HV Substation Design: Applications and Considerations

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HV Engineering
www.hv-eng.com
Agenda

- Substation Basics
- One Lines and One Line Relaying & Meter Diagrams
- AC Fundamentals
- Three Lines Diagrams
- Physical Arrangement
- Surge and Lightning Protection
- Grounding Considerations
- Engineering & Construction Coordination
- Supplement Topics-Slides
- Appendix-Slides
Electrical System

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

<table>
<thead>
<tr>
<th>Voltage Level</th>
<th>Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>765 kV</td>
<td>161 kV</td>
</tr>
<tr>
<td>500 kV</td>
<td>138 kV</td>
</tr>
<tr>
<td>345 kV</td>
<td>115 kV</td>
</tr>
<tr>
<td>230 kV</td>
<td>69 kV</td>
</tr>
</tbody>
</table>

### DISTRIBUTION LEVEL VOLTAGES

<table>
<thead>
<tr>
<th>Voltage Level</th>
<th>Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>69kV</td>
<td></td>
</tr>
<tr>
<td>46 kV</td>
<td>15 kV</td>
</tr>
<tr>
<td>34.5 kV</td>
<td>4.16 kV</td>
</tr>
<tr>
<td>23 kV</td>
<td>480 V</td>
</tr>
</tbody>
</table>

Grey area…
…sometimes referred to a sub-transmission also.
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
765 kV Live Tank and Dead Tank Breakers
Substation Switching Equipment

- Disconnect/Isolation Switches (visual isolation)
- Fuses (single phase protection device)
- Circuit Switcher (three phase protection device)
- Circuit Breaker
Switch

Arcing Horns (will only break very small amounts of charging or magnetizing current)
Switch

High Speed Whip (will break larger currents than just a switch with just arcing horns but not load break)
Switch

Load Break
Fuses
Circuit Switcher

138 kV
Circuit Breaker

69 kV Oil Dead Tank
Circuit Breaker

230 kV SF$_6$ Dead Tank
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 1 - Bushing Data**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>34.5</td>
<td>38.0</td>
<td>200</td>
<td>22</td>
<td>27</td>
<td>35</td>
<td>42</td>
</tr>
<tr>
<td>46</td>
<td>48.0</td>
<td>250</td>
<td>29</td>
<td>37</td>
<td>46</td>
<td>56</td>
</tr>
<tr>
<td>69</td>
<td>72.5</td>
<td>350</td>
<td>44</td>
<td>55</td>
<td>69</td>
<td>85</td>
</tr>
<tr>
<td>115</td>
<td>121.0</td>
<td>550</td>
<td>73</td>
<td>91</td>
<td>115</td>
<td>141</td>
</tr>
<tr>
<td>138</td>
<td>145.0</td>
<td>650</td>
<td>88</td>
<td>110</td>
<td>138</td>
<td>169</td>
</tr>
<tr>
<td>161</td>
<td>169.0</td>
<td>750</td>
<td>102</td>
<td>128</td>
<td>161</td>
<td>198</td>
</tr>
<tr>
<td>230</td>
<td>242.0</td>
<td>900</td>
<td>146</td>
<td>183</td>
<td>230</td>
<td>282</td>
</tr>
<tr>
<td>345</td>
<td>362.0</td>
<td>1175</td>
<td>220</td>
<td>274</td>
<td>345</td>
<td>423</td>
</tr>
<tr>
<td>500</td>
<td>550.0</td>
<td>1675</td>
<td>318</td>
<td>398</td>
<td>500</td>
<td>614</td>
</tr>
<tr>
<td>765</td>
<td>800.0</td>
<td>2050</td>
<td>487</td>
<td>609</td>
<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.

### Physical Questions to Address
Electrical Studies

- Power/Load Flow
- Short-Circuit / Device Evaluation
- Device Coordination
- Arc-Flash Risk 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
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

<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>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-Doubler Bus</td>
<td>190%</td>
</tr>
</tbody>
</table>

Reference: IEEE 605-2008
\[ \lambda = \text{Annual Fail Rate} \]

\[ r = \text{Annual Outage Time} \]

\[ U = \text{Average Outage Time} \]

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>

- a. Single bus
- b. Sectionalized single bus
- c. Breaker-and-a-half
- d. Double breaker-double bus
- e. Ring bus

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.

Tap Substation
• Most Basic Design
• Tapped Line is Source of Power
• Interrupting Device Optional but Recommended
• No Operating Flexibility

Tap Substation

Depending on configuration, second disconnect switch may not be necessary
Tap Substation
• Most Basic Design
• Tapped Line is Source of Power
• Interrupting Device Optional but Recommended
• No Operating Flexibility

Tap Substation

Fault at any location results in total outage.
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
<table>
<thead>
<tr>
<th><strong>Pros</strong></th>
<th><strong>Cons</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Each Circuit has Breaker</td>
<td>• Circuit Breaker Maintenance Requires Circuit Outage</td>
</tr>
<tr>
<td>• Only One Set of VTs Required</td>
<td>• Bus Fault Clears all Circuits</td>
</tr>
<tr>
<td>• Simple Design</td>
<td>• Breaker Failure Clears all Circuits</td>
</tr>
<tr>
<td></td>
<td>• Single Points of Failure Between Circuits are in Series</td>
</tr>
<tr>
<td></td>
<td>• Expansion requires complete station outage</td>
</tr>
</tbody>
</table>

**Single Breaker Single Bus**
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

- 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

Normal Configuration is with transfer bus de-energized.
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

In the event of an outage of the feeder breaker, the load is fed via the transfer bus. Protection is compromised.
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

- 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

Load can be fed via the tie breaker. Settings on tie breaker can be adjusted as req’d.
Pros

- Breaker Maintenance w/o Circuit Interruption
- Only One Set of VTs Required

Cons

- More Costly with Addition of Transfer Bus
- Adaptable Protection is Necessary
- If Not Adaptable, Protection Compromise During Maintenance
- Normal Operation Is Single Breaker Single Bus

Operating/Transfer Buses with Single Breaker
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

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)
Breaker-And-A-Half

- Line fault
Breaker-And-A-Half

• Breaker Failure
Breaker-And-A-Half

- Breaker Failure
### Breaker-And-A-Half

<table>
<thead>
<tr>
<th><strong>Pros</strong></th>
<th><strong>Cons</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Robust</td>
<td>Cost</td>
</tr>
<tr>
<td>Highly Expandable</td>
<td>Physically Large</td>
</tr>
<tr>
<td>Failed Outer Breakers</td>
<td>Failed Center Breaker</td>
</tr>
<tr>
<td>Result in Loss of One</td>
<td>Result in Loss of Two</td>
</tr>
<tr>
<td>Circuit Only</td>
<td>Circuits</td>
</tr>
<tr>
<td>Breaker Maintenance</td>
<td></td>
</tr>
<tr>
<td>w/o Circuit Interruption</td>
<td></td>
</tr>
</tbody>
</table>
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

- Line Fault
Double Breaker Double Bus

- Breaker failure
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

Double Breaker Double Bus
One Line and One Line Relaying & Metering Diagrams
The one line diagram is probably the single most important document, and should contain specific design information. Sometimes this drawing is separated into two documents:

- Equipment identification
- Protection

As a minimum, it is recommended that the following information should be included:

- Name of utility and ownership demarcation
- Design data/basis (high side and low side)
- Phase designation and rotation
- Equipment identification
- Equipment ratings
- Protection schemes (One Line Relaying & Metering Diagram)
- Future equipment
### 138 kV Design Basis

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Maximum Voltage</td>
<td>145 kV</td>
</tr>
<tr>
<td>System Grounding</td>
<td>Effectively Grounded</td>
</tr>
<tr>
<td>Rated Continuous Current</td>
<td>1200 A</td>
</tr>
<tr>
<td>Rated Short-Circuit Current</td>
<td>40 kA</td>
</tr>
</tbody>
</table>

**Basic Impulse Insulation Level (BIL)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulators</td>
<td>650 kV</td>
</tr>
<tr>
<td>Bushings</td>
<td>650 kV</td>
</tr>
<tr>
<td>Transformer Winding</td>
<td>550 kV</td>
</tr>
</tbody>
</table>

### 4.16 kV Design Basis

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Maximum Voltage</td>
<td>4.78 kV</td>
</tr>
<tr>
<td>System Grounding</td>
<td>Low Resistance</td>
</tr>
<tr>
<td>Rated Continuous Current</td>
<td>2000 A</td>
</tr>
<tr>
<td>Rated Short-Circuit Current</td>
<td>50 kA</td>
</tr>
</tbody>
</table>

**Basic Impulse Insulation Level (BIL)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switchgear</td>
<td>60 kV</td>
</tr>
<tr>
<td>Bushings</td>
<td>110 kV</td>
</tr>
<tr>
<td>Transformer Winding</td>
<td>75 kV</td>
</tr>
</tbody>
</table>
Single Line
One Line Relaying & Metering

CTs not shown for clarity
Phase Rotation / Designation

It is always recommended that the client phasor designation is 1-2-3 to coincide with the transformer bushings (i.e. X1, X2, X3)
Equipment Ratings

Sufficient data should be included that will identify the equipment.

