Substation Equipment Application Considerations

HV

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IEEE Houston Section

IEEE

Introduction

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

Where Do I Start My Design?

Questions to Address

- Service Conditions?
  - Location, Altitude, High and Low Mean Temperatures, Temperature Extremes, Wind Loading, Ice Loading, Seismic Qualifications, Area Classification, Contamination
- Primary System Characteristics?
  - Local Utility, Nominal Voltage, Maximum Operating Voltage, System Frequency, System Grounding, System Impedance Data
- Secondary System Characteristics?
  - Nominal Voltage, Maximum Operating Voltage, System Grounding
- Facility Load/Generation Characteristics?
  - Load Type, Average Running Load, Maximum Running Load, On-Site Generation, Future Load Growth, Harmonic Loads

Questions to Address

- Substation Layout Considerations?
  - Available Real Estate, Substation Configuration, Necessary Degree of Reliability and Redundancy, Number of Incoming Lines, Proximity to Transmission Lines and Loads
- Utility Requirements?
  - Application of Utility Specifications, Application of Utility Standards, Application of Utility Protection and Control Schemes, SCADA/RTU Interface, Metering Requirements
- Insulation Requirements?
  - BIL, Insulator Creep, Bushing Creep, Minimum Clearances, Phase Spacing, Arrester Duty

Questions to Address

- Current Requirements?
  - Rated Continuous Current, Maximum 3-Phase Short-Circuit Current, Maximum Phase-to-Ground Short-Circuit Current
- Substation Monitoring?
  - Manned or Unmanned, Power Management/Trending, Fault Recording, Local & Remote Annunciation, Local & Remote Control
- Geotech Conditions?
  - Soil Boring Results, Soil Resistivity, SPCC (spill prevention) Plans, SWPPP (storm water) Plan
- Electrical Studies?
  - Power Flow, Short-Circuit, Device Evaluation, Device Coordination, Arc-Flash Hazard Assessment, Motor Starting, Transient Stability, Insulation Coordination, Harmonic Analysis

Major Factors in Substation Selection

- Required Power (1 MVA, 10 MVA, 100 MVA)
- Budgeted Capital for Substation
- Effect of Power Loss on Process and/or Safety
- Associated Outage Cost (Lost Revenue)
- Future Growth Considerations
- Reliability Study
  - Estimate Cost of Alternate Designs
  - Determine Lost Revenue During Outages
  - Calculate Probability of Outage Based on Design
  - Compare Cost, Lost Revenues, and Outage Probabilities

Electrical Configuration

Electrical Configuration

- Single Breaker Arrangements
  - Tap Substation
  - Single Breaker Single Bus
  - Operating/Transfer Bus
- Multiple Breaker Arrangements
  - Ring Bus
  - Breaker and a Half
  - Double Breaker Double Bus

Electrical Configuration

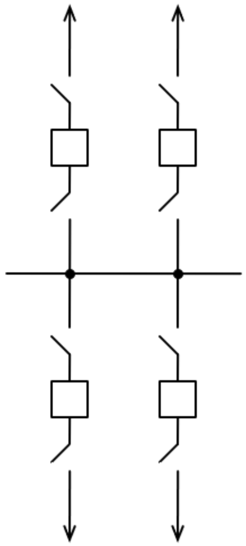
Configuration	Relative Cost Comparison
Single Breaker-Single Bus	100%
Ring Bus	125%
Breaker and Half	145%
Double Breaker-Double Bus	190%

Reference: IEEE 605-2008

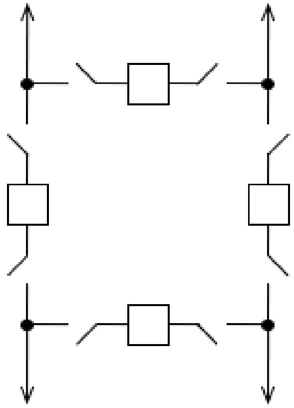
It should be noted that these figures are estimated for discussion purposes. Actual costs vary depending on a number of variables, including:

