadmissible
 - A generator other than bus 1 would be required



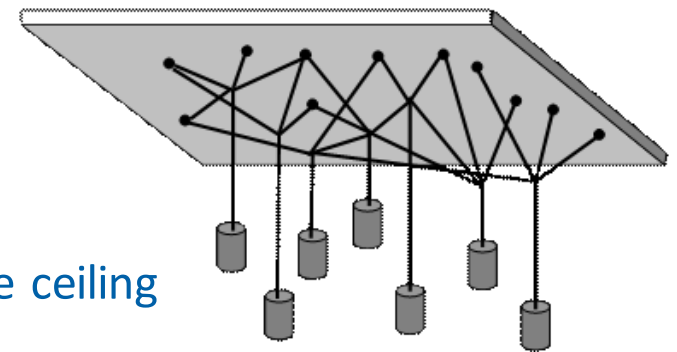
7.3 Example With Interpretation Of Results (13)

- Conceptualizing power flow
 - Power flow analysis
 - Deals with a steady operating state of the system
 - Describing the stable equilibrium consisting of a pulse
 - Had to make its rounds through the system as a disturbance, while the grid was being energized by the first generator on-line
 - Established as an ambient, steady-state condition and appears to reside everywhere in the system at once
 - The voltage-angle difference between two ends of a link
 - Is not explicitly a function of length
 - Depends on
 - The amount of power flow
 - The impedance of the link



7.3 Example With Interpretation Of Results (14)

- Conceptualizing power flow
 - Visualize power flow by way of a mechanical analogy
 - Transmission lines
 - Rubber bands tied together into a grid
 - Generation
 - Bands are suspended by hooks from the ceiling
 - Loads
 - Bands have weights hanging from them
 - Real power injected or consumed at each node
 - Weight or amount of force pulling the node up or down
 - The voltage angle
 - The elevation of each point in the rubber-band grid



<http://nptel.ac.in>



7.3 Example With Interpretation Of Results (15)

■ Conceptualizing power flow

■ Visualize power flow by way of a mechanical analogy

■ Power injected equals power consumed

- Rubber-band grid be in balance

■ Dynamic stability:

- A load is lost : weight suddenly falls off

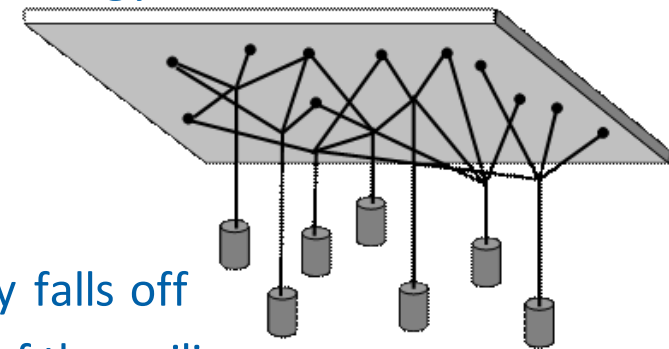
- A generator goes off-line : hook pops out of the ceiling

- Generators compensate for the change in system load

- Assuming the remaining hooks can accommodate the weight
- The network of rubber bands will bounce up and down

■ Steady-state stability

- Any given rubber band can only be stretched so far before it breaks

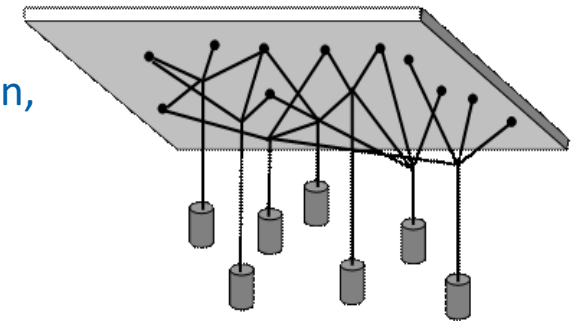


<http://nptel.ac.in>



7.3 Example With Interpretation Of Results (16)

- Conceptualizing power flow
 - Visualize power flow by way of a mechanical analogy
 - Line impedance
 - Rubber bands have different elasticities and strengths
 - A line with a high impedance :
 - A band stretches farther under a given tension,
 - Longer
 - More elastic
 - The thermal limit
 - The amount of tension that can be sustained by each band regardless of stretch
 - Reactive power and voltage magnitude (Not obvious)
 - Reactive power: rapid vibration in the weight (load) → met by a matching vibration in the suspension (generation)

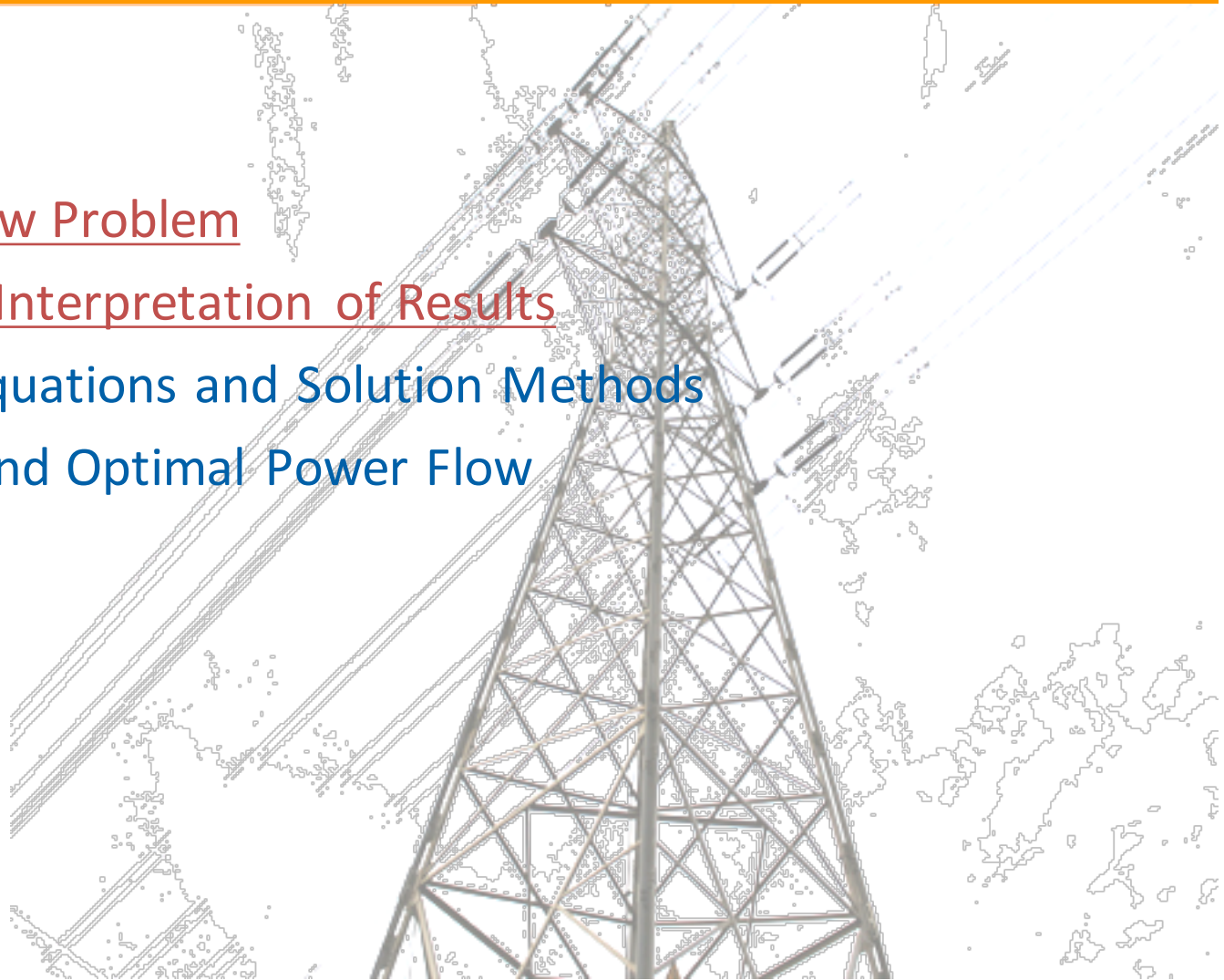


<http://nptel.ac.in>

7. Power Flow Analysis

■ Contents

- 1) Introduction
- 2) The Power Flow Problem
- 3) Example with Interpretation of Results
- 4) Power Flow Equations and Solution Methods
- 5) Applications and Optimal Power Flow
- 6) Summary



7.4 Power Flow Equations And Solution Methods (1)

- Derivation of power flow equations
 - Show explicitly how the variables are related to each other
 - Complex power $S_i = V_i I_i^*$;
 - i : indicates the bus of the network
 - The asterisk denotes the complex conjugate of the current
 - All variables are complex quantities
 - Power at load buses is positive, at generator buses is negative.
 - Not very helpful, no idea what the I_i are
 - Using Ohm's law to substitute known variables (voltages and impedances) for the unknowns (currents)
 - $I = V/Z = VY$; Z is the complex impedance
 - $Y = 1/Z$; Y is the admittance



7.4 Power Flow Equations And Solution Methods (2)

- Derivation of power flow equations
 - $Y = G + jB$; G is the conductance; B is the susceptance
 - Admittance matrix Y :
 - Summarize the admittances of all the links in the network
 - $y_{ik} = g_{ik} + b_{ik}$; The matrix element that connects nodes i and k
 - $y_{ik} = 0$; The absence of a transmission link
 - $I_{ik} = V_k y_{ik}$; The current between nodes i and k
 - $I_{ik} = V_k (g_{ik} + b_{ik})$;
 - V_k : The voltage difference between nodes i and k
 - $S_i = V_i I_i^* = V_i \left(\sum_{k=1}^n y_{ik} V_k \right)^*$
 - Index k : accounting for all the current that is entering or leaving node i



7.4 Power Flow Equations And Solution Methods (3)

■ Derivation of Power Flow Equations

- $S_i = V_i \sum_{k=1}^n (g_{ik} - jb_{ik}) V_k^*$

- $S_i = \sum_{k=1}^n |V_i| |V_k| e^{j(\theta_i - \theta_k)} (g_{ik} - jb_{ik})$

- $S_i = \sum_{k=1}^n |V_i| |V_k| [\cos(\theta_i - \theta_k) + j \sin(\theta_i - \theta_k)] (g_{ik} - jb_{ik})$

- $(\theta_i - \theta_k)$: The difference in voltage angle between nodes i and k

- $P_i = \sum_{k=1}^n |V_i| |V_k| [g_{ik} \cos(\theta_i - \theta_k) + b_{ik} \sin(\theta_i - \theta_k)]$

- $Q_i = \sum_{k=1}^n |V_i| |V_k| [g_{ik} \sin(\theta_i - \theta_k) - b_{ik} \cos(\theta_i - \theta_k)]$



7.4 Power Flow Equations And Solution Methods (4)

- Solution methods
 - No analytical, closed-form solution for the set of power flow equations
 - Use numerical approximation (iterative solution method)
 - First, assume certain values for unknown variables at every bus except the slack bus
 - Flat start: voltage angle (θ) zero, voltage magnitude (V) 1 p.u.
 - Based on the starting values, a different set of the known P 's and Q 's will be produced (contradiction or mismatch)
 - The objective is to get rid of this mismatch by repeatedly inserting a better set of (θ, V)
 - Depending on the required degree of precision, we can continue this process to reach some close approximation



7.4 Power Flow Equations And Solution Methods (5)

- Solution methods
 - Use numerical approximation (iterative solution method)
 - The heart of the iterative method is to know how to modify each guess with each iteration, so as to arrive the correct solution as quickly as possible.
 - There are several standard techniques: such as
 - Newton-Raphson,
 - Gauss, and
 - Gauss-Seidel iterations



7.4 Power Flow Equations And Solution Methods (6)

- Solution methods
 - Newton's method
 - Combine the initial guess for the unknown variables with the set of power flow equations and its partial derivatives in such a way that it suggests a helpful modification of the unknowns
 - Jacobian matrix **J** consists of the partial derivatives of the power flow equations, or their rates of change with respect to voltage angle and magnitude

$$\mathbf{J} = \begin{pmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{pmatrix}$$



7.4 Power Flow Equations And Solution Methods (7)

- Solution methods
 - Newton's method
 - \mathbf{x}^i refers to vector composed of the values of θ 's and V 's from the i th iteration
 - $\mathbf{f}(\mathbf{x})$ refers to a vector containing difference between power flow equations $P(\theta, V)$ and $Q(\theta, V)$ and the actual values of P and Q at each of the buses, which are known (i.e. $\mathbf{f}(\mathbf{x})$ represents the mismatch, which we want to get as close as reasonable to zero)
 - $\Delta \mathbf{x}^i = -\mathbf{J}^{-1} \mathbf{f}(\mathbf{x}^i)$
 - $\mathbf{x}^{i+1} = \mathbf{x}^i + \Delta \mathbf{x}^i$
 - When $\mathbf{f}(\mathbf{x}^i) = \mathbf{0}$, it means that there is no more mismatch, and the \mathbf{x}^i represents the operating state of the power system that is consistent with the known P 's and Q 's



7.4 Power Flow Equations And Solution Methods (8)

- Solution methods
 - After having found θ , V for each P,Q bus and θ , Q for each P,V bus, we can write the power flow equation for the slack bus and determine the amount of general power generated there
 - To determine how many MW of losses in the system, we can compare total MW generated to the total MW of load demand



7.4 Power Flow Equations And Solution Methods (9)

- Decoupled power flow
 - There is a general rule that relates
 - voltage angle mainly to real power, and
 - voltage magnitude to reactive power
 - There are two assumptions behind this rule
 - The reactive properties of transmission lines tend to outweigh the effect of their resistance
 - The voltage angle differences between buses are small (usually less than 10°)



7.4 Power Flow Equations And Solution Methods (10)

- Decoupled power flow
 - Therefor, based on these dependencies
 - For real power, $\frac{\partial P}{\partial \theta}$ ought to be substantial, while $\frac{\partial P}{\partial V}$ ought to be small
 - For reactive power, $\frac{\partial Q}{\partial \theta}$ ought to be small, while $\frac{\partial Q}{\partial V}$ should be substantial
 - Second, we must distinguish whether the dependence of real or reactive power on voltage angle or magnitude at the same bus, or at a neighboring bus. Thus, we will consider only the derivatives with unequal indices (such as $\partial P_2 / \partial \theta_3$)



7.4 Power Flow Equations And Solution Methods (11)

- Decoupled power flow

- Let us examine the derivatives for sample bus pair 2 and 3

- $\frac{\partial P_2}{\partial V_3} = V_2 [g_{23} \cos(\theta_2 - \theta_3) + b_{23} \sin(\theta_2 - \theta_3)]$

- $\frac{\partial Q_2}{\partial \theta_3} = V_2 V_3 [g_{23} \cos(\theta_2 - \theta_3) + b_{23} \sin(\theta_2 - \theta_3)]$

- Since the transmission link's reactive effects outweigh its resistive effects, the conductance g_{23} is a much smaller number than susceptance $b_{23} \rightarrow$ this makes cosine terms small
 - Since the voltage angle difference between buses is small, then the sine term is also small
 - As a result, we might deem these derivatives small enough to be negligible



7.4 Power Flow Equations And Solution Methods (12)

- Decoupled power flow

- By contrast, consider the following derivatives

- $\frac{\partial P_2}{\partial \theta_3} = V_2 V_3 [g_{23} \sin(\theta_2 - \theta_3) - b_{23} \cos(\theta_2 - \theta_3)]$

- $\frac{\partial Q_2}{\partial V_3} = V_2 [g_{23} \cos(\theta_2 - \theta_3) - b_{23} \cos(\theta_2 - \theta_3)]$

- Here, the g's multiply the sine terms, so these terms vanish on both accounts

- But neither b's nor cosine terms are negligible.

- Since cosine of a small angle is nearly 1, we obtain the following approximations

- $\frac{\partial P_2}{\partial \theta_3} = -V_2 V_3 b_{23}$

- $\frac{\partial Q_2}{\partial V_3} = -V_2 b_{23}$



7.4 Power Flow Equations And Solution Methods (13)

- Decoupled power flow
 - Decoupled power flow analysis takes advantage of these observations, where the term **decoupling** refers to the separation of the two variable (P and θ , on one hand; Q and V, on the other hand)
 - By assuming the small derivative to be zero, we greatly simplify the Jacobian matrix.

$$\blacksquare \mathbf{J} = \begin{pmatrix} \frac{\partial P}{\partial \theta} & \mathbf{0} \\ \mathbf{0} & \frac{\partial Q}{\partial V} \end{pmatrix}$$



7.4 Power Flow Equations And Solution Methods (14)

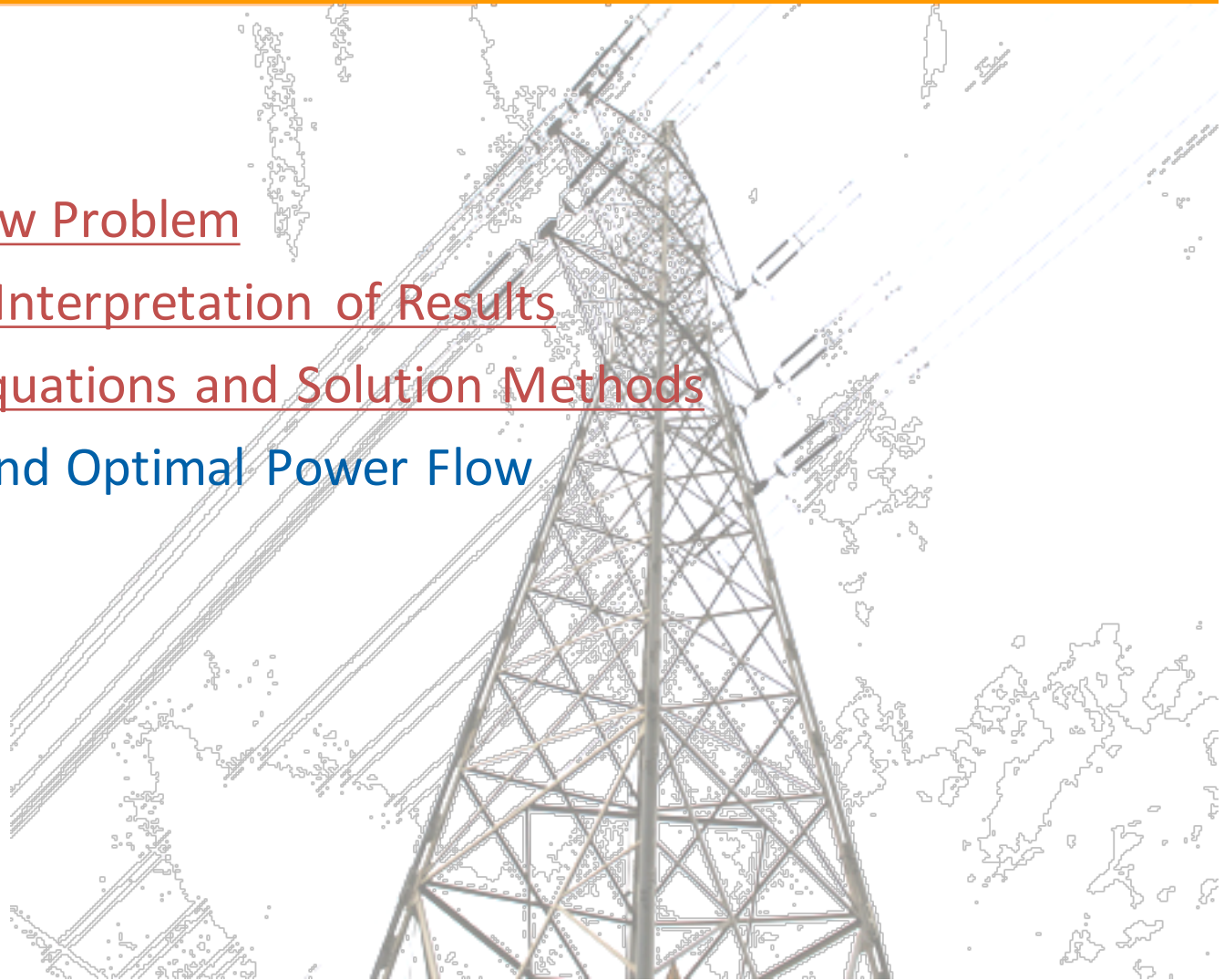
- Fast-decoupled power flow
 - Here we add a third assumption to the previous two assumptions about transmission lines and voltage angles
 - The voltage magnitude profile throughout the system is flat, meaning that all buses are very near the same voltage magnitude
 - As a result, we get an approximation for Jacobian that is independent of the voltage magnitude/angle and stays the same during each iteration → J is only built and inverted once
 - Therefore, it saves more computational effort → the computation is vastly sped up
 - Since the iteration process is self-correcting in nature, the simplifying assumptions are only a crutch for the process of approaching the correct power flow solution



7. Power Flow Analysis

■ Contents

- 1) Introduction
- 2) The Power Flow Problem
- 3) Example with Interpretation of Results
- 4) Power Flow Equations and Solution Methods
- 5) Applications and Optimal Power Flow
- 6) Summary



7.5 Applications And Optimal Power Flow (1)

- System operator's responsibility
 - Approving feasible generation schedules
 - Prepared on the basis of some economic considerations
 - Scrutinize them for technical feasibility
 - No important constraints (line loading limits) would be violated
- Optimal power flow (OPF) program
 - Identify the operating configuration or “solution” that best meets a particular set of evaluation criteria
 - Evaluating scenarios with different real and reactive power contributions



7.5 Applications And Optimal Power Flow (2)

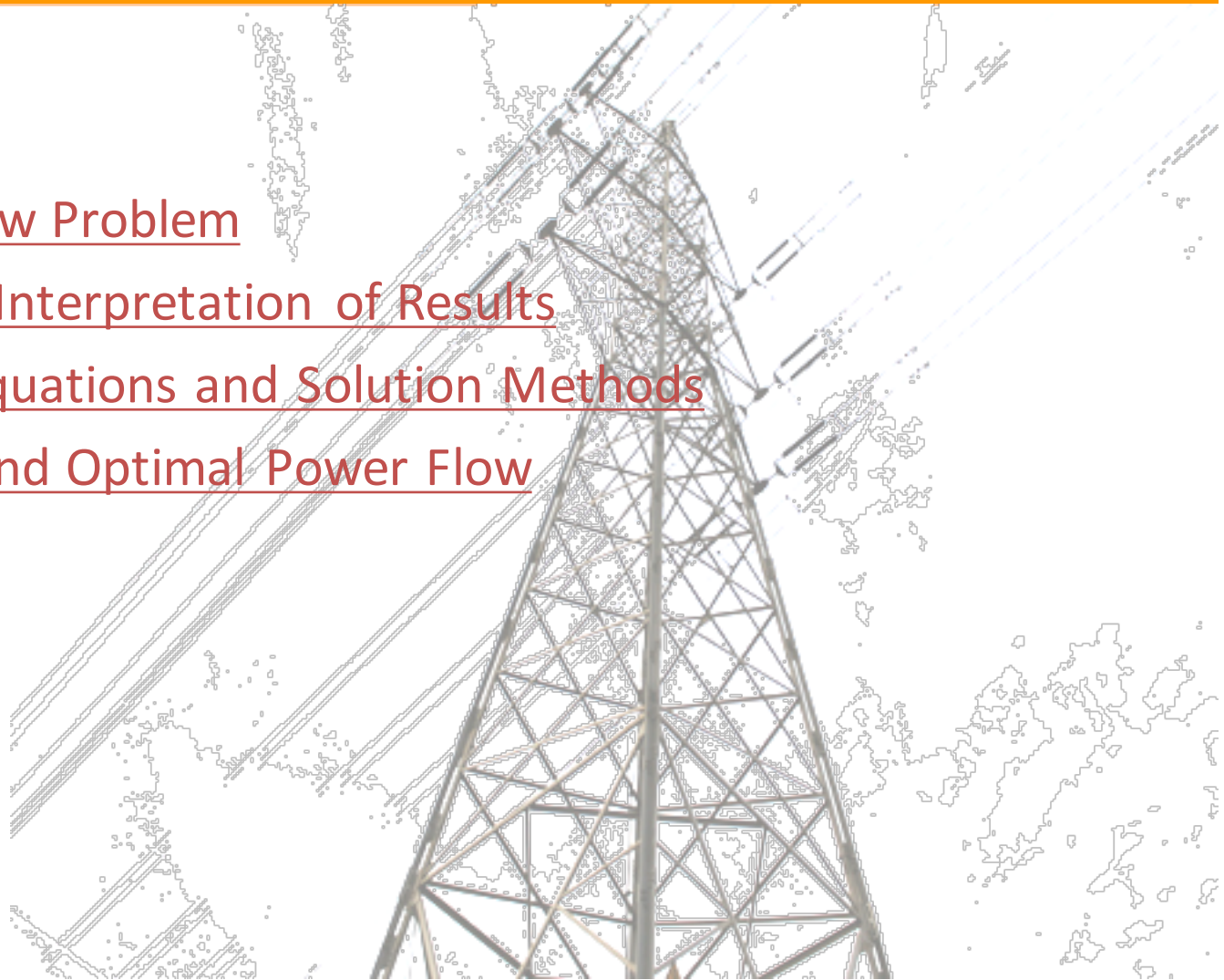
- Optimal power flow (OPF) program
 - Numerous power flow analysis runs
 - The output of each is power flow solution in terms of bus voltage magnitudes and angles
 - Power flow solution is evaluated according to one or more criteria (*objective function*)
 - The sum of all line losses in megawatts,
 - The sum of all generating costs when line losses are included
 - Optimality of the system depends on how the objective function is defined
 - Reality does not always conform to plans
 - OPF solution by actual planning and operating decisions is not clear-cut



7. Power Flow Analysis

■ Contents

- 1) Introduction
- 2) The Power Flow Problem
- 3) Example with Interpretation of Results
- 4) Power Flow Equations and Solution Methods
- 5) Applications and Optimal Power Flow
- 6) Summary



7.6 Summary

- Power flow analysis
 - Is a numerical analysis of the flow of electric power in an interconnected system
 - Focuses on various aspects of AC power parameters
 - Voltages
 - Voltage angles
 - Real power
 - Reactive power
 - Analyzes the power systems in normal steady-state operation



Electric Power System

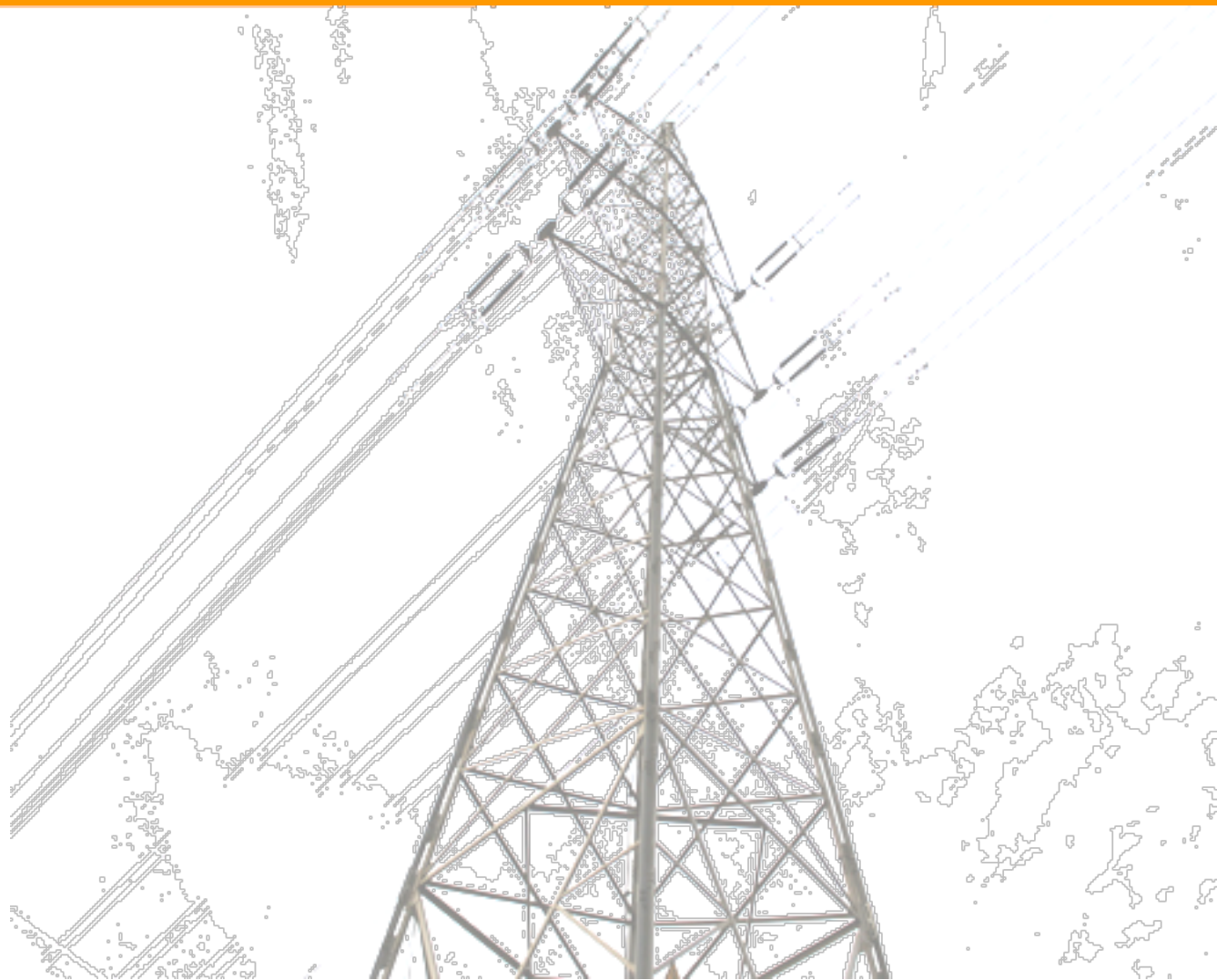
Chapter 08: System Performance



8. System Performance

■ Contents

- 1) Reliability
- 2) Security
- 3) Stability
- 4) Power Quality
- 5) Summary



8.1 Reliability (1)

- Reliability
 - The continuity of electric service to customers
 - Depends on
 - The availability of sufficient generation resources to meet demand
 - Generation capacity must be greater than load
 - The ability of the transmission and distribution system to deliver the power
 - Transmission must not be overloaded
 - Voltages must be within limits



Source: <http://commons.wikimedia.org>



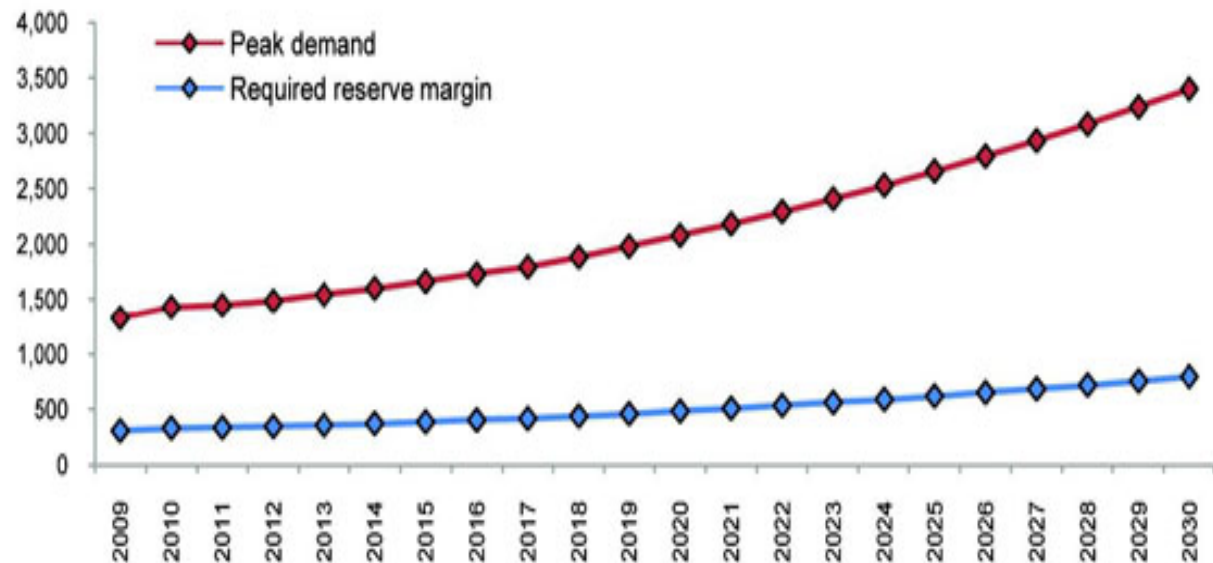
8.1 Reliability (2)

