BASIC CONCEPTS

Yahia Baghzouz
Electrical & Computer Engineering Department
INSTANTANEOUS VOLTAGE, CURRENT AND POWER, RMS VALUES

\[
\begin{align*}
\nu(t) &= V_m \cos(\omega t + \theta_v) \\
i(t) &= I_m \cos(\omega t + \theta_i) \\
p(t) &= \nu(t) i(t)
\end{align*}
\]

\[
\theta = \theta_v - \theta_i \quad V_m = \sqrt{2} |V| \quad I_m = \sqrt{2} |I|
\]

\[
p(t) = |V| |I| \cos \theta \left(1 + \cos 2(\omega t + \theta_v)\right) + |V| |I| \sin \theta \sin 2(\omega t + \theta_v)
\]

**energy flow into the circuit**

**energy borrowed and returned by the circuit**
AVERAGE (REAL) POWER, REACTIVE POWER, APPARENT POWER, POWER FACTOR

\[ p(t) = |V| |I| \left\{ 1 + \cos 2(\omega t + \theta_v) \right\} \cos \theta + |V| |I| \sin 2(\omega t + \theta_v) \sin \theta \]

\[ p_R(t) = |V| |I| \left\{ 1 + \cos 2(\omega t + \theta_v) \right\} \cos \theta = \bar{P} \left\{ 1 + \cos 2(\omega t + \theta_v) \right\} \]

\[ p_X(t) = |V| |I| \sin 2(\omega t + \theta_v) \sin \theta = S \sin \theta \sin 2(\omega t + \theta_v) \]

\[ \bar{P} = |V| |I| \cos \theta \]

\[ S = |V| |I| \]

\[ Q = S \sin \theta = |V| |I| \sin \theta \]

\[ pf = \cos \theta = \frac{\bar{P}}{|V| |I|} \]
INSTANTANEOUS POWER IN PURE RESISTIVE AND INDUCTIVE CIRCUITS
PHASOR NOTATION, IMPEDANCE AND ADMITTANCE

Transformation of a sinusoidal signal to and from the time domain to the phasor domain:

\[ v(t) = \sqrt{2}|V|\cos(\omega t + \theta_v) \quad \rightarrow \quad V = |V| \angle \theta_v \]

(time domain)  
(phasor domain)

<table>
<thead>
<tr>
<th>Element</th>
<th>Impedance</th>
<th>Admittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>( Z = R )</td>
<td>( Y = \frac{1}{R} )</td>
</tr>
<tr>
<td>L</td>
<td>( Z = j\omega L )</td>
<td>( Y = \frac{1}{j\omega L} )</td>
</tr>
<tr>
<td>C</td>
<td>( Z = -j\frac{1}{\omega C} )</td>
<td>( Y = j\omega C )</td>
</tr>
</tbody>
</table>
RESISTIVE-INDUCTIVE, RESISTIVE-CAPACITIVE LOAD

![Circuit Diagrams]

Source $G$, circuit with a resistor ($R$), inductive load ($I_p$), capacitive load ($I_q$), and current $I$. Diagrams illustrate the relationships between voltage $E$, current $I$, and the components $I_p$, $I_q$.
POWER IN INDUCTIVE AND CAPACITIVE CIRCUITS
**COMPLEX POWER, POWER TRIANGLE**

\[ V \ I^* = |V| |I| \angle (\theta_v - \theta_i) = |V| |I| \angle \theta = S \]

\[ S = |V| |I| \cos \theta + j |V| |I| \sin \theta = P + jQ \]

\[ |S| = \sqrt{P^2 + Q^2} \]
EXAMPLE: POWER FACTOR CORRECTION

The power triangle below shows that the power factor is corrected by a shunt capacitor from 65% to 90% (lag).
CONSERVATION OF POWER

- At every node (bus) in the system,
  - the sum of real powers entering the node must be equal to the sum of real powers leaving that node.
  - The same applies for reactive power,
  - The same applies for complex power
  - The same does not apply for apparent power

- The above is a direct consequence of Kirchhoff’s current law, which states that the sum of the currents flowing into a node must equal the sum of the currents flowing out of that node.
Bulk power systems are almost exclusively 3-phase. Single phase is used primarily only in low voltage, low power settings, such as residential and some commercial customers.

