First Course on

POWER SYSTEMS

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A 345-kV Example System
## TOPICS IN POWER SYSTEMS

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\[ R_{\text{base}}, X_{\text{base}}, Z_{\text{base}} = \frac{V_{\text{base}}}{I_{\text{base}}} \quad \text{(in } \Omega) \quad (2-48) \]

\[ G_{\text{base}}, B_{\text{base}}, Y_{\text{base}} = \frac{I_{\text{base}}}{V_{\text{base}}} \quad \text{(in } \Omega) \quad (2-49) \]

\[ P_{\text{base}}, Q_{\text{base}}, (VA)_{\text{base}} = V_{\text{base}}I_{\text{base}} \quad \text{(in Watt, VAR, or VA)} \quad (2-50) \]

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

\[ \text{Per-Unit Value} = \frac{\text{actual value}}{\text{base value}} \quad (2-51) \]
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\[ \eta = \frac{P_o}{P_{in}} \]

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Visit the following website for Power Plant Animations:
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PWR: http://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html
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<table>
<thead>
<tr>
<th>Nominal Voltage</th>
<th>$R (Ω/ km)$</th>
<th>$ωL (Ω/ km)$</th>
<th>$ωC (μF/ km)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>230 kV</td>
<td>0.055</td>
<td>0.489</td>
<td>3.373</td>
</tr>
<tr>
<td>345 kV</td>
<td>0.037</td>
<td>0.376</td>
<td>4.518</td>
</tr>
<tr>
<td>500 kV</td>
<td>0.029</td>
<td>0.326</td>
<td>5.220</td>
</tr>
<tr>
<td>765 kV</td>
<td>0.013</td>
<td>0.339</td>
<td>4.988</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Nominal Voltage</th>
<th>$Z_c (\Omega)$</th>
<th>SIL (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230 kV</td>
<td>375</td>
<td>140 MW</td>
</tr>
<tr>
<td>345 kV</td>
<td>280</td>
<td>425 MW</td>
</tr>
<tr>
<td>500 kV</td>
<td>250</td>
<td>1000 MW</td>
</tr>
<tr>
<td>765 kV</td>
<td>255</td>
<td>2300 MW</td>
</tr>
</tbody>
</table>
## Loadability of Transmission Lines

### Table 4-3
Loadability of Transmission Lines [6]

<table>
<thead>
<tr>
<th>Line Length (km)</th>
<th>Limiting Factor</th>
<th>Multiple of SIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 80</td>
<td>Thermal</td>
<td>&gt; 3</td>
</tr>
<tr>
<td>80 - 240</td>
<td>5% Voltage Drop</td>
<td>1.5 - 3</td>
</tr>
<tr>
<td>240 - 480</td>
<td>Stability</td>
<td>1.0 – 1.5</td>
</tr>
</tbody>
</table>
Long-Line Representation

\[ I_S(s) \quad + \quad Z_{series} \quad - \quad I_R(s) \]

\[ V_S(s) \quad \frac{Y_{shunt}}{2} \quad \frac{Y_{shunt}}{2} \quad V_R(s) \]

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<table>
<thead>
<tr>
<th>Line</th>
<th>Series Impedance $Z$ in Ω (pu)</th>
<th>Total Susceptance $B$ in μ＜sup＞Ω＜/sup＞ (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>$Z_{12} = (5.55 + j56.4)Ω = (0.0047 + j0.0474)pu$</td>
<td>$B_{Total} = 675μ\Omega = (0.8034)pu$</td>
</tr>
<tr>
<td>1-3</td>
<td>$Z_{13} = (7.40 + j75.2)Ω = (0.0062 + j0.0632)pu$</td>
<td>$B_{Total} = 900μ\Omega = (1.0712)pu$</td>
</tr>
<tr>
<td>2-3</td>
<td>$Z_{23} = (5.55 + j56.4)Ω = (0.0047 + j0.0474)pu$</td>
<td>$B_{Total} = 675μ\Omega = (0.8034)pu$</td>
</tr>
</tbody>
</table>
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(a)

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Symbols and Capabilities of Power Semiconductor Devices

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Table 8-1 Power Factor and Voltage Sensitivity of Power Systems Load

<table>
<thead>
<tr>
<th>Type of Load</th>
<th>Power Factor</th>
<th>$a = \partial P / \partial V$</th>
<th>$b = \partial Q / \partial V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Heating</td>
<td>1.0</td>
<td>2.0</td>
<td>0</td>
</tr>
<tr>
<td>Incandescent Lighting</td>
<td>1.0</td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td>Fluorescent Lighting</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Motor Loads</td>
<td>0.8 – 0.9</td>
<td>0.05 – 0.5</td>
<td>1.0 – 3.0</td>
</tr>
<tr>
<td>Modern Power-Electronics based</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Loads</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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Table 8-1 Harmonic current distortion \((I_h / I_1)\)

<table>
<thead>
<tr>
<th>(I_{sc} / I_1)</th>
<th>(h &lt; 11)</th>
<th>(11 \leq h &lt; 17)</th>
<th>(17 \leq h &lt; 23)</th>
<th>(23 \leq h &lt; 35)</th>
<th>(35 \leq h)</th>
<th>Total Harmonic Distortion(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 20</td>
<td>4.0</td>
<td>2.0</td>
<td>1.5</td>
<td>0.6</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>20 – 50</td>
<td>7.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>50 – 100</td>
<td>10.0</td>
<td>4.5</td>
<td>4.0</td>
<td>1.5</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>100 – 1000</td>
<td>12.0</td>
<td>5.5</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>15.0</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>15.0</td>
<td>7.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>20.0</td>
</tr>
</tbody>
</table>
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\[ \alpha \leq 90^\circ \]

\[ \alpha > 90^\circ \]

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\[ V_{bus} \]

\[ I_L \]

\[ 0 \]

\[ V_{bus} \]
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Fig. 12-2 (a) The Interconnections in North America, (b) Control Areas [Source: 2]
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Load Sharing

Fig. 12-4 Response of two generators to load-frequency control.

