HV Substation Design: Applications and Considerations

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Agenda

- Substation Basics
- Electrical Configuration
- Physical Design
- Protection and Controls
- Design and Construction Coordination
Electrical System

- **Substation** - A set of equipment reducing the high voltage of electrical power transmission to that suitable for supply to consumers.

- **Switching Station** - A set of equipment used to tie together two or more electric circuits.
### TRANSMISSION LEVEL VOLTAGES

- 765 kV
- 500 kV
- 345 kV
- 230 kV
- 161 kV
- 138 kV
- 115 kV

### DISTRIBUTION LEVEL VOLTAGES

- 69 kV
- 46 kV
- 34.5 kV
- 23 kV
- 15 kV
- 4.16 kV
- 480 V
Typical 138 kV Substation – Four (4) Breaker Ring Bus w/ Oil Circuit Breakers
Typical 138 kV Substation
Typical 138 kV Substation
230 kV Generating Substation – Built on the side of a mountain
230 kV Indoor Generating Substation
765 kV Generating Substation – Four (4) Breaker Ring Bus w/ Live Tank GCBs
765 kV Generating Substation
765 kV Generating Substation
765 kV Generating Substation
Relative Size of HV Power Transformers
Relative Size of HV and EHV Power Transformers
Relative Size of HV and EHV Gas Circuit Breakers
Dimensions for 765 kV Installation
Where Do I Start My Design?
Electrical Questions to Address

• Service Conditions?
  ◦ Location, Altitude
  ◦ High and Low Mean Temperatures
  ◦ Temperature Extremes
  ◦ Wind Loading and Ice Loading
  ◦ Seismic Qualifications
  ◦ Area Classification
  ◦ Contamination
• Primary System Characteristics?
  ◦ Local Utility
  ◦ Nominal Voltage
  ◦ Maximum Operating Voltage
  ◦ System Frequency
  ◦ System Grounding
  ◦ System Impedance Data

Electrical Questions to Address
• Secondary System Characteristics?
  ◦ Nominal Voltage
  ◦ Maximum Operating Voltage
  ◦ System Grounding

Electrical Questions to Address
Facility Load/Generation Characteristics?
  - Load Type
  - Average Running Load
  - Maximum Running Load
  - On-Site Generation
  - Future Load Growth
  - Harmonic Loads

Electrical Questions to Address
Equipment Ratings

• Insulation Requirements
  ◦ BIL
  ◦ Insulator and Bushing Creep
  ◦ Minimum Clearances
  ◦ Phase Spacing
  ◦ Arrester Duty

• Current Requirements
  ◦ Rated Continuous Current
  ◦ Maximum 3-Phase Short-Circuit Current
  ◦ Maximum Phase-to-Ground Short-Circuit Current
• Contamination Levels

<table>
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<td>220</td>
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<td>500</td>
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<td>318</td>
<td>398</td>
<td>500</td>
<td>614</td>
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<tr>
<td>765</td>
<td>800.0</td>
<td>2050</td>
<td></td>
<td>487</td>
<td>609</td>
<td>765</td>
<td>939</td>
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Notes:
[1] Creepage distances shown in Table 1 are recommended values, based on IEEE standards C57.19.100-1995 & C37.010-1999.

Table 2 shows the multiplying factor for each level of contamination. The multiplying factors are applied to nominal line to ground voltage.

Physical Questions to Address
Physical Questions to Address
Electrical Studies

- Power/Load Flow
- Short-Circuit / Device Evaluation
- Device Coordination
- Arc-Flash Hazard Assessment
- Motor Starting, Transient Stability
- Insulation Coordination
- Harmonic Analysis
• Substation Layout Considerations?
  ◦ Available Real Estate
  ◦ Substation Configuration
  ◦ Necessary Degree of Reliability and Redundancy
  ◦ Number of Incoming Lines
  ◦ Proximity to Transmission Lines and Loads

Physical Questions to Address
• Utility Requirements?
  ◦ Application of Utility Specifications
  ◦ Application of Utility Standards
  ◦ Application of Utility Protection and Control Schemes
  ◦ SCADA/RTU Interface
  ◦ Metering Requirements

• Communication/Monitoring Requirements
  ◦ Manned or Unmanned
  ◦ Power Management/Trending
  ◦ Fault Recording
  ◦ Local & Remote Annunciation
  ◦ Local & Remote Control
  ◦ Automation
  ◦ Communication Protocol

Other Questions to Address
• Other Studies / Field Tests
  • Soil Boring Results – Foundation Design
  • Soil Resistivity – Ground Grid Design
  • Spill Prevention, Control, and Countermeasure (SPCC) Plans - Contamination
  • Stormwater Pollution Prevention Plan (SWPPP) - Runoff During Construction
  • Stormwater Management – Detention Pond Requirements

Other Questions to Address
Major Factors in Substation Selection

- Budgeted Capital for Substation
- Required Power (1 MVA, 10 MVA, 100 MVA)
- Effect of Power Loss on Process and/or Safety
- Associated Outage Cost (Lost Revenue)
- Future Growth Considerations
- Reliability Study
  - Estimate Cost of Alternate Designs
  - Determine Lost Revenue During Outages
  - Calculate Probability of Outage Based on Design
  - Compare Cost, Lost Revenues, and Outage Probabilities
Electrical Configuration
- **Single Breaker Arrangements**
  - Tap Substation
  - Single Breaker Single Bus
  - Operating/Transfer Bus
- **Multiple Breaker Arrangements**
  - Ring Bus
  - Breaker and a Half
  - Double Breaker Double Bus
<table>
<thead>
<tr>
<th>Configuration</th>
<th>Relative Cost Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Breaker-Single Bus</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>120% (with sect. breaker)</td>
</tr>
<tr>
<td>Main-Transfer Bus</td>
<td>140%</td>
</tr>
<tr>
<td>Ring Bus</td>
<td>125%</td>
</tr>
<tr>
<td>Breaker and Half</td>
<td>145%</td>
</tr>
<tr>
<td>Double Breaker-Double Bus</td>
<td>190%</td>
</tr>
</tbody>
</table>

Reference: IEEE 605-2008

It should be noted that these figures are estimated for discussion purposes. Actual costs vary depending on a number of variables, including:

- Real Estate Costs
- Complexity of Protective Relaying Schemes
- Raw material costs
- Local Labor Costs
\( \lambda = \) Annual Fail Rate

\( r = \) Annual Outage Time

\( U = \) Average Outage Time

Table 3: Substation Reliability Indices (Ignoring Line Failure)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( \lambda ) (/yr)</th>
<th>( r ) (min)</th>
<th>( U ) (min/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.0489</td>
<td>72.15</td>
<td>3.53</td>
</tr>
<tr>
<td>b</td>
<td>0.0453</td>
<td>71.95</td>
<td>3.26</td>
</tr>
<tr>
<td>c</td>
<td>0.00301</td>
<td>184.56</td>
<td>0.56</td>
</tr>
<tr>
<td>d</td>
<td>0.00567</td>
<td>124.216</td>
<td>0.70</td>
</tr>
<tr>
<td>e</td>
<td>0.0174</td>
<td>81.88</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Table 4: Substation Reliability Indices (Including Line Failures)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( \lambda ) (/yr)</th>
<th>( r ) (min)</th>
<th>( U ) (min/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.0549</td>
<td>80.50</td>
<td>4.42</td>
</tr>
<tr>
<td>b</td>
<td>0.0459</td>
<td>76.35</td>
<td>3.50</td>
</tr>
<tr>
<td>c</td>
<td>0.00356</td>
<td>175.76</td>
<td>0.63</td>
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<tr>
<td>d</td>
<td>0.00572</td>
<td>125.14</td>
<td>0.72</td>
</tr>
<tr>
<td>e</td>
<td>0.0235</td>
<td>92.20</td>
<td>2.17</td>
</tr>
</tbody>
</table>

Reference: “Reliability of Substation Configurations”, Daniel Nack, Iowa State University, 2005
Reliability Models

- IEEE Gold Book
- For high voltage equipment data is a “generic” small sample set
- Sample set collected in minimal certain conditions (i.e. what really caused the outage)
- Calculated indices may not represent reality...

