HV Substation Design: Applications and Considerations

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IEEE CED – Feb 17/18, 2015

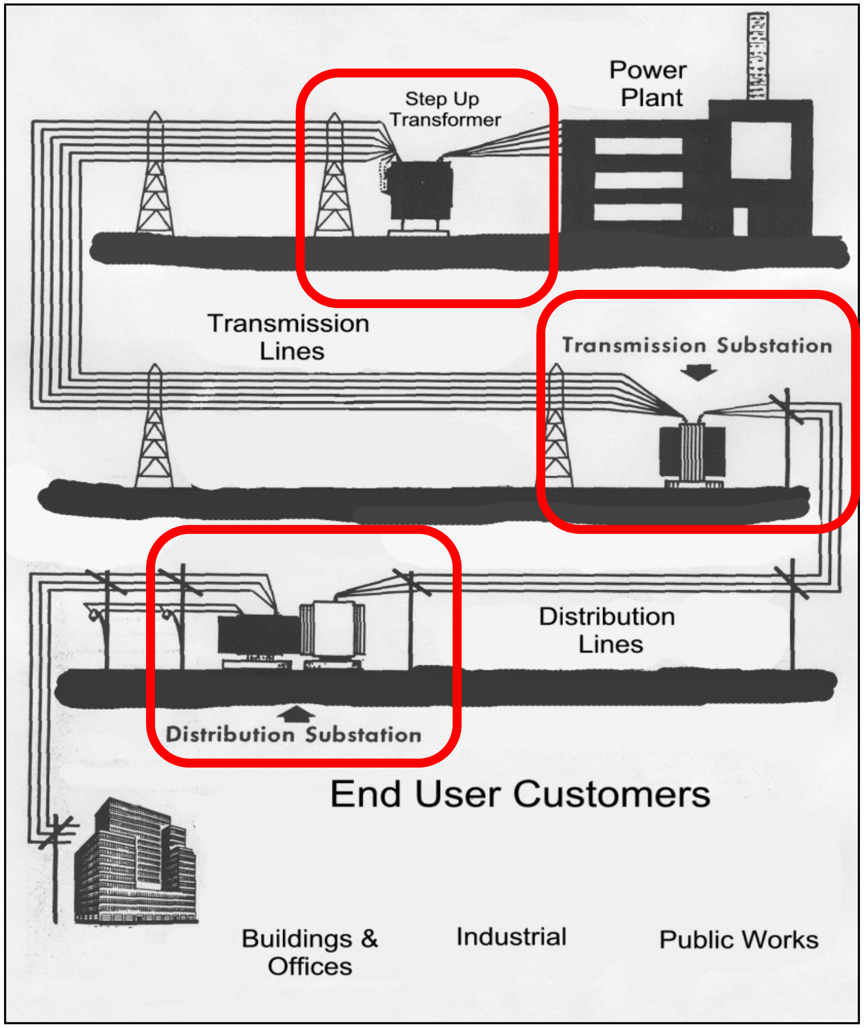
HV
Engineering
www.hv-eng.com

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



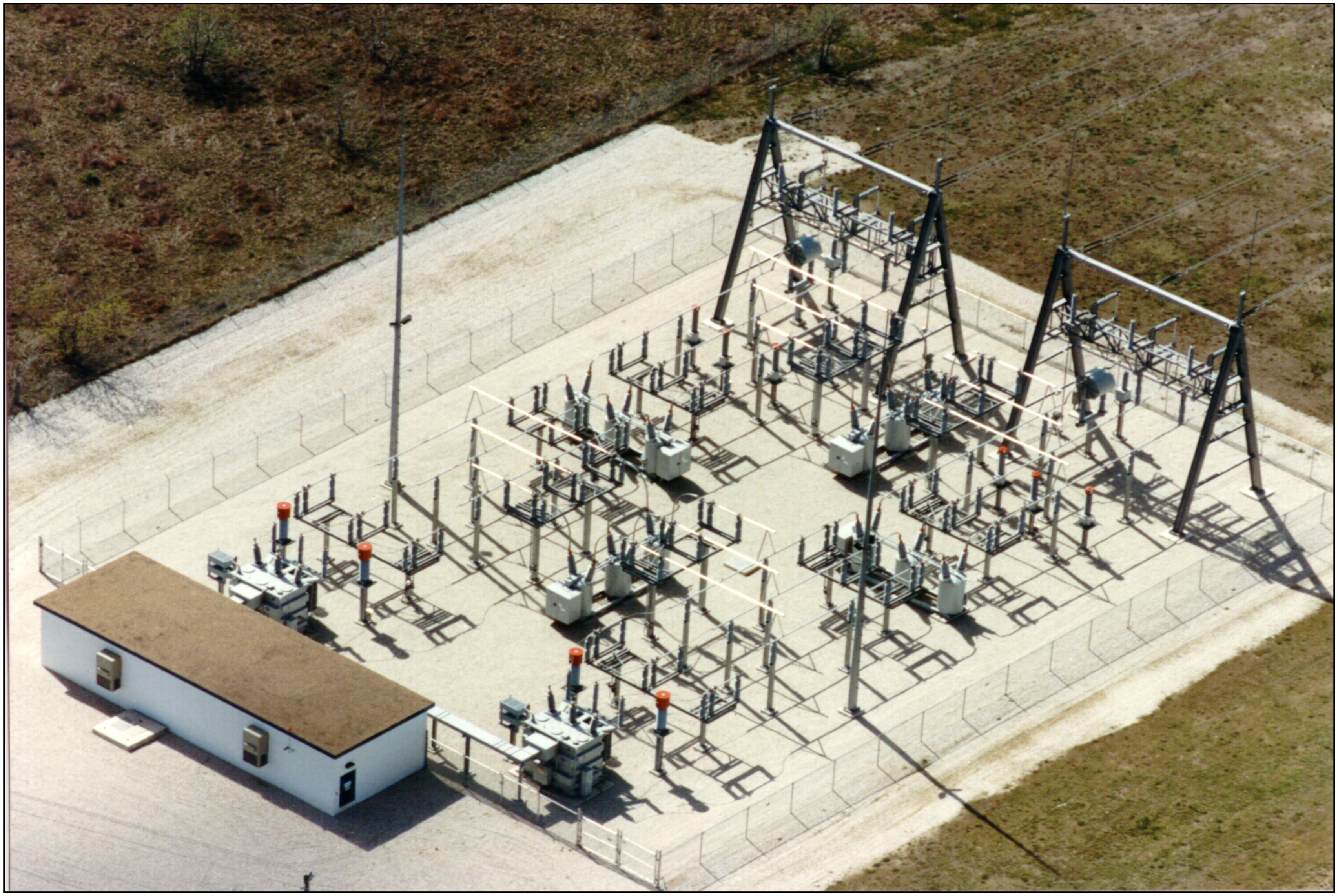
TRANSMISSION LEVEL VOLTAGES

765 kV	161 kV
500 kV	138 kV
345 kV	115 kV
230 kV	69 kV

Grey area…
…sometimes referred to a sub-transmission also

DISTRIBUTION LEVEL VOLTAGES

69kV	
46 kV	15 kV
34.5 kV	4.16 kV
23 kV	480 V



Typical 138 kV Substation – Four (4) Breaker Ring Bus w/ Oil Circuit Breakers

Typical 138 kV Substation

Typical 138 kV Substation

230 kV Generating Substation – Built on the side of a mountain

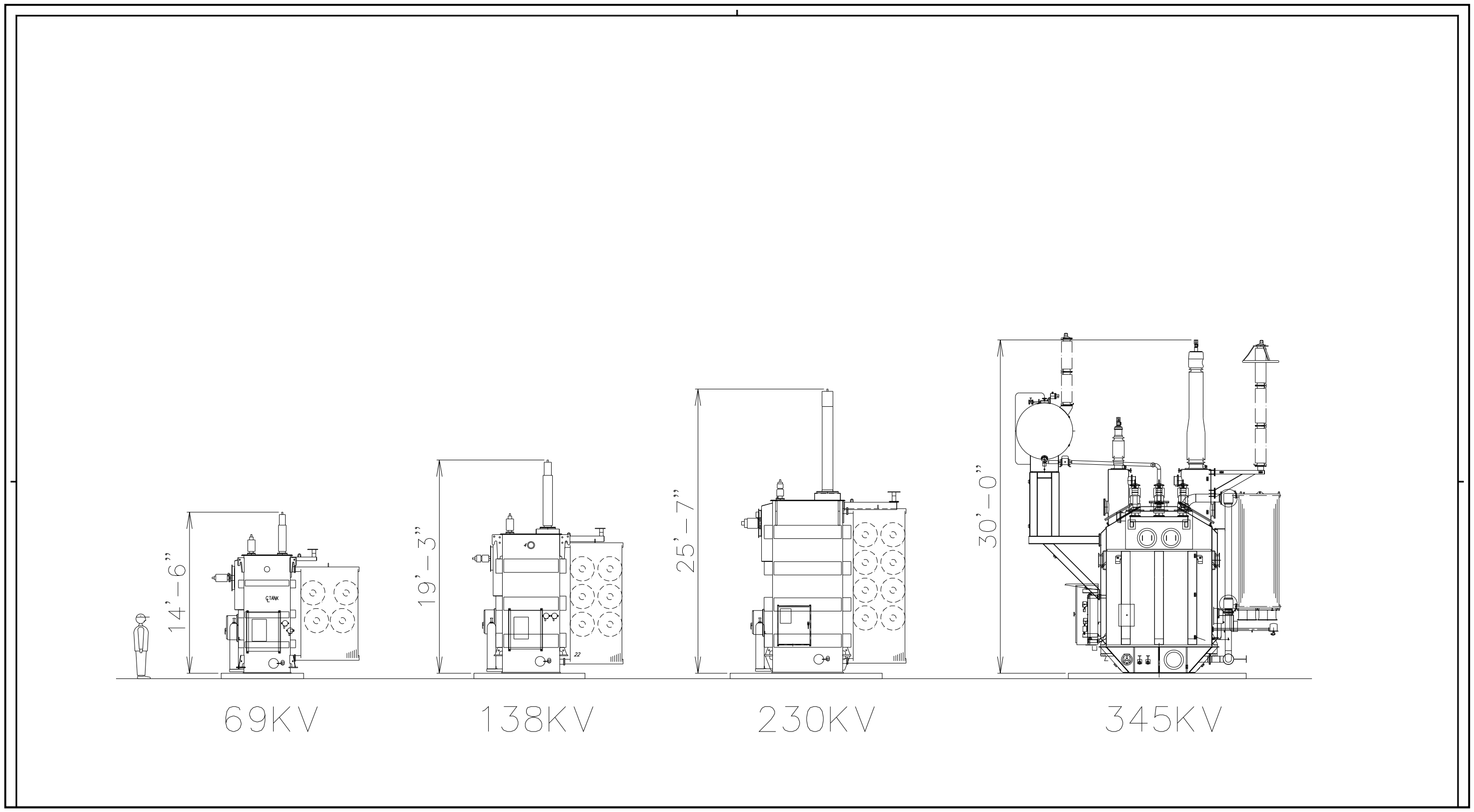
230 kV Indoor Generating Substation

765 kV Generating Substation – Four (4) Breaker Ring Bus w/ Live Tank GCBs

765 kV Generating Substation

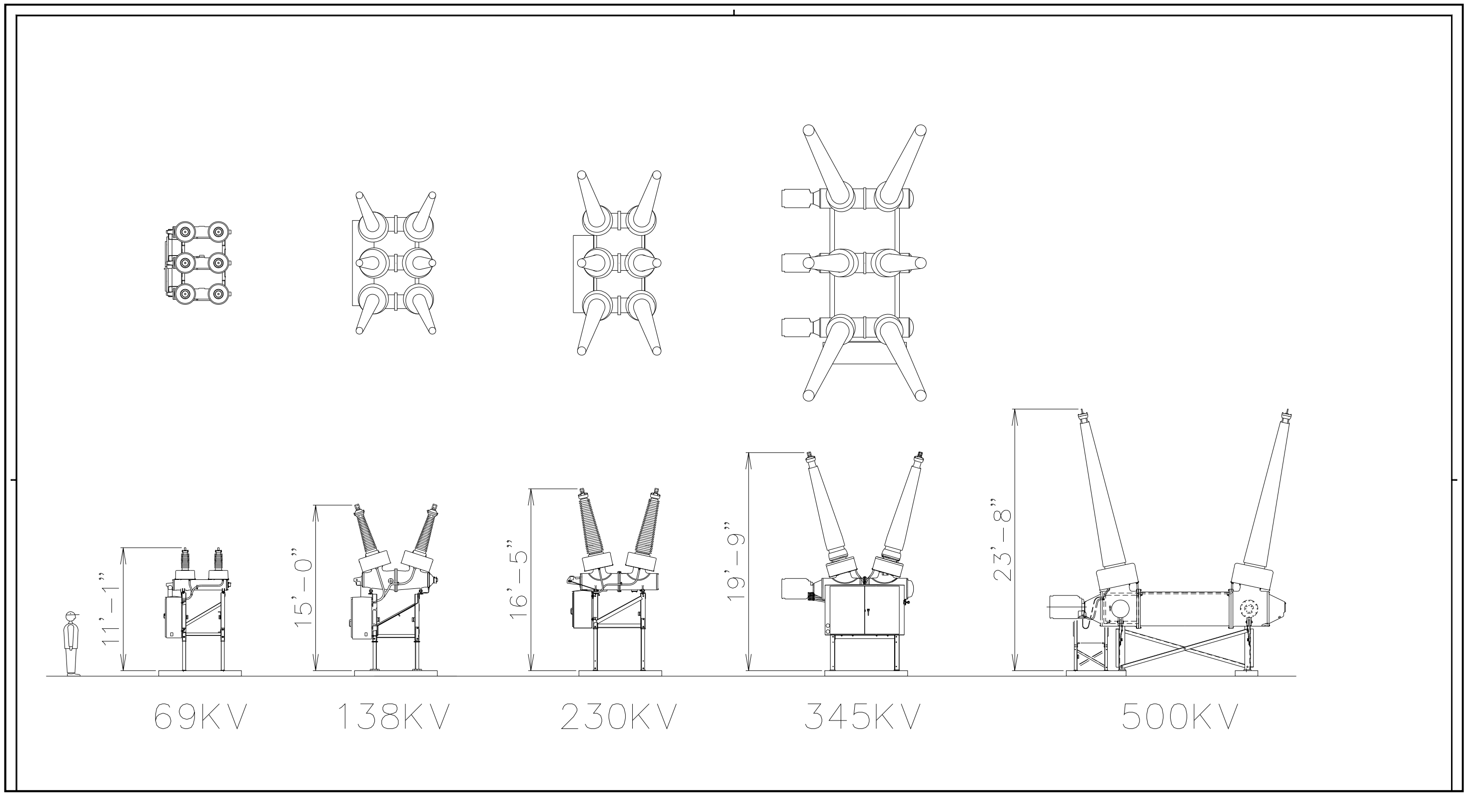
765 kV Generating Substation

765 kV Generating Substation

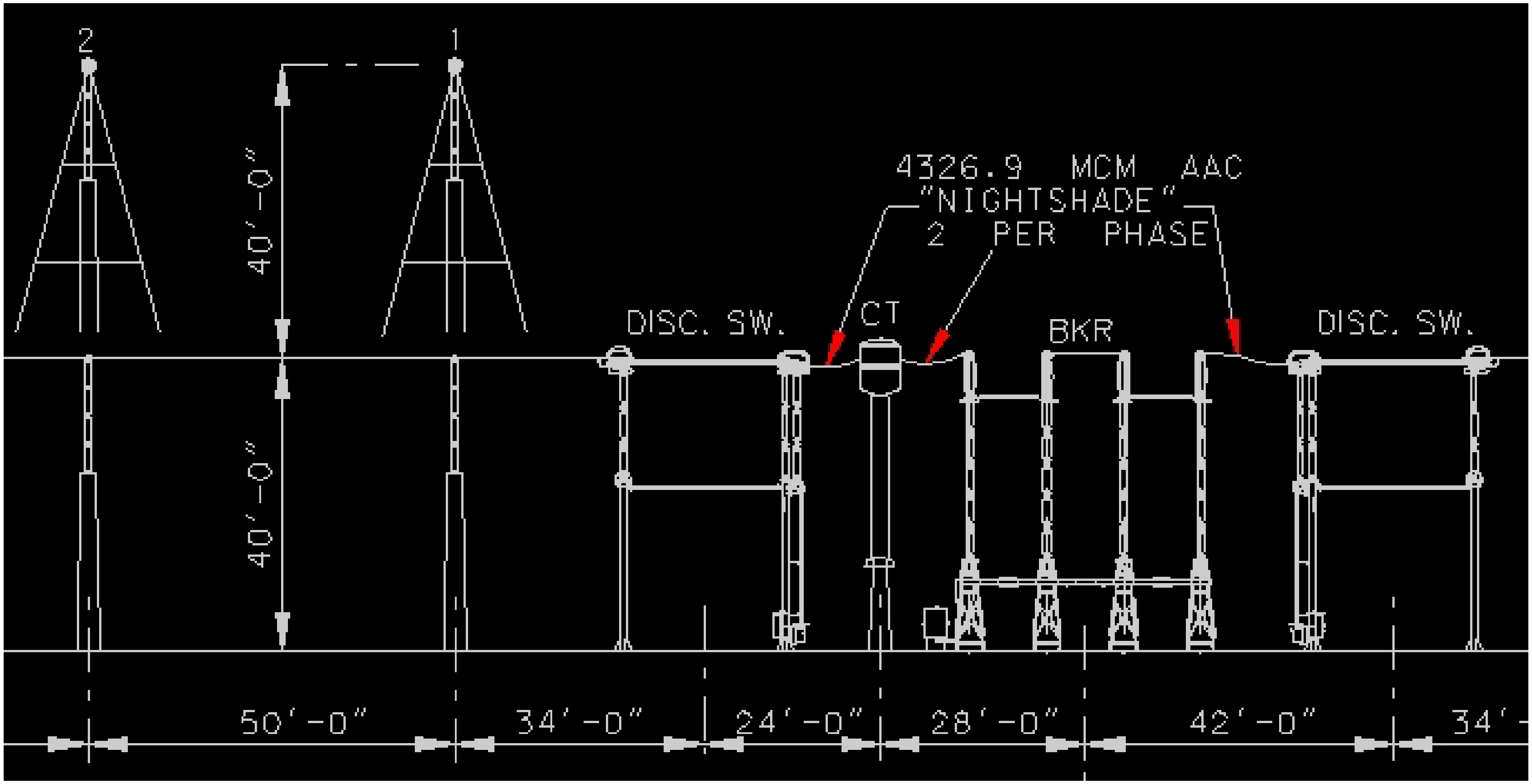


Relative Size of HV Power Transformers

Relative Size of HV and EHV Power Transformers



Relative Size of HV and EHV Gas Circuit Breakers



Dimensions for 765 kV Installation

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?

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

Electrical Questions to Address

- 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

Multiplier applied to phase-to-ground voltage

Table 1 - Bushing Data

System Voltage		Bushing	Creepage Distance in Inches			
Nominal kV	**Maximum kV**	**BIL kV**	**Light** [1]	**Medium** [1]	**Heavy** [1]	**Extra-Heavy** [1]
34.5	38.0	200	22	27	35	42
46	48.0	250	29	37	46	56
69	72.5	350	44	55	69	85
115	121.0	550	73	91	115	141
138	145.0	650	88	110	138	169
161	169.0	750	102	128	161	198
230	242.0	900	146	183	230	282
345	362.0	1175	220	274	345	423
500	550.0	1675	318	398	500	614
765	800.0	2050	487	609	765	939

Table 2 - Contamination Multipliers

Contamination Level	Multiplying Factor
Light	28mm/kV
Medium	35mm/kV
Heavy	44mm/kV
Extra Heavy	54mm/kV

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

Physical Questions to Address

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

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

- 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

Major Factors in Substation Selection

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

Configuration	Relative Cost Comparison
Single Breaker-Single Bus	100%
Main-Transfer Bus	140%
Ring Bus	125%
Breaker and Half	145%
Double Breaker-Double Bus	190%

Reference: IEEE 605-2008

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

- Real Estate Costs
- Complexity of Protective Relaying Schemes
- Raw material costs
- Local Labor Costs

λ = Annual Fail Rate

r = Annual Outage Time

U = Average Outage Time

Table 3: Substation Reliability Indices (Ignoring Line Failure)

Configuration	λ (/yr)	r (min)	U (min/yr)
a	0.0489	72.15	3.53
b	0.0453	71.95	3.26
c	0.00301	184.56	0.56
d	0.00567	124.216	0.70
e	0.0174	81.88	1.42

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

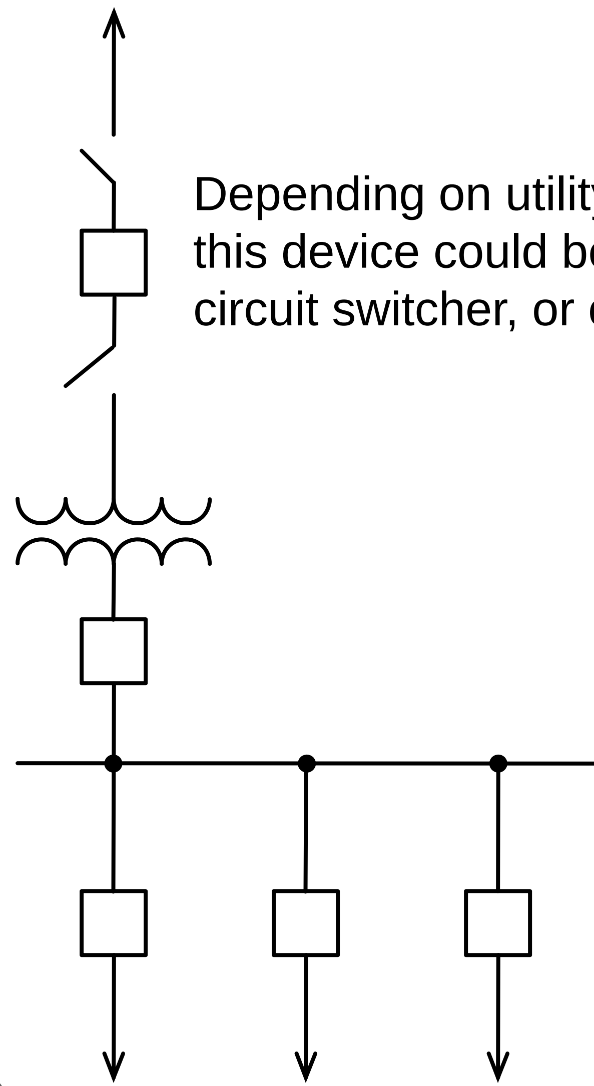
Reference: "Reliability of Substation Configurations", Daniel Nack, Iowa State University, 2005

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

Tap Substation

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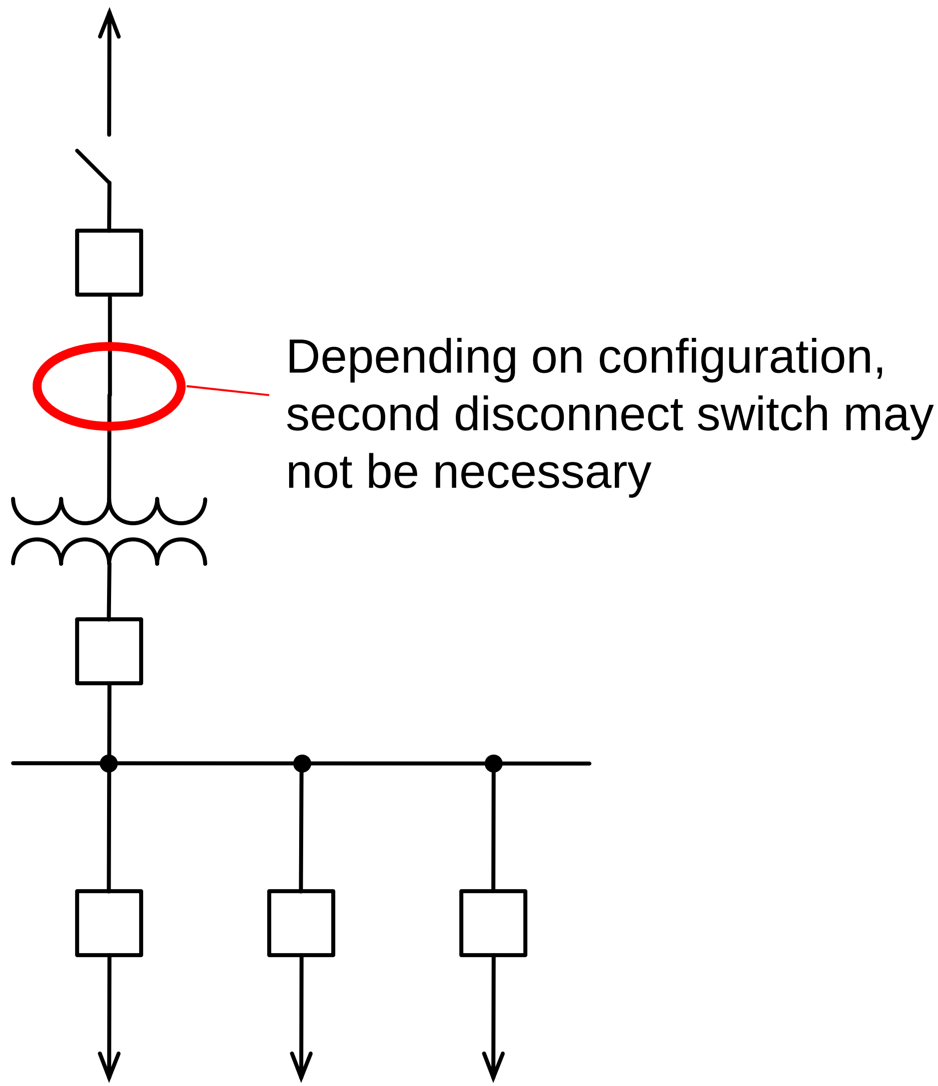

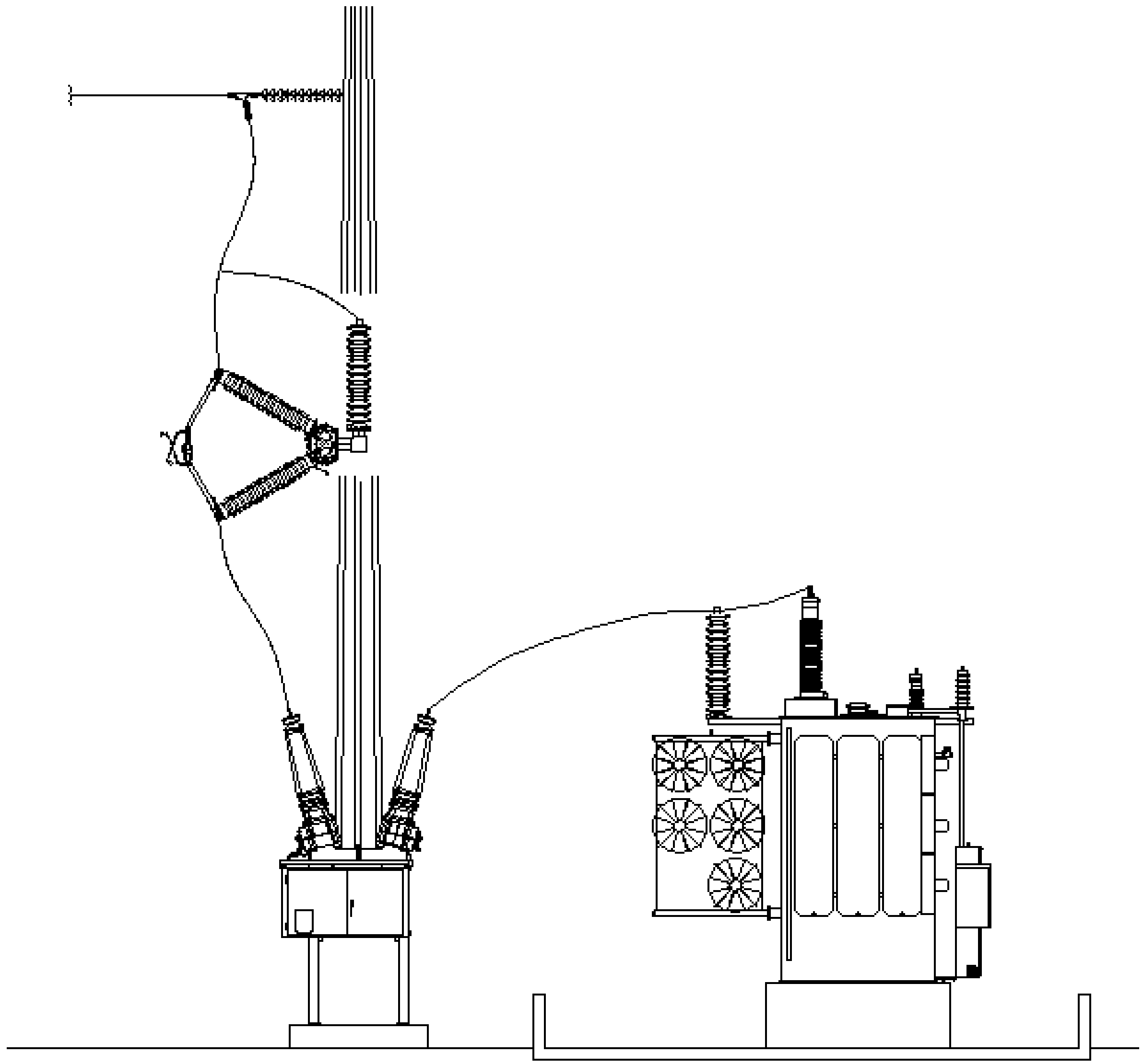

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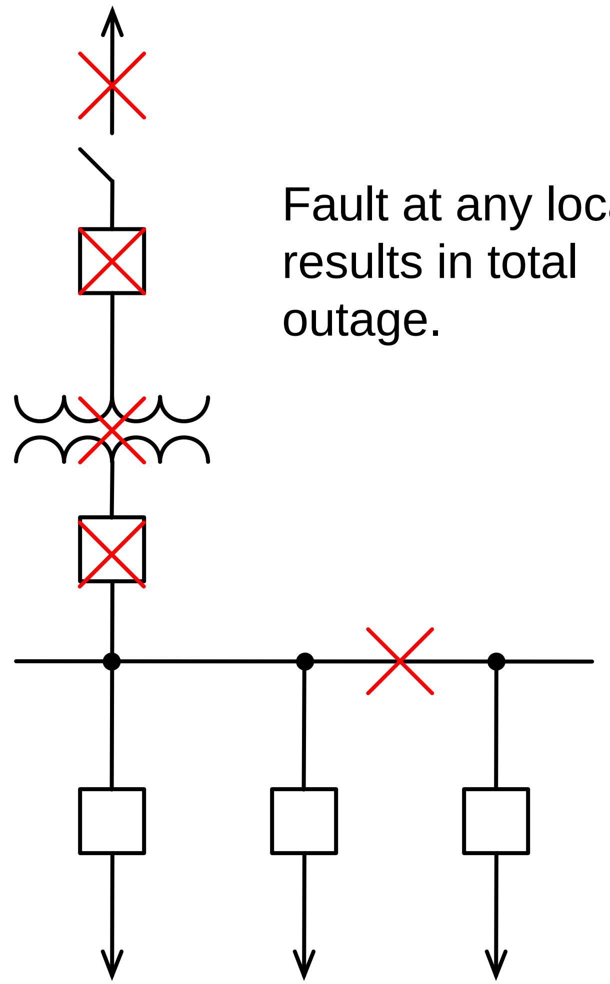


Tap Substation

Tap Substation

Pros

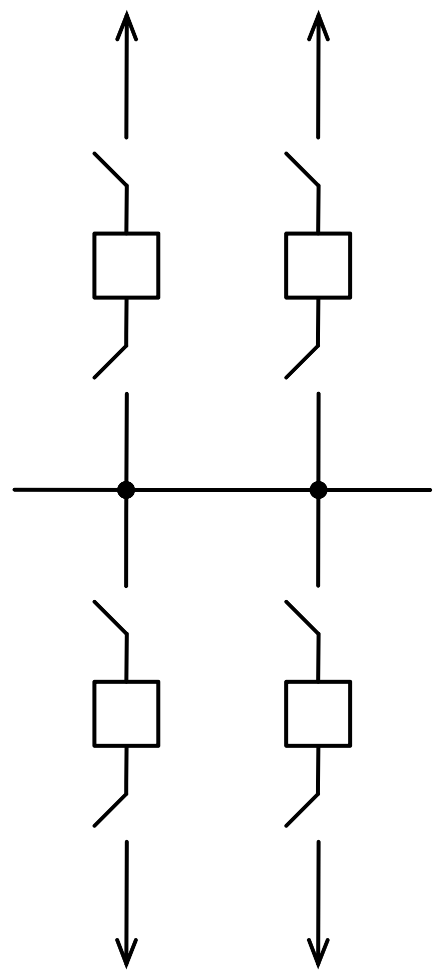
- Small Plot Size
- Low Initial Cost
- Low Maintenance Costs

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



Pros

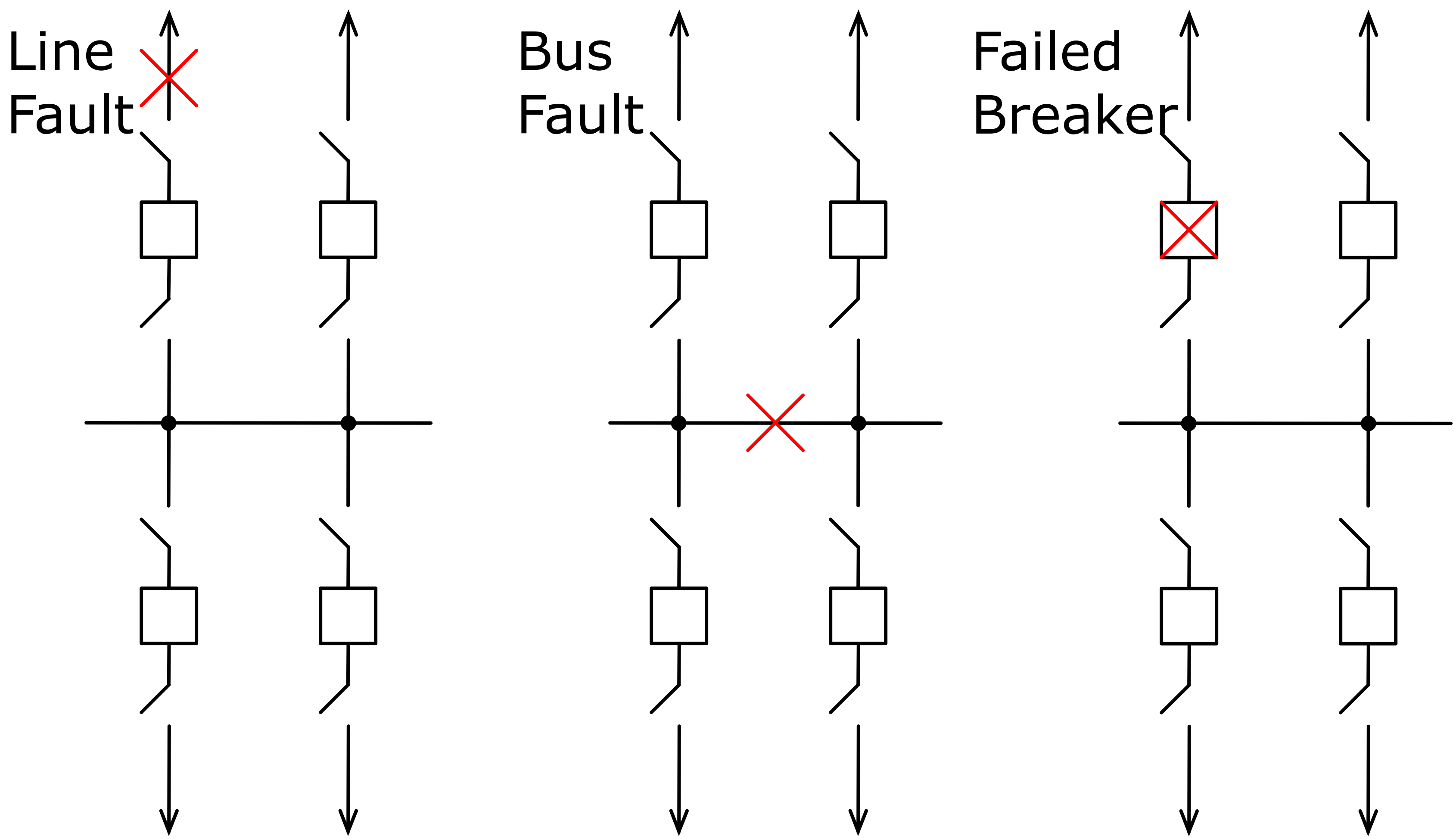
- Each Circuit has Breaker
- Only One Set of VTs Required
- Simple Design

Cons

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

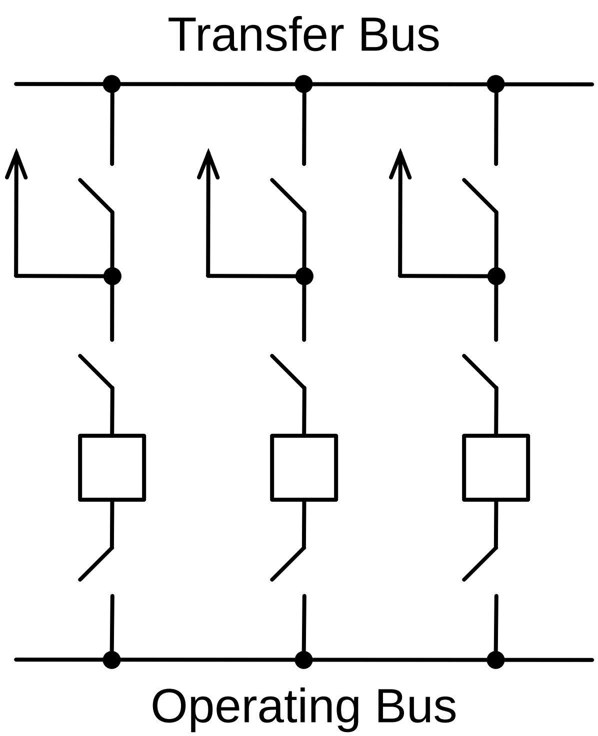
Single Breaker Single Bus

Single Breaker Single Bus



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



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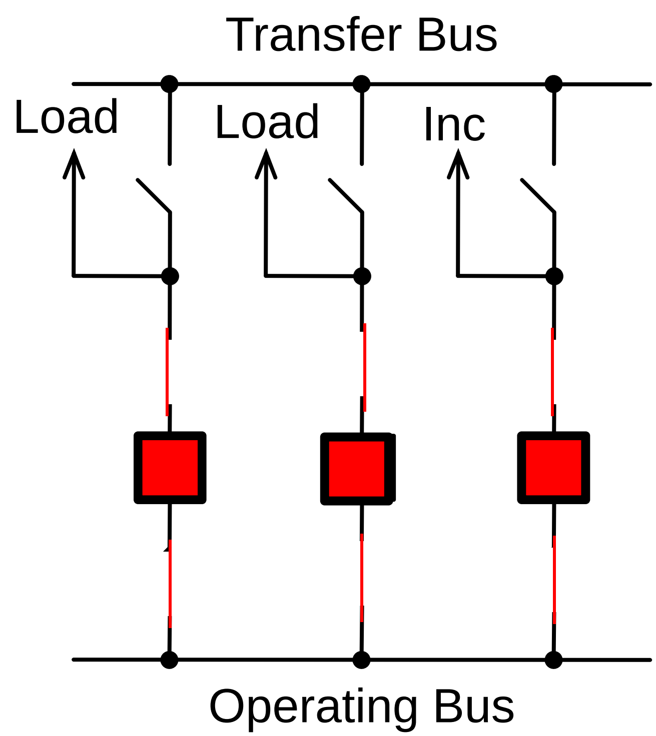

Normal Configuration is with transfer bus de-energized

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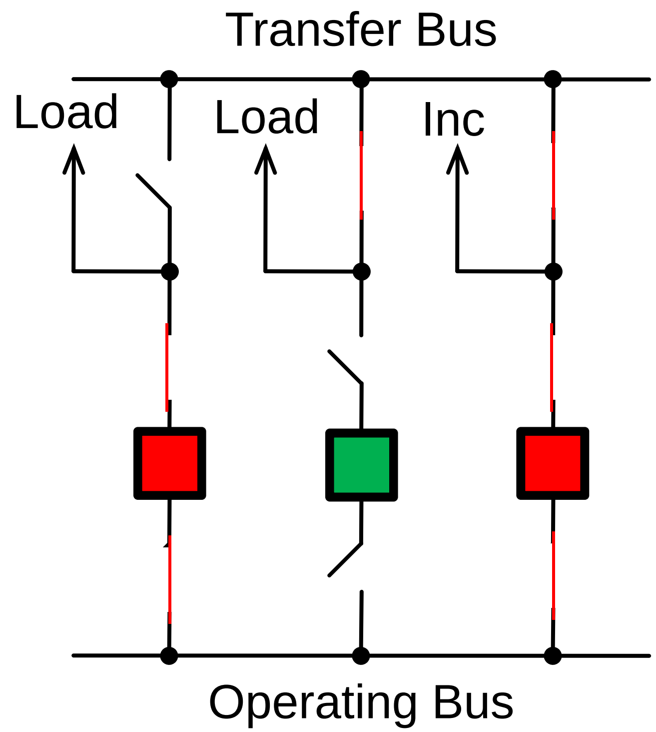

In the event of an outage of the feeder breaker, the load is fed via the transfer bus. Protection is compromised.