(a) Load Sharing

(b) Graph showing the response of the two generators to load-frequency control.
Synchronizing Torque between Two Control Areas

Fig. 12-5 Two control areas.
Automatic Generation Control (AGC) and Area Control Error (ACE)

Fig. 12-6 Area Control Error (ACE) for Automatic Generation Control (AGC).
Fig. 12-7 Two control areas in the example power system with 3 buses.
Power Flow on Tie-Lines between Two Control Areas Following a Load Change
Electrical Equivalent of Two Areas

Fig. 12-9 Electrical equivalent of two area interconnection.
Modeling of Two Control Areas with AGC

Fig. 12-10 Two-area system with AGC. Source: adapted from [6].
Results of Simulink Modeling Following a Step Load Change in Control Area 1

Fig. 12-11 Simulink results of the two-area system with AGC in Example 12-3.
Economic Dispatch: Heat Rate of a Power Plant

Fig. 12-12 Heat Rate at various generated power levels.

At this point, to produce 40 MW
Fuel Consumption = 400 MBTU-per-Hour
Cost Curve and Marginal Cost of a Power Plant

Fig. 12-13 (a) Fuel cost and (b) Marginal cost, as functions of the power output.
Fig. 12-14 Marginal costs for the three generators.
CHAPTER 13

TRANSMISSION LINE FAULTS, RELAYING AND CIRCUIT BREAKERS
Fault (Symmetric or Unsymmetric) on a Balanced Network

Fig. 13-1 Fault in power system.
Symmetrical Components

Fig. 13-2 Sequence components.
Sequence Networks: Per-Phase Representation of a Balanced Three-phase representation

Fig. 13-3 Sequence networks.
Three-Phase Symmetrical Fault (ground may or may no be involved)

Fig. 13-4 Three-phase symmetrical fault.
Single-Line to Ground (SLF) Fault through a Fault Impedance

Fig. 13-5 Single line to ground fault.
Double-Line to Ground Fault

Fig. 13-6 Double line to ground fault.
Fig. 13-7 Double line fault (ground not involved).
Path for Zero-Sequence Currents

(a)  (b)  (c)

Fig. 13-8 Path for zero-sequence currents in transformers.
Neutral Grounded through an Neutral Impedance

Fig. 13-9 Neutral grounded through an impedance.
One-Line Diagram of a Simple System

Fig. 13-10 (a) One-line diagram of a simple power system and bus voltages.
Thee-phase Fault on Bus-2 in the Simple System

Fig. 13-11 Positive-sequence circuit for calculating a 3-phase fault on bus-2.

\[ E' \]

\[ V_1 = 1.0 \angle 0 \text{ pu} \]

\[ R_{load} = 0.9604 \text{ pu} \]
Single-Line to Ground (SLG) Fault in the Simple System

Fig. 13-12 Sequence networks for calculating fault current due to SLG fault on bus-2.
An SLG Fault in the Example 3-Bus System

Fig. 13-13 A SLG fault in the example 3-bus power system.
Protection in Power System

Fig. 13-14 Protection equipment.
Current Transformers (CT)

Fig. 13-15 Current Transformer (CT) [5].
Capacitor-Coupled Voltage Transformers (CCVT)

Fig. 13-16 Capacitor-Coupled Voltage Transformer (CCVT) [5].
Differential Relays

Fig. 13-17 Differential relay.
Directional Over-Current Relays

Fig. 13-18 Directional over-current Relay.
Ground Directional Over-Current Relays for Ground Faults

Fig. 13-19 Ground directional over-current Relay.
Fig. 13-20 Impedance (distance) relay.
Microwave Terminal for Pilot Relays

Fig. 13-21 Microwave terminal [5].
Zones of Protection

Fig. 13-22 Zones of protection.
Protection of Generator and its Step-up Transformer

Fig. 13-23 Protection of generator and the step-up transformer.
Fig. 13-24 Relaying in the example 3-bus power system.
Fig. 13-25 $SF_6$ circuit breaker [5].
Illustration of Current Offset in R-L Circuits

Fig. 13-26 Current in an RL circuit.
CHAPTER 14

TRANSIENT OVER-VOLTAGES, SURGE PROTECTION AND INSULATION COORDINATION
Fig. 14-1 Lightening current impulse.
Lightening Strike to Shield Wire and Backflash

Fig. 14-2 Lightening strike to the shield wire.
**Switching Surges**

Fig. 14-3 Over-voltages due to switching of transmission lines.
Fig. 14-4 Frequency dependence of the transmission line parameters [Source: 2].
Calculation of Switching Over-Voltages on Line 1-3 in the Example 3-Bus Power System

Fig. 14-5 Calculation of switching over-voltages on a transmission line.
Standard Voltage Impulse to Define Basic Insulation Level (BIL)

Fig. 14-6 Standard Voltage Impulse Wave to define BIL.
Fig. 14-7 A 345-kV transformer voltage insulation levels.