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

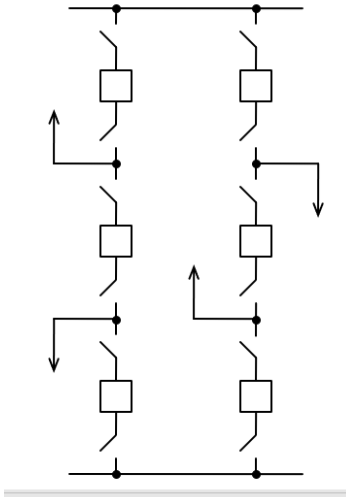
Electrical Configurations



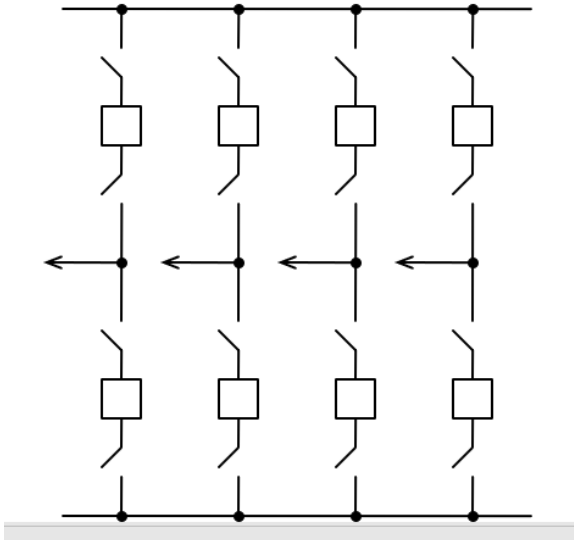
Single Breaker /Single Bus



Ring Bus



Breaker and a Half



Double Breaker / Double Bus

Electrical Configuration

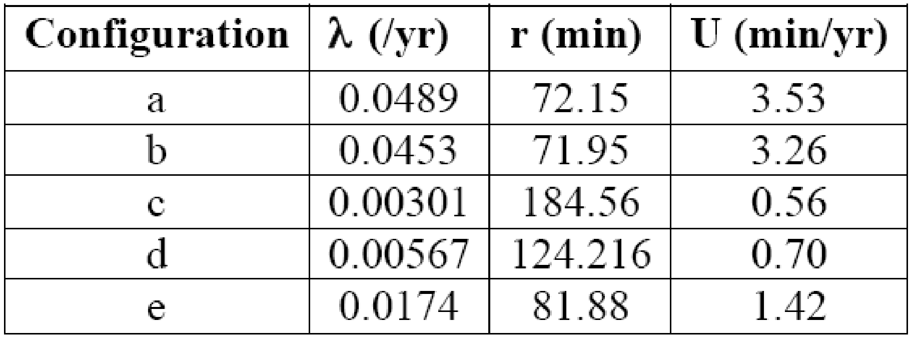
λ = Annual Fail Rate

r = Annual Outage Time

U = Average Outage Time

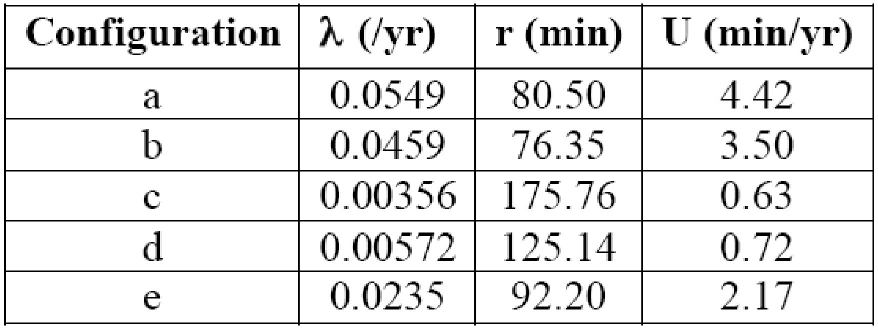
a. Single bus
b. Sectionalized single bus
c. Breaker-and-a-half
d. Double breaker-double bus
e. Ring bus