Some advantages of three-phase system:

- Can transmit more power for the same amount of wire (twice as much as single phase)
- Torque produced by 3φ machines is constant, easy start.
- Three phase machines use less material for same power rating
PHASE AND LINE VOLTAGES

\[ V_{an} = |V| \angle \alpha^\circ \]
\[ V_{bn} = |V| \angle \alpha^\circ - 120^\circ \]
\[ V_{cn} = |V| \angle \alpha^\circ + 120^\circ \]

\( (\alpha = 0 \text{ in this case}) \)

\[ V_{ab} = V_{an} - V_{bn} = |V|(1 \angle \alpha - 1 \angle \alpha + 120^\circ) \]
\[ = \sqrt{3} |V| \angle \alpha + 30^\circ \]

\[ V_{bc} = \sqrt{3} |V| \angle \alpha - 90^\circ \]

\[ V_{ca} = \sqrt{3} |V| \angle \alpha + 150^\circ \]

Line to line voltages are also balanced.
NEUTRAL WIRE

\[ I_n = I_a + I_b + I_c \]

\[ I_n = \frac{V}{Z} (1 \angle 0^\circ + 1 \angle -120^\circ + 1 \angle 120^\circ) = 0 \]
POWER IN BALANCED 3-PHASE CIRCUITS

The real power, reactive power, apparent power, complex power and power factor are the same in each phase.

\[ P = 3V_p I \cos(\theta) = \sqrt{3}V_L I \cos(\theta) \]

\[ Q = 3V_p I \sin(\theta) = \sqrt{3}V_L I \sin(\theta) \]

\[ S = 3V_p I = \sqrt{3}V_L \]
PER-PHASE ANALYSIS IN BALANCED 3-PHASE CIRCUITS

- Per phase analysis allows analysis of balanced 3Φ systems with the same effort as for a single phase system

- **To do per phase analysis**
  1. Convert all 3Φ load/sources to equivalent Y’s
  2. Solve phase “a” independent of the other phases
  3. Total system power $S = 3 V_a I_a^*$
  4. If desired, phase “b” and “c” values can be determined by inspection (i.e., ±120° degree phase shifts)
  5. If necessary, go back to original circuit to determine line-line values or internal 3Φ values.
EXAMPLE OF PER-PHASE ANALYSIS

Find the complex power supplied by each of the two sources.
To solve the circuit, write the KCL equation at a’

\[ (V_a' - 1\angle 0)(-10\angle 0) + V_a'(3\angle 0) + (V_a' - \frac{1}{\sqrt{3}}\angle -30\degree)(-10\angle 0) = 0 \]

\[ (10 + \frac{10}{\sqrt{3}}\angle 60\degree) = V_a'(10\angle 0 - 3\angle 0 + 10\angle 0) \]

\[ V_a' = 0.9 \angle -10.9\degree \text{ volts} \quad V_b' = 0.9 \angle -130.9\degree \text{ volts} \]

\[ V_c' = 0.9 \angle 109.1\degree \text{ volts} \quad V_{ab}' = 1.56 \angle 19.1\degree \text{ volts} \]

\[ S_{\text{gen}} = 3V_a I_a^* = V_a \left( \frac{V_a - V_a'}{j0.1} \right)^* = 5.1 + j3.5 \text{ VA} \]

\[ S_{\Delta \text{gen}} = 3V''_a \left( \frac{V''_a - V_a}{j0.1} \right)^* = -5.1 - j4.7 \text{ VA} \]
EXAMPLE: POWER FACTOR CORRECTION IN THREE-PHASE CIRCUIT.

\[ P_m = \sqrt{3} \times 4 \times 0.462 \times \cos(25.8^\circ) = 2.88 \text{ MW} \]

\[ Q_m = \sqrt{3} \times 4 \times 0.462 \times \sin(25.8^\circ) = 1.39 \text{ MVAR} \]

\[ Q_c = 1.8 \text{ MVAR} \]

\[ Q_L = Q_m - Q_c = -0.41 \text{ MVAR} \]
THE PER-UNIT SYSTEM

The voltages, currents, powers, impedances, and other electrical quantities are measured as fractions of some base level instead of conventional units.