A great reference is John Propst’s 2000 PCIC Paper "IMPROVEMENTS IN MODELING AND EVALUATION OF ELECTRICAL POWER SYSTEM RELIABILITY"
• Most Basic Design
• Tapped Line is Source of Power
• Interrupting Device Optional but Recommended
• No Operating Flexibility

Depending on utility voltage, this device could be a fuse, circuit switcher, or circuit breaker
• Most Basic Design
• Tapped Line is Source of Power
• Interrupting Device Optional but Recommended
• No Operating Flexibility
Tap Substation

**Pros**
- Small Plot Size
- Low Initial Cost
- Low Maintenance Costs

**Cons**
- Line Operations Result in Plant Outages
- Multiple Single Points of Failure
- Failure Points are in Series
- Outages Expected
- Line Faults Cleared by Others
- Low Maintainability
Single Breaker Single Bus Substation

- Basic Design
- One Circuit Breaker per Circuit
- One Common Bus
- No Operating Flexibility
- Widely Used at Distribution Level
- Limited Use at High Voltage
## Single Breaker Single Bus

**Pros**
- Each Circuit has Breaker
- Only One Set of VTs Required
- Simple Design

**Cons**
- Circuit Breaker Maintenance Requires Circuit Outage
- Bus Fault Clears all Circuits
- Breaker Failure Clears all Circuits
- Single Points of Failure Between Circuits are in Series
- Expansion requires complete station outage
Single Breaker Single Bus

Line Fault

Bus Fault

Failed Breaker
Operating/Transfer Buses with Single Breaker

- Similar to Single Breaker Single Bus
- Add Transfer Bus
- Transfer Bus Switches Normally Open
- Only 1 Circuit Operated From Transfer Bus
- Widely Used in Outdoor Distribution Applications
### Operating/Transfer Buses with Single Breaker

<table>
<thead>
<tr>
<th><strong>Pros</strong></th>
<th><strong>Cons</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Breaker Maintenance w/o</td>
<td>• More Costly with Addition of</td>
</tr>
<tr>
<td>Circuit Interruption</td>
<td>Transfer Bus</td>
</tr>
<tr>
<td>• Only One Set of VTs Required</td>
<td>• Adaptable Protection is Necessary</td>
</tr>
<tr>
<td></td>
<td>• If Not Adaptable, Protection Compromise During Maintenance</td>
</tr>
<tr>
<td></td>
<td>• Normal Operation Is Single Breaker Single Bus</td>
</tr>
</tbody>
</table>
Ring Bus

- Popular at High Voltage
- Circuits and Breakers Alternate in Position
- No Buses per se
Pros

- High Flexibility with Minimum of Breakers
- Dedicated Bus Protection not Required
- Highly Adaptable
- Failed Circuit Does Not Disrupt Other Circuits
- Breaker Maintenance w/o Circuit Interruption

Cons

- Failed Breaker May Result in Loss of Multiple Circuits
- Physically Large With 6 or More Circuits

Ring Bus
Ring Bus

Line/Bus Fault

Failed Breaker
Breaker-And-A-Half

- More Operating Flexibility than Ring Bus
- Requires 3 Breakers for Every Two Circuits
- Widely Used at High Voltage, Especially Where Multiple Circuits Exist (e.g. Generating Plants)
<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
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<tbody>
<tr>
<td>Robust</td>
<td>Cost</td>
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<tr>
<td>Highly Expandable</td>
<td>Physically Large</td>
</tr>
<tr>
<td>Failed Outer Breakers</td>
<td>Failed Center Breaker</td>
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<tr>
<td>Result in Loss of One Circuit Only</td>
<td>Results in Loss of Two Circuits</td>
</tr>
<tr>
<td>Breaker Maintenance</td>
<td></td>
</tr>
<tr>
<td>w/o Circuit Interruption</td>
<td></td>
</tr>
</tbody>
</table>

**Breaker-And-A-Half**
Double Breaker Double Bus

- Highly Flexible Arrangement
- Two Buses, Each Separated by Two Circuit Breakers
- Two Circuit Breakers per Circuit
- All Breakers Normally Closed
<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Bus Faults Do Not Interrupt Any Circuit</td>
<td>• Cost – Two Breakers &amp; Four Switches per Circuit</td>
</tr>
<tr>
<td>• Circuit Faults Do Not Interrupt Any Buses or Other Circuits</td>
<td>• Physical Size</td>
</tr>
<tr>
<td>• Failed Breaker Results in Loss of One Circuit Only</td>
<td></td>
</tr>
<tr>
<td>• Breaker Maintenance w/o Circuit Interruption</td>
<td></td>
</tr>
<tr>
<td>• Highly Expandable</td>
<td></td>
</tr>
<tr>
<td>• Robust</td>
<td></td>
</tr>
</tbody>
</table>

**Double Breaker Double Bus**
Physical Arrangement
• NEMA SG-6
  ◦ Withdrawn, but still used by many
  ◦ BIL Based
  ◦ Provides
    • Bus spacings
    • Horn Gap Spacings
    • Side Break Switch Spacings
    • Minimum Metal-to-Metal
    • Minimum Phase-to-Ground
### Table 36-2
OUTDOOR SUBSTATIONS—BASIC PARAMETERS

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Rated Max. Impulse 12 x 50 μs Wavecrest</th>
<th>Rated 60 Hz KVRMS, Wet, 10 sec.</th>
<th>Recommended Minimum</th>
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<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
</tr>
<tr>
<td>1</td>
<td>8.3 95 30</td>
<td>7 (0.18)</td>
<td>7.5 (0.19)</td>
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<tr>
<td>2</td>
<td>15.5 110 45</td>
<td>12 (0.30)</td>
<td>10 (0.25)</td>
</tr>
<tr>
<td>3</td>
<td>27 150 60</td>
<td>15 (0.38)</td>
<td>10 (0.25)</td>
</tr>
<tr>
<td>4</td>
<td>38 200 80</td>
<td>18 (0.46)</td>
<td>15 (0.38)</td>
</tr>
<tr>
<td>5</td>
<td>48.3 250 100</td>
<td>21 (0.53)</td>
<td>18 (0.45)</td>
</tr>
<tr>
<td>6</td>
<td>72.5 350 145</td>
<td>31 (0.79)</td>
<td>29 (0.74)</td>
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<tr>
<td>7</td>
<td>123 500 230</td>
<td>53 (1.35)</td>
<td>47 (1.19)</td>
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<tr>
<td>8</td>
<td>145 650 275</td>
<td>63 (1.60)</td>
<td>52 (1.33)</td>
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<tr>
<td>9</td>
<td>170 750 315</td>
<td>72 (1.83)</td>
<td>51.5 (1.56)</td>
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<tr>
<td>10</td>
<td>245 900 365</td>
<td>89 (2.26)</td>
<td>76.5 (1.93)</td>
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<td>11</td>
<td>245 1050 455</td>
<td>105 (2.67)</td>
<td>90.5 (2.30)</td>
</tr>
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<td>12</td>
<td>362 1050 455</td>
<td>105 (2.67)</td>
<td>90.5 (2.30)</td>
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<td>13</td>
<td>362 1300 525</td>
<td>119 (3.02)</td>
<td>106 (2.39)</td>
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<td>14</td>
<td>550 1550 620</td>
<td>124 (3.15)*</td>
<td>124 (3.15)</td>
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<tr>
<td>15</td>
<td>550 1800 710</td>
<td>144 (3.66)*</td>
<td>144 (3.66)</td>
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<tr>
<td>16</td>
<td>800 2050 830</td>
<td>166 (4.22)*</td>
<td>166 (4.22)</td>
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</table>

