Introduction

• Where Do I Start My Design?
• Substation Design
  • Electrical Configuration
  • Equipment Specification
  • Protection & Control
  • Physical Arrangement
  • Grounding Considerations
• Design & Construction Coordination
  • Engineering Process
  • Build Process
Where Do I Start My Design?
Questions to Address

• Service Conditions?
  • Location, Altitude, High and Low Mean Temperatures, Temperature Extremes, Wind Loading, Ice Loading, Seismic Qualifications, Area Classification, Contamination

• Primary System Characteristics?
  • Local Utility, Nominal Voltage, Maximum Operating Voltage, System Frequency, System Grounding, System Impedance Data

• Secondary System Characteristics?
  • Nominal Voltage, Maximum Operating Voltage, System Grounding

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

• Substation Layout Considerations?
  • Available Real Estate, Substation Configuration, Necessary Degree of Reliability and Redundancy, Number of Incoming Lines, Proximity to Transmission Lines and Loads

• Utility Requirements?
  • Application of Utility Specifications, Application of Utility Standards, Application of Utility Protection and Control Schemes, SCADA/RTU Interface, Metering Requirements

• Insulation Requirements?
  • BIL, Insulator Creep, Bushing Creep, Minimum Clearances, Phase Spacing, Arrester Duty
Questions to Address

• Current Requirements?
  • Rated Continuous Current, Maximum 3-Phase Short-Circuit Current, Maximum Phase-to-Ground Short-Circuit Current

• Substation Monitoring?
  • Manned or Unmanned, Power Management/Trending, Fault Recording, Local & Remote Annunciation, Local & Remote Control

• Geotech Conditions?
  • Soil Boring Results, Soil Resistivity, SPCC (spill prevention) Plans, SWPPP (storm water) Plan

• Electrical Studies?
  • Power Flow, Short-Circuit, Device Evaluation, Device Coordination, Arc-Flash Hazard Assessment, Motor Starting, Transient Stability, Insulation Coordination, Harmonic Analysis
Major Factors in Substation Selection

• Required Power (1 MVA, 10 MVA, 100 MVA)
• Budgeted Capital for Substation
• 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
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
Electrical Configuration

<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>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
Electrical Configurations

- Single Breaker / Single Bus
- Ring Bus
- Breaker and a Half
- Double Breaker / Double Bus
Electrical Configuration

\( \lambda = \) 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>
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<tr>
<td>c</td>
<td>0.00301</td>
<td>184.56</td>
<td>0.56</td>
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<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>
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<tr>
<td>b</td>
<td>0.0459</td>
<td>76.35</td>
<td>3.50</td>
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<tr>
<td>c</td>
<td>0.00356</td>
<td>175.76</td>
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<tr>
<td>d</td>
<td>0.00572</td>
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<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"
Tap Substation

- Most Basic Design
- Tapped Line is Source of Power
- No Operating Flexibility
Tap Substation

Other client

Other client

Other client

HV Engineering, LLC   -   High Voltage Substation Design
A tap substation is at the subjected to any reliability problems with other clients on the same line.
Tap Substation

- 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

Line Fault

Bus Fault

Failed Breaker
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
Ring Bus

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

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 (standard)

Line/Bus Fault

Failed Breaker

Load 1  Load 2  Line 1  Line 2

Load 1  Load 2  Line 1  Line 2
Ring Bus (line-load-line-load)

Line/Bus Fault

Failed Breaker

Line 1

Load 2

Line 1

Load 2

Load 1

Line 2

Load 1

Line 2
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)
Breaker-And-A-Half

Pros
• Robust
• Highly Expandable
• Failed Outer Breakers Result in Loss of One Circuit Only
• Breaker Maintenance w/o Circuit Interruption

Cons
• Cost
• Physically Large
• Failed Center Breaker Results in Loss of Two Circuits
Double Breaker Double Bus