- Measure of Reliability

- Reserve margin of generation resources

- Does not take into consideration the characteristics of specific generation units

- Failure rates



Source: DOE

8.1 Reliability (3)

■ Measure of Reliability

■ Loss-of-load probability (*LOLP*)

- The probability that a system demand will exceed capacity during a given period
- May be considered on a daily basis Looking at the peak load for that day or for each individual hour

■ Loss-of-load expectation (*LOLE*)

- Summing up the probability of loss-of-load for each day over a time period and expressed as an inverse
- Expecting one loss-of-load event during this period



8.1 Reliability (4)

- Measure of Reliability
 - Expected unserved energy (*EUE*)
 - Calculated by combining
 - The probability of loss-of-load
 - The actual megawatt (MW) amount of load that would be in excess of total generating capacity
 - The excess load would be *shed*, or involuntarily disconnected
 - Outage frequency & outage duration



8.1 Reliability (5)

■ Valuation of Reliability

■ One-day-in-ten-years criterion in USA

- The systemwide generation capacity is expected to fall short of demand, presumably at the peak demand hour of that day, once every ten years

- Benchmark value for reliability

- The duration of an outage is not certain

■ Willingness to pay

- What level of reliability is “optimal” for a given type of customer
- The amount of money spent on providing this level of service
- The amount this customer would be willing to pay for it if given the option



8.1 Reliability (6)

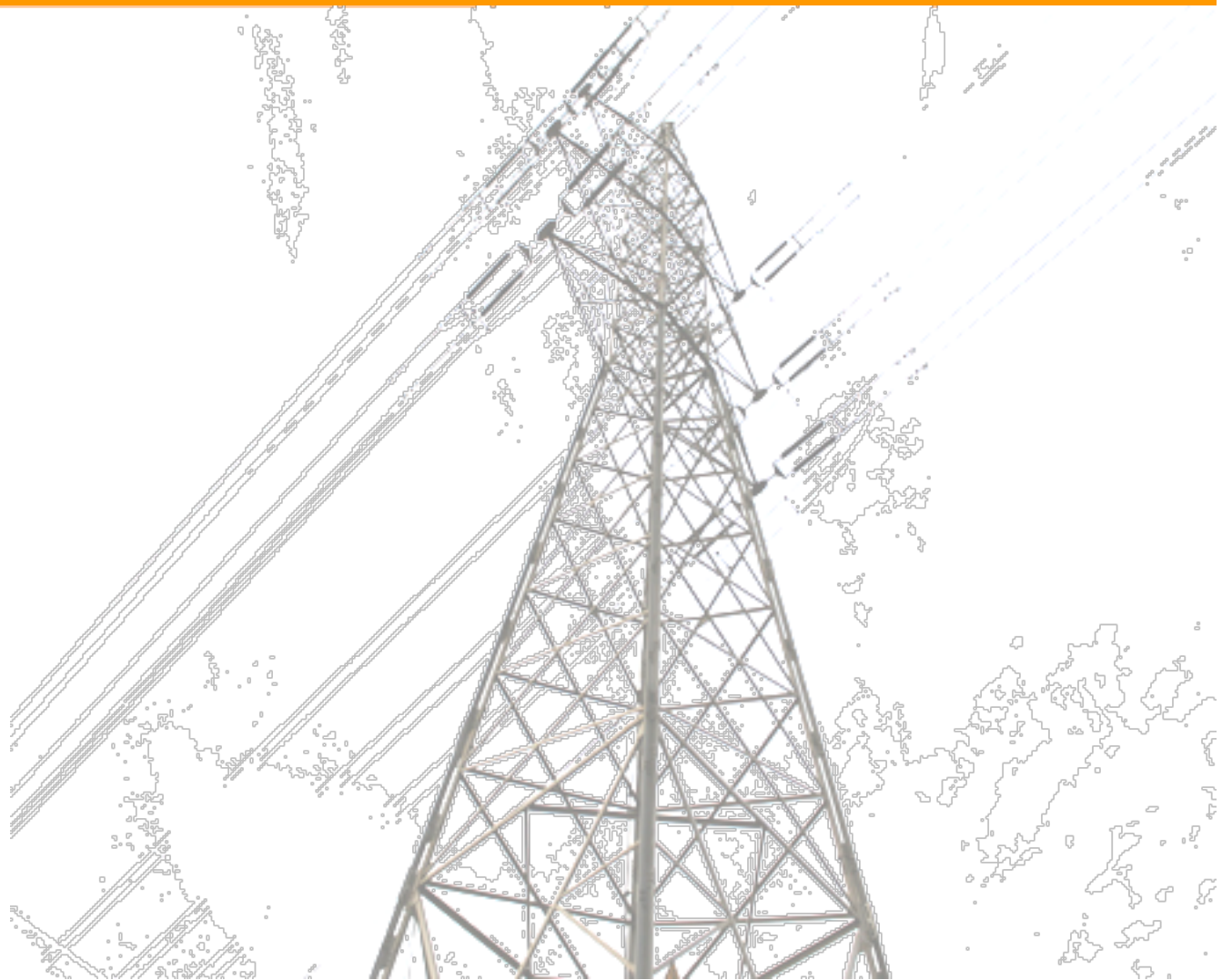
- Valuation of Reliability
 - Identify and distinguish how much service reliability is worth to different types of customers
 - Linear relationship between outage cost and duration
 - Lost kilowatt-hours : Those that would have been demanded over the course of the outage period
 - Outage cost : Dollars per kilowatt-hour (kWh)



8. System Performance

■ Contents

- 1) Reliability
- 2) Security
- 3) Stability
- 4) Power Quality
- 5) Summary



8.2 Security (1)

- Definition
 - How many things can go wrong before service is actually compromised
- A secure system
 - Can sustain one or several *contingencies*
 - A transmission line going down
 - A generator unexpectedly going off-line
 - Continue to function without interruption
 - Transitioning into a new configuration in which the burden is shifted to other equipment



8.2 Security (2)

- How?
 - Generator fails
 - Reserve margin
 - Transmission line fails
 - “Reserve” of transmission capacity
 - Alternate routes for power to flow
- Contingency analysis
 - The analysis of the fail scenarios
 - *N-1* (“normal minus one”) criterion
 - The system must remain functional after one contingency,
 - e.g. loss of a major line



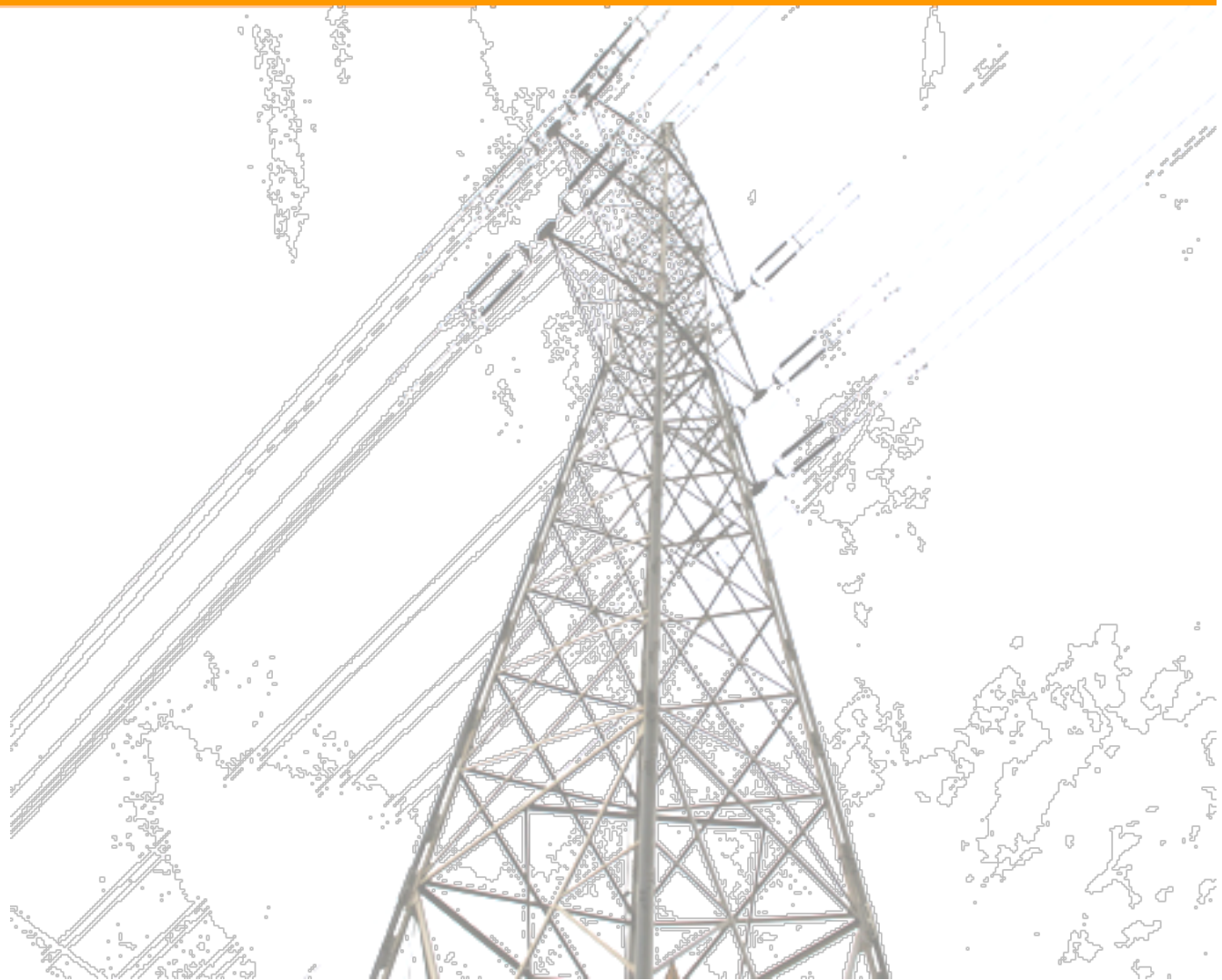
8.2 Security (3)

- Line flow limits
 - The amount of current or power transfer permissible on each transmission link
 - If one line is lost
 - Loading on the other lines will not exceed their ratings
 - Voltages can be held within the permissible range
 - The resulting operating state does not violate any constraints
 - Line ratings are based on
 - Thermal limits
 - Stability limits



■ Contents

- 1) Reliability
- 2) Security
- 3) Stability
- 4) Power Quality
- 5) Summary



8.3 Stability (1)

- The Concept of Stability
 - The tendency of an alternating current (a.c.) power system to maintain a synchronous and balanced operating state
 - Angle stability
 - All the system's components remain locked "in step" at a given frequency
 - Stability analysis
 - concerned with the differences in phase or angle between current and voltage and their implications for keeping the system locked in step



Source: <http://commons.wikimedia.org>



8.3 Stability (2)

- The Concept of Stability

- Steady state

- A system's stability under some fixed set of operating conditions

- Constant generator outputs and loads

- A crucial factor

- The length of transmission lines in relation to the amount of the transmitted power

- Transient stability (*dynamic*)

- The system's ability to accommodate sudden changes and return quickly through this transient condition to a sustainable state

- Faults (short circuits)

- Loss of a transmission link

- Failure of a large generating unit



Source: <http://commons.wikimedia.org>



8.3 Stability (3)

- The Concept of Stability

- In an a.c. power system

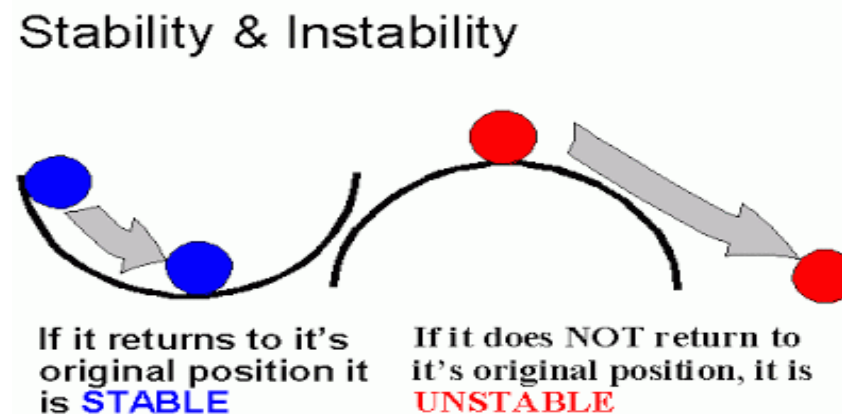
- Power angle is a variable at any point in the system

- Our conceptual challenge

- Understanding the power angle as a dynamic variable

- The changes of it over time interest us

- Relates different and remote parts of a power system to each other



<http://tokyophysio.com>

8.3 Stability (4)

- **Steady-State Stability**
 - A given set of loads
 - A given set of power contributions from generators
 - A given network of transmission lines
 - Synchronism among all components
 - The frequency and the phase of two or more oscillating components match
 - Synchronous generators are connected together
 - Spinning at the same rate
 - Their voltage output peak at about the same time
 - Generators simultaneously contribute to feed power into a network



8.3 Stability (5)

- **Steady-State Stability**
 - **Synchronism**
 - Requires a stable equilibrium condition
 - Restoring force== Negative feedback effect
 - Slow down a generator that has sped up
 - A generator must supply additional power
 - Thus tending to restrain the turbine more
 - Speed up a generator that has slowed down
 - A generator must supply less power
 - Relieving the restraint on the turbine



8.3 Stability (6)

- **Steady-State Stability**
 - **Negative feedback effect**
 - Depending on the difference of phases between generators
 - The most when the phases are very close together
 - The difference between the phase angles grows
 - A greater difference in power generation,
 - A greater transmission of power between them
 - A weak stabilizing effect, weakens.



Source: <http://commons.wikimedia.org>



8.3 Stability (7)

■ Steady-State Stability

■ Mathematical expression and stability limit

■ $P = (V_1 V_2 / X) \sin \delta_{12}$

■ P : The (real) power transmitted along a line

■ V_1, V_2 : The voltage magnitudes on either end of the line

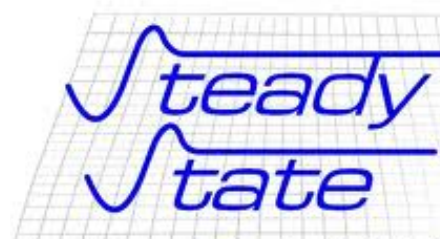
■ X : The reactance of the line

■ δ_{12} : The difference between power angles at the two ends

■ $\delta_{12} = 90^\circ$ is not generally safe to do

■ Stability limit on δ_{12}

■ δ_{12} too large : risk losing the negative feedback between generators



<http://www.steadystate.co.uk>



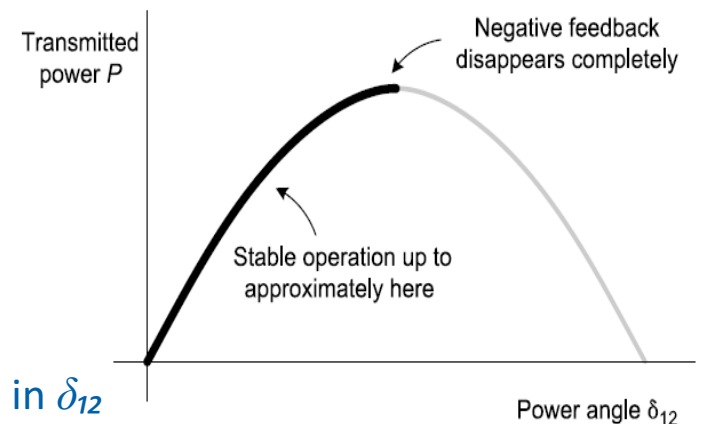
8.3 Stability (8)

■ Steady-State Stability

■ Negative feedback as a function of power angle

■ Mathematical

- If δ_{12} increases beyond 90°
 - Represent an unstable equilibrium
 - Power would actually decrease
 - speed up the generator
 - leads to a further increase in δ_{12}
- The slope of the sine curve
 - Increment in δ_{12}
 - only a small increment in P
- A reasonable limit on δ_{12} is 40° to 50°



Copyright John Wiley & Sons



8.3 Stability (9)

- **Steady-State Stability**

- Negative feedback as a function of power angle

- circulating currents

- Increasing the load of the generator that is ahead of the other (Unit 1)

- Reducing the load of the one that is behind (Unit 2)

- Difference voltage between generators

- Approximately 90° ahead of the main voltage from the perspective of the ahead generator

- The circulating current

- Lags about 90° behind the difference voltage

- just about into phase with

- The main voltage output of the ahead generator

- The previously existing current



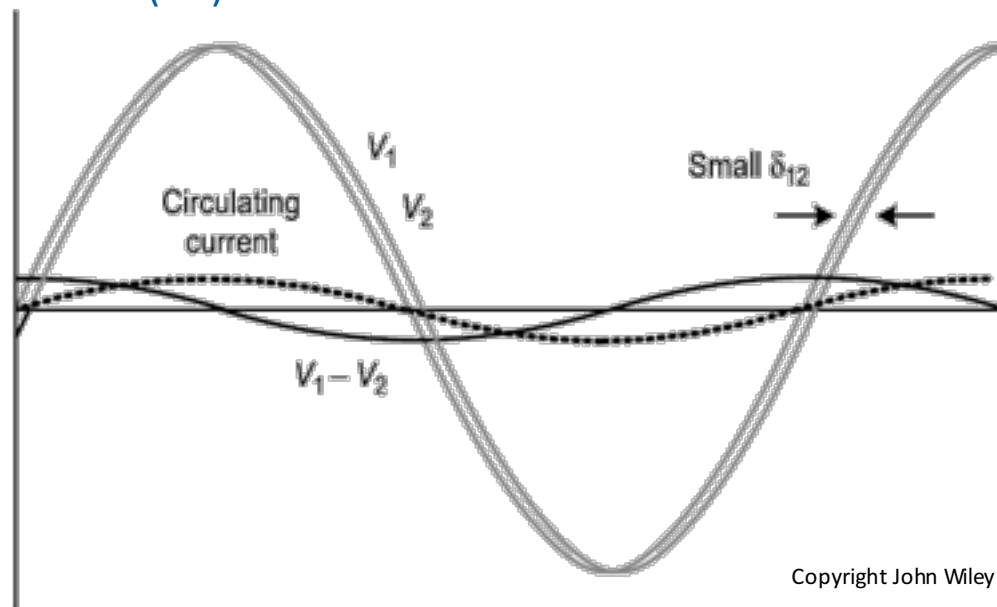
8.3 Stability (10)

- **Steady-State Stability**
 - Negative feedback as a function of power angle
 - circulating currents
 - In Unit 1 is associated with an additional positive power output
 - In Unit 2
 - Appears to be negative
 - 180° out of phase with its regular voltage and current
 - Acts to diminish its power output
 - Its power is being supplied to the behind generator



8.3 Stability (11)

- Steady-State Stability
 - Negative feedback as a function of power angle
 - circulating currents
 - The difference in power angle δ_{12} is small
 - Circulating current is almost exactly in phase with the generator voltage that is ahead (V1)

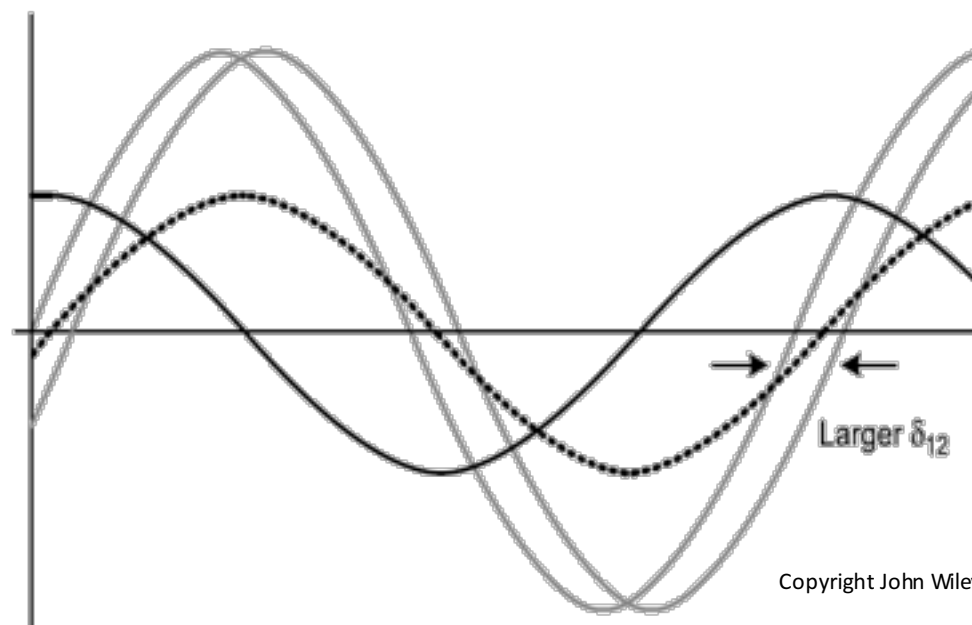


Copyright John Wiley & Sons



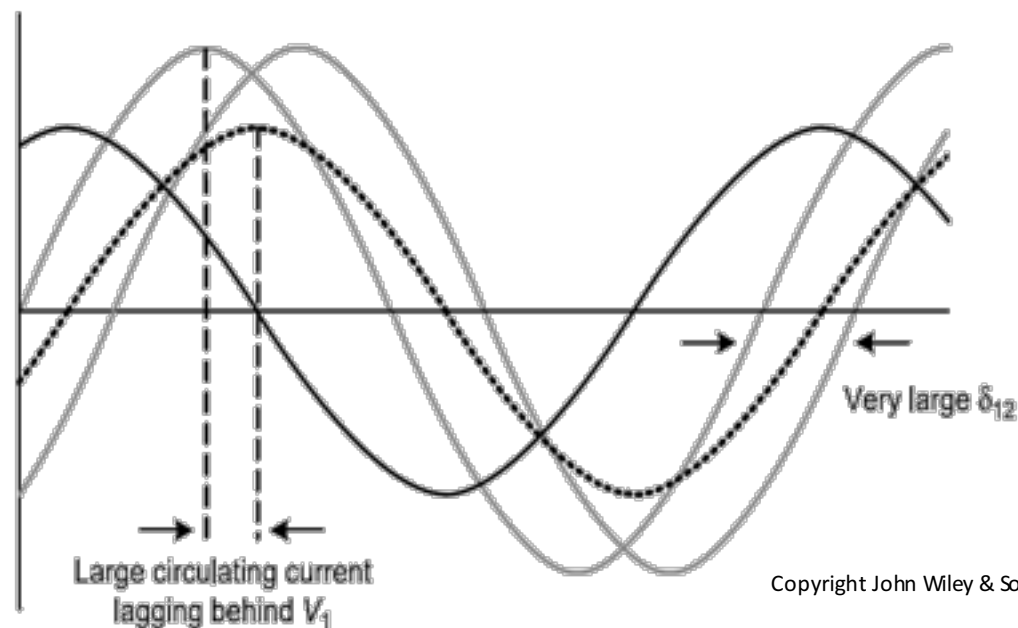
8.3 Stability (12)

- Steady-State Stability
 - Negative feedback as a function of power angle
 - circulating currents
 - The difference in power angle δ_{12} is larger
 - The circulating current is shifted slightly out of phase with V_1



8.3 Stability (13)

- Steady-State Stability
 - Negative feedback as a function of power angle
 - circulating currents
 - The difference in power angle δ_{12} is very large
 - The Phase shift of circulating current is more pronounced



Copyright John Wiley & Sons

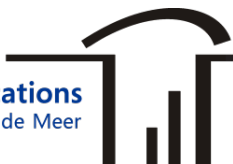
8.3 Stability (14)

- **Steady-State Stability**
 - Negative feedback as a function of power angle
 - circulating currents
 - The difference in power angle δ_{12} is 45°
 - The circulating current peaks at 22.5° behind V_1
 - The power transferred is sometimes positive and sometimes negative
 - Oscillation of power back and forth, rather than a continuous transfer from one generator to the other
 - The stabilizing effect is gradually lost as the difference in power angles increases



8.3 Stability (15)

- Dynamic Stability
 - Called transient stability
 - The displacement of the power angle is generally due to a temporary, transient disturbance
 - How large a disturbance can the generator sustain and still return to equilibrium?
 - Will it return to equilibrium in a reasonable amount of time?
 - In electric generators
 - The mechanical torque from the turbine shaft equals the sum of two powers:
 - The electrical power that is pushed out the armature windings through the magnetic field
 - A certain amount of *damping power* that acts to slow down the rotor



8.3 Stability (16)

■ Dynamic Stability

■ In electric generators

- Excess mechanical power supplied from the turbine, the rotor speeds up
- The power supplied from the turbine is less than the electrical and damping power drawn out, the rotor slows down
 - The generator swing equation
 - Differential equation
 - Describes the behavior of the power angle δ
 - $M \ddot{\delta} + D \dot{\delta} + P_G(\delta) = P_M^0$
 - P_M^0 : The mechanical power input from the turbine (constant)
 - The superscript (0) : Indicates the value at equilibrium



8.3 Stability (17)

■ Dynamic Stability

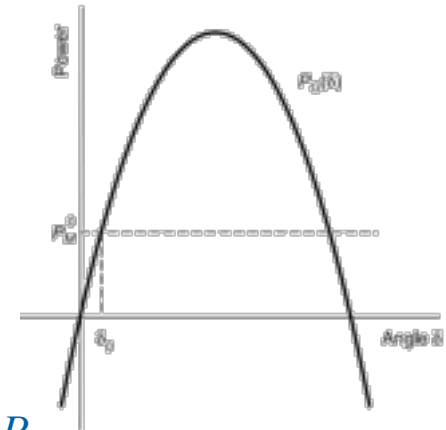
■ In electric generators

■ The generator swing equation

■ $P_G(\delta)$: The electrical power output

- Varies as a function of the power angle δ
- Over a reasonable range of δ , as δ increases, so does P_G
- For extremely large δ , P_G eventually becomes negative.
 - δ describes the position or timing of a generator *relative to others*
- As the restoring force
 - Pushes back on the rotor through the magnetic field
 - Farther we displaced δ , the harder the magnetic force pushes back
 - At the equilibrium point δ_0

- $P_G = P_M^0$



Copyright John Wiley & Sons



8.3 Stability (18)

■ Dynamic Stability

■ In electric generators

■ The generator swing equation

- $\dot{\delta}$: The rate of change of δ with respect to time
 - Positive : The rotor frequency is greater than the system frequency
 - Negative : The rotor frequency is less than the system frequency
- Constant D : A measure of the damping force
 - Resisting any changes in δ
- $D \dot{\delta}$: The power absorbed by friction
- $\ddot{\delta}$: Acceleration, or change of speed, of the rotor
- Constant M : A measure of the generator's inertia
 - Resisting changes in rotational speed
- $M \ddot{\delta}$: The power that goes into speeding up or that comes out of slowing down the generator rotor



8.3 Stability (19)

■ Dynamic Stability

- What will happen if δ is somehow displaced from equilibrium?
 - Determining just how far δ can be displaced before there is trouble
 - The classic case for study
 - A transmission link is momentarily interrupted and then quickly reconnected
 - The transmission link is a generator's only connection to the grid
 - During the very short time period where the link is interrupted
 - Generator cannot send out electric power
 - The steam turbine output cannot be adjusted.
 - Constant mechanical power input P_M^0
 - No power goes out in the form of electricity,
 - All of P_M^0 goes into accelerating the rotor
 - Small amount to overcome friction
 - The power angle δ increases, as does its rate of increase $\dot{\delta}$
 - The generator thus acquires a certain amount of excess energy

8.3 Stability (20)

■ Dynamic Stability

■ The classic case for study

- The generator thus acquires a certain amount of excess energy
 - Manifests as kinetic energy of the rotor,
 - The rotor is now spinning at a higher than normal frequency
 - Up to a certain amount, it can be dissipated
 - More than a certain limit, the generator cannot return to equilibrium
- Transient stability analysis
 - Determining the critical amount of excess energy
 - The length of the time interval of generator disconnection



8.3 Stability (21)

■ Dynamic Stability

- The classic case for study
 - When the generator is reconnected
 - Relieving itself of excess energy into the grid
 - The initial displacement of δ is reasonable
 - $P(\delta)$ excess P^0_M
 - The rotor decelerates
 - until δ is less than δ_o , and $P(\delta)$ is less than P^0_M
 - The rotor begins to accelerate again
 - This movement would continue back and forth indefinitely
 - Damping force slows the motion of δ and causes the excursions to gradually diminish until δ settles at δ_o
 - The initial displacement of δ is too far
 - δ will not settle at δ_o
 - The nonlinear characteristic of $P(\delta)$

8.3 Stability (21)

- Dynamic Stability
 - What physically happens to the energy during the generator's oscillation?
 - A generator is disconnected and speeding up
 - Other generator in the system is slowing down
 - Supplying the extra load
 - After the connection is reestablished
 - The two generators now have a symmetric power imbalance
 - The exchange of energy back and forth between these two generators
 - By means of the circulating currents
 - The generators alternately speed up and slow down until they again share the load according to their set points.