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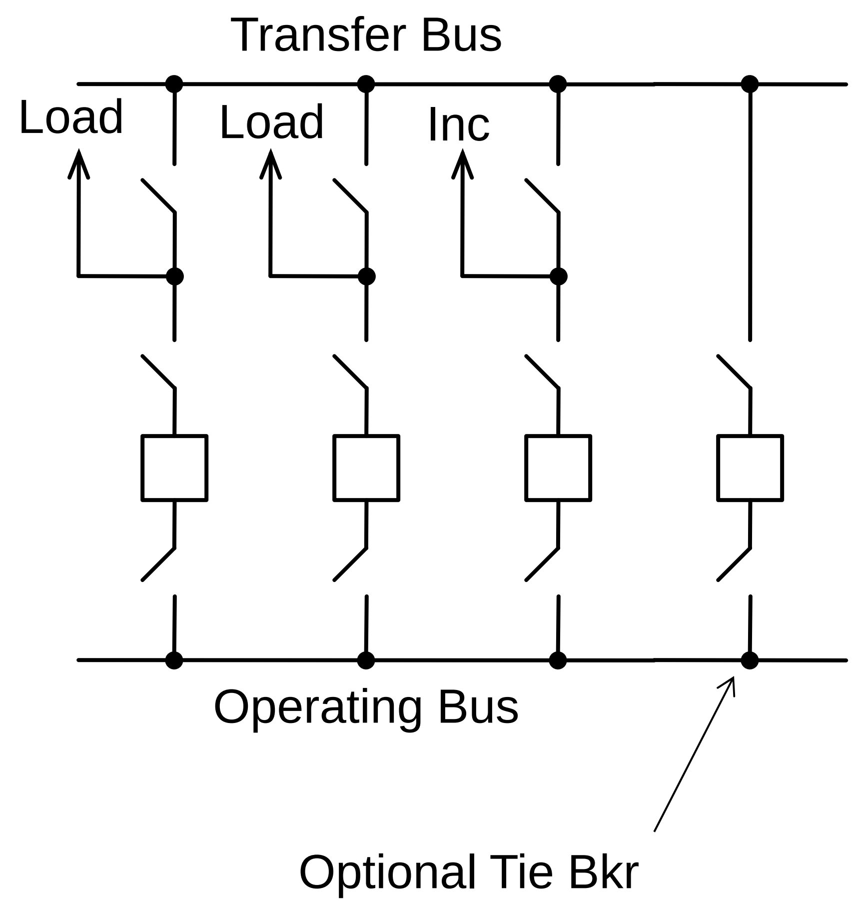

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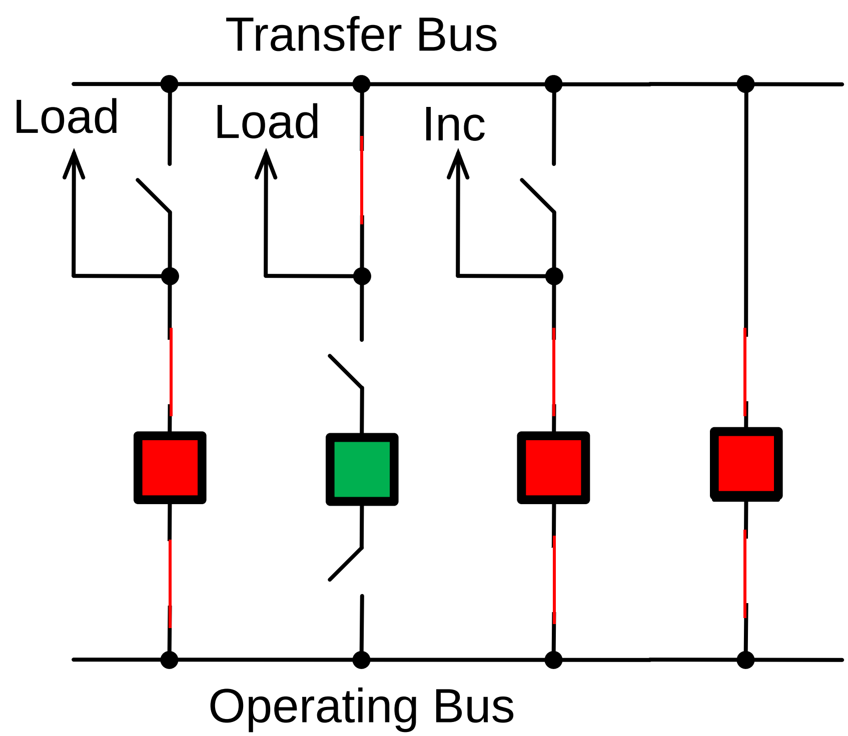


Load can be fed via the tie breaker. Settings on tie breaker can be adjusted as req'd.

Operating/Transfer Buses with Single Breaker

Pros

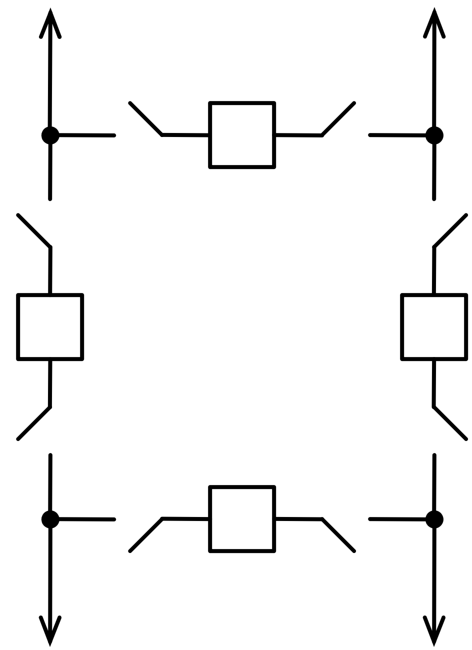
- Breaker Maintenance w/o Circuit Interruption
- Only One Set of VTs Required

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

Ring Bus

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



Pros

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

Cons

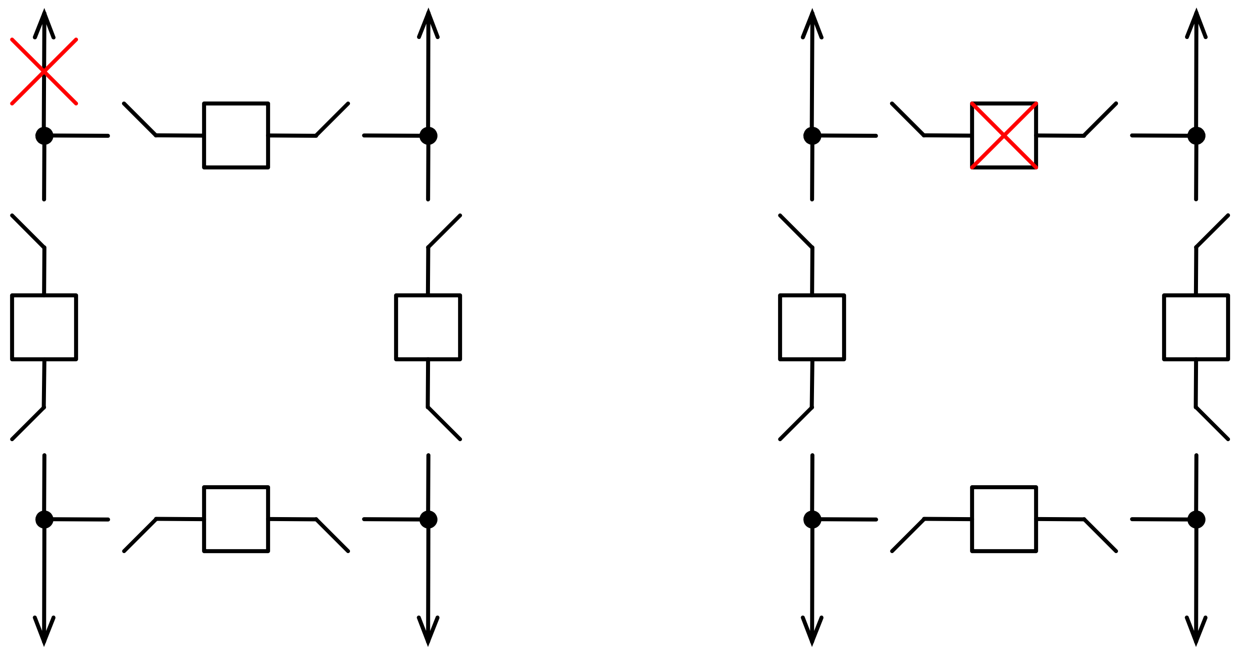
- Failed Breaker May Result in Loss of Multiple Circuits
- Physically Large With 6 or More Circuits

Ring Bus

Ring Bus

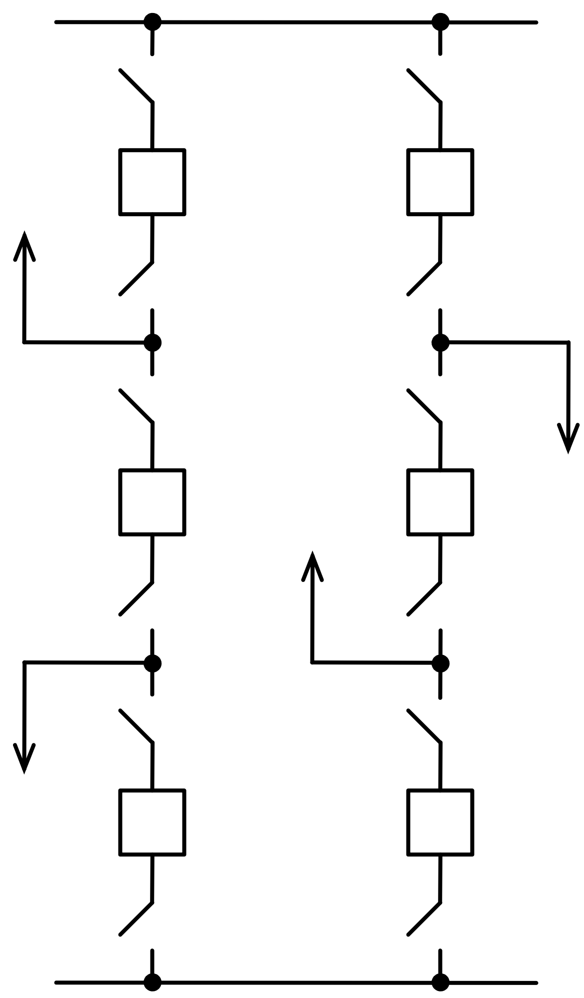
Line/Bus Fault

Failed Breaker



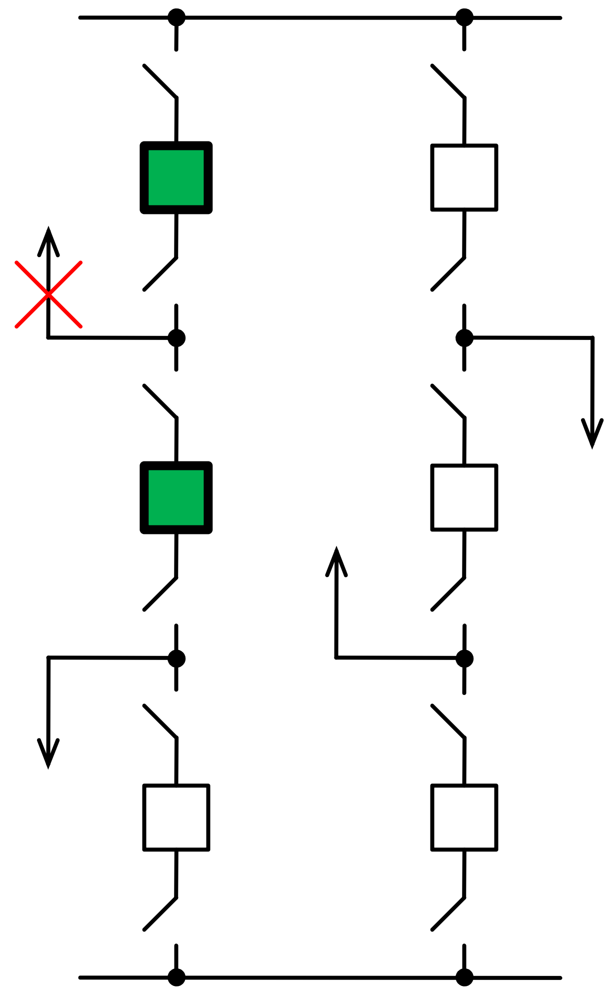
Breaker-And-A-Half

- More Operating Flexibility than Ring Bus
- Requires 3 Breakers for Every Two Circuits
- Widely Used at High Voltage, Especially Where Multiple Circuits Exist (e.g. Generating Plants)



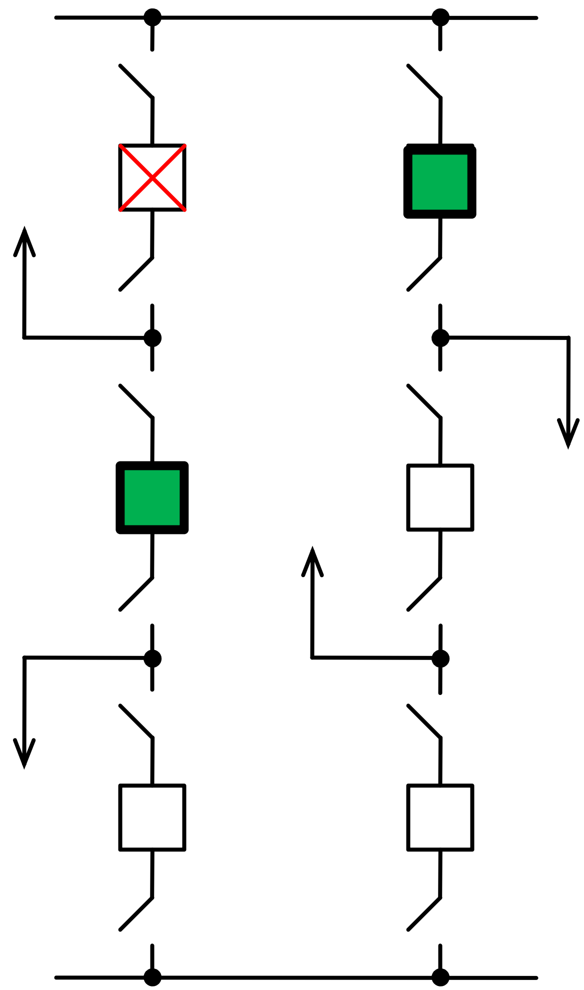
Breaker-And-A-Half

- Line fault



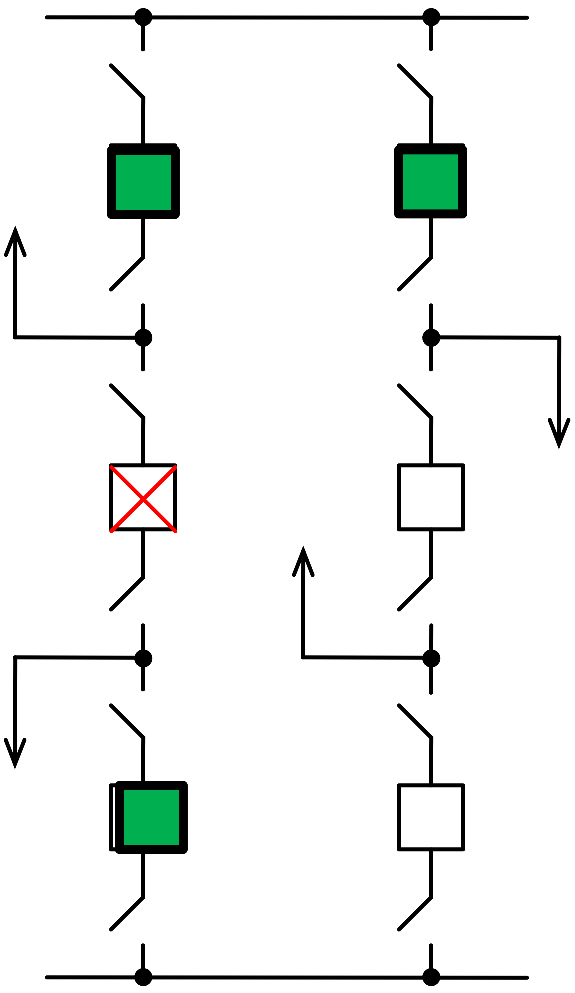
Breaker-And-A-Half

- Breaker Failure



Breaker-And-A-Half

- Breaker Failure



Breaker-And-A-Half

Pros

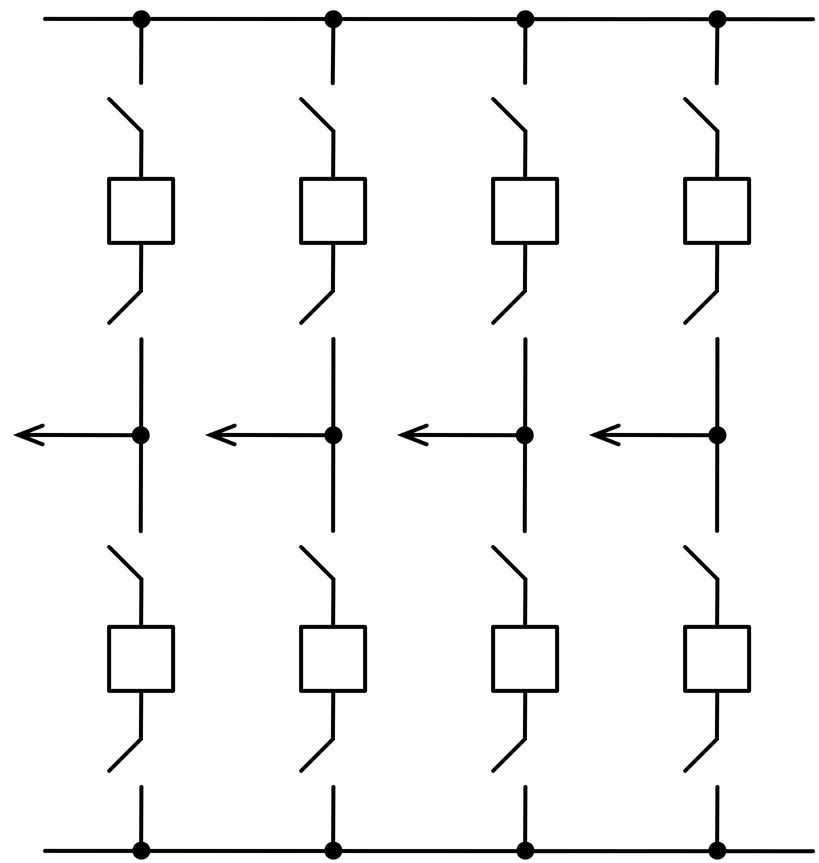
- Robust
- Highly Expandable
- Failed Outer Breakers Result in Loss of One Circuit Only
- Breaker Maintenance w/o Circuit Interruption

Cons

- Cost
- Physically Large
- Failed Center Breaker Results in Loss of Two Circuits

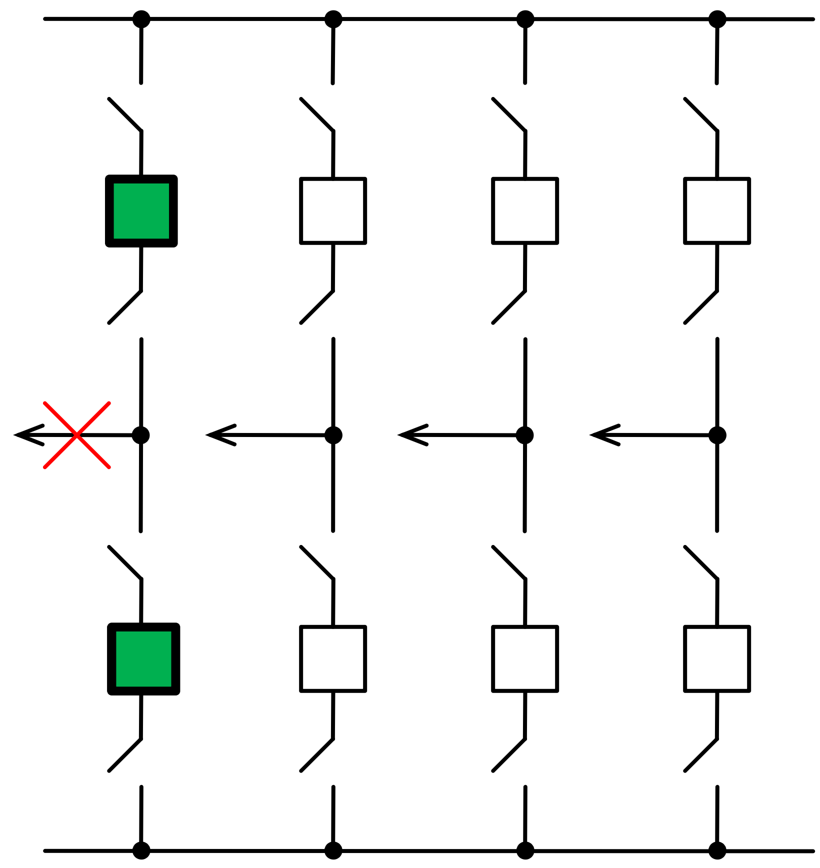
Double Breaker Double Bus

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



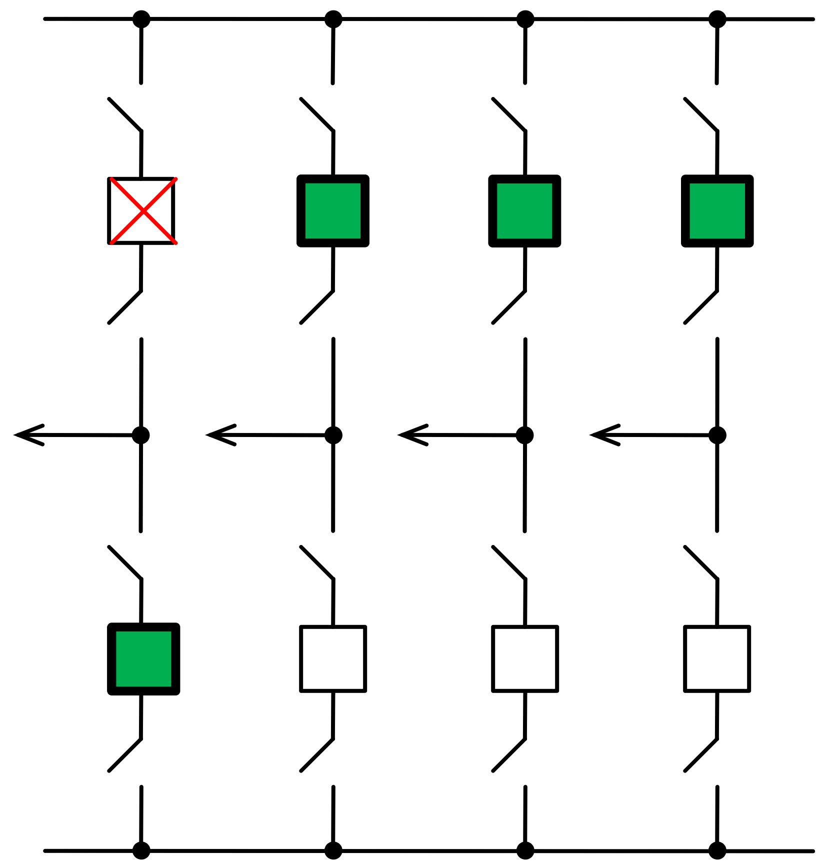
Double Breaker Double Bus

- Line Fault



Double Breaker Double Bus

- Breaker failure



Double Breaker Double Bus

Pros

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

Cons

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

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

Design Data / Basis

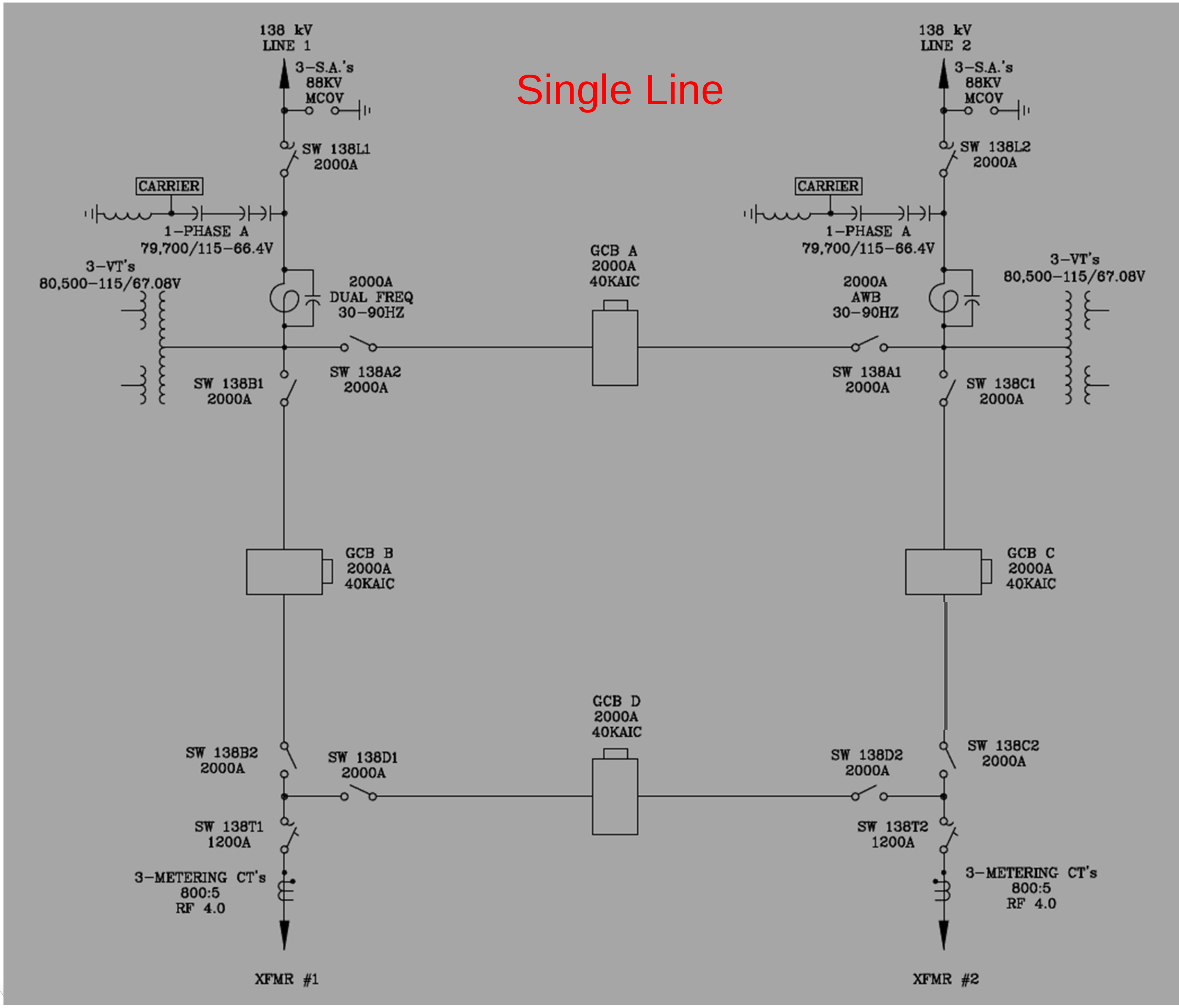
138 kV DESIGN BASIS

RATED MAXIMUM VOLTAGE	145 kV
SYSTEM GROUNDING	EFFECTIVELY GROUNDED
RATED CONTINUOUS CURRENT	1200 A
RATED SHORT–CIRCUIT CURRENT	40 kA
BASIC IMPULSE INSULATION LEVEL (BIL)	
– INSULATORS	650 kV
– BUSHINGS	650 kV
– TRANSFORMER WINDING	550 kV

4.16 kV DESIGN BASIS

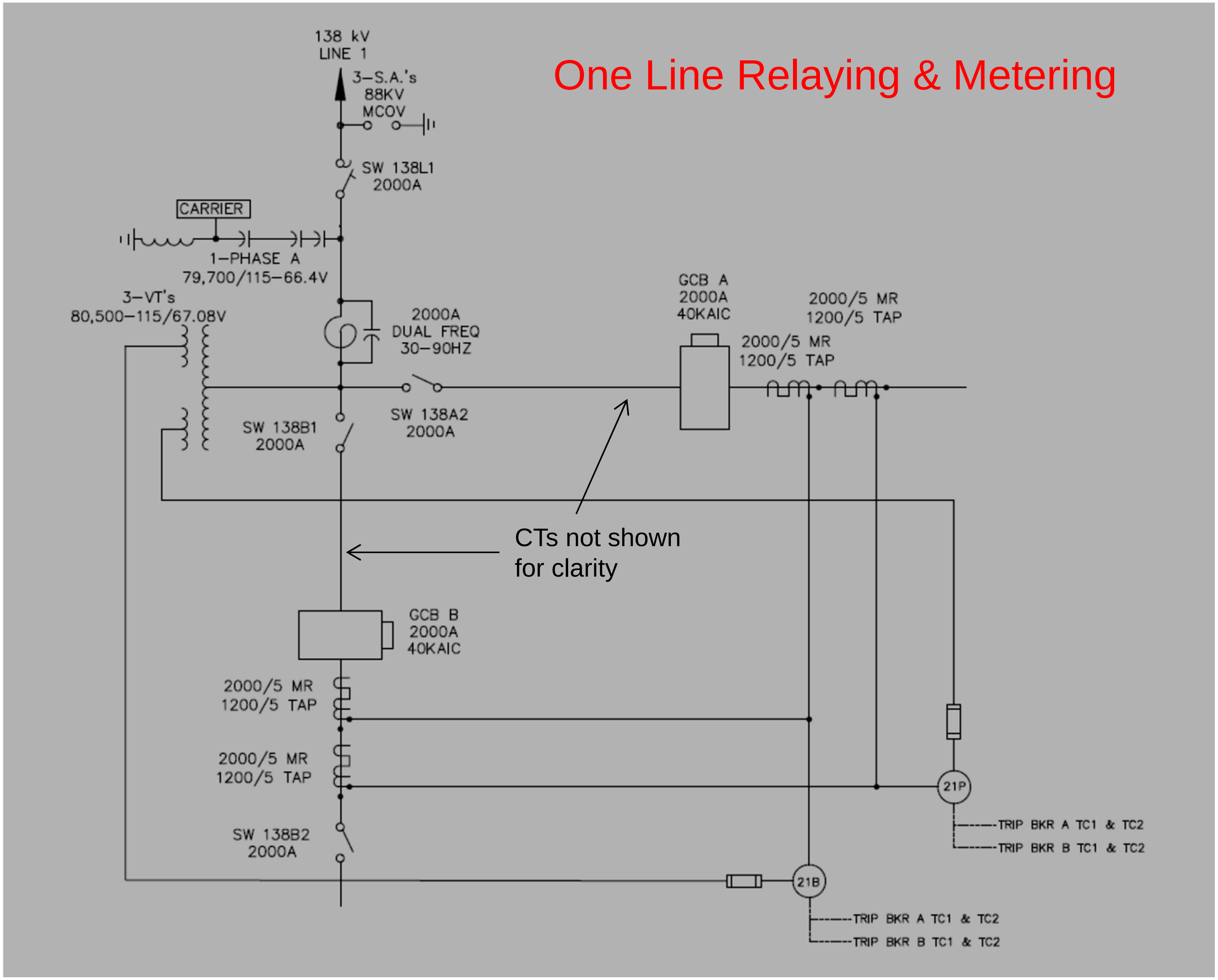
RATED MAXIMUM VOLTAGE	4.76 kV
SYSTEM GROUNDING	LOW RESISTANCE
RATED CONTINUOUS CURRENT	2000 A
RATED SHORT–CIRCUIT CURRENT	50 kA
BASIC IMPULSE INSULATION LEVEL (BIL)	
– SWITCHGEAR	60 kV
– BUSHINGS	110 kV
– TRANSFORMER WINDING	75 kV

Single Line

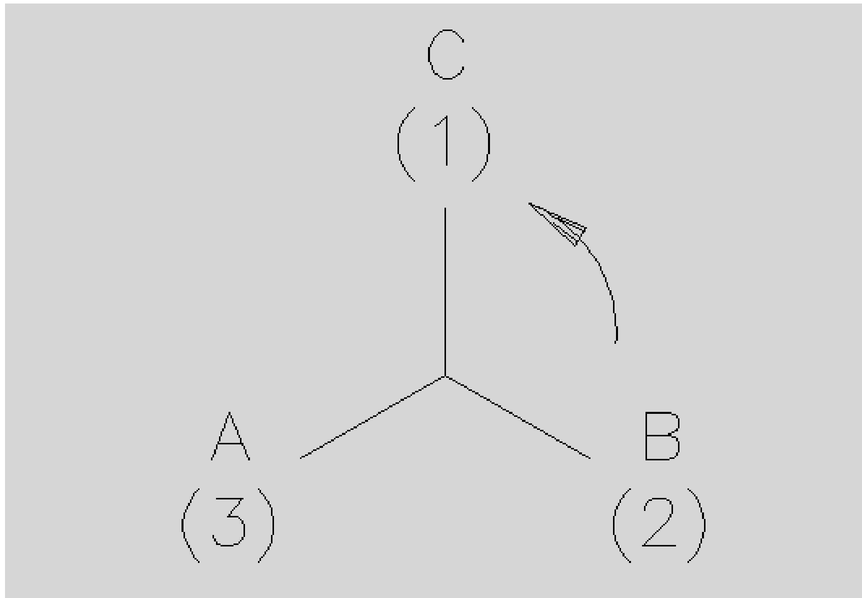


138 kV
LINE 1
3–S.A.'s
88KV
MCOV
SW 138L1
2000A
CARRIER
1–PHASE A
79,700/115–66.4V
3–VT's
80,500–115/67.08V
2000A
DUAL FREQ
30–90HZ
SW 138B1
2000A
SW 138A2
2000A
GCB A
2000A
40KAIC
138 kV
LINE 2
3–S.A.'s
88KV
MCOV
SW 138L2
2000A
CARRIER
1–PHASE A
79,700/115–66.4V
3–VT's
80,500–115/67.08V
2000A
AWB
30–90HZ
SW 138A1
2000A
SW 138C1
2000A
GCB B
2000A
40KAIC
GCB C
2000A
40KAIC
GCB D
2000A
40KAIC
SW 138B2
2000A
SW 138D1
2000A
SW 138D2
2000A
SW 138C2
2000A
SW 138T1
1200A
SW 138T2
1200A
3–METERING CT's
800:5
RF 4.0
3–METERING CT's
800:5
RF 4.0
XFMR #1
XFMR #2

One Line Relaying & Metering



Phase Rotation / Designation



CenterPoint C-B-A
Client (1-2-3)

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

ANSI C37.06-2000
Page 6

Table 3 – Preferred ratings for outdoor circuit breakers rated 123 kV and above, including circuit breakers applied in gas insulated substations*

	Ratings									
					Rated Transient Recovery Voltage (6)					
Line	Rated Maximum Voltage (1) kV, rms	Rated Voltage Range Factor K	Rated Continuous Current Amperes, rms	Rated Short-Circuit and Short-Time Current kA, rms	Rated Time to Peak T_2 (4) μsec	Rated Rate R kV/μsec	Rated Delay Time T_1 μsec	Rated Interrupting Time (5) ms	Maximum Permissible Tripping Time Delay Y Sec	Rated Closing and Latching Current (2) kA, peak
No.	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10
1	123	1.0	1200, 2000	31.5	260	2.0	2	50	1	82
2	123	1.0	1600, 2000, 3000	40	260	2.0	2	50	1	104
3	123	1.0	2000, 3000	63	260	2.0	2	50	1	164
4	145	1.0	1200, 2000	31.5	310	2.0	2	50	1	82
5	145	1.0	1600, 2000, 3000	40	310	2.0	2	50	1	104
6	145	1.0	2000, 3000	63	310	2.0	2	50	1	164
7	145	1.0	2000, 3000	80	310	2.0	2	50	1	208

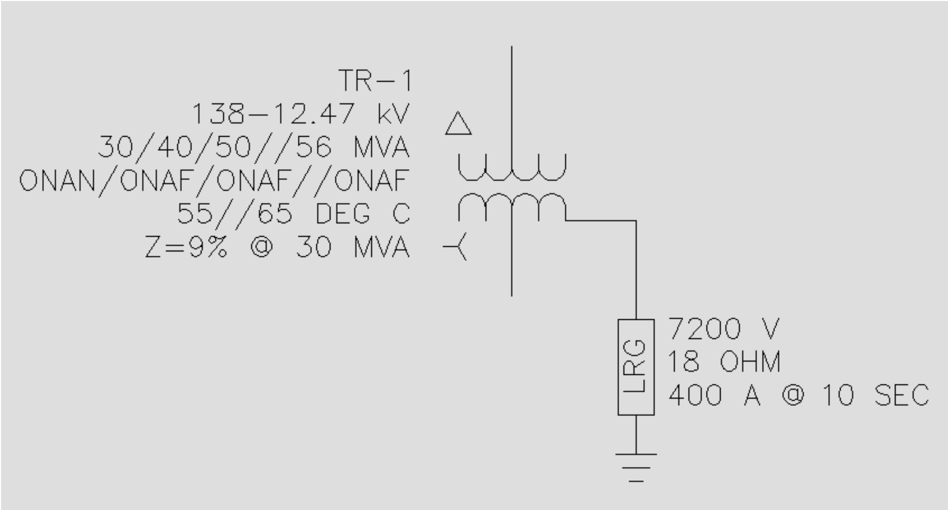
Equipment Ratings

Power Transformers

• ID	TR-1
• Voltage ratings	138 – 12.47 kV
• Capacity	30/40/50//56 MVA
	ONAN/ONAF/ONAF//ONAF @ 55//65 deg C
• % Impedance	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.



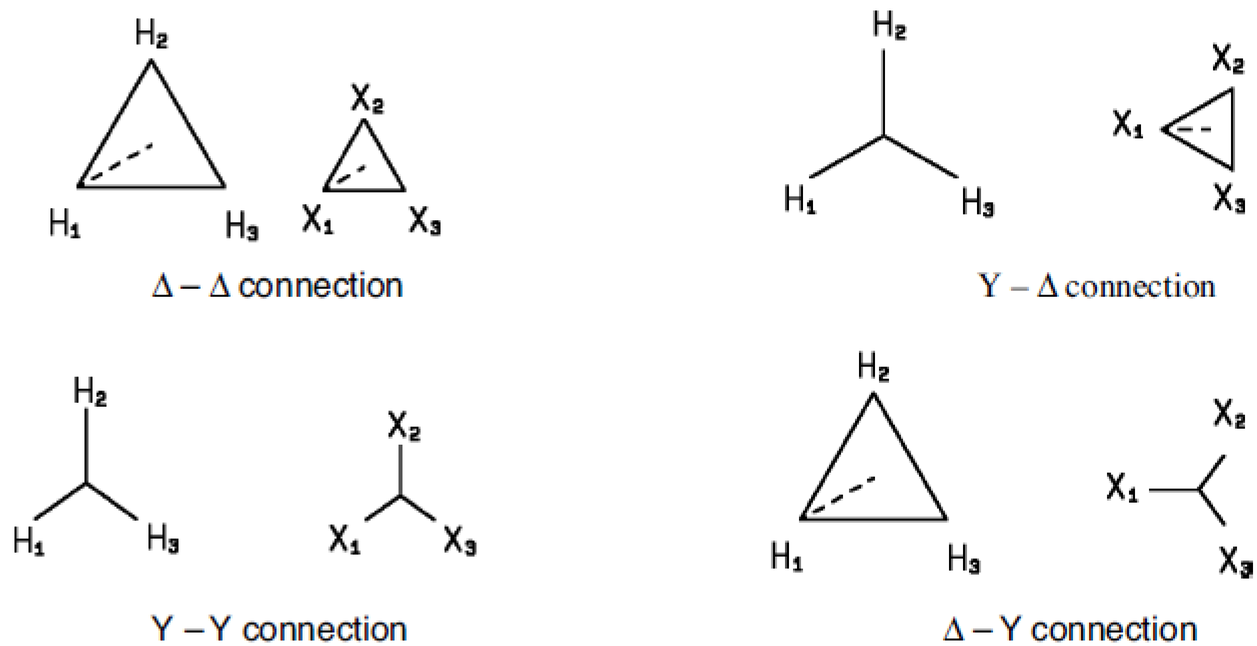


Figure 1—Phase relation of terminal designations for three-phase transformers

Equipment Ratings

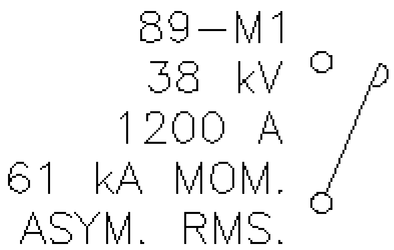
Disconnect Switch

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

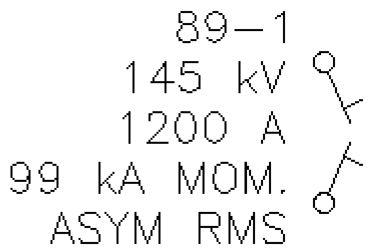
Notes:

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.