- Highly Flexible Arrangement
- Two Buses, Each Separated by Two Circuit Breakers
- Two Circuit Breakers per Circuit
- All Breakers Normally Closed
Double Breaker Double Bus

Pros
- Bus Faults Do Not Interrupt Any Circuit
- Circuit Faults Do Not Interrupt Any Buses or Other Circuits
- Failed Breaker Results in Loss of One Circuit Only
- Breaker Maintenance w/o Circuit Interruption
- Highly Expandable
- Robust

Cons
- Cost – Two Breakers & Four Switches per Circuit
- Physical Size
Protection & Control
Protection & Control

• Protection
  • Fundamentals
  • Bus
  • Transformers
  • Motors
  • Primary/Back-up Systems
  • Breaker Failure
A.C. Fundamentals
Phasor Relationships

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

Residual CT connection
Zero sequence CT
Protected Bus

IEEE Engineering, LLC - High Voltage Substation Design
January 9, 2019
A.C. Fundamentals
Tap Substation
Tap Substation

- Phase Protection
  - Overcurrent
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

HV Engineering, LLC   - High Voltage Substation Design

January 9, 2019
Tap Substation

- Phase Protection
  - Full Differential
  - Overcurrent

- Pros
  - Higher selectivity

- Cons
  - Higher cost

HV Engineering, LLC   - High Voltage Substation Design
Tap Substation

• Ground Protection
Secondary Selective Arrangement – N.O. Tie

Partial relaying scheme shown for clarity.

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

Partial relaying scheme shown for clarity.

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

Partial relaying scheme shown for clarity.

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

(High Speed Bus Protection)

Partial relaying scheme shown for clarity.

Relaying not shown for clarity.
Partial relaying scheme shown for clarity.

Special care must be taken when operating with tie closed due to CT performance mis-match / CT saturation.

Suggest setting 50P element:
- > 20% max fault current
- < 50% minimum arcing fault

Time delay depends on relay operation time.
Secondary Selective Arrangement – N.C. Tie

Polarizing input not shown for clarity

Relaying not shown for clarity
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
Bus Protection

• Concerns
  • Large number of circuits and different fault levels
  • Different levels of DC saturation

• 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

Linear couplers are like CTs except no iron in the core and number of secondary turns is much higher.

No saturation due to air core design

Voltage Differential – Using Air Core CTs called “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:

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

<table>
<thead>
<tr>
<th>Type</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overcurrent w/o Restraint</td>
<td>Simple</td>
<td>Slow Not selective/reliable</td>
</tr>
<tr>
<td></td>
<td>Low cost</td>
<td></td>
</tr>
<tr>
<td>ZSI</td>
<td>High Speed</td>
<td>Dependent on inputs/outputs Additional Wiring</td>
</tr>
<tr>
<td></td>
<td>Selective</td>
<td></td>
</tr>
<tr>
<td>High Z Impedance</td>
<td>High Speed</td>
<td>Dedicated CTs</td>
</tr>
<tr>
<td></td>
<td>Selective</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Easy to Expand</td>
<td>Difficult to test system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lack of trip info</td>
</tr>
<tr>
<td>Low Z Impedance w/ Restraint</td>
<td>High Speed</td>
<td>Size of relay (relay inputs) Cost</td>
</tr>
<tr>
<td></td>
<td>Share CTs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CT Mismatch Allowed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Event record data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexible</td>
<td></td>
</tr>
<tr>
<td>Linear Coupler</td>
<td>High speed</td>
<td>Expensive</td>
</tr>
<tr>
<td></td>
<td>Selective</td>
<td>Dedicated couplers</td>
</tr>
<tr>
<td></td>
<td>Reliable</td>
<td></td>
</tr>
</tbody>
</table>
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

• 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
  - Residually connected phase CTs
  - Internally calculated neutral current
- 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
Motor Protection

• Typically Zero Sequence CT
  • 50:5, C10
Motor Protection

• Typically Zero Sequence CT
  • 50:5, C10

...but rarely is the system grounding considered.