8.3 Stability (22)

■ Dynamic Stability

- A generator which is affected by the transient disturbance get impacts on two types of energy:
 - Kinetic energy
 - The generator gains and loses rotational kinetic energy as its rotational speed increases and decreases
 - Maximum when the rotor is spinning fastest
 - The rotational frequency $\dot{\delta}$ is maximum, while δ increases and passes δ_0
 - Minimum when the rotor is spinning slowest
 - On the way back δ decreases and passes δ_0
 - Does not care whether the speed relative to the nominal 60 cycles is positive or negative
 - Kinetic energy is again at a maximum as δ passes δ_0 in the opposite direction, when $\dot{\delta}$ is greatest in the negative direction



8.3 Stability (23)

■ Dynamic Stability

- A generator which is affected by the transient disturbance gets impacts on two types of energy:
 - Potential energy
 - Analogous to the gravitational potential energy
 - As the accumulation of restoring power
 - Equals zero when $\delta = \delta_0$
 - The generator acquires as δ is displaced, in either direction
 - Maximum potential energy at the point of maximum and minimum δ
 - At maximum
 - It has the greatest capability of doing work on other generators
 - Relieve their load by carrying extra power and thereby slowing down, sacrificing its own “lead” in δ
 - At minimum : The situation is reversed

8.3 Stability (24)

■ Dynamic Stability

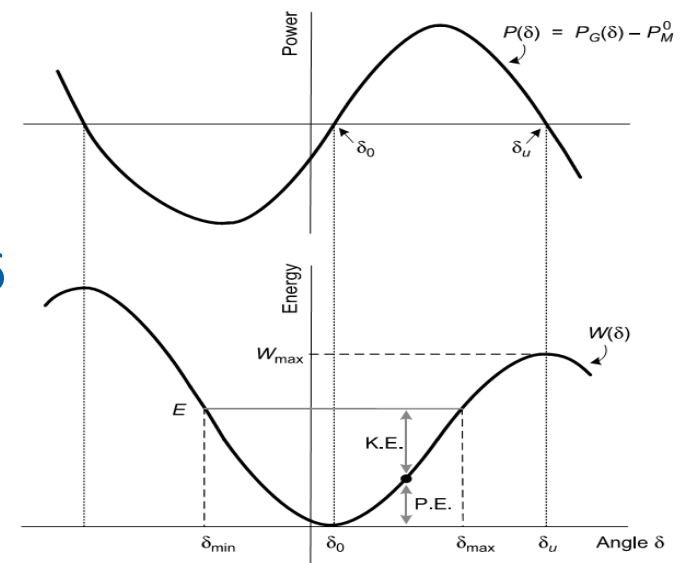
■ Restoring power

- The difference between the electrical power output and the mechanical power input
- The portion of the $P_G(\delta)$ curve that extends above the line representing P_M^0

■ K.E. Kinetic energy

■ P.E. Potential energy

- Integral of the restoring power over δ
- The area under the curve between δ_0 and the given δ
- $W(\delta)$: The curve of cumulative potential energy as a function of δ

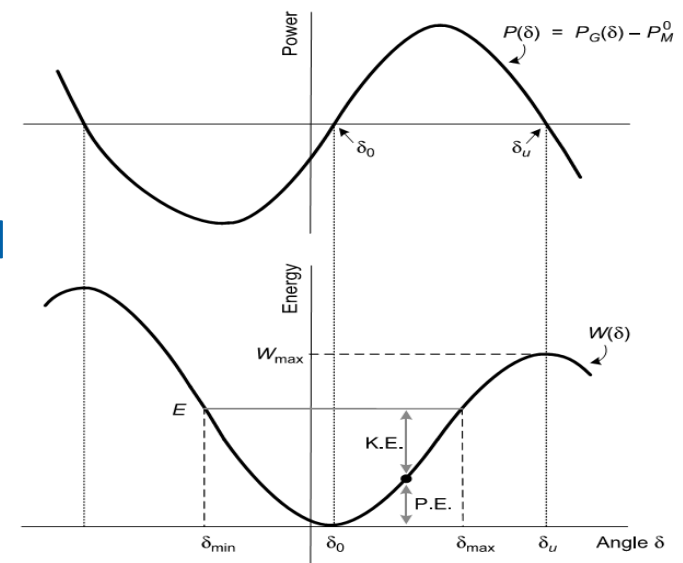


Copyright John Wiley & Sons

8.3 Stability (25)

■ Dynamic Stability

- The peak of the potential energy curve W_{max} *(on the right)*
 - Indicates the maximum amount of restoring work that can be done on the generator to bring it “back in line”
 - The maximum energy that the generator can dump into the grid by running ahead of others
 - The accumulated restoring power from δ_0 to the upper limit δ_u
 - The area between the $P_G(\delta)$ curve and P_M^0



Copyright John Wiley & Sons

8.3 Stability (26)

- Dynamic Stability
 - During the transient condition, the generator acquires both
 - Potential energy : because δ is displaced
 - Kinetic energy : because δ is in the process of changing
 - The generator is transient stable
 - If the total energy acquired during the transient period is no more than the maximum amount of energy that can be gotten rid of, W_{max}
 - Very general and assumes nothing about the peculiarities of the transient disturbance.



8.3 Stability (27)

■ Dynamic Stability

■ Equal area criterion

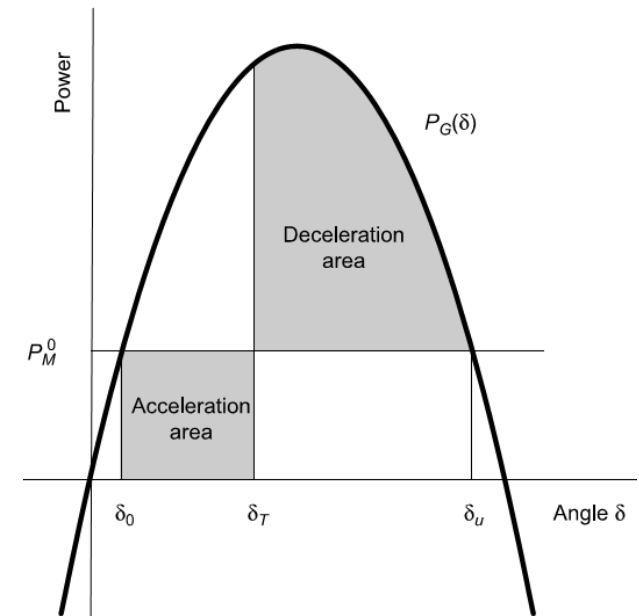
- δ_u : The maximum δ for which there is still any restoring force at all

■ Acceleration area

- Below P_M^0
- Between δ_0 and the displaced δ_T at the end of the transient
- Represents the amount of excess energy acquired by the generator during the transient period

■ Deceleration area

- The area between $P_G(\delta)$ and P_M^0 up to their intersection point at δ_u



Copyright John Wiley & Sons



8.3 Stability (28)

- Dynamic Stability
 - Equal area criterion
 - Deceleration area
 - The area between $P_G(\delta)$ and P_M^0 up to their intersection point at δ_u
 - Represents the cumulative deceleration power
 - The total amount of energy that the generator can dump into the grid, minus the amount to which it is already committed due to its displacement of δ
 - The generator is transient stable if
 - Acceleration area is no greater than deceleration area
 - In other words
 - There must be enough deceleration power left to absorb the kinetic energy that is left once the potential energy has been accounted for



8.3 Stability (29)

■ Voltage Stability

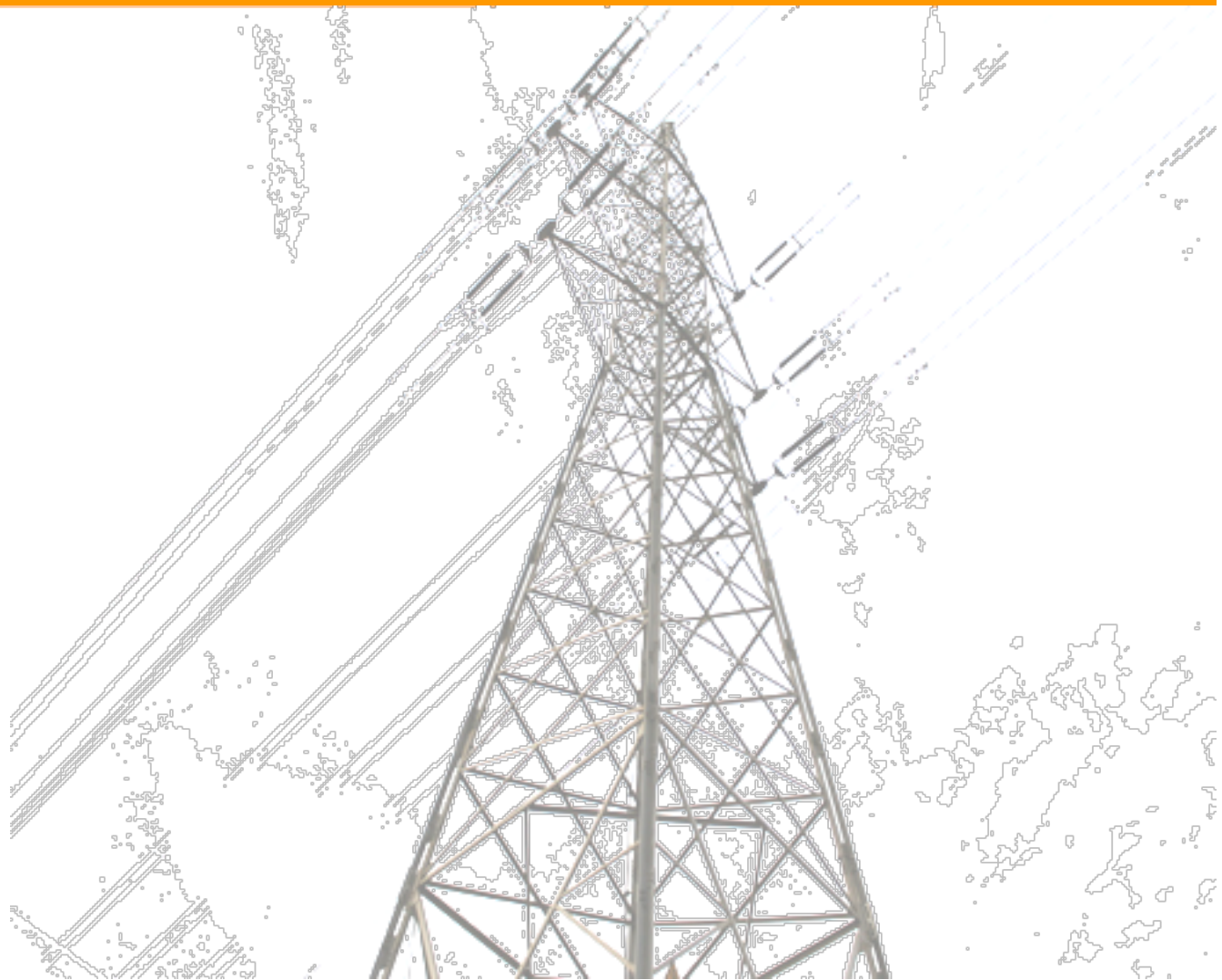
- The stability of the voltage magnitude
- The interactions between voltage and angle instability are so complex
- System can become unstable with respect to only voltage magnitude but not angle, or vice versa
- Voltage stability
 - As load increases, power consumption also increases
 - Voltage does not go down
- Voltage collapse: Voltage instability
 - Voltage and power cannot be controlled



8. System Performance

■ Contents

- 1) Reliability
- 2) Security
- 3) Stability
- 4) Power Quality
- 5) Summary



8.4 Power Quality (1)

■ Power Quality

- Encompasses voltage, frequency, and waveform
- The voltage supplied by the utility at the customer's service entrance is steady and within the prescribed range

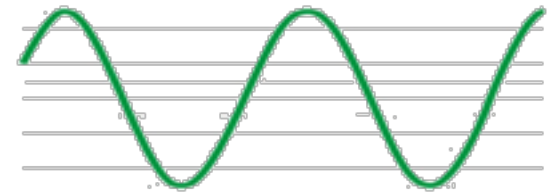
- The a.c. frequency

- Steady and very close to its nominal value

- The waveform

- Absence of *harmonic distortion*

- The *compatibility* between what comes out of an electric outlet and the load that is plugged into it



8.4 Power Quality (2)

■ Voltage

■ Voltage drop

- The difference between the voltage supplied at the generation end and that received by a given load varies continuously with demand
- Systemwide and local
- Low voltage
 - Power system's resources are overtaxed by exceedingly high demand
- High voltage
 - Damage appliances simply by overloading their circuits

■ Temporary voltage increase

- Voltage impulse : Last on the order of microseconds
- Voltage swell : A longer event



Source: <http://commons.wikimedia.org>



8.4 Power Quality (3)

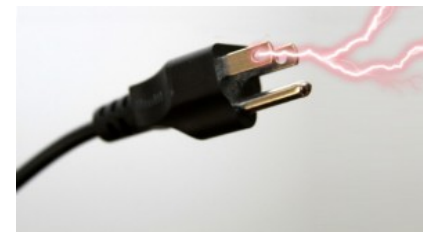
■ Voltage

■ Sags (*American*) or dips (*British*)

- Temporary decreases in voltage
- Cause electronic loads to shut off or otherwise behave strangely
- Noticeable as a occasional rebooting of a computer
- Much more often than swells
- Economic losses : \$5 billion per year in the United States

■ Spike protector

- To protect against increased current that may quickly overheat a small component inside an appliance
- Mitigating *sags*
- Mitigating *swell*



Source: <http://commons.wikimedia.org>



8.4 Power Quality (4)

- Frequency
 - Drifting frequency
 - Cause : Generation and demand are not balanced
 - A risk mainly for synchronous machines
 - Generators and synchronous motors
 - Some of their windings may become overloaded
 - Synchronous generators are equipped with relays to disconnect them from the grid in the event of over- or under frequency conditions
 - The sensitivity of these relays is a matter of some discretion, but would typically be on the order of 1%



8.4 Power Quality (5)

- Frequency
 - Drifting frequency
 - A risk for the transmission and distribution system
 - Sections of the T&D may be separated by over- and under frequency relays
 - In USA as example 58 and 59 Hz for 60-Hz
 - A significant departure from the nominal frequency would indicate a very serious problem in the system
 - Preventing cascading blackouts
 - One portion of the grid that has lost its ability to maintain frequency control pulls other sections down with it as generators become unable to stabilize the frequency and eventually trip off-line



8.4 Power Quality (6)

- Frequency
 - Maintaining a very exact frequency
 - Electric clocks
 - Go slower if the frequency is low and faster if it is high
 - Keep track of cycles lost during periods of underfrequency over the course of a week
 - Make up those cycles on a certain evening or weekend, outside regular business hours
 - Any advanced technological application that requires synchronization of components
 - Rely not on the a.c. grid
 - Rely on subatomic oscillators



8.4 Power Quality (7)

- **Waveform**
 - The oscillation of voltage and current follow the mathematical form of a sine or cosine function
 - Geometry of the generator windings that produce voltage
 - The sinusoidal waveform can be altered by
 - Transient disturbances
 - Imperfect behavior of either generators or loads
 - Waveform distortions created by
 - Voltage : Generators
 - Current : Loads

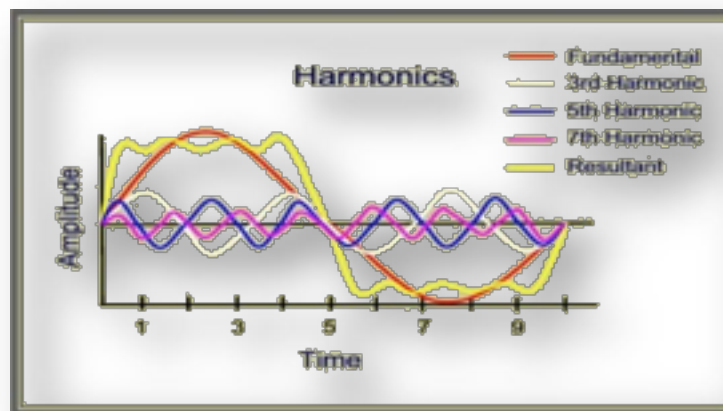


8.4 Power Quality (8)

■ **Waveform**

■ **Harmonics**

- The distortions of voltage or current occur in the form of oscillations that are more rapid than 60 Hz
- Periodic : Steadily observable
- Exact multiples of the basic a.c. frequency
- Manifest as jagged or squiggly wave
 - The sum of sinusoidal curves of different frequencies and magnitudes



8.4 Power Quality (9)

- **Waveform**

- **Harmonics**

- **Total harmonic distortion (*THD*)**

- A percentage indicating the amount of power carried by the harmonic frequencies
 - A common standard for power generation equipment
 - To produce voltage *THD* below 5%

- **Effect**

- Resistive loads: No
 - Motors and electronic equipment : vibration, buzzing
 - Transformers : Losses and overheating

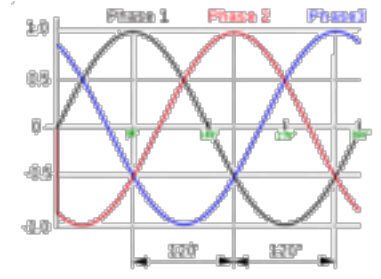


8.4 Power Quality (10)

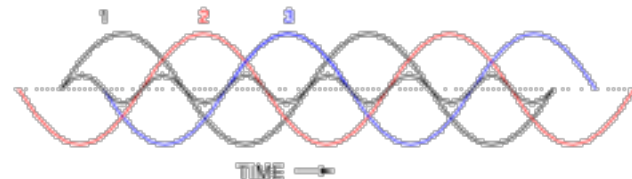
■ Waveform

■ Harmonics

- Special behavior owing to symmetries
- Transformer with a delta connection on its primary side
 - The third harmonic of the a.c. base frequency (60 Hz)
 - A small oscillation at 180 Hz
 - The one of phase A is indistinguishable from that of Phase B or C
 - The waves are superimposed on each other
 - The same is true for all multiples of the third harmonic (6th, 9th, etc.)
 - Voltage component alternates at a multiple of 180 Hz on all three phases
 - There is no phase-to-phase difference to be had
 - No power to be transferred by the transformer



<http://it.wikipedia.org>



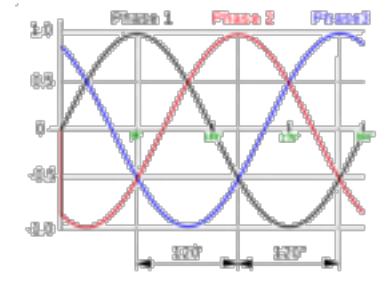
Source: <http://commons.wikimedia.org>

8.4 Power Quality (11)

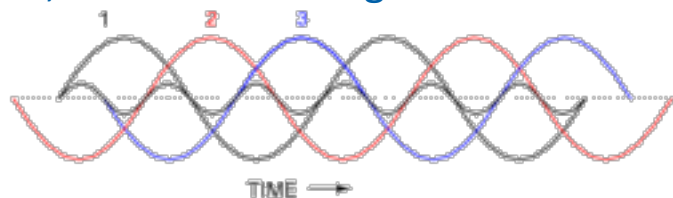
■ Waveform

■ Harmonics

- Special behavior owing to symmetries
- Transformer with a delta connection on its primary side
 - The third harmonic of the a.c. base frequency (60 Hz)
 - One-third of all the integer multiples of the base frequency are also multiples of three
 - One-third of all the power contained in harmonic components of a wave is blocked by any delta connection
 - Keep cycling through conductors until it is consumed as waste heat
 - If THD represents, 3% of the power carried by a wave
 - 1% loss, which is not insignificant



<http://it.wikipedia.org>

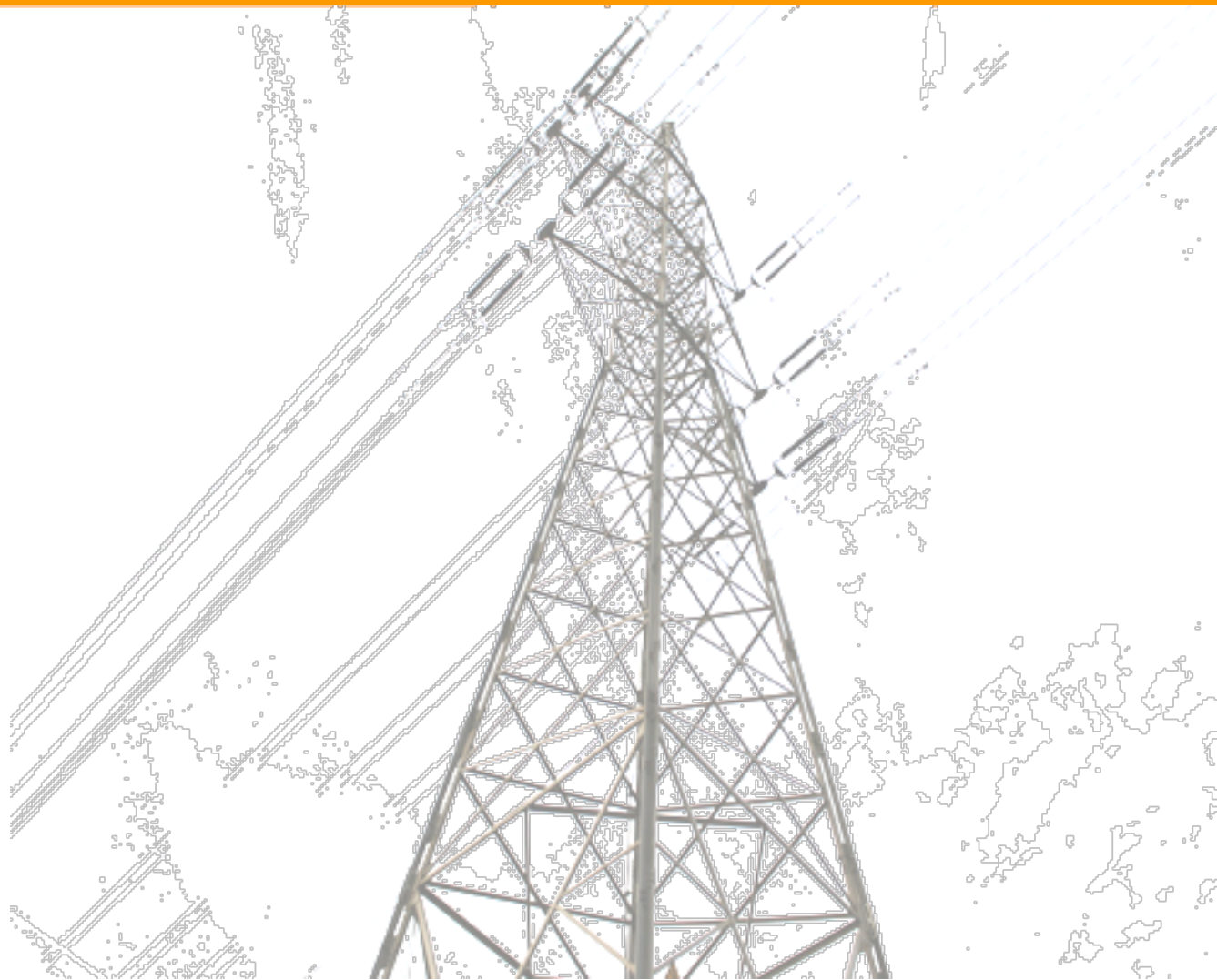


Source: <http://commons.wikimedia.org>

8. System Performance

■ Contents

- 1) Reliability
- 2) Security
- 3) Stability
- 4) Power Quality
- 5) Summary



8.5 Summary

- System performance contains is a mixture of many properties
 - Reliability
 - The availability of sufficient generation resources to meet demand
 - The ability of the transmission and distribution system to deliver the power
 - Security
 - Sustain one or several *contingencies*
 - Stability
 - The ability of the of the system to bring back its operation to steady state condition within minimum possible time after having undergone some sort of transience or disturbance in the line
 - Power quality : Voltage, frequency, and waveform



Electric Power System

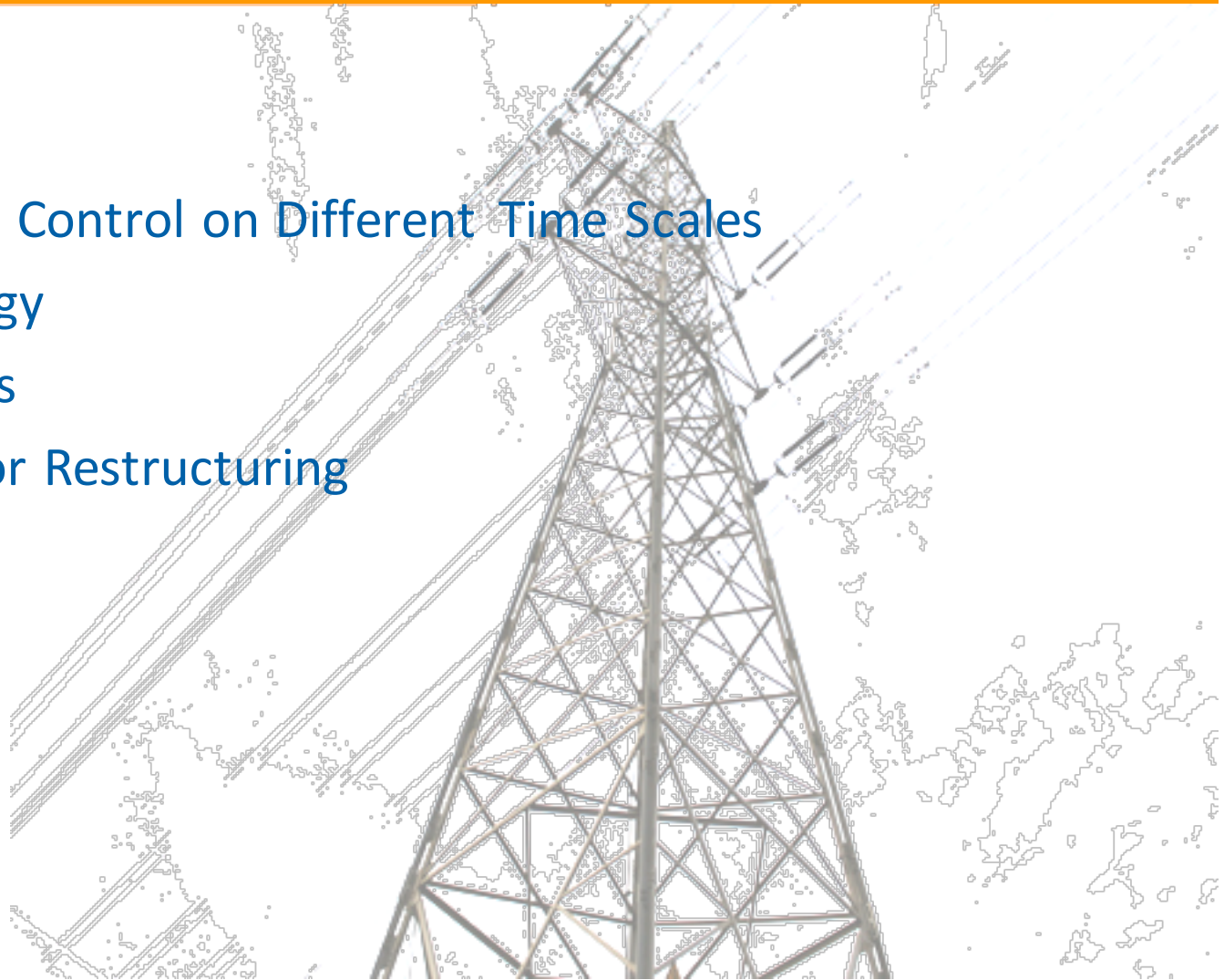
Chapter 09: System Operation, Management, and New Technology



9. System Operation, Management, and New Technology

■ Contents

- 1) Motivation
- 2) Operation and Control on Different Time Scales
- 3) New Technology
- 4) Human Factors
- 5) Implications for Restructuring
- 6) Summary



9.1 Motivation

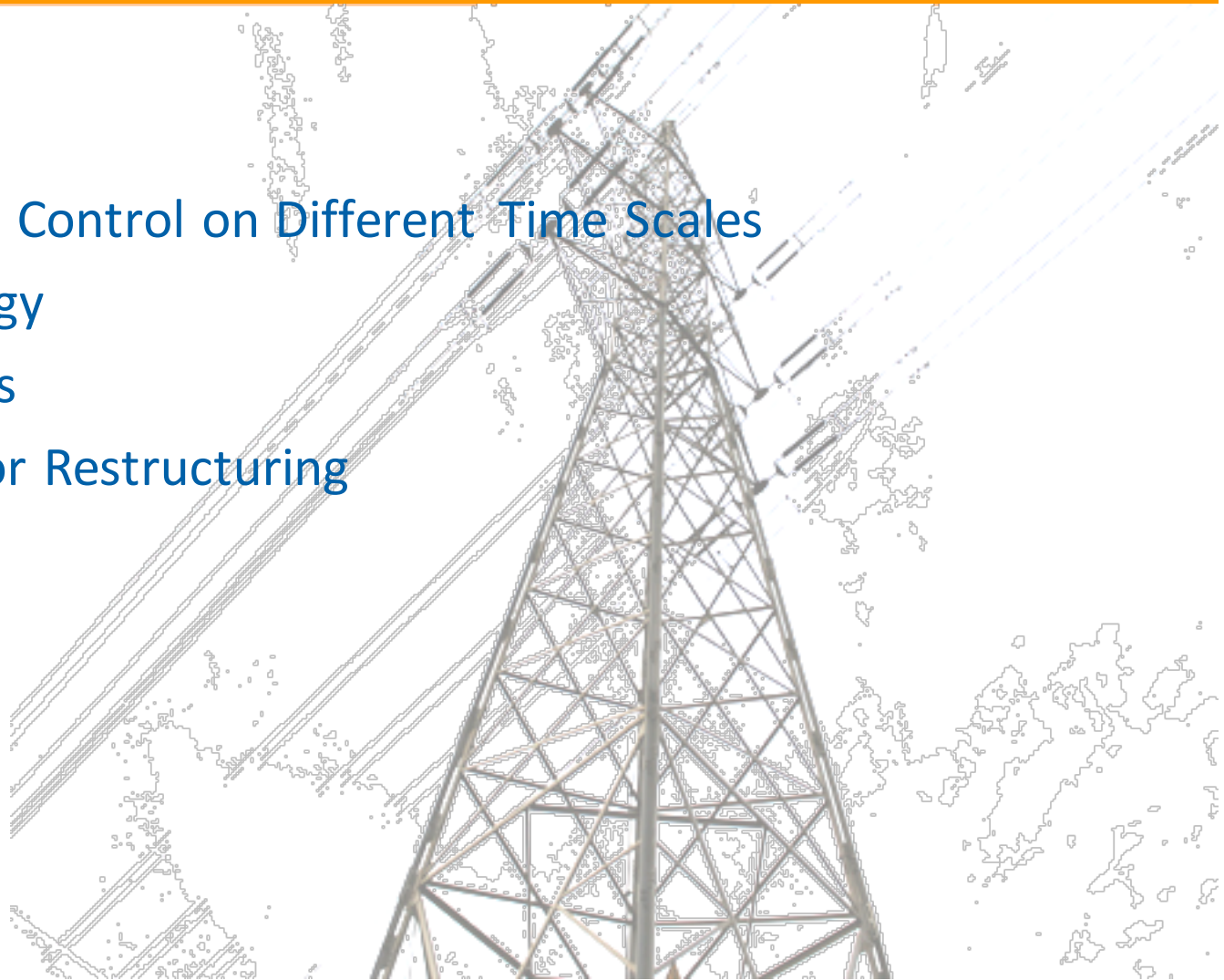
- Electric grid
 - Complex system
 - Consisting of interconnected or interwoven parts
 - No single entity can simultaneously monitor, control, and troubleshoot every
 - Generator
 - Load
 - Piece of conductor in between
 - Possible external disturbance
 - Any one of which has the intrinsic ability to affect every other system component almost instantaneously and sometimes severely



9. System Operation, Management, and New Technology

■ Contents

- 1) Motivation
- 2) Operation and Control on Different Time Scales
- 3) New Technology
- 4) Human Factors
- 5) Implications for Restructuring
- 6) Summary



9.2 Operation And Control On Different Time Scales (1)

- Introduction
 - Electricity must be generated in the exact moment that it is consumed
 - Moving electric power through a grid
 - Obey the law of energy conservation
 - Transmission line cannot store electricity
 - Some grids include small storage facilities
 - If there were exactly zero energy storage → would be impossible to operate a grid
 - Some physical energy storage is provided by the standard components of a power system



9.2 Operation And Control On Different Time Scales (2)

- Introduction
 - Generation and load have to be exactly balanced
 - Equalized within the time scale (a fraction of a second)
 - Short time scale is permitted by the system's capacity to
 - Store and release energy
 - Adapt to new operating conditions
 - Intrinsic energy storage capacity in a conventional power system resides within large rotating machinery (*fraction of second*)
 - Generators provide stability to the system
 - Absorbing and releasing kinetic energy in response to changes in the electric load (in a fraction of a second)
 - On the load side
 - Power consumption is not precisely fixed



9.2 Operation And Control On Different Time Scales (3)

■ Introduction

- If real power into the grid is less than real power out
 - A.c. frequency will drop
 - Poor power quality
 - Stored kinetic energy from the generators is being used
 - Some loads (motors) will also consume somewhat less power
 - Ultimate damage is possible
 - A low voltage level caused by reactive power deficit
 - Affects power consumption by loads more than frequency
 - Make lights dimmer “brownout”
 - A buffer of last resort
 - Prevents immediate system collapse during moderate, inadvertent mismatches of generation and load.