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

Table 4: Substation Reliability Indices (Including Line Failures)



Configuration	λ (/yr)	r (min)	U (min/yr)
a	0.0549	80.50	4.42
b	0.0459	76.35	3.50
c	0.00356	175.76	0.63
d	0.00572	125.14	0.72
e	0.0235	92.20	2.17

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

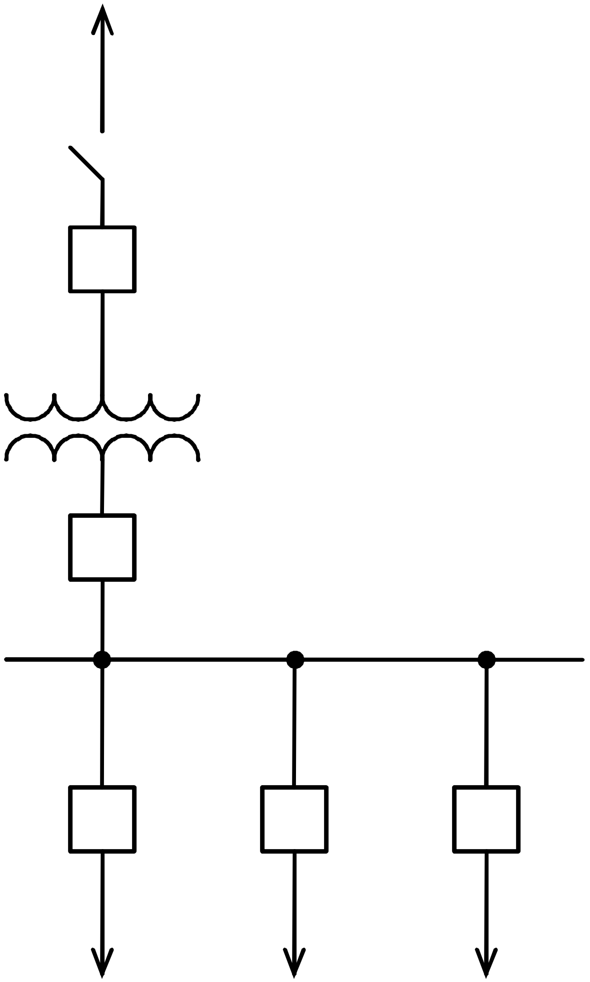
Reliability Models

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

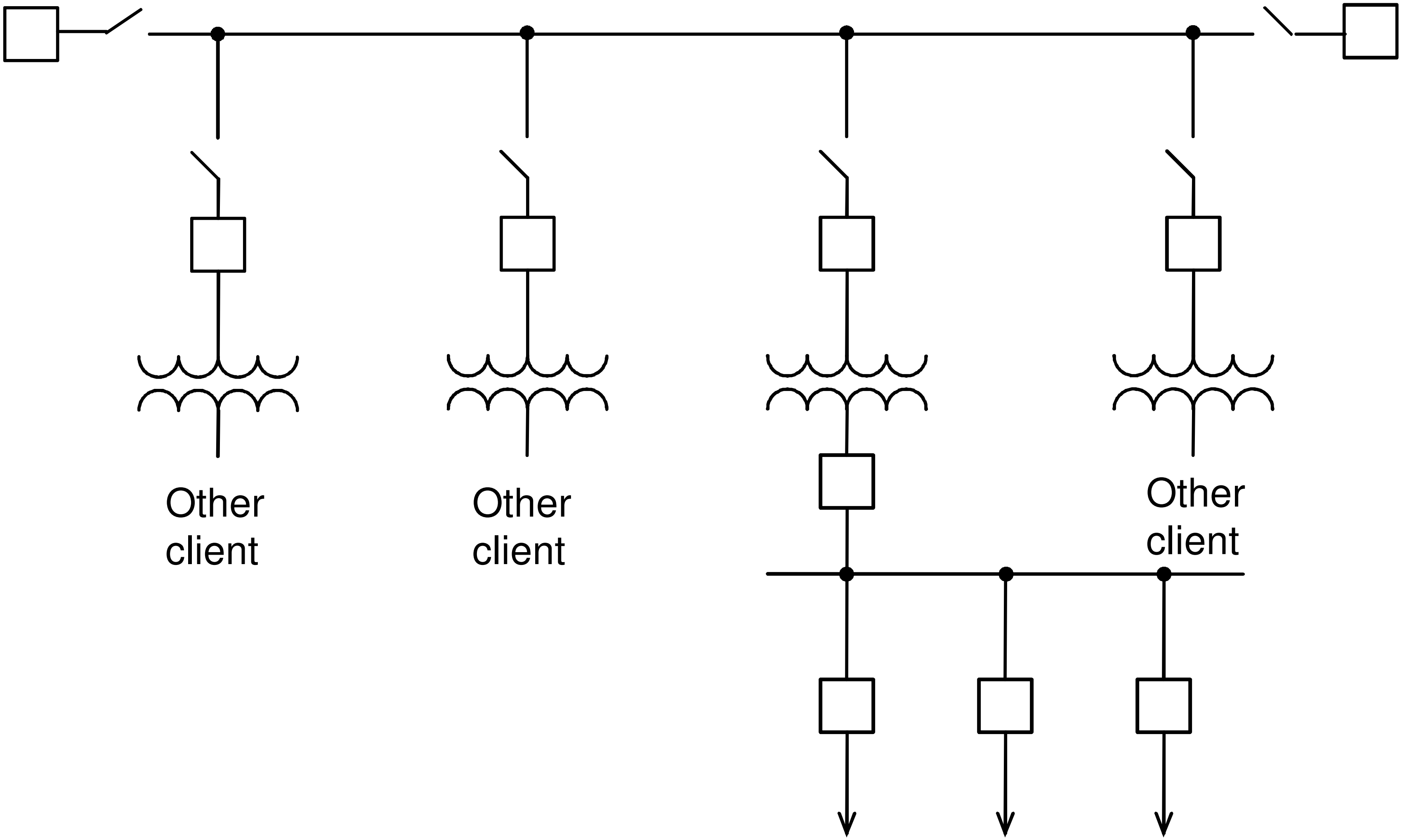
A great reference is John Propst’s 2000 PCIC Paper "IMPROVEMENTS IN MODELING AND EVALUATION OF ELECTRICAL POWER SYSTEM *RELIABILITY*"