This configuration works well on a low resistance grounded system (LRG), but what if the system is effectively grounded??

- Will the relay really produce 2000 A secondary?
- Will the relay inputs burn up?
- Will the wiring burn up?
- Will the CT produce any current?
Motor Protection

• An option is to use residually connected CTs or have the relay calculate the residual current

• This works well but often does not allow setting of an instantaneous trip because the CTs will see different currents during LRA and may saturate differently
Motor Protection

- Consider a larger GFCT
- Reduce secondary current from 2,000 A to 166 A
- Increase the accuracy class to ensure CT does not lay down
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
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!!!
Physical Arrangement
### Spacing & Clearances

- NEMA SG-6 (has been withdrawn, but still used across industry)
- IEEE 1427-2006
  - BIL Based
  - Rec. Phase-to-Phase, Min. Metal-to-Metal, Min. Phase to Ground
  - Rec. Bus Spacings including Horn Gap

#### Table 36.2: Outdoor Substations—Basic Parameters

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Rated Withstand Voltage</th>
<th>Minimum Metal-to-Metal Distance Between Rigidly Supported Energized Conductors, Inches (meters)</th>
<th>Minimum Ground Clearance, Inches (meters)</th>
<th>Recommended Phase Spacing, Center to Center, Inches (meters)</th>
<th>BIL Based</th>
<th>Rec. Bus Spacings including Horn Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8.3</td>
<td>95.0</td>
<td>30.0</td>
<td>7.8 (0.19)</td>
<td>10.7 (0.27)</td>
<td>3.6 (0.09)</td>
</tr>
<tr>
<td>2</td>
<td>15.5</td>
<td>110.0</td>
<td>45.0</td>
<td>8.8 (0.20)</td>
<td>11.6 (0.29)</td>
<td>3.9 (0.10)</td>
</tr>
<tr>
<td>3</td>
<td>27.5</td>
<td>160.0</td>
<td>60.0</td>
<td>11.0 (0.22)</td>
<td>15.7 (0.39)</td>
<td>4.3 (0.11)</td>
</tr>
<tr>
<td>4</td>
<td>36.0</td>
<td>200.0</td>
<td>80.0</td>
<td>14.1 (0.36)</td>
<td>19.3 (0.48)</td>
<td>4.7 (0.12)</td>
</tr>
<tr>
<td>5</td>
<td>48.3</td>
<td>250.0</td>
<td>100.0</td>
<td>18.2 (0.46)</td>
<td>24.6 (0.62)</td>
<td>5.1 (0.13)</td>
</tr>
<tr>
<td>6</td>
<td>72.5</td>
<td>350.0</td>
<td>145.0</td>
<td>25.0 (0.64)</td>
<td>34.3 (0.87)</td>
<td>5.7 (0.15)</td>
</tr>
<tr>
<td>7</td>
<td>123</td>
<td>550.0</td>
<td>230.0</td>
<td>31.0 (0.79)</td>
<td>44.5 (1.12)</td>
<td>6.3 (0.16)</td>
</tr>
<tr>
<td>8</td>
<td>145</td>
<td>650.0</td>
<td>275.0</td>
<td>37.0 (1.13)</td>
<td>53.5 (1.34)</td>
<td>7.0 (0.18)</td>
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<tr>
<td>9</td>
<td>170</td>
<td>750.0</td>
<td>350.0</td>
<td>43.0 (1.53)</td>
<td>66.0 (1.67)</td>
<td>7.6 (0.20)</td>
</tr>
<tr>
<td>10</td>
<td>245</td>
<td>900.0</td>
<td>385.0</td>
<td>51.0 (1.33)</td>
<td>79.0 (1.99)</td>
<td>8.2 (0.21)</td>
</tr>
<tr>
<td>11</td>
<td>245</td>
<td>1050.0</td>
<td>465.0</td>
<td>59.0 (2.30)</td>
<td>92.0 (2.33)</td>
<td>8.8 (0.22)</td>
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<tr>
<td>12</td>
<td>352</td>
<td>1050.0</td>
<td>465.0</td>
<td>67.0 (2.67)</td>
<td>119.0 (3.02)</td>
<td>9.4 (0.24)</td>
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<tr>
<td>13</td>
<td>352</td>
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<td>625.0</td>
<td>75.0 (2.95)</td>
<td>136.0 (3.44)</td>
<td>10.0 (0.26)</td>
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<tr>
<td>14</td>
<td>550</td>