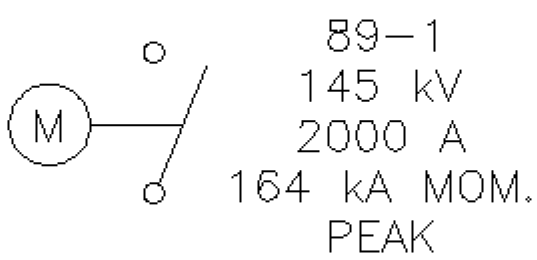
Some examples below:



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 Stds C62.11 and C62.22 for additional information on application and ratings.

IEEE Std C62.22-2009
IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

Table 1—Typical station and intermediate class arrester characteristics from IEEE Std C62.22-1991

Refer to the manufacturer's current data

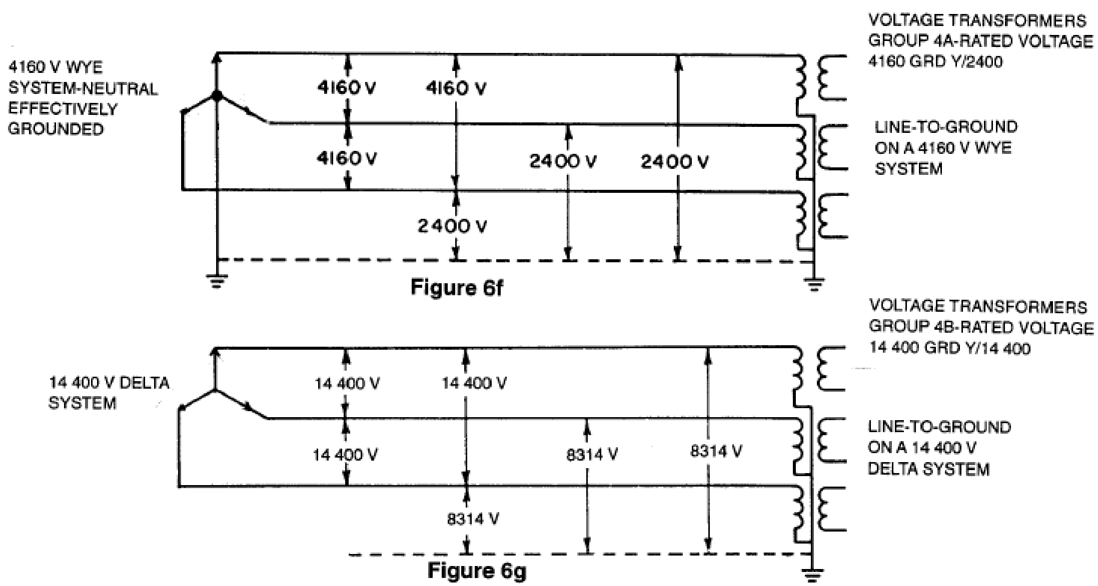
Station Class									
Steady-state operation system voltage and arrester ratings effectively grounded systems (NOTE 1)				Protective levels range of industry maxima per unit (crest of 60 Hz) of MCOV			Durability characteristics IEEE Std C62.11-2005		
Max system rms L-L voltage kV*	Max system rms L-G voltage kV*	Min rms MCOV rating kV	Duty-cycle rms voltage rating kV	0.5 µs FOW protective level (NOTE 2)	8/20 µs protective level (NOTE 3)	Switching surge protective level (NOTE 4)	High crest current withstand A	Trans. line discharge mi	Pressure relief rms symmetrical current kA (NOTE 5)
4.37	2.52	2.55	3	2.32–2.48	2.10–2.20	1.70–1.85	65 000	150	40–80
8.73	5.04	5.1	6–9	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
13.1	7.56	7.65	9–12	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
13.9	8.00	8.4	10–15	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
14.5	8.37	8.4	10–15	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
26.2	15.1	15.3	18–27	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
36.2	20.9	22	27–36	2.43–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
48.3	27.8	29	36–48	2.43–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
72	41.8	42	54–72	2.19–2.40	1.97–2.18	1.64–1.84	65 000	150	40–80
121	69.8	70	90–120	2.19–2.40	1.97–2.18	1.64–1.84	65 000	150	40–80
145	83.7	84	108–144	2.19–2.39	1.97–2.17	1.64–1.84	65 000	150	40–80
169	97.5	98	120–172	2.19–2.39	1.97–2.17	1.64–1.84	65 000	175	40–80
242	139	140	172–240	2.19–2.36	1.97–2.15	1.64–1.84	65 000	175	40–80
362	209	209	258–312	2.19–2.36	1.97–2.15	1.71–1.85	65 000	200	40–80
550	317	318	396–564	2.01–2.47	2.01–2.25	1.71–1.85	65 000	200	40–80
800	461	462	576–612	2.01–2.47	2.01–2.25	1.71–1.85	65 000	200	40–80
Intermediate class									
4.37–145	2.52–83.7	2.8–84	3–144	2.38–2.85	2.28–2.55	1.71–1.85	65 000	100	16.1

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.



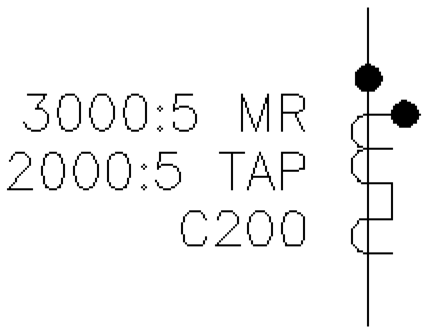
Figures 6f and 6g —Typical primary connections

Equipment Ratings

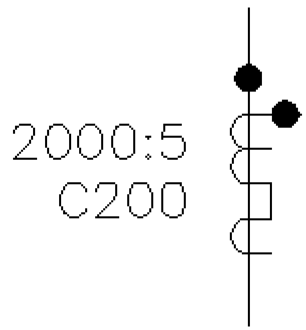
Current Transformers

- Maximum ratio
- Connected ratio
- Accuracy class

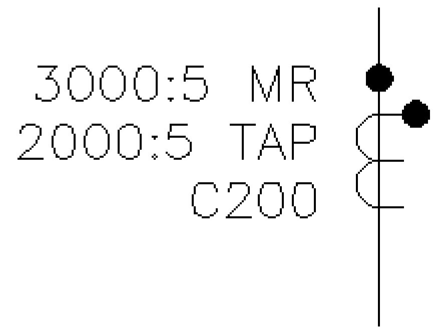
Note: Polarity dots designated the H1 and X1 relative positions



Multi-ratio
Bushing-type CT



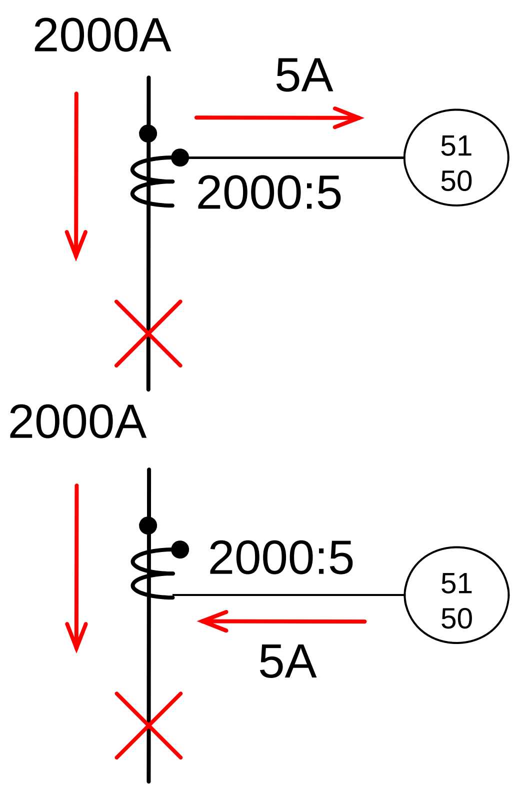
Single-ratio
Bushing-type CT



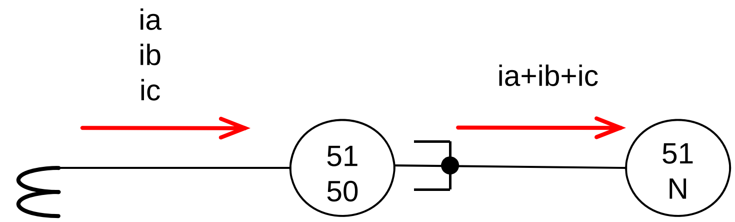
Multi-ratio
Window-type CT

A.C. Fundamentals

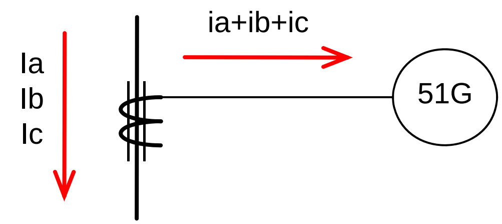
A.C. Fundamentals
Phasor Relationships



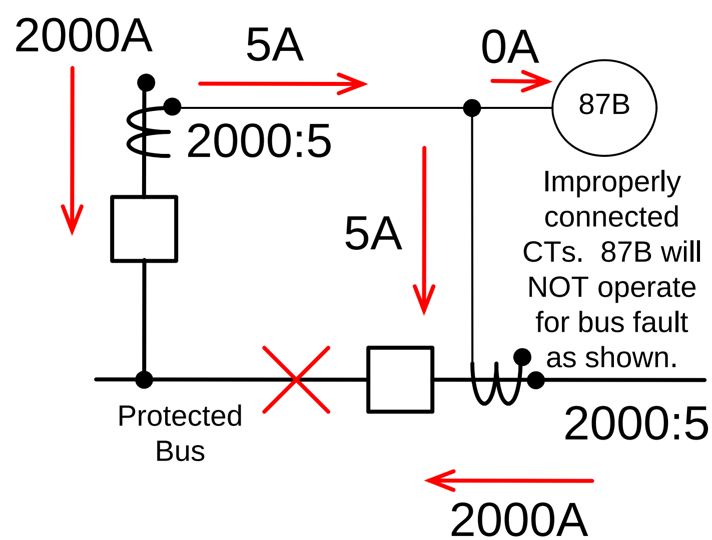
IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes - IEEE Std C37.110



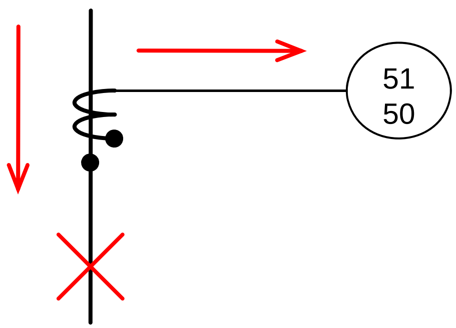
Residual CT connection

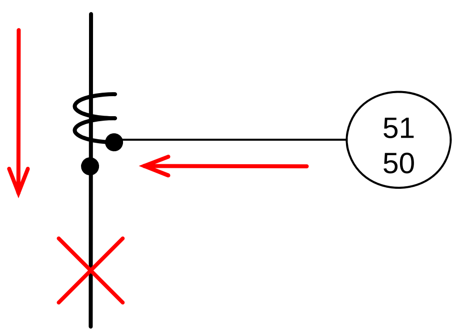


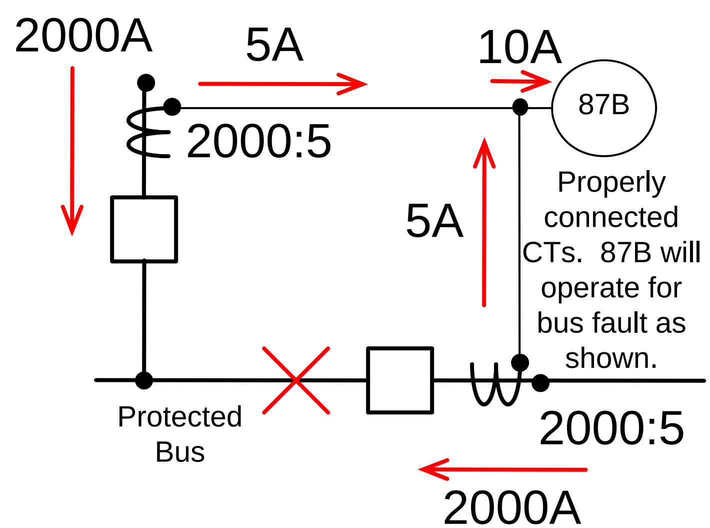
Zero sequence CT



A.C. Fundamentals
Phasor Relationships

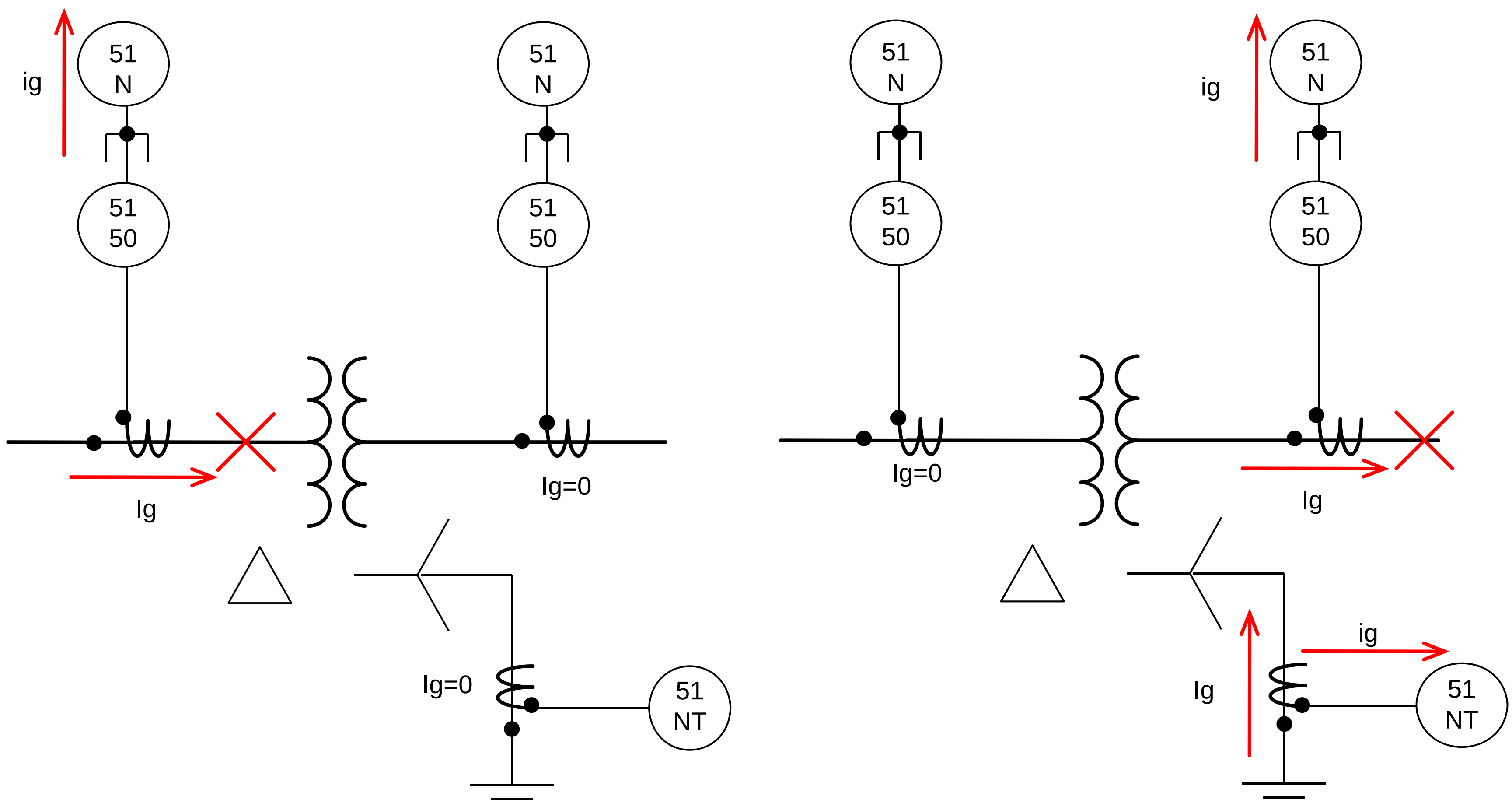




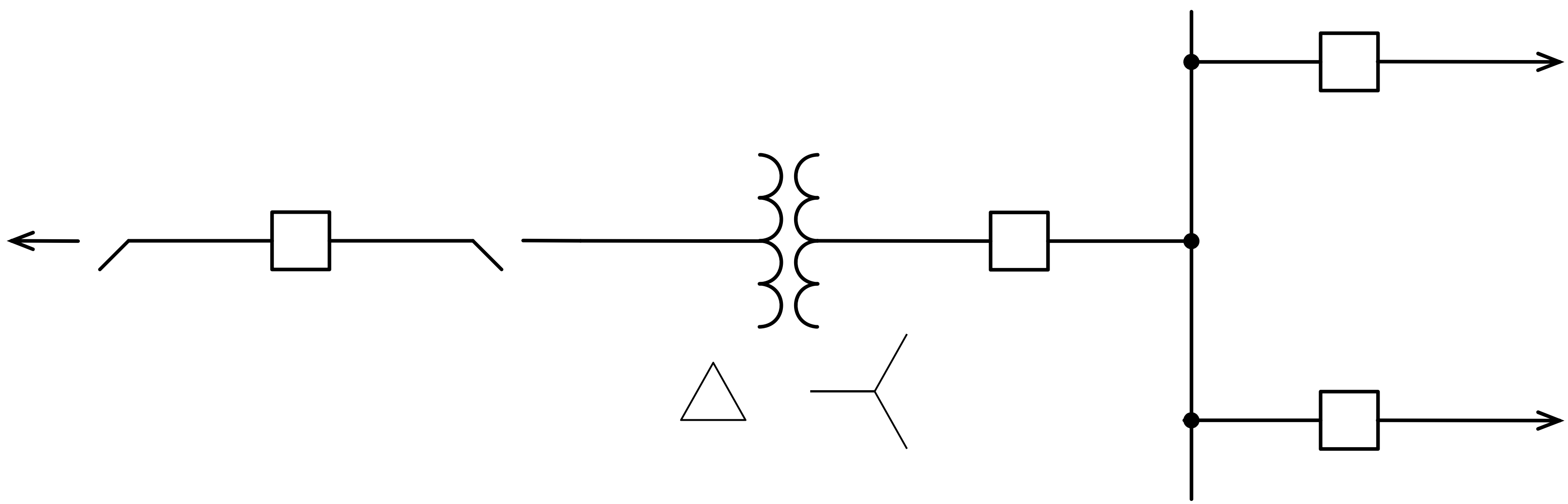


IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes - IEEE Std C37.110

A.C. Fundamentals



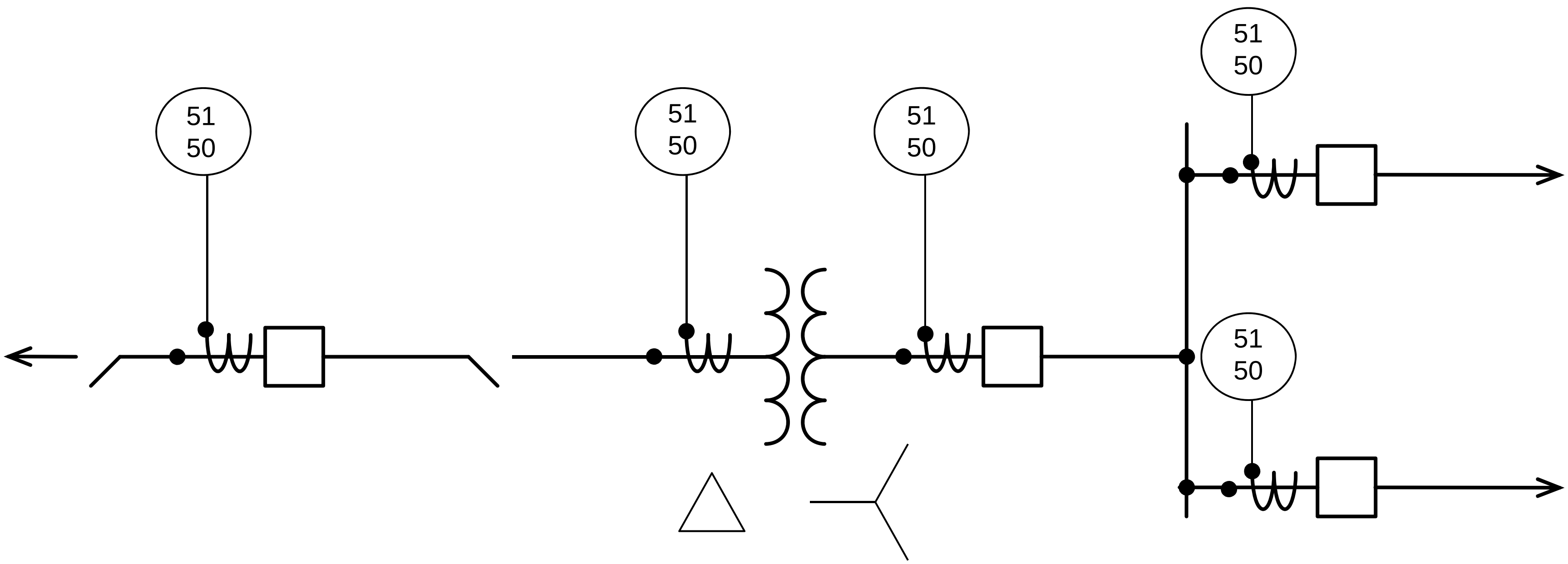
Tap Substation



Tap Substation

- Phase Protection
  - Overcurrent

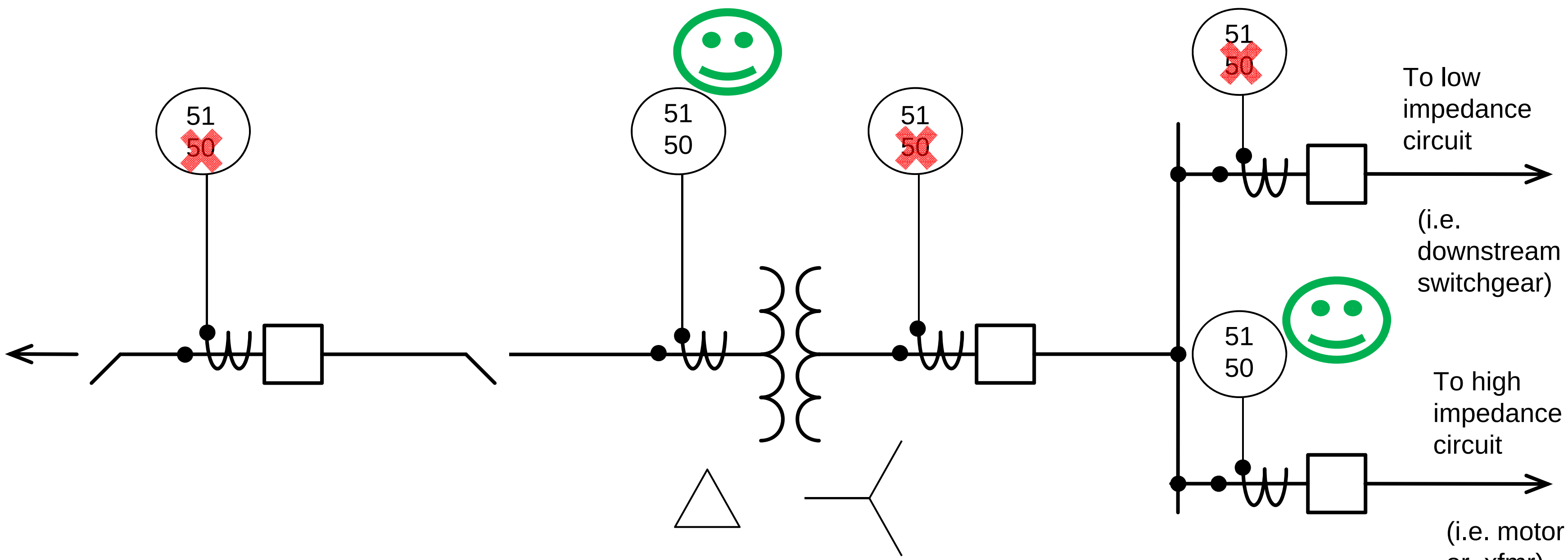
Should 50 elements be set on all relays?



Tap Substation

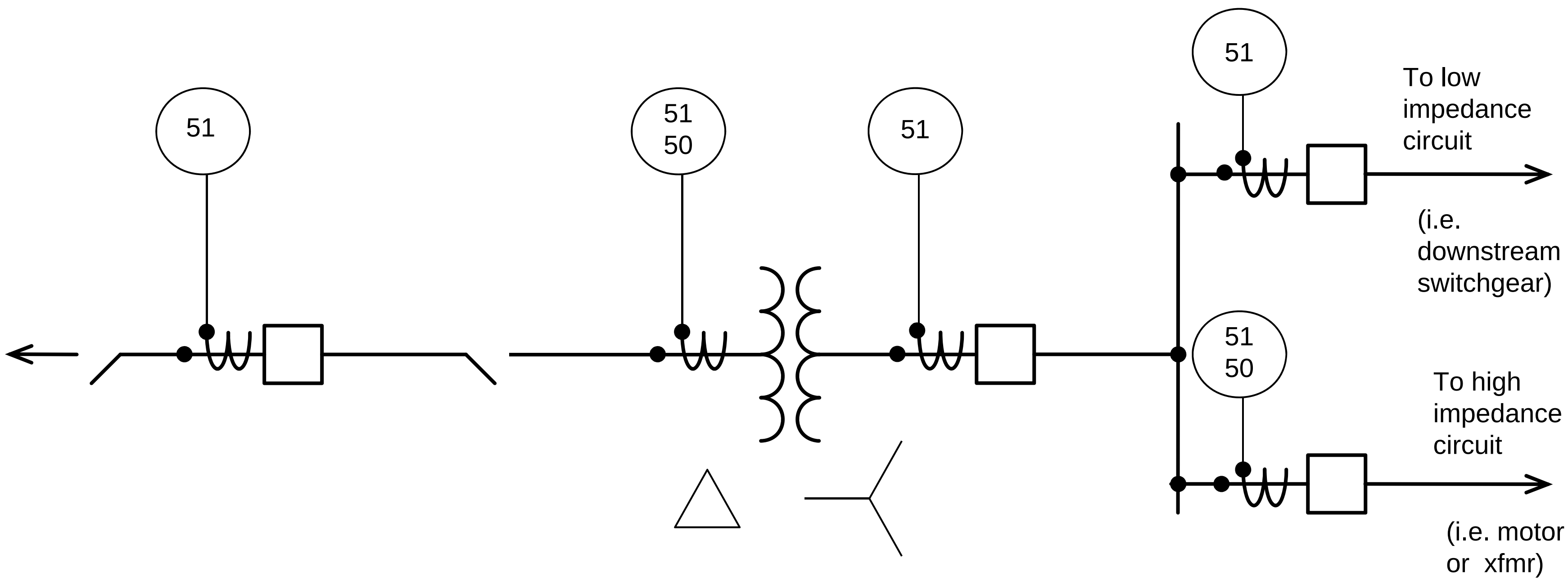
- Phase Protection
  - Overcurrent

Should 50 elements be set on all relays?



Tap Substation

- Phase Protection
  - Overcurrent

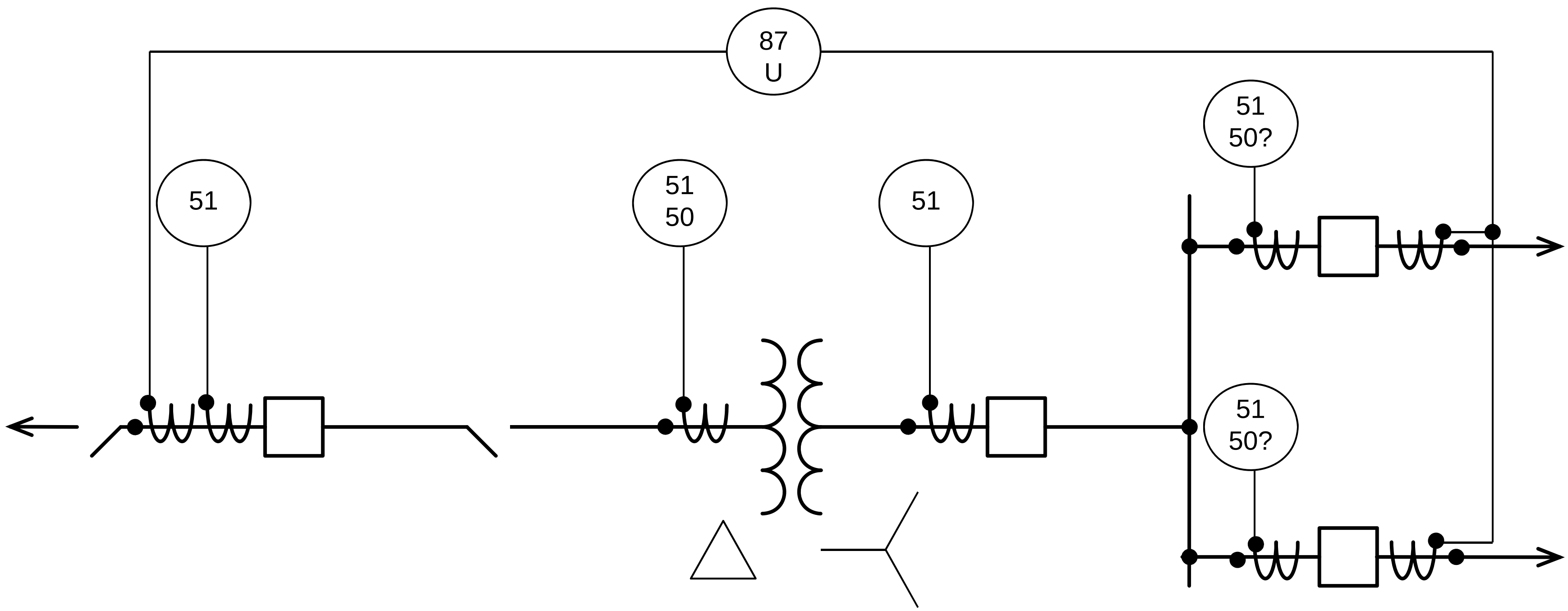


Tap Substation

This configuration is not preferred.

Safe/fast…..
but no selectivity

- Phase Protection
  - Unit Differential
  - Overcurrent

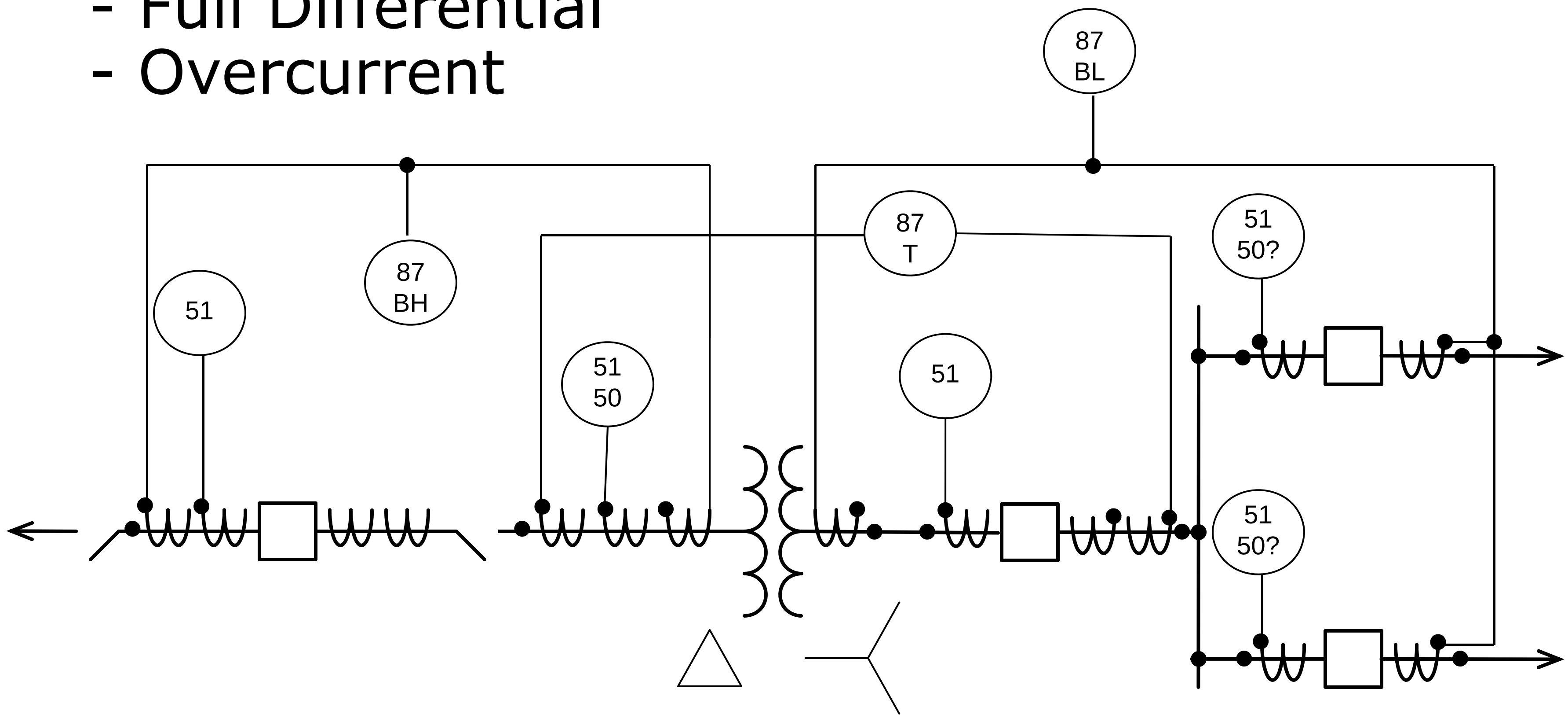


- Pros
  - Lower cost

- Cons
  - Lower selectivity

Tap Substation

- Phase Protection
  - Full Differential
  - Overcurrent

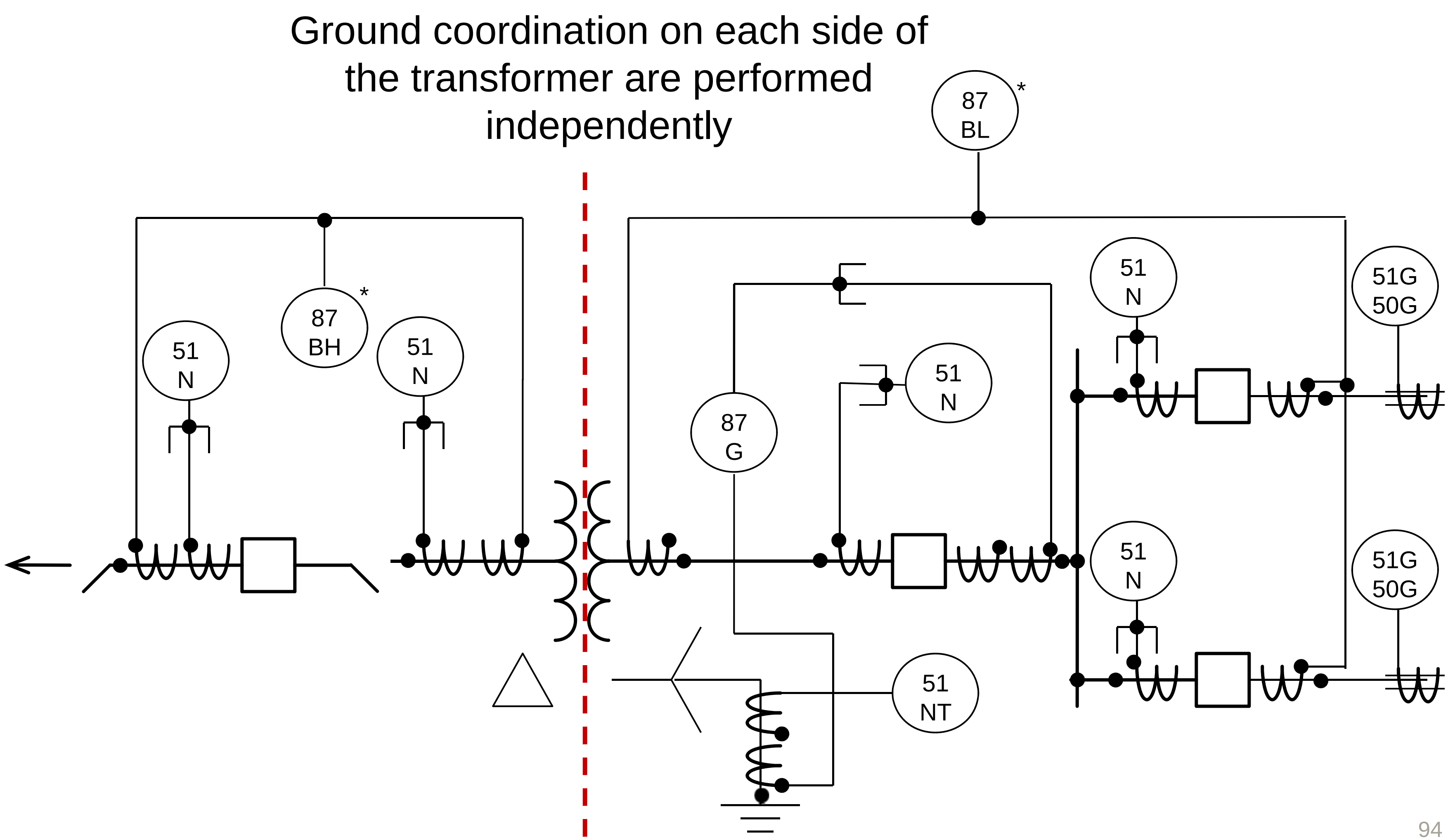


- Pros
  - Higher selectivity
- Cons
  - Higher cost

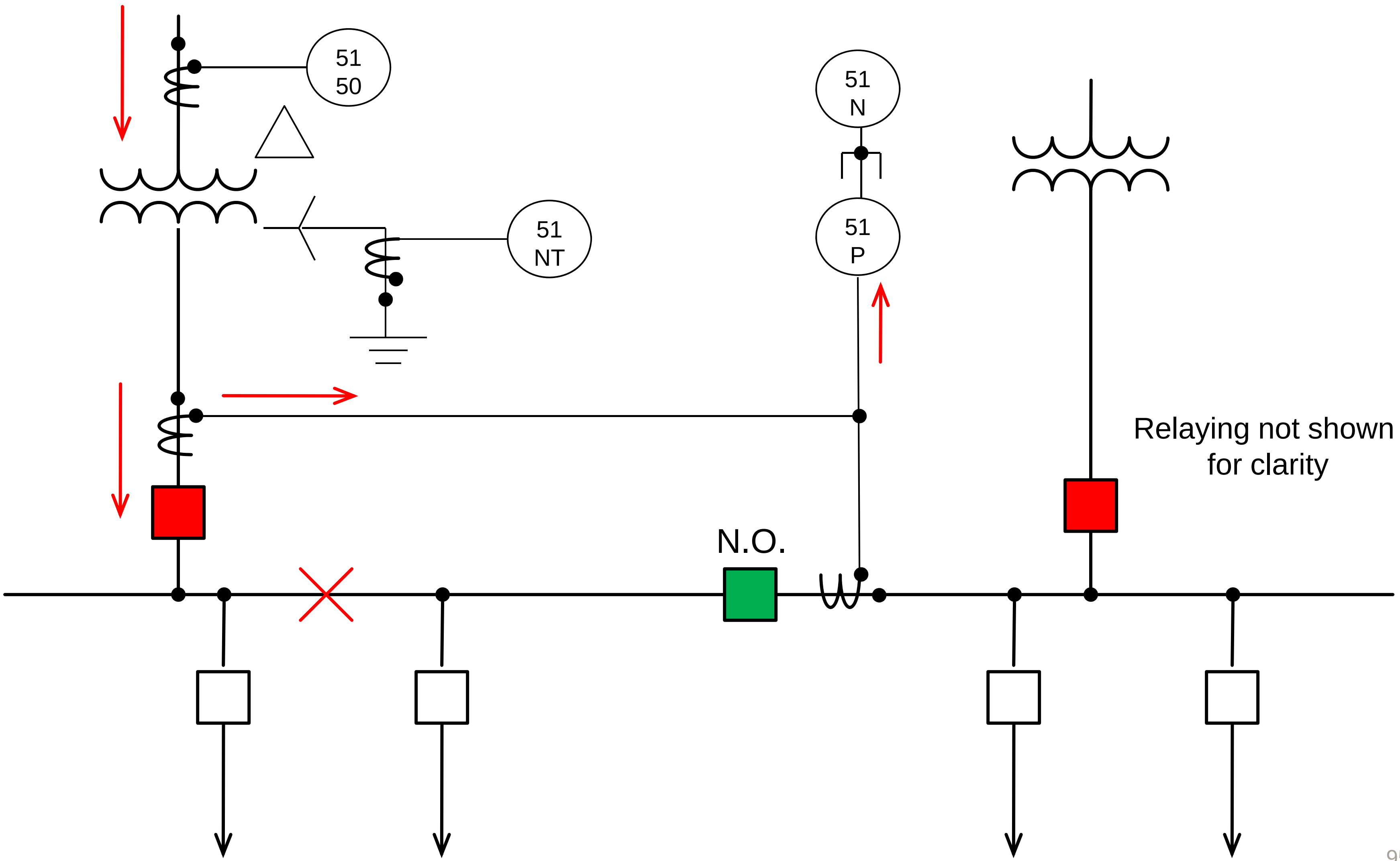
Tap Substation

- Ground Protection

(*) relays measure phase quantities, but are often set to operate for ground faults in the zone of protection.