\[
\text{Quantity per unit} = \frac{\text{actual value}}{\text{base value of quantity}}
\]

Usually, two base quantities are selected to define a given per-unit system. Often, such quantities are voltage and apparent power. In a single-phase circuit, once the base values of \( S \) and \( V \) are selected, all other base values can be computed from:

\[
\begin{align*}
P_{\text{base}}, Q_{\text{base}}, \text{ or } S_{\text{base}} &= V_{\text{base}} I_{\text{base}} \\
Y_{\text{base}} &= \frac{I_{\text{base}}}{V_{\text{base}}} \\
Z_{\text{base}} &= \frac{V_{\text{base}}}{I_{\text{base}}} = \frac{(V_{\text{base}})}{S_{\text{base}}}
\end{align*}
\]
In a 3-phase circuit, given the base apparent power (3—phase) and base voltage (line-to-line), the base current and base impedance are given by

\[
I_{\text{base}} = \frac{S_{3\phi,\text{base}}}{\sqrt{3}V_{LL,\text{base}}}
\]

\[
Z_{\text{base}} = \frac{V_{LL,\text{base}}}{\sqrt{3}I_{\text{base}}} = \left(\frac{V_{LL,\text{base}}}{S_{3\phi,\text{base}}}\right)^2
\]
The per-unit impedance may be transformed from one base to another as

\[
Per-unit \ Z_{new} = per-unit \ Z_{old} \left( \frac{V_{old}}{V_{new}} \right)^2 \left( \frac{S_{new}}{S_{old}} \right)
\]
Machine ratings, impedances, consumed and/or supplied powers are usually included in the diagrams.
EXAMPLE OF CONVERSION OF ONE-LINE DIAGRAM TO IMPEDANCE DIAGRAM
The most common technique used to solve circuit problems is nodal analysis. To simplify the equations,

- Replace the generators by their Norton equivalent circuits
- Replace the impedances by their equivalent admittances
- Represent the loads by the current they draw (for now)
KCL is used to establish and solve a system of simultaneous equations with the unknown node voltages:

\[
\begin{align*}
(V_1 - V_2)Y_a + (V_1 - V_3)Y_b + V_1Y_d &= I_1 \\
(V_2 - V_1)Y_a + (V_2 - V_3)Y_c + V_2Y_e &= I_2 \\
(V_3 - V_1)Y_b + (V_3 - V_2)Y_c + V_3Y_f &= I_3
\end{align*}
\]
NODE EQUATIONS – THE $Y_{bus}$ MATRIX

In matrix form,

$$
\begin{bmatrix}
Y_a + Y_b + Y_d & -Y_a & -Y_b \\
-Y_a & Y_a + Y_c + Y_e & -Y_c \\
-Y_b & -Y_c & Y_b + Y_c + Y_f
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3
\end{bmatrix}
= 
\begin{bmatrix}
I_1 \\
I_2 \\
I_3
\end{bmatrix}
$$

Which is an equation of the form:

$$Y_{bus}V = I$$

where $Y_{bus}$ is the bus admittance matrix of a system, which has the form:

$$Y_{bus} = \begin{bmatrix}
Y_{11} & Y_{12} & Y_{13} \\
Y_{21} & Y_{22} & Y_{23} \\
Y_{31} & Y_{32} & Y_{33}
\end{bmatrix}$$

$Y_{bus}$ has a regular form that is easy to calculate:

1) The diagonal elements $Y_{ii}$ equal the sum of all admittances connected to node $i$.
2) Other elements $Y_{ij}$ equal to the negative admittances connected to nodes $i$ and $j$.