**NOTE**—For insulator data, refer to ANSI C29.8 and C29.9.

*Ground clearance for voltages 362 kV and above is selected on the premise that at this level, selection of the insulation depends on switching surge levels of the system. The values were selected from Table 1 of IEEE Transaction Paper T-72-13-1-5 (Vol. No. 5, page 1924), which is a report of the Transmission Substations Subcommittee. For additional switching surge values and ground clearances, refer to ANSI C2.*
• IEEE 1427-2006 – Guide for Electrical Clearances & Insulation Levels in Air Insulated Electrical Power Substations
  ◦ BIL/BSL Based
  ◦ Rec. Phase-to-Phase
  ◦ Min. Metal-to-Metal
  ◦ Min. Phase to Ground
  ◦ Rec. Bus Spacings including Horn Gap

Spacing & Clearances
### Spacing & Clearances

#### Table 3—Recommended minimum electrical clearances for air-insulated substations when lightning impulse conditions govern

<table>
<thead>
<tr>
<th>Basic BIL</th>
<th>Minimum phase-to-ground clearances</th>
<th>Minimum phase-to-phase clearances</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kV, rms)</td>
<td>(mm) (in)</td>
<td>(mm) (in)</td>
</tr>
<tr>
<td>1.2</td>
<td>30</td>
<td>57 (2.3)</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>115 (4.5)</td>
</tr>
<tr>
<td>15</td>
<td>95</td>
<td>145 (5.6)</td>
</tr>
<tr>
<td>26.2</td>
<td>150</td>
<td>285 (11)</td>
</tr>
<tr>
<td>36.2</td>
<td>200</td>
<td>430 (16)</td>
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<tr>
<td>48.3</td>
<td>250</td>
<td>475 (19)</td>
</tr>
<tr>
<td>72.5</td>
<td>250</td>
<td>475 (19)</td>
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<tr>
<td>121</td>
<td>350</td>
<td>665 (26)</td>
</tr>
<tr>
<td>145</td>
<td>550</td>
<td>855 (34)</td>
</tr>
<tr>
<td>169</td>
<td>650</td>
<td>1045 (41)</td>
</tr>
<tr>
<td>242</td>
<td>750</td>
<td>1325 (52)</td>
</tr>
<tr>
<td>362</td>
<td>950</td>
<td>1710 (67)</td>
</tr>
<tr>
<td>550</td>
<td>1850</td>
<td>2470 (97)</td>
</tr>
</tbody>
</table>

#### Table 4—Recommended minimum electrical clearances for air-insulated substations when switching surge conditions govern

<table>
<thead>
<tr>
<th>Maximum system voltage (kV, crest)</th>
<th>Equivalent P.U.</th>
<th>Minimum phase-to-ground clearances (k_{eq} = 1.3)^{1,6}</th>
<th>Minimum phase-to-phase clearances (k_{eq} = 1.3)^{1,6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>562</td>
<td>1.86</td>
<td>1265 (50)</td>
<td>1730 (68)</td>
</tr>
<tr>
<td>650</td>
<td>2.20</td>
<td>1540 (61)</td>
<td>2125 (84)</td>
</tr>
<tr>
<td>750</td>
<td>2.54</td>
<td>1835 (72)</td>
<td>2560 (100)</td>
</tr>
<tr>
<td>850</td>
<td>2.79</td>
<td>2065 (81)</td>
<td>2910 (115)</td>
</tr>
<tr>
<td>900</td>
<td>3.04</td>
<td>2205 (91)</td>
<td>3280 (130)</td>
</tr>
<tr>
<td>950</td>
<td>3.30</td>
<td>2560 (100)</td>
<td>3680 (145)</td>
</tr>
<tr>
<td>1050</td>
<td>3.55</td>
<td>2825 (110)</td>
<td>4110 (160)</td>
</tr>
<tr>
<td>550</td>
<td>900</td>
<td>2305 (91)</td>
<td>3280 (130)</td>
</tr>
<tr>
<td>1175</td>
<td>2.62</td>
<td>3300 (130)</td>
<td>4870 (190)</td>
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<td>1300</td>
<td>2.89</td>
<td>3820 (150)</td>
<td>5795 (230)</td>
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<td>1425</td>
<td>3.17</td>
<td>4385 (175)</td>
<td>6825 (270)</td>
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<tr>
<td>1725</td>
<td>3.45</td>
<td>5010 (195)</td>
<td>8025 (315)</td>
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<tr>
<td>1800</td>
<td>3.76</td>
<td>5705 (225)</td>
<td>9435 (370)</td>
</tr>
<tr>
<td>2000</td>
<td>4.07</td>
<td>6475 (255)</td>
<td>11120 (440)</td>
</tr>
</tbody>
</table>

#### Table 5—Recommended minimum electrical clearances for air-insulated substations when lightning impulse conditions govern

<table>
<thead>
<tr>
<th>Basic BIL</th>
<th>Minimum phase-to-ground clearances</th>
<th>Minimum phase-to-ground clearances</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kV, rms)</td>
<td>(mm) (in)</td>
<td>(mm) (in)</td>
</tr>
<tr>
<td>650</td>
<td>50</td>
<td>50 (2.0)</td>
</tr>
<tr>
<td>52.5</td>
<td>52.5</td>
<td>52.5 (2.0)</td>
</tr>
<tr>
<td>63</td>
<td>63</td>
<td>63 (2.5)</td>
</tr>
</tbody>
</table>

#### Table 6—Recommended minimum electrical clearances for air-insulated substations when switching surge conditions govern

<table>
<thead>
<tr>
<th>Maximum system voltage (kV, crest)</th>
<th>Equivalent P.U.</th>
<th>Minimum phase-to-ground clearances (k_{eq} = 1.3)^{1,6}</th>
<th>Minimum phase-to-phase clearances (k_{eq} = 1.3)^{1,6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>50</td>
<td>50 (2.0)</td>
<td>50 (2.0)</td>
</tr>
<tr>
<td>52.5</td>
<td>52.5</td>
<td>52.5 (2.0)</td>
<td>52.5 (2.0)</td>
</tr>
<tr>
<td>63</td>
<td>63</td>
<td>63 (2.5)</td>
<td>63 (2.5)</td>
</tr>
</tbody>
</table>

**650 kV BIL Ex:** SG-6 IEEE 1427

- Min Ph-Gnd: 50” (49”)
- Rec. Ph-Gnd: 52.5” (N/A)
- Min Ph-Ph: 63” (54”)

---

**HV Substation Design: Applications and Considerations**  
IEEE CED Houston Chapter 2012-2013
## BIL/Voltage Ratio

### Table 8—Ratio of BIL to maximum system voltage

<table>
<thead>
<tr>
<th>Maximum system voltage phase-to-phase (kV, rms)</th>
<th>Typical BIL (kV, crest)</th>
<th>Ratio of BIL to maximum system voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>72.5</td>
<td>350</td>
<td>4.83</td>
</tr>
<tr>
<td>121</td>
<td>550</td>
<td>4.55</td>
</tr>
<tr>
<td>145</td>
<td>650</td>
<td>4.48</td>
</tr>
<tr>
<td>169</td>
<td>750</td>
<td>4.44</td>
</tr>
<tr>
<td>242</td>
<td>900</td>
<td>3.72</td>
</tr>
<tr>
<td></td>
<td>1050</td>
<td>3.34</td>
</tr>
<tr>
<td>362</td>
<td>1050</td>
<td>2.90</td>
</tr>
<tr>
<td></td>
<td>1300</td>
<td>3.59</td>
</tr>
<tr>
<td>550</td>
<td>1550</td>
<td>2.82</td>
</tr>
<tr>
<td></td>
<td>1800</td>
<td>3.27</td>
</tr>
<tr>
<td>800</td>
<td>1800</td>
<td>2.25</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td>2300</td>
<td>2.88</td>
</tr>
</tbody>
</table>

Table 8 shows the comparison between various maximum system voltages and BILs associated with these voltages. The comparison is intended **ONLY** to illustrate the ratio has decreased with use of higher system voltages.