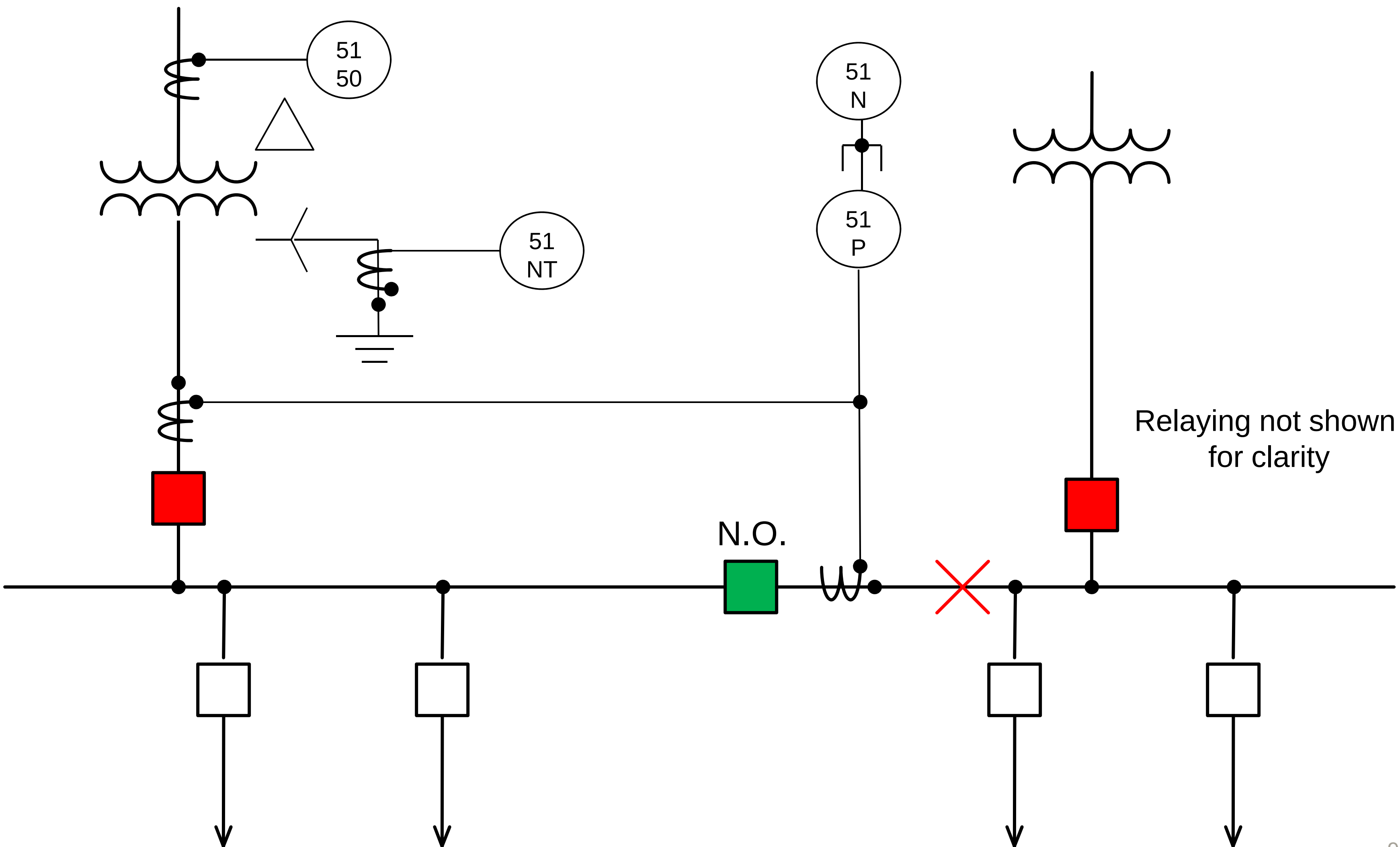


Secondary Selective Arrangement – N.O. Tie

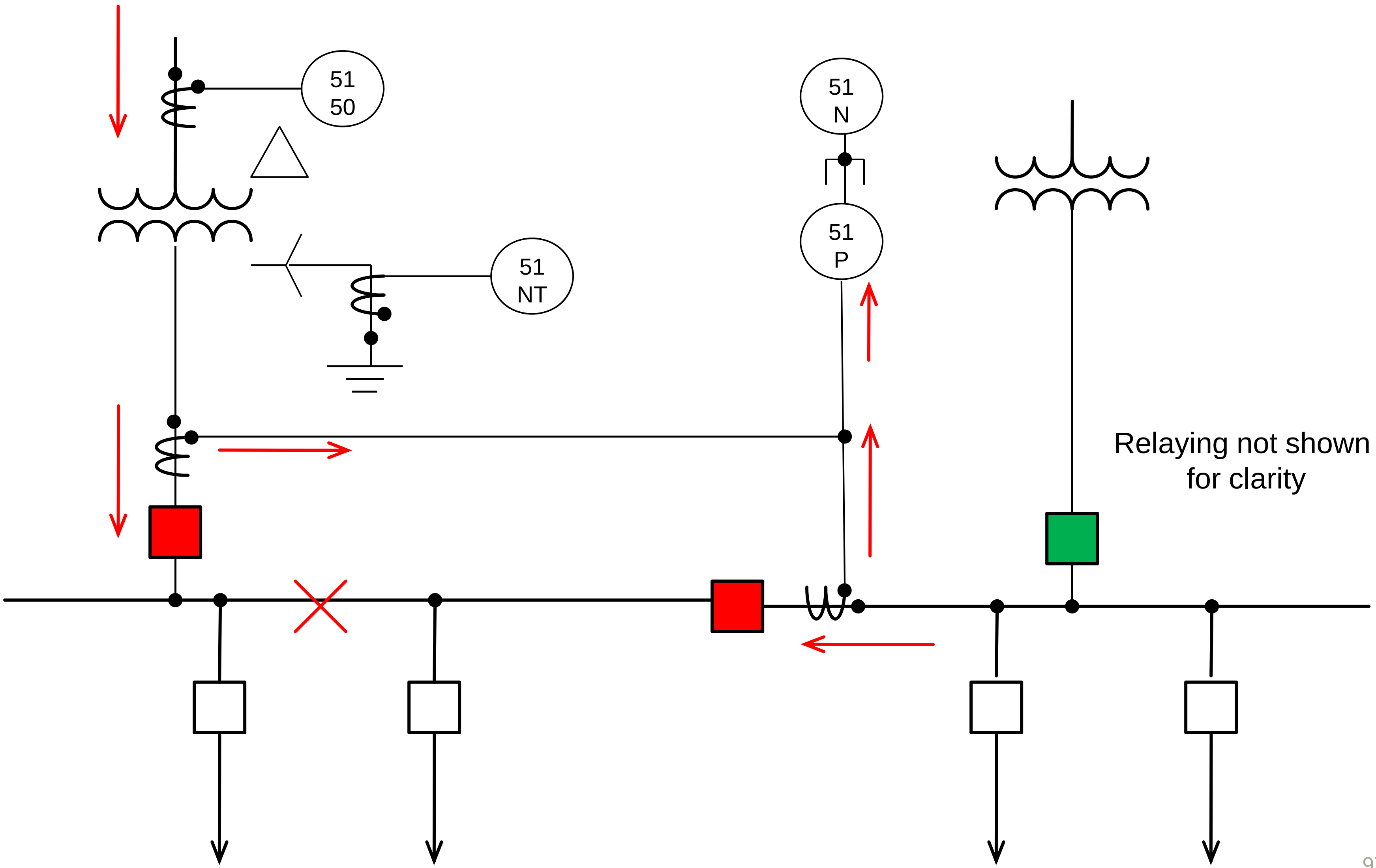


Relaying not shown for clarity

Secondary Selective Arrangement – N.O. Tie

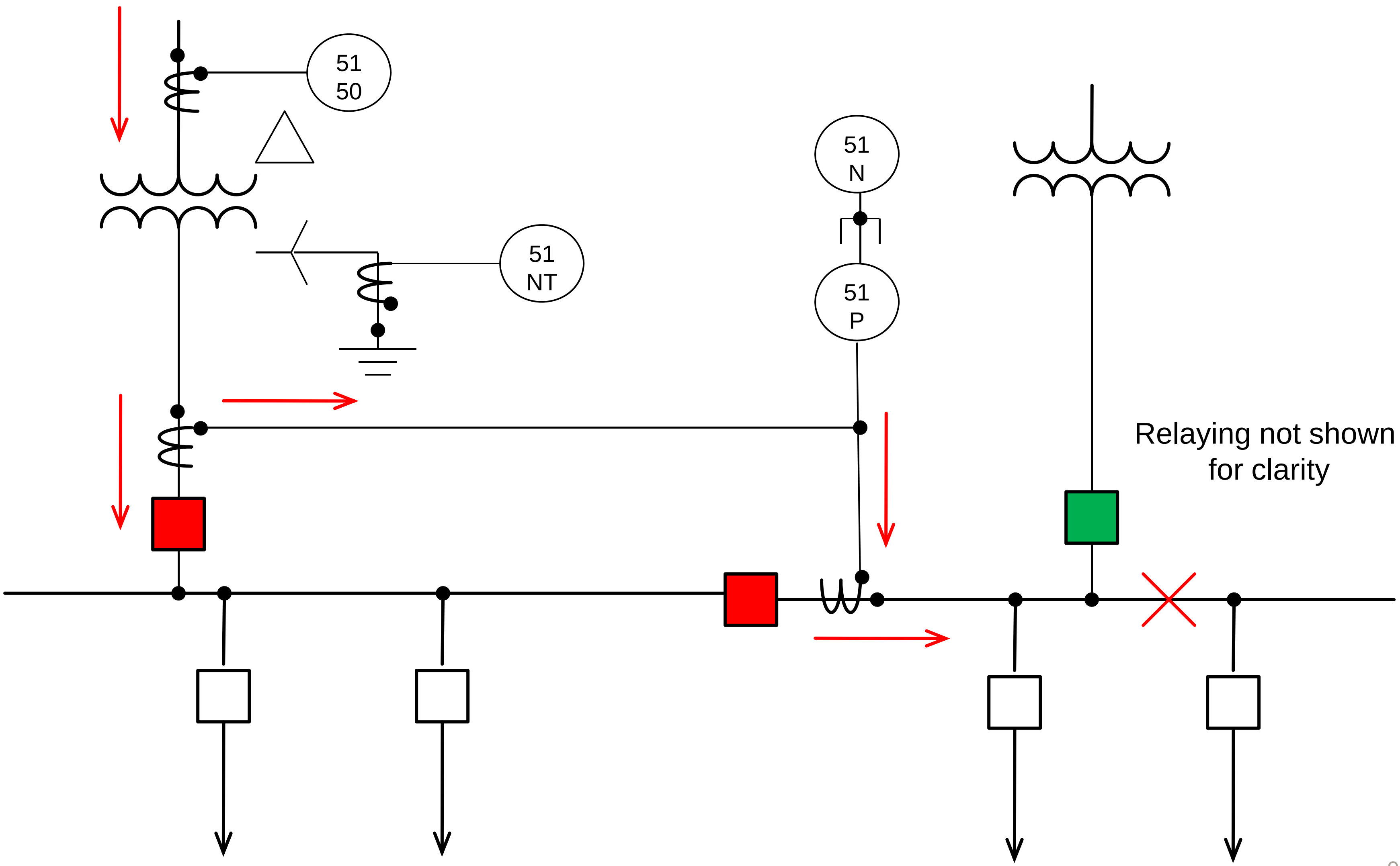


Secondary Selective Arrangement – N.O. Tie



Relaying not shown for clarity

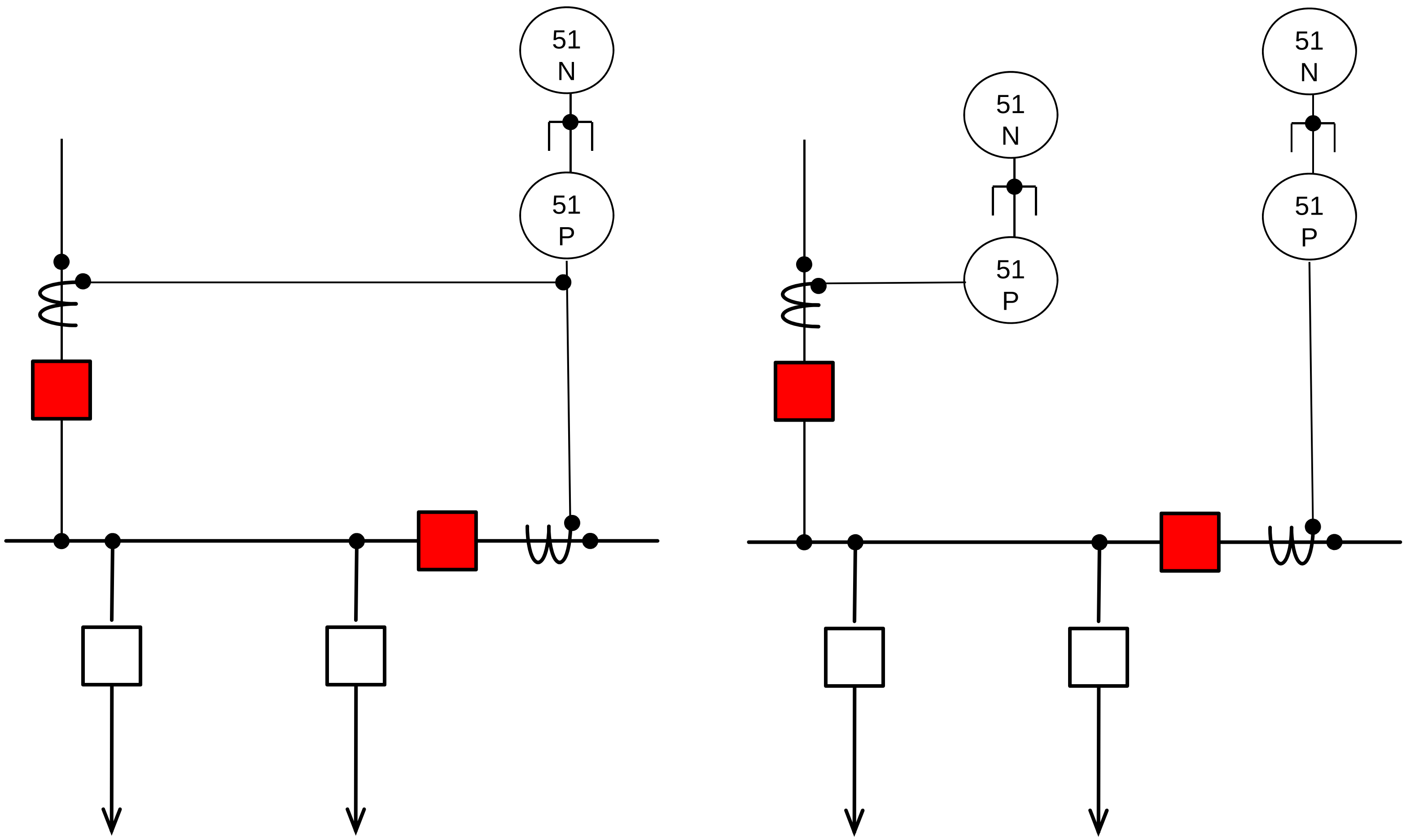
Secondary Selective Arrangement – N.O. Tie



Relaying not shown for clarity

Secondary Selective Arrangement – N.O. Tie

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



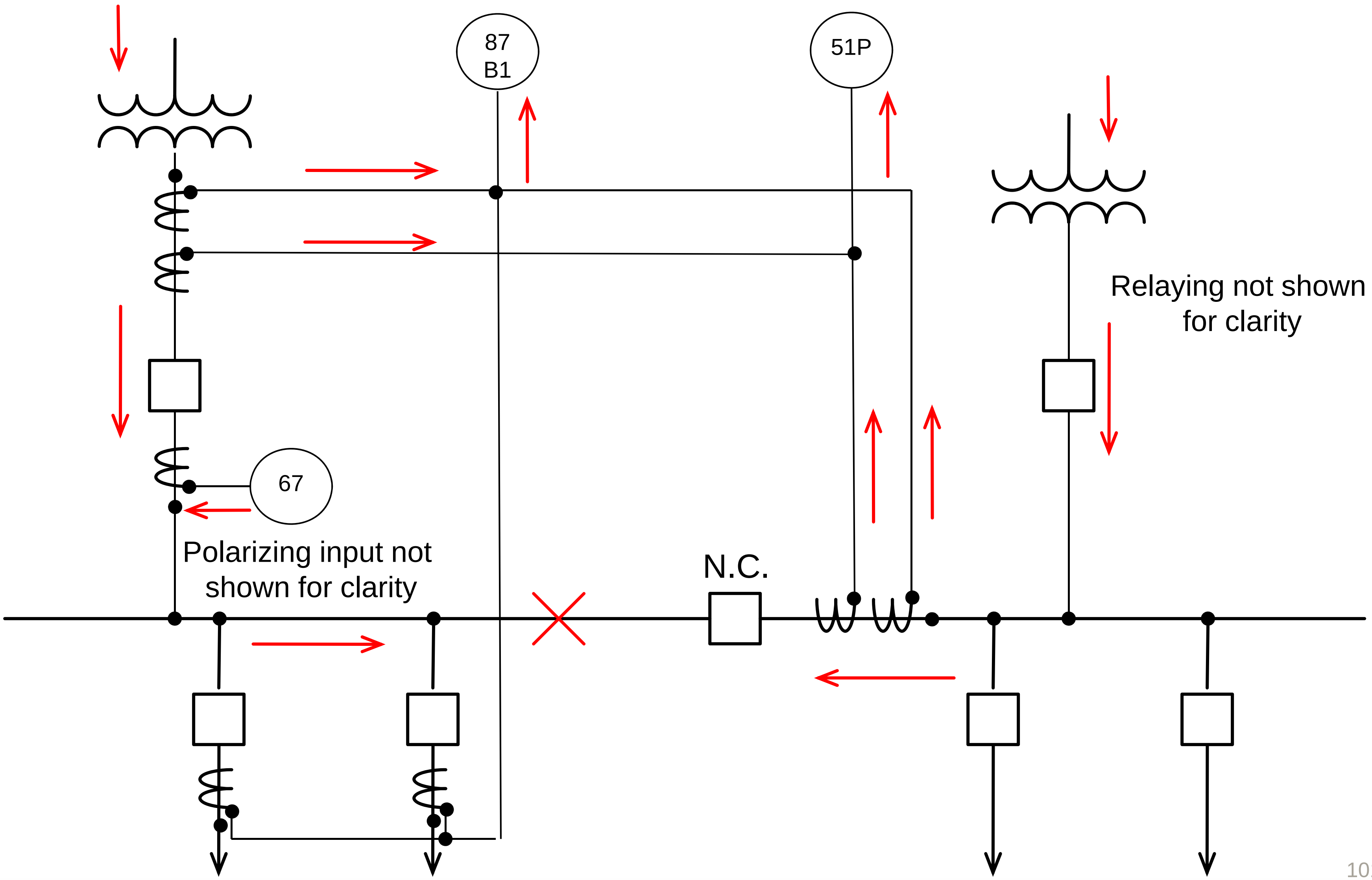
Secondary Selective Arrangement – N.O. Tie

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

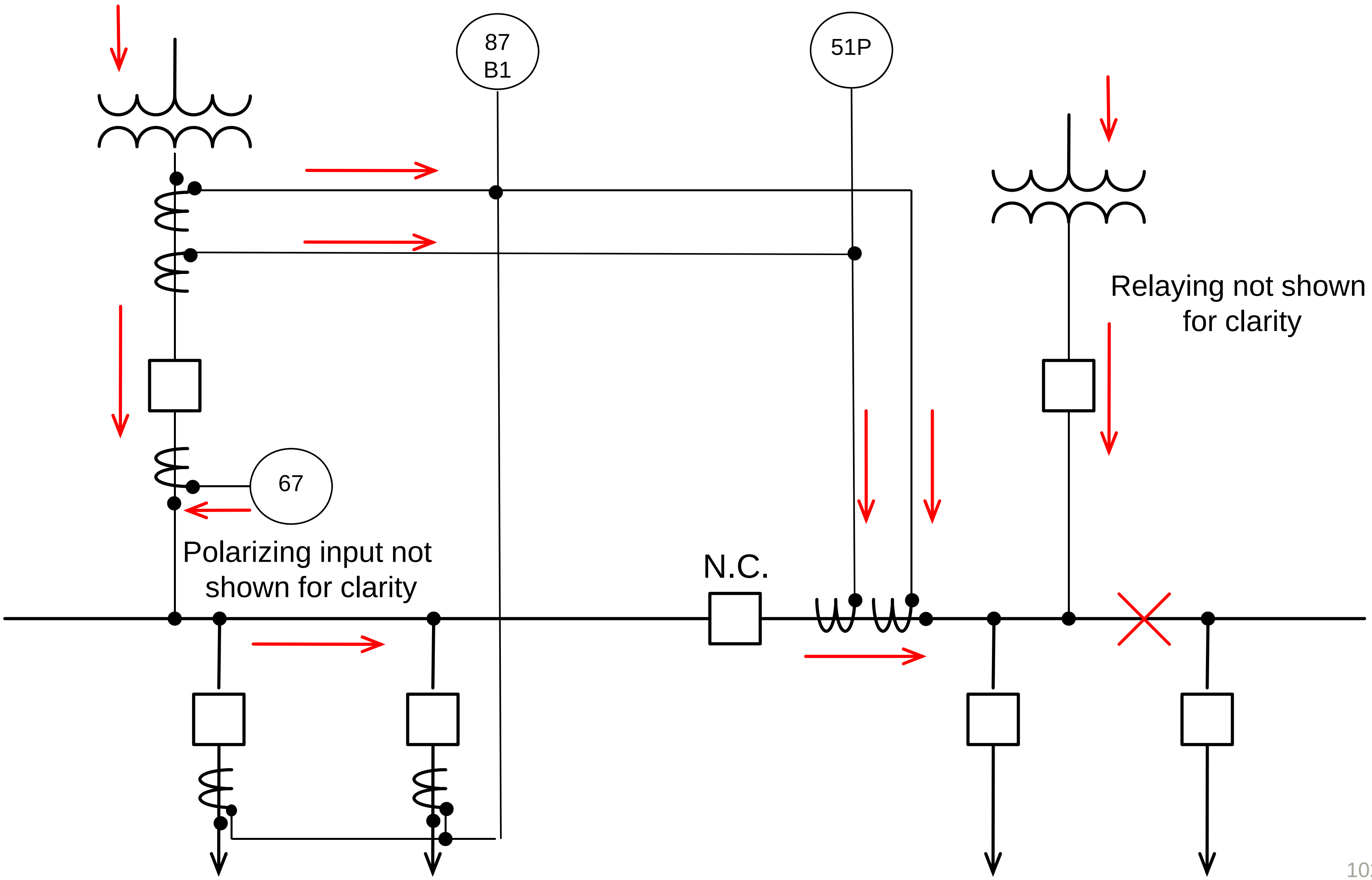
Pros (Partial Differential):
Use one (1) less relay
Eliminate one (1) level of coordination

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

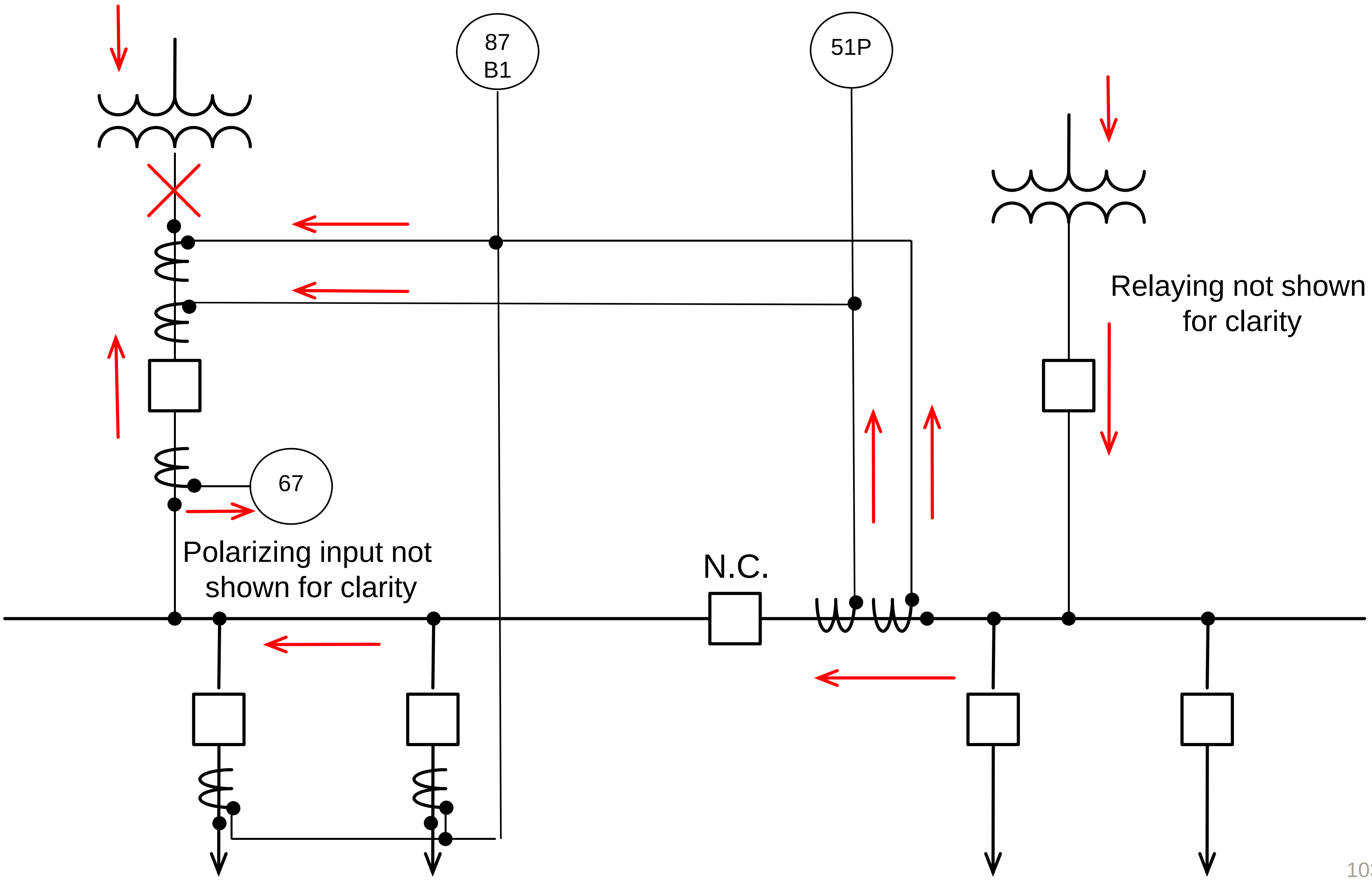
Secondary Selective Arrangement – N.C. Tie



Secondary Selective Arrangement – N.C. Tie



Secondary Selective Arrangement – N.C. Tie



Special Considerations for System Grounding

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

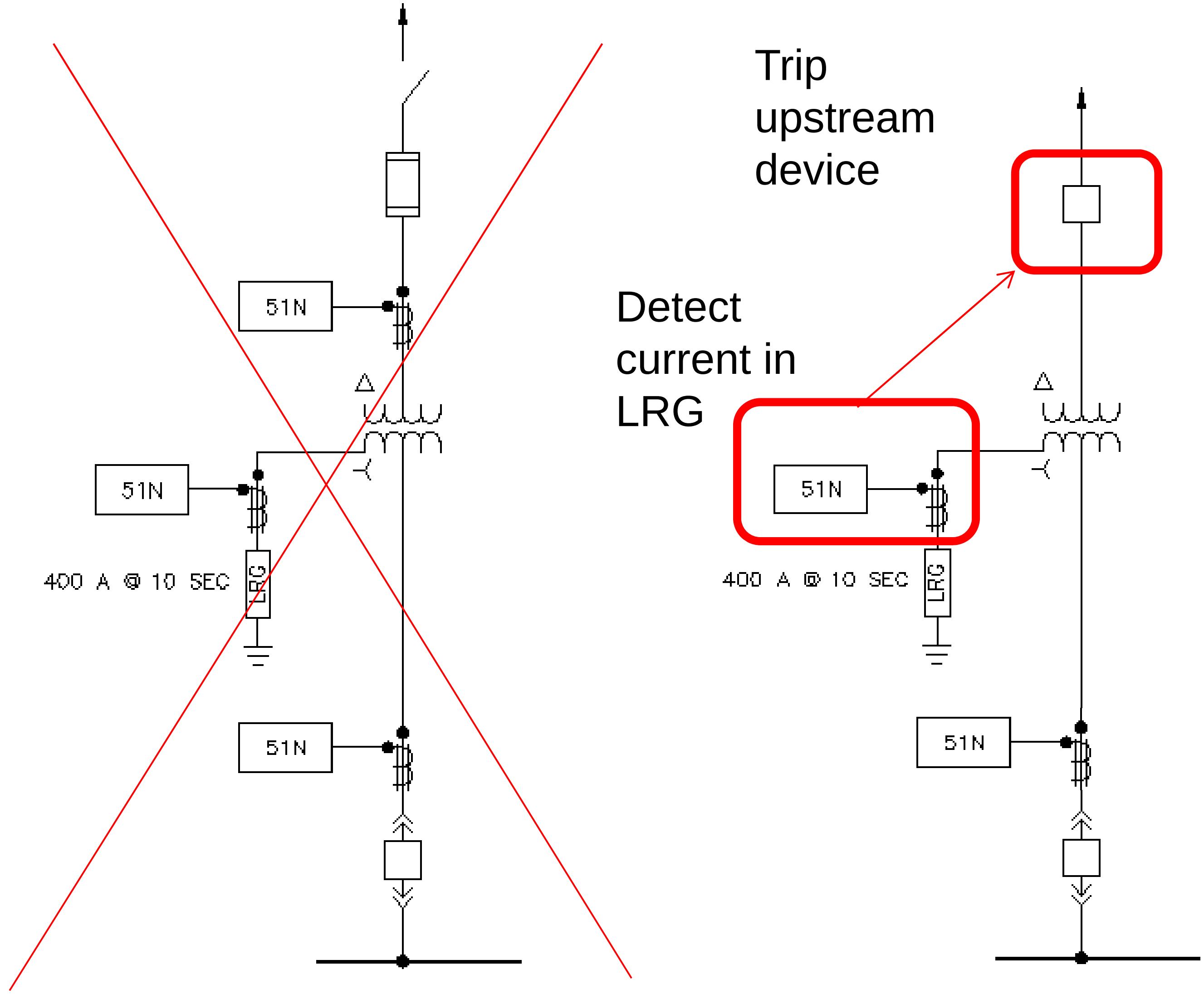
- Maintain line-line voltage during ground faults
- Limit ground fault current, hence limit damage
- Continue to operate during ground fault (HRG system)
- Reduce arc flash hazard exposure

…to name a few.

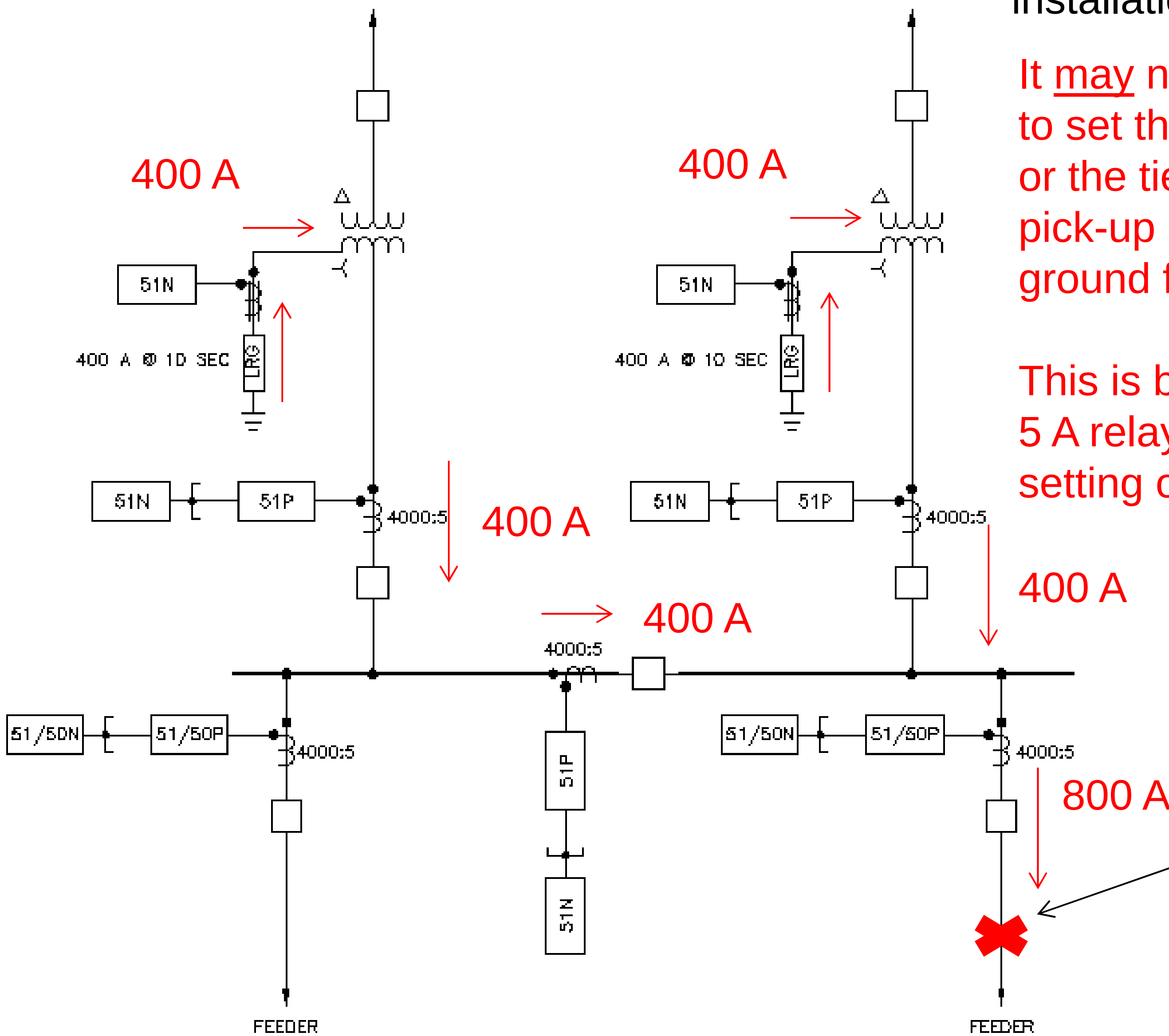
However, care must be taken to ensure proper protection and means of isolation is provided.

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



Special Considerations for System Grounding



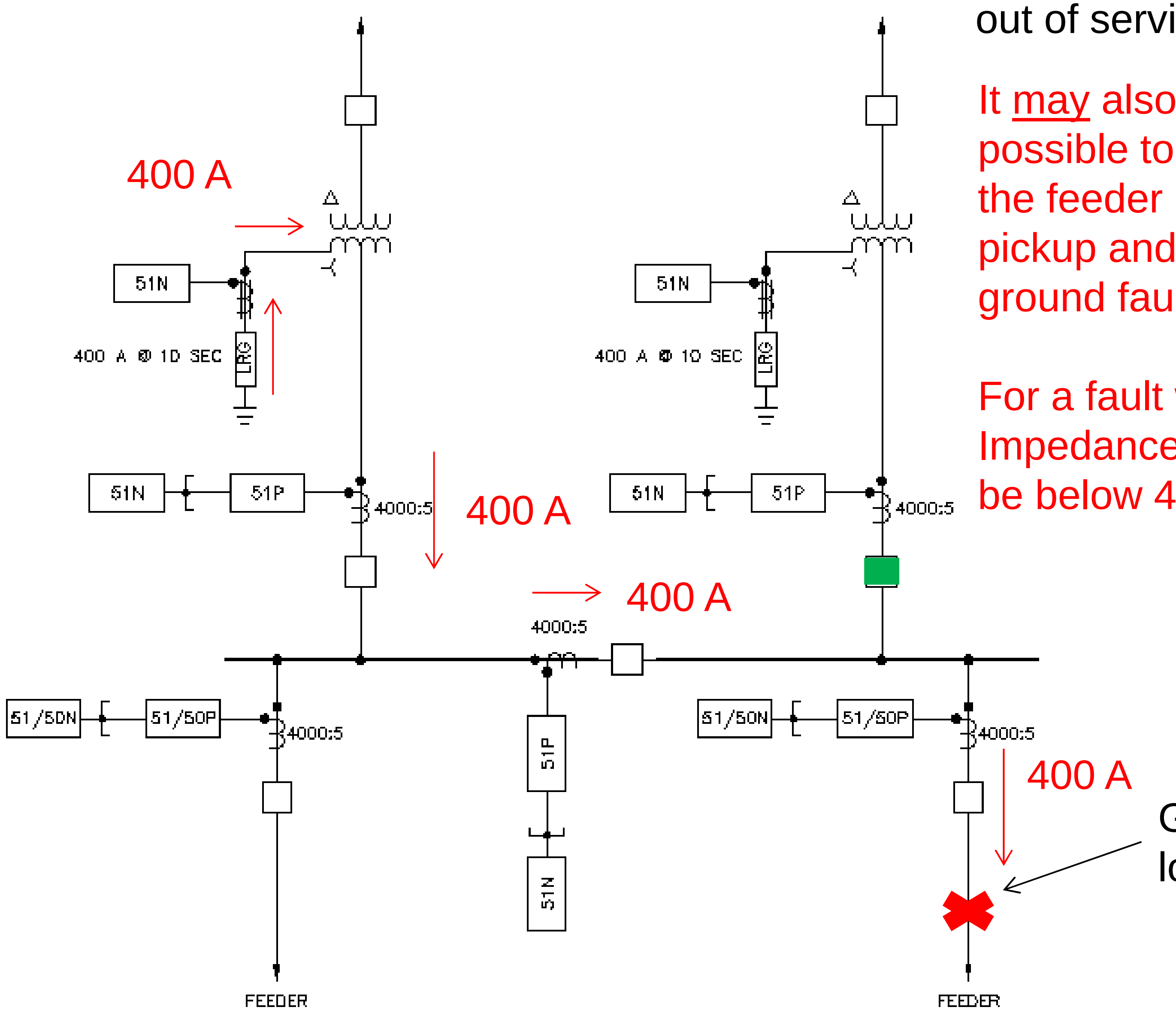
Ground fault location

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 min. 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.