<td>1500.0</td>
<td>620.0</td>
<td>94.0 (3.66)</td>
<td>150.0 (3.79)</td>
<td>10.6 (0.28)</td>
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<td>550</td>
<td>1800.0</td>
<td>710.0</td>
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<td>166.0 (4.22)</td>
<td>11.2 (0.30)</td>
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<tr>
<td>16</td>
<td>800</td>
<td>2050.0</td>
<td>830.0</td>
<td>132.0 (4.85)</td>
<td>184.0 (4.95)</td>
<td>11.8 (0.32)</td>
</tr>
</tbody>
</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-72-151-6 (Vol. No. 5, page 1224), which is a report of the Transmission Substations Subcommittee. For additional switching surge values and ground clearances, refer to ANSI C2.
<table>
<thead>
<tr>
<th>Maximum system voltage (kV, rms)</th>
<th>Basic BIL</th>
<th>Minimum phase-to-ground clearance (mm, in)</th>
<th>Minimum phase-to-phase clearance (mm, in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>30</td>
<td>57 (2.3)</td>
<td>63 (2.5)</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>115 (4.5)</td>
<td>125 (5)</td>
</tr>
<tr>
<td>15</td>
<td>95</td>
<td>180 (7)</td>
<td>200 (8)</td>
</tr>
<tr>
<td>26.2</td>
<td>120</td>
<td>285 (11)</td>
<td>315 (12)</td>
</tr>
<tr>
<td>36.2</td>
<td>200</td>
<td>380 (16)</td>
<td>420 (16)</td>
</tr>
<tr>
<td>48.3</td>
<td>250</td>
<td>475 (19)</td>
<td>525 (21)</td>
</tr>
<tr>
<td>72.5</td>
<td>350</td>
<td>665 (26)</td>
<td>750 (29)</td>
</tr>
<tr>
<td>121</td>
<td>330</td>
<td>685 (26)</td>
<td>730 (29)</td>
</tr>
<tr>
<td>450</td>
<td>350</td>
<td>685 (26)</td>
<td>940 (37)</td>
</tr>
<tr>
<td>150</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>145</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>430</td>
<td>350</td>
<td>685 (26)</td>
<td>940 (37)</td>
</tr>
<tr>
<td>550</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>650</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>169</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>750</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>242</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>322</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>400</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>450</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>500</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>550</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>600</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>650</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>700</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>750</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</td>
</tr>
<tr>
<td>800</td>
<td>350</td>
<td>685 (26)</td>
<td>1150 (45)</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”

*Clearances shown are based on a 605 kV/\text{in} Flashover gradient. See 6.3.1 for other choices.
*Switching surge conditions normally govern for system voltages above 242 kV. See Table 5.
*Values for maximum system voltages and BIL levels are from Table 1 and Table 2 of IEEE Std 1313-1-1996, except for the 1.2 kV and 5 kV system voltage and the 30 kV, 45 kV, 60 kV, 75 kV, and 1320 kV BIL values.
*For specific equipment clearance values, see relevant apparatus standards.
*For specific equipment clearances shown in this table are metal-to-metal clearances not bus-to-bus clearances.
*Additional considerations for safety clearances must be evaluated separately (see Clause 7).