### Spacing & Clearances
IEEE 1427-2006 – What It Doesn’t Address

- Uprating (Discussion Only)
- Wildlife Conservation
- Shielding Effects
- Contamination
- Hardware & Corona
- Arcing During Switch Operation
- Mechanical Stress Due to Fault Currents
- Safety

Spacing & Clearances
• NESC (ANSI/IEEE C2)
  ◦ Safety Based
  ◦ Standard Installation and Maintenance Requirements
    • Stations
    • Aerial Lines
    • Underground Circuits
  ◦ Grounding Methods
• NFPA 70E
  ◦ Safe Working Clearances for Low and Medium-Voltage Equipment

Spacing & Clearances
- NESC Fence Safety Clearance

Spacing & Clearances
### IEEE C37.32

#### Table 4-8: Phase Spacing of Outdoor Air Switches

Ref. ANSI Std. C37.32-1996, Table 5.

Reproduced with permission of the National Electrical Manufacturers Association.

<table>
<thead>
<tr>
<th>Nominal Phase-to-Phase Voltage (kV)</th>
<th>Maximum Phase-to-Phase Voltage (kV)</th>
<th>BIL (kV)</th>
<th>Minimum Metal-to-Metal for Air Switches (meters)</th>
<th>Centerline-to-Centerline Phase Spacing (inches)</th>
<th>Vertical Break Disconnect Switches</th>
<th>Side or Horizontal Break Disconnect Switches</th>
<th>All Horn Gap Switches</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>8.3</td>
<td>95</td>
<td>0.175 (7)</td>
<td>0.457 (18)</td>
<td>0.610 (24)</td>
<td>0.762 (30)</td>
<td>0.914 (36)</td>
</tr>
<tr>
<td>14.4</td>
<td>15.5</td>
<td>110</td>
<td>0.305 (12)</td>
<td>0.762 (30)</td>
<td>0.762 (30)</td>
<td>1.22 (48)</td>
<td>1.52 (60)</td>
</tr>
<tr>
<td>23</td>
<td>25.8</td>
<td>150</td>
<td>0.381 (15)</td>
<td>0.914 (36)</td>
<td>1.22 (48)</td>
<td>1.83 (72)</td>
<td>2.13 (84)</td>
</tr>
<tr>
<td>34.5</td>
<td>38</td>
<td>200</td>
<td>0.457 (18)</td>
<td>1.52 (60)</td>
<td>1.83 (72)</td>
<td>2.74 (108)</td>
<td>3.05 (120)</td>
</tr>
<tr>
<td>46</td>
<td>48.3</td>
<td>250</td>
<td>0.533 (21)</td>
<td>1.52 (60)</td>
<td>1.83 (72)</td>
<td>2.74 (108)</td>
<td>3.05 (120)</td>
</tr>
<tr>
<td>69</td>
<td>72.5</td>
<td>350</td>
<td>0.787 (31)</td>
<td>2.13 (84)</td>
<td>2.74 (108)</td>
<td>3.35 (132)</td>
<td>3.66 (144)</td>
</tr>
<tr>
<td>115</td>
<td>121</td>
<td>550</td>
<td>1.35 (53)</td>
<td>2.44 (96)</td>
<td>3.35 (132)</td>
<td>3.66 (144)</td>
<td>3.66 (144)</td>
</tr>
<tr>
<td>138</td>
<td>145</td>
<td>650</td>
<td>1.60 (63)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>161</td>
<td>169</td>
<td>750</td>
<td>1.83 (72)</td>
<td>2.74 (108)</td>
<td>3.96 (156)</td>
<td>4.27 (168)</td>
<td></td>
</tr>
<tr>
<td>230</td>
<td>242</td>
<td>900</td>
<td>2.26 (89)</td>
<td>3.35 (132)</td>
<td>4.87 (192)</td>
<td>4.87 (192)</td>
<td></td>
</tr>
<tr>
<td>230</td>
<td>242</td>
<td>1050</td>
<td>2.67 (105)</td>
<td>3.96 (156)</td>
<td>5.50 (216)</td>
<td>5.50 (216)</td>
<td></td>
</tr>
<tr>
<td>345</td>
<td>362</td>
<td>1050</td>
<td>2.67 (105)</td>
<td>3.96 (156)</td>
<td>5.49 (216)</td>
<td>5.49 (216)</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
1. Values taken from ANSI C37.32 and NEMA SG6.
2. Values listed are for altitudes of 1000 meters (3300 feet) or less. For higher altitudes, the altitude correction factors listed in Table 4-3 should be applied.

**Spacing & Clearances**
Typical 138 kV Substation – Four (4) Breaker Ring Bus w/ Oil Circuit Breakers
Spacing & Clearances
Dielectric Fluids

NEC® Requirement Guidelines
2011 Code Options for the Installation of Listed
Less-Flammable Liquid-Filled Transformers

Less-flammable liquids for transformers: fire point > 300 deg C

TABLE 7. FM Required Separation Distance
Between Outdoor Liquid Insulated Transformers and Buildings.*

<table>
<thead>
<tr>
<th>Liquid</th>
<th>FM Approved Transformer or Equivalent</th>
<th>Liquid Volume gal/(m²)</th>
<th>Fire Resistant ft/(m)</th>
<th>Non-Combustible ft/(m)</th>
<th>Combustible ft/(m)</th>
<th>Vertical Distance ft/(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less-Flammable (Approved)</td>
<td>Yes</td>
<td>N/A</td>
<td>3 (0.9)</td>
<td>3 (0.9)</td>
<td>3 (0.9)</td>
<td>5 (1.5)</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>≤10,000 (38)</td>
<td>5 (1.5)</td>
<td>5 (1.5)</td>
<td>25 (7.6)</td>
<td>25 (7.6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;10,000 (38)</td>
<td>15 (4.6)</td>
<td>15 (4.6)</td>
<td>50 (15.2)</td>
<td>50 (15.2)</td>
</tr>
<tr>
<td>Mineral Oil</td>
<td>N/A</td>
<td>&lt;500 (19)</td>
<td>15 (4.6)</td>
<td>25 (7.6)</td>
<td>50 (15.2)</td>
<td>50 (15.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500–5,000 (19–19)</td>
<td>25 (7.6)</td>
<td>50 (15.2)</td>
<td>100 (30.5)</td>
<td>100 (30.5)</td>
</tr>
</tbody>
</table>

*R. FM Global Loss Prevention Data Sheet 5-4, Table 2a.
**All transformer components must be accessible for inspection and maintenance.

TABLE 8. FM Outdoor Fluid Insulated Transformers Equipment Separation Distance.*

<table>
<thead>
<tr>
<th>Liquid</th>
<th>FM Approved Transformer or Equivalent</th>
<th>Fluid Volume gal/(m³)</th>
<th>Distance ft/(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less-Flammable (Approved)</td>
<td>Yes</td>
<td>N/A</td>
<td>3 (0.9)</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>≤10,000 (38)</td>
<td>5 (1.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;10,000 (38)</td>
<td>25 (7.6)</td>
</tr>
<tr>
<td>Mineral Oil</td>
<td>N/A</td>
<td>&lt;500 (19)</td>
<td>6 (1.8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500–5,000 (19–19)</td>
<td>25 (7.6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;5,000 (19)</td>
<td>50 (15.2)</td>
</tr>
</tbody>
</table>

*R. FM Global Loss Prevention Data Sheet 5-4, Table 2b.
**All transformer components must be accessible for inspection and maintenance.