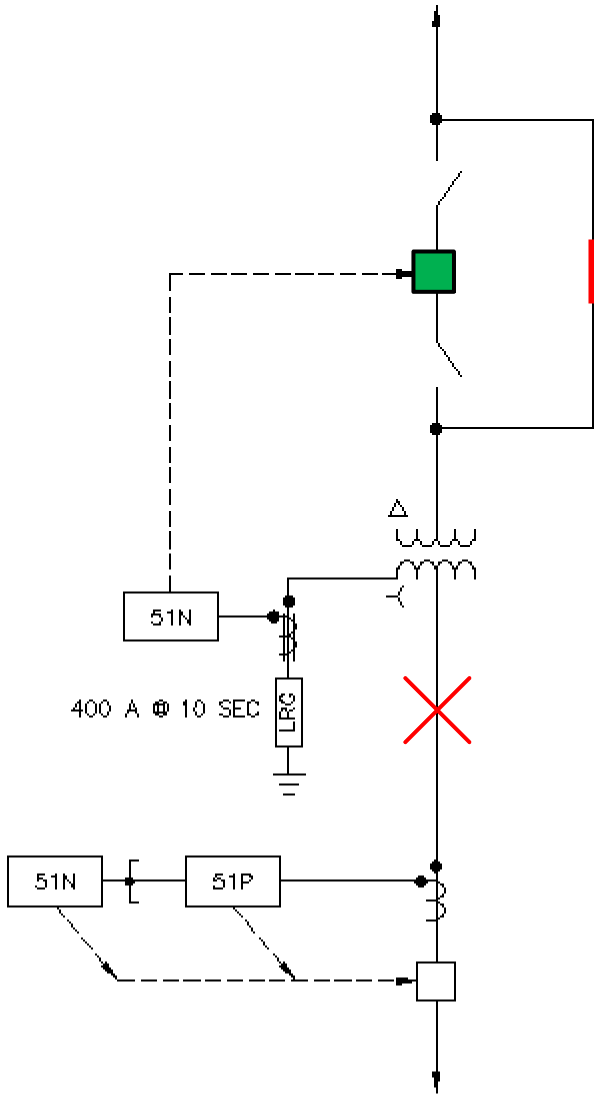
For a fault with any Impedance, the fault will be below 400 A.

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 Lines

Three-Line Diagram

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

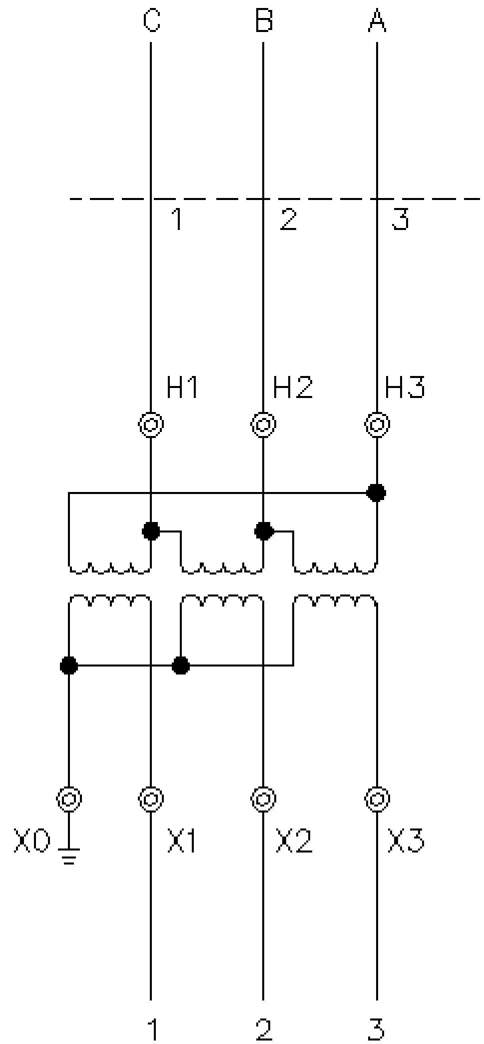
- Phase designation and rotation
- Equipment identification
- Equipment layout
- Equipment ratings
- AC connections

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



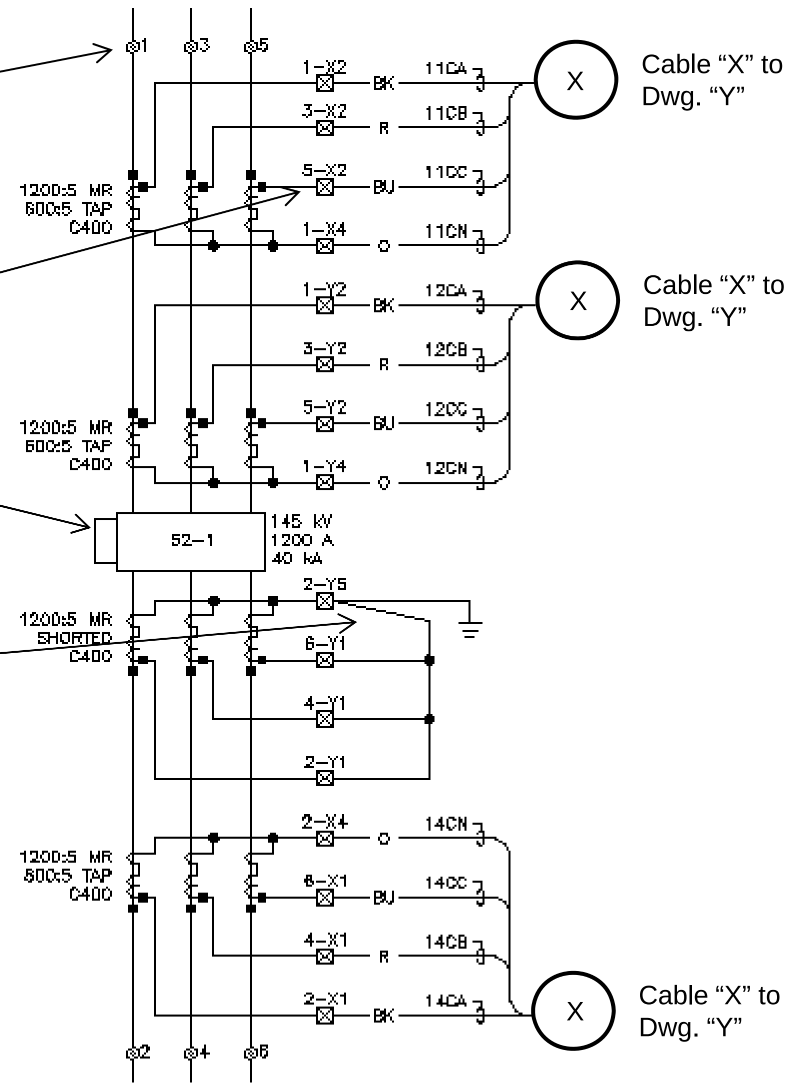
Excerpt of HV Breaker Three-Line

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

Spacing & Clearances

Table 36-2
OUTDOOR SUBSTATIONS—BASIC PARAMETERS

Line No.	Rated Max. Volt, kV rms	Rated Withstand Voltage: Impulse 1.2 x 50 μs Wave kV Crest	Rated Withstand Voltage: 60 Hz kV rms, Wet, 10 sec.	Minimum Metal-to-Metal Distance Between Rigidly Supported Energized Conductors, Inches (meters)	Ground Clearance, Inches (meters): Recommended	Ground Clearance, Inches (meters): Minimum	Recommended Phase Spacing, Center to Center, Inches (meters): Horn Gap Switch and Expulsion Type Fuses	Recommended Phase Spacing, Center to Center, Inches (meters): Horizontal Break Disc. Switches	Recommended Phase Spacing, Center to Center, Inches (meters): Bus Supports, Vertical Brk. Disc. Switches Power Fuses Non-expulsion Types Rigid Conductors	Recommended Minimum Clearance Between Overhead Conductor and Ground for Personal Safety, Feet (Meters)	Withstand S.S., Crest kV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	8.3	95	30	7 (0.18)	7.5 (0.19)	6 (0.15)	36 (0.91)	30 (0.76)	18 (0.46)	8 (2.44)	. . .
2	15.5	110	45	12 (0.30)	10 (0.25)	7 (0.18)	36 (0.91)	30 (0.76)	24 (0.61)	9 (2.74)	. . .
3	27	150	60	15 (0.38)	12 (0.30)	10 (0.25)	48 (1.22)	36 (0.91)	30 (0.76)	10 (3.05)	. . .
4	38.	200	80	18 (0.46)	15 (0.38)	13 (0.33)	60 (1.52)	48 (1..22)	36 (0.91)	10 (3.05)	. . .
5	48.3	250	100	21 (0.53)	18 (0.46)	17 (0.43)	72 (1.83)	60 (1.52)	48 (1.22)	10 (3.05)	. . .
6	72.5	350	145	31 (0.79)	29 (0.74)	25 (0.64)	84 (2.13)	72 (1.83)	60 (1.52)	11 (3.35)	. . .
7	123	550	230	53 (1.35)	47 (1.19)	42 (1.07)	120 (3.05)	108 (2.74)	84 (2.13)	12 (3.66)	. . .
8	145	650	275	63 (1.60)	52.5 (1.33)	50 (1.27)	144 (3.66)	132 (3.35)	96 (2.44)	13 (3.96)	. . .
9	170	750	315	72 (1.83)	61.5 (1.56)	58 (1.47)	168 (4.27)	156 (3.96)	108 (2.74)	14 (4..27)	. . .
10	245	900	385	89 (2.26)	76 (1.93)	71 (1.80)	192 (4.88)	192 (4.88)	132 (3.35)	15 (4.57)	. . .
11	245	1050	455	105 (2.67)	90.5 (2.30)	83 (2.11)	216 (5.49)	216 (5.49)	156 (3.96)	16 (4.88)	. . .
12	362	1050	455	105 (2.67)	90.5 (2.30)	84 (2.13)*	216 (5.49)	216 (5.49)	156 (3.96)	16 (4.88)	650
13	362	1300	525	119 (3.02)	106 (2.69)	104 (2.64)*	. . .	. . .	174 (4.43)	18 (5.49)	739
14	550	1550	620	. . .	. . .	124 (3.15)*	. . .	. . .	. . .	. . .	808
15	550	1800	710	. . .	. . .	144 (3.66)*	. . .	. . .	300 (7.62)	. . .	898
16	800	2050	830	. . .	. . .	166 (4.22)*	. . .	. . .	. . .	. . .	982

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-72-131-6 (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.

Spacing & Clearances

- IEEE 1427-2006 – Guide for Electrical Clearances & Insulation Levels in Air Insulated Electrical Power Substations
  - BIL/BSL Based
  - Rec. Phase-to-Phase
  - Min. Metal-to-Metal
  - Min. Phase to Ground
  - Rec. Bus Spacings including Horn Gap

Spacing & Clearances

Table 3—Recommended minimum electrical clearances for air-insulated substations when lightning impulse conditions govern[a,b]

Maximum system[c] voltage phase-to-phase	Basic BIL[c]	Minimum phase-to-ground[d,f] clearances		Minimum phase-to-phase[d,e,f] clearances	
(kV, rms)	(kV, crest)	mm	(in)	mm	(in)
1.2	30	57	(2.3)	63	(2.5)
	45	86	(3.3)	95	(3.6)
5	60	115	(4.5)	125	(5)
	75	145	(5.6)	155	(6.2)
15	95	180	(7)	200	(8)
	110	210	(8)	230	(9)
26.2	150	285	(11)	315	(12)
36.2	200	380	(15)	420	(16)
48.3	250	475	(19)	525	(21)
72.5	250	475	(19)	525	(21)
	350	665	(26)	730	(29)
121	350	665	(26)	730	(29)
	450	855	(34)	940	(37)
	550	1045	(41)	1150	(45)
145	350	665	(26)	730	(29)
	450	855	(34)	940	(37)
	550	1045	(41)	1150	(45)
	650	1235	(49)	1360	(54)
169	550	1045	(41)	1150	(45)
	650	1235	(49)	1360	(54)
	750	1325	(56)	1570	(62)
242	650	1235	(49)	1360	(54)
	750	1425	(56)	1570	(62)
	825	1570	(62)	1725	(68)
	900	1710	(67)	1880	(74)
	975	1855	(73)	2040	(80)
	1050	2000	(79)	2200	(86)
362	900	1710	(67)	1880	(74)
	975	1855	(73)	2040	(80)
	1050	2000	(79)	2200	(86)
	1175	2235	(88)	2455	(97)
	1300	2470	(97)	2720	(105)
550	1300	2470	(97)	2720	(105)
	1425	2710	(105)	2980	(115)
	1550	2950	(115)	3240	(130)
	1675	3185	(125)	3500	(140)
	1800	3420	(135)	3765	(150)
800	1800	3420	(135)	3765	(150)
	1925	3660	(145)	4025	(160)
	2050	3900	(155)	4285	(170)
	2300	4375	(170)	4815	(190)

[a]Clearances shown are based on a 605 kV/m flashover gradient. See 6.3.1 for other choices.
[b]Switching surge conditions normally govern for system voltages above 242 kV. See Table 5.
[c]Values for maximum system voltages and BIL levels are from Table 1 and Table 2 of IEEE Std 1313.1-1996, except for the 1.2 kV and 5 kV system voltage and the 30 kV, 45 kV, 60 kV, 75 kV, and 2300 kV BIL values.
[d]For specific equipment clearance values, see relevant apparatus standards.
[e]Phase-to-phase clearances shown in this table are metal-to-metal clearances not bus-to-bus centerlines.
[f]Additional considerations for safety clearances must be evaluated separately (see Clause 7).

Table 5—Recommended minimum electrical clearances for air-insulated substations when switching surge conditions govern[a,b]

Maximum system voltage phase-to-phase[c]	BSL	Equivalent PU[i]	Minimum phase-to-ground clearances (k_g = 1.3)[d,e,h]		Minimum phase-to-ground clearances (k_g = 1.0)[d,e,h]		Minimum phase-to-phase clearances (k_g = 1.3)[d,f,g,h]	
(kV, rms)	(kV, $_{Ph-g}$,crest)	SSF	mm	(in)	mm	(in)	mm	(in)
362	550	1.86	1265	(50)	1730	(68)	1630	(64)
	650	2.20	1540	(61)	2125	(84)	2000	(79)
	750	2.54	1835	(72)	2560	(100)	2405	(95)
	825	2.79	2065	(81)	2910	(115)	2725	(105)
	900	3.04	2305	(91)	3280	(130	3065	(120)
	975	3.30	2560	(100)	3680	(145)	3505	(140)
	1050	3.55	2825	(110)	4110	(160)	3905	(155)
550	900	2.00	2305	(91)	3280	(130)	3065	!120)
	975	2.17	2560	(100)	3680	(145)	3505	(140)
	1050	2.34	2825	(110)	4110	(160)	3905	(155)
	1175	2.62	3300	(130)	4895	(190)	4640	(180)
	1300	2.89	3820	(150)	5795	(230)	5475	(215)
	1425	3.17	4385	(175)	6825	(270)	6420	(250)
	1550	3.45	5010	(195)	8025	(315)	7840	(310)
800	1175	1.80	3300	(130)	4895	(190)	4540	(180)
	1300	2.00	3820	(150)	5795	(230)	5475	(215)
	1425	2.18	4385	(175)	6825	(270)	6420	(250)
	1550	2.37	5010	(195)	8025	(315)	7840	(310)
	1675	2.56	5705	(225)	9435	(370)	9200	(360)
	1800	2.76	6475	(255)	11120	(440)	10815	(425)

[a]Clearances shown are based on specific gap factors. See Table 4 and Table 7 for other choices.
[b]Lightning impulse conditions may govern when low BSL levels are used. See Table 3.
[c]Values for maximum system voltages are from Table 2 of IEEE Std 1313.1-1996.
[d]See relevant apparatus standards for specific equipment clearance values.
[e]Assumptions for phase-to-ground clearances: altitude = sea level, coefficient of variation = 0.07.
[f]Assumptions for phase-to-phase clearances: altitude = sea level, coefficient of variation = 0.035. BSL_{ph-ph}/BSL_{ph-g} = 1.56 to 1.74.
[g]Phase-to-phase clearances shown in Table 5 are metal-to-metal clearances not bus-to-bus centerlines.
[h]Additional considerations for safety clearances must be evaluated separately (see Clause 7).
[i]Equivalent SSF = BSL ÷ $V_{crest\ ph-g}$, where $V_{crest\ ph-g} = \sqrt{2}V_m / \sqrt{3}$.

650 kV BIL Ex:	SG-6	IEEE 1427
Min Ph-Gnd	50”	49”
Rec. Ph-Gnd	52.5”	N/A
Min Ph-Ph	63”	54”

Spacing & Clearances

BIL/Voltage Ratio

Table 8—Ratio of BIL to maximum system voltage

Maximum system voltage phase-to-phase (kV, rms)	Typical BIL (kV, crest)	Ratio of BIL to maximum system voltage
72.5	350	4.83
121	550	4.55
145	650	4.48
169	750	4.44
242	900 1050	3.72 4.34
362	1050 1300	2.90 3.59
550	1550 1800	2.82 3.27
800	1800 2050 2300	2.25 2.46 2.88

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.

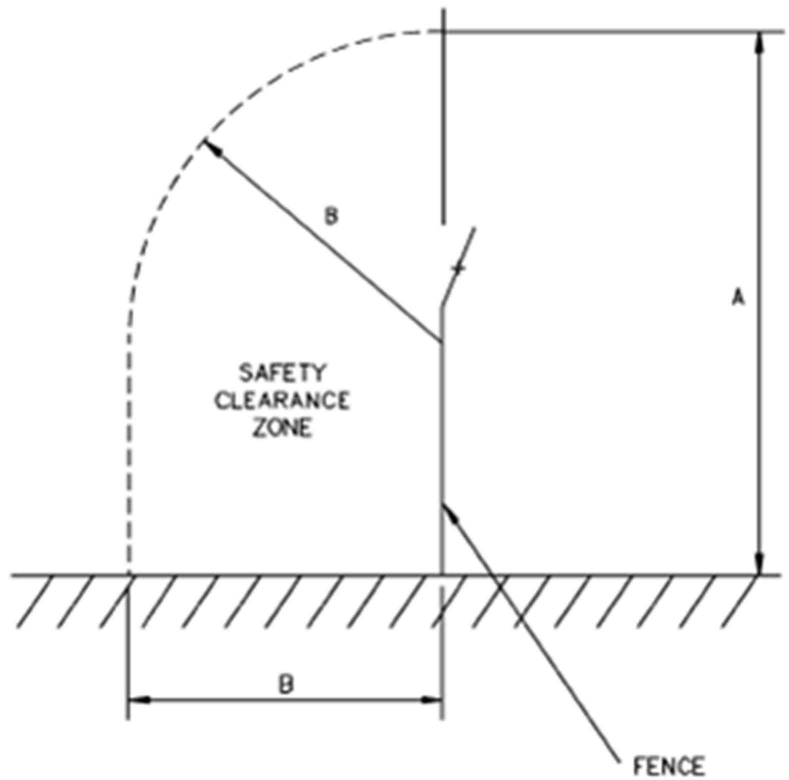
- IEEE 1427-2006 – What It Doesn’t Address
  - Uprating (Discussion Only)
  - Wildlife Conservation
  - Shielding Effects
  - Contamination
  - Hardware & Corona
  - Arcing During Switch Operation
  - Mechanical Stress Due to Fault Currents
  - Safety

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.

Spacing & Clearances

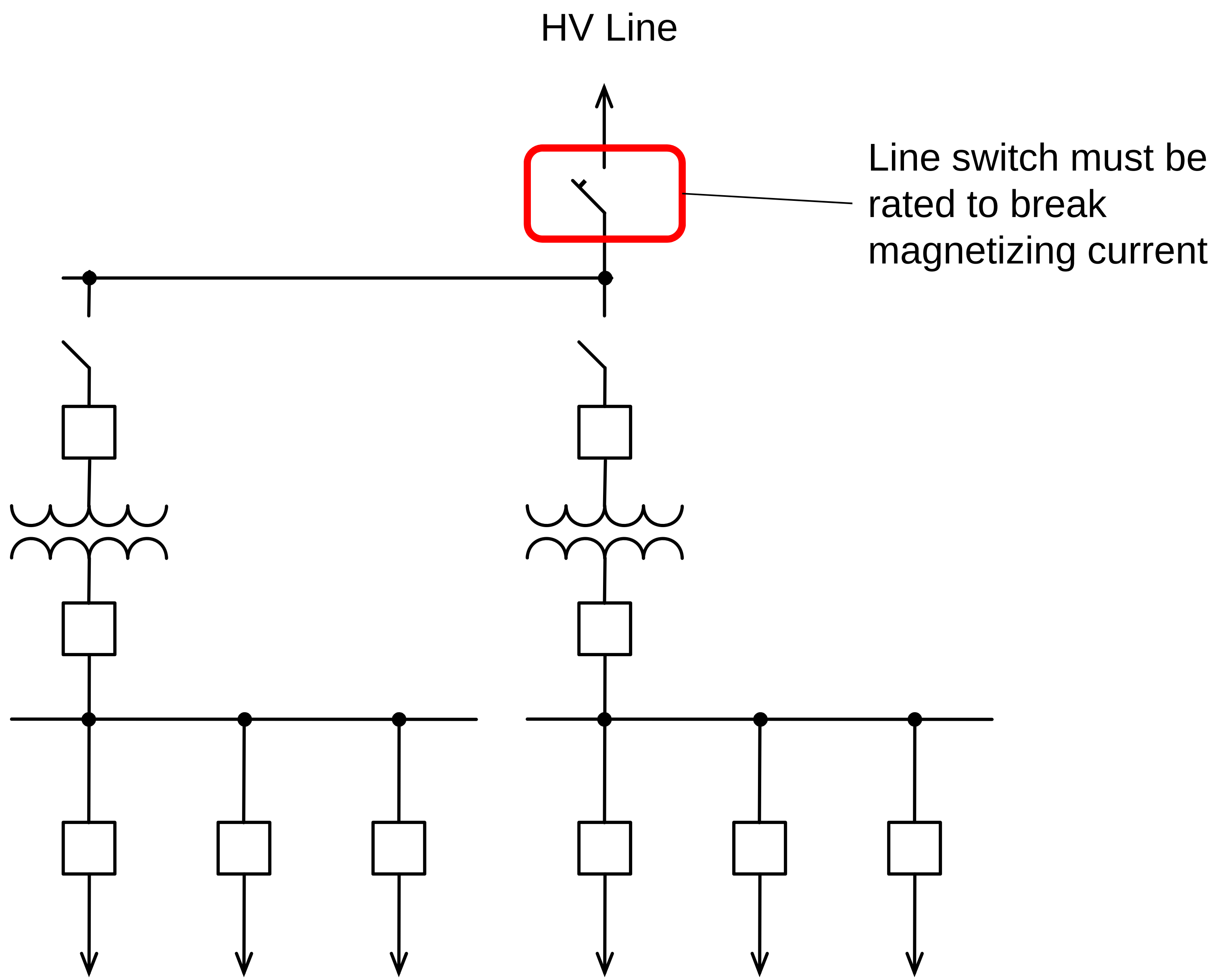
IEEE C37.32

Table 4-8: Phase Spacing of Outdoor Air Switches. Ref. ANSI Std. C37.32-1996, Table 5.
Reproduced with permission of the National Electrical Manufacturers Association.

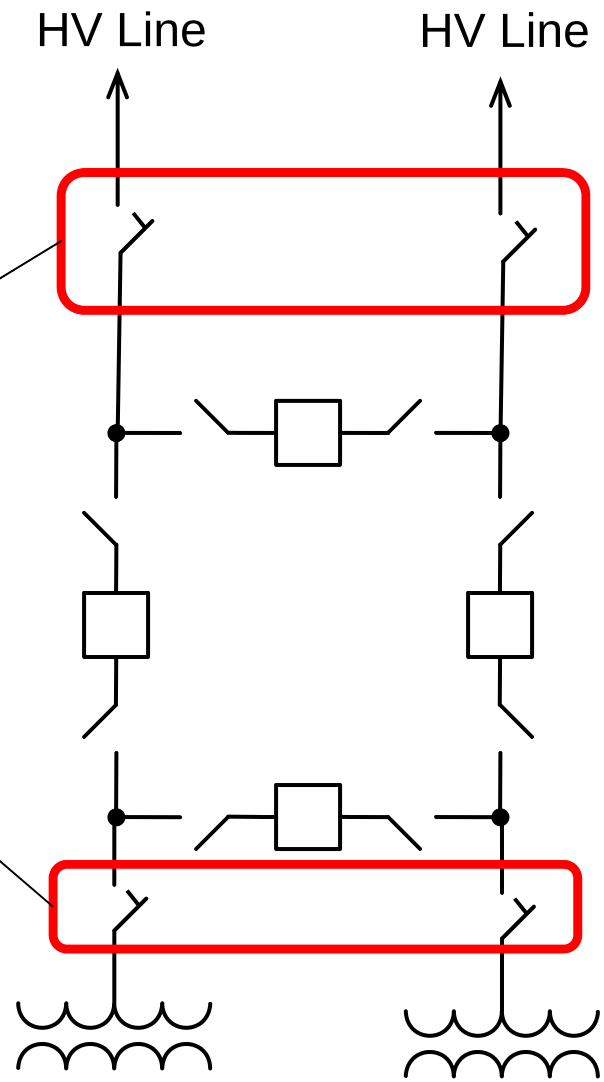
Nominal Phase-to-Phase Voltage kV	Maximum Phase-to-Phase Voltage kV	BIL kV	Minimum Metal-to-Metal for Air Switches meters (inches)	Centerline-to-Centerline Phase Spacing meters (inches)		
				Vertical Break Disconnect Switches	Side or Horizontal Break Disconnect Switches	All Horn Gap Switches
7.5	8.3	95	0.175 (7)	0.457 (18)	0.762 (30)	0.914 (36)
14.4	15.5	110	0.305 (12)	0.610 (24)	0.762 (30)	0.914 (36)
23	25.8	150	0.381 (15)	0.762 (30)	0.914 (36)	1.22 (48)
34.5	38	200	0.457 (18)	0.914 (36)	1.22 (48)	1.52 (60)
46	48.3	250	0.533 (21)	1.22 (48)	1.52 (60)	1.83 (72)
69	72.5	350	0.787 (31)	1.52 (60)	1.83 (72)	2.13 (84)
115	121	550	1.35 (53)	2.13 (84)	2.74 (108)	3.05 (120)
138	145	650	1.60 (63)	2.44 (96)	3.35 (132)	3.66 (144)
161	169	750	1.83 (72)	2.74 (108)	3.96 (156)	4.27 (168)
230	242	900	2.26 (89)	3.35 (132)	4.87 (192)	4.87 (192)
230	242	1050	2.67 (105)	3.96 (156)	5.50 (216)	5.50 (216)
345	362	1050	2.67 (105)	3.96 (156)	5.49 (216)	5.49 (216)
345	362	1300	3.02 (119)	4.43 (174)	— —	— —

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

Spacing & Clearances


HV Line
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

Spacing & Clearances

Switch Interrupter Guide

Type of Switch	Line/Cable Dropping	Transformer Magnetizing	Loop Splitting	Load Breaking
Standard Arcing Horns	X	X		
Whip	X	X		
Load Break	X	X	X	X

Never a good idea at HV installations. Arcing generates high transient voltages and risks damage to transformers

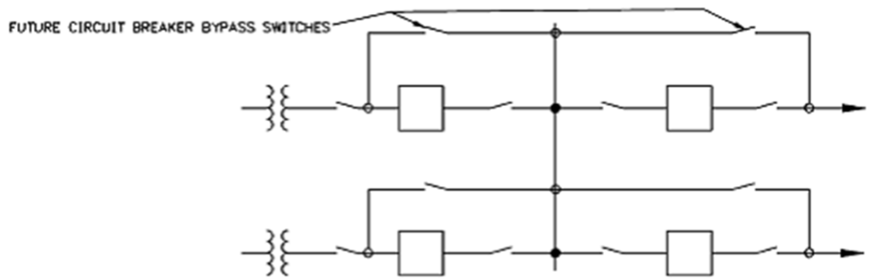
Switch Failure

115 kV Switch Opening

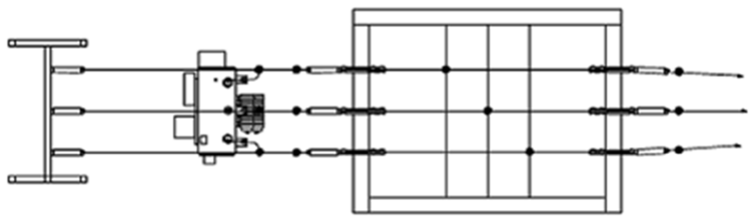
Spacing & Clearances

Types of Substation Structures

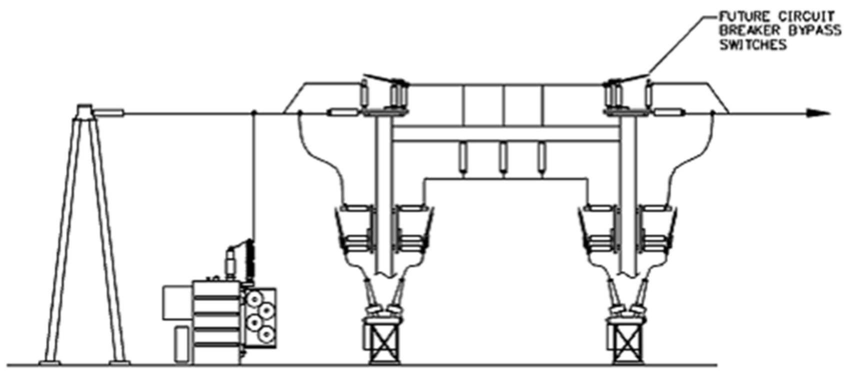
- **Conventional** (Lattice Structures)
  - Angle (Chord & Lace) Members
  - Minimum Structure Weight
  - Requires Minimum Site Area
  - Stable and Rigid Construction
  - Requires Considerable Bolting & Erection Time



TYPICAL ONE-LINE DIAGRAM



PLAN VIEW-TYPICAL BAY



ELEVATON-TYPICAL BAY

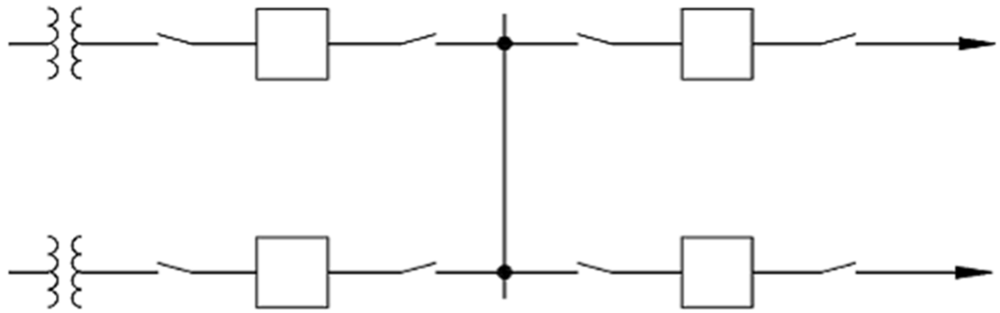
Conventional Design

Conventional Design

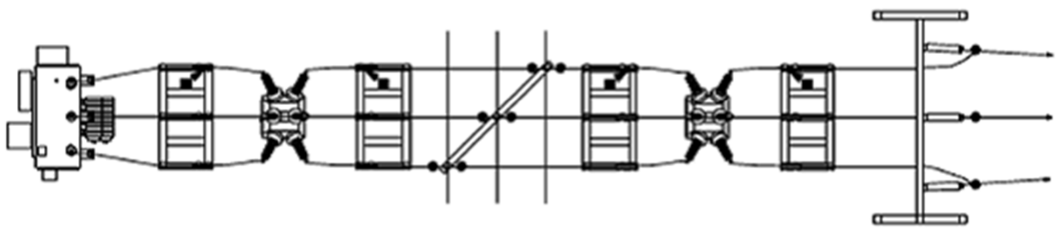
Conventional Design

- **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

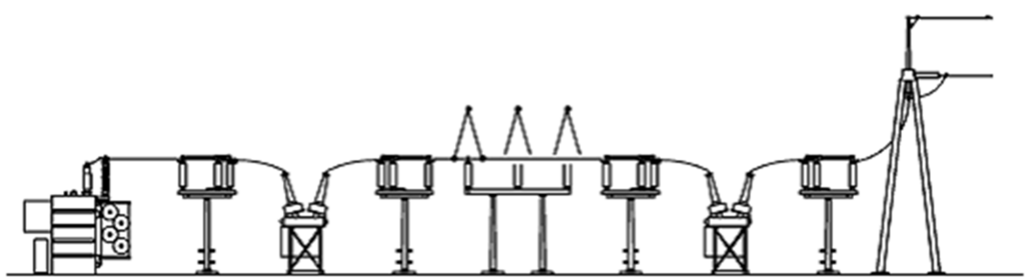
Station Physical Layout



TYPICAL ONE-LINE DIAGRAM



PLAN VIEW—TYPICAL BAY



ELEVATION—TYPICAL BAY

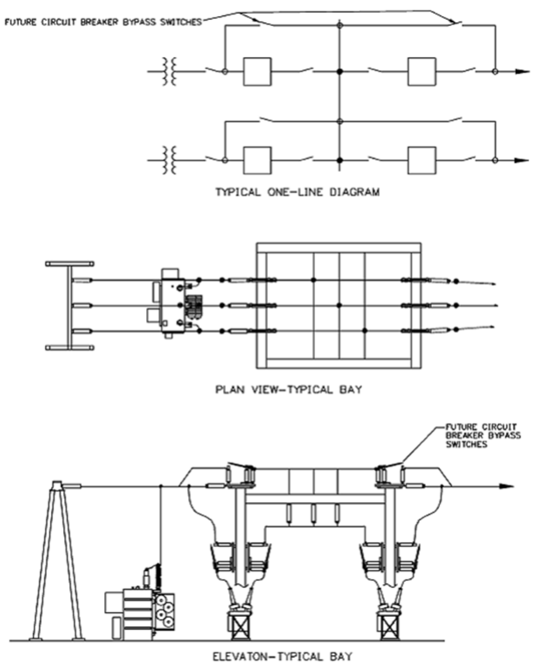
Low Profile (tube steel)

141

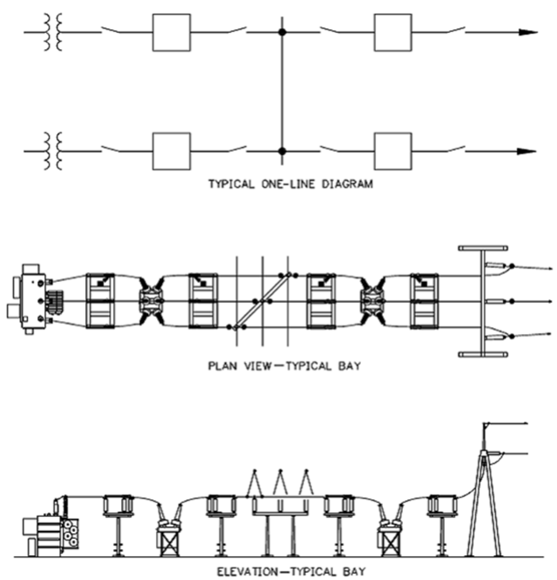
Low Profile (tapered tubular steel)

Low Profile (tube)

Conventional

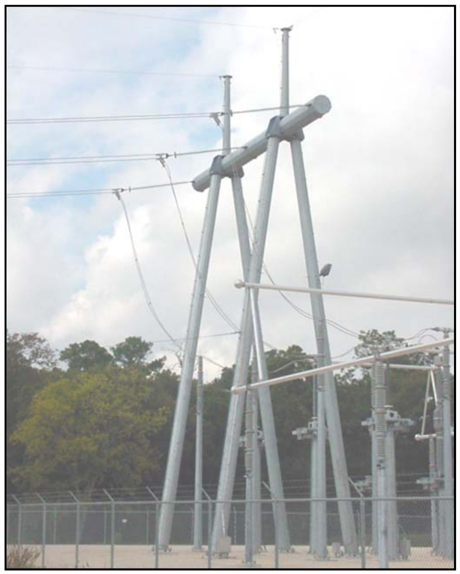


Low Profile



Station Physical Layout

- **Common Designs**
  - A-Frame or H-Frame
  - Lattice, Wide Flange, Structural Tubing
  - Inboard or Outboard Leg Design

Deadend Structures

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)

Surge & Lightning Protection

- 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 & Lightning Protection

- Surge Protection (Arresters)
  - Use Arresters (Station Class)
  - Transformer Protection (High Z Causes High V Reflected Wave)
  - Line Protection (Open End Causes High V Reflected Wave)
  - Systems above 169 kV Require Special Attention
  - IEEE C62.22 – IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

Surge & Lightning Protection

- Lightning Protection
  - Strokes to Tall Structures; Strokes to Ground
  - Frequency – Isokeraunic Levels at Station Location
  - Design Methods
    - Fixed Angles (good at or below 69 kV, generally applied up to 138 kV)
    - Empirical Curves (not used widely)
    - Whitehead's EGM
    - Revised EGM
    - Rolling Sphere
- Combination of Surge Arresters and Lightning Shielding Provides Acceptable Levels of Protection
- IEEE 998 – IEEE Guide for Direct Lightning Stroke Shielding of Substations

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

Surge & Lightning Protection

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

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

where

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

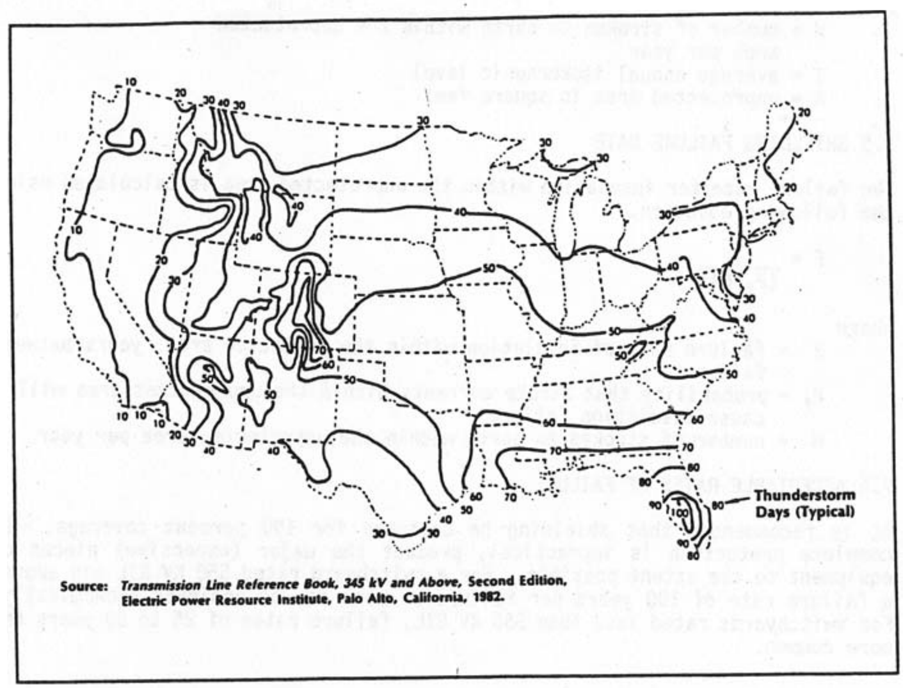


Figure 13
USA Annual Isokeraunic Map

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 = failure rate of insulation within the protected area, years between failures
- P_f = probability that stroke currents within the unprotected area will cause insulation failure
- N = number of strokes to earth within the unprotected area per year

7.6 ACCEPTABLE RATES OF FAILURE

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

Surge & Lightning Protection

- Fixed Angle Method

ANGLE	RANGE	RECOMMENDED
A	20° TO 60°	30°
B	40° TO 60°	45°

SINGLE MAST OR SHIELD WIRE   TWO MASTS OR SHIELD WIRES

Reference: IEEE Std 998

Surge & Lightning Protection

Rolling Sphere Method

$$S_m = 8\,k\,I^{0.65} \tag{5-1A}$$

or

$$S_f = 26.25\,k\,I^{0.65} \tag{5-1B}$$

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]:

$$I_S = \frac{\text{BIL} \times 1.1}{(Z_S/2)} = \frac{2.2\ (\text{BIL})}{Z_S} \tag{5-2A}$$

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]:

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

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:

$$R_c' = R_0 + R_c \qquad (C.2)$$

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

Surge & Lightning Protection

Rolling Sphere Method

C.3 Surge impedance under corona

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

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

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

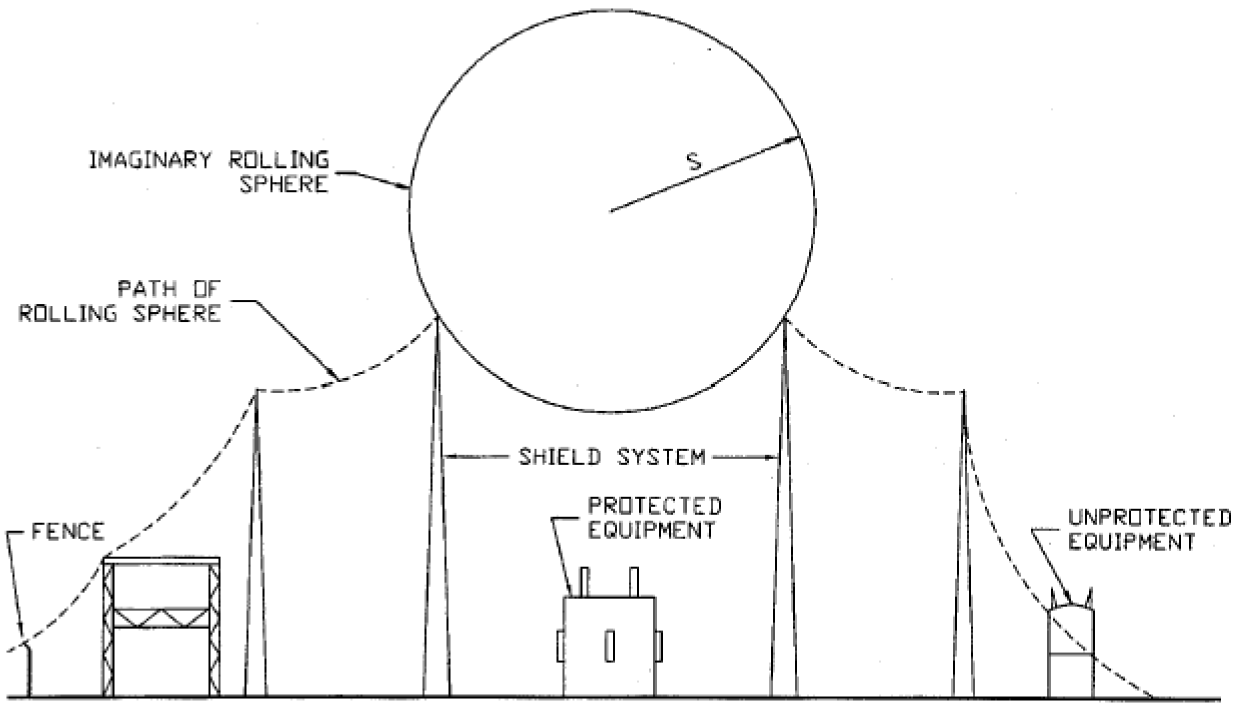
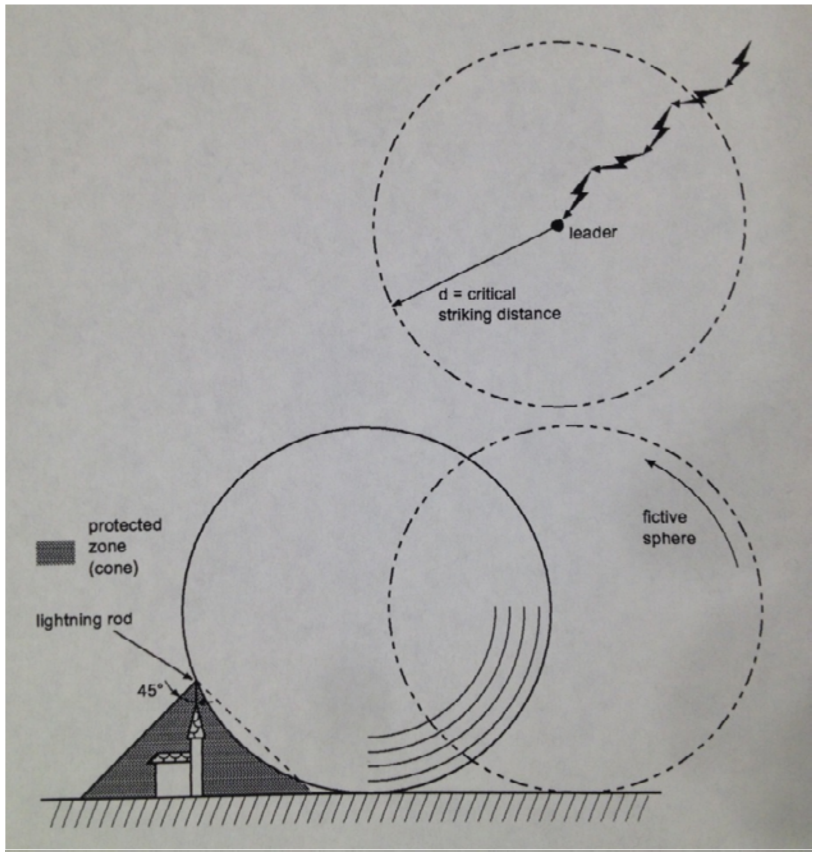


Figure 5-3 —Principle of rolling sphere

Reference: IEEE Std 998

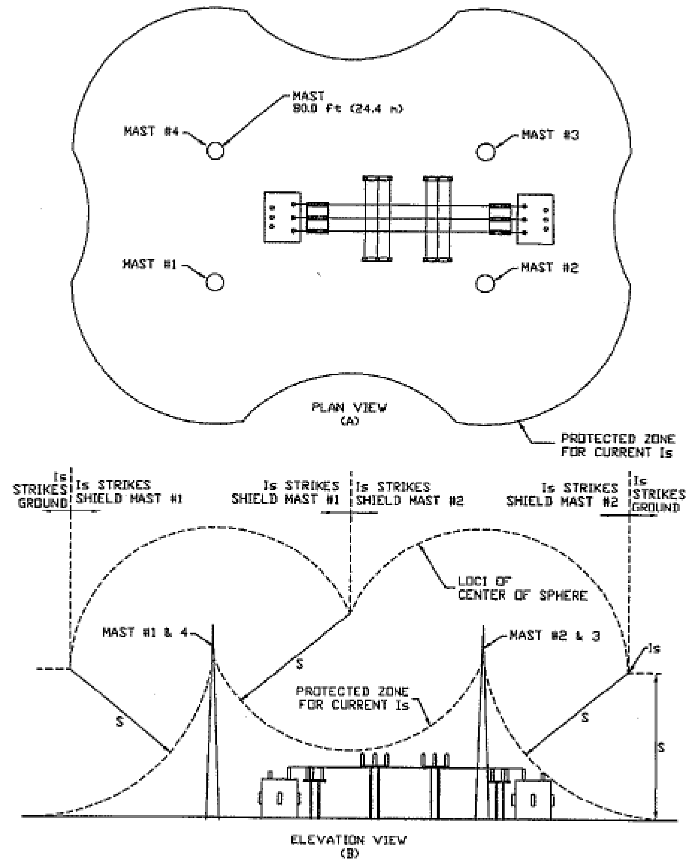
Surge & Lightning Protection

Rolling Sphere Method



Surge & Lightning Protection

Rolling Sphere Method



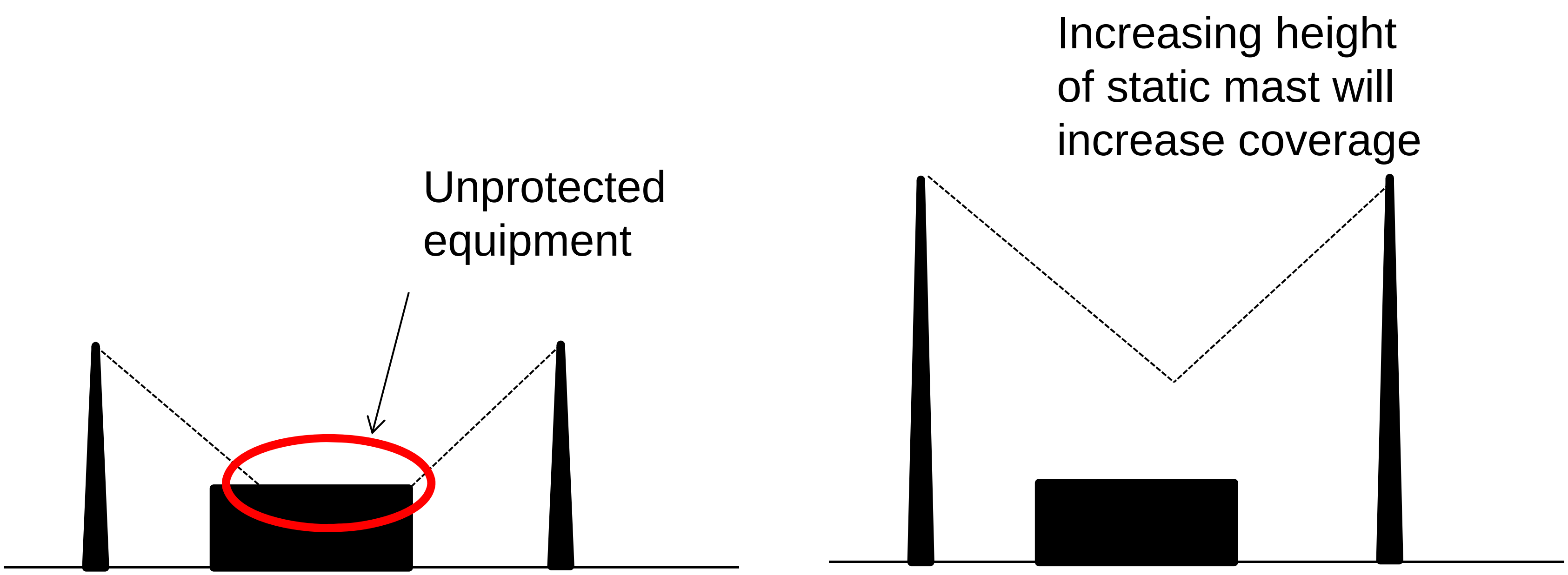
Reference: IEEE Std 998

Source: Adapted from [B74]

Figure 5-7 —Multiple shield mast protection for stroke current I_s

Surge & Lightning Protection

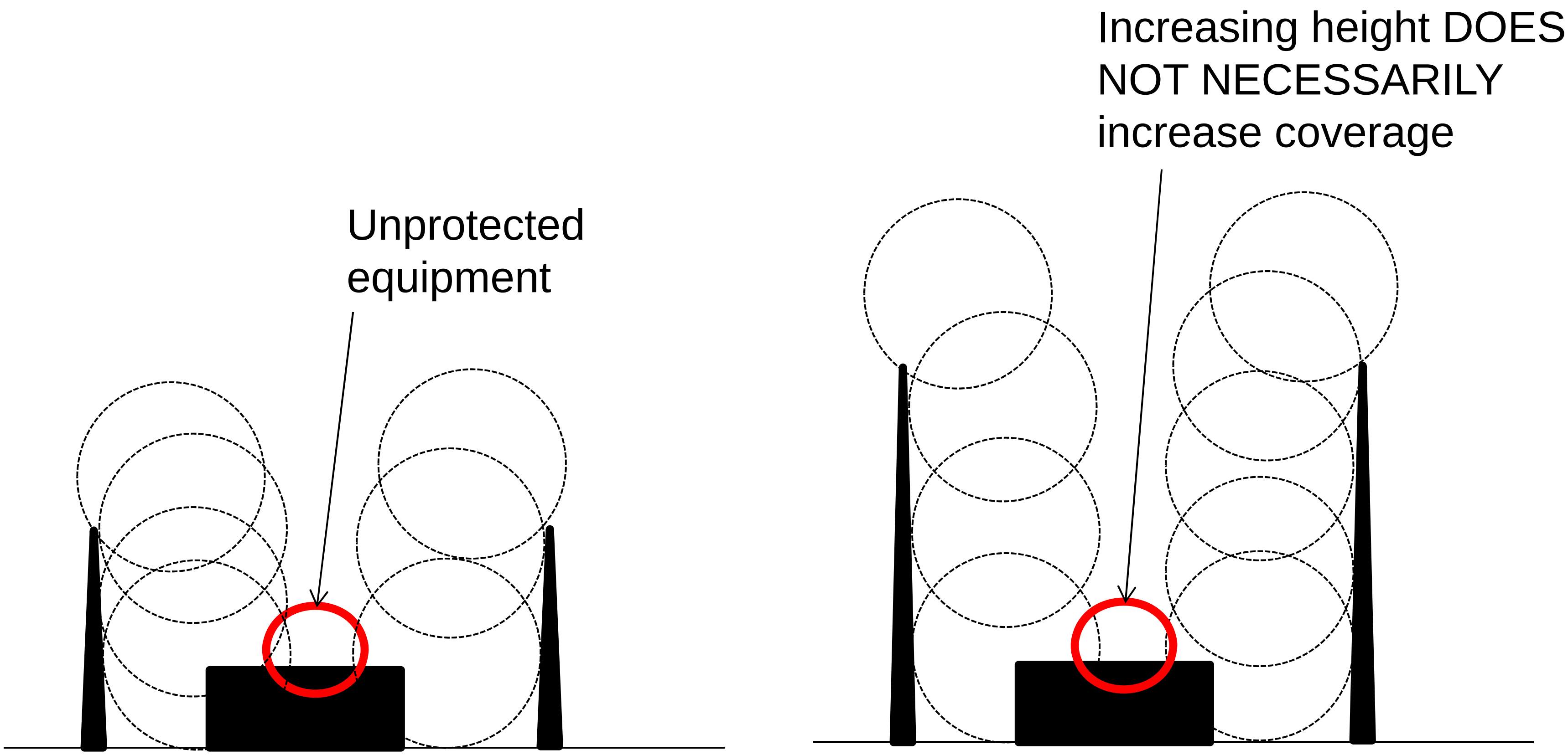
Comparing Fixed Angle and Rolling Sphere Methods



Fixed Angle Method

Surge & Lightning Protection

Comparing Fixed Angle and Rolling Sphere Methods



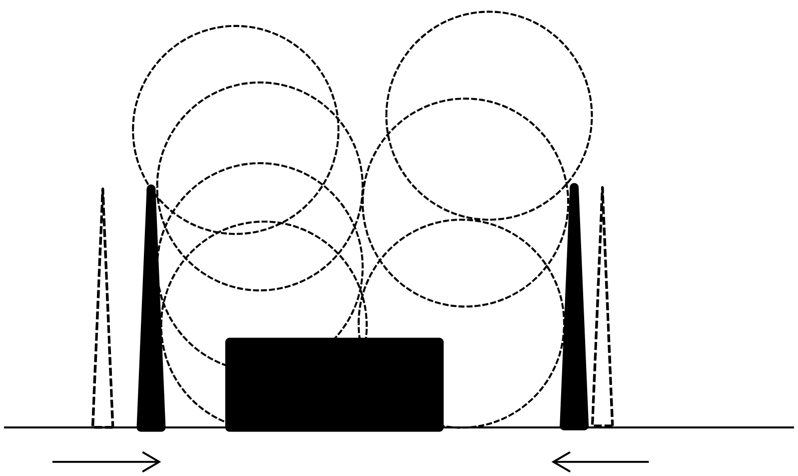
Rolling Sphere Method

Surge & Lightning Protection

Comparing Fixed Angle and Rolling Sphere Methods

Decrease distance between static masts

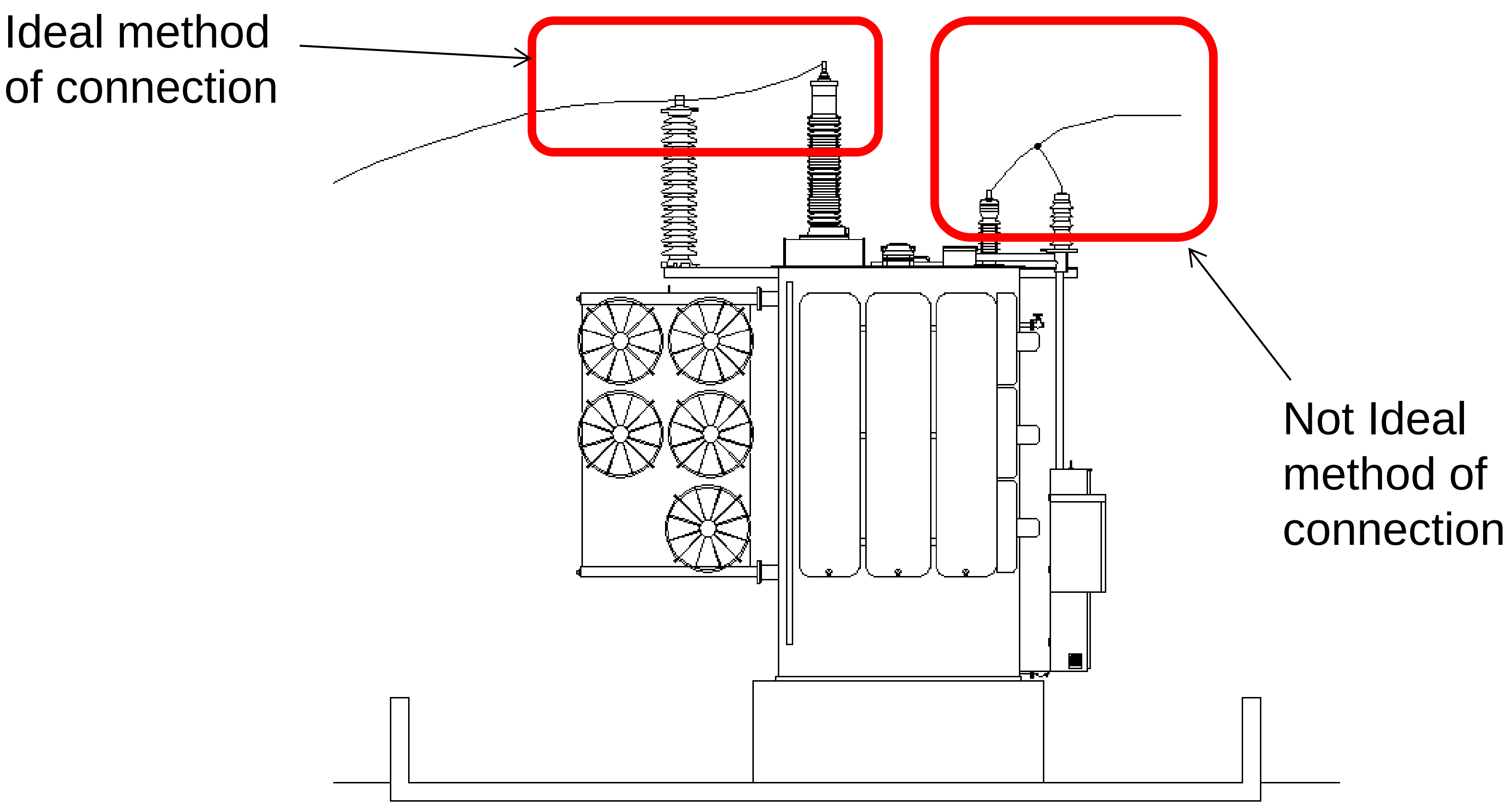
…or install static wires between static masts



Rolling Sphere Method

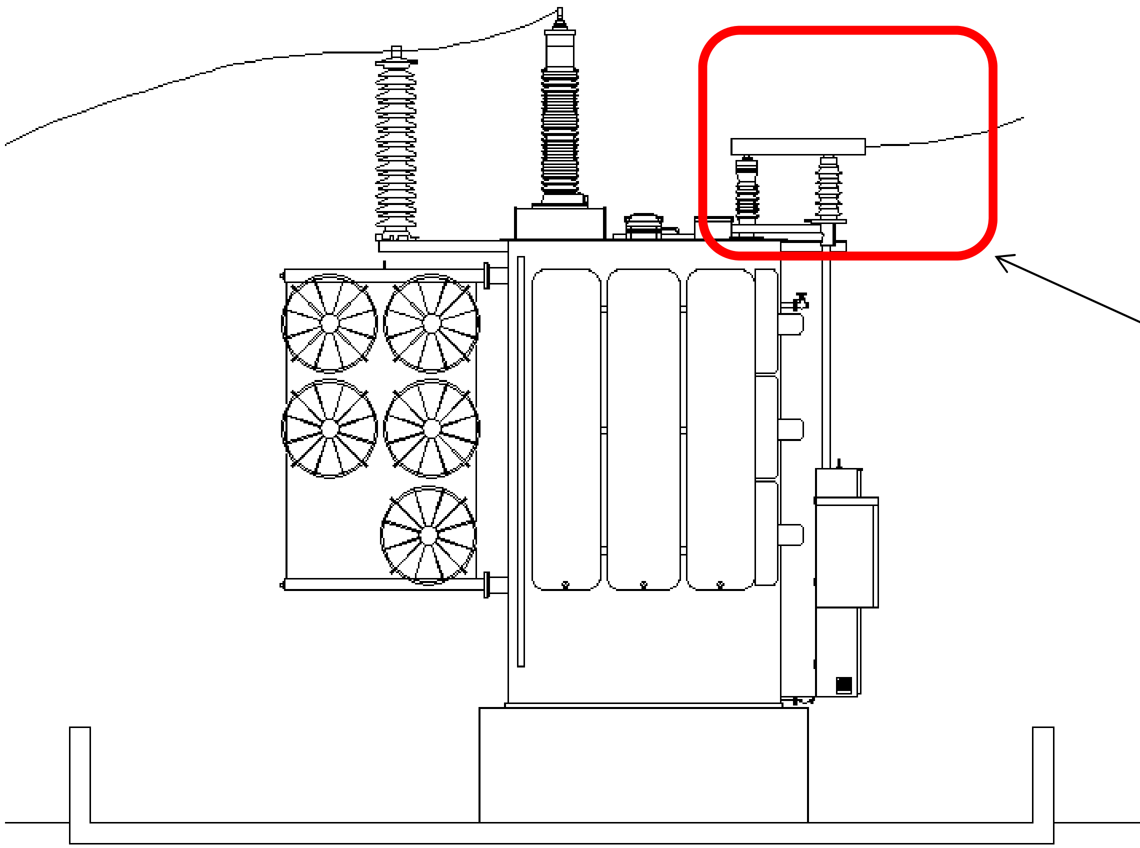
Surge & Lightning Protection

Minimize distance / impedance to maximize effective protection



Surge / Lightning Arresters

Minimize distance / impedance to maximize effective protection



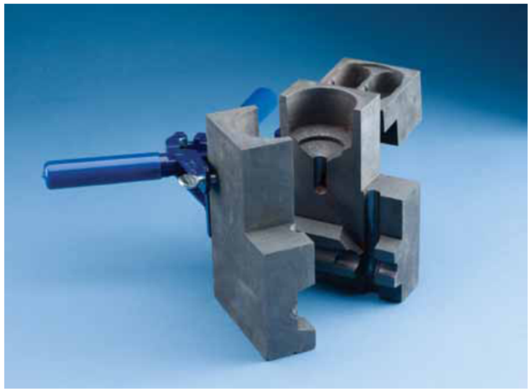
Preferable Installation (hard bus between bushings and arresters)

Surge / Lightning Arresters

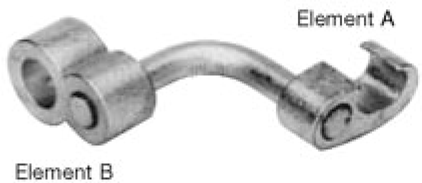
Grounding Considerations

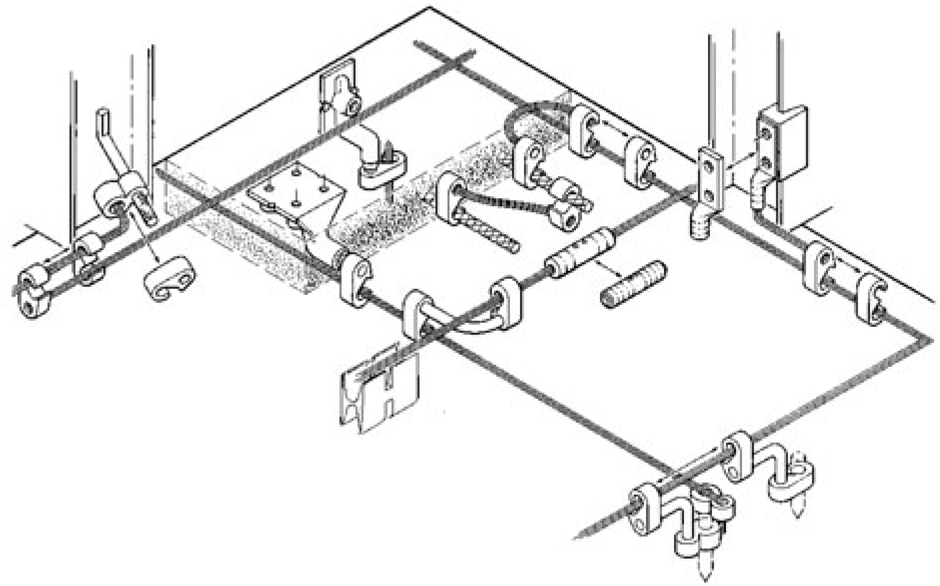
- IEEE 80 – IEEE Guide for Safety in AC Substation Grounding
  - Safety Risks
  - Humans as Electrical Components
  - Soil Modeling
  - Fault Currents and Voltage Rise
  - Demands Use of Analytical Software
- NESC
  - Points of Connection
  - Messengers & Guys, Fences
  - Grounding Conductors, Ampacity, Strength, Connections
  - Grounding Electrodes
  - Ground Resistance Requirements

Grounding

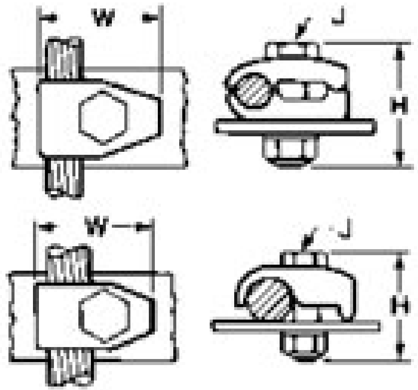


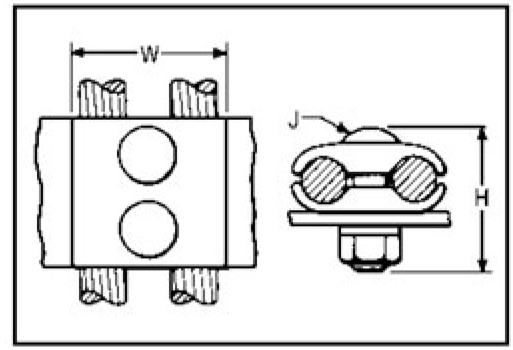
Grounding – Exothermic

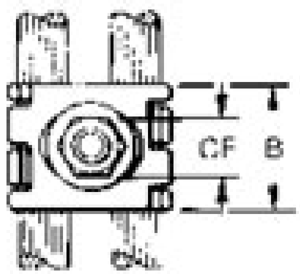


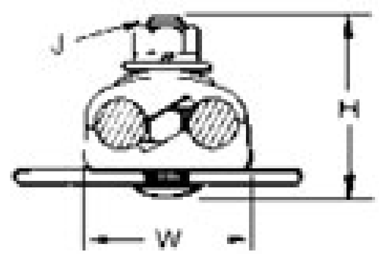


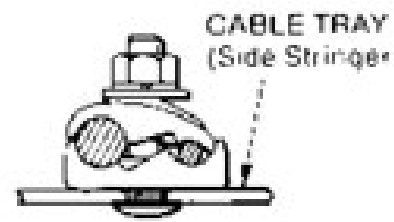
Grounding – Compression











Grounding – Mechanical

OBJECTIVES

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

Grounding Design

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

Grounding Objectives

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

Cause of Electric Shock

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

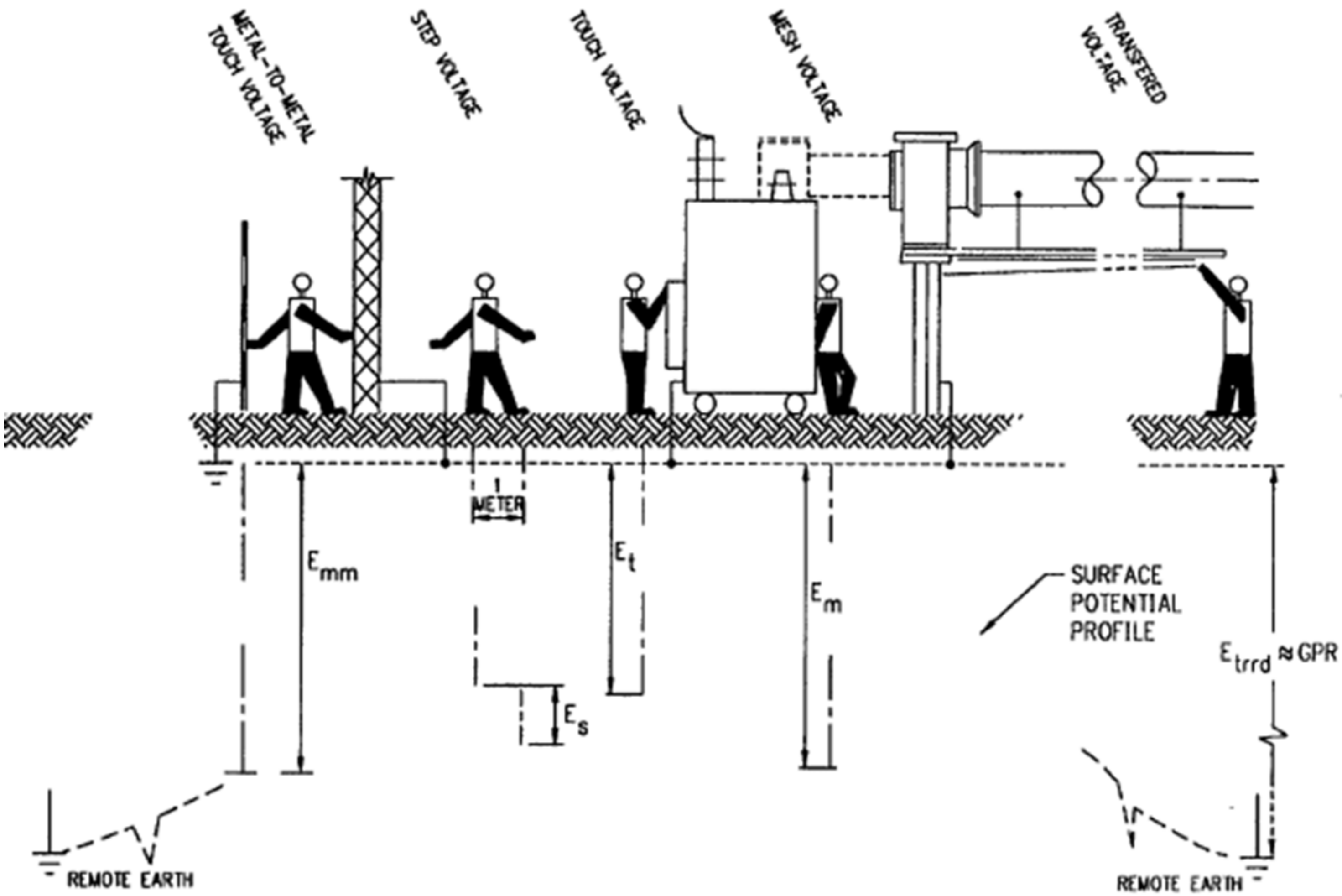


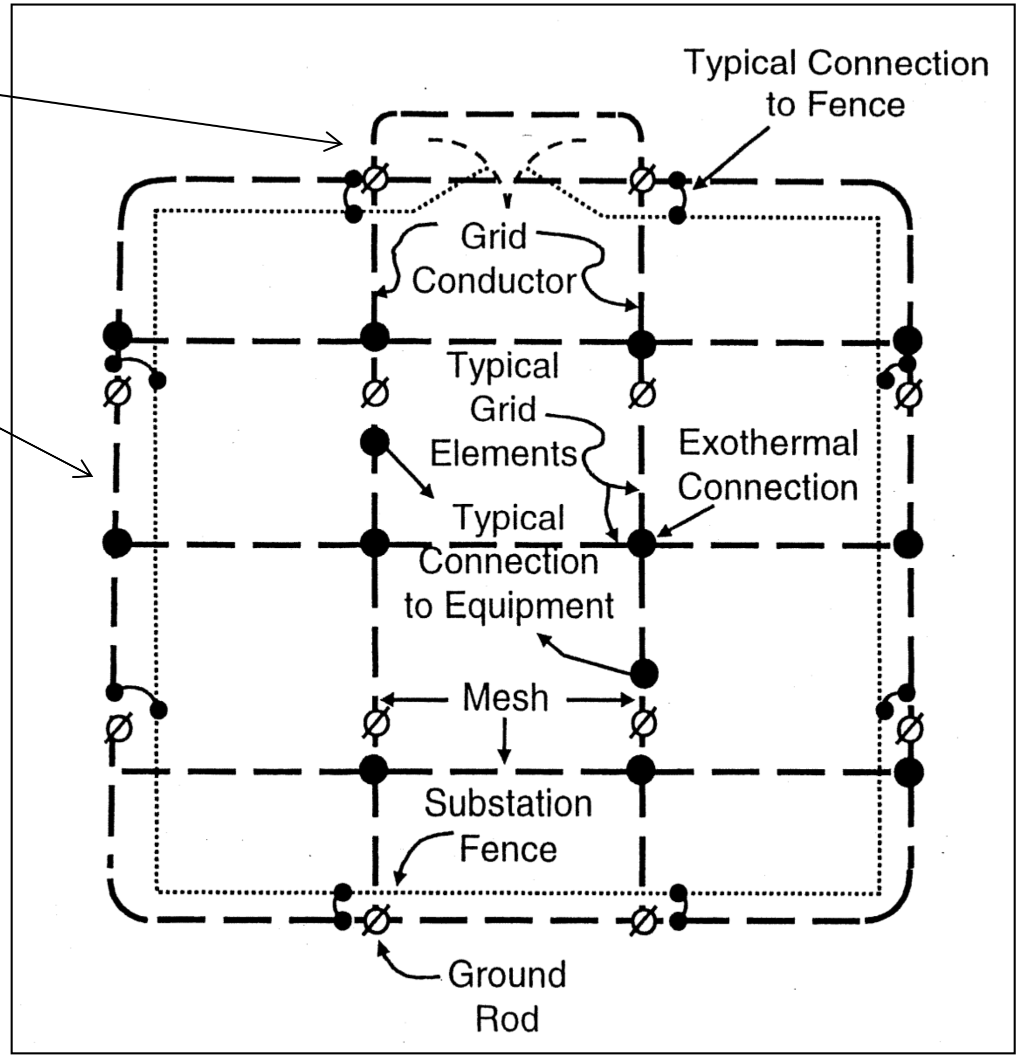
Figure 12—Basic shock situations

Source: IEEE 80

Basic Shock Situations

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

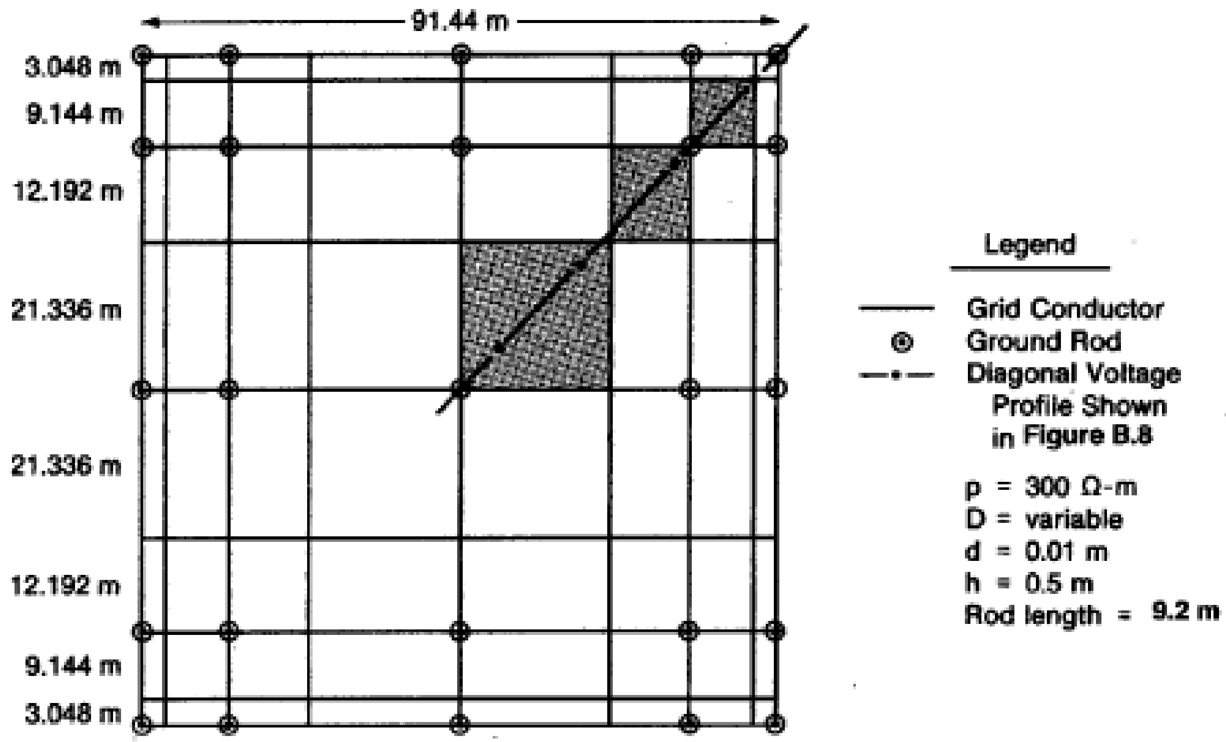


Figure B.7—Unequally spaced square grid with twenty-five 9.2 m rods

Simple Grid Design

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.