Tap Substation

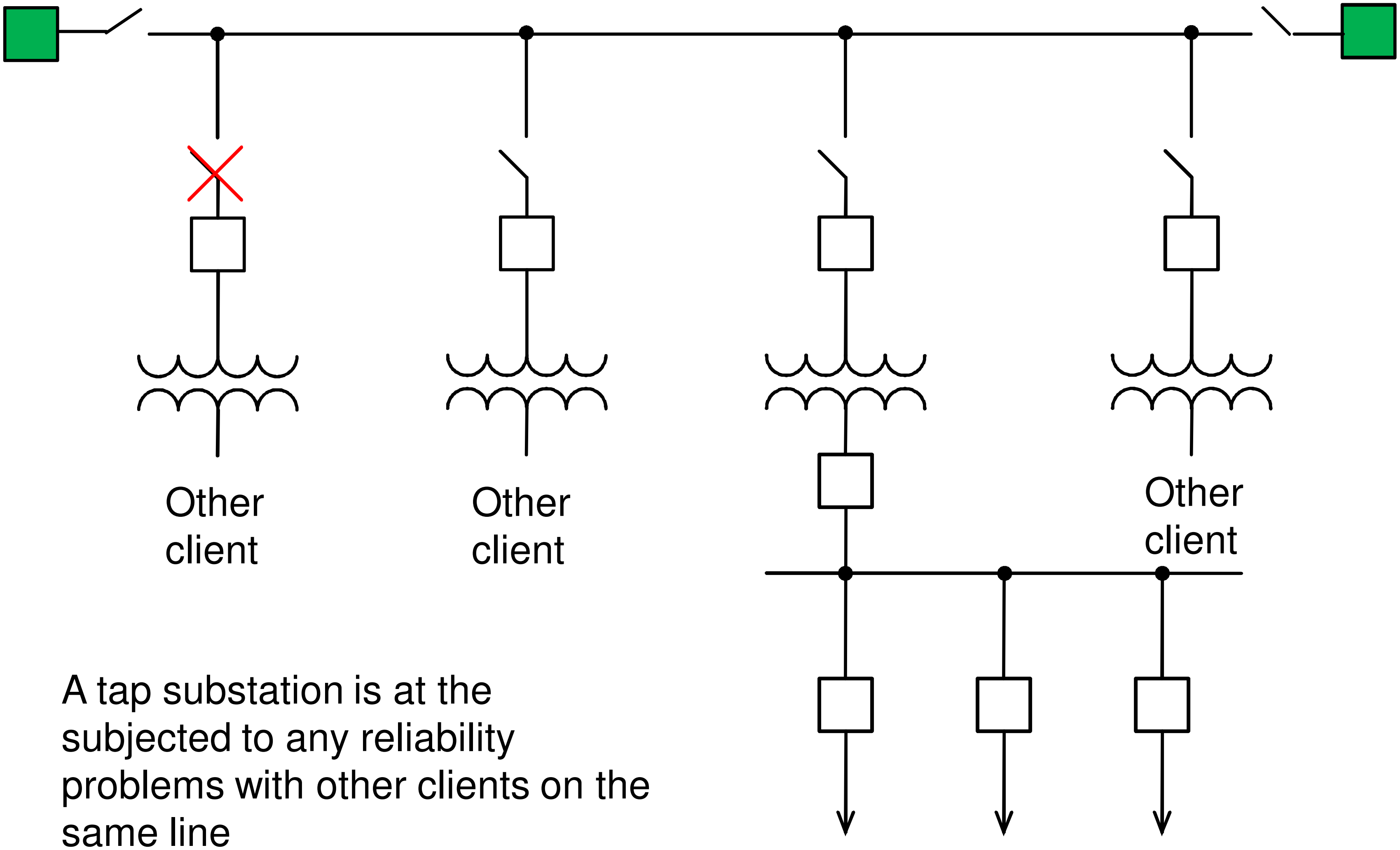
- Most Basic Design
- Tapped Line is Source of Power
- No Operating Flexibility