Spacing & Clearances
Spacing & Clearances

HV Substation Design: Applications and Considerations  
IEEE CED Houston Chapter 2012-2013
Spacing Affects Structural Design

Spacing & Clearances
• Applied Forces
  ◦ Wind
  ◦ Ice
  ◦ Forces from Short-Circuit Faults

• Design Considerations
  ◦ Insulator strength to withstand forces from short-circuit faults
  ◦ Structural steel strength under short-circuit fault forces (moments)
  ◦ Foundation design under high moments
  ◦ Ice loading, bus bar strength, and bus spans
  ◦ Thermal expansion and use of expansion joints


Structural Requirements
**Deflection**

Class A: Those Structures Intended for the Support of High Voltage Equipment Which Requires Sufficient Rigidity for Proper Operation (i.e., Air Switches, etc.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Deflection Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A Structures</td>
<td></td>
</tr>
<tr>
<td>Horizontal Deflection of Vertical Members</td>
<td>( \frac{L}{100} )</td>
</tr>
<tr>
<td>Vertical Deflection of Horizontal Members</td>
<td>( \frac{L}{200} )</td>
</tr>
<tr>
<td>Horizontal Deflection of Horizontal Members</td>
<td>( \frac{L}{200} )</td>
</tr>
</tbody>
</table>
## Deflection

Class B: Those structures on which the deflections within the limit stated do not affect the performance of the support equipment (i.e., bus support, line termination structures, etc.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Deflection Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class B Structures</td>
<td></td>
</tr>
<tr>
<td>Horizontal Deflection of Vertical Members</td>
<td>$l/50$</td>
</tr>
<tr>
<td>Vertical Deflection of Horizontal Members</td>
<td>$l/200$</td>
</tr>
<tr>
<td>Horizontal Deflection of Horizontal Members</td>
<td>$l/100$</td>
</tr>
</tbody>
</table>
• Bus Supports
  ◦ Short-Circuit Forces
  ◦ Wind Loading
  ◦ Ice Loading
  ◦ Seismic Forces

Structural Design
Short-Circuit Forces

\[ F(t) = \frac{\mu}{4\pi r^2} \left[ i_1(t) i_2(t) \right] \left[ d_1 \times (u_r \times d_2) \right] \]

where

- \( \mu \) is the magnetic permeability equal to \( 4\pi \times 10^{-7} \) V-s/(A-m)
- \( r \) is the distance between the two conductor segments
- \( u_r \) is the unit directional vector in the direction \( r \)
- \( d_1 \) is a vector of length \( d_1 \) in the direction of the current flow in conductor segment 1
- \( d_2 \) is a vector of length \( d_2 \) in the direction of the current flow in conductor segment 2

NOTE—The symbol \( \times \) is the vectorial cross product.

Figure 19—Illustration of two conductor segments carrying electric current
Short-Circuit Forces

The equation for the force between parallel, infinitely long conductors in a flat configuration due to a fully asymmetrical short circuit current is as follows.

For metric units:

\[ F_x = \frac{16II_x^2}{10^7D} \]  

(14)

For English units:

\[ F_x = \frac{3.6II_x^2}{10^7D} \]  

(15)

where

- \( F_{sc} \) is the fault current force by unit length, N/m (lbf/ft)
- \( I_{sc} \) is the symmetrical RMS fault current, A
- \( D \) is the conductor spacing center-to-center, m (ft)
- \( \Gamma \) is a constant based on type of fault and conductor location (Table 13)
### Short-Circuit Forces

#### Table 13 — \( \Gamma \) constant for simplified calculation short circuit basic force equation

<table>
<thead>
<tr>
<th>Type of short circuit</th>
<th>Configuration</th>
<th>Conductor</th>
<th>( \Gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase to phase</td>
<td></td>
<td>A or B</td>
<td>1.000</td>
</tr>
<tr>
<td>Three phase</td>
<td></td>
<td>B</td>
<td>0.866</td>
</tr>
<tr>
<td>Three phase</td>
<td></td>
<td>A or C</td>
<td>0.808</td>
</tr>
<tr>
<td>Phase to phase</td>
<td>Triangular arrangement—equilateral triangle—side D</td>
<td>A or B</td>
<td>1.0</td>
</tr>
<tr>
<td>Three phase</td>
<td>Triangular arrangement—equilateral triangle—side D</td>
<td>A or B or C</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**NOTE**—For a three-phase fault, this table indicates that the maximum force is on the central conductor B. However, results from finite-element calculations (which provide a much closer estimation of the maximum forces than the preceding equation) indicate that in most cases, the maximum stresses and transmitted effects on the support structure are in either conductor A or C.
Short-Circuit Forces

Equation (14) [or Equation (15)] for the basic force by unit length between infinitely long conductors provides in most cases an overly conservative estimate of the maximum force that will occur in practice. Many inherent hypotheses underlying this equation are not realistic in practice, among others:

a) Infinite conductor length; in practice, the conductors are of finite length.

b) The peak current is twice the RMS value; in practice, the peak current is a function of the time constant of the circuit.

c) The structure responds instantaneously to the electromagnetic load and reaches its maximum response at the same time the current is at its peak; in practice the maximum response of the structure is attained after the current has reach its peak value, due to the flexibility of the supporting structure and of the conductors themselves.

d) Damping of the insulator, supporting structure, and conductors is not accounted for in these equations.

The following corrected basic force equation is proposed to alleviate some of the conservatism present in the basic force equation for infinitely long conductors:

Structural Design
Short-Circuit Forces

\[ F_{sc\text{ corrected}} = D_f^2 K_f F_{sc} \]  

(16)

where

- \( D_f \) is the half-cycle decrement factor to account for the momentary peak factor effect
- \( K_f \) is the mounting structure flexibility factor to account for the structure’s flexibility
- \( F_{sc} \) is the basic force Equation (14) [or Equation (15) in British units].

The evaluation of the constants \( D_f \) and \( K_f \) is presented in the following discussion. It is to be underlined that even with these factors, the resulting force equation is still a conservative estimate of the force acting on the structure, as compared with finite-element calculations that provide a more realistic estimate as supported by correlations with tests. Also, this equation is valid only for parallel conductors and cannot take into account 3D effects, corner effects, etc., which are present in most cases in practice.

Structural Design
Table 14—Half-cycle decrement factor $D_r$ for various values of $X/R$ ratio

<table>
<thead>
<tr>
<th>$X/R$</th>
<th>$T_r$</th>
<th>$D_r$</th>
<th>$D_r^2$</th>
<th>$X/R$</th>
<th>$T_r$</th>
<th>$D_r$</th>
<th>$D_r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.0796</td>
<td>0.950</td>
<td>0.903</td>
<td>30</td>
<td>0.0955</td>
<td>0.950</td>
<td>0.903</td>
</tr>
<tr>
<td>20</td>
<td>0.0531</td>
<td>0.927</td>
<td>0.860</td>
<td>20</td>
<td>0.0637</td>
<td>0.927</td>
<td>0.860</td>
</tr>
<tr>
<td>10</td>
<td>0.0265</td>
<td>0.865</td>
<td>0.749</td>
<td>10</td>
<td>0.0318</td>
<td>0.865</td>
<td>0.749</td>
</tr>
<tr>
<td>5</td>
<td>0.0133</td>
<td>0.767</td>
<td>0.588</td>
<td>5</td>
<td>0.0159</td>
<td>0.767</td>
<td>0.588</td>
</tr>
<tr>
<td>2</td>
<td>0.0053</td>
<td>0.604</td>
<td>0.365</td>
<td>2</td>
<td>0.0064</td>
<td>0.604</td>
<td>0.365</td>
</tr>
<tr>
<td>1</td>
<td>0.0027</td>
<td>0.522</td>
<td>0.272</td>
<td>1</td>
<td>0.0032</td>
<td>0.522</td>
<td>0.272</td>
</tr>
</tbody>
</table>

Equation (19) gives the maximum decrement factor in the first half cycle of the fault. The actual correction when maximum conductor span deflection occurs is usually less because of the following:

- Most conductor spans will not reach maximum deflection until after the first quarter-cycle.
- Additional current decrement occurs as the fault continues, especially for low $X/R$ ratios.
Short-Circuit Forces

Because of their flexibility, the bus and mounting structures are capable of absorbing energy during a fault. Thus, depending on the type of mounting structures and their heights, the effective fault current forces will be lower than the half-cycle maximum value. The effect of the structure flexibility is accounted with the mounting-structure flexibility factor, $K_f$.

Values of $K_f$ for single-phase mounting structures are given in Figure 20. $K_f$ is usually assumed to be unity for three-phase mounting structures.