HV Breakers

- ID: 52-1
- Continuous current: 2000 A
- Interrupting rating: 40 kA

The remainder of the data can be obtained from standards.
**Equipment Ratings**

**Power Transformers**

- **ID**: TR-1
- **Voltage ratings**: 138 – 12.47 kV
- **Capacity**: 30/40/50/56 MVA
- **% Impedance**: ONAN/ONAF/ONAF//ONAF @ 55//65 deg C
  
  9% @ 30 MVA
- **Winding Configuration**: LTC (if included)

**Notes:**

1. For 4-Wire systems, both the line-line and line-neutral ratings should be specified.
2. Note the winding phasor designation.
IEEE Std C57.12.00-2000

IEEE STANDARD GENERAL REQUIREMENTS FOR

<table>
<thead>
<tr>
<th>Δ – Δ connection</th>
<th>Y – Δ connection</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Y – Y connection</th>
<th>Δ – Y connection</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Figure 1—Phase relation of terminal designations for three-phase transformers
Equipment Ratings

Disconnect Switch

- ID: TR-1
- Voltage class: 145 kV
- Continuous current: 2000 A
- Short circuit: 104 kA Mom Peak
- Motor operator (if any)

Notes:
1. Common mistake not to specify short-circuit rating basis. This does not make clear whether the rating is 2 second withstand (sym rms), momentary asym rms, or momentary peak.
2. Symbol should demonstrate type, motor operator, and if arcing horns are included.

Some examples below:

- Hook-stick switch
- Vee-switch w/ arcing horns
- Vertical break w/ motor operator
Equipment Ratings

Arrester

- MCOV rating (Maximum Continuous Operating Voltage)

Note: The arrester is one of most commonly misapplied pieces of equipment.

See IEEE Std s C62.11 and C62.22 for additional information on application and ratings.
Equipment Ratings

Voltage Transformers

- Ratio
- Accuracy class
- Qty / Configuration

Note: See IEEE Std. C57.13 for application guide. It is very important that the VT insulation is adequate when applying wye connection on an ungrounded or resistance grounded system.
Equipment Ratings

Current Transformers

- Maximum ratio
- Connected ratio
- Accuracy class

Note: Polarity dots designated the H1 and X1 relative positions

Multi-ratio Bushing-type CT

Single-ratio Bushing-type CT

Multi-ratio Window-type CT
A.C. Fundamentals
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

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.

Protected Bus

2000A

5A

10A

2000:5

2000A

5A

5A

87B
A.C. Fundamentals

\[ Ig = 0 \]

51
50

51
N

51
N

51
50

51
N

51
50

51
NT

\[ Ig = 0 \]
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

- 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.**
Safe/fast.....
but no selectivity

- **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
Secondary Selective Arrangement – N.O. Tie
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”?

Diagram showing secondary selective arrangement with N.O. tie.
Secondary Selective Arrangement – N.O. Tie

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

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

**Cons (Partial Differential):**
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
Special Considerations for System Grounding

There are many advantages to resistance/impedance grounding of electrical systems:

- Maintain line-line voltage during ground faults
- Limit ground fault current, hence limit damage
- Continue to operate during ground fault (HRG system)
- Reduce arc flash hazard exposure

…to name a few.

However, care must be taken to ensure proper protection and means of isolation is provided.

Additionally, coordination with downstream fuses will typically not be achieved…this means that you will trip the main breaker for a feeder fault protected by a fuse.
Special Considerations for System Grounding

Trip upstream device

Detect current in LRG

51N

400 A @ 10 SEC
Special Considerations for System Grounding

Consider this installation....

It may not be possible to set the main breaker or the tie breaker to pick-up and trip for a ground fault.

This is because most 5 A relays have a minimum setting of 0.5 A.
Special Considerations for System Grounding

Consider one xfmr out of service...

It may also not be possible to securely set the feeder breaker to pickup and trip for a ground fault.

For a fault with any Impedance, the fault will be below 400 A.

Ground fault location
Special Considerations for System Grounding

Remedies may include:
1. Specify relays with lower minimum pickup range
2. Zero-sequence CT (GFCT)
3. Lower CT ratio, perhaps with higher rating factor
4. Auxiliary CTs for neutral connection
5. Neutral resistor with higher nominal current rating
6. Configure 51NT relay to stage tripping of tie breaker and main breaker
Special Considerations for System Grounding

Consider the system, and operating condition…the event the transformer high-side breaker is open and bypass switch closed.

For a **ground fault** between the transformer and low-side main breaker, there is no provision to clear the fault.

As a result, the neutral resistor will burn open…and bad things will happen.
Three-Line Diagram

As a minimum, it is recommended that the following information should be included on the three-line:

- Phase designation and rotation
- Equipment identification
- Equipment layout
- Equipment ratings
- AC connections

The purpose of the three-line diagram is to demonstrate phase arrangement and how CTs and VTs are connected to devices (meters, protective relays, etc).
Include phasor rotation diagram and relationship.

The three line and the physical plan are ideal drawings to set the relationship between the phase designations and transformer phases.

Make sure 3-line and electrical plan match up.
Excerpt of HV Breaker Three-Line

Bushing arrangement

CT ratio and tap setting, terminal blocks correspond to tap

Breaker control cabinet position to fix orientation of bushings

Note that CT ckt ground should be at first indoor panel. Ground should be in bkr cabinet if shorted.
Physical Arrangement
The electrical plan / layout is probably the second most important document (behind the one line), and should contain specific design information.

As a minimum, it is recommended that the following information should be included:

- Name of utility and ownership demarcation
- North arrow
- Design data/basis (high side and low side)
- Phase designation and rotation
- Equipment ratings
- Equipment identification
- Dimensions (including tie-in point to known benchmark)
- Fence and gates (typically sets the boundary)
- Future equipment
It should be noted that if the one line diagram and electrical plan are complete and accurate, obtaining approval of these two documents essentially fixes the design and allows detail engineering to proceed at full speed.
• 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 Withstand Voltage</th>
<th>Impulse Max. Volt (kV)</th>
<th>Impulse Max. Volt (kV RMS)</th>
<th>60 Hz KV rms, Wet (kV)</th>
<th>12 x 50 μs Wave (kV)</th>
<th>60 Hz Wave (kV RMS)</th>
<th>Supported Energized Conductors, Inches (meters)</th>
<th>Ground Clearance, Inches (meters)</th>
<th>Recommended Phase Spacing, Center to Center, Inches (meters)</th>
<th>Bus Supports, Vertical Break Disc. Switches Power Fuses Non-expulsion Types of Rigid Conductors</th>
<th>Recommended Minimum Clearance Between Overhead Conductor and Ground for Personal Safety, Feet (Meters)</th>
<th>Withstand S.S. Crest (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.3</td>
<td>95</td>
<td>30</td>
<td>7 (0.18)</td>
<td>7.5 (0.19)</td>
<td>6 (0.15)</td>
<td>36 (0.91)</td>
<td>30 (0.76)</td>
<td>18 (0.46)</td>
<td>8 (2.44)</td>
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<td>...</td>
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<tr>
<td>2</td>
<td>15.5</td>
<td>110</td>
<td>45</td>
<td>12 (0.30)</td>
<td>10 (0.25)</td>
<td>7 (0.18)</td>
<td>36 (0.91)</td>
<td>30 (0.76)</td>
<td>24 (0.61)</td>
<td>9 (2.74)</td>
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<td>...</td>
</tr>
<tr>
<td>3</td>
<td>27.0</td>
<td>150</td>
<td>60</td>
<td>15 (0.38)</td>
<td>12 (0.30)</td>
<td>10 (0.25)</td>
<td>48 (1.22)</td>
<td>36 (0.91)</td>
<td>30 (0.76)</td>
<td>10 (3.05)</td>
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<td>...</td>
</tr>
<tr>
<td>4</td>
<td>38.5</td>
<td>200</td>
<td>80</td>
<td>18 (0.46)</td>
<td>15 (0.38)</td>
<td>13 (0.33)</td>
<td>60 (1.52)</td>
<td>48 (1.22)</td>
<td>36 (0.91)</td>
<td>10 (3.05)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>5</td>
<td>48.3</td>
<td>250</td>
<td>100</td>
<td>21 (0.53)</td>
<td>18 (0.46)</td>
<td>17 (0.43)</td>
<td>72 (1.83)</td>
<td>60 (1.52)</td>
<td>48 (1.22)</td>
<td>10 (3.05)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>6</td>
<td>72.5</td>
<td>350</td>
<td>145</td>
<td>31 (0.79)</td>
<td>29 (0.74)</td>
<td>25 (0.64)</td>
<td>84 (2.13)</td>
<td>72 (1.83)</td>
<td>60 (1.52)</td>
<td>11 (3.35)</td>
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<td>...</td>
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<tr>
<td>7</td>
<td>123.0</td>
<td>500</td>
<td>230</td>
<td>53 (1.35)</td>
<td>47 (1.19)</td>
<td>42 (1.07)</td>
<td>120 (3.05)</td>
<td>108 (2.74)</td>
<td>84 (2.13)</td>
<td>12 (3.66)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>8</td>
<td>145.0</td>
<td>650</td>
<td>275</td>
<td>63 (1.60)</td>
<td>52 (1.33)</td>
<td>50 (1.27)</td>
<td>144 (3.66)</td>
<td>132 (3.35)</td>
<td>96 (2.44)</td>
<td>13 (3.36)</td>
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<td>...</td>
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<tr>
<td>9</td>
<td>170.5</td>
<td>750</td>
<td>315</td>
<td>72 (1.83)</td>
<td>51.6 (1.56)</td>
<td>52 (1.47)</td>
<td>168 (4.27)</td>
<td>156 (3.96)</td>
<td>108 (2.74)</td>
<td>14 (4.27)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>10</td>
<td>245.0</td>
<td>900</td>
<td>365</td>
<td>89 (2.26)</td>
<td>76 (1.93)</td>
<td>71 (1.60)</td>
<td>192 (4.88)</td>
<td>192 (4.88)</td>
<td>132 (3.35)</td>
<td>15 (4.57)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>11</td>
<td>245.0</td>
<td>1050</td>
<td>455</td>
<td>105 (2.67)</td>
<td>90.5 (2.30)</td>
<td>83 (2.11)</td>
<td>216 (5.49)</td>
<td>216 (5.49)</td>
<td>156 (3.96)</td>
<td>16 (4.88)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>12</td>
<td>362.0</td>
<td>1050</td>
<td>455</td>
<td>105 (2.67)</td>
<td>90.5 (2.30)</td>
<td>84 (2.13)</td>
<td>216 (5.49)</td>
<td>216 (5.49)</td>
<td>156 (3.96)</td>
<td>16 (4.88)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>13</td>
<td>362.0</td>
<td>1300</td>
<td>525</td>
<td>119 (3.02)</td>
<td>106 (2.99)</td>
<td>104 (2.84)*</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>14</td>
<td>550.0</td>
<td>1500</td>
<td>620</td>
<td>...</td>
<td>124 (3.15)*</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<td>...</td>
</tr>
<tr>
<td>15</td>
<td>550.0</td>
<td>1800</td>
<td>710</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>16</td>
<td>800.0</td>
<td>2050</td>
<td>830</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</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-72-131-5 (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
### Table 3—Recommended minimum electrical clearances for air-insulated substations when lightning impulse conditions govern\(^\text{a,b}\)