9.2 Operation And Control On Different Time Scales (4)

- Introduction
 - The prime directive for power system designers and operators
 - Balance generation and load at every instant with the time scale permitted by the system's capacity to buffer the discrepancies
 - On multiple levels
 - With control methods appropriate to each time scale



9.2 Operation And Control On Different Time Scales (5)

- The scale of a cycle
 - Frequency regulation occurs on the time scale of cycle
 - One cycle at 60 Hz measures $1/60$ of second or about 16 ms
 - Two levels of frequency regulation (stability)
 - 1) The passive negative feedback effect (intrinsic)
 - The generator speeds up : the torque holding it back increases
 - The generator slows down : the restraining torque decreases
 - Requires no intervention on the part of any human or machine
 - 2) The active negative feedback effect
 - Involves an active intervention, though also automatic
 - The negative feedback between
 - Generator revolutions per minute (rpms)
 - The rate at which power is delivered to the turbine



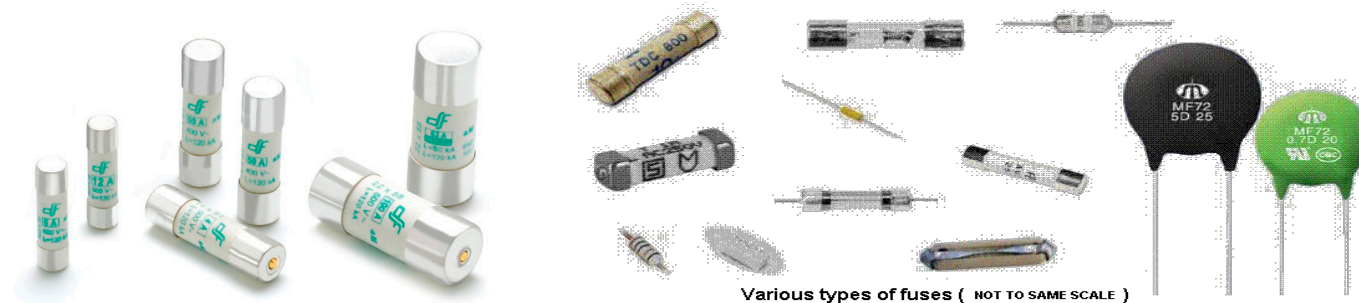
9.2 Operation And Control On Different Time Scales (6)

- The scale of a cycle
 - Frequency regulation occurs on the time scale of cycle
 - Two levels of frequency regulation (stability)
 - 1) The passive negative feedback effect (intrinsic)
 - 2) The active negative feedback effect
 - The generator is spinning too fast, the governor closes the valve
 - The generator is too slow, the governor opens the valve
 - The actual physical response take place on the order of seconds fractions of a second
 - The system can follow loads
 - Some generators are set to produce a fixed amount of power
 - At least some units in a power system are operating on the governor



9.2 Operation And Control On Different Time Scales (7)

- The scale of a cycle
 - Circuit protection occurs on the time scale of cycles (max sec.)
 - Current flow is interrupted automatically and as soon as possible
 - In the event of a fault, or short circuit on any system component
 - Prevent harm to people or equipment
 - Distinguishing a fault current from an unusually high but tolerable current
 - Instantaneously and automatically without the need for supervision or intelligent intervention.



9.2 Operation And Control On Different Time Scales (8)

- The Scale of Real-Time Operation
 - Real-time operation
 - The time scale on which humans perceive and analyze information, make decisions, and take action
 - In order of minutes though some actions may be executed within seconds.
 - Human intervention in real-time
 - 1) Individual generation units
 - During start-up or shutdown and sometimes to implement changes in output
 - In emergency situations where a plant is supplying a power island or part of a severely disrupted grid
 - Manually match a generation unit's output with load when the load variations exceed the normal range of the governor system



9.2 Operation And Control On Different Time Scales (9)

■ The Scale of Real-Time Operation

■ Human intervention in real-time

- 1) Individual generation units
- 2) The system operator level or dispatcher
 - a) Arranging for the correct amount of real and reactive power actually demanded by the system
 - Hourly power schedules cannot be physically accurate
 - Load variation
 - Generator inaccuracies
 - Line loss
 - b) Necessary to define the boundary of the “system” to be balanced
 - Geographic boundary with a finite number of transmission links crossing into neighboring areas



9.2 Operation And Control On Different Time Scales (10)

- The Scale of Real-Time Operation
 - Human intervention in real-time
 - 2) The system operator level
 - c) Independent system operator (ISO)
 - Responsible for a given region that typically spans several utilities' territories
 - The system operator's jurisdiction or control area has a clearly defined geographic boundary with a finite number of transmission links crossing into neighboring areas
 - Transmission links carry a certain amount of power between jurisdictions according to Kirchhoff's laws
 - The system operator keeps track of these flows to and from each adjacent one



9.2 Operation And Control On Different Time Scales (11)

■ The Scale of Real-Time Operation

■ Human intervention in real-time

2) The system operator level

d) Area control error (ACE)

- A single number
- The real-time difference between actual and scheduled imports or exports
- A positive ACE
 - More generation than load within the territory
 - The local generation can be reduced
- A negative ACE
 - The local generation should be increased
- Based on it : Information about actual system needs is sent to selected generators to respond



9.2 Operation And Control On Different Time Scales (12)

- The scale of real-time operation
 - Human intervention in real-time
 - 2) The system operator level
 - e) The information transfer occurs
 - Automatically
 - Through human negotiation
 - f) Automatic generation control (AGC)
 - Some units are equipped with
 - Receive a signal directly from the system operator to their governor
 - This signal overrides or preempts the response of the governor to its own measurement of generator rpms



9.2 Operation And Control On Different Time Scales (13)

- The scale of real-time operation
 - Human intervention in real-time
 - 2) The system operator level
 - g) If generation is insufficient
 - Shedding load (hours): triggered at distribution level
 - Selectively disconnecting large customers
 - Remunerating customers with interruptible loads
 - Rotating outage blocks
 - By using groups of customers
 - 3) Transmission and distribution switching in real-time
 - Reconfiguring the system for
 - Maintenance and restoration purposes
 - Preempting local problems such as overloading a particular circuit
 - By opening and closing specific switches or circuit breakers carefully



9.2 Operation And Control On Different Time Scales (14)

- The scale of scheduling
 - Emphasizing optimization around economic criteria
 - Which generation units to operate when and at what power level so as to minimize overall cost
 - The responsibility for the key economic decisions is assigned in the restructured environment to separate organizational entity known as a *scheduling coordinator*
 - Unit commitment
 - Scheduling generation units to match the forecast load
 - On a daily and hourly basis
 - *Economic dispatch* algorithm (in the “old world”)
 - Which generator contributes how much and when
 - Central scheduling process



9.2 Operation And Control On Different Time Scales (15)

- The scale of scheduling
 - *Economic dispatch algorithm*
 - Using load duration curve (LDC) as a reference
 - “Filling in” the area under the curve with various types of generation
 - Minimize overall cost while meeting all operating constraints
 - The optimization algorithm takes into account
 - The marginal cost of each unit’s output of fuel and operational expense per additional megawatt hour
 - The approximate line losses associated with supplying power from each location (penalty factor)



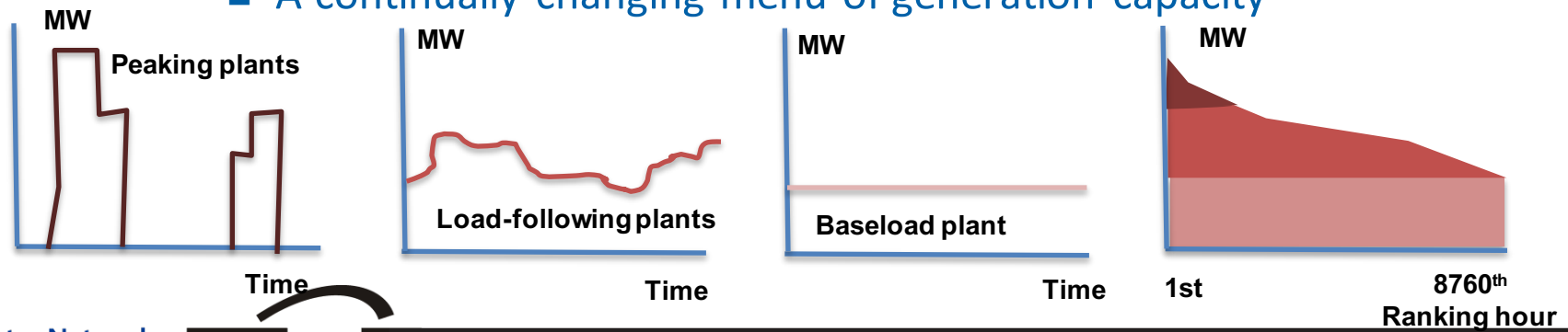
9.2 Operation And Control On Different Time Scales (16)

- The scale of scheduling
 - *Economic dispatch* algorithm
 - Using load duration curve (*LDC*) as a reference
 - Three general categories of generation
 - a) Base load generation unit
 - The cheapest energy and are best operated on a continuous basis
 - Coal or nuclear plants
 - b) Load-following unit
 - Respond to changes in demand
 - Hydroelectric and selected steam generation units
 - c) Peaking units
 - Expensive to operate and are used to meet demand peaks
 - Kept in reserve for the extreme days or hours.
 - Gas turbines, diesel generators



9.2 Operation And Control On Different Time Scales (17)

- The scale of scheduling
 - *Economic dispatch* algorithm
 - Using load duration curve (LDC) as an reference
 - Obviously somewhat idealized
 - Generation units have specific constraints on their operation
 - Scheduled outages for maintenance
 - Unscheduled outages
 - Limitations on the (*ramp rates*) : safely increase and decrease their output power
 - A continually changing menu of generation capacity



9.2 Operation And Control On Different Time Scales (18)

- The scale of scheduling
 - In the competitive “new world” of electricity (restructured markets)
 - Optimal allocation is better achieved through market transactions
 - Some entity serves as a scheduling coordinator
 - May be more than one in the same geographical area
 - Keeping track of megawatts to be bought and sold
 - Calling upon the lowest bidders to generate during each hour
 - The auction could include *day-ahead* and *hour-ahead* markets
 - Proposed generation schedule
 - Does not violate any technical operating constraints
 - Such as transmission line loading



9.2 Operation And Control On Different Time Scales (19)

- The scale of scheduling
 - Spinning reserve
 - Or automatic generation control
 - Generating units are remunerated not for the megawatt-hours of energy they provide but for being “on call” to respond instantaneously to the grid’s needs
 - *Ancillary services* provided by generators to the grid
 - Provision of reactive power
 - Schedule reactive contributions from specific generators ahead of time in order to achieve an optimization
 - Similar to the way real power is allocated



9.2 Operation And Control On Different Time Scales (20)

- The planning scale
 - Hourly and daily generation scheduling as well as the real-time operation of power systems take place within a set of boundary conditions
 - a) Generation capacity
 - b) Transmission capacity
 - c) Distribution capacity
 - d) Loads
 - These boundary conditions are addressed in the realm of planning
 - On a time scale of years
 - Demand projections for ten or twenty years



9.2 Operation And Control On Different Time Scales (21)

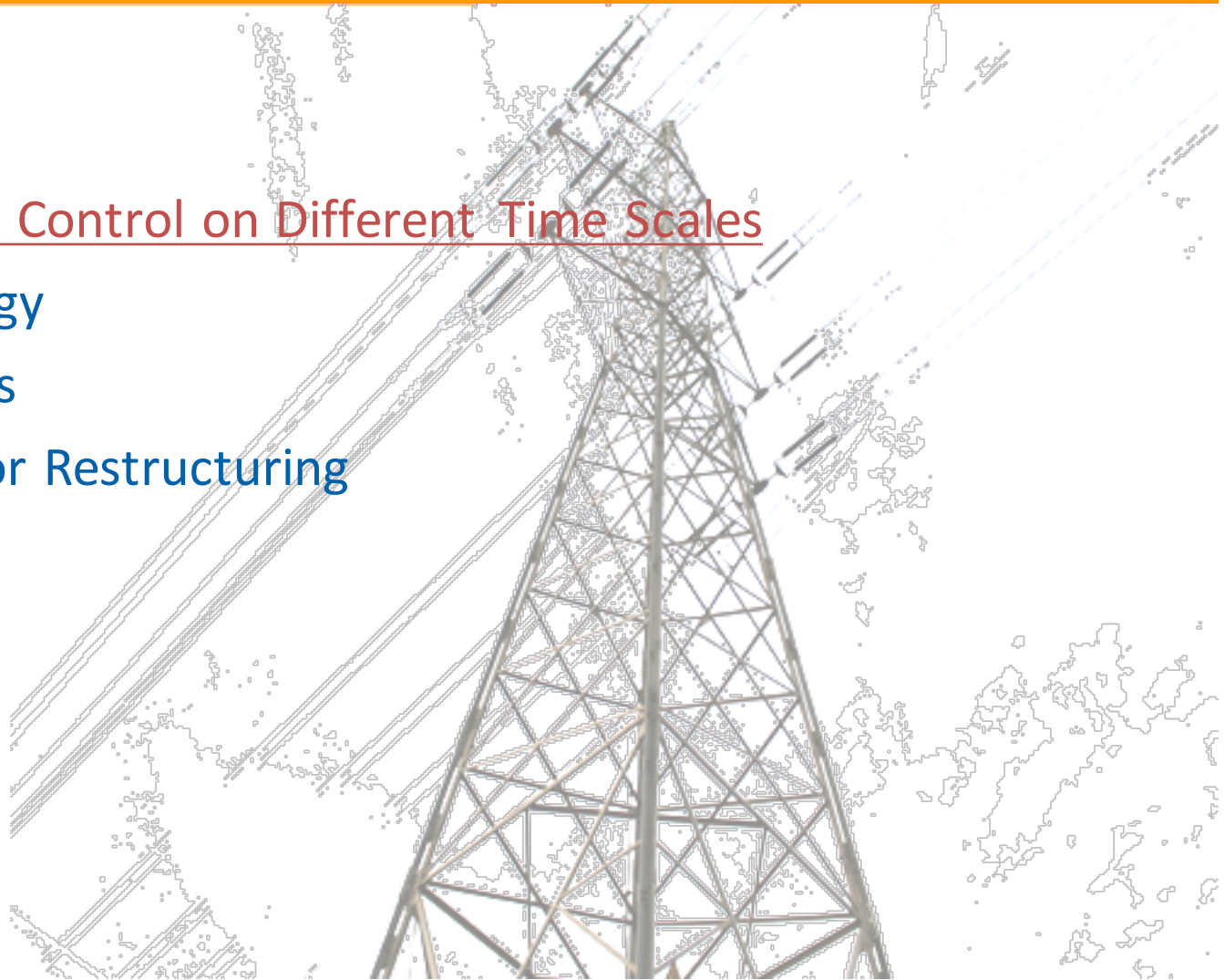
- The planning scale
 - Driven almost entirely by load forecasts
 - Purely technical parameter determined by population growth and consumption levels as independent variables
 - Estimating load growth in megawatts, locally and systemwide
 - Accommodating this growth with appropriate upgrades
 - a) Transmission and distribution hardware
 - b) New construction of generation units
 - c) Securing of electricity imports
 - d) Oversized transmission and distribution (T&D) capacity
 - Market ought to provide incentives
 - Not only short-term production, but long-term investment



9. System Operation, Management, and New Technology

■ Contents

- 1) Motivation
- 2) Operation and Control on Different Time Scales
- 3) New Technology
- 4) Human Factors
- 5) Implications for Restructuring
- 6) Summary



9.3 New Technology (1)

■ Storage

■ Energy storage

- Economic reasons
- Guarantee sufficient supply
 - During times of peak demand
 - Resources are unavailable

1) On the subutility scale

- Synonymous with batteries
- Banks of lead –acid batteries
 - Storing intermittently generated energy from renewable sources
 - Providing a reliable backup in case of a generator failure
 - Designed to be more tolerant of repeated deep discharge



9.3 New Technology (2)

■ Storage

1) On the subutility scale

■ Banks of lead –acid batteries

- Very expensive
- Their cost is compared to the cost of generating the energy itself
- Toxic, corrosive, potentially explosive, and bulky
- Their performance is sensitive to proper treatment and maintenance
- Batteries intrinsically work with direct current (d.c.), so that their use for a.c. systems always requires an inverter

2) On the scale of utility power systems

a) A “pumped hydro” storage unit

- The most common and practical form of storage



9.3 New Technology (3)

■ Storage

2) On the scale of utility power systems

a) A “pumped hydro” storage unit

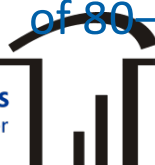
■ Requires

- A reversible turbine–generator
- Reservoirs uphill and downhill for water to be stored

■ Pumping at night and generating during the day

■ Examples

- Goldisthal pumped storage station in the Thüringen mountains at the upper run of the river Schwarz
- Switzerland serves as a storage bank of electric energy for the western European grid (Alpine elevations)
- In the United States there are only few pumped hydro units
- The efficiencies of pumping and generating each in the neighborhood of 80–90%, a round-trip efficiency of 75% is readily attained



9.3 New Technology (4)

■ Storage

2) On the scale of utility power systems

b) Compressed-air energy storage (CAES)

- Electric energy is used to operate pump motors that fill a confined space such as an underground cavern with air at high pressure
- The pumps are operated in reverse as generators

c) Flywheels

- Energy is stored in the form of rotational kinetic energy of a spinning disk or wheel

d) Superconducting magnetic energy storage (SMES)

- “High-temperature” superconducting materials
 - Requiring cooling by liquid nitrogen
- Affording the option to correct power quality



9.3 New Technology (5)

■ Storage

2) On the scale of utility power systems

e) Superconducting magnetic energy storage (SMES)

- Electric power can be injected to the grid at generator buses and withdrawn at load buses on time scale of cycle
 - To correct power quality and to store bulk energy

f) Capacitors

- Extremely short-term energy storage (duration of each a.c. cycle)
- Used in uninterruptible power supply systems
 - To bridge the very brief gap during switching From one power source to another
- Widely used in power systems for reactive power compensation
- Not practical for bulk-storage applications
 - Because of the ability to rapidly absorb and release power.



9.3 New Technology (6)

■ Storage

2) On the scale of utility power systems

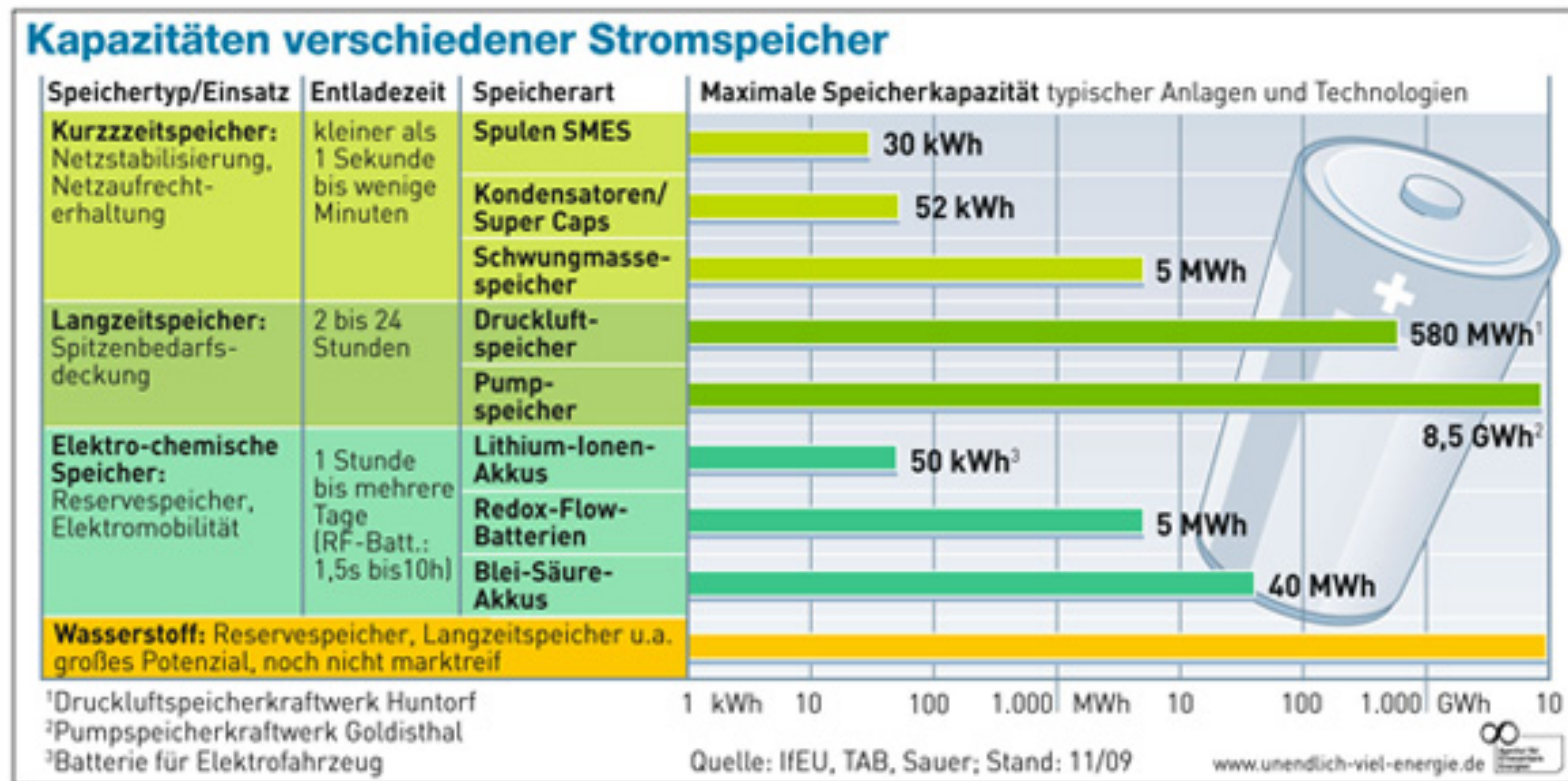
g) Electrolyzing water into hydrogen and oxygen

- Hydrogen gas becomes clean chemical fuel that is converted back to electricity by means of fuel cells
- The key advantages of hydrogen
 - Suitability for mobile and stationary applications
 - Ease of extending the storage time without local constraints
- The efficiency of each item ranges in the sixties and seventies of percent, making for a low round-trip efficiency



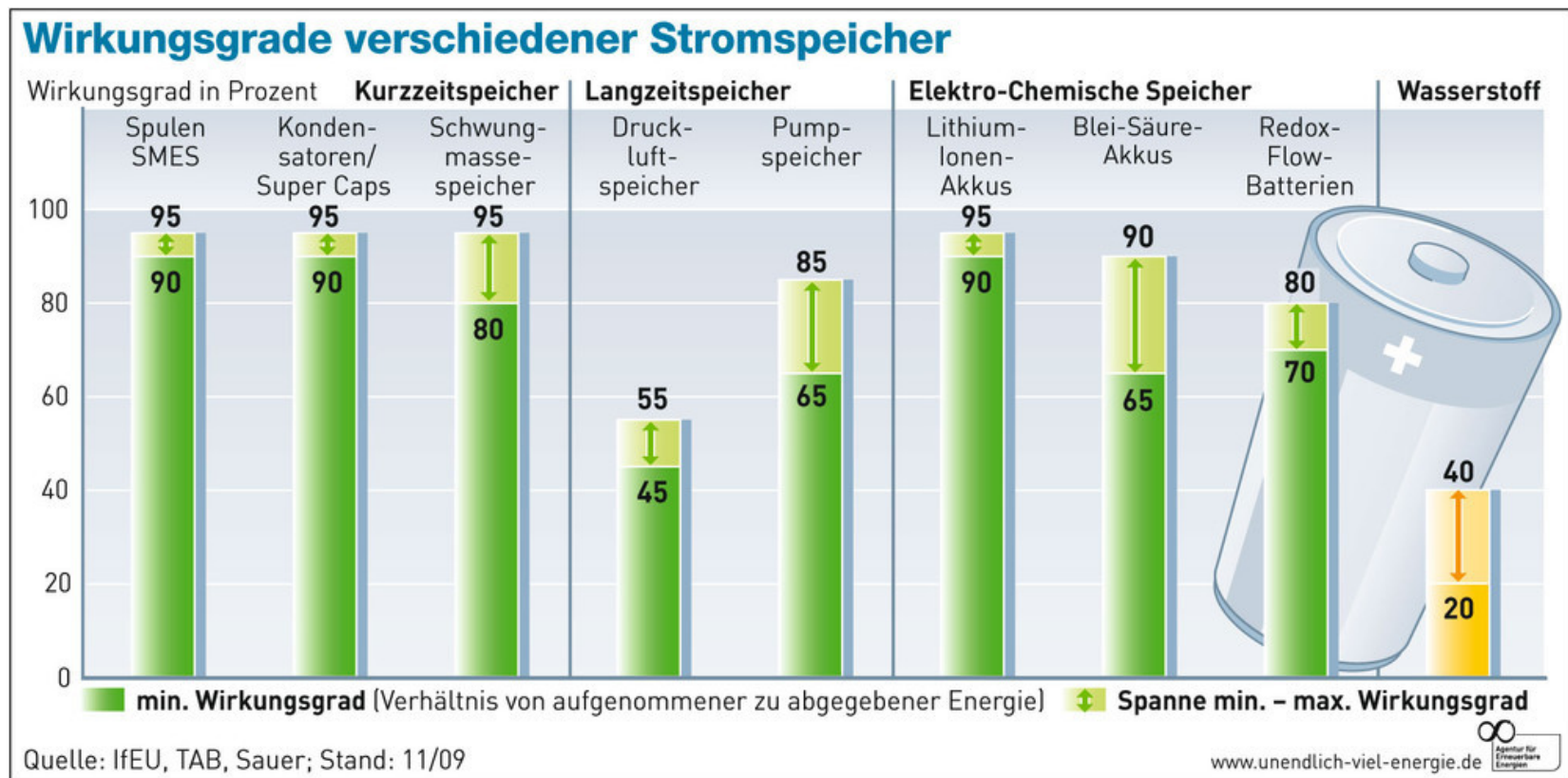
9.3 New Technology (7)

- Storage
 - Capacities of various current storage



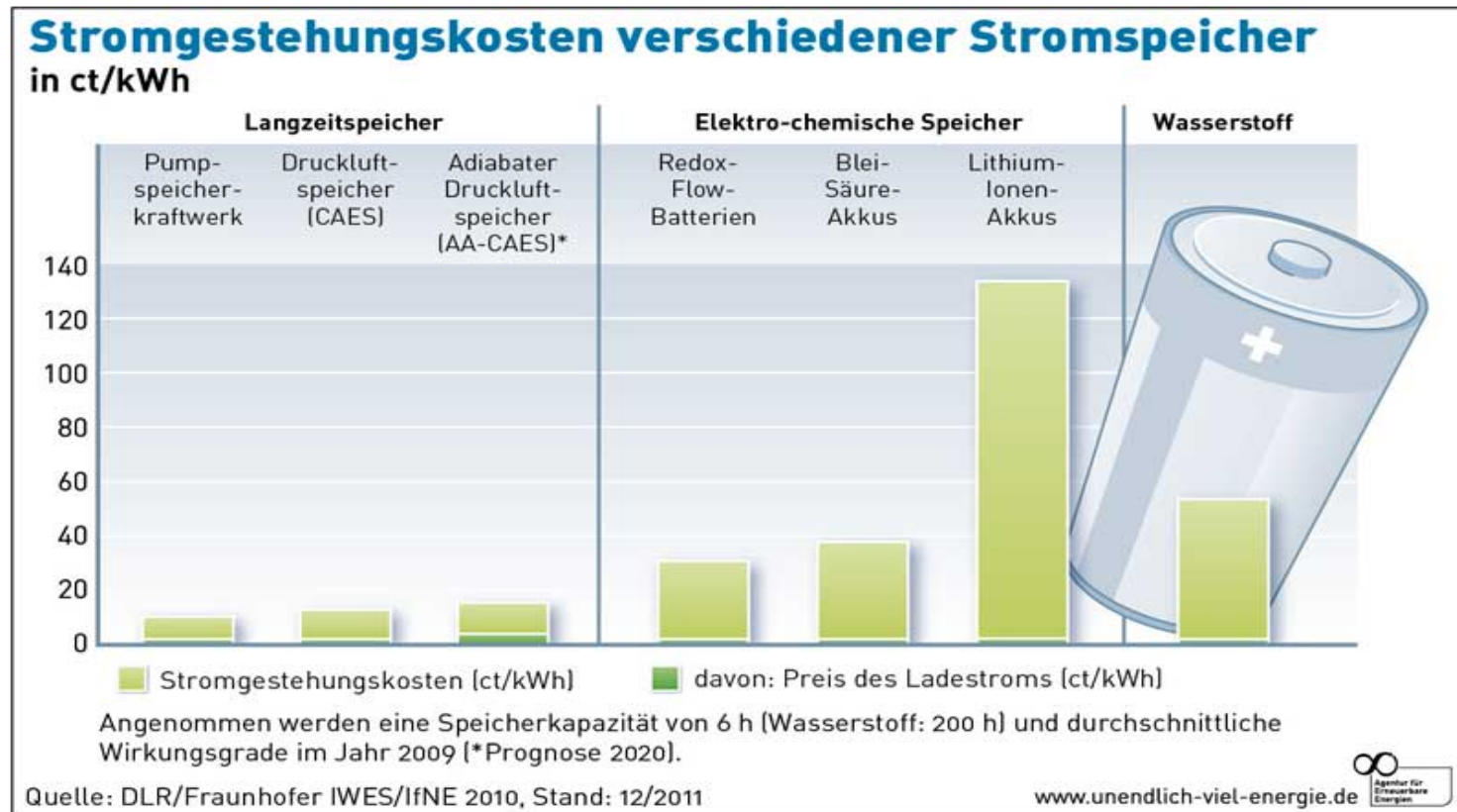
9.3 New Technology (8)