HV Engineering, LLC - High Voltage Substation Design
January 9, 2019
Spacing & Clearances

- NESC (ANSI/IEEE C2)
  - Installation and Maintenance Requirements for Stations, Aerial Lines, Underground Circuits
  - Grounding Methods
  - Safety Based Standard
# Contamination Levels

Multiplier applied to phase-to-ground voltage

**Table 1 - Bushing Data**

<table>
<thead>
<tr>
<th>System Voltage</th>
<th>Maximum kV</th>
<th>BIL kV</th>
<th>Creepage Distance in Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Light [1]</td>
</tr>
<tr>
<td>34.5</td>
<td>38.0</td>
<td>200</td>
<td>22</td>
</tr>
<tr>
<td>46</td>
<td>48.0</td>
<td>250</td>
<td>29</td>
</tr>
<tr>
<td>69</td>
<td>72.5</td>
<td>350</td>
<td>44</td>
</tr>
<tr>
<td>115</td>
<td>121.0</td>
<td>550</td>
<td>73</td>
</tr>
<tr>
<td>138</td>
<td>145.0</td>
<td>650</td>
<td>88</td>
</tr>
<tr>
<td>161</td>
<td>169.0</td>
<td>750</td>
<td>102</td>
</tr>
<tr>
<td>230</td>
<td>242.0</td>
<td>900</td>
<td>146</td>
</tr>
<tr>
<td>345</td>
<td>362.0</td>
<td>1175</td>
<td>220</td>
</tr>
<tr>
<td>500</td>
<td>550.0</td>
<td>1675</td>
<td>318</td>
</tr>
<tr>
<td>765</td>
<td>800.0</td>
<td>2050</td>
<td>487</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>44</td>
</tr>
<tr>
<td>69</td>
<td>85</td>
</tr>
<tr>
<td>115</td>
<td>141</td>
</tr>
<tr>
<td>138</td>
<td>169</td>
</tr>
<tr>
<td>161</td>
<td>198</td>
</tr>
<tr>
<td>230</td>
<td>282</td>
</tr>
<tr>
<td>345</td>
<td>423</td>
</tr>
<tr>
<td>500</td>
<td>614</td>
</tr>
<tr>
<td>765</td>
<td>939</td>
</tr>
</tbody>
</table>

**Table 2 - Contamination Multipliers**

<table>
<thead>
<tr>
<th>Contamination Level</th>
<th>Multiplying Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>28mm/kV</td>
</tr>
<tr>
<td>Medium</td>
<td>35mm/kV</td>
</tr>
<tr>
<td>Heavy</td>
<td>44mm/kV</td>
</tr>
<tr>
<td>Extra Heavy</td>
<td>54mm/kV</td>
</tr>
</tbody>
</table>

**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.
BIL vs Creep

Typical Draw-Lead Bushing
Spacing & Clearances

• IEEE 979 – Substation Fire Protection

4.3 Fire barriers

The manner of oil contained in power transformers and circuit breakers varies with the manufacturer, voltage rating, and MVA rating. Some typical volumes are given in Table 1. The contents of the possible fire area and the hazards resulting from the igniting of oil-laid equipment units can be exaggerated by the factors that 1.5 gal (7L) of oil will cover an uncontrolled fire so that the volume of oil-vaporized steam in a normally ventilated enclosure is a fire hazard, and that an oil-laid equipment unit of 30 gal (114L) has a 50% chance of backfire, and that an oil-laid equipment unit of 100 gal (378L) has a 25% chance of backfire.

Removable fire barriers should be considered when space is needed for equipment maintenance or replacement.