<table>
<thead>
<tr>
<th>Maximum system voltage (kV, rms)</th>
<th>Basic BIL(^\text{c})</th>
<th>Minimum phase-to-ground(^\text{d})</th>
<th>Minimum phase-to-phase(^\text{e})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kV, crest)</td>
<td>mm (in)</td>
<td>mm (in)</td>
<td>mm (in)</td>
</tr>
<tr>
<td>1.2</td>
<td>30</td>
<td>57 (2.3)</td>
<td>63 (2.5)</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>36 (1.4)</td>
<td>75 (3.0)</td>
</tr>
<tr>
<td>5</td>
<td>75</td>
<td>145 (5.7)</td>
<td>155 (6.1)</td>
</tr>
<tr>
<td>15</td>
<td>95</td>
<td>130 (5.1)</td>
<td>200 (8.0)</td>
</tr>
<tr>
<td>26.2</td>
<td>150</td>
<td>285 (11.2)</td>
<td>315 (12.4)</td>
</tr>
<tr>
<td>36.3</td>
<td>200</td>
<td>360 (14.2)</td>
<td>430 (16.9)</td>
</tr>
<tr>
<td>48.3</td>
<td>250</td>
<td>475 (18.7)</td>
<td>525 (20.6)</td>
</tr>
<tr>
<td>72.5</td>
<td>250</td>
<td>665 (26.1)</td>
<td>720 (28.2)</td>
</tr>
<tr>
<td>121</td>
<td>350</td>
<td>855 (33.5)</td>
<td>940 (37.0)</td>
</tr>
<tr>
<td>145</td>
<td>350</td>
<td>855 (33.5)</td>
<td>940 (37.0)</td>
</tr>
<tr>
<td>169</td>
<td>550</td>
<td>1045 (41.2)</td>
<td>1150 (45.3)</td>
</tr>
<tr>
<td>242</td>
<td>650</td>
<td>1235 (48.7)</td>
<td>1360 (53.5)</td>
</tr>
<tr>
<td>362</td>
<td>900</td>
<td>1710 (67.2)</td>
<td>1880 (74.1)</td>
</tr>
<tr>
<td>550</td>
<td>1300</td>
<td>2470 (96.5)</td>
<td>2720 (107.1)</td>
</tr>
<tr>
<td>800</td>
<td>1800</td>
<td>3420 (135.0)</td>
<td>3765 (148.2)</td>
</tr>
</tbody>
</table>

---

### Table 5—Recommended minimum electrical clearances for air-insulated substations when switching surge conditions govern\(^\text{d}\)

<table>
<thead>
<tr>
<th>Maximum system voltage (kV, rms)</th>
<th>BSL</th>
<th>Equivalent (\text{P}^\text{c})</th>
<th>Minimum phase-to-ground clearances (k_v = 1.3y)^\text{d})</th>
<th>Minimum phase-to-ground clearances (k_v = 1.5y)^\text{d})</th>
<th>Minimum phase-to-phase clearances (k_v = 1.3y)^\text{d})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kV, crest)</td>
<td>(k_v\text{, mm (in)})</td>
<td>(\text{SSF})</td>
<td>(k_v\text{, mm (in)})</td>
<td>(k_v\text{, mm (in)})</td>
<td>(k_v\text{, mm (in)})</td>
</tr>
<tr>
<td>562</td>
<td>550</td>
<td>1.23</td>
<td>1265 (50)</td>
<td>1370 (54)</td>
<td>1630 (64)</td>
</tr>
<tr>
<td>650</td>
<td>2.31</td>
<td>1540 (61)</td>
<td>1812 (72)</td>
<td>2000 (79)</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>2.79</td>
<td>1835 (72)</td>
<td>2360 (93)</td>
<td>2400 (95)</td>
<td></td>
</tr>
<tr>
<td>825</td>
<td>2.79</td>
<td>2065 (81)</td>
<td>2910 (115)</td>
<td>2725 (105)</td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>3.32</td>
<td>2205 (87)</td>
<td>3280 (128)</td>
<td>3065 (120)</td>
<td></td>
</tr>
<tr>
<td>1050</td>
<td>3.50</td>
<td>2560 (100)</td>
<td>3680 (145)</td>
<td>3505 (140)</td>
<td></td>
</tr>
<tr>
<td>1150</td>
<td>3.69</td>
<td>2825 (111)</td>
<td>4310 (169)</td>
<td>3950 (155)</td>
<td></td>
</tr>
</tbody>
</table>

---

650 kV BIL Ex: \(\text{SG-6}\), IEEE 1427

- Min Ph-Gnd: 50”
- Rec. Ph-Gnd: 52.5”
- Min Ph-Ph: 63”

**Spacing & Clearances**

---

**HV Substation Design: Applications and Considerations**

HV Engineering, LLC

IEEE CED 2014-2015
### 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>
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<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.
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
Don’t forget to increase phase spacing for switches with arcing horns.

Arcing horns are typically shipped with all switches...where spacing does not accommodate use of arcing horns, note on drawings should state that arcing horns should be removed.

Arcing Horns are required where disconnect switch has a risk of breaking magnetizing current.

High-voltage disconnect switches are not rated for breaking load...unless specifically noted.
### IEEE C37.32

#### Spacing & Clearances

<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 (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>0.762 (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>0.610 (24)</td>
<td>0.762 (30)</td>
<td>0.914 (36)</td>
</tr>
<tr>
<td>23</td>
<td>25.8</td>
<td>150</td>
<td>0.381 (15)</td>
<td>0.762 (30)</td>
<td>0.914 (36)</td>
<td>1.22 (48)</td>
</tr>
<tr>
<td>34.5</td>
<td>38</td>
<td>200</td>
<td>0.457 (18)</td>
<td>0.914 (36)</td>
<td>1.22 (48)</td>
<td>1.52 (60)</td>
</tr>
<tr>
<td>46</td>
<td>48.3</td>
<td>250</td>
<td>0.533 (21)</td>
<td>1.22 (48)</td>
<td>1.52 (60)</td>
<td>1.83 (72)</td>
</tr>
<tr>
<td>69</td>
<td>72.5</td>
<td>350</td>
<td>0.787 (31)</td>
<td>1.52 (60)</td>
<td>1.83 (72)</td>
<td>2.13 (84)</td>
</tr>
<tr>
<td>115</td>
<td>121</td>
<td>550</td>
<td>1.35 (53)</td>
<td>2.13 (84)</td>
<td>2.74 (108)</td>
<td>3.05 (120)</td>
</tr>
<tr>
<td>138</td>
<td>145</td>
<td>650</td>
<td>1.60 (63)</td>
<td>2.44 (96)</td>
<td>3.35 (132)</td>
<td>3.66 (144)</td>
</tr>
</tbody>
</table>

<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 (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>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>
</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>
</tr>
<tr>
<td>345</td>
<td>362</td>
<td>1050</td>
<td>2.67 (105)</td>
<td>3.96 (156)</td>
<td>5.50 (216)</td>
<td>5.50 (216)</td>
</tr>
<tr>
<td>345</td>
<td>362</td>
<td>1300</td>
<td>3.02 (119)</td>
<td>3.96 (156)</td>
<td>5.49 (216)</td>
<td>5.49 (216)</td>
</tr>
<tr>
<td>345</td>
<td>362</td>
<td>1300</td>
<td>3.02 (119)</td>
<td>4.43 (174)</td>
<td>—</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.
Line switch must be rated to break magnetizing current.
Line switches and transformer primary switches must be rated to break magnetizing current.
Operation of energized disconnect switch while breaking magnetizing current. The increased spacing between phases for switches with arcing horns is to prevent a phase to phase flashover.