NOTE—A, lattice and tubular aluminum; B, tubular and wide-flange steel and wood pole; C, lattice steel; D, solid concrete.
• Rated Continuous Current
• Selected Ambient Base
• Allowable Temperature Rise
• Equipment Limitations
• Interaction with Transmission Lines
• Other Factors
  ◦ Wind
  ◦ Ice Loading
  ◦ Emissivity

Current Ratings
IEEE 605-2008 is a great resource:

- Conductor Physical Properties
- Conductor Electrical Properties
- Examples of Calculations

**Figure H.1—General bus layout**

Using the data from Table H.1 and information from the guide, the following design parameters can be determined:

a) Determine bus conductor size required for both maximum normal load and short circuit current (Clause 8 and Annex C).
b) Determine maximum corona on the bus and equipment (Clause 9 and Annex D).
c) Determine maximum forces on the structures (Clause 11).
d) Determine maximum span length of the bus based on vertical deflection limit and fiber stress (12.1 and 12.2).
e) Determine maximum required insulator rating (12.3 and 12.4).
f) Determine thermal expansion requirements (11.4).
g) Determine bus vibration and damping requirements (12.5, 12.6, and 12.7).
Types of Substation Structures

Station Physical Layout
• **Conventional** (Lattice Structures)
  - Angle (Chord & Lace) Members
  - Minimum Structure Weight
  - Requires Minimum Site Area
  - Stable and Rigid Construction
  - Requires Considerable Bolting & Erection Time

**Station Physical Layout**
Conventional Design
Conventional Design
Conventional Design
• **Low Profile** (Standard “Extruded” Shapes)
  - Wide Flange, Channel, Plates, Structural Tubing (Round, Square, Rectangular)
  - Short Erection Time
  - Aesthetically Pleasing
  - Most Sizes Readily Available
  - Requires Greater Site Area
TYPICAL ONE-LINE DIAGRAM

PLAN VIEW—TYPICAL BAY

ELEVATION—TYPICAL BAY
Low Profile (tube)
Low Profile (tube)
Low Profile (tube)
Conventional Station Physical Layout

Low Profile Station Physical Layout
• **GIS** (Gas Insulated Substation)
• Maintenance
• Equipment Removal
• Vehicle Mobility
• Exterior Access

Station Physical Layout
• **Common Designs**
  ◦ A-Frame or H-Frame
  ◦ Lattice, Wide Flange, Structural Tubing
  ◦ Inboard or Outboard Leg Design
Surge and Lightning Protection
- **Design Problems**
  - Probabilistic nature of lightning
  - Lack of data due to infrequency of lightning strokes in substations
  - Complexity and economics involved in analyzing a system in detail
  - No known practical method of providing 100% shielding (excluding GIS)
Common Approaches

- Lower voltages (69 kV and below): Simplified rules of thumb and empirical methods
  - Fixed Angle
  - Empirical Curves
- EHV (345 kV and above): Sophisticated electrogeometric model (EGM) studies
  - Whitehead’s EGM
  - Revised EGM
  - Rolling Sphere
Surge Protection ( Arresters)
- Use Arresters (Station Class)
- Transformer Protection (High Z Causes High V Reflected Wave)
- Line Protection (Open End Causes High V Reflected Wave)
- Systems above 169 kV Require Special Attention
• Lightning Protection
  ◦ Strokes to Tall Structures; Strokes to Ground
  ◦ Frequency – Isokeraunic Levels at Station Location
  ◦ Design Methods
    • Fixed Angles (good at or below 69 kV, generally applied up to 138 kV)
    • Empirical Curves (not used widely)
    • Whitehead’s EGM
    • Revised EGM
    • Rolling Sphere
• Combination of Surge Arresters and Lightning Shielding Provides Acceptable Levels of Protection
• IEEE 998 – IEEE Guide for Direct Lightning Stroke Shielding of Substations

*A properly designed ground grid is critical for proper surge and lightning protection.*

Surge & Lightning Protection
The number of strokes expected to strike the unprotected area each year is calculated, based on the isokeraunic level (see Figure 13) at the substation site using the following equation.

\[ N = 1.112 \times 10^{-8}T(A) \]

where

- \( N \) = number of strokes to earth within the unprotected area per year
- \( T \) = average annual isokeraunic level
- \( A \) = unprotected area in square feet

Figure 13
USA Annual Isokeraunic Map

7.5 SHIELDING FAILURE RATE

The failure rate for insulation within the unprotected area is calculated using the following equation.

\[
F = \frac{1}{(P_f)(N)}
\]

where

\( F \) = failure rate of insulation within the protected area, years between failures

\( P_f \) = probability that stroke currents within the unprotected area will cause insulation failure

\( N \) = number of strokes to earth within the unprotected area per year

7.6 ACCEPTABLE RATES OF FAILURE

It is recommended that shielding be designed for 100 percent coverage. If complete protection is impractical, protect the major (expensive) pieces of equipment to the extent possible. For a switchyard rated 550 KV BIL and above, a failure rate of 100 years per failure or more can be achieved economically. For switchyards rated less than 550 KV BIL, failure rates of 25 to 50 years are more common.
• Fixed Angle Method

<table>
<thead>
<tr>
<th>ANGLE</th>
<th>RANGE</th>
<th>RECOMMENDED</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20° TO 60°</td>
<td>30°</td>
</tr>
<tr>
<td>B</td>
<td>40° TO 60°</td>
<td>45°</td>
</tr>
</tbody>
</table>

SINGLE MAST OR SHIELD WIRE

TWO MASTS OR SHIELD WIRES

Surge & Lightning Protection
Rolling Sphere Method

Source: Adapted from [874]

Figure 5.7 — Multiple shield mast protection for stroke current $I_s$
Rolling Sphere Method

C.1 Corona radius

In case of a single conductor, the corona radius \( R_c \) is given by Anderson [B4]:

\[
R_c \times \ln \left( \frac{2 \times R}{R_c} \right) - \frac{V_c}{E_0} = 0
\]  

(C.1)

where:
- \( R_c \) is the corona radius in meters
- \( h \) is the average height of the conductor in meters
- \( V_c \) is the allowable insulator voltage for a negative polarity surge having a 6 \( \mu \)s front in kilovolts (\( V_c = \) the BiL for post insulators)
- \( E_0 \) is the limiting corona gradient, this is taken equal to 1500 kV/m

Eq C.1 can be solved by trial and error using a programmable calculator (an approximate solution is given in figure C.1).

In the case of bundle conductors, the radius of the bundle under corona \( R_c' \) [D4] is taken as follows:

\[
R_c' = R_0 + R_c
\]  

(C.2)

where:
- \( R_c \) is the value for a single conductor as given by Eq C.1
- \( R_0 \) is the equivalent radius of the bundle.

The calculation method of \( R_0 \) is given in C.2.
Grounding Considerations
• IEEE 80 – IEEE Guide for Safety in AC Substation Grounding
  ◦ Safety Risks
  ◦ Humans as Electrical Components
  ◦ Soil Modeling
  ◦ Fault Currents and Voltage Rise
  ◦ Demands Use of Analytical Software
• NESC
  ◦ Points of Connection
  ◦ Messengers & Guys, Fences
  ◦ Grounding Conductors, Ampacity, Strength, Connections
  ◦ Grounding Electrodes
  ◦ Ground Resistance Requirements
Grounding – Exothermic
Grounding – Compression
Grounding – Mechanical
OBJECTIVES

- To Identify Components of a Grounding System
- To Review Key Design Considerations and Parameters Needed for a Grounding Analysis
- To Review the Grounding Problem
- To Identify Grounding Analysis Methods and Applicability

Grounding Design
1. Assure that persons in or near any substation are not exposed to electric shock above tolerable limits.
2. Provide means to dissipate normal and abnormal electric currents into the earth without exceeding operating or equipment limits.