Testing Ground Grid

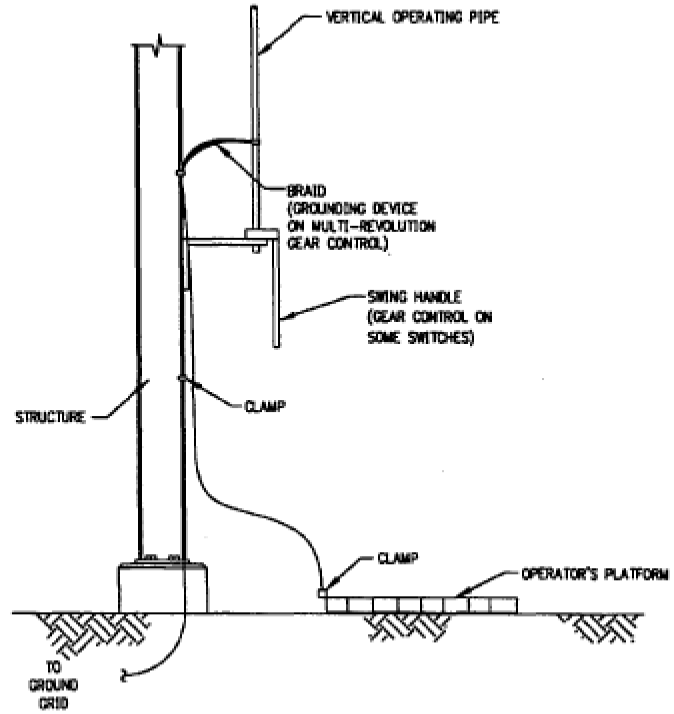


Figure 34—Typical switch shaft grounding

Source: IEEE 80

Switch Operator

Table 3—Ultimate current carrying capabilities of copper grounding cables; currents are RMS values, for frequency of 60 Hz, X/R = 40; current in kiloamperes

Cable size, AWG	Nominal cross section, mm^2	6 cycles (100 ms)	15 cycles (250 ms)	30 cycles (500 ms)	45 cycles (750 ms)	60 cycles (1 s)	180 cycles (3 s)
#2	33.63	22	16	12	10	9	5
#1	42.41	28	21	16	13	11	7
1/0	53.48	36	26	20	17	14	8
2/0	67.42	45	33	25	21	18	11
3/0	85.03	57	42	32	27	23	14
4/0	107.20	72	53	40	34	30	17
250 kcmil	126.65	85	62	47	40	35	21
350 kcmil	177.36	119	87	67	56	49	29

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 7—Typical surface material resistivities

Number	Description of surface material (U.S. state where found)	Resistivity of sample Ω·m	
		Dry	Wet
1	Crusher run granite with fines (N.C.)	140×10^6	1300 (ground water, 45 Ω·m)
2	1.5 in (0.04 m) crusher run granite (Ga.) with fines	4000	1200 (rain water, 100 W)
3	0.75–1 in (0.02–0.025 m) granite (Calif.) with fines	—	6513 (10 min after 45 Ω·m water drained)
4	#4 (1 -2 in) (0.025-0.05 m) washed granite (Ga.)	1.5×10^6 to 4.5×10^6	5000 (rain water, 100 Ω·m)
5	#3 (2–4 in) (0.05-0.1 m) washed granite (Ga.)	2.6×10^6 to 3×10^6	10 000 (Rain water, 100 Ω·m)
6	Size unknown, washed limestone (Mich.)	7×10^6	2000–3000 (ground water, 45 Ω·m)
7	Washed granite, similar to 0.75 in (0.02 m) gravel	2×10^6	10 000
8	Washed granite, similar to pea gravel	40×10^6	5000
9	#57 (0.75 in) (0.02 m) washed granite (N.C.)	190×10^6	8000 (ground water, 45 Ω·m)
10	Asphalt	2×10^6 to 30×10^6	10 000 to 6×10^6
11	Concrete	1×10^6 to 1×10^9 [a]	21 to 100

[a]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

Type of earth	Average resistivity (Ω·m)
Wet organic soil	10
Moist soil	10^2
Dry soil	10^3
Bedrock	10^4

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

Mineral oil volume, L (gal)	Separation distance, m (ft)
<1890 (500)	Footnote a
1890 to 18 930 (500 to 5000)	7.6 (25)
>18 930 (5000)	15.2 (50)

[a] 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

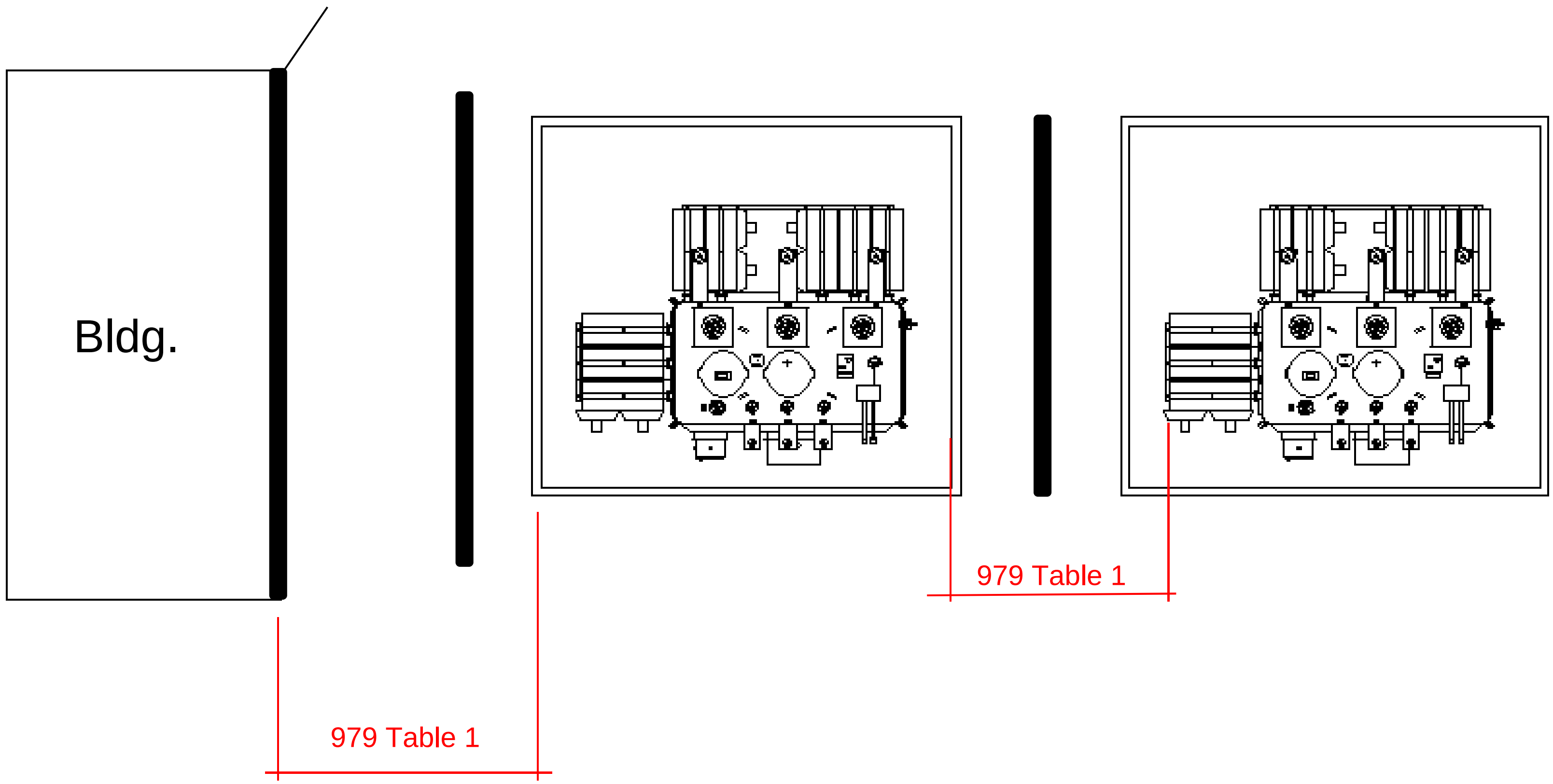
7.2.3 Equipment to buildings

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.[6] 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*.

NEC 450

TABLE 601
FIRE-RESISTANCE RATING REQUIREMENTS FOR BUILDING ELEMENTS (HOURS)

BUILDING ELEMENT	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
	A	B	A[d]	B	A[d]	B	HT	A[d]	B
Primary structural frame[g] (see Section 202)	3[a]	2[a]	1	0	1	0	HT	1	0
Bearing walls Exterior[f, g] Interior	 3 3[a]	 2 2[a]	 1 1	 0 0	 2 1	 2 0	 2 1/HT	 1 1	 0 0
Nonbearing walls and partitions Exterior	See Table 602								
Nonbearing walls and partitions Interior[e]	0	0	0	0	0	0	See Section 602.4.6	0	0
Floor construction and associated secondary members (see Section 202)	2	2	1	0	1	0	HT	1	0
Roof construction and associated secondary members (see Section 202)	$1\frac{1}{2}$[b]	1[b,c]	1[b,c]	0[c]	1[b,c]	0	HT	1[b,c]	0

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® **107**

NFPA

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 be 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-o-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.

Note that this is a "Classification…not a "Listing" UL Listing is completely something else

Internal

External

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

CLASSIFIED UL

Envirotemp FR3. Classed 4 to 5 less hazardous than paraffin oil in respect to fire hazard. Fire point 358 C (676 F). Ignition temperature 428 C (802 F).

Also Classified as a "less-flammable liquid" as specified in the National Electric Code® when used in 3-phase transformers, 45 through 10,000 kVA with the following "use restrictions":

A. For use only in 3-phase transformers having tanks capable of withstanding an internal pressure of 12 psig without rupture.

B. Required use of pressure relief devices on transformer tank in accordance with the following tabulation to limit internal pressure buildup and prevent tank rupture due to gas generation under low current arcing faults, and

C. Required use of current limiting fusing in the transformer primary having I^2t characteristics not exceeding the values in the following tabulation. Under-fluid expulsion fuses may be used in series with the current-limiting fuses, in accordance with the manufacturer's protection scheme, or

D. Required use of overcurrent protection in the transformer primary having I^2t characteristics not exceeding the values in the following tabulation. If the fuse is designed to vent during operation (such as an expulsion fuse), it shall be located external to the transformer tank.

TRANSFORMER	REQUIRED PROTECTION		REQUIRED PRC
3-Phase Transformer Rating kVA	Required Current Limiting Fusing (+) Maximum I^2t (A^2s) OR	Required Overcurrent Protection (+) Maximum I^2t (A^2s)	Minimum Required Pressure Relief Capacity, (++) SCFM at 15 psi
45	500,000	700,000	35
75	500,000	800,000	35
112.5	550,000	900,000	35
150	600,000	1,000,000	50
225	650,000	1,200,000	100
300	750,000	1,400,000	100
500	900,000	1,900,000	350
750	1,100,000	2,200,000	350
1,000	1,250,000	3,400,000	350
1,500	1,500,000	4,500,000	700
2,000	1,750,000	6,000,000	700
2,500	2,000,000	7,500,000	5,000
3,000	2,250,000	9,000,000	5,000
3,750	2,500,000	11,000,000	5,000
5,000	3,000,000	14,000,000	5,000
7,500	3,000,000	14,000,000	5,000
10,000	3,000,000	14,000,000	5,000

(+) This is an additional requirement to the overcurrent protection required in accordance with Section 450.3 of the current National Electrical Code®.
(++) Opening pressure, 10 psig maximum.

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 m^3) of mineral oil could be released
  OR
- More than 1320 gal (5 m^3) of FM Approved less-flammable fluid could be released
  OR
- More than 2,640 gal (10 m^3) 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.)

Dielectric Fluids

COOPER Power Systems

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

Reference Information

R900-20-13

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

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

Liquid	FM Approved Transformer or Equivalent	Liquid Volume gal/(m^3)	Horizontal Distance**			Vertical Distance ft/(m)
			Fire Resistant ft/(m)	Non-Combustible ft/(m)	Combustible ft/(m)	
Less-Flammable (Approved)	Yes	N/A	3 (0.9)	3 (0.9)	3 (0.9)	5 (1.5)
	No	≤10,000 (38)	5 (1.5)	5 (1.5)	25 (7.6)	25 (7.6)
		>10,000 (38)	15 (4.6)	15 (4.6)	50 (15.2)	50 (15.2)
Mineral Oil	N/A	<500 (1.9)	5 (1.5)	15 (4.6)	25 (7.6)	25 (7.6)
		500-5,000 (1.9-19)	15 (4.6)	25 (7.6)	50 (15.2)	50 (15.2)
		>5,000 (19)	25 (7.6)	50 (15.2)	100 (30.5)	100 (30.5)

* 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.*

Liquid	FM Approved Transformer or Equivalent	Fluid Volume gal/(m^3)	Distance** ft/(m)
Less-Flammable (Approved)	Yes	N/A	3 (0.9)
	No	≤10,000 (38)	5 (1.5)
		>10,000 (38)	25 (7.6)
Mineral Oil	N/A	<500 (1.9)	6 (1.5)
		500-5,000 (1.9-19)	25 (7.6)
		>5,000 (19)	50 (15.2)

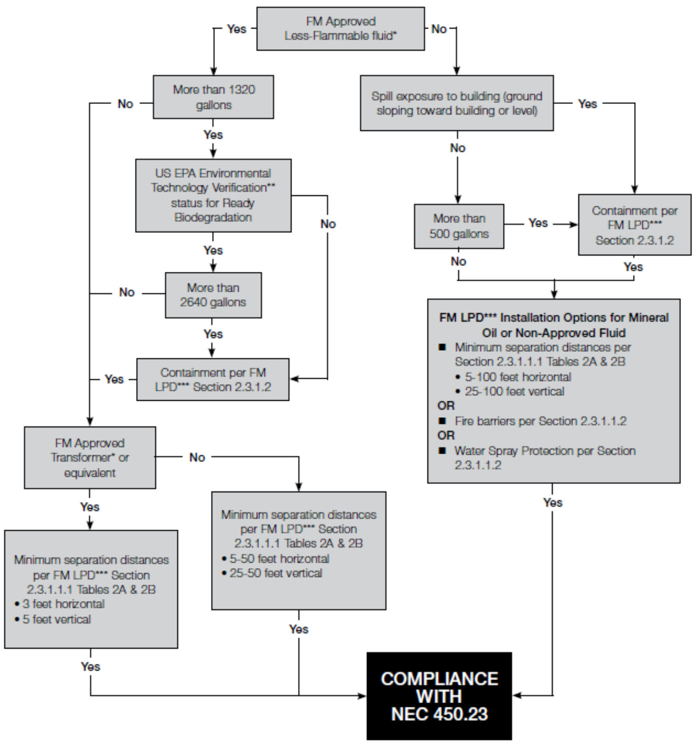
* FM Global Loss Prevention Data Sheet 5-4, Table 2b
** All transformer components must be accessible for inspection and maintenance.

Spacing & Clearances

Less-Flammable Liquid-Insulated Transformers Compliance to NEC 2011 Section 450.23 per FM Listing

Requirement Highlights for Outdoor Installations

FM Requirements Detail

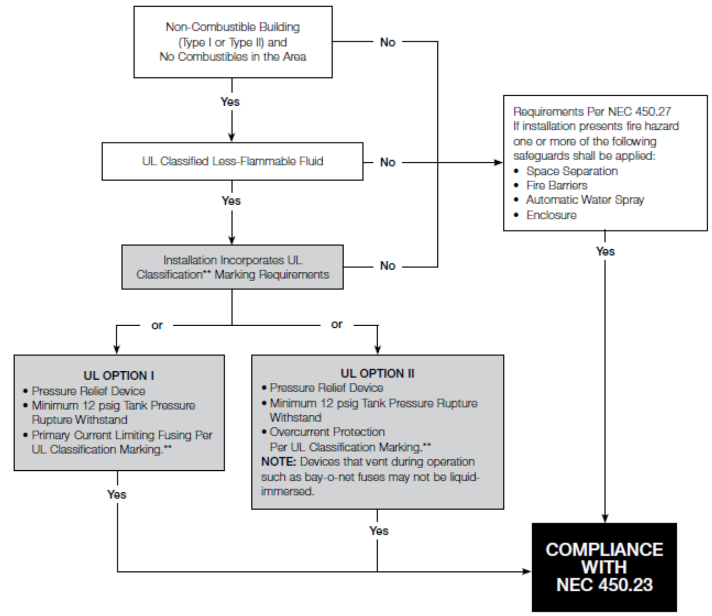


* FM Global Approval Guide
** Environmental Technology Verification Program, U.S. Environmental Protection Agency (Envirotemp FR3 fluid and BIOTEMP® fluid have ETV status for Ready Biodegradation)
*** FM Global Property Loss Prevention Data Sheets 5-4 — Transformers

Appendix 3

Less-Flammable Liquid-Insulated Transformers Compliance to NEC 2011 Section 450.23 per UL Listing

Requirement Highlights for Outdoor Installations



☐ NEC Code Requirements
☐ UL Listing Requirements

UL Classified Transformer Fluids:*
Envirotemp FR3 Fluid (natural ester), Option I or Option II
Dow Corning® 561 (silicone), Option II only

* Refer to NFPA 220 for definition of non-combustible Type I and II building construction
** Transformer Fluids (EOVK), Underwriters Laboratories Certifications Directory

NOTES: UL Classification Dielectric Mediums (EOUV) states that "Liquids intended for use as dielectric and cooling mediums in electrical transformers are covered under Transformer Fluids (EOVK)."

Appendix 4

Spacing & Clearances

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:

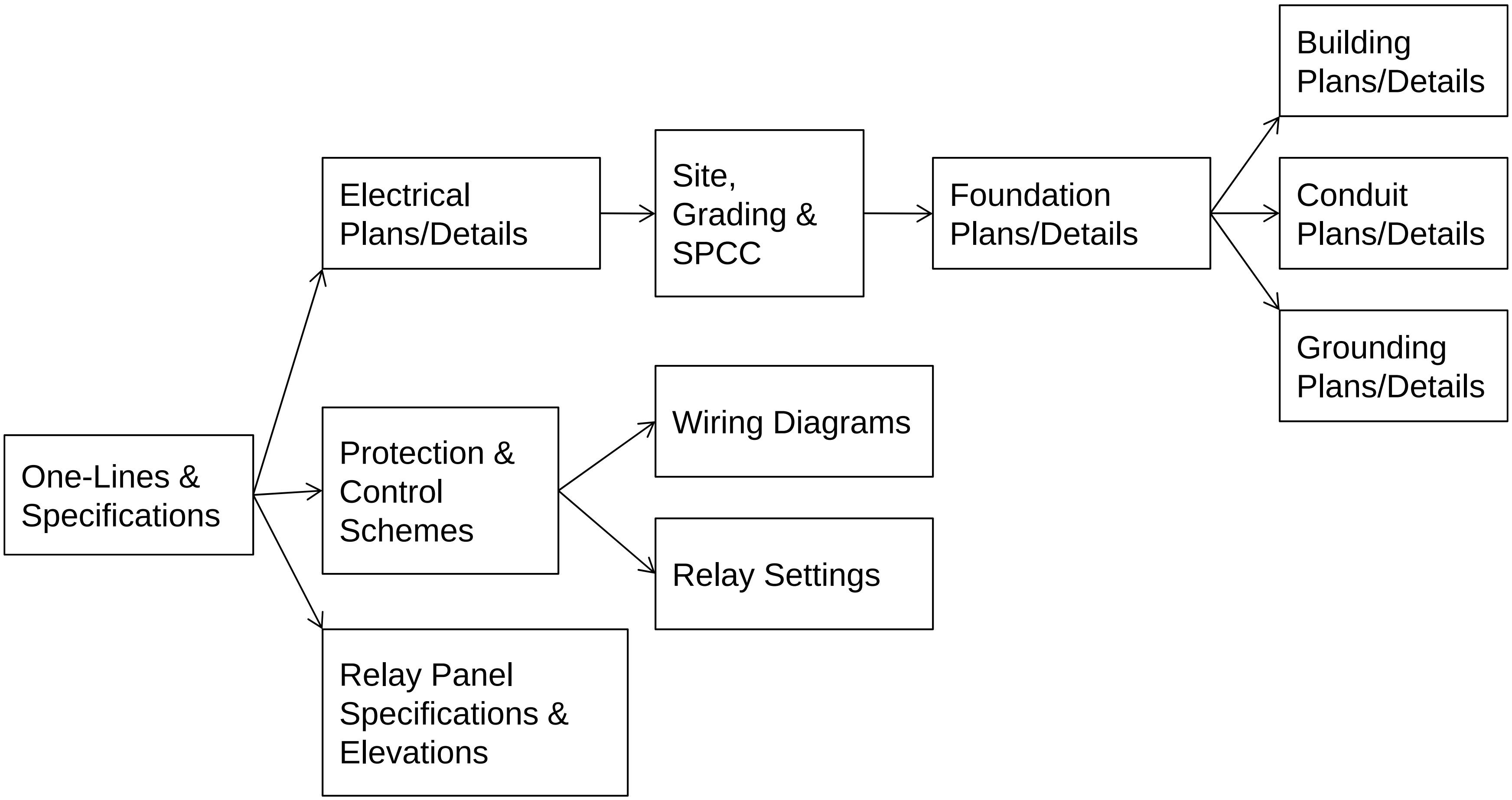
IEEE Standard for Relays and Relay Systems Associated with Electric Power Apparatus – IEEE C37.90
Transformer Protection – IEEE Std C37.91
Motor Protection – IEEE C37.96
Bus Protection – IEEE C37.97 (withdrawn)
Shunt Capacitor Bank Protection – IEEE C37.99
Generator Protection – IEEE C37.102
Automatic Reclosing of Line Circuit Breakers for AC Distribution and Transmission Lines - IEEE Std C37.104
Shunt Reactor Protecction - 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

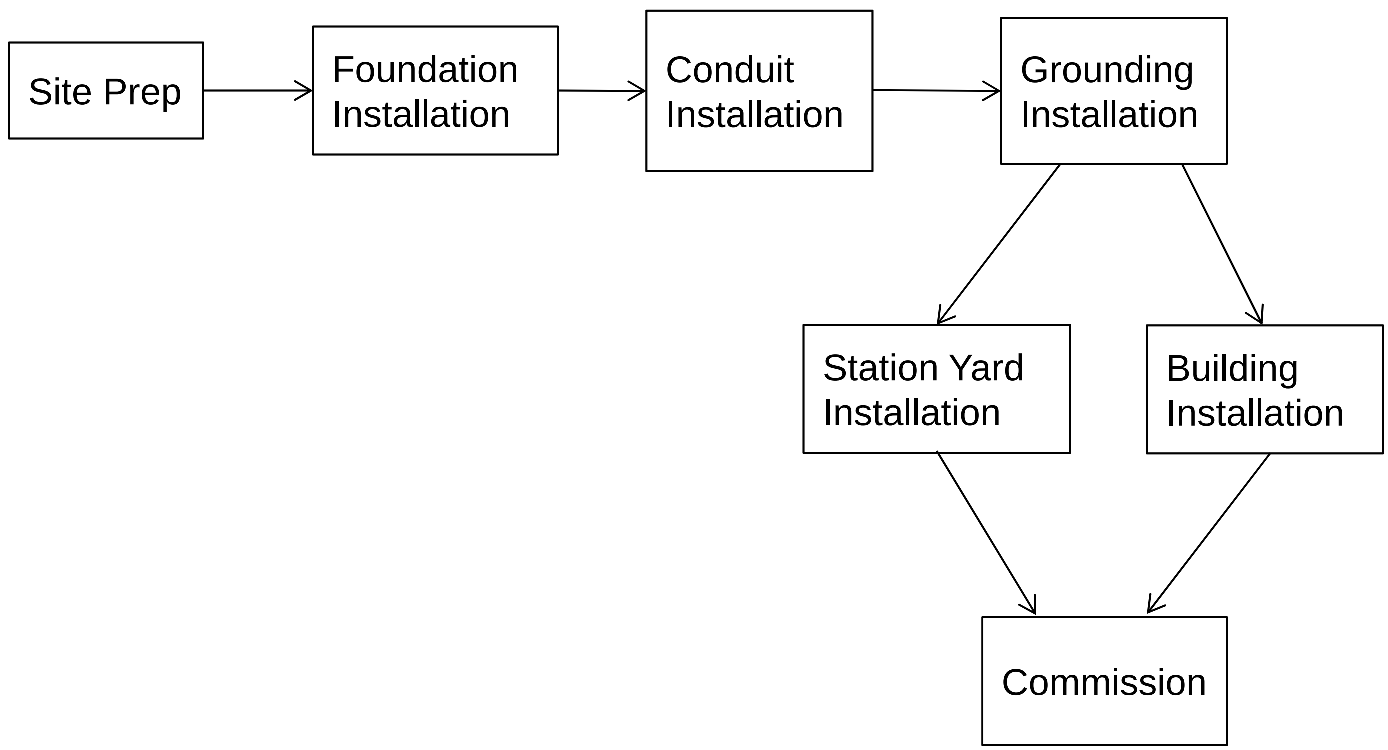
- Redundant DC power sources
- SER and DFR (oscillography) default settings enable only basic functionality at best case. Default settings by some manufacturers disable the SER and DFR.
- Synchronization of clocks
- Integration of protective relays with other IEDs
- Utilize outputs from “non-intelligent”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

Engineering & Construction Coordination

Engineering Process



Construction Process



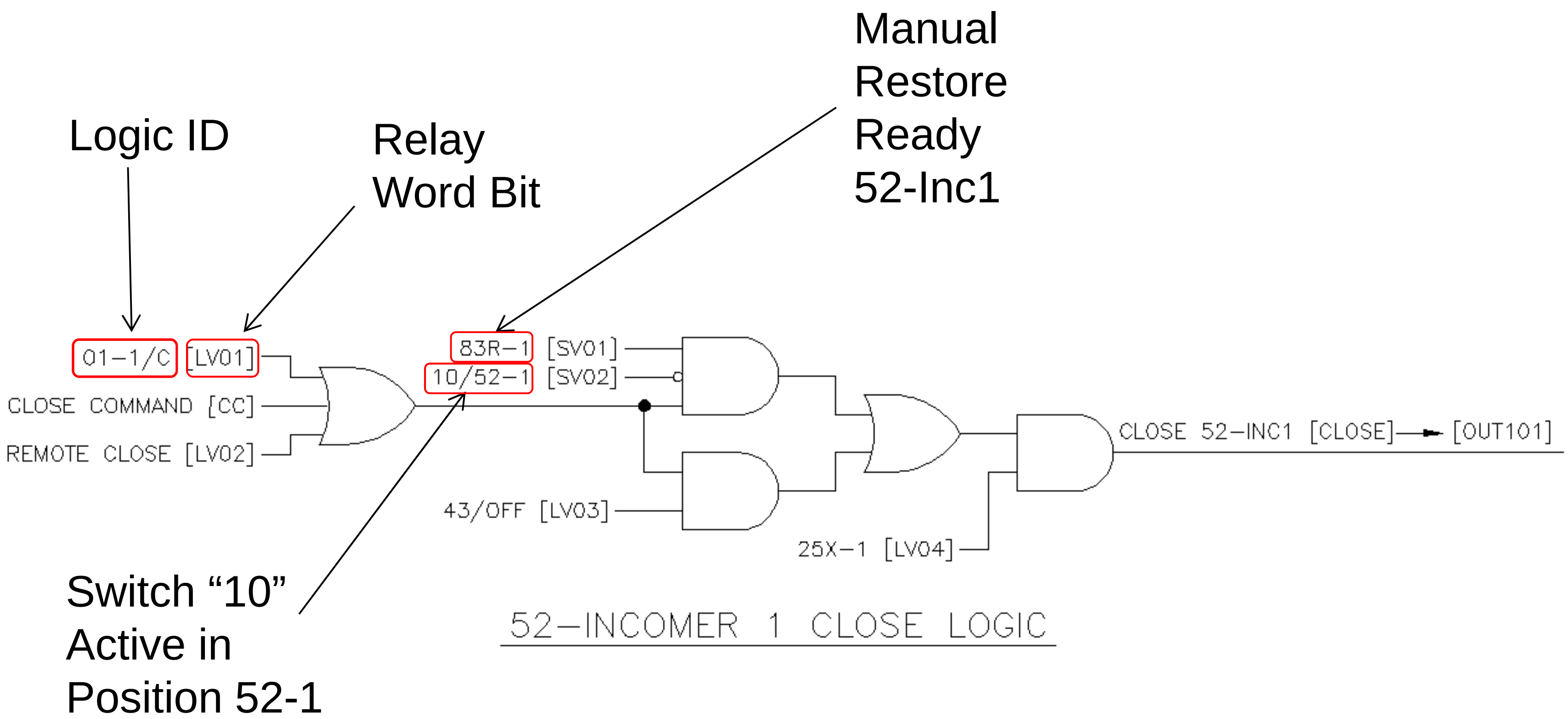
Supplemental Topics

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

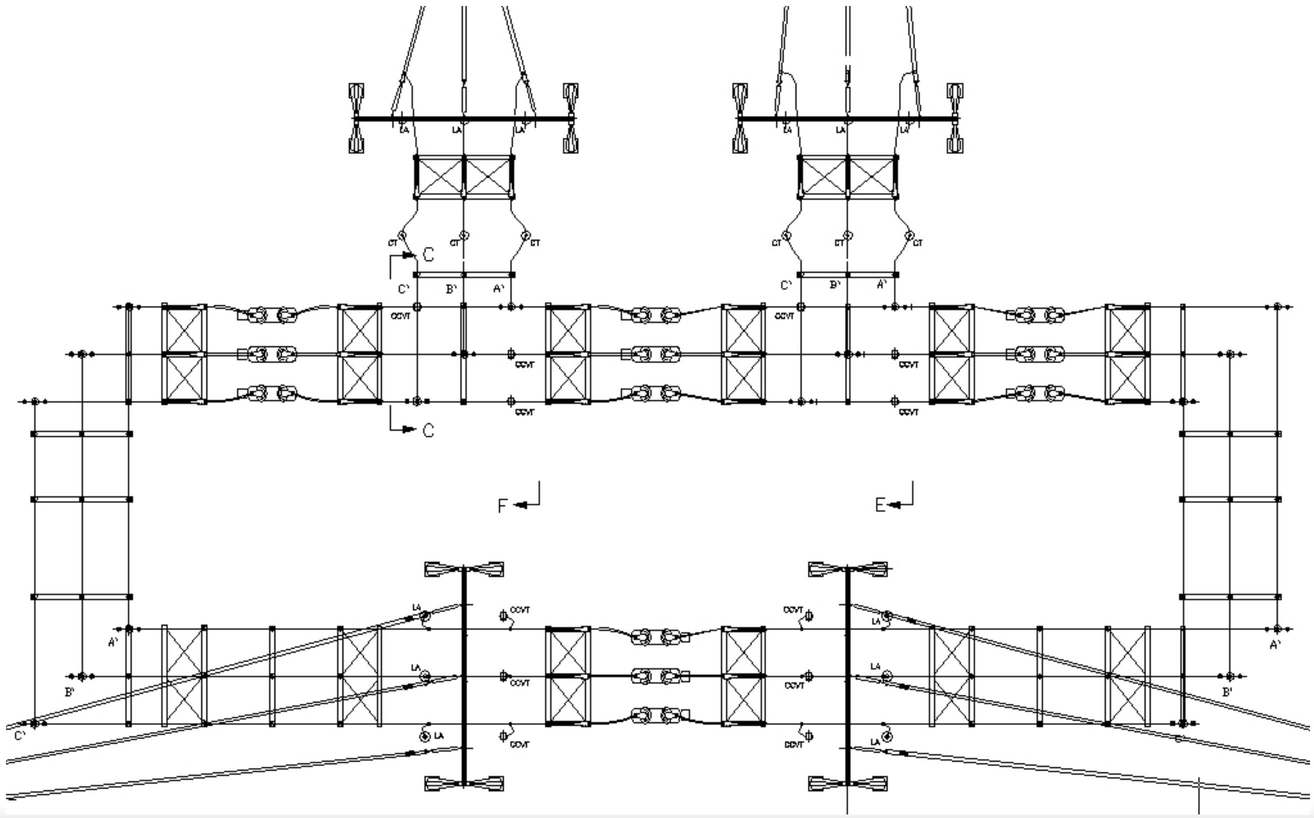


Future Expansion Possibilities

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

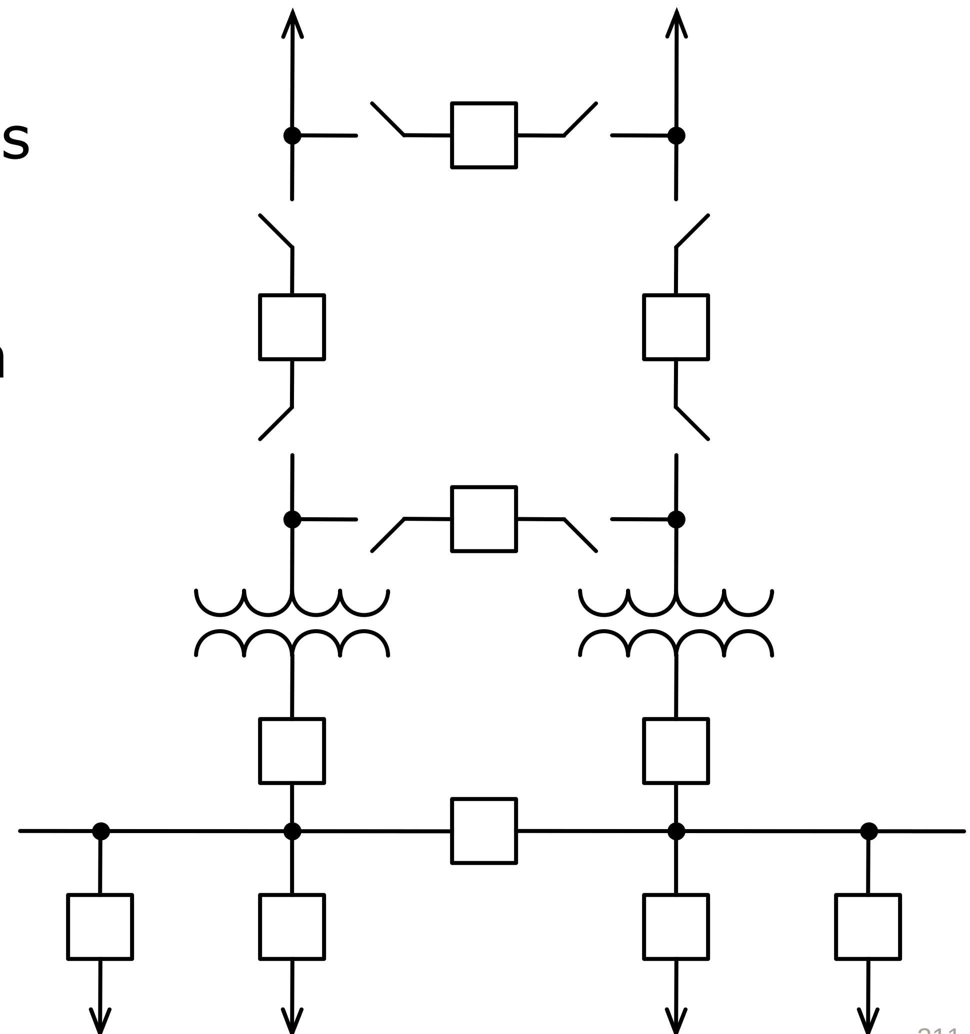
Future Expansion Possibilities

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



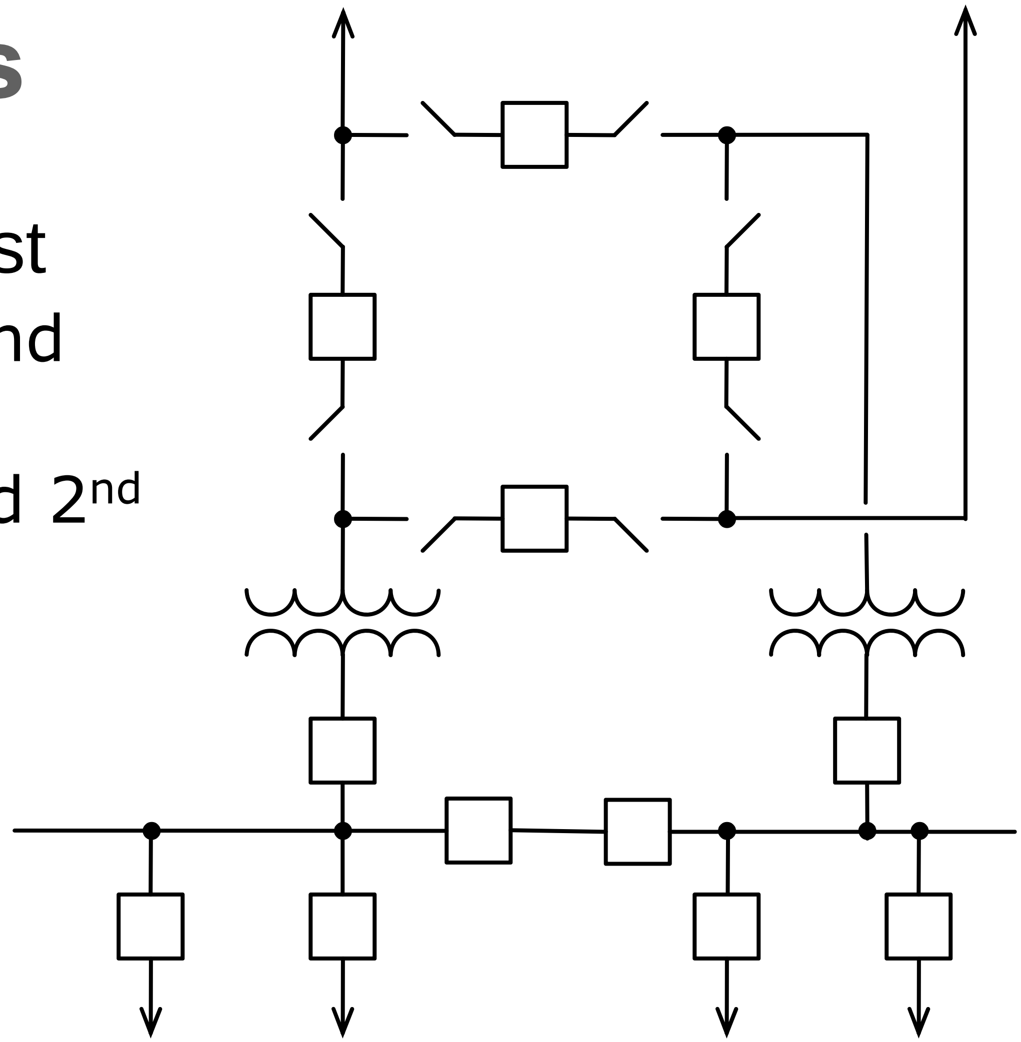
Mixing Bus Arrangements

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



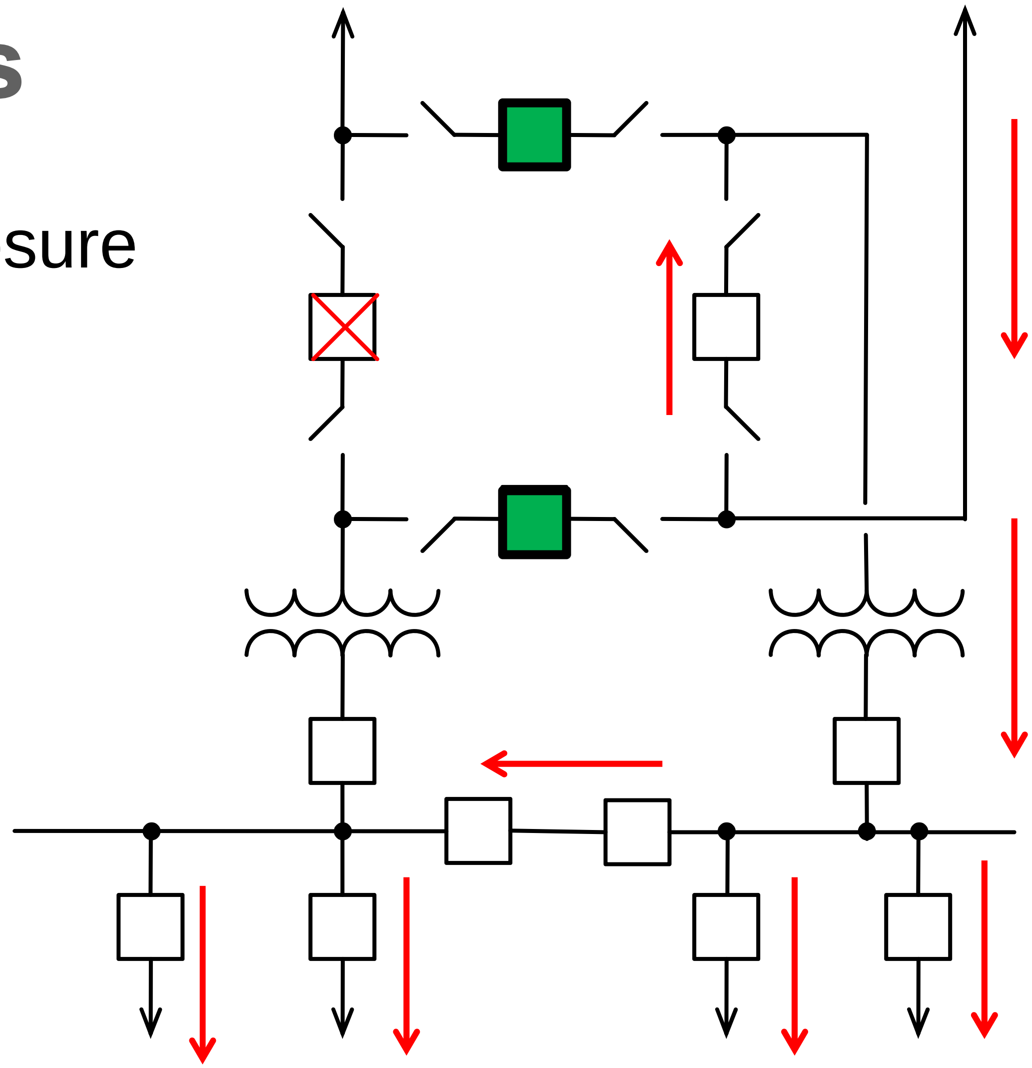
Variations

- Variations Exist
  - Swap Line and Transformer
  - Positions Add 2nd Tie Breaker