### Table 1: Typical oil quantities in equipment

<table>
<thead>
<tr>
<th>Transformers</th>
<th>Circuit breakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>Typical MVA rating</td>
</tr>
<tr>
<td>12500 and below</td>
<td>150 MVA oil-filled</td>
</tr>
<tr>
<td>15000-30000</td>
<td>50-150 MVA oil-filled</td>
</tr>
<tr>
<td>30000-50000</td>
<td>50-150 MVA oil-filled</td>
</tr>
<tr>
<td>50000-75000</td>
<td>5-50 MVA oil-filled</td>
</tr>
<tr>
<td>100M and below</td>
<td>1 MVA oil-filled</td>
</tr>
</tbody>
</table>

4.4 Transformer outdoor installations

Subsections 4.4.1 and 4.4.2 give recommendations for separation, barrier installations, and grounding systems for the termination of conductor connections.

4.4.5 Separation of large transformers from buildings

Transformers containing 3000 gal (11400L) or more of containing oil should be at least 20 ft (6.1 m) from any building. If these large oil-filled transformers are located between 20 and 50 ft (6.1-15.2 m) of a building, the exposed walls of the building should be considered, as well as the height of the building, and the transformer should be protected by a barrier installation. If transformers are located within 20 ft (6.1 m) of a building, the transformer should be considered as a potential hazard, and a barrier installation should be provided. If transformers are located within 50 ft (15.2 m) of a building, the transformer should be considered as a potential hazard, and a barrier installation should be provided. If transformers are located within 100 ft (30.5 m) of a building, the transformer should be considered as a potential hazard, and a barrier installation should be provided. If transformers are located within 200 ft (61 m) of a building, the transformer should be considered as a potential hazard, and a barrier installation should be provided. If transformers are located within 300 ft (91 m) of a building, the transformer should be considered as a potential hazard, and a barrier installation should be provided. If transformers are located within 400 ft (122 m) of a building, the transformer should be considered as a potential hazard, and a barrier installation should be provided.

4.6.2 Separation of small transformers from buildings

Transformers containing less than 3000 gal (11400L) of containing oil should be separated from buildings by the minimum distance shown in Table 2.

#### Table 2: Separation of small transformers from buildings

<table>
<thead>
<tr>
<th>Transformer rating</th>
<th>Minimum separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>From building</td>
</tr>
<tr>
<td>1000 kVA</td>
<td>15 ft (4.6 m)</td>
</tr>
<tr>
<td>2500 kVA</td>
<td>30 ft (9.1 m)</td>
</tr>
<tr>
<td>5000 kVA</td>
<td>45 ft (13.7 m)</td>
</tr>
</tbody>
</table>

Where a transformer is installed less than the minimum distance, the building should be fire-resistant with a minimum 1 hr fire-rated barrier.

4.6.3 Separation between large transformers

Large oil-filled transformers should be separated by at least 30 ft (9.1 m) of clear space and a minimum 1 hr fire-rated barrier.

4.6.4 Fire barrier size

The height of a fire barrier should be at least 1 ft (0.3 m) above the height of the oil-filled circuit breaker, transformer tank, or oil-sprayed (impregnated) transformer terminal, transformer housing, or transformer-rated switch. This height should extend from 1 ft (0.3 m) and terminate at the top of the transformer tank, or oil-sprayed (impregnated) transformer terminal, transformer housing, or transformer-rated switch. The height should be increased to 2 ft (0.6 m) in high fire hazard areas, and 3 ft (0.9 m) in very high fire hazard areas.

4.6.5 Electrical grounding systems

Automatic grounding systems should be considered for oil-filled capacitor banks, except those that are adequately protected in accordance with 4.4.1 and 4.4.2. 4.4.3, and 4.4.4, or that qualify as:

a) Space transformers are intended to be used in place, or
b) Transformers contain less than 30 gal (114L) of combustible transformer fluid.