- Storage
 - Efficiency of various current storage



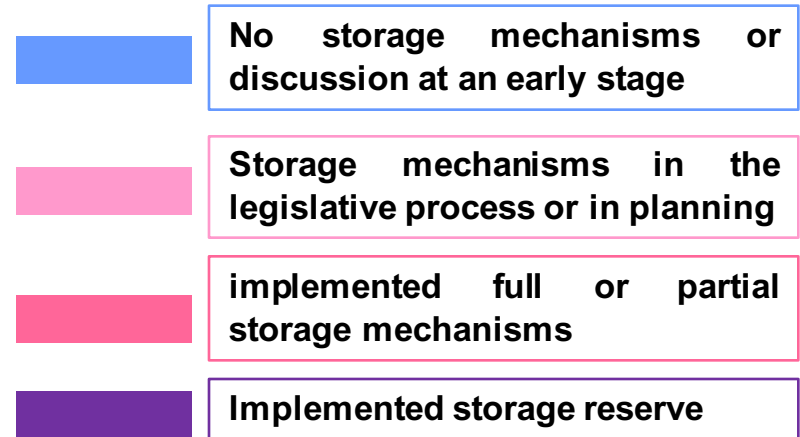
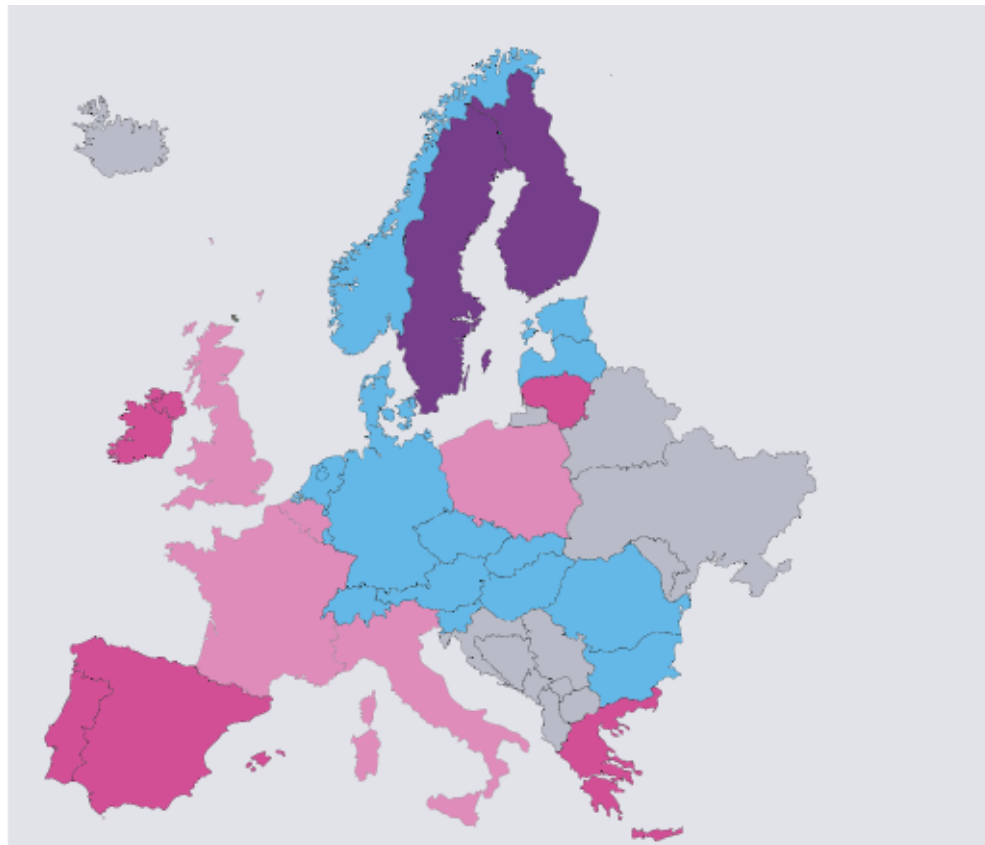
9.3 New Technology (9)

- Storage
 - Electricity production costs of various current storage



9.3 New Technology (10)

- Storage mechanisms in Europe (March 2013)



Source: Agora Energiewende



9.3 New Technology (11)

- No storage (missing money problem)
 - 1) Negative prices
 - Power generators are willing to pay the consumer to buy energy
 - Due to a combination of
 - High production from renewable energy sources (RES)
 - Very low or zero marginal generation costs and low demand
 - Occur on very sunny and/or windy, low-demand, non-working days, such as Summer Sundays or Christmas



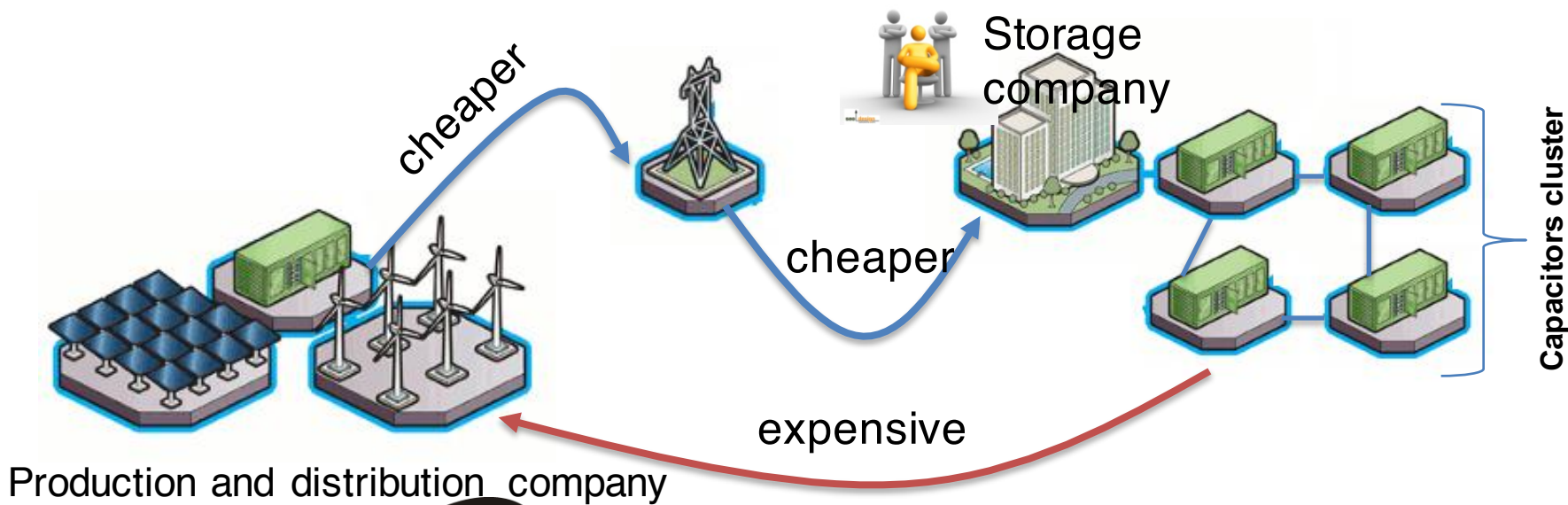
9.3 New Technology (12)

- No storage (missing money problem)
 - 1) **Negative prices**
 - Reducing the reward for RES generators
 - Take the incentive minus the market price at least in the countries where RES are subsidized through the green certificate or feed-in schema
 - Green producer give back to energy consumers at least a portion of the extra money they have been taken because of generous subsidies



9.3 New Technology (13)

- No storage (missing money problem)
 - 1) Negative prices
 - 2) payments for non-generation
 - Customers could store grid electricity on their batteries and then sell it back to the grid at higher price



9.3 New Technology (14)

- Distributed generation (*DG*)
 - Definition
 - Geographically distributed or spread out across the grid
 - Smaller in scale than traditional power plants
 - Located closer to the load, often on customers' property
 - *DG* is associated with interesting questions about
 - a) The overall design of the grid
 - b) Operating strategies
 - c) Economics
 - d) Environmental impact of electricity production
 - e) Energy politics



9.3 New Technology (15)

- Distributed generation (*DG*)
 - 1) Classical electric generation technologies (*synchronous generator*)
 - a) Hydroelectric turbines
 - Convert the downhill movement of water into rotation of a generator
 - b) Steam generation plants
 - Burn fossil fuels to boil water and push a turbine-generator with the force of hot steam
 - Nuclear reactors added uranium to the industry's repertoire of fuels
 - Solar thermal power plants (collectors)
 - Biomass (anything organic that burns) and geothermal power
 - Geothermal power
 - c) Tidal power
 - Technically just a variation on conventional hydroelectric power



9.3 New Technology (16)

- Distributed generation (*DG*)
 - 2) New type of electric generation technologies
 - Differ from conventional resources in
 - The electrical properties of the generator component
 - The patterns of resource availability
 - Their scale
 - The range of suitable locations for their deployment
 - a) Early wind turbines
 - Inexpensive induction generators
 - Cannot be considered a fully controllable generation resource
 - Is not capable of controlling bus voltage or reactive power output
 - Is not capable of controlling a.c. frequency or starting up without an a.c. signal already present at the bus
 - Always consumes VARs while injecting watts to the grid



9.3 New Technology (17)

- Distributed generation (*DG*)
 - 2) New type of electric generation technologies
 - a) Wind turbines
 - Recently, built with an a.c. to d.c. and back to a.c. Inversion step, hence:
 - complete control over reactive power, output voltage, and frequency
 - Wind rotor to operate at variable rotational speeds as a function of wind speed



commons.wikimedia.org



9.3 New Technology (18)

- Distributed generation (*DG*)
 - 2) New type of electric generation technologies
 - b) Microturbines
 - Operate at very high rotational speeds
 - a.c. output therefore must be adapted to the grid frequency
 - Powered by natural gas “methane CH_4 ” (*higher emission*)
 - Smaller than steam turbines or even gas turbines
 - *Combined heat and power (CHP) option (higher efficiency)*
 - Simultaneously make use of electricity and waste heat
 - c) Solar photovoltaic (PV) and fuel cells
 - No rotating parts
 - Produce d.c., not a.c. ; Behaves to grid as batteries
 - Require inverters as an interface with the grid



9.3 New Technology (19)

- Distributed generation (*DG*)
 - 2) New type of electric generation technologies
 - c) Solar photovoltaic (PV) and fuel cells
 - PV cells : treated semiconductor material (usually silicon) that produces an electric potential when exposed to light
 - A fuel cell
 - A chemical reaction forces electrons to one side
 - The reactants (hydrogen and oxygen) are continually supplied from an external source
 - The supplied voltage is determined by the electrochemical properties of the materials (one volt per cell)
 - PV modules or fuel cell stacks
 - Multiple individual cells are connected together in series
 - PV system can be built at just about any scale



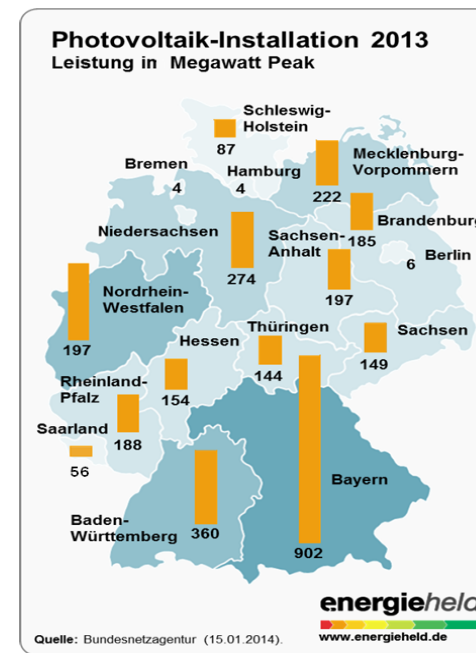
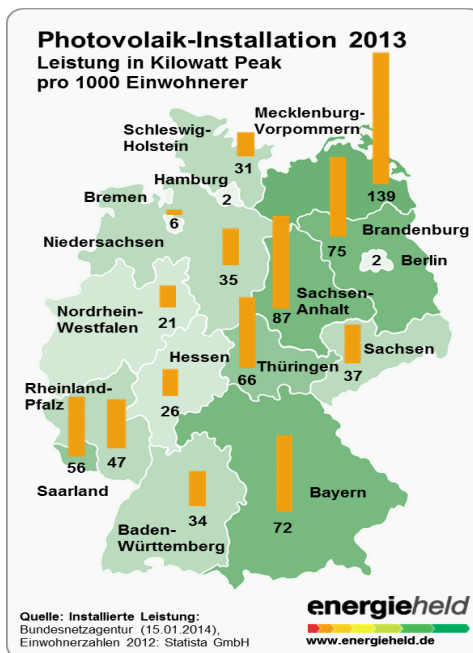
9.3 New Technology (20)

■ Distributed generation (*DG*)

2) New type of electric generation technologies

c) Solar photovoltaic (PV)

■ PV adoption History



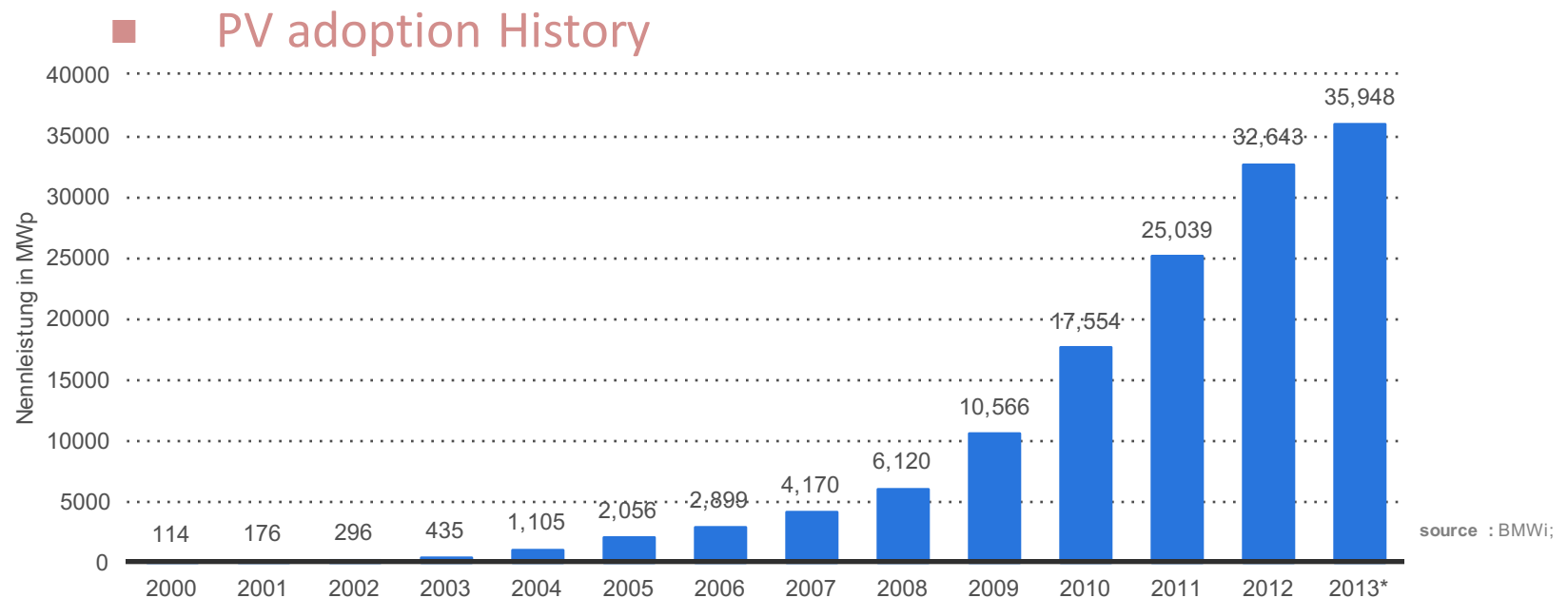
New installation in 2013

9.3 New Technology (21)

- Distributed generation (*DG*)

- 2) New type of electric generation technologies

- c) Solar photovoltaic (PV)



Installed capacity (cumulatively) of photovoltaic systems in Germany in the years 2000 to 2013 (in Megawattpeak)



9.3 New Technology (22)

- Distributed generation (*DG*)
 - Economies of scale
 - a) Steam generation
 - The optimal unit size in terms of cost per output is typically in the hundreds of megawatts
 - b) PV technology
 - One large plant is not cheaper than 10 small ones
 - Can be used in location- and load-specific applications that tend to be of smaller size
 - Zero emissions
 - No noise
 - Minimal aesthetic impact,
 - Options to integrate power installations with buildings
 - The maintenance requirements are also minimal

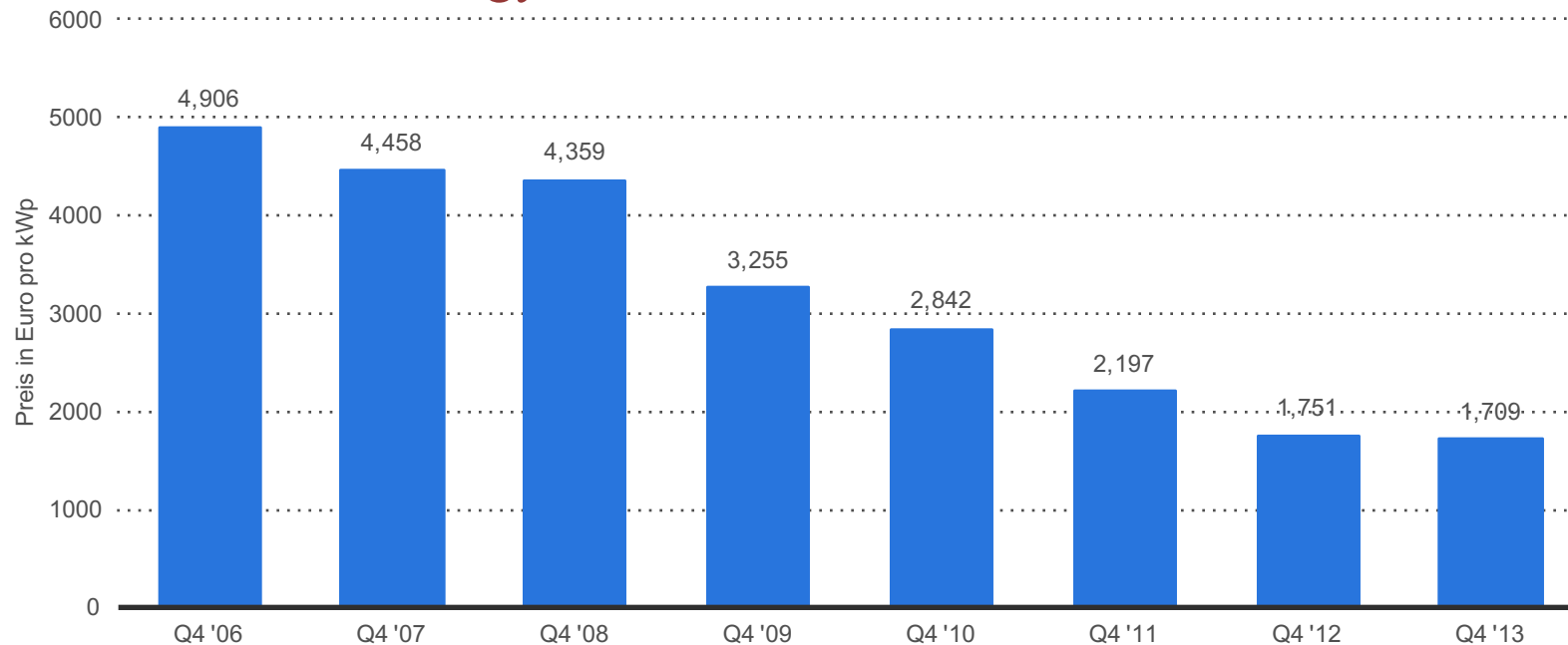


9.3 New Technology (23)

- Distributed generation (*DG*)

 - Economies of scale

 - b) PV technology

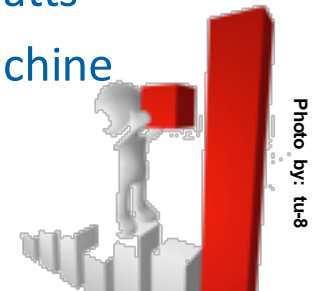


Price history for a fully installed solar system in Germany in the years 2006-2013 (in Euro per Kilowatt peak)



9.3 New Technology (24)

- Distributed generation (*DG*)
 - Economies of scale
 - c) Fuel cells
 - Optimal size ranges between kilowatts and a few megawatts
 - A somewhat lower cost per unit output for the larger machine
 - Their waste products are heat and water, require more supervision,
 - Installations in spaces such as office basements
 - The higher power density
 - d) Wind turbines
 - Optimal size ranges between kilowatts and a few megawatts
 - A somewhat lower cost per unit output for the larger machine
 - More constrained with respect to siting
 - Resource availability
 - Intrinsic hazard of moving rotor blades



9.3 New Technology (25)

- Distributed generation (*DG*)
 - Economies of scale
 - e) Microturbines
 - Similar to fuel cells
 - The emissions from combustion include undesirable components
 - Absence of pronounced economies of scale
 - One key characteristic of distributed generation
 - To be suitable for applications very near loads
 - Generation must also be environmentally compatible
 - The easiest technology to site is PV (properties in slide 48)
 - Fuel cells require somewhat more supervision
 - Benign waste products (heat and water)
 - Not too hazardous to operate in occupied buildings



9.3 New Technology (26)

- Distributed generation (*DG*)
 - Economies of scale
 - Absence of pronounced economies of scale
 - Fuel cells require somewhat more supervision
 - Standard for office basements
 - Higher power density for compact
 - Micro turbines have the same siting considerations as fuel cells
 - Except that the emissions from combustion include undesirable components
 - Wind power is more constrained with respect to siting because of
 - Resource availability (easier to find a sunny than a windy spot)
 - The intrinsic hazard of moving rotor blades



9.3 New Technology (27)

- Distributed Generation (*DG*)
 - Significant technical implications for the grid
 - a) Thermal line losses throughout the grid to be reduced
 - Generation occurs next to a load of comparable size
 - Lowering current flow in the transmission and distribution lines that connect this load to major generation sources in the grid
 - Thermal energy losses are then reduced in proportion to the square of the current and the resistance of all the affected lines
 - b) Can offer voltage or reactive power (VAR) support
 - Offsetting the need for other devices such as capacitors and voltage regulators



9.3 New Technology (28)

- Distributed Generation (*DG*)
 - Significant technical implications for the grid
 - c) Distributed generation coincides with load
 - Reduce the demand on transmission and distribution capacity such as conductors and transformers (designed for peak load)
 - d) Generation in the distribution system impacts protection needs and coordination
 - Distributed generation introduces the radically new possibility of power flowing (from load to substation)
 - Any section of line or piece of equipment therefore being energized from the load side without existing fuse or circuit breaker
 - An electrocution risk for utility line workers



9.3 New Technology (29)

- Distributed Generation (*DG*)
 - Significant technical implications for the grid
 - e) The problem of control and availability
 - *DG* is generally *nondispatchable*
 - Power system operators cannot call on it to provide power on demand or at specified times
 - Utility or system operator has no control over operating schedules
 - Lack of completely automated
 - The lack of control is not necessarily problematic
 - *DG* can often be expected to coincide fairly well with local load
 - Solar power in areas of summer-peaking demand
 - Customers use *DG* to meet their own demand
 - Customers use *DG* to receive credit on net metering arrangements



9.3 New Technology (30)

- Distributed Generation (*DG*)
 - Significant technical implications for the grid
 - e) The problem of control and availability
 - The lack of control is not necessarily problematic
 - System operators would tend to consider DG as “negative load”
 - Combining its statistical uncertainty with that of the demand, which as a whole is also beyond operators’ direct control
 - f) Reducing the grid’s vulnerability to sabotage
 - Any one smaller individual facility has less impact on the stability of the power system as a whole
 - DG implies less reliance overall on long-distance transmission links
 - DG introduces the possibility of local self-sufficiency in power generation
 - May dramatically reduce the social impact of grid failures



9.3 New Technology (31)

- Distributed Generation (*DG*)
 - Institutional implications for power systems at large
 - Generation is distributed geographically
 - Power distribution, as opposed to transmission
 - Dealing with generation is a fundamentally new responsibility for distribution engineers and operators
 - It entails new demands, complexities, and failure possibilities.
 - There are important social and political dimensions of ownership of resources and generation assets



9.3 New Technology (32)

- Distributed generation (*DG*)
 - Social and political aspects
 - a) Islanding
 - Operating parts of the system while disconnected from others
 - Extracting the full benefit from distributed generation resources
 - Interconnected system
 - Could routinely operate with local or regional power islands
 - Controversial aspects including safety, liability, accounting, and control
 - b) Economic cost–benefit analysis of distributed generation in relation to transmission and distribution infrastructure
 - The analytic problem of comparing and trading off what are qualitatively different investments
 - Comparing the cost of solar thermal electricity produced at two locations with different weather and different transmission distances to major loads



9.3 New Technology (33)

- Distributed generation (*DG*)
 - Social and political aspects
 - a) Islanding
 - b) Economic cost–benefit analysis of distributed generation in relation to transmission and distribution infrastructure
 - PV adjacent to a load with a fossil-fuel resource some distance away
 - A region where wind is the cheapest energy source available and supplies a substantial portion of local demand
 - Assess the maximum percentage of load that can be met by wind power before it becomes too unpredictable
 - To what extent the unpredictability ought to be compensated for by
 - 1) Introducing storage capacity
 - 2) Adding more expensive generation capacity
 - 3) Strengthening transmission ties to other regions
 - 4) Oversizing the wind power plant

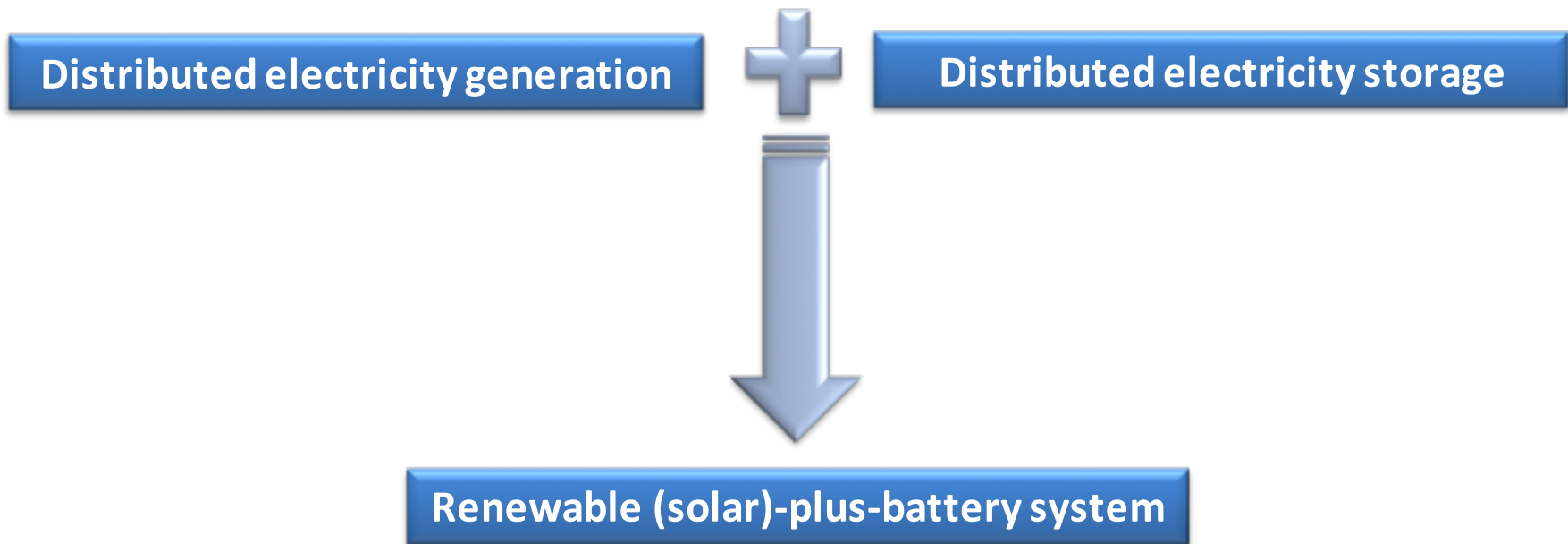


9.3 New Technology (34)

- Distributed generation (*DG*)
 - Social and political aspects
 - a) Islanding
 - b) Economic cost–benefit analysis of distributed generation in relation to transmission and distribution infrastructure
 - Sensitivity to time and geographic variables
 - c) Societal issues
 - Resource scarcity
 - Environment
 - The politics of ownership

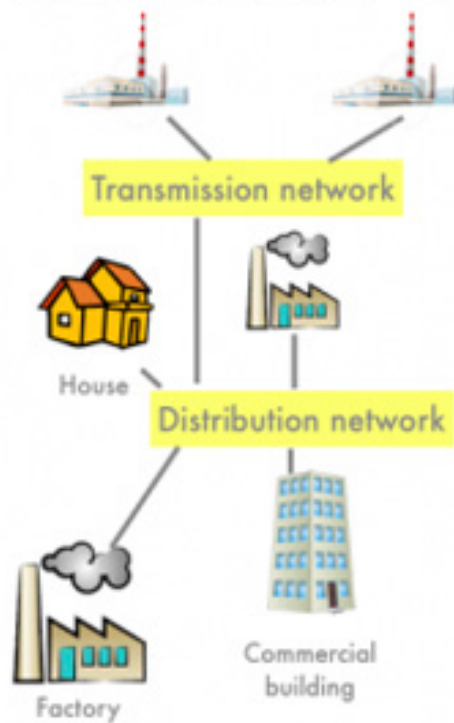


9.3 New Technology (35)

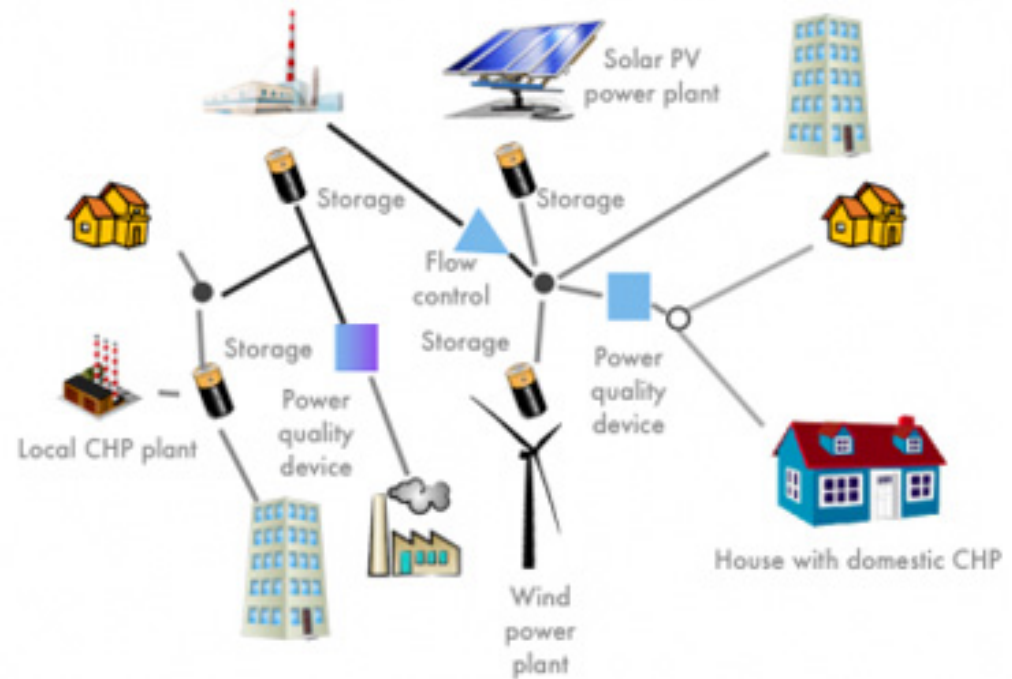


9.3 New Technology (36)


Yesterday Centralized Power



Tomorrow Clean, local power



9.3 New Technology (37)

- Automation : Technical control of DG
 - Supervisory control and data acquisition (scada)
 - Technology for streamlining or automating the operation of T&D systems
 - Used to reconfigure the system topology
 - Remote sensing along with remote operation of equipment such as switches and circuit breakers
 - The sensing and control nodes in the field may be connected to a staffed control room by one of several types of communication
 - Dedicated telephone lines
 - Microwave radio
 - Power line carrier signal



9.3 New Technology (38)

- Automation
 - Operation through expert systems
 - Recommend actions to the operator (open-loop)
 - Execute actions (closed-loop)
 - In T&D mean augmenting SCADA with “intelligence ”



<http://tv.schneider-electric.com>



9.3 New Technology (39)

- Flexible a.c. transmission systems (FACTS)
 - Modification of the grid's properties with the aid of solid-state technology
 - Offers ways to modify the electrical characteristics of transmission components
 - In real time
 - Increase operating efficiency
 - Relieve constraints without the need for adding major hardware
 - FACTS devices include various types of
 - a) Reactive compensation
 - b) Phase shifting
 - c) Power flow control