Grounding Objectives
1. High fault current to ground
2. Soil resistivity and distribution of ground currents
3. Body bridging two points of high potential difference
4. Absence of sufficient contact resistance
5. Duration of the fault and body contact

Cause of Electric Shock
Basic Shock Situations
Simple Grid Design
Protection & Control
One-Line Diagrams

- The one-line diagram is probably the single most important document in the substation design package.
- The one-line diagram defines the design parameters and scope of the design...a road map.
One-Line Diagrams

Key elements that should be included on relaying one-lines

- Substation Configuration
- Equipment Ratings
- Design Parameters
- Phasor Rotation Diagram
- Delineation of Scope
- Provisions for Future Expansion
One-Line Diagrams

Phasor Rotation

Future Equipment

Equipment Provided by Others

Extent of Scope

Device Function Table
One-Line Diagrams

- Modern microprocessor relays are fairly complex
- Functionality typically can not be adequate illustrated between the one-line diagram and schematic diagrams
- Creating Logic Diagrams is strongly recommended.
Protection & Control

• Protection
  ◦ Fundamentals
  ◦ Bus
  ◦ Transformers
  ◦ Motors
  ◦ Generators
  ◦ Line & Circuits

• Control
  ◦ Primary/Back-up Systems
  ◦ Breaker Failure
  ◦ Reclosing
  ◦ Pilot Systems & Communication Channels
A.C. Fundamentals
Phasor Relationships

IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes - IEEE Std C37.110
A.C. Fundamentals
Phasor Relationships

Residual CT connection

Zero sequence CT

IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes - IEEE Std C37.110

Properly connected CTs. 87B will operate for bus fault as shown.
A.C. Fundamentals
Tap Substation
Tap Substation

- Phase Protection - Overcurrent

Should 50 elements be set on all relays?
Tap Substation

- Phase Protection - Overcurrent

Should 50 elements be set on all relays?

To low impedance circuit (i.e. downstream switchgear)

To high impedance circuit (i.e. motor or xfmr)
Tap Substation

- Phase Protection - Overcurrent

Should 50 elements be set on all relays?

To low impedance circuit (i.e. downstream switchgear)
To high impedance circuit (i.e. motor or xfmr)
Tap Substation

- Phase Protection
  - Unit Differential
  - Overcurrent

This configuration is not preferred.

**Pros**
- Lower cost

**Cons**
- Lower selectivity
Tap Substation

- Phase Protection
  - Full Differential
  - Overcurrent

• Pros
  - Higher selectivity

• Cons
  - Higher cost
Tap Substation

- Ground Protection

Ground coordination on each side of the transformer are performed independently

(*) relays measure phase quantities, but are often set to operate for ground faults in the zone of protection.
Secondary Selective Arrangement – N.O. Tie

Relaying not shown for clarity
Secondary Selective Arrangement – N.O. Tie

Relaying not shown for clarity
Secondary Selective Arrangement – N.O. Tie

Relaying not shown for clarity
Secondary Selective Arrangement – N.O. Tie

Relaying not shown for clarity
Secondary Selective Arrangement – N.O. Tie

Why use “partial differential” or “bus overload”?
Secondary Selective Arrangement – N.O. Tie

Why use “partial differential” or “bus overload”?

Pros:
Use one (1) less relay
Eliminate one (1) level of coordination

Cons:
Require one (1) extra set of CTs on the tie breaker
Can not set 67 element on mains because currents are summed before the relay
Secondary Selective Arrangement – N.C. Tie

Polarizing input not shown for clarity

Relaying not shown for clarity
Secondary Selective Arrangement – N.C. Tie

Polarizing input not shown for clarity

Relaying not shown for clarity
Secondary Selective Arrangement – N.C. Tie

Polarizing input not shown for clarity

Relaying not shown for clarity
Bus Protection

- Differential Protection
  - Most sensitive and most reliable
  - Linear couplers – do not saturate (no iron core)
  - Multi-restraint differential – use restraint and variable percentage slopes to overcome iron core deficiencies at high currents
  - High impedance differential – forces false differentials through CTs and not relay
Bus Protection

- Other Protection Methods
  - Instantaneous overcurrent
  - Low impedance overcurrent
    - Not recommended to use parallel CT connection
    - Relay cost is low, but engineering cost and application considerations is high
  - “Partial Differential”
    - Only sources are considered
  - Directional Comparison Blocking (Zone-Interlocking Schemes)
    - Feeders communicate with sources
    - Use caution with directional relays as directional unit may not operate properly on close-in hard three-phase faults
Bus Protection

Current Differential
Not Recommended

Voltage Differential – Using Linear Couplers
Bus Protection

Current Differential

Not Recommended

Voltage Differential – Using Linear Couplers
Bus Protection

Voltage Differential using CTs

Main drawback is the inability to share the CT with different circuits.

Current Differential with Restraint Elements

Current differential with restraint elements can be used for many applications (bus, transformer, generator, etc). The relay can account for different CT ratios (great for retrofit installations). However, since each CT has its own input, consider a 15 kV swgr application with 10 feeders per bus:

\[(10 + \text{Main} + \text{Tie}) \times 3 = 36 \text{ current inputs!}\]
Transformer Protection

- Considerations
  - Differential Protection
    - Different Voltage Levels Including Taps
    - Mismatch Due to CT Ratios
    - 30° Phase Shift on Delta-Wye Connections
    - Magnetizing Inrush
  - Overcurrent Protection
    - CT Performance During High-Current Faults
  - Transformer Type
    - Delta-Wye
    - Zig-Zag Grounding Transformer
    - Autotransformer with Delta Tertiary
    - Phase-Shifting Transformer

- IEEE Std C37.91 – IEEE Guide for Protective Relay Applications to Power Transformers
Motor Protection

- Low-Voltage Protection
  - Time-delayed undervoltage (27)
- Phase Rotation/Reversal Protection
  - Not typically necessary
- Negative Sequence Overvoltage Protection (47)
  - Time-delayed depending on amount of $V_2$
- Phase Unbalance/Negative Sequence Overcurrent (46)
  - Select curve below $(I_2)^2t = k$ damage curve
  - $k = 40$ generally considered conservative value
- Out-of-Step Protection/Loss of Excitation
  - Power Factor Sensing (55)
  - Distance Relay
Motor Protection

Source: Schweitzer SEL651A Application Guide

SV42 := (27YAB1 OR 27YBC1 OR 27YCA1) AND (59YAB1 OR 59YBC1 OR 59YCA1). The selected spare SELLogic control equation variable combines any phase-to-phase undervoltage and any phase-to-phase overvoltage to detect a high-side blown fuse/open-phase condition.
Motor Protection

- Abnormal Conditions
  - Faults in Windings
  - Excessive Overloads
  - Reduction or Loss of Supply Voltage
  - Phase Reversal
  - Phase Unbalance
  - Out-of-step Operation (Synchronous Machines)
  - Loss of Excitation (Synchronous Machines)
Motor Protection

- Phase Fault Protection
  - Differential
  - Core Balance CT
  - Instantaneous Overcurrent
- Ground Fault Protection
  - Zero Sequence CT
- Locked Rotor Protection
  - Time Overcurrent – Set below rotor damage curve
  - Distance Relay (Large Machines)
- Overload Protection
  - Time overcurrent – Set below stator damage curve
- Thermal Protection – RTDs
Primary & Back-up Protection

- Primary/Back-up Protection Philosophy
  - Each protected component has two sets of protection
  - Each protection set is independent of the other
  - Failure of any one component must not compromise protection

- DC Battery Systems
  - Single Battery System
    - Primary protection on different circuit from back-up protection
    - Blown fuse or open DC panel breaker cannot compromise protection
    - Battery itself is a single point of failure
  - Dual Battery System
    - Primary protection on different battery than back-up
    - Battery is no longer single point of failure
Breaker Failure Protection

- More common at high voltage
- Communication assisted tripping required for line breakers (i.e. direct transfer trip)
- Typical Protection Logic
  - Trip signal received by breaker
  - Identical signal starts breaker failure timing
  - After a pre-set amount of time (6 cycles is common) and if current is still present in the breaker, then the breaker has failed
  - Trip zones on either side of the breaker
  - Dedicated lockout relay used for tripping, transfer tripping, fault recording, annunciation, and alarm
Breaker Failure Protection

Line/Bus Fault

Failed Breaker
Some considerations for protective relay applications...