January 9, 2019
HV Engineering, LLC - High Voltage Substation Design
# Dielectric Fluids

**NEC® Requirement Guidelines**

**2011 Code Options for the Installation of Listed Less-Flammable Liquid-Filled Transformers**

## 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/(m³)</th>
<th>Horizontal Distance**</th>
<th>Vertical Distance ft/(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fire Resistant ft/(m)</td>
<td></td>
</tr>
<tr>
<td>Loss-Flammable</td>
<td>Yes</td>
<td>N/A</td>
<td>3 (0.9)</td>
<td>3 (0.9)</td>
</tr>
<tr>
<td>(Approved)</td>
<td></td>
<td></td>
<td>5 (1.5)</td>
<td>25 (7.6)</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td></td>
<td>15 (4.6)</td>
<td>50 (15.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15 (4.6)</td>
<td>50 (15.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;500 (1.9)</td>
<td>15 (4.6)</td>
<td>25 (7.6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500-5,000 (1.9-19)</td>
<td>25 (7.6)</td>
<td>50 (15.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;5,000 (19)</td>
<td>25 (7.6)</td>
<td>100 (30.5)</td>
</tr>
<tr>
<td>Mineral Oil</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 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></td>
<td></td>
<td>N/A</td>
<td>3 (0.9)</td>
</tr>
<tr>
<td>Loss-Flammable</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Approved)</td>
<td></td>
<td>&lt;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></td>
<td></td>
<td>&lt;500 (1.9)</td>
<td>6 (1.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500-5,000 (1.9-19)</td>
<td>25 (7.6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;5,000 (19)</td>
<td>50 (15.2)</td>
</tr>
<tr>
<td>Mineral Oil</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* FM Global Loss Prevention Data Sheet 5-4, Table 2b

** All transformer components must be accessible for inspection and maintenance.
Less-Flammable Liquid-Insulated Transformers
Compliance to NEC 2011 Section 450.23 per FM Listing

Requirement Highlights for Outdoor Installations

FM Requirements Detail

- **FM Approved Less-Flammable Fluid**
  - Yes
  - No

- **More than 10,200 gallons**
  - Yes
  - No

- **Spill exposure to building (ground sloping toward building or over)**
  - Yes
  - No

- **UL/EPAL Environmental Technology Verification (ETV)** status for Ready Degradation
  - Yes
  - No

- **More than 20,000 gallons**
  - Yes
  - No

- **Containment per FM LPD**
  - Yes
  - No

- **FM LPD Installation Options for Mineral Oil or Non-Approved Fluid**
  - Minimum separation distances per Section 2.3.1.1, Tables 2A & 2B
    - 5-100 feet horizontal
    - 25-500 feet vertical OR
    - 25-50 feet horizontal
    - 35-50 feet vertical

- **FM Approved “Transformer” or equivalent**
  - Yes
  - No

- **Minimum separation distances per FM LPD**
  - Yes
  - No

- **Compliance with NEC 450.23**
  - Yes
  - No

UL Classification Marking Requirements

- **UL Classification Marking**
  - Yes
  - No

2011 Code Options for the Installation of Listed Less-Flammable Liquid-Filled Transformers

- **Compliance with NEC 450.23**
  - Yes
  - No

Appendix 3

- FM Global Approval Guide
- Environmental Technology Verification Program, U.S. Environmental Protection Agency (Envirowatts FR fluid and Enviromax SR fluid have ETV status for Ready Degradation)

Appendix 4

- UL Classification Dielectric Fluids (EOD) states that “liquids intended for use as dielectric and cooling mediums in electrical transformers are covered under Transformer Fluids (EOD).”