Consider the impact to the arc during windy conditions.
Switch Interrupter Guide

<table>
<thead>
<tr>
<th>Type of Switch</th>
<th>Line/Cable Dropping</th>
<th>Transformer Magnetizing</th>
<th>Loop Splitting</th>
<th>Load Breaking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Arcing Horns</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whip</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load Break</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Never a good idea at HV installations. Arcing generates high transient voltages and risks damage to transformers.
Switch Failure
115 kV Switch Opening

Spacing & Clearances
Types of Substation Structures
• **Conventional** (Lattice Structures)
  ◦ Angle (Chord & Lace) Members
  ◦ Minimum Structure Weight
  ◦ Requires Minimum Site Area
  ◦ Stable and Rigid Construction
  ◦ Requires Considerable Bolting & Erection Time
Conventional Design
Conventional Design
Conventional 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
Low Profile (tube steel)
Low Profile (tapered tubular steel)
Low Profile (tube)
Conventional

Low Profile

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
  ◦ IEEE C62.22 – IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems
- 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

A properly designed ground grid is critical for proper surge and 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

Source: IEEE C62.22

Surge & Lightning Protection
Example of lightning strike data and report provider:

STRIKEnet lightning verification report data is provided by the National Lightning Detection Network (NLDN) and/or Environment Canada's Canadian Lightning Detection Network (CLDN)—operated by Vaisala. STRIKEnet is built upon 35 years of scientific heritage and is over 99% accurate at detecting the presence or absence of a lightning event within 5 miles of a U.S. property. Furthermore, NLDN is the most scientifically-referenced, reputable and accurate lightning network available, with lightning data back to 1989. For more information about STRIKEnet or the lightning data within the report, please visit Weather Fusion's website and frequently asked questions at: http://www.weatherfusion.com/about-us/faq

If you have any questions about this report, or would like more information about Weather Fusion, please contact us at 888.929.4245 or sales@weatherfusion.com
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

\[ F = \text{failure rate of insulation within the protected area, years between failures} \]
\[ P_f = \text{probability that stroke currents within the unprotected area will cause insulation failure} \]
\[ N = \text{number of strokes to earth within the unprotected area per year} \]

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>

Reference: IEEE Std 998

Surge & Lightning Protection
Rolling Sphere Method

\[ S_m = 8 k I^{0.65} \]  

or

\[ S_f = 26.25 k I^{0.65} \]

where

- \( S_m \) is the strike distance in meters
- \( S_f \) is the strike distance in feet
- \( I \) is the return stroke current in kiloamperes
- \( k \) is a coefficient to account for different striking distances to a mast, a shield wire, or the ground plane.

Mousa [B67] gives a value of \( k = 1 \) for strokes to wires or the ground plane and a value of \( k = 1.2 \) for strokes to a lightning mast.

Reference: IEEE Std 998
Rolling Sphere Method

5.2.2 Allowable stroke current

Some additional relationships need to be introduced before showing how the EGM is used to design a zone of protection for substation equipment. Bus insulators are usually selected to withstand a basic lightning impulse level (BIL). Insulators may also be chosen according to other electrical characteristics including negative polarity impulse critical flashover (C.F.O.) voltage. Flashover occurs if the voltage produced by the lightning stroke current flowing through the surge impedance of the station bus exceeds the withstand value. This may be expressed by the Gilman & Whitehead equation [B33]:

\[
I_s = \frac{BIL \times 1.1}{(Z_s/2)} = \frac{2.2 \times (BIL)}{Z_s}
\]

(5-2A)

Reference: IEEE Std 998

Surge & Lightning Protection
Rolling Sphere Method

C.1 Corona radius

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

$$R_c \times \ln \left( \frac{2 \times h}{R_c} \right) \frac{V_c}{E_0} = 0 \quad \text{(C.1)}$$

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 μs 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 $R_c'$ [B4] is taken as follows:

$$R_c' = R_0 + R_c \quad \text{(C.2)}$$

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.

Reference: IEEE Std 998
Rolling Sphere Method

C.3 Surge impedance under corona

The surge impedance of conductors under corona in ohms is given by Brown [B15]:

\[ Z_s = 60 \times \ln \left( \frac{2 \times h}{R_c} \right) \times \ln \left( \frac{2 \times h}{r} \right) \]

where

- \( h \) is the average height of the conductor
- \( R_c \) is the corona radius (use Eq C.2 as appropriate)
- \( r \) is the metallic radius of the conductor, or equivalent radius in the case of bundled conductors

Reference: IEEE Std 998
Rolling Sphere Method

Figure 5-3 — Principle of rolling sphere

Reference: IEEE Std 998
Rolling Sphere Method

Surge & Lightning Protection
Rolling Sphere Method

Reference: IEEE Std 998

Surge & Lightning Protection
Comparing Fixed Angle and Rolling Sphere Methods

Fixed Angle Method

Unprotected equipment

Increasing height of static mast will increase coverage

Surge & Lightning Protection
Comparing Fixed Angle and Rolling Sphere Methods

Unprotected equipment

Increasing height DOES NOT NECESSARILY increase coverage

Rolling Sphere Method

Surge & Lightning Protection
Comparing Fixed Angle and Rolling Sphere Methods

Decrease distance between static masts
…or install static wires between static masts

Rolling Sphere Method
Minimize distance / impedance to maximize effective protection

Surge / Lightning Arresters
Minimize distance / impedance to maximize effective protection

Preferable Installation (hard bus between bushings and arresters)

Surge / Lightning Arresters
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 – 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 Objectives

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.
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
What affects ground grid calculations?

Some things include:
1. Available ground fault
2. Soil resistivity
3. Surfacing material
4. Area station
5. Current split (how much will return through earth vs static wires and other distribution circuits)
6. Duration of fault (Zone 1, Zone 2, BF, etc)
7. Weight of person
8. Safety factor
Basic Shock Situations

Figure 12—Basic shock situations

Source: IEEE 80
Extend grid past the swing of the gate...or swing gate to the interior

Extend grid 3’-0” past fence, and extend final surfacing at least 5’-0” beyond fence

If substation fence is part of an overall facility fence, ensure isolation between the two fences. Otherwise the entire ground system must be evaluated.

**Simple Grid Design**
Typically this is what a ground grid design ends up looking like:

- Perimeter cables approx. 3ft on either side of fence
- Ground rod distributed closer to the perimeter and corners of the grid

Figure B.7—Unequally spaced square grid with twenty-five 9.2 m rods
Best method to verify ground grid design and integrity is the Fall of Potential test.

1. This test can not be performed once utility wires are pulled in
2. This test requires a significant amount of area outside of the station without electrical obstructions (approximately 3.5x diagonal of station area)

This test is not easily done.
Switch Operator

Source: IEEE 80
IEEE 80: Tables 3 – 6 provide ultimate current carrying capabilities of grounding cable based on different X/R.

For other size conductors and different conductor material, see equations provided in IEEE 80 Section 11.3.