Tap Substation



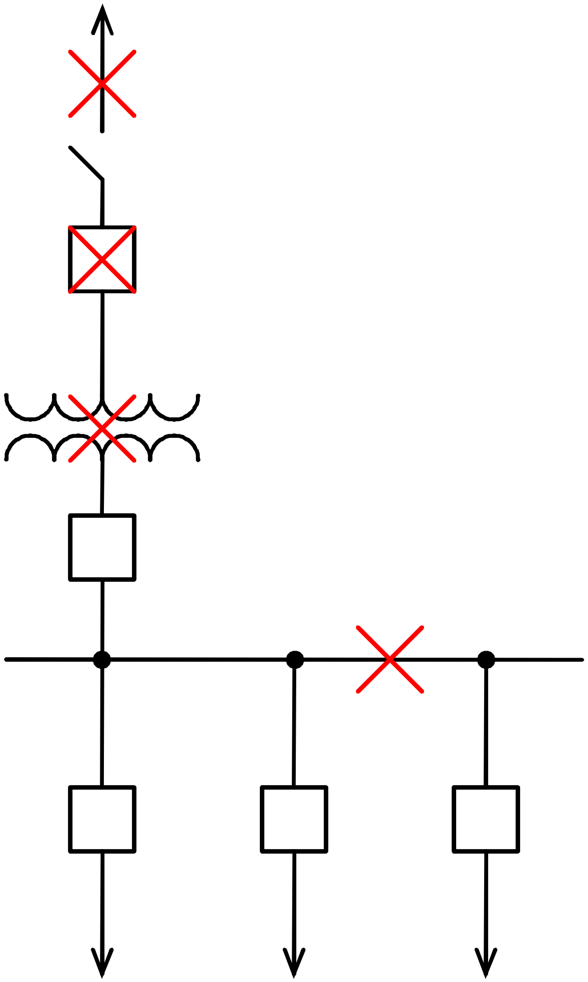
Tap Substation



A tap substation is at the subjected to any reliability problems with other clients on the same line

Tap Substation

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



Tap Substation

Pros

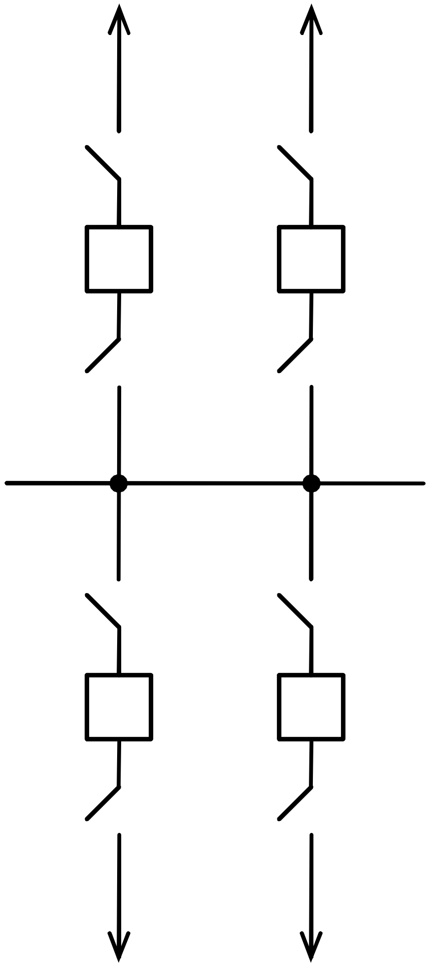
- Small Plot Size
- Low Initial Cost
- Low Maintenance Costs

Cons

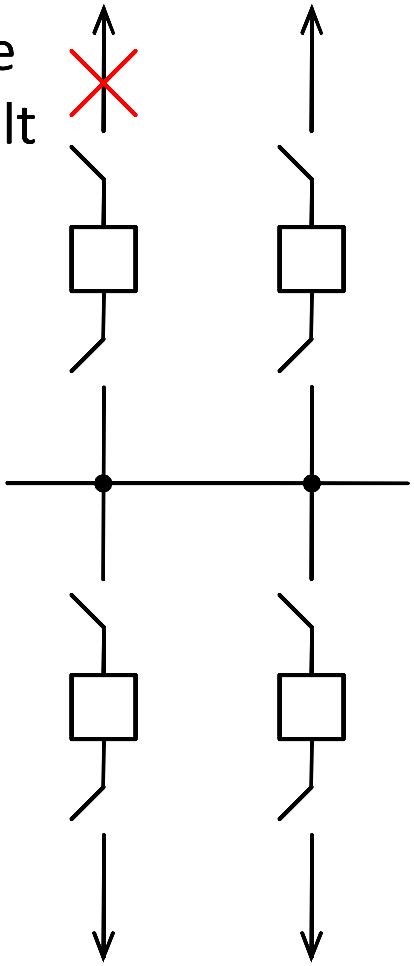
- Line Operations Result in Plant Outages
- Multiple Single Points of Failure
- Failure Points are in Series
- Outages Expected
- Line Faults Cleared by Others
- Low Maintainability