Variations

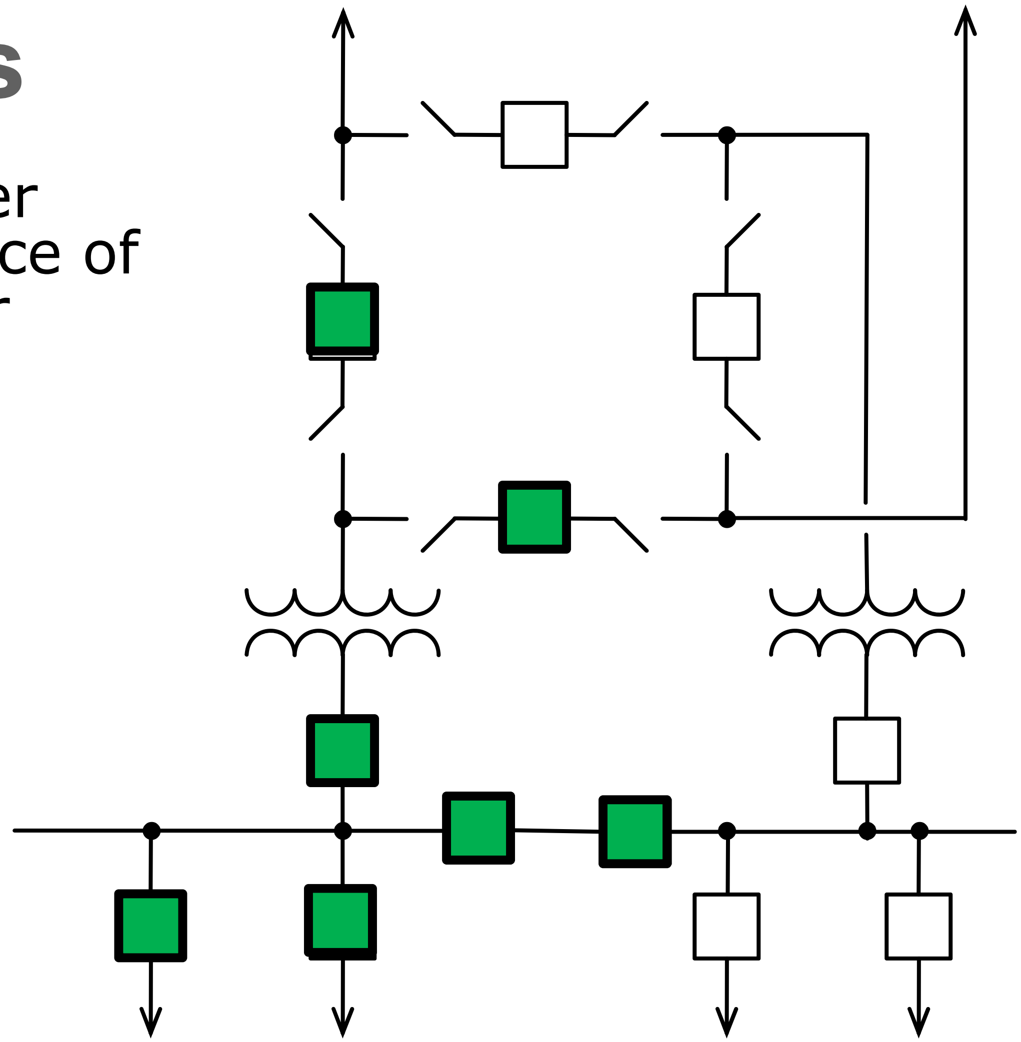
- Decrease exposure during breaker failure event



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

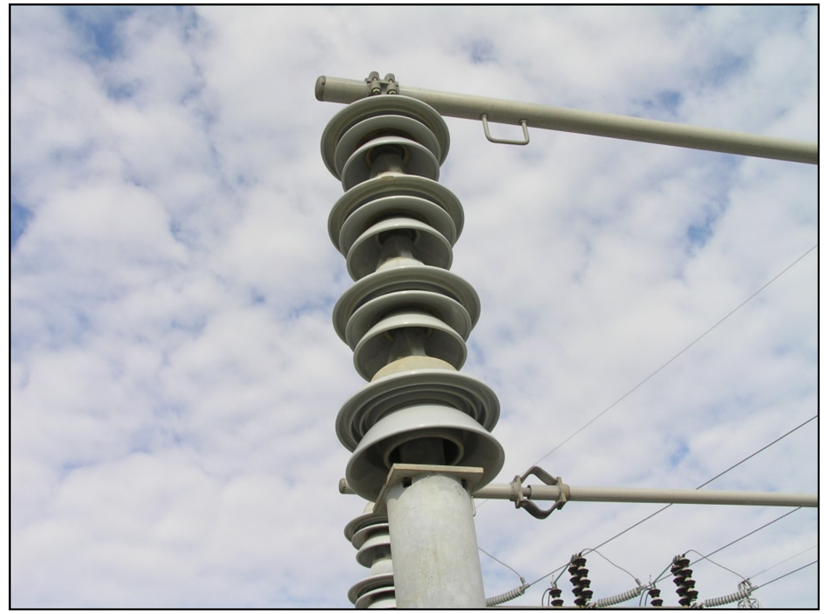
Post Insulators

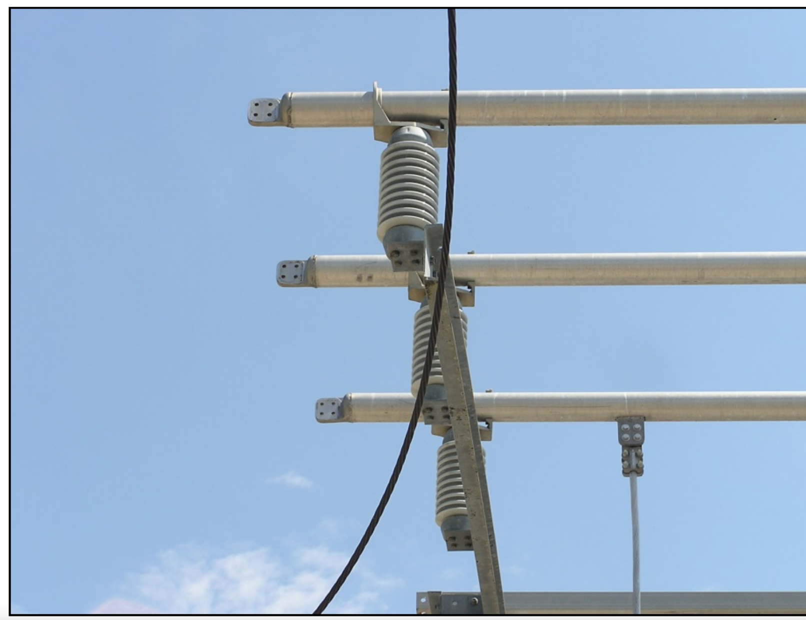
Bulletin 1724E-300
Page 150

Table 4-5: Typical Characteristics of Post-Type Insulators. Ref. ANSI Std. C29.9-1983, Tables 1 and 2. Reproduced with permission of the National Electrical Manufacturers Association.

BIL (IMPULSE WITHSTAND)	TECHNICAL REFERENCE	UPRIGHT CANTILEVER STRENGTH		UNDERHUNG CANTILEVER STRENGTH		BOLT CIRCLE				HEIGHT		LEAKAGE DISTANCE	
						TOP		BOTTOM					
kV	NUMBER	POUNDS	(NEWTONS)	POUNDS	(NEWTONS)	IN.	(CM)	IN.	(CM)	IN.	(CM)	IN.	(CM)
95	202	2000	(8896)	2000	(8896)	3	(7.62)	3	(7.62)	7.5	(19.1)	10.5	(26.7)
95	202	4000	(17792)	4000	(17792)	5	(12.7)	5	(12.7)	7.5	(19.1)	10.5	(26.7)
110	205	2000	(8896)	2000	(8896)	3	(7.62)	3	(7.62)	10	(25.4)	15.5	(39.4)
110	225	4000	(17792)	4000	(17792)	5	(12.7)	5	(12.7)	12	(30.5)	15.5	(39.4)
150	208	2000	(8896)	2000	(8896)	3	(7.62)	3	(7.62)	14	(35.6)	24	(61.0)
150	227	4000	(17792)	4000	(17792)	5	(12.7)	5	(12.7)	15	(38.1)	24	(61.0)
200	210	2000	(8896)	2000	(8896)	3	(7.62)	3	(7.62)	18	(45.7)	37	(94)
200	231	4000	(17792)	4000	(17792)	5	(12.7)	5	(12.7)	20	(50.8)	37	(94)
250	214	2000	(8896)	2000	(8896)	3	(7.62)	3	(7.62)	22	(55.9)	43	(109)
250	267	4000	(17792)	4000	(17792)	5	(12.7)	5	(12.7)	24	(61.0)	43	(109)
350	216	1500	(6672)	1500	(6672)	3	(7.62)	3	(7.62)	30	(76.2)	72	(183)
350	278	3000	(13344)	3000	(13344)	5	(12.7)	5	(12.7)	30	(76.2)	72	(183)
550	286	1700	(7562)	1700	(7562)	5	(12.7)	5	(12.7)	45	(114)	99	(251)
550	287	2600	(11564)	2600	(11564)	5	(12.7)	5	(12.7)	45	(114)	99	(251)
650	288	1400	(6227)	1400	(6227)	5	(12.7)	5	(12.7)	54	(137)	116	(295)
650	289	2200	(9786)	2200	(9786)	5	(12.7)	5	(12.7)	54	(137)	116	(295)
750	291	1200	(5338)	1200	(5338)	5	(12.7)	5	(12.7)	62	(157)	132	(335)
750	295	1850	(8229)	1850	(8229)	5	(12.7)	5	(12.7)	62	(157)	132	(335)
900	304	950	(4226)	950	(4226)	5	(12.7)	5	(12.7)	80	(203)	165	(419)
900	308	1450	(6450)	1450	(6450)	5	(12.7)	5	(12.7)	80	(203)	165	(419)
1050	312	800	(3558)	800	(3558)	5	(12.7)	5	(12.7)	92	(234)	198	(503)
1050	316	1250	(5560)	1250	(5560)	5	(12.7)	5	(12.7)	92	(234)	198	(503)
1050	362	2300	(10230)	2300	(10230)	7	(17.8)	7	(17.8)	92	(234)	198	(503)
1300	324	1000	(4448)	1000	(4448)	5	(12.7)	5	(12.7)	106	(269)	231	(587)
1300	367	1450	(6450)	1450	(6450)	5	(12.7)	7	(17.8)	106	(269)	231	(587)
1300	368	2000	(8896)	2000	(8896)	7	(17.8)	7	(17.8)	106	(269)	231	(587)
1300	369	2050	(9118)	2050	(9118)	5	(12.7)	7	(17.8)	106	(269)	231	(587)

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

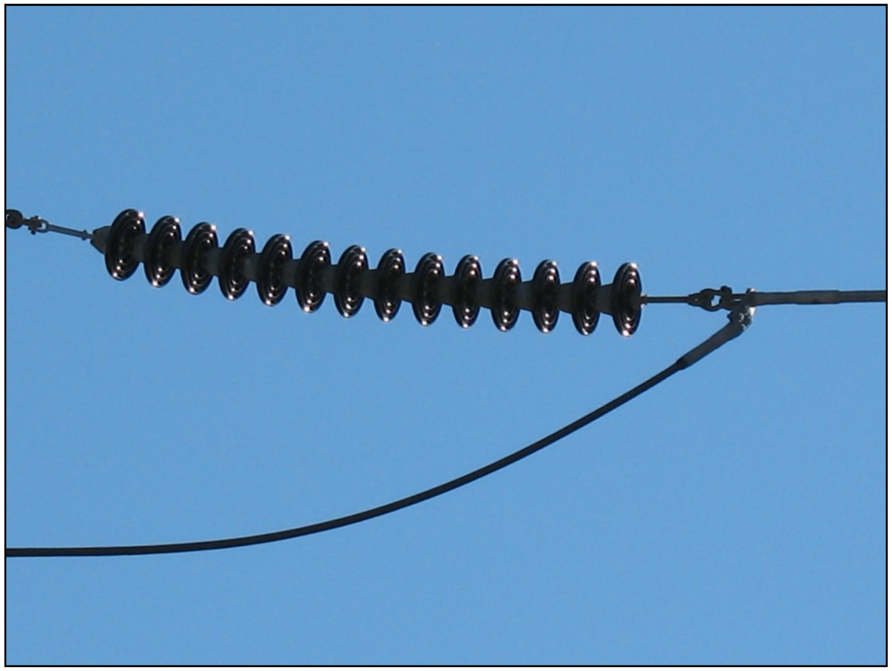
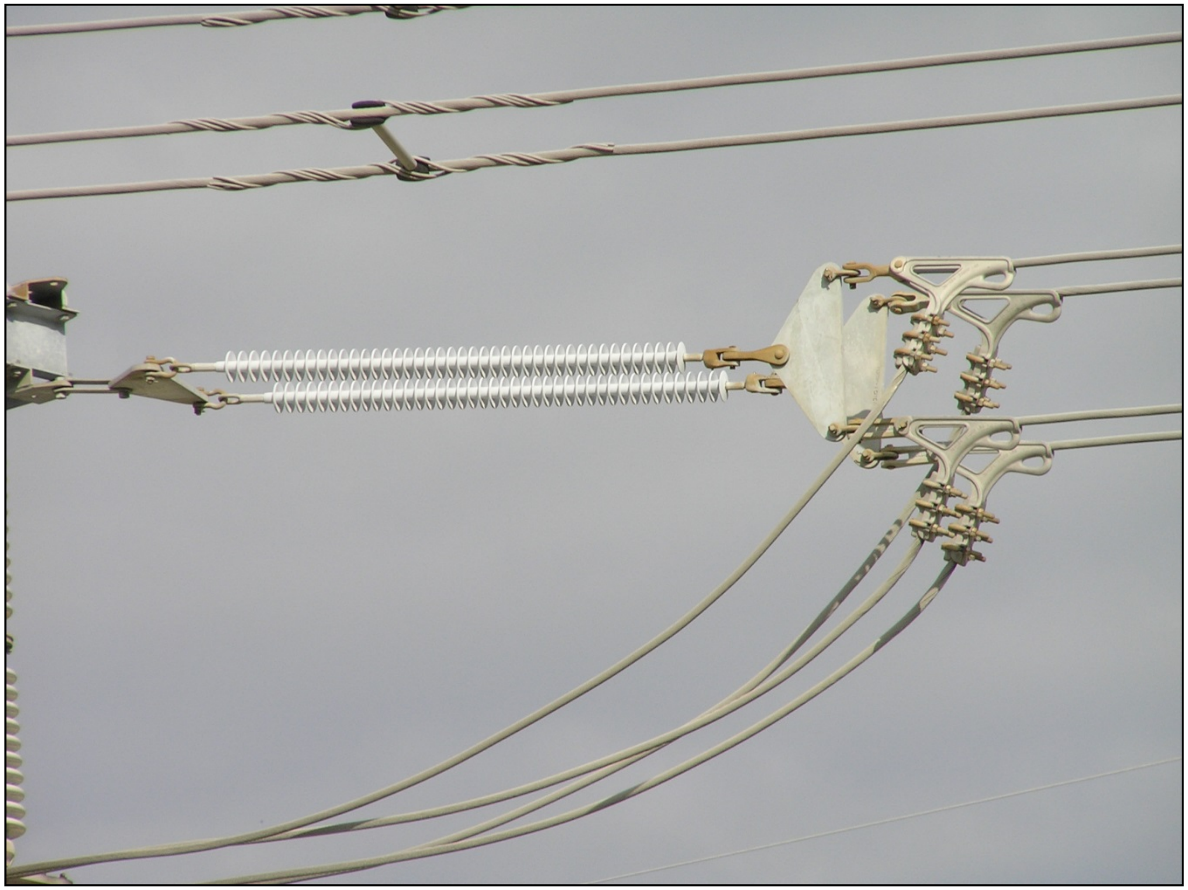


Table 4-6: Minimum Quantity of Suspension Insulators

Nominal System Phase-to-Phase Voltage kV	BIL kV	Minimum Quantity of Suspension Insulators*
7.5	95	1
14.4	110	2
23	150	2
34.5	200	3
46	250	4
69	350	5
115	550	8
138	650	9
161	750	10
230	900	12
230	1050	14
345	1300	20

*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 ← typically controls
- 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
- IEEE 605 – IEEE Guide for Design of Substation Rigid-Bus Structures

Structural Requirements

Deflection

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

Description	Deflection Limit
Class A Structures	
Horizontal Deflection of Vertical Members	$\ell/100$
Vertical Deflection of Horizontal Memebers	$\ell/200$
Horizontal Deflection of Horizontal Members	$\ell/200$

Structural Design

Deflection

Class B: Those Sturctures 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.)

Description	Deflection Limit
Class B Structures	
Horizontal Deflection of Vertical Members	$\ell/50$
Vertical Deflection of Horizontal Memebers	$\ell/200$
Horizontal Deflection of Horizontal Members	$\ell/100$

Structural Design

- Bus Supports
  - Short-Circuit Forces
  - Wind Loading
  - Ice Loading
  - Seismic Forces

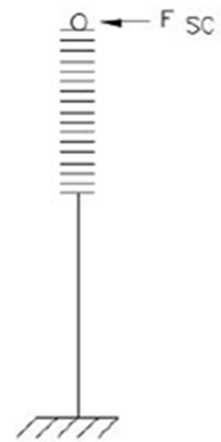
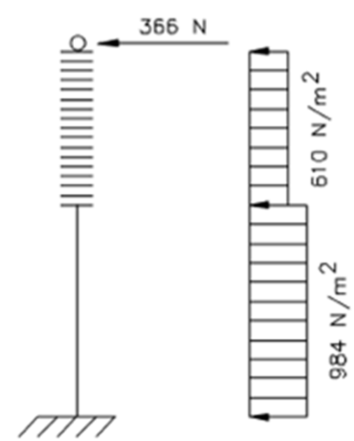


Figure 7-2: Tubular Structure—Short-Circuit Loading



Structural Design

Short-Circuit Forces

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

where

μ	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 ⊗ is the vectorial cross product.

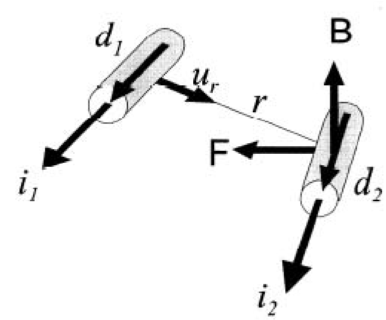


Figure 19 —Illustration of two conductor segments carrying electric current

Structural Design

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:

$$F_{sc} = \frac{16\Gamma I_{sc}^{2}}{10^{7} D} \tag{14}$$

For English units:

$$F_{sc} = \frac{3.6\Gamma I_{sc}^{2}}{10^{7} D} \tag{15}$$

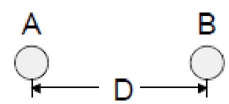
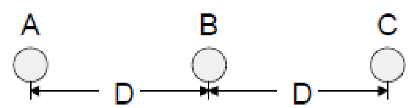
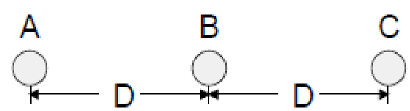
where

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

Structural Design

Short-Circuit Forces

Table 13—Γ constant for simplified calculation short circuit basic force equation

Type of short circuit	Configuration	Conductor	Γ
Phase to phase		A or B	1.000
Three phase		B	0.866
Three phase		A or C	0.808
Phase to phase	Triangular arrangement—equilateral triangle—side D	A or B	1.0
Three phase	Triangular arrangement—equilateral triangle—side D	A or B or C	0.5

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.

Structural Design

Short-Circuit Forces

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

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

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

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

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

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

Structural Design

Short-Circuit Forces

$$\boxed{F_{sc\_corrected} = D_f^2 K_f F_{sc}} \tag{16}$$

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

60 Hz				50 Hz			
X/R	T_a	D_f	D_f^2	X/R	T_a	D_f	D_f^2
30	0.0796	0.950	0.903	30	0.0955	0.950	0.903
20	0.0531	0.927	0.860	20	0.0637	0.927	0.860
10	0.0265	0.865	0.749	10	0.0318	0.865	0.749
5	0.0133	0.767	0.588	5	0.0159	0.767	0.588
2	0.0053	0.604	0.365	2	0.0064	0.604	0.365
1	0.0027	0.522	0.272	1	0.0032	0.522	0.272

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

— Most conductor spans will not reach maximum deflection until after the first quarter-cycle.

— Additional current decrement occurs as the fault continues, especially for low X/R ratios.

Short-Circuit Forces

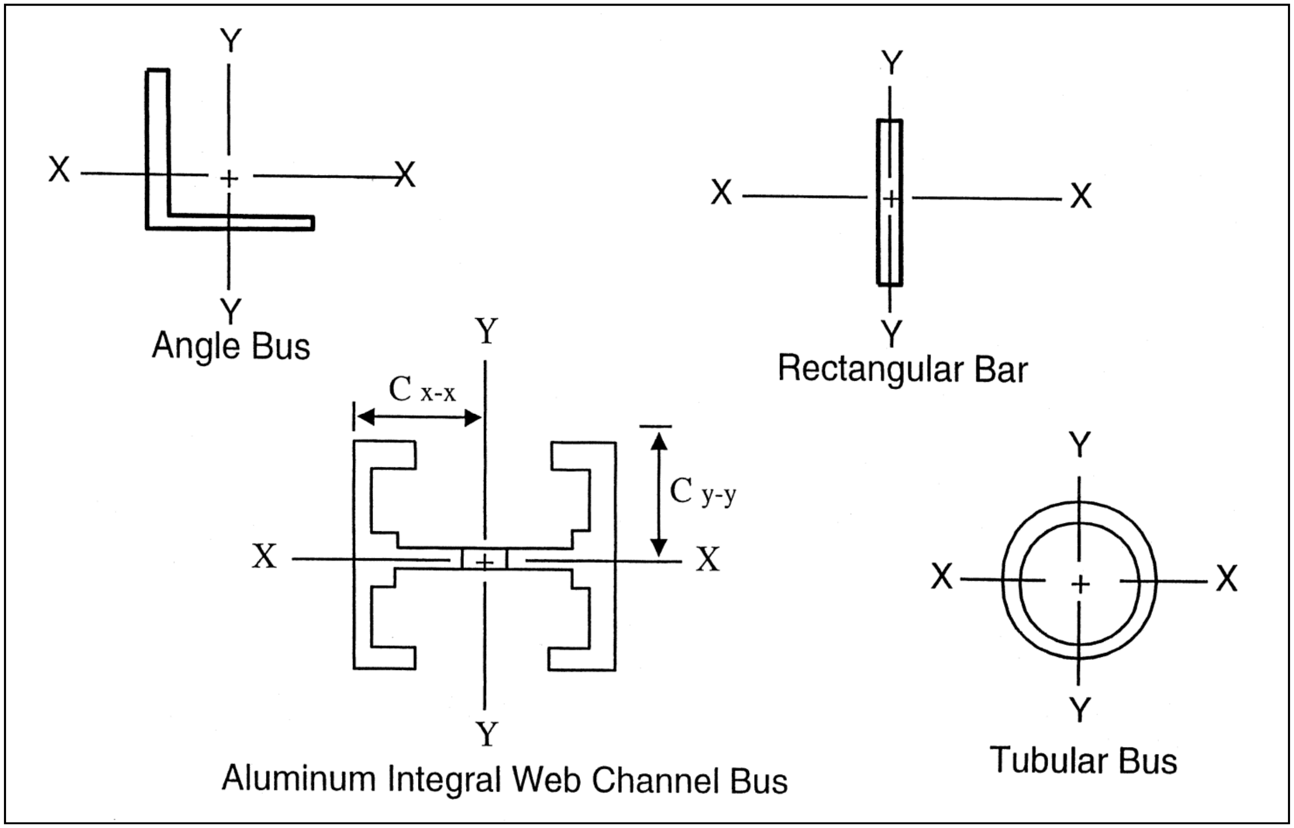
Because of their flexibility, the bus and mounting structures are capable of absorbing energy during a fault. Thus, depending on the type of mounting structures and their heights, the effective fault current forces will be lower than the half-cycle maximum value. The effect of the structure flexibility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

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

NOTE—A, lattice and tubular aluminum; B, tubular and wide-flange steel and wood pole; C, lattice steel; D, solid concrete.

Structural Design

Rigid Bus Shapes



Source: Aluminum Electrical
Conductor Handbook

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

Current Ratings

Rigid Aluminum Tube Bus

Frequency = 60 Hertz

*2 FPS Crosswind, Emissivity = 0.5
**Still, But Unconfined Air, Emissivity = 0.35

6063-T6 Alloy

Size in.	OD in.	ID in.	Weight lb/ft	Ampacity – Outdoor* – Temp Rise Above 40 C – 30 C	40 C	50 C	Ampacity – Indoor** – Temp Rise Above 40 C – 30 C	40 C	50 C
Schedule 40									
1/2	0.84	0.622	0.294	416	493	562	292	346	394
3/4	1.05	0.824	0.391	517	612	698	369	437	498
1	1.315	1.049	0.581	681	807	920	493	584	666
1-1/2	1.90	1.610	0.940	984	1,165	1,329	731	866	987
2	2.375	2.067	1.264	1,234	1,462	1,667	930	1,101	1,256
2-1/2	2.875	2.469	2.004	1,663	1,970	2,246	1,267	1,501	1,711
3	3.50	3.068	2.621	2,040	2,416	2,755	1,573	1,863	2,124
3-1/2	4.00	3.548	3.151	2,347	2,780	3,170	1,824	2,160	2,463
4	4.50	4.026	3.733	2,664	3,155	3,598	2,085	2,469	2,816
4-1/2	5.001	4.507	4.337	2,984	3,534	4,030	2,349	2,782	3,172
5	5.563	5.047	5.057	3,348	3,965	4,521	2,652	3,141	3,582
6	6.625	6.065	6.564	4,064	4,813	5,488	3,249	3,848	4,388
Schedule 80									
1/2	0.84	0.546	0.376	470	567	635	330	391	446
3/4	1.05	0.742	0.510	590	699	797	421	499	569
1	1.315	0.957	0.751	774	917	1,045	561	664	758
1-1/2	1.90	1.50	1.256	1,137	1,347	1,536	844	1,000	1,140
2	2.375	1.939	1.737	1,446	1,713	1,953	1,089	1,290	1,471
2-1/2	2.875	2.323	2.650	1,907	2,259	2,575	1,454	1,722	1,964
3	3.50	2.90	3.547	2,363	2,799	3,191	1,823	2,159	2,462
3-1/2	4.00	3.364	4.326	2,735	3,239	2,694	2,127	2,519	2,873
4	4.50	3.826	5.183	3,118	3,693	4,211	2,441	2,891	3,297
4-1/2	5.001	4.291	6.092	3,505	4,151	4,734	2,762	3,271	3,730
5	5.563	4.183	7.188	3,949	4,677	5,333	3,130	3,707	4,227
6	6.625	5.761	9.884	4,891	5,793	6,605	3,916	4,638	5,289

Note that these tabulations are based on specified conditions.

Rigid Aluminum Tube Bus

Outdoor Substation Conductor Ratings

Transmission and Substation Design Committee
Substation Conductor Rating Task Force

PJM Interconnection, LLC

December 16, 2004 – Revision 1

PJM Substation Conductor Rating Task Force:

Baltimore Gas & Electric	Robert W. Munley (Chairman)
Allegheny Power	Joseph F. Leighty
Conectiv	William M. Ruggeri
FirstEnergy	Alan E. Kollar
PECO Energy	Bernie O'Hara
PECO Energy	Harry E. Hackman
Potomac Electric Power	Chih C. Chow
PPL Electric Utilities	Alan L. Tope
Public Service Electric & Gas	John Hearon

Great Resource

Rigid Aluminum Tube Bus

Bus Conductor: **6" Alum, Sched 40, 6063 Alloy**

		Assumed Wind Speed = 2 fps											
		Ambient Temperature (°C)											
Rating	Rated Operating Temperature	-15	-10	-5	0	5	10	15	20	25	30	35	40
	60	5599	5382	5154	4912	4655	4380	4083	3759	3399	2991	2511	1904
	70	6000	5804	5600	5385	5159	4921	4667	4395	4101	3781	3425	3023
	80	6367	6188	6003	5810	5608	5396	5172	4936	4684	4415	4125	3807
Normal	**90**	**6707**	**6544**	**6374**	**6198**	**6014**	**5823**	**5623**	**5413**	**5192**	**4957**	**4708**	**4441**
	100	7027	6876	6719	6557	6389	6215	6033	5843	5645	5437	5217	4984
	110	7330	7189	7043	6893	6738	6578	6412	6239	6058	5870	5673	5466
Emergency (<24 hrs)	**115**	**7476**	**7339**	**7199**	**7055**	**6905**	**6751**	**6591**	**6425**	**6253**	**6073**	**5886**	**5689**
	120	7618	7487	7351	7211	7068	6919	6765	6606	6441	6269	6090	5903
Emergency (< 1 hr)	**130**	**7895**	**7772**	**7645**	**7514**	**7380**	**7242**	**7099**	**6952**	**6799**	**6641**	**6477**	**6306**
	140	8163	8046	7927	7805	7679	7550	7416	7279	7137	6991	6839	6682
	150	8422	8312	8200	8085	7966	7845	7720	7592	7459	7323	7182	7036
							WINTER					SUMMER	

Weather Assumptions:

Emissivity =	0.5	
Absorptivity =	0.5	
Atmosphere =	Clear	
Azimuth of Conductor (N-S = 0, E-W = 90) =	90	
Suntime =	14	
Degrees North Latitude=	40	
Elevation Above Sea Level=	1000	
Z_1 (Angle between wind and conductor)	90	

Conductor : 6" Alum, Sched 40, 6063 Alloy

T_{low} =	20	°C
R_{low} =	2.8E-06	ohms/ft
Outside Diameter =	6.625	inches
T_{high} =	70	°C
R_{high} =	3.3E-06	ohms/ft

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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.

Voltage [kV]	Wire	Tubing [inches]
15	#2 AWG	½
34.5	#1/0 AWG	½
69	#1/0 AWG	½
115	#4/0 AWG	½
230	750 kcmil	1 ½
345	-	2
500	-	4

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 2-1
RUS Recommended Minimum Conductor Sizes(1)

kV_{LL}	ACSR	AAAC-6201
34.5	1/0	123.3 kcmil
46	2/0	155.4 kcmil
69	3/0	195.7 kcmil
115	266.8 kcmil	312.8 kcmil
138	336.4 kcmil	394.5 kcmil
161	397.5 kcmil	465.4 kcmil
230	795 kcmil	927.2 kcmil

(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

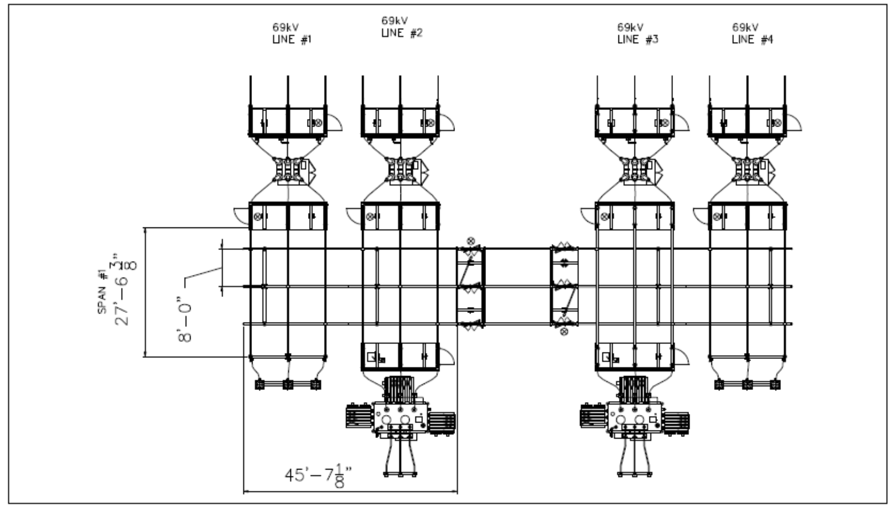

Figure H.1—General bus layout

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

a) Determine bus conductor size required for both maximum normal load and short circuit current (Clause 8 and Annex C).

b) Determine maximum corona on the bus and equipment (Clause 9 and Annex D).

c) Determine maximum forces on the structures (Clause 11).

d) Determine maximum span length of the bus based on vertical deflection limit and fiber stress (12.1 and 12.2).

e) Determine maximum required insulator rating (12.3 and 12.4).

f) Determine thermal expansion requirements (11.4).

g) Determine bus vibration and damping requirements (12.5, 12.6, and 12.7).

Bus Design

Appendix

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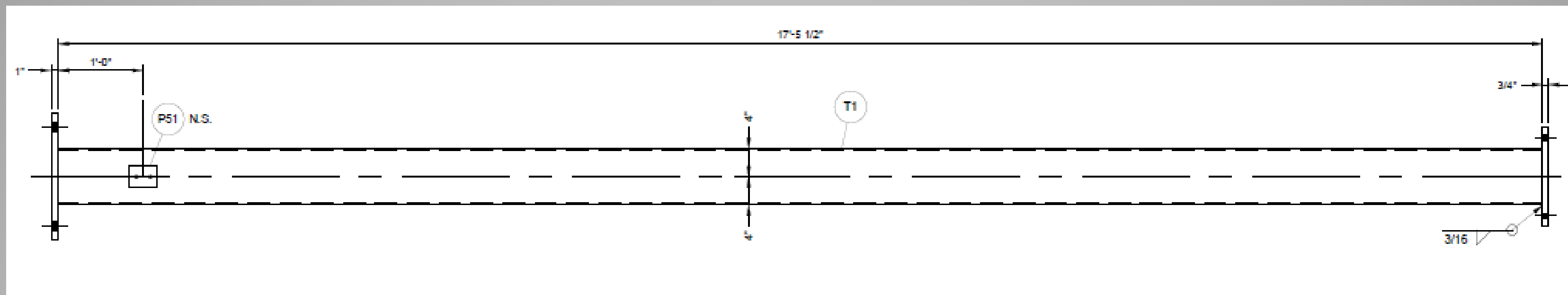
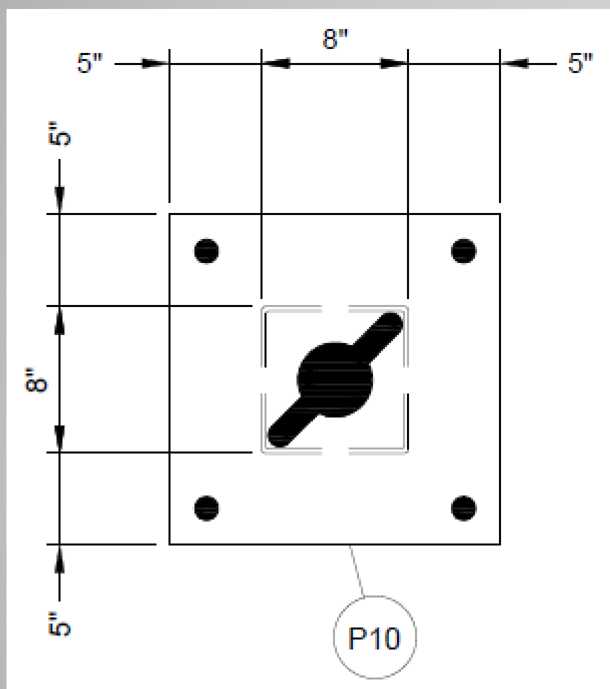
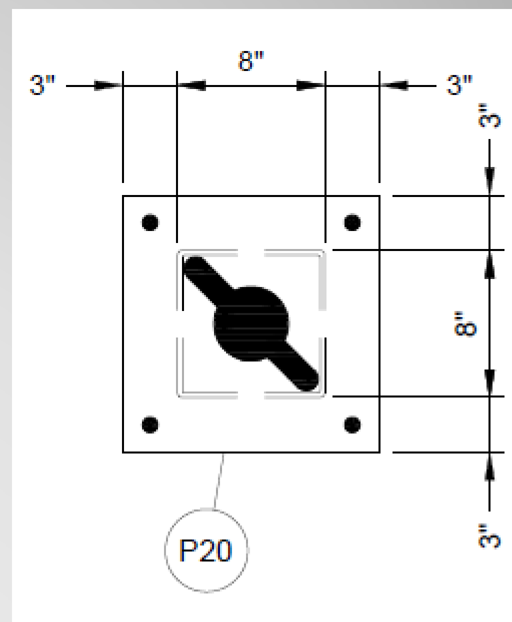
Example of low profile substation using lattice structures

Sh. 245

Example of conventional design







Typical detail of tube bus support

Sh. 247

Grout makes the installation look pretty, but the consequence is that the water has no where to drain.

Typical detail of tube bus support

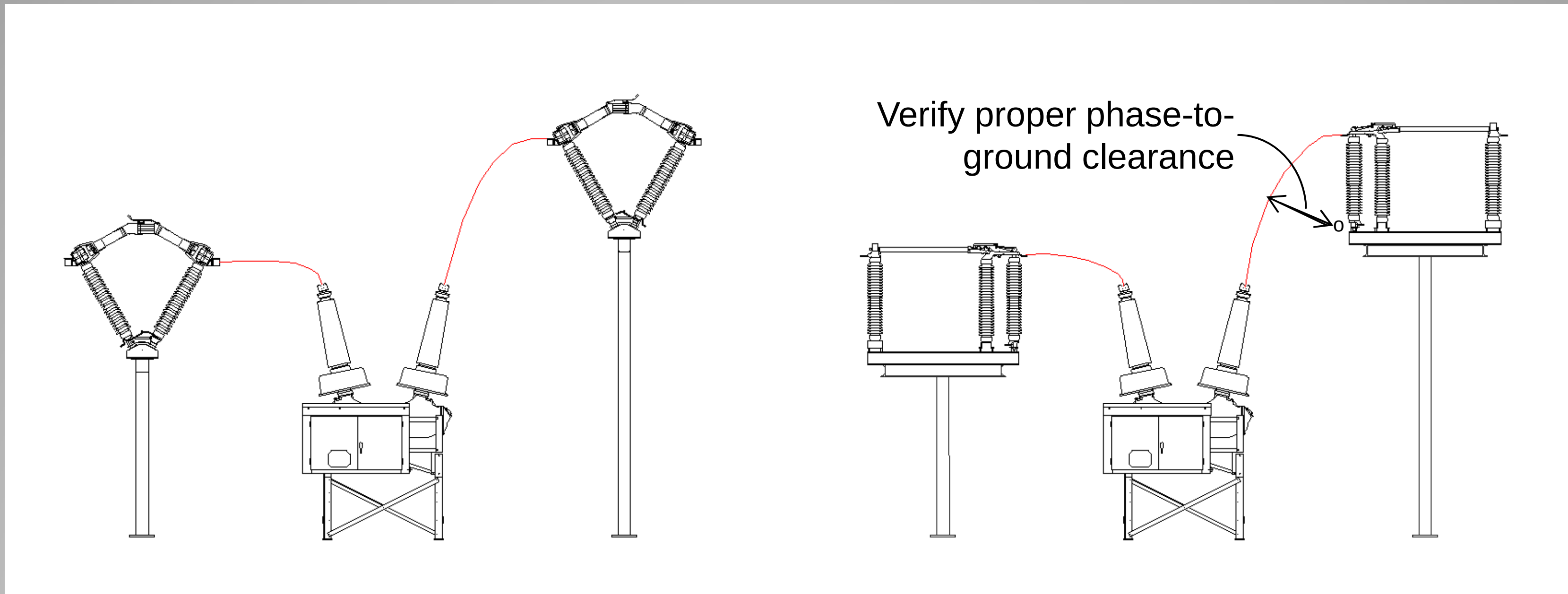
Base plates with grout

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

Sh. 251

ANSI C37.32-1996

Table 15— Preferred rated switching currents for interrupter switches*

Line Number	Rated maximum voltage kV rms (1)	Load and loop current amps (2)	Unloaded Transformer current amps (3)	Line-charging current: Quick-break amps‡ (4)	Line-charging current: Interrupter amps** (5)	Isolated Capacitor bank current amps † (6)	Cable-charging current amps (7)
1	8.25	RCC 2)	See Note 2	10	10	400	10
2	15.0, 15.5	RCC 2)	See Note 2	10	10	400	15
3	25.8, 27.0	RCC 2)	See Note 2	10	10	400	20
4	38.0	RCC 2)	See Note 2	10	10	250	20
5	48.3	RCC 2)	10	10	10	250	50
6	72.5	RCC 2)	10	13	15	630	80
7	121.0	RCC 2)	10	10	35	315	90
8	145.0	RCC 2)	8	8	50	315	100
9	169.0	RCC 2)	8	7	75	400	100
10	242.0	RCC 2)	8	5	150	400	115
11	362.0	RCC 2)	5	-	350	-	-

NOTES:
1 — RCC = rated continuous current from tables 3, 9 or 12 ie., 200, 400, 600, 1200, 1600, 2000, 3000, 4000, 5000 and 6000 amps.
2 — These switches are capable of switching unloaded transformers rated 2500 kVA or less provided the switches have demonstrated their ability to switch their rated load current. For larger transformers or switches not having load switching ratings, consult manufacturer.

*Interrupter switches may have one or more specifically assigned switching ratings. Refer to Annex A for typical system values.
†Values given are for station class switches. Preferred ratings for distribution class switches have not been established. Consult manufacturer.
‡These devices are typically high-velocity whips 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

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

Thank You!

Questions?

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