<table>
<thead>
<tr>
<th>Cable size, AWG</th>
<th>Nominal cross section, mm²</th>
<th>6 cycles (100 ms)</th>
<th>15 cycles (250 ms)</th>
<th>30 cycles (500 ms)</th>
<th>45 cycles (750 ms)</th>
<th>60 cycles (1 s)</th>
<th>180 cycles (3 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2</td>
<td>33.63</td>
<td>22</td>
<td>16</td>
<td>12</td>
<td>10</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>#1</td>
<td>42.41</td>
<td>28</td>
<td>21</td>
<td>16</td>
<td>13</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>1/0</td>
<td>53.48</td>
<td>36</td>
<td>26</td>
<td>20</td>
<td>17</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>2/0</td>
<td>67.42</td>
<td>45</td>
<td>33</td>
<td>25</td>
<td>21</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>3/0</td>
<td>85.03</td>
<td>57</td>
<td>42</td>
<td>32</td>
<td>27</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>4/0</td>
<td>107.20</td>
<td>72</td>
<td>53</td>
<td>40</td>
<td>34</td>
<td>30</td>
<td>17</td>
</tr>
<tr>
<td>250 kcmil</td>
<td>126.65</td>
<td>85</td>
<td>62</td>
<td>47</td>
<td>40</td>
<td>35</td>
<td>21</td>
</tr>
<tr>
<td>350 kcmil</td>
<td>177.36</td>
<td>119</td>
<td>87</td>
<td>67</td>
<td>56</td>
<td>49</td>
<td>29</td>
</tr>
<tr>
<td>Number</td>
<td>Description of surface material (U.S. state where found)</td>
<td>Resistivity of sample $\Omega \cdot \text{m}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------------</td>
<td>---------------------------------------------</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td>Wet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Crusher run granite with fines (N.C.)</td>
<td>$140 \times 10^6$</td>
<td>1300 (ground water, 45 $\Omega \cdot \text{m}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.5 in (0.04 m) crusher run granite (Ga.) with fines</td>
<td>4000</td>
<td>1200 (rain water, 100 W)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.75–1 in (0.02–0.025 m) granite (Calif.) with fines</td>
<td>—</td>
<td>6513 (10 min after 45 $\Omega \cdot \text{m}$ water drained)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>#4 (1 -2 in) (0.025-0.05 m) washed granite (Ga.)</td>
<td>$1.5 \times 10^6$ to $4.5 \times 10^6$</td>
<td>5000 (rain water, 100 $\Omega \cdot \text{m}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>#3 (2-4 in) (0.05-0.1 m) washed granite (Ga.)</td>
<td>$2.6 \times 10^5$ to $3 \times 10^6$</td>
<td>10 000 (Rain water, 100 $\Omega \cdot \text{m}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Size unknown, washed limestone (Mich.)</td>
<td>$7 \times 10^5$</td>
<td>2000–3000 (ground water, 45 $\Omega \cdot \text{m}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Washed granite, similar to 0.75 in (0.02 m) gravel</td>
<td>$2 \times 10^5$</td>
<td>10 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Washed granite, similar to pea gravel</td>
<td>$40 \times 10^5$</td>
<td>5000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>#57 (0.75 in) (0.02 m) washed granite (N.C.)</td>
<td>$190 \times 10^6$</td>
<td>8000 (ground water, 45 $\Omega \cdot \text{m}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Asphalt</td>
<td>$2 \times 10^6$ to $30 \times 10^6$</td>
<td>10 000 to $6 \times 10^5$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Concrete</td>
<td>$1 \times 10^6$ to $1 \times 10^9$</td>
<td>21 to 100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Oven dried concrete (Hammond and Robson [B78]). Values for air-cured concrete can be much lower due to moisture content.

### Table 8—Range of earth resistivity

<table>
<thead>
<tr>
<th>Type of earth</th>
<th>Average resistivity ($\Omega \cdot \text{m}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet organic soil</td>
<td>10</td>
</tr>
<tr>
<td>Moist soil</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Dry soil</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Bedrock</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>

Source: IEEE 80
Some clients require grounding test wells.

I have never been able to determine the precise purpose of a test well...what do we test, what is the procedure, what are acceptable limits, what do we do with the results?
Substation Fire Prevention
Spacing and Separation Requirements

IEEE Guide for Substation Fire Protection
IEEE 979-2012

6. Fire protection for substation buildings

6.1 General

Substation buildings should be designed in accordance with applicable local building codes. In the absence of applicable building code requirements, the following recommendations may be followed for the design and construction of substation buildings.
### 6.2 Use and occupancy

In the absence of explicit local building code classification criteria, electrical equipment buildings and battery buildings should be classified as special-purpose industrial occupancies. Warehouse buildings should be classified as storage occupancies. Maintenance shop areas should be considered as industrial occupancies. Office areas separate from control building spaces should be considered business occupancies.

Refer to A.9 for additional information.

#### 6.2.1 Control buildings and rooms

Control buildings and rooms should be reserved for control equipment, metering equipment, SCADA equipment, telemetry and communications equipment, low-voltage (<1 kV) station service distribution equipment, metal-enclosed (non-oil-filled) switchgear cubicles and associated relays, and minimal work and office areas necessary to facilitate these operations. Uses for other purposes should be discouraged.

Storage of paper products (drawings, test reports, and instruction books), cleaning fluids, and other combustible supplies in a control building are discouraged. If stored in the control building, then they should be stored in separated areas with a 1 h or 2 h fire separation rating based on the hazard or in cabinets to preclude a fire from spreading to the main control and relay areas (see A.11). Flammable liquids should only be stored in approved containers and/or cabinets. Welding and other flammable gases should never be stored in control buildings.
7.2.2 Equipment to equipment

Individual pieces of mineral-oil-insulated equipment should be separated from the anticipated flame fronts of one another by the distances given in Table 1. Separation distances to adjacent equipment should be measured from the edge of the postulated flame front to the nearest mineral-oil-filled component of the adjacent equipment.

Table 1—Separation distances

<table>
<thead>
<tr>
<th>Mineral oil volume, L (gal)</th>
<th>Separation distance, m (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1890 (500)</td>
<td>Footnote a</td>
</tr>
<tr>
<td>1890 to 18,930 (500 to 5000)</td>
<td>7.6 (25)</td>
</tr>
<tr>
<td>&gt;18,930 (5000)</td>
<td>15.2 (50)</td>
</tr>
</tbody>
</table>

*Determining the type of physical separation to be used for mineral oil volumes less than 1890 L (500 gal) should be based on consideration of the following:

- Type and quantity of oil in the equipment
- Size of a postulated oil spill (surface area and depth)
- Construction of adjacent structures
- Rating and bushing type
- Fire-suppression systems provided
- Protection clearing time

7.2.3 Equipment to buildings

Noncombustible or limited combustible buildings should be separated from adjacent mineral-oil-insulated equipment containment area(s) by a 2 h rated firewall or the separation values in Table 1.
Maintain minimum spacing, or…
Alternately, install 2-hour rated firewalls
Alternately, bldg wall can be fire rated

For Mineral Oil Filled Transformers
7.2.5 Exceptions

Multiple pieces of mineral-oil-insulated equipment used as a group on the same electrical circuit may be permitted to be any distance apart with increased risk to all units. Risk and reliability issues should be considered when taking this exception. This exception would typically be made for medium voltage (≤35 kV) equipment (e.g., single-phase oil circuit breakers or voltage regulators) with per-phase mineral oil volumes less than 1890 L (500 gal) or when the insulating fluid is listed as less flammable.

Mineral-oil-insulated equipment with small oil volumes (e.g., auxiliary transformers) associated with larger, mineral-oil-insulated piece of equipment (or three-phase group) may use the smaller spacing criteria with the acknowledgment of increased risk of damage to the smaller piece of equipment.

7.2.6 Other types of adjacent equipment

Where containment is provided in accordance with 8.1, other types of substation equipment should be no closer than 10.7 m (35 ft) to an adjacent piece of mineral-oil-insulated equipment’s anticipated flame front (or containment boundary). This distance is considered the minimum spatial separation distance.

Where crushed stone is provided in accordance with 8.2, the minimum separation distance may be reduced to 4.6 m (15 ft).

Where containment is not provided in accordance with 8.1, the minimum separation distance should be calculated in accordance with 7.3.
7.5.1 Cable trenches

Cable trenches within 3 m (10 ft) of mineral-oil-insulated equipment containing less than 1890 L (500 gal) should have noncombustible, liquid-tight covers and be arranged to prevent liquids from entering the trench.

Cable trenches within 7.6 m (25 ft) of mineral-oil-insulated equipment containing 1890 L (500 gal) or more should have noncombustible, liquid-tight covers and be arranged to prevent liquids from entering the trench.

Cable trenches within 6.1 m (20 ft) of buildings should have noncombustible covers.

The walls of cable trenches should be designed to prevent the entry of burning liquid through the sides of the trench walls. Typically, this is achieved by having trench walls project above and below grade and by having all joints and seams sealed liquid tight.
8.1 Oil-spill-containment systems

Substation oil-spill-containment systems have typically been installed for environmental reasons, but they also provide fire protection benefits. By minimizing the surface area of a mineral-oil spill fire, the following benefits arise:

— Reduced overall size of the spill fire
— Contained fire from spreading within the substation
— Reduced flame height
— Reduced radiant heat flux to noninvolved exposures
— Reduced clean up and restoration area following the event

If oil-spill containment is not required for environmental reasons, then the substation designer should consider the oil-spill containment for fire protection.

An oil-spill-containment system should be designed in accordance with IEEE Std 980. In addition to containing the oil volume, the containment volume should allow for precipitation (typically 24 h of the 25-year storm density), automatic fire-suppression systems (refer to ANSI/NFPA 15-2012 [B16] for guidance), and manual firefighting activities, as applicable.

Oil-containment systems should be designed to survive exposure to a minimum 3 h fire occurring within the bounds of the containment system. This minimum fire-resistance time may be reduced to a 2 h exposure with the installation of automatic suppression systems.

The perimeter of the spill containment should generally be located between 2 m and 3 m (6.6 ft and 9.8 ft) beyond the portions of the electrical equipment containing oil, based on the height of typical bushings and conservators.

Stone is frequently used in oil-containment pits. Refer to 8.2 for recommendations.
450.23 Less-Flammable Liquid-Insulated Transformers. Transformers insulated with listed less-flammable liquids that have a fire point of not less than 300°C shall be permitted to be installed in accordance with 450.23(A) or 450.23(B).

(B) Outdoor Installations. Less-flammable liquid-filled transformers shall be permitted to be installed outdoors, attached to, adjacent to, or on the roof of buildings, where installed in accordance with (1) or (2):

(1) For Type I and Type II buildings, the installation shall comply with all restrictions provided for in the listing of the liquid.

Informational Note: Installations adjacent to combustible material, fire escapes, or door and window openings may require additional safeguards such as those listed in 450.27.