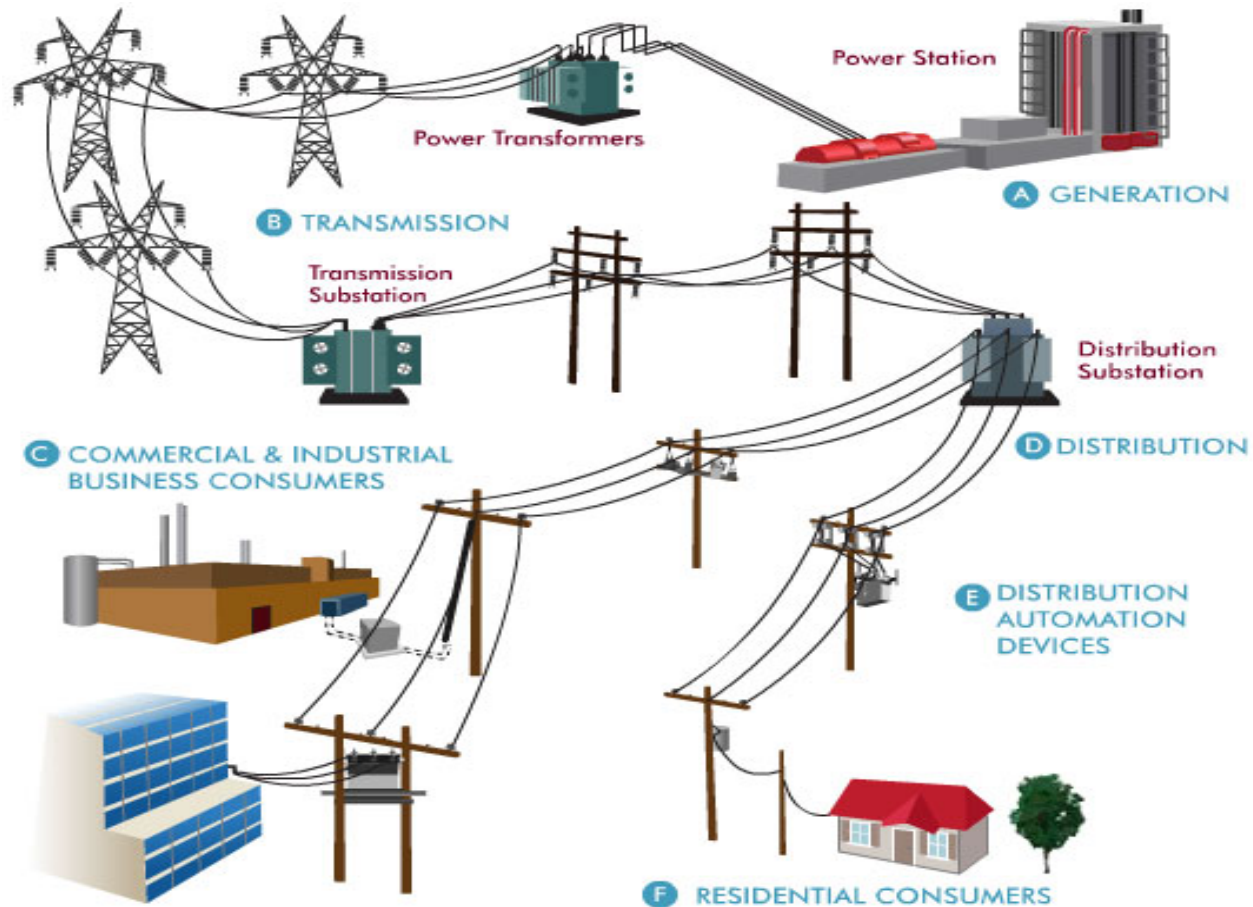


9.3 New Technology (40)

- Flexible a.c. transmission systems (FACTS)
 - The idea is to effectively change the impedance of a given transmission link
 - The key to achieving control lies in the time dimension
 - The properties of the hardware components, including the connections among them, are unchanging
 - Solid-state technology affords the ability to
 - Add or subtract a.c. waveforms at specific points during the cycle
 - Open and close connections between elements such as transformers, inductors, or capacitors
 - Change the shape of a voltage
 - Timing or phase angle
 - Magnitude,
 - The relationship to current (in effect controlling reactive power flow)



How The Grid Looks Like



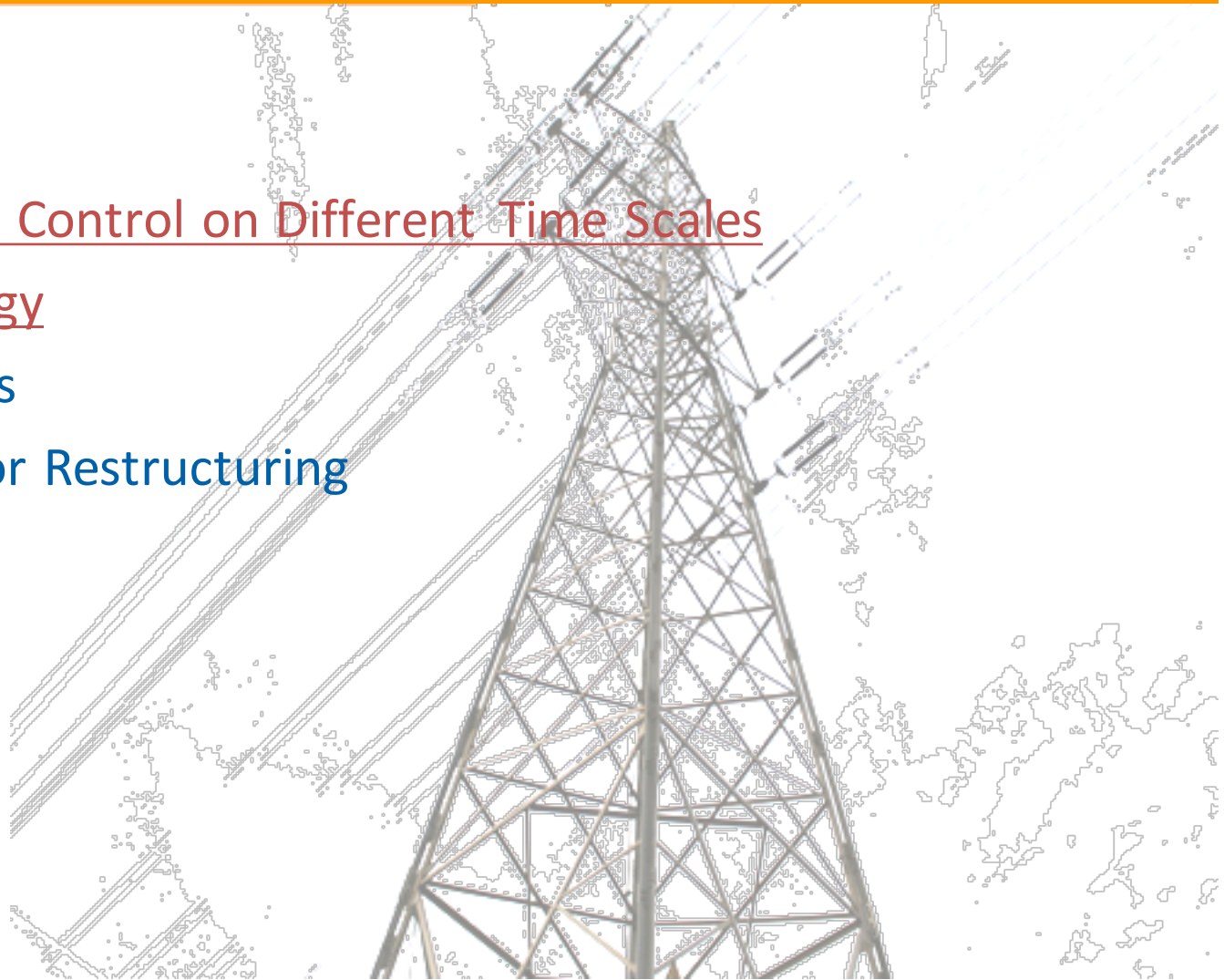
<http://texaselectricityalliance.wordpress.com>



9. System Operation, Management, and New Technology

■ Contents

- 1) Motivation
- 2) Operation and Control on Different Time Scales
- 3) New Technology
- 4) Human Factors
- 5) Implications for Restructuring
- 6) Summary



9.4 Human factors (1)

- Operators and engineers

Engineers	Operators
They represent the academic view of power systems	They represent the practical view of power systems
They make design drawings, calculate specifications, select components, evaluate performance and analyze problems	They must keep the system working in real time. They monitor and direct ongoing reconfiguration of their system of interconnected lines and components
Their goal is to optimize performance	Their goal is to maintain the system in a state of equilibrium
Their work is more remote from the field	They work from switching stations and in the field



9.4 Human factors (2)

- Cognitive representations of power systems
 - Classic engineering representation of the technical system can be characterized as
 - Abstract, analytic, formal, and deterministic
 - A system is considered as a composite of individual components
 - Components and their interaction are idealized
 - By contrast, the operator representation can be typified as
 - Physical, holistic, empirical, and fuzzy
 - A system is considered as a whole
 - Components that look the same on a drawing are not necessarily identical for an operator



9.4 Human factors (3)

- Operational criteria
 - The most important goals of technical systems are
 - Efficiency, reliability, and safety
 - In the academic engineering context
 - Reliability and safety have been already achieved
 - But, improving efficiency represents a continuing challenge
 - Efficiency refers to the relationship of output, production, or benefit to input, materials, effort, or cost
 - There is a set of indirect or supporting criteria that are desirable in engineering culture



9.4 Human factors (4)

- Operational criteria
 - There is a set of indirect or supporting criteria that are desirable in engineering culture
 - Speed: a system that operates faster will involve less waste
 - Faster restoring service means less waste of time, waste of man-hours, and waste of potential revenues
 - More information
 - Precision: represents the level of detail of information
 - Precision can be chosen
 - Accuracy: the information with a high level of detail should be known to be correct to that level
 - Accuracy can not be chosen
 - The ability to control



9.4 Human factors (5)

- Operational criteria
 - The system criteria from the perspective of operations (managing the system in real time) have different meaning
 - Safety takes a special priority in operations, while efficiency is less of a tangible concern
 - Because the consequences of errors face the operators immediately (risk of death)
 - Speed is more problematic in operations
 - The faster the action propagates, the less traceable it will be for the operator and the less time to be observed → the more severe the problems
 - Thus, **stability** is more desirable than speed
 - It's preferable that the system remains in its state, or move only slowly, allowing for chance to intervene and bring it back into balance



9.4 Human factors (6)

- Operational criteria
 - The system criteria from the perspective of operations (managing the system in real time) have different meaning
 - Information can also be problematic in the context of operations
 - The more information the operator is gathering, the more time and the mental effort he needs to classify it (delayed response) → the more likely he discards critical information
 - Thus, **transparency** is more desired than great amount of information
 - Transparency refers to the fact available information is readily interpreted and placed into the context
 - Maintaining an overview of the behavior of the whole system is more important than having detailed knowledge about its components



9.4 Human factors (7)

- Operational criteria
 - The system criteria from the perspective of operations (managing the system in real time) have different meaning
 - Similarly, more precision is not always better for operators
 - Because precision can be distracting or even misleading, suggesting greater accuracy than it is in fact given
 - **Veracity** of the information is emphasized over precision
 - Precision offers a narrow explicit margin of error, while veracity offers confidence that the value in question truly lies within that margin, and that the value really represents that which it is assumed to represent
 - Operators prefer to base decisions on a reliable confidence interval, even if it is wide (less precise)



9.4 Human factors (8)

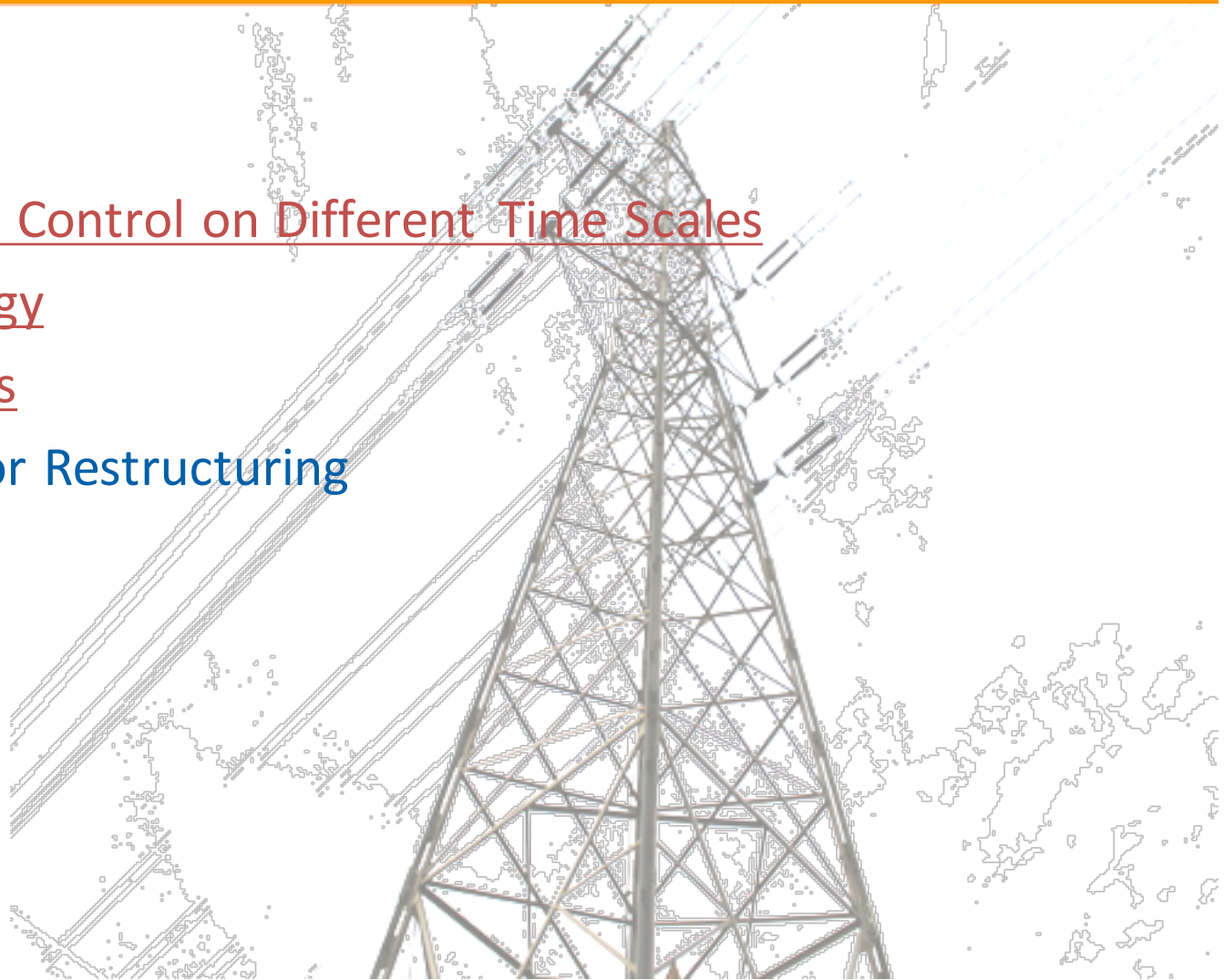
- Operational criteria
 - The system criteria from the perspective of operations (managing the system in real time) have different meaning
 - Similarly, more controlling options mean that the operators have more to do and keep in mind (increase stress level) → their performance will be devalued by the increased expectation
 - Robustness is more desirable than the ability to control
 - Robustness refers to the system's tendency to stay in a viable equilibrium by itself



9. System Operation, Management, and New Technology

■ Contents

- 1) Motivation
- 2) Operation and Control on Different Time Scales
- 3) New Technology
- 4) Human Factors
- 5) Implications for Restructuring
- 6) Summary



9.5 Implications For Restructuring (1)

- The restructuring of the electric industry
 - Passionately debated subject in the field of power systems
 - The transition from a regulated, vertically integrated monopoly to some form of competitive marketplace for electricity
 - Involves any aspect of
 - Production
 - Delivery
 - Consumption
 - The focus until now has been primarily on wholesale energy
 - Pure regulation vs pure market
 - Every arrangement for the buying and selling of electric power has in fact been some hybrid of approaches



9.5 Implications For Restructuring (2)

- The restructuring of the electric industry
 - Pure regulation vs pure market
 - Every arrangement for the buying and selling of electric power has in fact been some hybrid of approaches
 - One thing on which experts tend to agree
 - Consequences to society
 - Favorable or unfavorable
 - A key set of questions concerns
 - Which competitive markets can produce socially optimal outcomes?
 - What constitutes market failures?
 - When and how government intervention is required?



9.5 Implications For Restructuring (3)

- The restructuring of the electric industry
 - Electricity is not a commodity (like wheat, or petroleum)
 - Because of its physical nature and the attendant technical constraints in its production and distribution
 - In an ideal competitive market
 - The intersection of demand and supply curves yields an equilibrium price and quantity
 - At which the market clears
 - In theory, maximizes social utility or overall benefit to participants
 - The central requirement of such a market is that demand and supply can vary freely with respect to price
 - *For several reasons such a condition is very tricky to achieve in the case of electricity*



9.5 Implications For Restructuring (4)

- The restructuring of the electric industry
 - Varying demand and supply freely with respect to price is tricky
 - a) Price elasticity of demand is low
 - Demand for electricity tends not to respond very much to price signals
 - 1) Electricity is so indispensable to our economy and our everyday lives
 - People and businesses are organized around being able to consume electricity at any time they choose
 - Many are willing to pay a considerable amount of money in order not to have their service interrupted.



9.5 Implications For Restructuring (5)

- The restructuring of the electric industry
 - Varying demand and supply freely with respect to price is tricky
 - a) Price elasticity of demand is low
 - 2) Demand elasticity is limited by institutional and technical factors
 - Electricity should be:
 - Available to anyone in arbitrary amounts around the clock
 - At a known and fixed price deemed reasonable by public regulators
 - Electric load was defined as the independent variable
 - Its satisfaction became the central objective of technical, organizational, and regulatory efforts throughout the power industry
 - Consumers only experienced rate changes on the time scale of years
 - Consumers continue to be shielded from short-term price volatility
 - Therefore receive no direct incentive to respond to power shortages by lowering their demand during critical hours



9.5 Implications For Restructuring (6)

- The restructuring of the electric industry
 - Varying demand and supply freely with respect to price is tricky
 - a) Price elasticity of demand is low
 - A proposed solution in the ideal market
 - Real-time pricing or related incentive mechanisms to encourage *electric demand response*
 - May involve communication only or include direct control
 - Inviting a certain customer behavior under specific conditions
 - Physically disconnecting designated loads under specific conditions
 - An extension of well-established mechanisms such as *time-of-use*
 - *Demand response* requires addressing a broad set of factors
 - 1) Customer behavior
 - 2) Education, economic preferences to control hardware
 - 3) Information management
 - 4) Communications protocols



9.5 Implications For Restructuring (7)

- The restructuring of the electric industry
 - Varying demand and supply freely with respect to price is tricky
 - b) Electric generation is intrinsically uninviting for smaller businesses :
 - The capital-intensive nature of electric generation along with economies of scale and a measure of risk
 - Illegal to run independent lines from a supplier to a consumer
 - A wire from my rooftop PV system to my neighbor across the street is forbidden
 - The transaction costs of becoming an electricity seller through the grid are not negligible and may include fees, bureaucratic procedures, and special equipment to interface with the utility on its terms



9.5 Implications For Restructuring (8)

- The restructuring of the electric industry
 - Varying demand and supply freely with respect to price is tricky
 - c) The quantity of supply constrained
 - Existing generation facilities cannot arbitrarily increase output beyond their rated capacity
 - Impossible for new generation capacity to appear in response to acute shortages
 - Because of the time scale on which conventional power plants are planned, built, and licensed



9.5 Implications For Restructuring (9)

- The restructuring of the electric industry
 - Varying demand and supply freely with respect to price is tricky
 - d) Transmission congestion
 - The grid's ability to transmit the quantity of supply to the desired location is constrained
 - Not readily relieved by simply constructing more power lines
 - Upgrading transmission capacity tends to be slow, expensive, and politically contentious
 - “Rerouting” power cannot make it to go away
 - Electric power flow obeys only physical law; it is difficult enough to predict, let alone control and direct



9.5 Implications For Restructuring (10)

- The restructuring of the electric industry
 - Varying demand and supply freely with respect to price is tricky
 - e) Market power by sellers
 - Are market participants price takers?
 - Have market participants the power to influence the market clearing price ?
 - Can market participants manipulate outcomes in their favor—gaming the market?
 - Gaming is possible
 1. No individual supplier holds too large a market share, they cannot exercise market power
 2. The system is vulnerable to the withholding of even small amounts of generation capacity
 - The extreme inelasticity of demand and supply
 - The system nears its limits



9.5 Implications For Restructuring (11)

- The restructuring of the electric industry
 - Varying demand and supply freely with respect to price is tricky
 - e) Market power by sellers
 - Gaming is possible
 - 3. Line flows are sensitive to the amount of power injected at specific locations
 - Generation capacity can be used strategically to create transmission congestion



9.5 Implications For Restructuring (12)

- The restructuring of the electric industry
 - Varying demand and supply freely with respect to price is tricky
 - f) The external costs of many of grid components
 - Fail to be included in the apparent costs of production and consumption



9.5 Implications For Restructuring (13)

- The restructuring of the electric industry
 - The debate about electric industry restructuring is thus very much about what is fair, who pays how much, and how society should decide
 - Federally subsidized rural electrification brought villages and farms onto the grid
 - Rural areas might have been far more cost-effectively supplied with local sources such as wind power
 - The electric grid was designed to reach out even to customers who were expensive to serve, while splitting the price tag among everyone
 - Urban customers continue to subsidize rural customers
 - Large commercial and industrial customers subsidize smaller customers under regulated utility rates



9.5 Implications For Restructuring (14)

- The restructuring of the electric industry
 - The historical dimension of the grid
 - The electric grid
 - A social artifact as much as a fascinating incarnation of physics and engineering
 - Electrification of industrial society
 - Not only as a logical result of technical and economic driving forces, but as an embodiment of ideas and values
 - “On the grid”
 - Meant not only receiving electrons, but being part of progress in the modern world
 - “Off the grid”
 - Implies independence, self-sufficiency, and sometimes environmentalism



9.5 Implications For Restructuring (15)

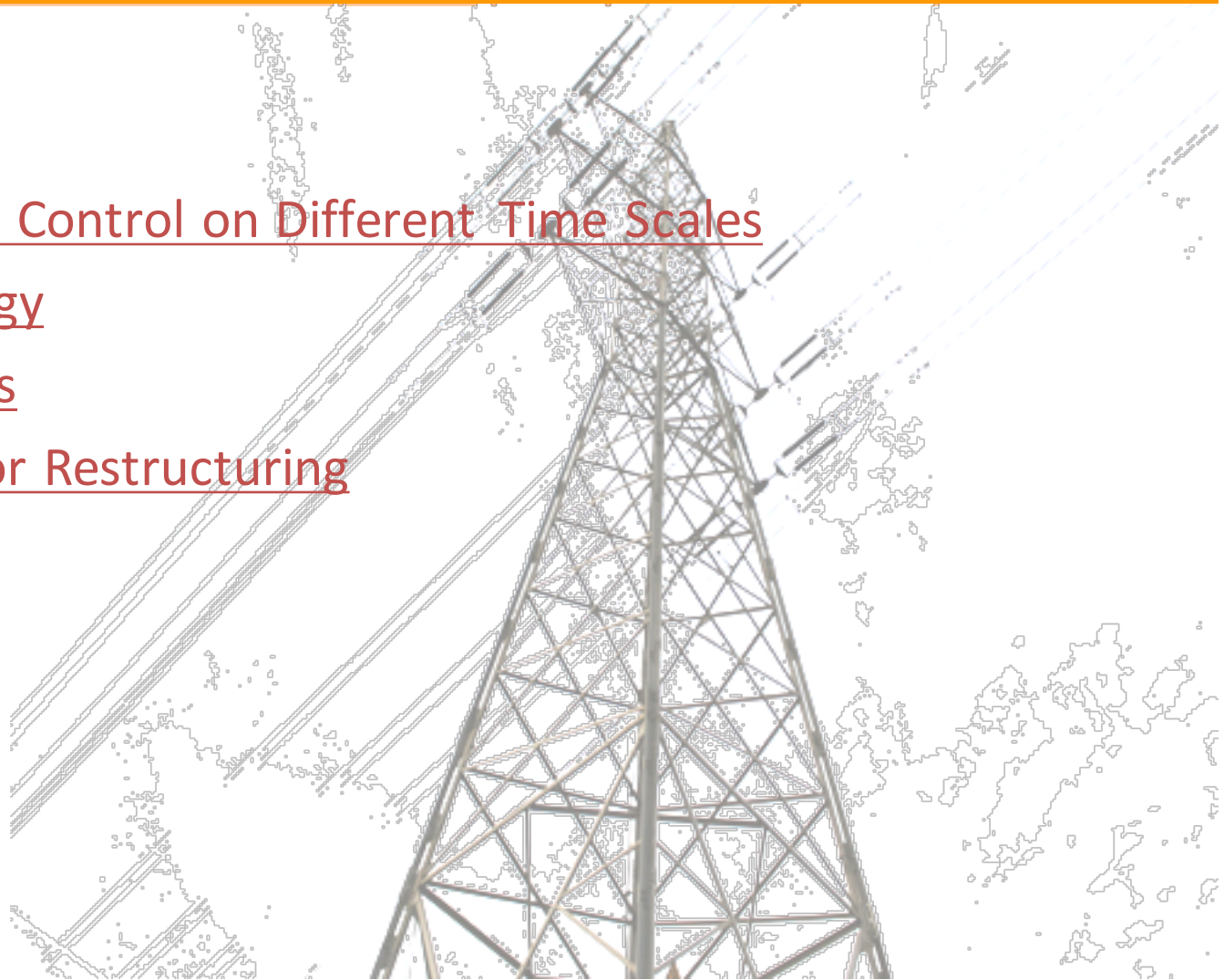
- The restructuring of the electric industry
 - The historical dimension of the grid
 - The idea of equal access to the grid
 - Represented a fundamental sense of social equality, with electricity considered not a privilege affordable to some but an entitlement of all citizen
 - The more widely electric power systems in all their complexity
 - Embody social values, explicit or implicit
 - Better understood, then greater opportunity for people to guide this evolution with awareness and conscious choice



9. System Operation, Management, and New Technology

■ Contents

- 1) Motivation
- 2) Operation and Control on Different Time Scales
- 3) New Technology
- 4) Human Factors
- 5) Implications for Restructuring
- 6) Summary



9.6 Summary

- Electric grid is a complex system
- The prime directive for power system designers and operators is to balance generation and load at every instant
- This balancing act occurs on multiple levels, with control methods appropriate to each time scale
- Many new technologies are proposed and implemented to improve the performance of electric grid
- Operators vs engineers
- Evaluating the performance of any technical systems, can be summarized as efficiency, reliability, and safety



Electric Power System

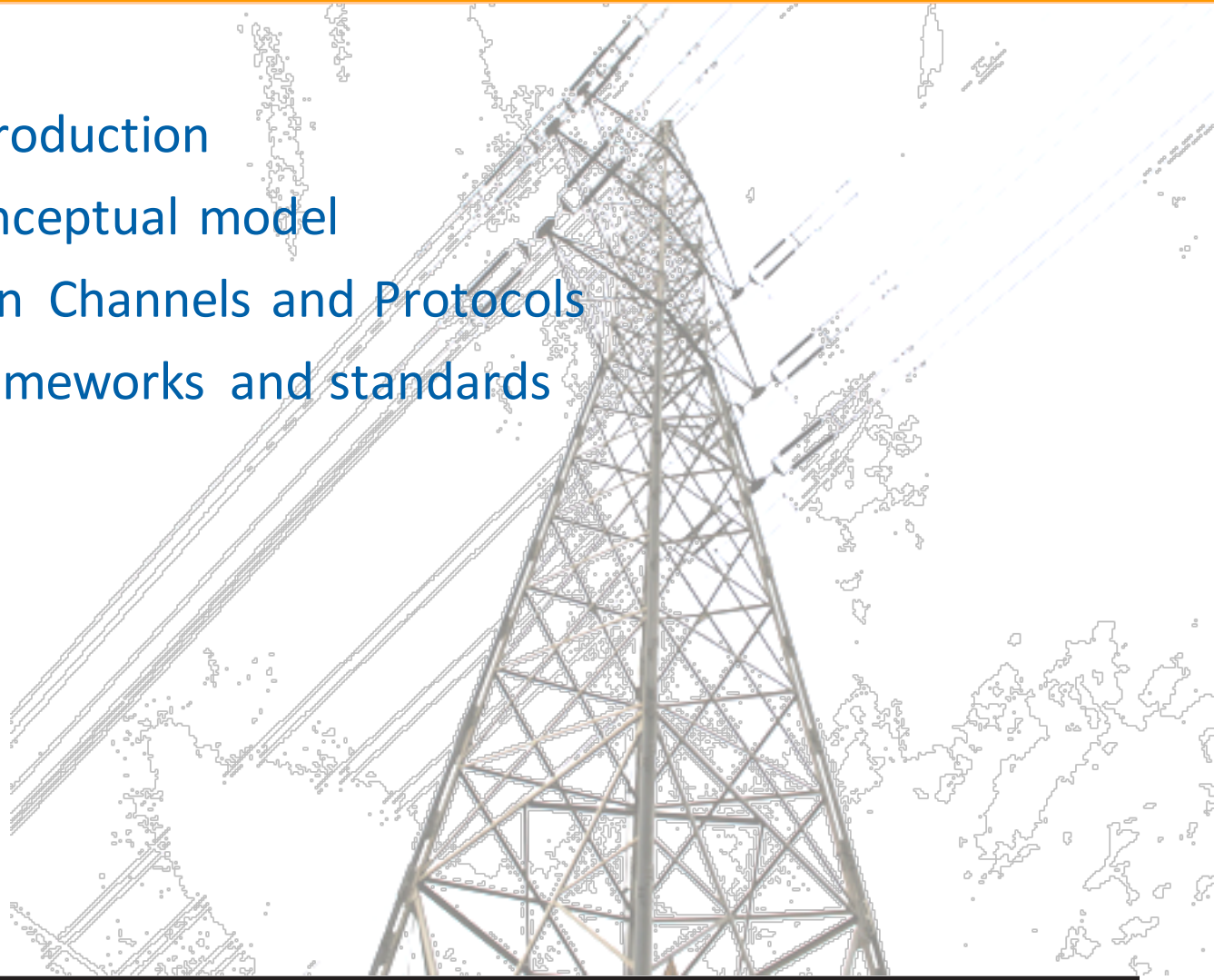
Chapter 10: Smart Grid



10. Smart Grid

■ Contents

- 1) Smart Grid introduction
- 2) Smart Grid conceptual model
- 3) Communication Channels and Protocols
- 4) Smart Grid Frameworks and standards
- 5) Summary
- 6) Literature



10.1 Smart Grid introduction (1)

Smart Grid definitions

- **International Electrotechnical Commission (IEC)**
 - A Smart Grid “is an electricity network that can **intelligently** integrate the actions of all users connected to it – generators, consumers and those that do both – in order to **efficiently deliver sustainable, economic and secure electricity supplies.**”



10.1 Smart Grid introduction (2)

Smart Grid definitions

■ International Electrotechnical Commission (IEC)

- A Smart Grid employs innovative products and services together with intelligent **monitoring, control, communication, and self-healing** technologies to:
 - facilitate the connection and operation of generators of all sizes and technologies;
 - allow consumers to play a part in optimizing the operation of the system;
 - provide consumers with greater information and choice of supply;
 - significantly reduce the environmental impact of the whole electricity supply system;
 - deliver enhanced levels of reliability and security of supply. Cited from: [IEC2013]



10.1 Smart Grid introduction (3)

Smart Grid definitions

- European Technology Platform Smart Grids (ETP SmartGrids)

“[A Smart Grid is] an electricity network that can intelligently integrate actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.”