Single Breaker Single Bus Substation

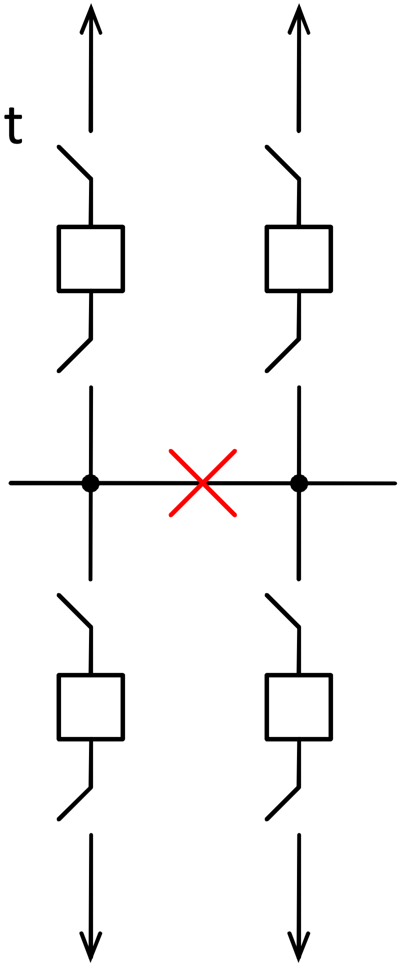
- Basic Design
- One Circuit Breaker per Circuit
- One Common Bus
- No Operating Flexibility
- Widely Used at Distribution Level
- Limited Use at High Voltage



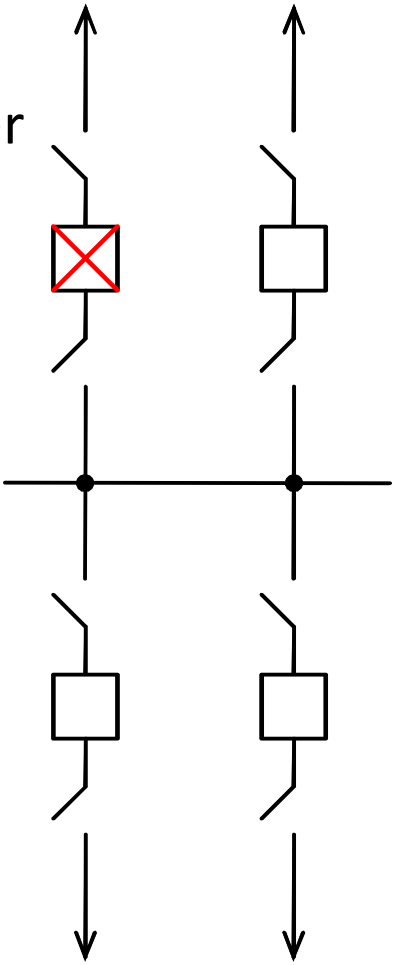
Single Breaker Single Bus



Line
Fault



Bus
Fault



Failed
Breaker

Single Breaker Single Bus

Pros

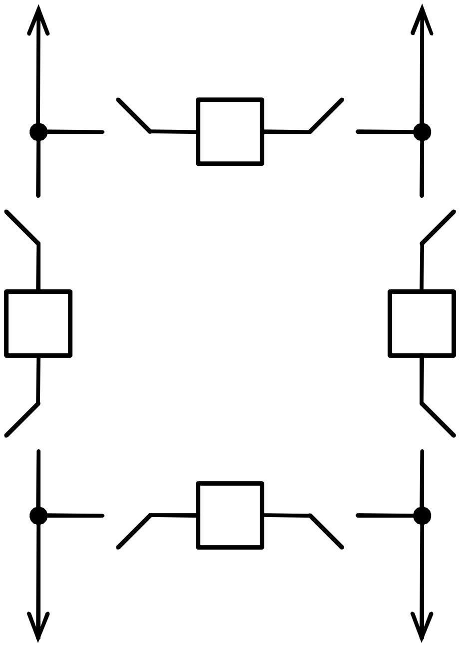
- Each Circuit has Breaker
- Only One Set of VTs Required
- Simple Design