(2) In accordance with 450.27.

Informational Note No. 1: As used in this section, Type I and Type II buildings refers to Type I and Type II building construction as defined in NFPA 220-2012, Standard on Types of Building Construction. Combustible materials refers to those materials not classified as noncombustible or limited-combustible as defined in NFPA 220-2012.

Informational Note No. 2: See definition of Listed in Article 100.

450.27 Oil-Insulated Transformers Installed Outdoors. Combustible material, combustible buildings, and parts of buildings, fire escapes, and door and window openings shall be safeguarded from fires originating in oil-insulated transformers installed on roofs, attached to or adjacent to a building or combustible material.

In cases where the transformer installation presents a fire hazard, one or more of the following safeguards shall be applied according to the degree of hazard involved:

(1) Space separations
(2) Fire-resistant barriers
(3) Automatic fire suppression systems
(4) Enclosures that confine the oil of a ruptured transformer tank

Oil enclosures shall be permitted to consist of fire-resistant dikes, curbed areas or basins, or trenches filled with coarse, crushed stone. Oil enclosures shall be provided with trapped drains where the exposure and the quantity of oil involved are such that removal of oil is important.

Informational Note: For additional information on transformers installed on poles or structures or under ground, see ANSI C2-2007, National Electrical Safety Code.
<table>
<thead>
<tr>
<th>BUILDING ELEMENT</th>
<th>TYPE I</th>
<th>TYPE II</th>
<th>TYPE III</th>
<th>TYPE IV</th>
<th>TYPE V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A&lt;sup&gt;a&lt;/sup&gt;</td>
<td>B</td>
<td>A&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Primary structural frame&lt;sup&gt;a&lt;/sup&gt; (see Section 202)</td>
<td>3&lt;sup&gt;i&lt;/sup&gt;</td>
<td>2&lt;sup&gt;i&lt;/sup&gt;</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Bearing walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior&lt;sup&gt;f,g&lt;/sup&gt;</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Interior</td>
<td>3</td>
<td>2&lt;sup&gt;i&lt;/sup&gt;</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Nonbearing walls and partitions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonbearing walls and partitions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interior&lt;sup&gt;e&lt;/sup&gt;</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Floor construction and associated secondary members (see Section 202)</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Roof construction and associated secondary members (see Section 202)</td>
<td>1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>1&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1&lt;sup&gt;b,c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

For SI: 1 foot = 304.8 mm.

a. Roof supports: Fire-resistance ratings of primary structural frame and bearing walls are permitted to be reduced by 1 hour where supporting a roof only.

b. Except in Group F-1, H, M and S-1 occupancies, fire protection of structural members shall not be required, including protection of roof framing and decking where every part of the roof construction is 20 feet or more above any floor immediately below. Fire-retardant-treated wood members shall be allowed to be used for such unprotected members.

c. In all occupancies, heavy timber shall be allowed where a 1-hour or less fire-resistance rating is required.

d. An approved automatic sprinkler system in accordance with Section 903.3.1.1 shall be allowed to be substituted for 1-hour fire-resistance-rated construction, provided such system is not otherwise required by other provisions of the code or used for an allowable area increase in accordance with Section 506.3 or an allowable height increase in accordance with Section 504.2. The 1-hour substitution for the fire resistance of exterior walls shall not be permitted.

e. Not less than the fire-resistance rating required by other sections of this code.

f. Not less than the fire-resistance rating based on fire separation distance (see Table 602).

g. Not less than the fire-resistance rating as referenced in Section 704.10

2012 INTERNATIONAL BUILDING CODE®

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LISTING OPTION - A
Underwriters Laboratories Requirements

The same UL Classification of less-flammable liquids per the NEC Section 450.23 for 3-Phase 45-10,000 kVA transformers applies to both indoor and outdoor applications and requires:

- Transformers equipped with tanks capable of withstanding 12 psig without rupture, AND
- Transformers be equipped with pressure relief devices with minimum pressure relief capacity per the UL Classification Marking, AND
- Transformer primaries be protected with overcurrent protection options per the UL Classification Marking.

Overcurrent Protection Option I, available exclusively with Envirotemp FR3 Fluid’s UL Classification, allows internal expulsion fuses (e.g. bay-a-net fuses) in series with current limiting fuses. Overcurrent Protection Option II allows stand-alone expulsion fuses, but they must be located outside the transformer tank.

To specify a UL Classified Envirotemp FR3 fluid-filled transformer for a specific kVA rating, refer to the UL Classification Marking for the fluid shown in Table 3.

Table 3: UL Classification Marking for Envirotemp FR3 Fluid (EOVK.MH10678)

<table>
<thead>
<tr>
<th>TRANSFORMER</th>
<th>REQUIRED PROTECTION</th>
<th>REQUIRED PRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Phase Transformer Rating kVA</td>
<td>Required Current Limiting Fusing (A)</td>
<td>Maximum P I (kA)</td>
</tr>
<tr>
<td>45</td>
<td>500,000</td>
<td>700,000</td>
</tr>
<tr>
<td>75</td>
<td>500,000</td>
<td>800,000</td>
</tr>
<tr>
<td>112.5</td>
<td>500,000</td>
<td>900,000</td>
</tr>
<tr>
<td>150</td>
<td>600,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>225</td>
<td>600,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>300</td>
<td>760,000</td>
<td>1,400,000</td>
</tr>
<tr>
<td>500</td>
<td>760,000</td>
<td>1,400,000</td>
</tr>
<tr>
<td>750</td>
<td>1,100,000</td>
<td>2,200,000</td>
</tr>
<tr>
<td>1,000</td>
<td>1,250,000</td>
<td>3,400,000</td>
</tr>
<tr>
<td>1,500</td>
<td>1,500,000</td>
<td>4,500,000</td>
</tr>
<tr>
<td>2,000</td>
<td>1,750,000</td>
<td>6,000,000</td>
</tr>
<tr>
<td>2,500</td>
<td>1,750,000</td>
<td>7,500,000</td>
</tr>
<tr>
<td>3,000</td>
<td>2,250,000</td>
<td>9,000,000</td>
</tr>
<tr>
<td>3,750</td>
<td>2,500,000</td>
<td>11,000,000</td>
</tr>
<tr>
<td>5,000</td>
<td>3,000,000</td>
<td>14,000,000</td>
</tr>
<tr>
<td>7,500</td>
<td>3,000,000</td>
<td>14,000,000</td>
</tr>
<tr>
<td>10,000</td>
<td>3,000,000</td>
<td>14,000,000</td>
</tr>
</tbody>
</table>

Note that this is a “Classification…not a “Listing” UL Listing is completely something else
LISTING OPTION - B
FM Global Requirements

The outdoor installation requirements according to FM Global Property Loss Prevention Data Sheets 5-4 - Transformers consist of requirements for transformer and fluid types. Specific requirements for less-flammable liquid-insulated transformers are included.

FM outdoor installation requirements are based on the FM Approval Status of the transformer and both the volume and FM Approval Status of the fluid. If transformers filled with conventional mineral oil or non-approved fluids would expose buildings and equipment to a release of oil, the transformer must comply with FM LPD requirements. This may include containment, separation distances, fire barriers, or water spray systems. Installation of FM Approved transformers or transformers with FM Approved less-flammable fluids must comply with FM LPD requirements for containment and separation distances. The FM LPD provides detailed requirements for fire barriers in Section 2.3.1.1.2 and water spray exposure protection in Section 2.3.2.1.

Fluid containment requirements as detailed in Section 2.3.1.2 of the FM LPD are:

- A release of mineral oil would expose buildings
  OR
- More than 500 gal (1.9 m³) of mineral oil could be released
  OR
- More than 1,320 gal (5 m³) of FM Approved less-flammable fluid could be released
  OR
- More than 2,640 gal (10 m³) of biodegradable FM Approved less flammable fluid could be released. For this purpose: 1) the fluid must be certified as a biodegradable fluid by the government environmental protection agency, 2) a release of the fluid must not expose navigable waterways (see Appendix A for definition) and 3) the transformer must be properly labeled.

LISTING OPTION - B
FM Global Requirements (continued)

Separation Distance: Separation distance requirements are based on whether the transformer is FM Approved or equivalent, or the volume of fluid, and if the fluid is FM Approved. For FM Listed less-flammable fluids, horizontal distance is measured from transformer; for non-listed fluids, horizontal distance is measured from inside of the outer edge of containment. (See Figure 1.)
## Spacing & Clearances

### 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>Horizontal Distance**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fire Resistant ft/(m)</td>
</tr>
<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>&lt;10,000 (38)</td>
<td>5 (1.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;10,000 (38)</td>
<td>15 (4.6)</td>
</tr>
<tr>
<td>Mineral Oil</td>
<td>N/A</td>
<td>&lt;500 (1.9)</td>
<td>15 (4.6)</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>25 (7.6)</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>Yes</td>
<td>N/A</td>
<td>3 (0.9)</td>
</tr>
<tr>
<td>Loss-Flammable (Approved)</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 (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>
</tbody>
</table>

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

HV Substation Design: Applications and Considerations

HV Engineering, LLC

IEEE CED 2014-2015
IEEE C57.154-2012

THE DESIGN, TESTING, AND APPLICATION OF LIQUID-IMMERSED DISTRIBUTION, POWER, AND REGULATING TRANSFORMERS USING HIGH-TEMPERATURE INSULATION SYSTEMS AND OPERATING AT ELEVATED TEMPERATURES.
Examples of Fire Walls
Installation of Precast Fire Wall
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
Engineering Process

One-Lines & Specifications

- Electrical Plans/Details
- Protection & Control Schemes
- Relay Panel Specifications & Elevations

Site, Grading & SPCC

- Wiring Diagrams
- Relay Settings

Foundation Plans/Details

- Building Plans/Details
- Conduit Plans/Details
- Grounding Plans/Details
Construction Process

Site Prep → Foundation Installation → Conduit Installation → Grounding Installation → Station Yard Installation → Building Installation → Commission
Supplemental Topics
Logic Diagrams

With modern relays, a tripping logic diagram is critical in conveying the logic in the microprocessor relay.