NOTES:
- UL Classification Dielectric Fluids (EOD) states that “liquids intended for use as dielectric and cooling mediums in electrical transformers are covered under Transformer Fluids (EOD).”
Structural Requirements

• 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

Station Design

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

• **Low Profile** (Tubular / Folded Plate Structures)
  - Polygonal Shapes > Four Sides
  - Common Shapes
    - Octagon – Eight Sides
    - Dodecagon – Twelve Sides
  - Short Erection Time
  - Aesthetical Pleasing
  - Requires Greater Site Area
  - Shapes are not Readily Available
Station Design

• **Low Profile** (Standard “Extruded” Shapes)
  • Wide Flange, Channel, Plates, Structural Tubing (Round, Square, Rectangular)
  • Short Erection Time
  • Aesthetical Pleasing
  • Most Sizes Readily Available
  • Requires Greater Site Area

• **GIS** (Gas Insulated Substation)
Typical Ring Bus Substation Installation
Station Design - Conventional
Station Design – Low Profile (tube)
Station Design – Low Profile (tube)
Station Design – Low Profile (tube)
Deadend Structures

- **Common Types**
  - A-Frame or H-Frame
  - Lattice, Wide Flange, Structural Tubing
  - Inboard or Outboard Leg Design
Deadend Structure
Prefab Switchgear Building
Surge & Lightning Protection

- 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
    - The keraunic (or ceraunic) level was the average number of days per year when thunder was heard in a given area
Surge & Lightning Protection

• Lightning Protection (cont’d)
  • 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
OPGW Installation

Considerations:
1. Ensure OPGW is suitable for available short circuit
2. Ensure proper grounding
3. Ensure safe installation
OPGW Installation
OPGW / Static Wire Installation

Remember
1. Surges (lightning and switching) are high frequency (>> 60 hz)
2. At high frequencies, the inductance significantly increases the impedance:

\[ Z = 2\pi f L \]

L steel structure >> L copper ground wire

Z steel structure >> Z copper ground wire

Additionally, skin effect causes the effective resistance of wire to be much greater at high frequencies.

As an example, a length wire at 60 hz has resistance of 25 Ω compared to 250 Ω at 10,000 hz

For effective lightning and surge protection, ensure that static wire or lightning rod is grounded effectively (via high strand copper ground wire) to the ground grid rather than relying on the highly inductive path of the steel structure.
OPGW / Static Wire Back Flashover (BFO)

V1 = Direct stroke of lightning to a transmission tower produces a voltage surge on the tower structure.
V2 = Surge voltage with same waveform and lower amplitude induces on the phase conductors. The coupling factor between V1 and V2 may be variable from 15% to 25%.

V = The voltage applied to the line insulator is equal to instantaneous difference between V1 and V2.

D = illustrates insulation strength of line insulator.

When these curves meet each other at t1 an electrical arc starts from tower structure toward phase conductor. Then the major part of electrical charges transmits to phase conductor’s throe the arcing pass and increase its voltage from V2 to V1 suddenly. So the surge voltage created on phase conductor as a result of BFO.

OHGW / Static Wire Installation
OHGW / Static Wire Installation
OHGW / Static Wire Installation
Grounding Considerations
Grounding

  - Safety Risks
  - Humans as Electrical Components
  - Soil Modeling
  - Fault Currents and Voltage Rise
- NESC
  - Points of Connection
  - Messengers & Guys, Fences
  - Grounding Conductors, Ampacity, Strength, Connections
  - Grounding Electrodes
  - Ground Resistance Requirements
Engineering & Construction Coordination
Engineering Process

One-Lines & Specifications

Electrical Plans/Details

Protection & Control Schemes

Relay Panel Specifications & Elevations

Site, Grading SPCC SWPPP

Wiring Diagrams

Relay Settings

Foundation Plans/Details

Building Plans/Details

Conduit Plans/Details

Grounding Plans/Details

HV Engineering, LLC   - High Voltage Substation Design

January 9, 2019
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
CenterPoint Tap Substation 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)
Future Expansion Possibilities

• Others
  • Ring Bus with Offset Lines
  • Expandable Bus
Mixing Bus Arrangements

• Example: Industrial
  • High-Voltage Ring Bus
  • Two Single Breaker Single Bus Medium-Voltage Systems with Tie Breaker (a.k.a. Secondary Selective)

• Variations Exist
  • Swap Line and Transformer Positions
  • Add 2nd Tie Breaker
Questions?