Cited from:
[SG2013]

- National Institute of Standards and Technology (NIST) Cited from:
[NI2013]

“The objective of the Smart Grid Program is to develop and deploy advances in measurement science to enable integration of interoperable and secure real-time sensing, control, communications, information and power technologies, in order to increase efficiency, reliability and sustainability of the nation’s electric grid.”



10.1 Smart Grid introduction (4)

From today's power grid to the Smart Grid

Today's (Distribution) Grid

- Uninformed, passive consumers
- Dominated by central energy generation
- Little amount of near real-time operational data
- Slow response to power quality issues
- Weak against cyber attack

Smart Grid

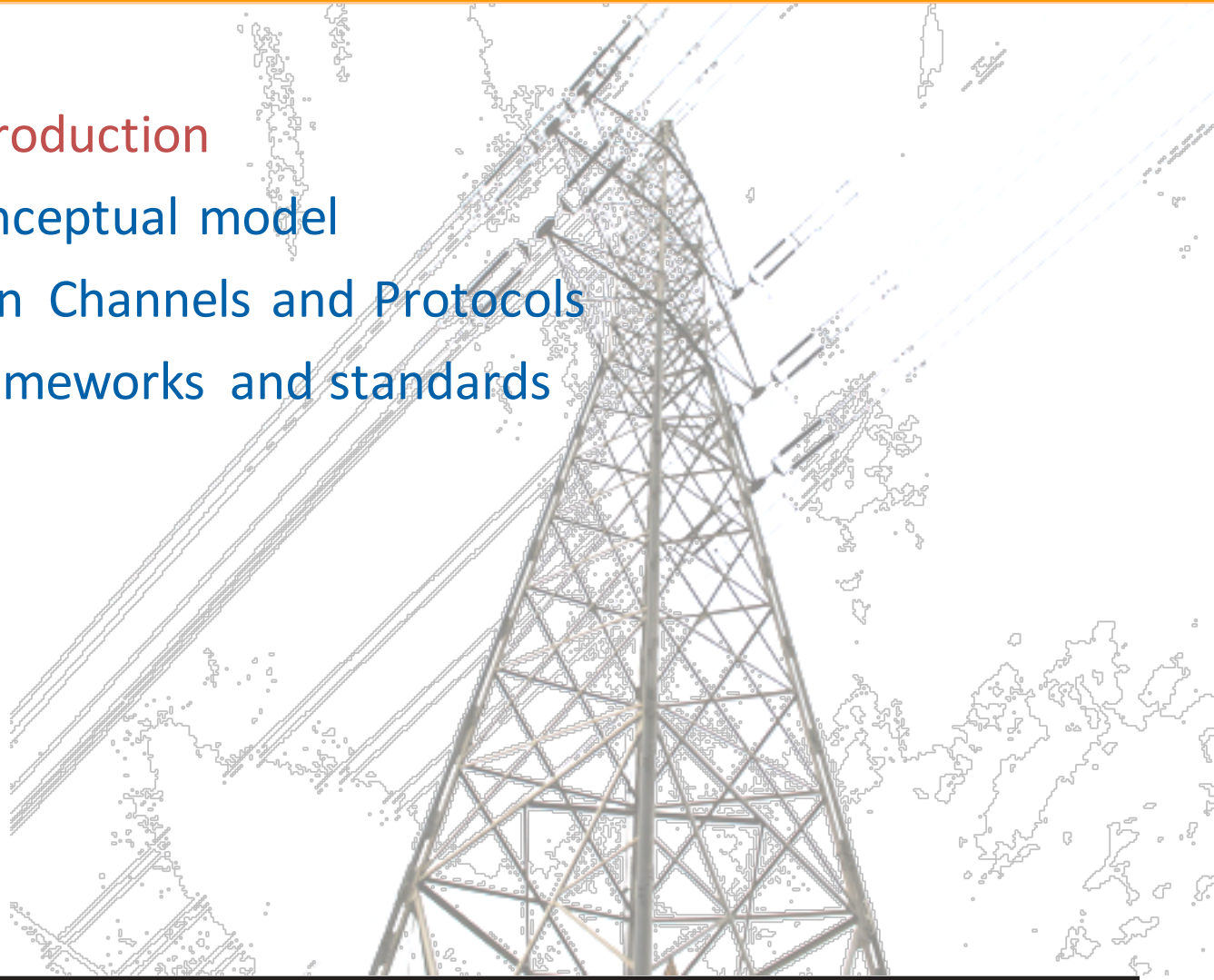
- Informed, involved consumers
- Distributed generation, focus on renewable energy
- Greatly expanded data acquisition
- High priority of power quality (SLAs)
- Resilient to cyber attack

Adapted from:
[MO2012] TABLE 1.1



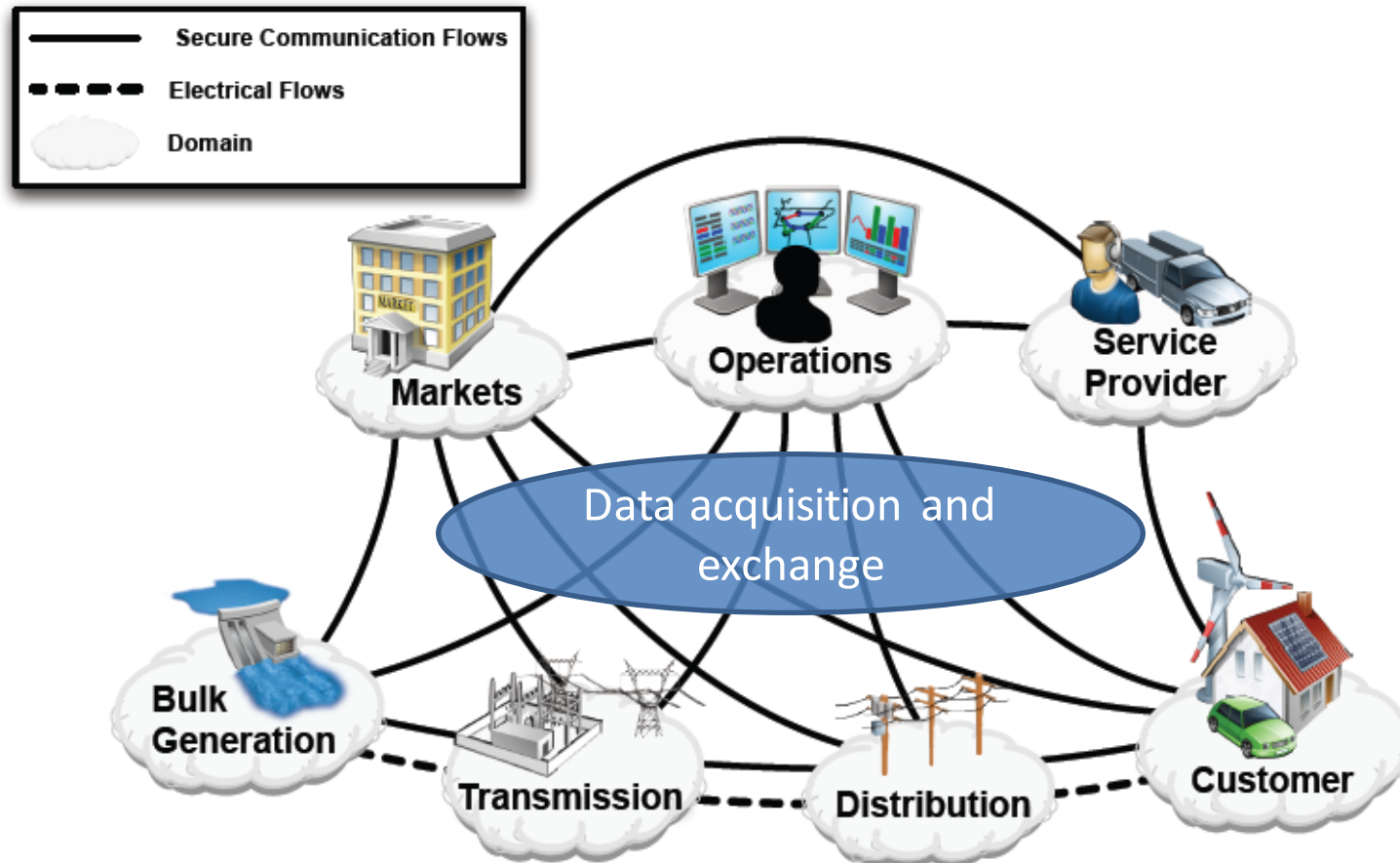
■ Contents

- 1) Smart Grid introduction
- 2) Smart Grid conceptual model
- 3) Communication Channels and Protocols
- 4) Smart Grid Frameworks and standards
- 5) Summary
- 6) Literature



10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Overview (1)



NIST Smart Grid Framework 1.0 January 2010

Source:
[IO2010] Figure 3-1

10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Overview (2)

- NIST adopted the approach of dividing the Smart Grid into seven domains, as described in Table 1.
- Each domain encompasses **actors** and **applications**
 - **Actors** include devices, systems, or programs that make decisions and exchange information necessary for performing applications
 - E.g. smart meters, solar generators, and control systems
 - Actors are connected by associations through interfaces, which represent point of access between domains
 - **Applications** are tasks performed by one or more actors within a domain
 - For example, home automation, solar energy generation and energy storage, and energy management

Cited from:
[IO2010]



10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Overview (3)

Domain	Actors in the Domain
Customers	The end users of electricity. May also generate, store, and manage the use of energy. Types: residential, commercial, and industrial
Markets	The operators and participants in electricity markets
Service Providers	The organizations providing services to electrical customers and utilities
Operations	The manager of the movement of electricity
Bulk generation	The generators of electricity in bulk quantities. May also store energy for later distribution
Transmission	The carriers of bulk electricity over long distances. May also store and generate electricity
Distribution	The distributors of electricity to and from customers. May also store and generate electricity

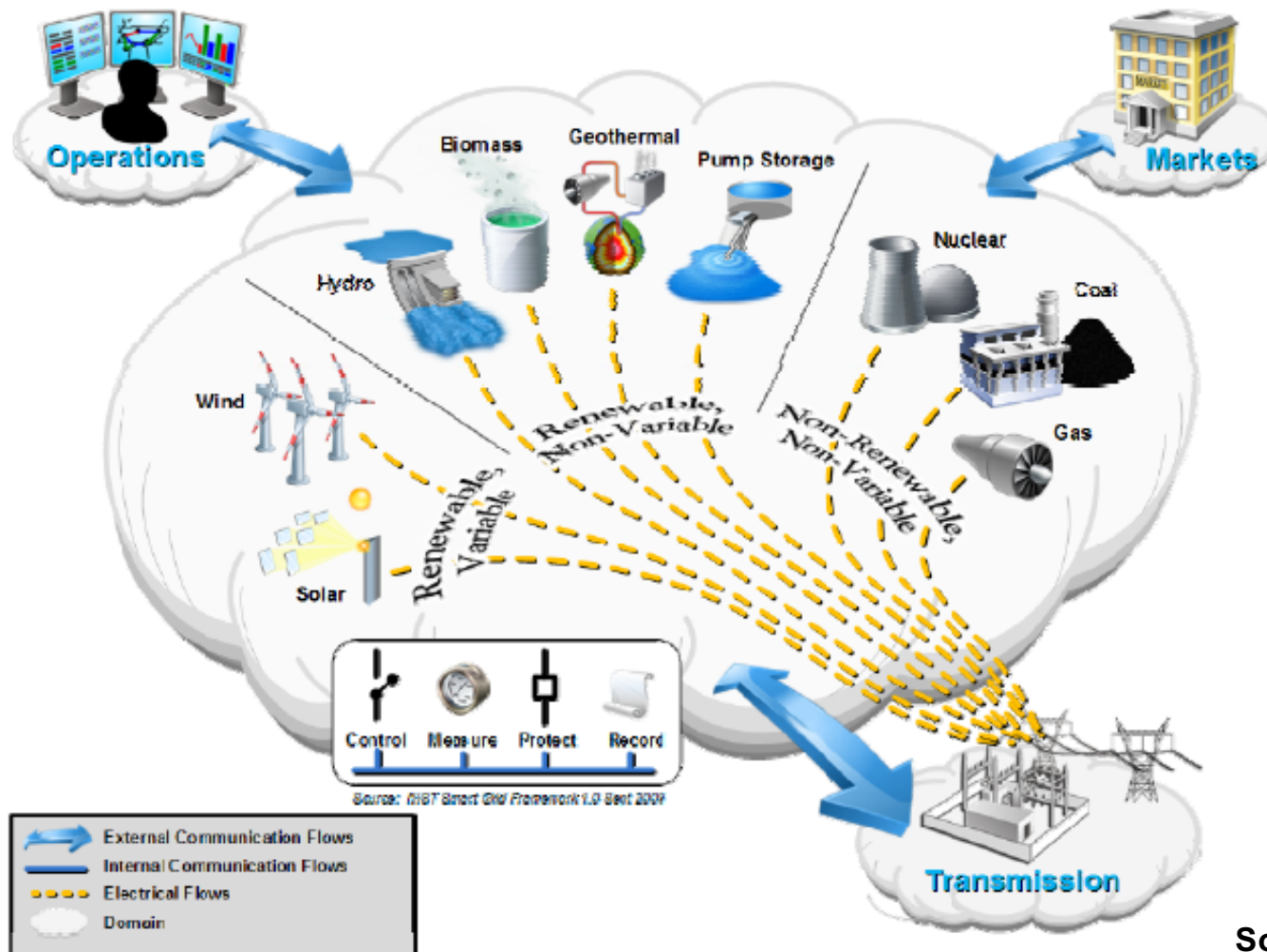
Table 1. Domains and Actors in the Smart Grid Conceptual Model

Source:
[IO2010] Table 3-1



10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Generators (4)



Source:
[IO2010] Figure 9-6

10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Generators (5)

- Changes in generation
 - Increasing prices for fossil power sources
 - Demand for “green” energy
 - Renewable energy sources are gaining ground
- Challenges of renewable energy generation
 - Output fluctuation
 - Coordination
 - Prediction
 - Storage
 - Decentralization
 - Transmission/Dispatch infrastructure upgrades



10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Generators (6)

- Communications with the transmission domain are the most critical because without transmission, customer cannot be served
- Lack of a sufficient supply can be addressed
 - Directly: via operations
 - Indirectly: via market

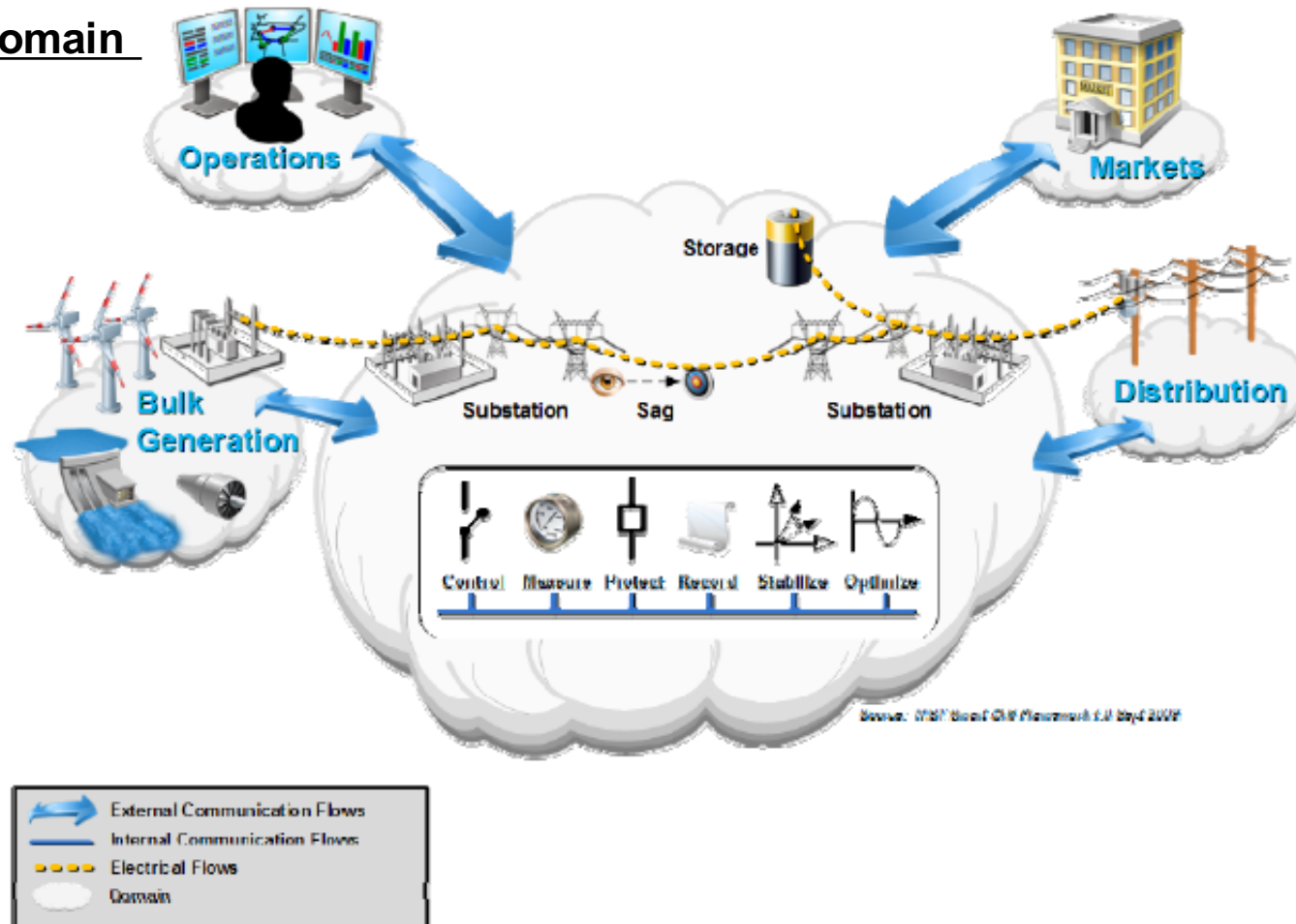


10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid:

Transmission and Distribution (7)

Transmission Domain

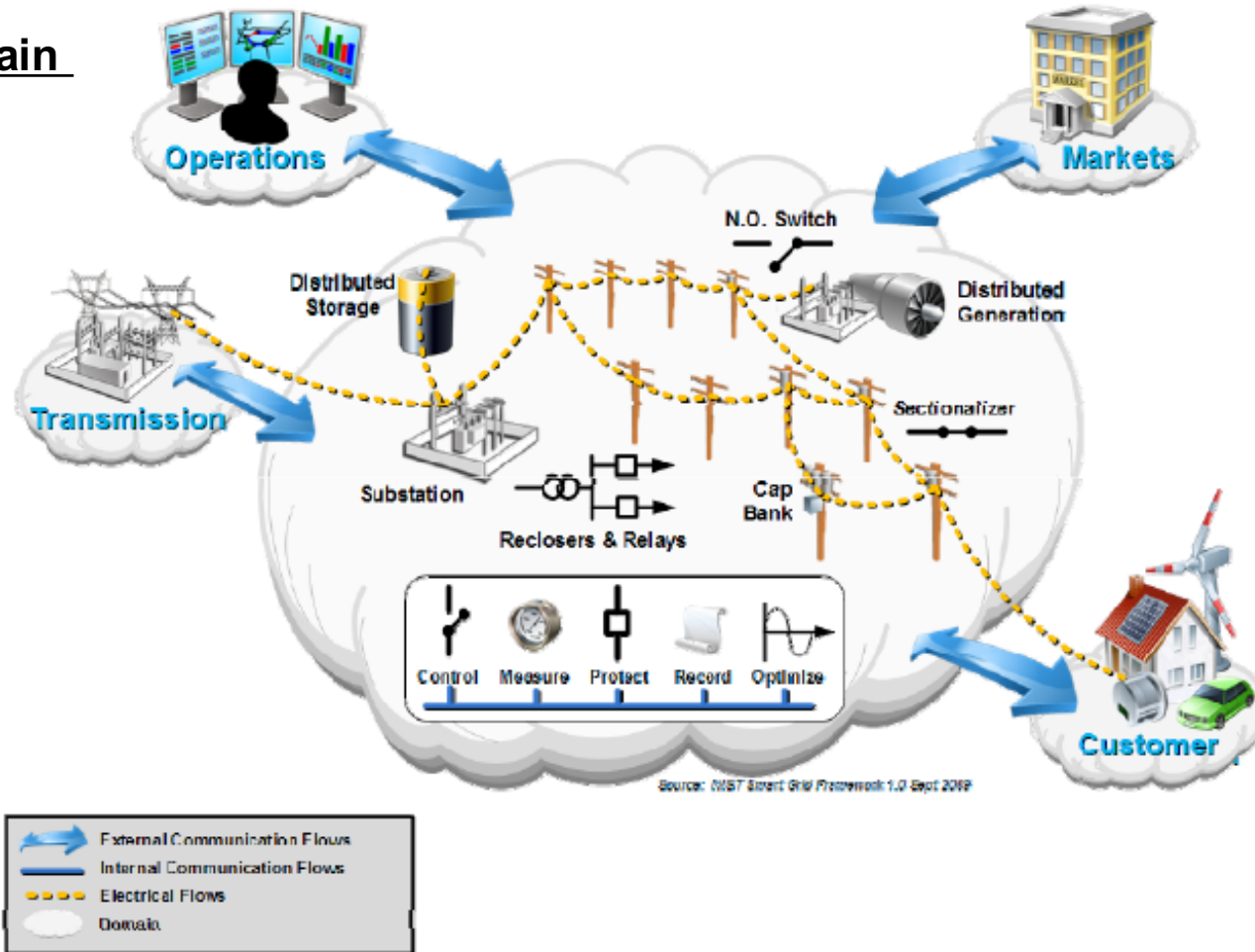


Source:
[IO2010] Figure 9-7

10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Transmission and Distribution (8)

Distribution Domain



Source:
[IO2010] Figure 9-8

10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid:

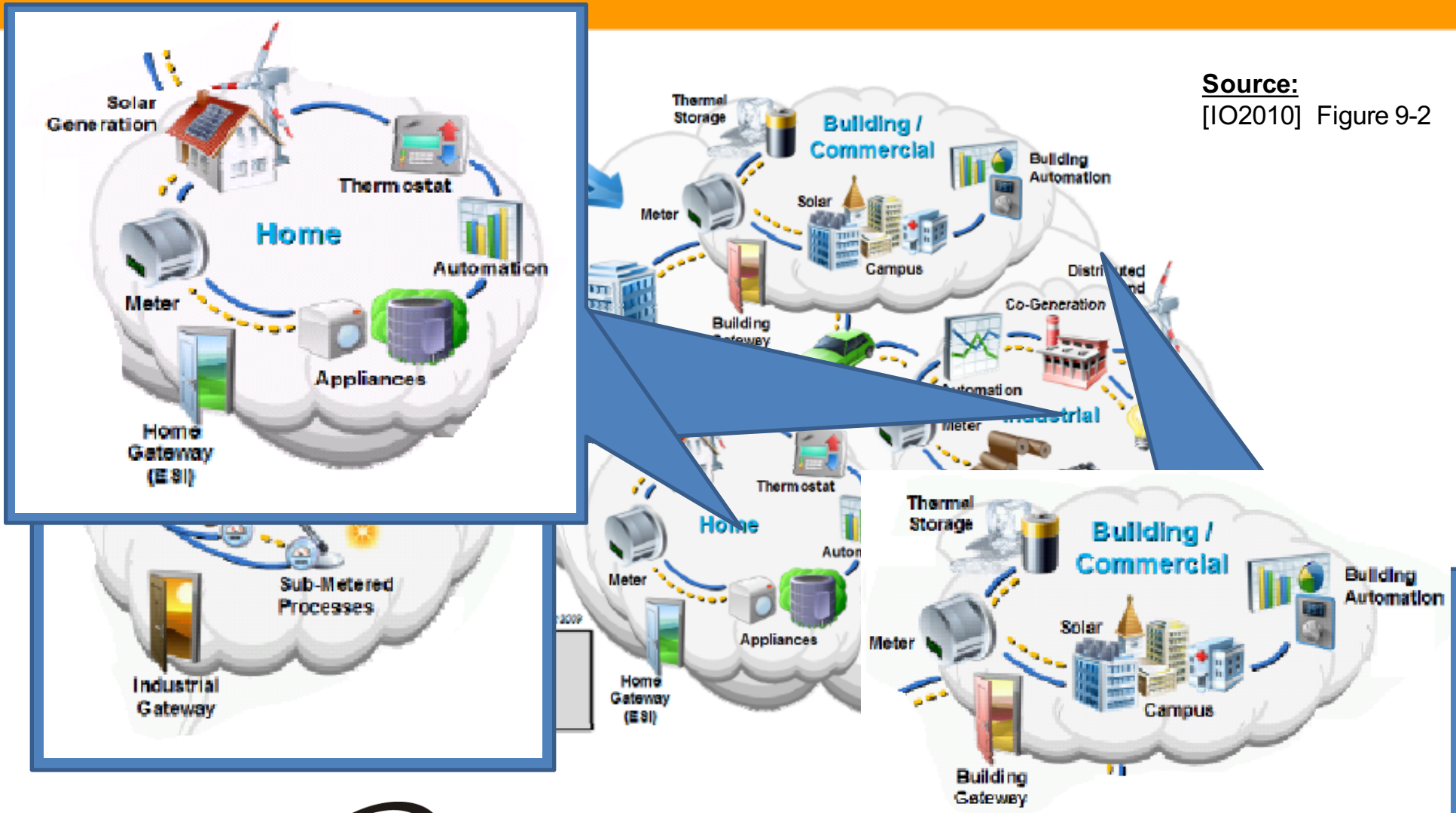
Transmission and Distribution (9)

- Transmission
 - Big scale power “transport” with (ultra) high voltage power lines
 - Backbone characteristics
 - Well suitable for large scale centralized energy generation (bulk generation)
 - Actors include RTUs, substation meters, protection relays, power quality monitors, sag monitors and many other.
- Distribution
 - Dispatches energy to customers
 - May include (smaller) distributed generators and storage
- Smart transmission and distribution
 - Measure, aggregate and process demand/generation/health status of the grid
 - Automated decisions to reach (local) optimum in power “routing”



10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Customers (10)



Source:
[IO2010] Figure 9-2



10.2 Smart Grid conceptual model

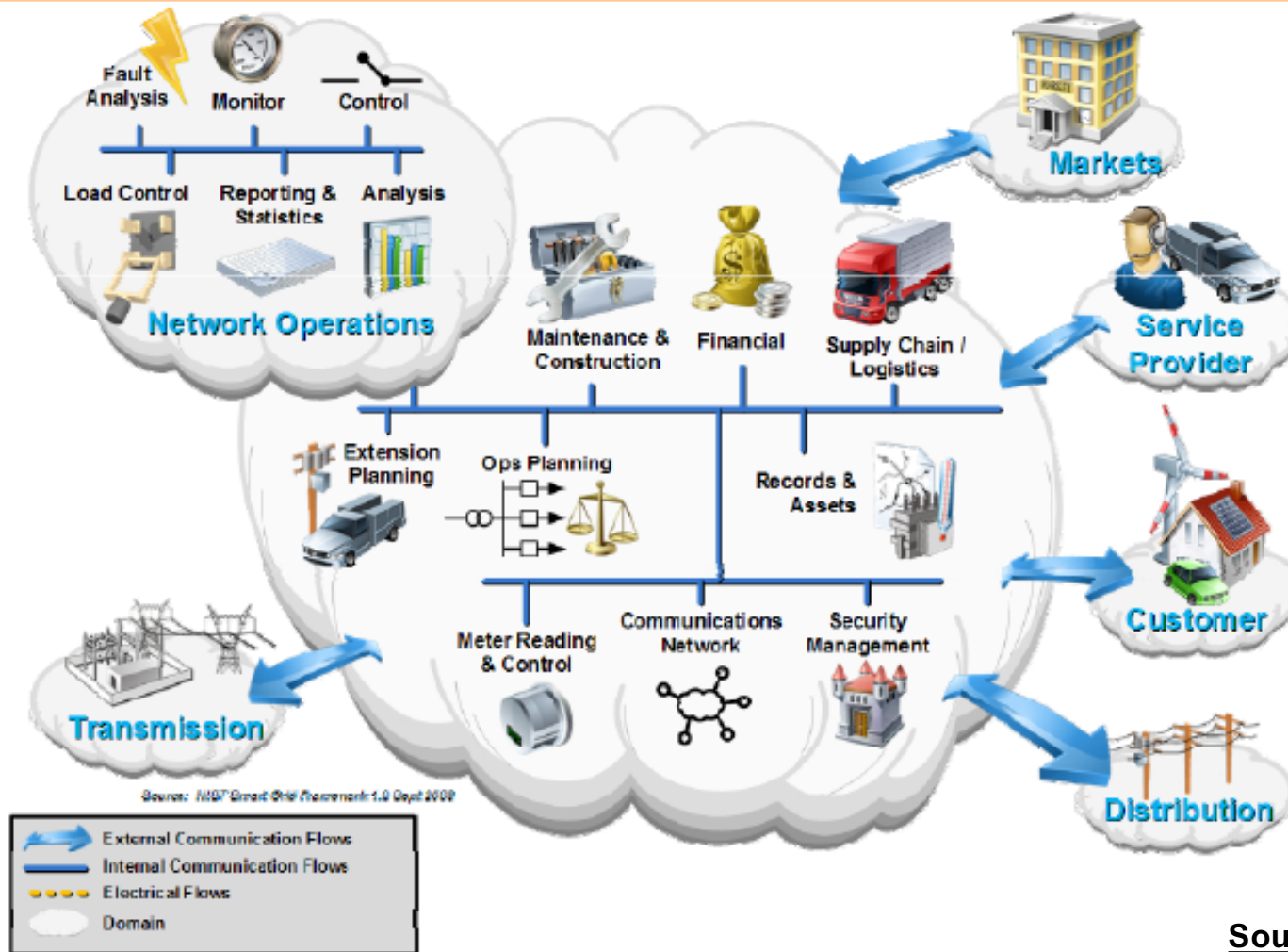
Parts/Actors of the Smart Grid: Customers (11)

- Customers represent the domain where electricity is consumed
- Actors in this domain, such as smart meters
 - enable customers to manage their energy usage and generation
 - provide control and information flow between customers and the other domains
- Typical applications in the customer domain
 - Building or home automation, industrial automation or micro-generation
- This domain is segmented into subdomains
 - Home, commercial and industrial
- The customer domain is electrically connect to the Distribution domain.
- It can communicates with Distribution, Operations, Market, and Service providers domains



10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Operators (12)



Source:
[IO2010] Figure 9-5

10.2 Smart Grid conceptual model

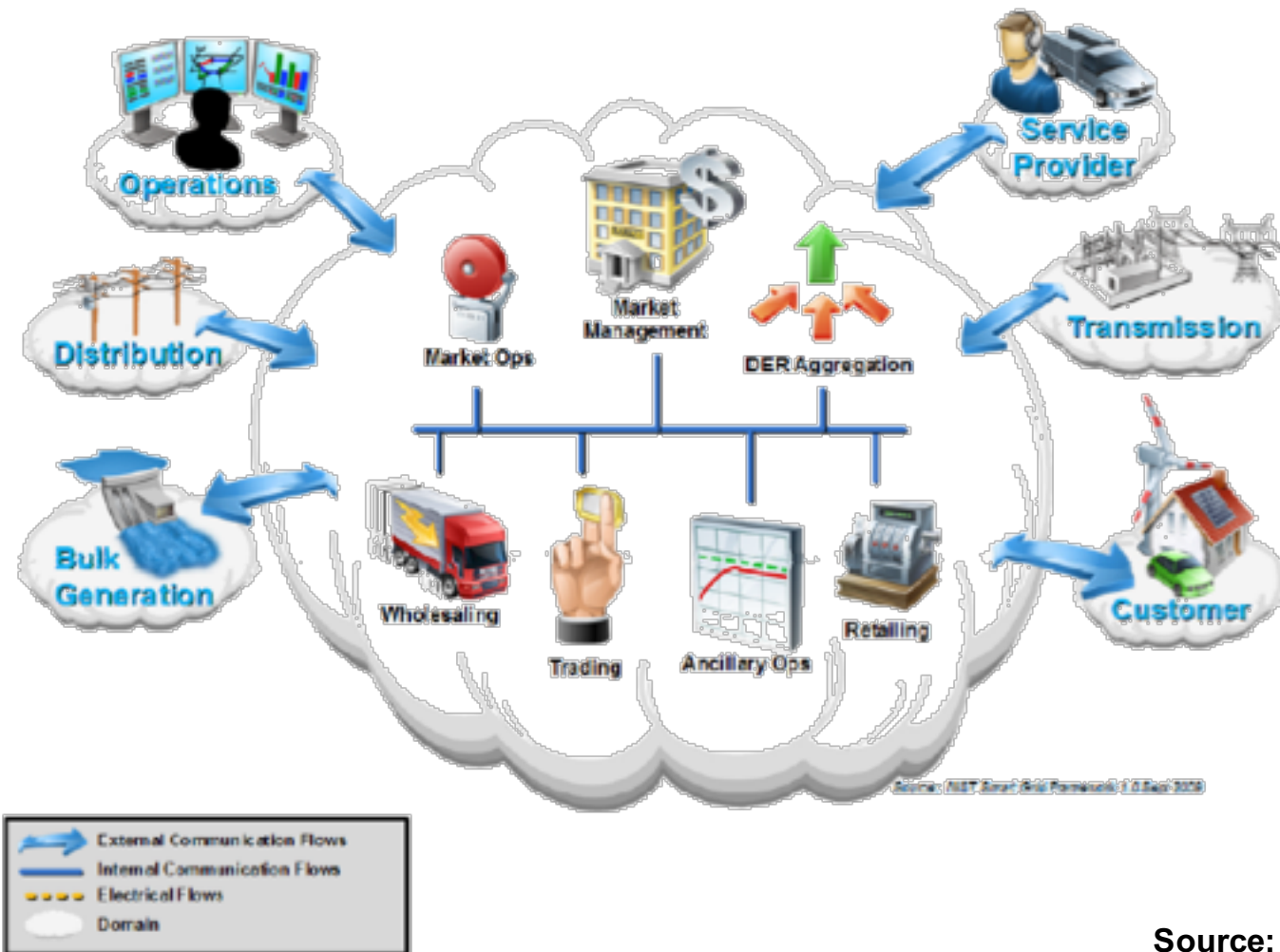
Parts/Actors of the Smart Grid: Operators (13)

- SG operators manage the Grid
 - Planning the Grid
 - Design and implement infrastructure for the Smart Grid
 - Enhance efficiency of current infrastructures
 - Expand the infrastructure
 - Data acquisition
 - Detect and react to load peaks
 - Predict future load → find (local) optimum of production and consumption
 - Detect faults in the grid → self-healing, quick recovery
 - Other applications: monitoring ,control, reporting and statistics, etc.