The diagonal elements of $Y_{bus}$ are called the self-admittance or driving-point admittances of the nodes; the off-diagonal elements are called the mutual admittances or transfer admittances of the nodes.
Inverting the bus admittance matrix $Y_{bus}$ yields the bus impedance matrix $Z_{bus}$:

$$Z_{bus} = Y_{bus}^{-1}$$

Then,

$$V = Y_{bus}^{-1} I$$

or

$$V = Z_{bus} I$$
EXAMPLE
The resulting admittance matrix is:

\[
Y_{bus} = \begin{bmatrix}
-j12.576 & j5.0 & 0 & j6.667 \\
 j5.0 & -j12.5 & j5.0 & j2.5 \\
 0 & j5.0 & -10.625 & j5.0 \\
 j6.667 & j2.5 & j5.0 & -j14.167
\end{bmatrix}
\]

The current vector for this circuit is:

\[
I = \begin{bmatrix}
1.0 \angle -80^\circ \\
0 \\
0.563 \angle -112^\circ \\
0
\end{bmatrix}
\]

The solution to the system of equations will be

\[
V = Y_{bus}^{-1}I = \begin{bmatrix}
0.989 \angle -0.60^\circ \\
0.981 \angle -1.58^\circ \\
0.974 \angle -2.62^\circ \\
0.982 \angle -1.48^\circ
\end{bmatrix}
\]
BASIC POWER SYSTEM LAYOUT

Color Key:
Black: Generation
Blue: Transmission
Green: Distribution

Generating Station
Generating Step Up Transformer
Transmission Customer 138kV or 230kV
Transmission lines 765, 500, 345, 230, and 138 kV
Substation Step Down Transformer

Conventional
primary energy source

Subtransmission Customer 26kV and 69kV
Primary Customer 13kV and 4kV
Secondary Customer 120V and 240V
US ELECTRICITY GENERATION BY FUEL

Source: U.S. Energy Information Administration

Major energy sources and percent share of total U.S. electricity generation in 2014:

- Coal = 39%
- Natural gas = 27%
- Nuclear = 19%
- Hydropower = 6%
- Other renewables = 7%
  - Biomass = 1.7%
  - Geothermal = 0.4%
  - Solar = 0.4%
  - Wind = 4.4%
- Petroleum = 1%
- Other gases < 1%

For latest trend, see http://newsletters.pennnet.com/powerengineeringenl/365650871.html
COAL FIRED POWER PLANTS:
NUMBER OF GENERATORS ≈ 1,450
TOTAL CAPACITY ≈ 350 GW

(Source: http://www.npr.org)
NUCLEAR POWER PLANTS:
NUMBER OF GENERATORS ≈ 100
TOTAL CAPACITY ≈ 100 GW
Steam turbines can have non-reheat, single-reheat or double-reheat.

The steam flow is controlled by the governor. The main amplifier of the governing system and valve mover is an oil servomotor that is controlled by a pilot valve.

Main and reheat stop valves are normally fully open - they are used only during generator start-up and shut down.
**THE ELECTRIC GENERATOR**

**Governor** controls turbine torque and power

**Exciter** controls voltage and reactive power
NATURAL GAS POWER PLANTS:
NUMBER OF GENERATORS ≈ 5,500
TOTAL CAPACITY ≈ 450 GW
Air-breathing jet engines are gas turbines optimized to produce thrust from the exhaust gases. In our case, the system is optimized to produce maximum shaft power.
COMBINED CYCLE POWER PLANT: TYPICAL EFFICIENCY: 60-65%

Efficiencies are even higher when the steam is used for district heating or industrial processes.
HYDRO POWER PLANTS:
NUMBER OF GENERATORS ≈ 4,000
TOTAL CAPACITY ≈ 80 GW
ELECTRICITY PRODUCTION FROM RENEWABLES

- Solar Derived Energy
- Wind
- Ocean ΔT
- Power Plant
- Clean Renewable Fuels
- Thermal Collector
- Solar Cells
- Direct Conversion
ELECTRICITY PRODUCTION FROM RENEWABLES: PHOTOVOLTAICS
GROWTH IN SOLAR PHOTOVOLTAIC

Top 10 PV-Countries of Year 2014 in (MW)