…otherwise a protection one line diagram will become very busy if all functions are to be shown.
Logic Diagrams

Logic ID

Relay Word Bit

Manual Restore Ready 52-Inc1

Switch “10” Active in Position 52-1

CLOSE COMMAND [CC]
REMOTE CLOSE [LV02]

52-INCOMER 1 CLOSE LOGIC
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 2nd Tie Breaker
Variations

• Decrease exposure during breaker failure event

If low side tie is N.C., plant service can be maintained.
Variations

Second tie breaker allows maintenance of 100% of the swgr equipment.
• 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
Special Considerations

- **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
Spacing Affects Structural Design

Spacing & Clearances
# Post Insulators

## Table 4-5: Typical Characteristics of Post-Type Insulators


<table>
<thead>
<tr>
<th>BIL (Impulse VMTHStnd)</th>
<th>Technical Reference</th>
<th>Upright Cantilever Strength</th>
<th>Underhung Cantilever Strength</th>
<th>Bolt Circle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pounds (Newtons)</td>
<td>Pounds (Newtons)</td>
<td>Top (In, cm)</td>
</tr>
<tr>
<td>95</td>
<td>202</td>
<td>2000 (8896)</td>
<td>2000 (8896)</td>
<td>3 (7.62)</td>
</tr>
<tr>
<td>95</td>
<td>202</td>
<td>4000 (17792)</td>
<td>4000 (17792)</td>
<td>5 (12.7)</td>
</tr>
<tr>
<td>110</td>
<td>205</td>
<td>2000 (8896)</td>
<td>2000 (8896)</td>
<td>3 (7.62)</td>
</tr>
<tr>
<td>110</td>
<td>225</td>
<td>4000 (17792)</td>
<td>4000 (17792)</td>
<td>5 (12.7)</td>
</tr>
<tr>
<td>150</td>
<td>205</td>
<td>2000 (8896)</td>
<td>2000 (8896)</td>
<td>3 (7.62)</td>
</tr>
<tr>
<td>150</td>
<td>227</td>
<td>4000 (17792)</td>
<td>4000 (17792)</td>
<td>5 (12.7)</td>
</tr>
<tr>
<td>200</td>
<td>210</td>
<td>2000 (8896)</td>
<td>2000 (8896)</td>
<td>3 (7.62)</td>
</tr>
<tr>
<td>200</td>
<td>231</td>
<td>4000 (17792)</td>
<td>4000 (17792)</td>
<td>5 (12.7)</td>
</tr>
<tr>
<td>250</td>
<td>214</td>
<td>2000 (8896)</td>
<td>2000 (8896)</td>
<td>3 (7.62)</td>
</tr>
<tr>
<td>250</td>
<td>267</td>
<td>4000 (17792)</td>
<td>4000 (17792)</td>
<td>5 (12.7)</td>
</tr>
<tr>
<td>350</td>
<td>216</td>
<td>1500 (6672)</td>
<td>1500 (6672)</td>
<td>3 (7.92)</td>
</tr>
<tr>
<td>350</td>
<td>276</td>
<td>3000 (13344)</td>
<td>3000 (13344)</td>
<td>5 (12.7)</td>
</tr>
<tr>
<td>500</td>
<td>286</td>
<td>1700 (7562)</td>
<td>1700 (7562)</td>
<td>5 (12.7)</td>
</tr>
<tr>
<td>550</td>
<td>287</td>
<td>2600 (11564)</td>
<td>2600 (11564)</td>
<td>5 (12.7)</td>
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<tr>
<td>650</td>
<td>288</td>
<td>1400 (6227)</td>
<td>1400 (6227)</td>
<td>5 (12.7)</td>
</tr>
<tr>
<td>650</td>
<td>289</td>
<td>2200 (9786)</td>
<td>2200 (9786)</td>
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<tr>
<td>750</td>
<td>291</td>
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<td>1200 (5338)</td>
<td>5 (12.7)</td>
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<tr>
<td>750</td>
<td>295</td>
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<td>900</td>
<td>304</td>
<td>1300 (5558)</td>
<td>1300 (5558)</td>
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</tr>
<tr>
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<td>308</td>
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<td>310</td>
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<td>5 (12.7)</td>
</tr>
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<td>2300 (10230)</td>
<td>5 (17.8)</td>
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<tr>
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<td>324</td>
<td>1000 (4448)</td>
<td>1000 (4448)</td>
<td>5 (12.7)</td>
</tr>
<tr>
<td>1300</td>
<td>367</td>
<td>1450 (6450)</td>
<td>1450 (6450)</td>
<td>5 (12.7)</td>
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<tr>
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<td>368</td>
<td>2000 (8896)</td>
<td>2000 (8896)</td>
<td>7 (17.8)</td>
</tr>
<tr>
<td>1300</td>
<td>366</td>
<td>2050 (9118)</td>
<td>2050 (9118)</td>
<td>5 (12.7)</td>
</tr>
</tbody>
</table>

Notes:
1. The insulators listed are representative of those currently available. Additional ratings are available for some voltages. Refer to manufacturers' data for information.
2. The characteristics listed are typical. Refer to manufacturers' data for actual ratings and additional characteristics.
Suspension

Ball and Socket Insulators
<table>
<thead>
<tr>
<th>Nominal System Phase-to-Phase Voltage (kV)</th>
<th>BIL (kV)</th>
<th>Minimum Quantity of Suspension Insulators*</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>95</td>
<td>1</td>
</tr>
<tr>
<td>14.4</td>
<td>110</td>
<td>2</td>
</tr>
<tr>
<td>23</td>
<td>150</td>
<td>2</td>
</tr>
<tr>
<td>34.5</td>
<td>200</td>
<td>3</td>
</tr>
<tr>
<td>46</td>
<td>250</td>
<td>4</td>
</tr>
<tr>
<td>69</td>
<td>350</td>
<td>5</td>
</tr>
<tr>
<td>115</td>
<td>550</td>
<td>8</td>
</tr>
<tr>
<td>138</td>
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<td>9</td>
</tr>
<tr>
<td>161</td>
<td>750</td>
<td>10</td>
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<td>230</td>
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<td>1050</td>
<td>14</td>
</tr>
<tr>
<td>345</td>
<td>1300</td>
<td>20</td>
</tr>
</tbody>
</table>

*For standard 14.6- x 25.4-centimeter (5 ¾- x 10-inch) suspension insulators.
Suspension
Polymer Insulators
• 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

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>l/100</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/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>( l/50 )</td>
</tr>
<tr>
<td>Horizontal Deflection of Vertical Members</td>
<td>( l/200 )</td>
</tr>
<tr>
<td>Vertical Deflection of Horizontal Members</td>
<td>( l/100 )</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
Short-Circuit Forces

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

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.

![Diagram of short-circuit forces](image)

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:

$$F_x = \frac{16II_x^2}{10^7 D}$$  \hspace{1cm} (14)

For English units:

$$F_x = \frac{3.6II_x^2}{10^7 D}$$  \hspace{1cm} (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><img src="image" alt="Phase to phase diagram" /></td>
<td>A or B</td>
<td>1.000</td>
</tr>
<tr>
<td>Three phase</td>
<td><img src="image" alt="Three phase diagram" /></td>
<td>B</td>
<td>0.866</td>
</tr>
<tr>
<td>Three phase</td>
<td><img src="image" alt="Another three phase diagram" /></td>
<td>A or C</td>
<td>0.808</td>
</tr>
<tr>
<td>Phase to phase</td>
<td><img src="image" alt="Triangular arrangement diagram" /></td>
<td>A or B</td>
<td>1.000</td>
</tr>
<tr>
<td>Three phase</td>
<td><img src="image" alt="Another triangular arrangement diagram" /></td>
<td>A or B or C</td>
<td>0.500</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:
Short-Circuit Forces

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

(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
Short-Circuit Forces

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

<table>
<thead>
<tr>
<th>$X/R$</th>
<th>$T_e$</th>
<th>$D_f$</th>
<th>$D_f^2$</th>
<th>$X/R$</th>
<th>$T_e$</th>
<th>$D_f$</th>
<th>$D_f^2$</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.