10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Markets (14)



Source:
[IO2010] Figure 9-3

10.2 Smart Grid conceptual model

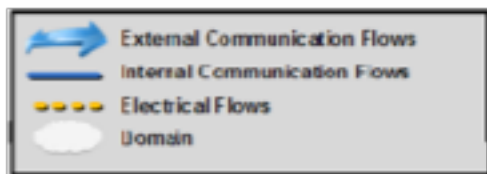
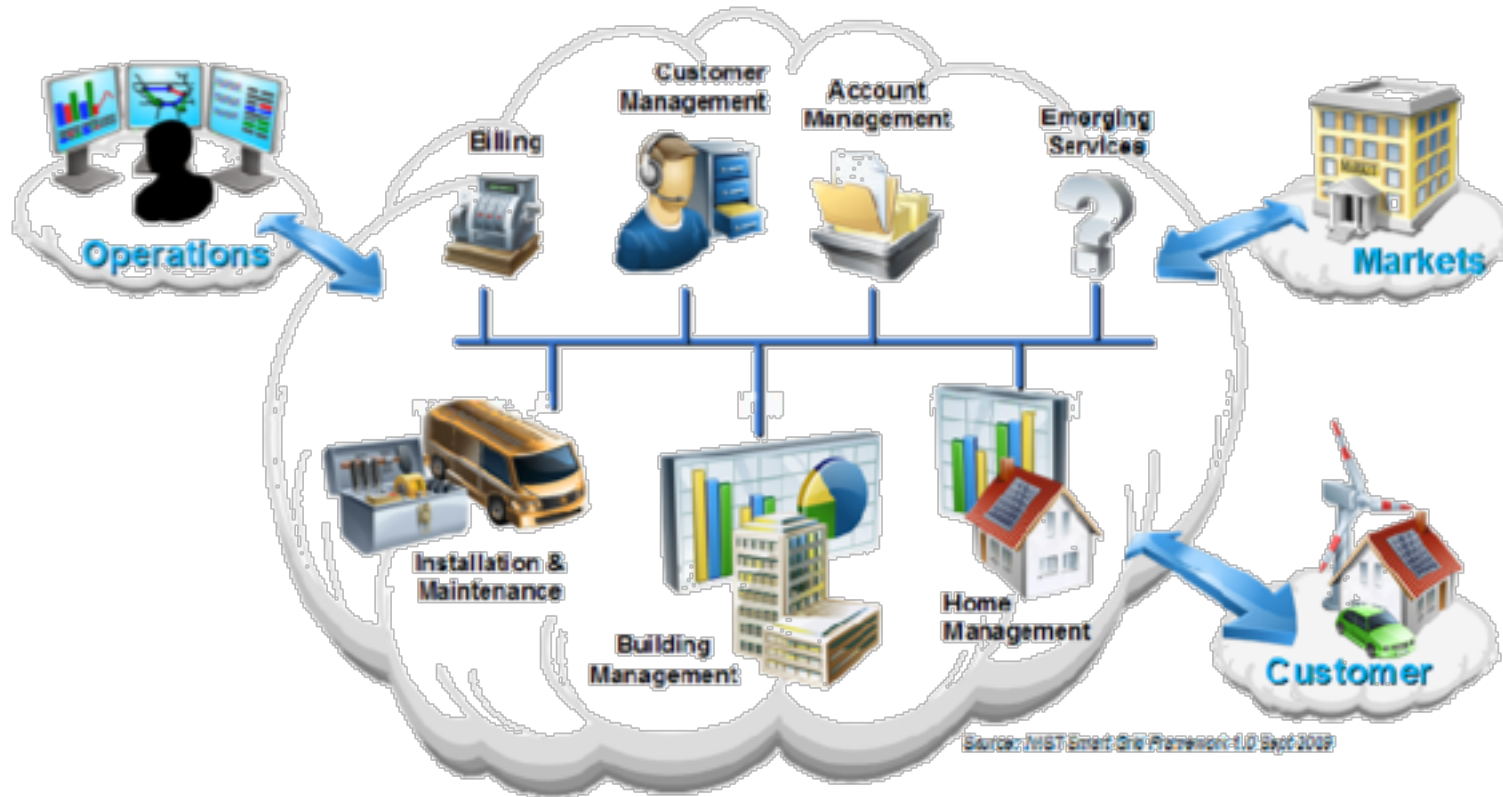
Parts/Actors of the Smart Grid: Markets (15)

- The markets are where grid assets are bought and sold
- Actors in the Markets domain exchange price and balance supply and demand within the power system
- Communication between the Markets domain and the domains supplying energy are critical
 - because efficient matching of production with consumption is dependent on markets.
- Communications for Markets domain interactions must be reliable. They must be traceable and auditable.



10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Service Provider (16)



Source:
[IO2010] Figure 9-4

10.2 Smart Grid conceptual model

Parts/Actors of the Smart Grid: Service Provider (17)

- Actors in the Service Provider domain perform services to support the business processes of power system producers, distributors and customers
- These business processes include
 - Traditional utility services, such as billing and customer account management, and
 - Enhanced customer services, such as management of energy use and home energy generation.
- The service provider must not compromise the cyber security, reliability, stability, integrity, or safety of the electrical power network when delivering existing or emerging services
- The Service Provider domain communicates with the Markets, Operations, and Customer domains
- Typical applications are customer/ building/home/Account management, Billing, emerging services



10.2 Smart Grid conceptual model

Communication (18)

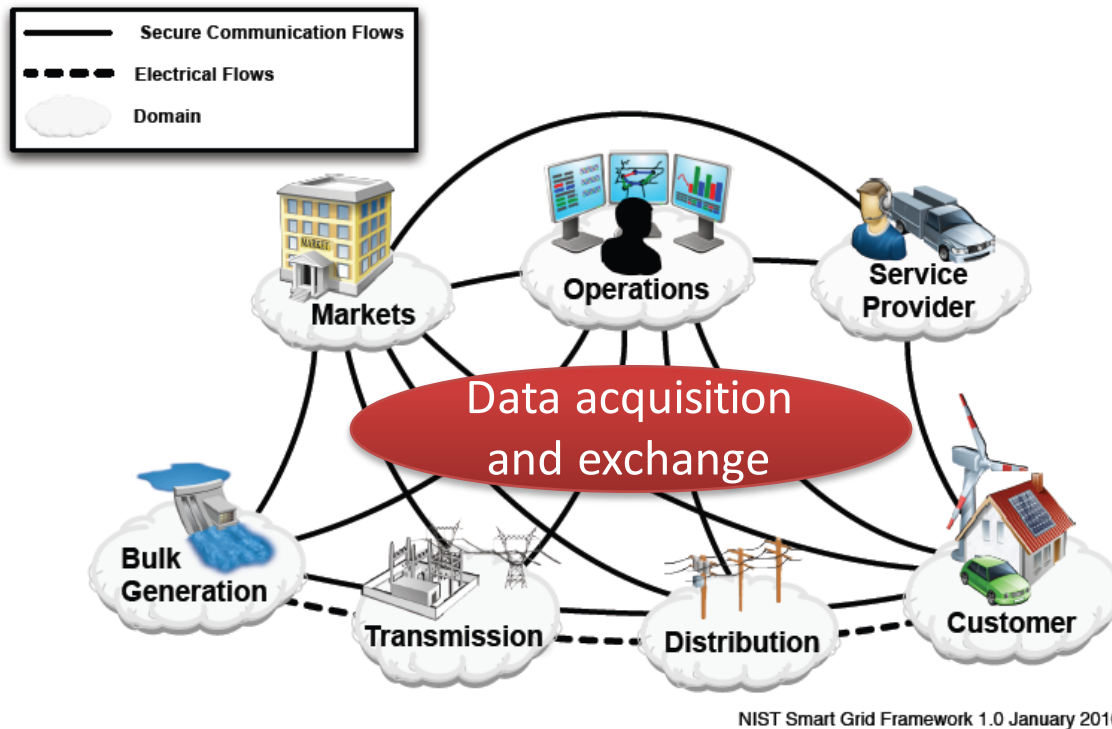


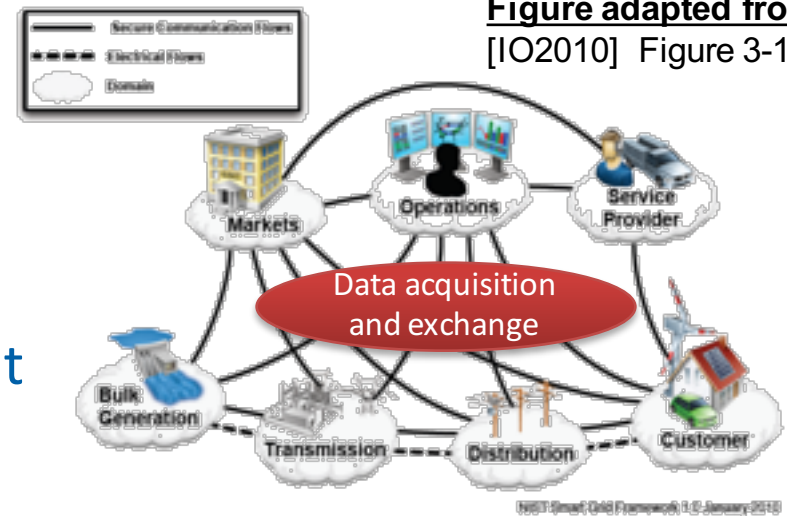
Figure adapted from:
[IO2010] Figure 3-1

- Coordination of generation, dispatch, storage and consumption of energy requires measurement, data aggregation and decision schemes.
- All parts of the Smart Grid have to be able to exchange information with each other.

10.2 Smart Grid conceptual model

Communication: Data Categories (19)

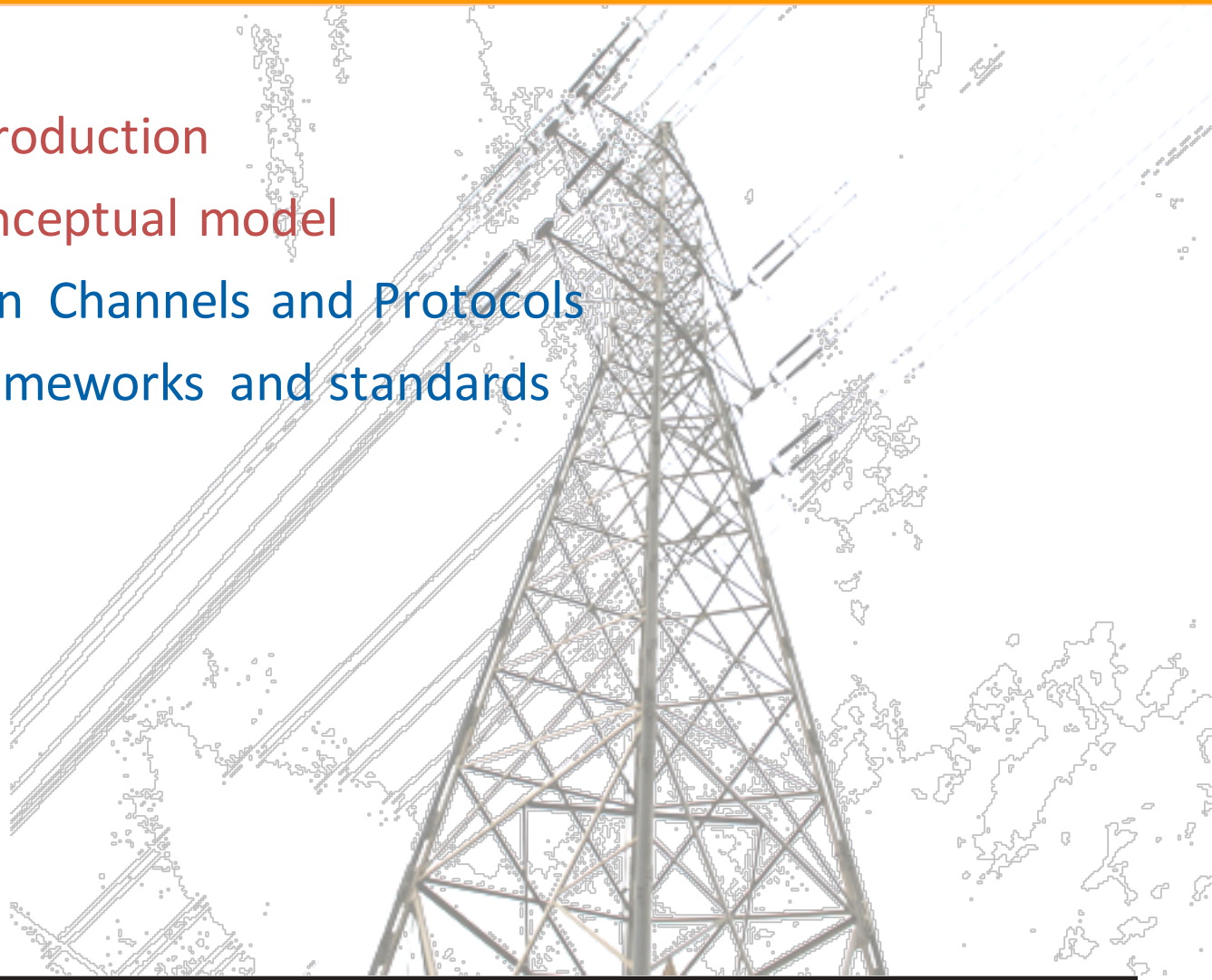
- Pricing Information
 - Enables customer to adopt his consumption to current pricing
- Energy Demand
 - Customer informs Operator about current/planned consumption
 - Near-real-time predictions
- Energy supply (analog to Energy Demand on Generator side)
- Grid Health
 - Fault detection
 - Load analysis/prediction



10. Smart Grid

■ Contents

- 1) Smart Grid introduction
- 2) Smart Grid conceptual model
- 3) Communication Channels and Protocols
- 4) Smart Grid Frameworks and standards
- 5) Summary
- 6) Literature



10.3 Communication Channels and Protocols

- Communication over Internet
 - HTTP(S) (Customer information/Feedback)
 - OpenADR messages (**A**utomated **D**emand **R**esponse)
 - RFC 6272, Internet Protocols for the Smart Grid
- Communication over power line communication (PLC)
 - IEEE 1901-2010 & ITU-T G.9972 (Broadband over Power Line)
- LAN, NAN (Neighborhood Area Network) and WAN approaches
 - SCADA (supervisory control and data acquisition) systems
 - IEC 60870-5 (esp. IEC 60870-5-104) & IEC 60870-6
 - IEC 61850 (substation automation)
 - DNP3

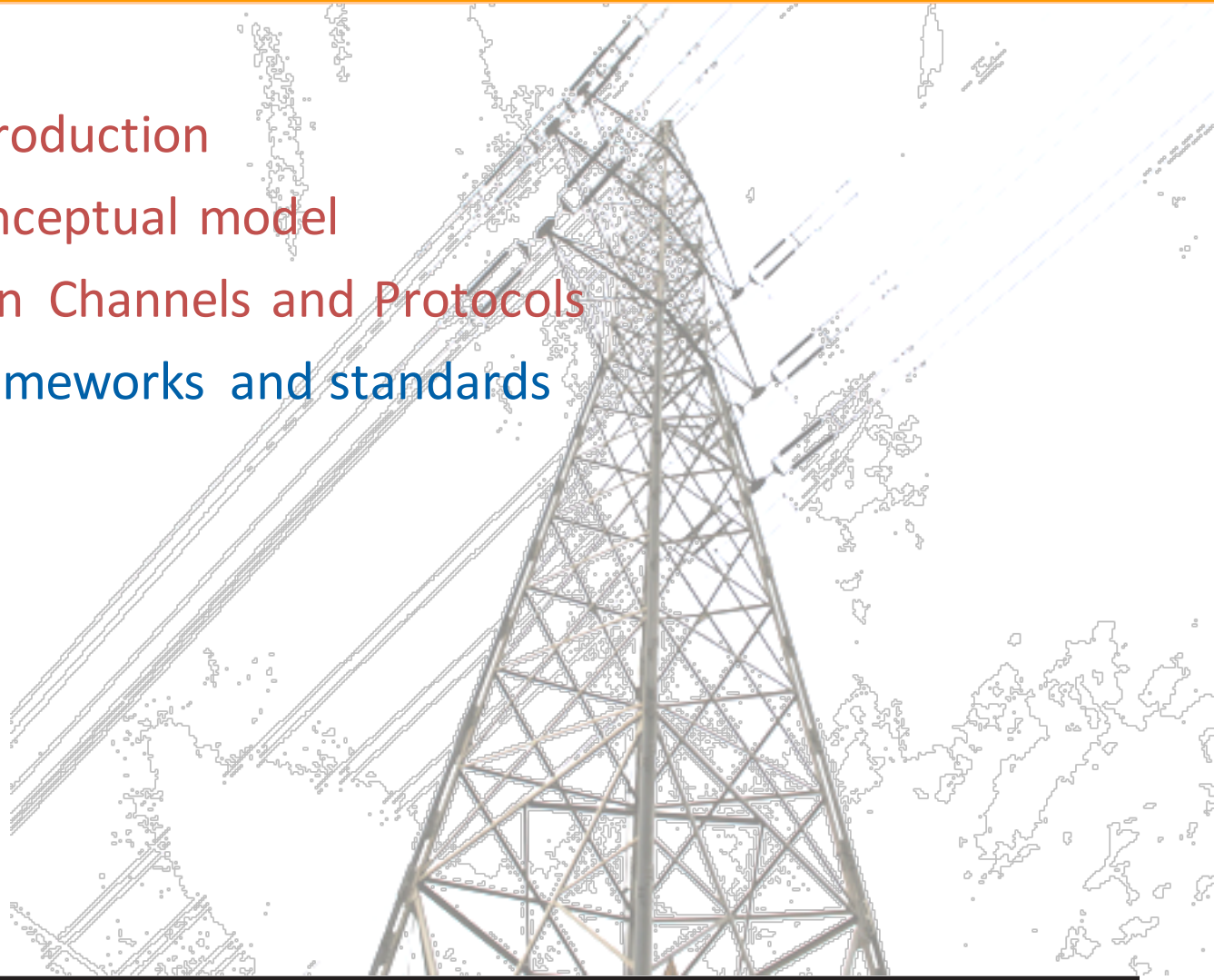
...and many more



10. Smart Grid

■ Contents

- 1) Smart Grid introduction
- 2) Smart Grid conceptual model
- 3) Communication Channels and Protocols
- 4) Smart Grid Frameworks and standards
- 5) Summary
- 6) Literature



10.4 Smart Grid Frameworks and standards

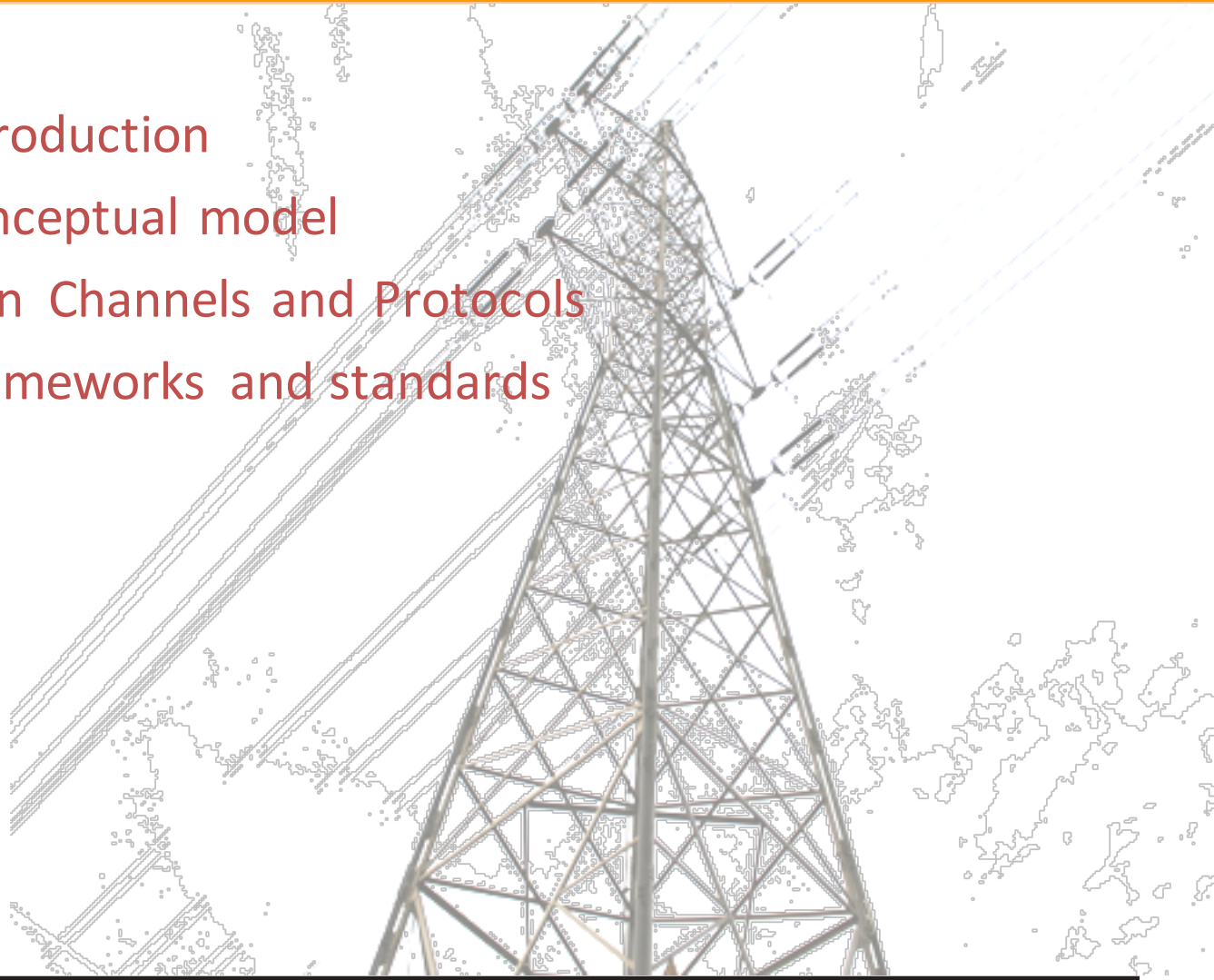
- The “NIST Framework and Roadmap for Smart Grid Interoperability” has identified over 100 standards relevant for the topic of Smart Grid. There are several areas covered by these standards:
 - Home/Building automation
 - Smart Meters and Communication
 - Advanced Metering Infrastructures (AMIs)
 - Demand-Response, Demand-Side-Management
 - Real-Time-Markets for Energy
 - Security Guidelines



10. Smart Grid

■ Contents

- 1) Smart Grid introduction
- 2) Smart Grid conceptual model
- 3) Communication Channels and Protocols
- 4) Smart Grid Frameworks and standards
- 5) Summary
- 6) Literature



10.5 Summary

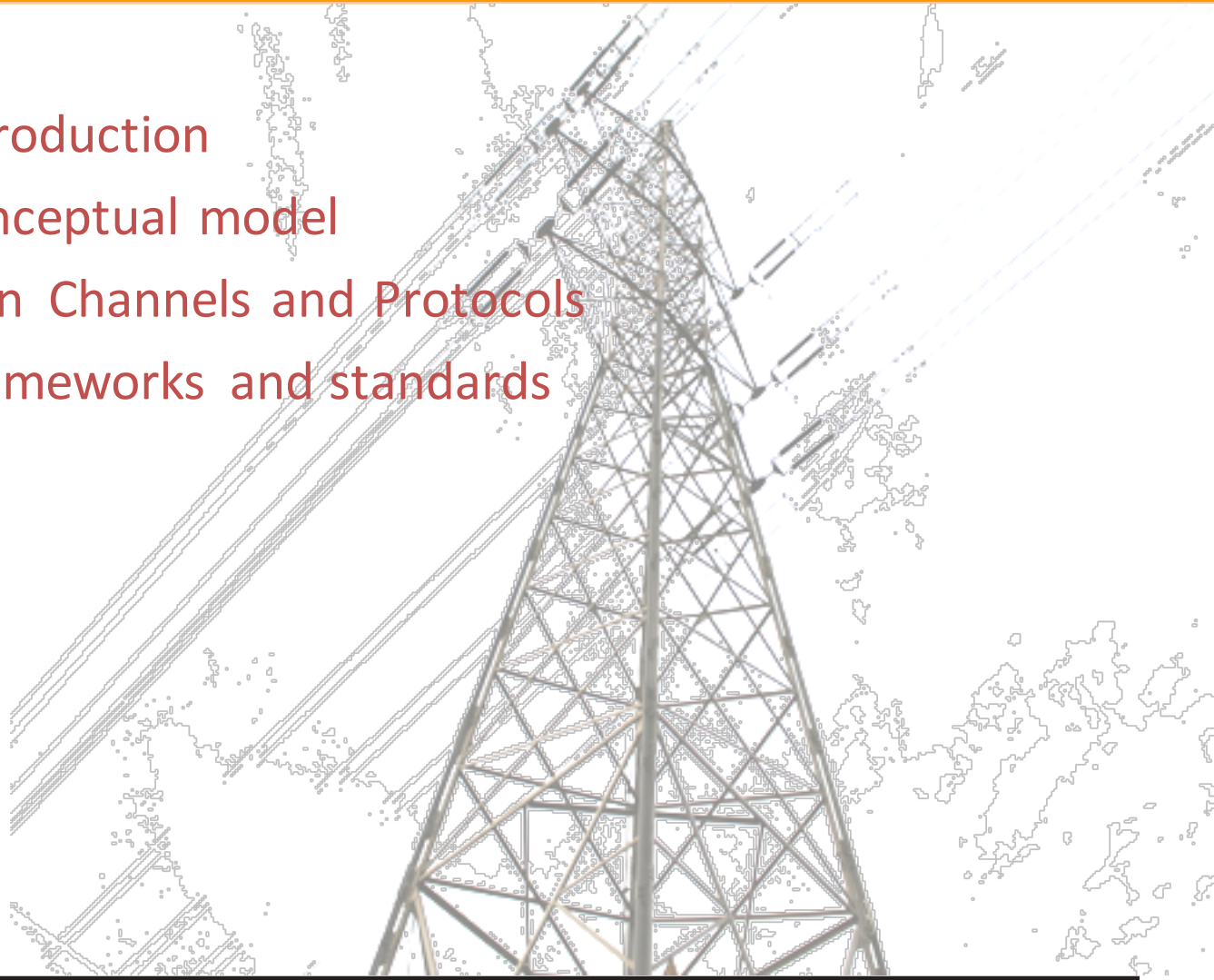
- The **power grid** is currently improved to become the **Smart Grid** within the next few years
 - Deeply integrated use of Information and Communication Technology (ICT) with power grid technology
 - Precisely predict energy demand and shape production accordingly → **Intelligent power production**
 - Reshape energy demand to fit current availability of energy → **Intelligent power demand**
 - Support the integration of highly variable renewable energy sources
- Smart Grid provides reliability, sustainability, flexibility and sufficient power quality



10. Smart Grid

■ Contents

- 1) Smart Grid introduction
- 2) Smart Grid conceptual model
- 3) Communication Channels and Protocols
- 4) Smart Grid Frameworks and standards
- 5) Summary
- 6) Literature



10.5 Literature (1)

- **[IO2010]**
NIST Framework and Roadmap for Smart Grid Interoperability Standards U.S. Department of Commerce, Office of the National Coordinator for Smart Grid Interoperability, NIST Special Publication 1108, Release 1.0
Published Jan. 2010
- **[Mo2012]**
Smart Grid: Fundamentals of Design and Analysis, First Edition. James Momoh. © 2012 IEEE, Published 2012 by John Wiley & Sons, Inc.,
ISBN13: 978-0-470-88939-8



10.5 Literature (2)

- **[IE2013]** International Electrotechnical Commission
<http://www.iec.ch/smartgrid/background/explained.htm>
Access Date: 09.01.2015
- **[SG2013]** European technology platform for the electricity networks of the future
<http://www.smartgrids.eu/FAQ#12>
Access Date: 09.01.2015
- **[NI2013]** (US) National Institute of Standards and Technology
<http://www.nist.gov/el/smartgrid/sgprogram.cfm>
Access Date: 09.01.2015