Recommended References:

Transformer Protection – IEEE Std C37.91
Motor Protection – IEEE C37.96
Bus Protection – IEEE C37.97 (withdrawn)
Shunt Capacitor Bank Protection – IEEE C37.99
Generator Protection – IEEE C37.102
Automatic Reclosing of Line Circuit Breakers for AC Distribution and Transmission Lines - IEEE Std C37.104
Shunt Reactor Protection - ANSI/IEEE Std C37.109
Transmission Line Protection – IEEE C37.113
Breaker Failure Protection of Power Circuit Breakers – IEEE C37.119
IEEE Buff Book
IEEE Brown Book
Applied Protective Relaying - Westinghouse
Other Considerations

- Redundant DC power sources
- SER and DFR (oscillography) default settings enable only basic functionality at best case. Default settings by some manufacturers disable the SER and DFR.
- Synchronization of clocks
- Integration of protective relays with other IEDs
- Utilize outputs from “non-intelligent” devices as inputs to IEDs
- Don’t forget about test switches!!!
Engineering & Construction Coordination
Construction Process

Site Prep → Foundation Installation → Conduit Installation → Grounding Installation

Station Yard Installation → Building Installation → Commission
Supplemental Topics
Future Expansion Possibilities

- Tap to Ring
  - Build as “Loop Tap”
  - Add switches to facilitate expansion
  - Initial layout considerate of final ring bus configuration
Future Expansion Possibilities

- Ring to Breaker-And-A-Half
  - Build as elongated ring bus
  - Allows future bay installations (i.e. additional circuits, two per bay)
Mixing Bus Arrangements

- Example: Industrial
  - High-Voltage Ring Bus
Variations

- Variations Exist
  - Swap Line and Transformer Positions
  - Add 2\textsuperscript{nd} Tie Breaker
• Single Breaker Designs
  ◦ Breaker maintenance requires circuit outage
  ◦ Typically contain multiple single points of failure
  ◦ Little or no operating flexibility

• Multiple Breaker Designs
  ◦ Breaker maintenance does not require circuit outage
  ◦ Some designs contain no single points of failure
  ◦ Flexible operation
  ◦ In general, highly adaptable and expandable

Conclusion
Questions?

HV Engineering, LLC
Consulting and Engineering Services
Houston, TX  (239)365-1299

Downloads
Dominik's Technical Bits ... of knowledge

TB01. Substation Batteries
TB02. Substation Battery Charger
TB03. Receiving Large Power Transformers
TB04. HV Oil-Filled Bushings
TB05. Instrument Transformer Wiring
TB06. Current Transformer Polarity Markings
TB07. Earth Resistance Testing

Previously Presented Paper and Tutorials

Motor Presentation.
IEEE CED 2006-2007
Improving Substation Reliability.
PCIC 2009 by Spievak, Pittman, Wilson, Weisse & Peniazek
Overcurrent Protection & Coordination.
IEEE CED 2009-2010 by Doug Durand
Overcurrent Protection Annex.
IEEE CED 2000-2010 by Dominik Peniazek
Power System Calculations Part II.
IEEE IAS 2010 by Kurt Edendorff

www hv-eng com
Example of low profile substation using lattice structures
Example of conventional design
Base plates with grout

Installation leads to rusting at base of support
Base plates without grout

Preferred Installation Method*

* Structural engineer should confirm base plate and anchor bolts are sized properly
Vee Break vs. Vertical Break

Verify proper phase-to-ground clearance
### Table 15

**Preferred rated switching currents for interrupter switches**

<table>
<thead>
<tr>
<th>Line Number</th>
<th>Rated maximum Voltage kV rms</th>
<th>Load and loop current amps</th>
<th>Unloaded Transformer current amps</th>
<th>Line charging current</th>
<th>Isolated Capacitor bank current amps</th>
<th>Cable charging current amps</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.25</td>
<td>RCC 2</td>
<td>See Note 2</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>15.0, 15.5</td>
<td>RCC 2</td>
<td>See Note 2</td>
<td>10</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>23.8, 27.0</td>
<td>RCC 2</td>
<td>See Note 2</td>
<td>10</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>4</td>
<td>38.0</td>
<td>RCC 2</td>
<td>See Note 2</td>
<td>10</td>
<td>10</td>
<td>250</td>
</tr>
<tr>
<td>5</td>
<td>48.3</td>
<td>RCC 2</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>250</td>
</tr>
<tr>
<td>6</td>
<td>72.5</td>
<td>RCC 2</td>
<td>10</td>
<td>13</td>
<td>15</td>
<td>630</td>
</tr>
<tr>
<td>7</td>
<td>121.0</td>
<td>RCC 2</td>
<td>10</td>
<td>10</td>
<td>35</td>
<td>315</td>
</tr>
<tr>
<td>8</td>
<td>145.0</td>
<td>RCC 2</td>
<td>8</td>
<td>8</td>
<td>50</td>
<td>315</td>
</tr>
<tr>
<td>9</td>
<td>169.0</td>
<td>RCC 2</td>
<td>8</td>
<td>7</td>
<td>75</td>
<td>400</td>
</tr>
<tr>
<td>10</td>
<td>242.0</td>
<td>RCC 2</td>
<td>8</td>
<td>5</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>11</td>
<td>362.0</td>
<td>RCC 2</td>
<td>5</td>
<td>-</td>
<td>350</td>
<td>-</td>
</tr>
</tbody>
</table>

**NOTES:**

1. RCC = rated continuous current from tables 3, 9 or 12 ye. 200, 400, 600, 1200, 1600, 2000, 3000, 4000, 5000 and 6000 amps.

2. These switches are capable of switching unloaded transformers rated 2500 kVA or less provided the switches have demonstrated their ability to switch their rated load current. For larger transformers or switches not having load switching ratings, consult manufacturer.

---

*Interrupter switches may have one or more specifically assigned switching ratings. Refer to Annex A for typical system values.*

**Values given are for station class switches. Preferred ratings for distribution class switches have not been established. Consult manufacturer.**

***These devices are typically high-velocity, wrap or rigid arm devices, having unconfined arcs with air as the dielectric medium and are usually inserted in the circuit during the opening process.***

****These devices are interrupters with gas, vacuum, or oil as the interrupting medium.***
## A.2

Typical system values for cable and line charging currents

<table>
<thead>
<tr>
<th>Rated Maximum Voltage kV rms</th>
<th>Overhead Line Current A/mile</th>
<th>Typical Line Length miles</th>
<th>Line Charging Current Amps</th>
<th>Cable Charging Current A/mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.25</td>
<td>0.03</td>
<td>10</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>15.0, 15.5</td>
<td>0.06</td>
<td>10</td>
<td>0.6</td>
<td>2.8</td>
</tr>
<tr>
<td>25.8, 27.0</td>
<td>0.10</td>
<td>20</td>
<td>2.0</td>
<td>3.2</td>
</tr>
<tr>
<td>38.0</td>
<td>0.14</td>
<td>30</td>
<td>4.2</td>
<td>3.5</td>
</tr>
<tr>
<td>48.3</td>
<td>0.17</td>
<td>30</td>
<td>5.1</td>
<td>9.8</td>
</tr>
<tr>
<td>72.5</td>
<td>0.28</td>
<td>50</td>
<td>14.0</td>
<td>15.7</td>
</tr>
<tr>
<td>121.0</td>
<td>0.44</td>
<td>80</td>
<td>35.2</td>
<td>18.2</td>
</tr>
<tr>
<td>145.0</td>
<td>0.52</td>
<td>100</td>
<td>52.0</td>
<td>19.4</td>
</tr>
<tr>
<td>169.0</td>
<td>0.61</td>
<td>120</td>
<td>73.2</td>
<td>20.0</td>
</tr>
<tr>
<td>242.0</td>
<td>0.87</td>
<td>170</td>
<td>147.9</td>
<td>22.3</td>
</tr>
<tr>
<td>362.0</td>
<td>1.31</td>
<td>250</td>
<td>327.5</td>
<td>-</td>
</tr>
</tbody>
</table>
## Switch Interrupter Selection Guide

<table>
<thead>
<tr>
<th>Product</th>
<th>Load Breaking</th>
<th>Loop Splitting</th>
<th>Line/Cable Dropping</th>
<th>Transformer Magnetizing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Arcing Horn</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Quick Break Whip</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>High Speed Whip-<strong>HSW</strong></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td><strong>MAG I™</strong></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Load and Line Switchers (<strong>LLS®</strong>)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Arcing Horn

Quick Break Whip
High Speed Whip  Magnetic Interrupter
Load and Line Switcher