<table>
<thead>
<tr>
<th>Total Capacity</th>
<th>Added Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Germany</td>
<td>1. China</td>
</tr>
<tr>
<td>2. China</td>
<td>2. Japan</td>
</tr>
<tr>
<td>3. Japan</td>
<td>3. United States</td>
</tr>
<tr>
<td>4. Italy</td>
<td>4. UK</td>
</tr>
<tr>
<td>5. United States</td>
<td>5. Germany</td>
</tr>
<tr>
<td>6. France</td>
<td>6. France</td>
</tr>
<tr>
<td>7. Spain</td>
<td>7. Australia</td>
</tr>
<tr>
<td>8. UK</td>
<td>8. South Korea</td>
</tr>
<tr>
<td>10. Belgium</td>
<td>10. India</td>
</tr>
</tbody>
</table>

Cumulative Capacity in Megawatts [MWp] Grouped by Region

ELECTRICITY PRODUCTION FROM RENEWABLES: CONCENTRATING SOLAR POWER

Solar Derived Energy

OCEAN ΔT

CLEAN RENEWABLE FUELS

THERMAL COLLECTOR

WIND

POWER PLANT

ELECTRICITY

SOLAR CELLS

Direct Conversion

Indirect Conversion

Direct Solar Radiation

Direct Conversion
CONCENTRATING SOLAR POWER

- CSP technologies use mirrors to reflect and concentrate sunlight onto receivers that collect the solar energy and convert it into heat.
- This thermal energy can then be used to produce electricity via a steam turbine or heat engine driving a generator.
POWER TOWER CSP

[Diagram showing components of a power tower CSP system]

[Image of a power tower CSP plant in a desert setting]

[Close-up image of heliostats]
ELECTRICITY PRODUCTION FROM RENEWABLES: BIOMASS
BIOMASS ENERGY SOURCES

Types of Biomass

Wood
Crops
Garbage
Landfill Gas
Alcohol Fuels

Landfill Energy near Las Vegas, NV (12 MW)
ELECTRICITY PRODUCTION FROM RENEWABLES: OCEAN POWER
CAPTURING OCEAN POWER

- Attenuator
- Point Absorber
- Tidal Power
- Oscillating Water Column
- Ocean Current
ELECTRICITY PRODUCTION FROM RENEWABLES: WIND
WIND POWER
Denmark has broken another record of wind energy in 2015, having generated an astonishing 42% of its power from windmills, the highest share ever produced by any country.

Source: http://www.energymarketprice.com/

### Top 10 windpower countries of 2014

<table>
<thead>
<tr>
<th>Country</th>
<th>Capacity (MW)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>114,763</td>
<td>31.0</td>
</tr>
<tr>
<td>United States</td>
<td>65,879</td>
<td>17.8</td>
</tr>
<tr>
<td>Germany</td>
<td>39,165</td>
<td>10.6</td>
</tr>
<tr>
<td>Spain</td>
<td>22,987</td>
<td>6.2</td>
</tr>
<tr>
<td>India</td>
<td>22,465</td>
<td>6.1</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>12,440</td>
<td>3.4</td>
</tr>
<tr>
<td>Canada</td>
<td>9,694</td>
<td>2.6</td>
</tr>
<tr>
<td>France</td>
<td>9,285</td>
<td>2.5</td>
</tr>
<tr>
<td>Italy</td>
<td>8,663</td>
<td>2.3</td>
</tr>
<tr>
<td>Brazil</td>
<td>5,939</td>
<td>1.6</td>
</tr>
<tr>
<td>(rest of world)</td>
<td>58,275</td>
<td>15.8</td>
</tr>
<tr>
<td><strong>World total</strong></td>
<td><strong>369,553</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
ELECTRICITY PRODUCTION FROM RENEWABLES: GEOTHERMAL
Dry steam plants use steam piped directly from a geothermal reservoir to turn the generator turbines. The first geothermal power plant was built in 1904 in Tuscany, Italy.

Flash steam plants take high-pressure hot water from deep inside the Earth and convert it to steam to drive the generator turbines. When the steam cools, it condenses to water and is injected back into the ground to be used over and over again.
Geothermal Resource of the United States
Locations of Identified Hydrothermal Sites and Favorability of Deep Enhanced Geothermal Systems (EGS)

- Map does not include shallow EGS resources located near hydrothermal sites or USGS assessment of undiscovered hydrothermal resources.
- Source data for deep EGS includes temperature at depth from 3 to 10 km provided by Southern Methodist University Geothermal Laboratory (Blackwell & Richards, 2009) and analyses for regions with temperatures ≥150°C performed by NREL (2009).
- Source data for identified hydrothermal sites from USGS Assessment of Moderate- and High-Temperature Geothermal Resources of the United States (2008).
- "N/A" regions have temperatures less than 150°C at 10 km depth and were not assessed for deep EGS potential.
- "Temperature at depth data for deep EGS in Alaska and Hawaii not available.