Structural Design
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.
Rigid Bus Shapes

Source: Aluminum Electrical Conductor Handbook
Current Ratings

- Rated Continuous Current
- Selected Ambient Base
- Allowable Temperature Rise
- Equipment Limitations
- Interaction with Transmission Lines
- Other Factors
  - Wind
  - Ice Loading
  - Emissivity
Rigid Aluminum Tube Bus

### 6063-T6 Alloy

<table>
<thead>
<tr>
<th>Size</th>
<th>OD in.</th>
<th>ID in.</th>
<th>Weight lb/ft</th>
<th>Ampacity Outdoor**</th>
<th>Ampacity Indoor**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Temp Rise Above 40 C</td>
<td>Temp Rise Above 40 C</td>
</tr>
<tr>
<td></td>
<td>30 C</td>
<td>40 C</td>
<td>50 C</td>
<td>30 C</td>
<td>40 C</td>
</tr>
<tr>
<td>1/2</td>
<td>0.84</td>
<td>0.622</td>
<td>0.294</td>
<td>416</td>
<td>493</td>
</tr>
<tr>
<td>3/4</td>
<td>1.05</td>
<td>0.824</td>
<td>0.391</td>
<td>517</td>
<td>612</td>
</tr>
<tr>
<td>1</td>
<td>1.315</td>
<td>1.049</td>
<td>0.581</td>
<td>681</td>
<td>807</td>
</tr>
<tr>
<td>1-1/2</td>
<td>1.90</td>
<td>1.610</td>
<td>0.940</td>
<td>984</td>
<td>1,165</td>
</tr>
<tr>
<td>2</td>
<td>2.375</td>
<td>2.067</td>
<td>1.264</td>
<td>1,234</td>
<td>1,462</td>
</tr>
<tr>
<td>2-1/2</td>
<td>2.675</td>
<td>2.469</td>
<td>2.004</td>
<td>1,663</td>
<td>1,970</td>
</tr>
<tr>
<td>3</td>
<td>3.50</td>
<td>3.068</td>
<td>2.621</td>
<td>2,040</td>
<td>2,416</td>
</tr>
<tr>
<td>3-1/2</td>
<td>4.00</td>
<td>3.548</td>
<td>3.151</td>
<td>2,347</td>
<td>2,780</td>
</tr>
<tr>
<td>4</td>
<td>4.50</td>
<td>4.026</td>
<td>3.733</td>
<td>2,664</td>
<td>3,155</td>
</tr>
<tr>
<td>4-1/2</td>
<td>5.001</td>
<td>4.507</td>
<td>4.337</td>
<td>2,984</td>
<td>3,534</td>
</tr>
<tr>
<td>5</td>
<td>5.663</td>
<td>5.047</td>
<td>5.057</td>
<td>3,348</td>
<td>3,965</td>
</tr>
<tr>
<td>6</td>
<td>6.625</td>
<td>6.065</td>
<td>6.564</td>
<td>4,064</td>
<td>4,813</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Size</th>
<th>OD in.</th>
<th>ID in.</th>
<th>Weight lb/ft</th>
<th>Ampacity Outdoor**</th>
<th>Ampacity Indoor**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 C</td>
<td>40 C</td>
<td>50 C</td>
<td>30 C</td>
<td>40 C</td>
</tr>
<tr>
<td>1/2</td>
<td>0.84</td>
<td>0.546</td>
<td>0.376</td>
<td>470</td>
<td>567</td>
</tr>
<tr>
<td>3/4</td>
<td>1.05</td>
<td>0.742</td>
<td>0.510</td>
<td>590</td>
<td>699</td>
</tr>
<tr>
<td>1</td>
<td>1.315</td>
<td>0.957</td>
<td>0.751</td>
<td>774</td>
<td>917</td>
</tr>
<tr>
<td>1-1/2</td>
<td>1.90</td>
<td>1.50</td>
<td>1.256</td>
<td>1,137</td>
<td>1,347</td>
</tr>
<tr>
<td>2</td>
<td>2.375</td>
<td>1.939</td>
<td>1.737</td>
<td>1,446</td>
<td>1,713</td>
</tr>
<tr>
<td>2-1/2</td>
<td>2.675</td>
<td>2.323</td>
<td>2.650</td>
<td>1,907</td>
<td>2,259</td>
</tr>
<tr>
<td>3</td>
<td>3.50</td>
<td>2.90</td>
<td>3.547</td>
<td>2,363</td>
<td>2,799</td>
</tr>
<tr>
<td>3-1/2</td>
<td>4.00</td>
<td>3.364</td>
<td>4.326</td>
<td>2,735</td>
<td>3,239</td>
</tr>
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<td>4</td>
<td>4.50</td>
<td>3.826</td>
<td>5.183</td>
<td>3,118</td>
<td>3,693</td>
</tr>
<tr>
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<td>4.291</td>
<td>6.092</td>
<td>3,505</td>
<td>4,151</td>
</tr>
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<td>5</td>
<td>5.663</td>
<td>4.183</td>
<td>7.188</td>
<td>3,949</td>
<td>4,677</td>
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<td>6.625</td>
<td>5.761</td>
<td>9.884</td>
<td>4,891</td>
<td>5,793</td>
</tr>
</tbody>
</table>

Note that these tabulations are based on specified conditions.
Rigid Aluminum Tube Bus

Great Resource
Rigid Aluminum Tube
Bus

Example of more specific calculations.
Corona Mitigation

Corona forms when the voltage gradient at the surface of the conductor exceeds the dielectric strength of the surrounding air. IEEE 605-Appendix D provides methods to calculate minimum conductor size (based on Peek’s equation).

Experience and best practices suggests the minimum conductor sizes as shown in the table below.

<table>
<thead>
<tr>
<th>Voltage [kV]</th>
<th>Wire</th>
<th>Tubing [inches]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>#2 AWG</td>
<td>½</td>
</tr>
<tr>
<td>34.5</td>
<td>#1/0 AWG</td>
<td>½</td>
</tr>
<tr>
<td>69</td>
<td>#1/0 AWG</td>
<td>½</td>
</tr>
<tr>
<td>115</td>
<td>#4/0 AWG</td>
<td>½</td>
</tr>
<tr>
<td>230</td>
<td>750 kcmil</td>
<td>1 ½</td>
</tr>
<tr>
<td>345</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>500</td>
<td>-</td>
<td>4</td>
</tr>
</tbody>
</table>
Corona Mitigation

Many utilities have standards for minimum conductor size:

Table 2-1 provides a list of minimum recommended conductor sizes for various operating voltages.

<table>
<thead>
<tr>
<th>kVLL</th>
<th>ACSR</th>
<th>AAAC-6201</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.5</td>
<td>1/0</td>
<td>123.3 kcmil</td>
</tr>
<tr>
<td>46</td>
<td>2/0</td>
<td>155.4 kcmil</td>
</tr>
<tr>
<td>69</td>
<td>3/0</td>
<td>195.7 kcmil</td>
</tr>
<tr>
<td>115</td>
<td>266.8 kcmil</td>
<td>312.8 kcmil</td>
</tr>
<tr>
<td>138</td>
<td>336.4 kcmil</td>
<td>394.5 kcmil</td>
</tr>
<tr>
<td>161</td>
<td>397.5 kcmil</td>
<td>465.4 kcmil</td>
</tr>
<tr>
<td>230</td>
<td>795 kcmil</td>
<td>927.2 kcmil</td>
</tr>
</tbody>
</table>

(1) The above minimum sizes are based on mechanical, corona and radio interference considerations. Larger conductors may very often be required because of the economics of power losses and other factors.

Source:

UNITED STATES DEPARTMENT OF AGRICULTURE
Rural Utilities Service

RUS BULLETIN 1724E-203

SUBJECT: Guide for Upgrading RUS Transmission Lines
Corona Mitigation

D.4 Methods of reducing the probability of substation corona

Substation bus corona will probably occur. There is no physical law that supports any specific onset voltage. The probability that corona will occur depends on many factors, such as bus contamination, weather, and surface nicks, as well as on field voltage gradient.

Although substantial guidance is available from transmission-line research, past design practice is the best guidance for achieving acceptable audible noise and light-emission levels for substation buses.

Reducing the probability of insulator damage from corona is an area that is still evolving. Continued research is needed to develop design practices that will lead to determination of a corona probability that leads to an acceptable level of insulator tolerance for damage.

There is some probability that corona-generated interference will occur. Following good practices in design and specification of substation bus hardware assemblies, and proper installation of the hardware, will reduce the probability.

Source: IEEE 605
IEEE 605-2008 is a great resource:
- Conductor Physical Properties
- Conductor Electrical Properties
- Examples of Calculations

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).
Appendix
Example of low profile substation using lattice structures
Example of conventional design
Typical detail of tube bus support
Grout makes the installation look pretty, but the consequence is that the water has no where to drain.
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>Quick-break current amps</th>
<th>Interrupter current amps</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>400</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>
<td>15</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>
<td>20</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>
<td>20</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>
<td>50</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>
<td>80</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>
<td>90</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>
<td>100</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>
<td>100</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>
<td>115</td>
</tr>
<tr>
<td>11</td>
<td>362.0</td>
<td>RCC 2</td>
<td>5</td>
<td>-</td>
<td>350</td>
<td>-</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.
† These devices are typically high-velocity plug 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>
Thank You!

Questions?

Dominik Pieniazek, P.E.
Mike Furnish, P.E.