Favorability of Deep EGS
- Most Favorable
- Least Favorable
- N/A*
- No Data**
- Identified Hydrothermal Site (≥ 90°C)

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy, October 13, 2009. Author: Billy J. Roberts

www.nrel.gov/gis
BASIC CONVENTIONAL POWER SYSTEM LAYOUT

Color Key:
Black: Generation
Blue: Transmission
Green: Distribution

Generating Station
Generating Step Up Transformer
Transmission Customer 138kV or 230kV
Transmission lines 765, 500, 345, 230, and 138 kV
Substation Step Down Transformer
Secondary Customer 120V and 240V
Primary Customer 13kV and 4kV
Subtransmission Customer 26kV and 69kV
STEP-UP (STATION) TRANSFORMERS:

Size to 1000 MVA
Generator voltage up to 25 kV
Transmission voltage up to 765 kV
Forced Air and Forced Oil Cooling.
BASIC CONVENTIONAL POWER SYSTEM LAYOUT

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Subtransmission Customer 26kV and 69kV
Primary Customer 13kV and 4kV
Secondary Customer 120V and 240V
HIGH VOLTAGE POWER LINES (OVERHEAD)

Common voltages in north America: 138, 230, 345, 500, 765 kV
Bundled conductors are used in extra-high voltage lines
Stranded instead of solid conductors are used.
HIGH VOLTAGE POWER CABLES (UNDERGROUND)

Cable lines are designed to be placed underground in urban areas or under water. The conductors are insulated from one another and surrounded by protective sheath.

Cable lines are more expensive and harder to maintain. They also have a large capacitance – not suitable for long distance.
LONG LINE SERIES AND SHUNT COMPENSATION

Shunt reactors are used to compensate the line shunt capacitance under light load or no load.

Series capacitors are often used to compensate the line inductive reactance in order to transfer more power.
BASIC CONVENTIONAL POWER SYSTEM LAYOUT

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Secondary Customer 120V and 240V
Primary Customer 13kV and 4kV
Subtransmission Customer 26kV and 69kV
SUBSTATION TRANSFORMERS

Typical size: 20 MVA
Primary voltage: 69 kV or 138 kV
Typical Secondary voltage: 12.47 kV or 13.2 kV
ELECTRICAL POWER UTILIZATION (ELECTRIC LOAD)

Utilization voltage: 120V, 208V*, 240V, 277V, 480V*, 600V*

2/3 –3/4 of electricity is consumed by motors
Changes in demand of individual customers is fast and frequent due to load switching.
The aggregated demand at the substation is smoother, and total load fluctuations are usually small.
MW AND MVAR LOADING ON A FEEDER – 4 MONTHS
The aggregated demand on the system is even smoother, and total load fluctuations are very small.

The overall daily profile of load can be predicted reasonably well using forecasting tools.
SEASONAL LOAD PATTERNS

The local load is dominated by winter and summer patterns, with May and October as shoulder months.
The power system of North America is divided into four major Interconnections which can be thought of as independent islands.

- **Western** – Generally everything west of the Rockies.
- **Texas** - Also known as Electric Reliability Council of Texas (ERCOT).
- **Eastern** – Generally everything east of the Rockies except Texas and Quebec.
- **Quebec**.
As electricity itself cannot presently be stored on a large scale, changes in customer demand are met by controlling conventional generation, using stored fuels.

Frequency is maintained as long as there is a balance between resources and customer demand (plus losses). An imbalance causes a frequency deviation.
Important Studies:
- Economic generation scheduling and unit commitment
- Power flow analysis
- Short-circuit analysis
- System stability and dynamic analysis
- Load forecasting
- System planning
- Etc ...