Cons

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

Ring Bus

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



Ring Bus

Pros

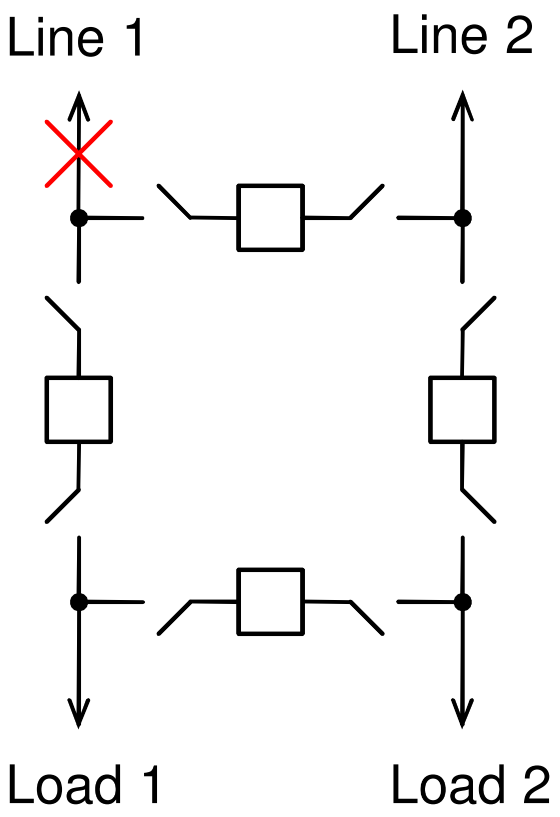
- High Flexibility with Minimum of Breakers
- Dedicated Bus Protection not Required
- Highly Adaptable
- Failed Circuit Does Not Disrupt Other Circuits
- Breaker Maintenance w/o Circuit Interruption

Cons

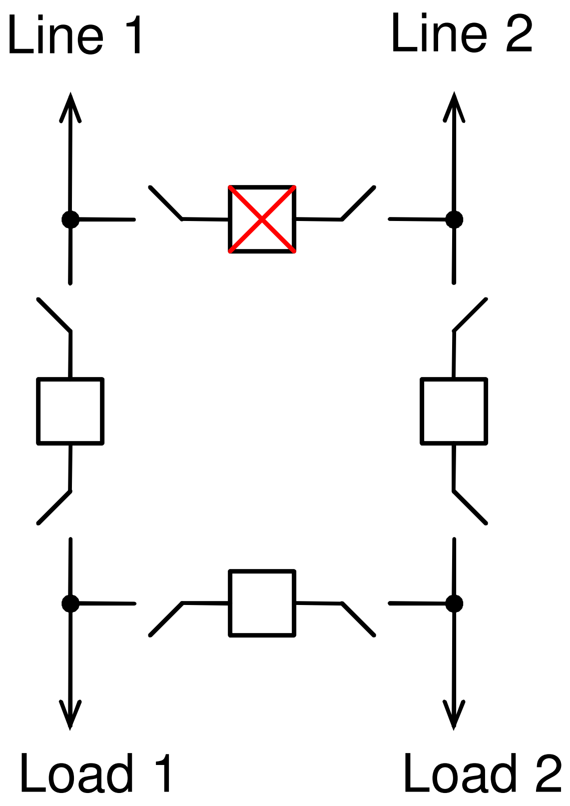
- Failed Breaker May Result in Loss of Multiple Circuits
- Physically Large With 6 or More Circuits

Ring Bus (standard)

Line/Bus Fault

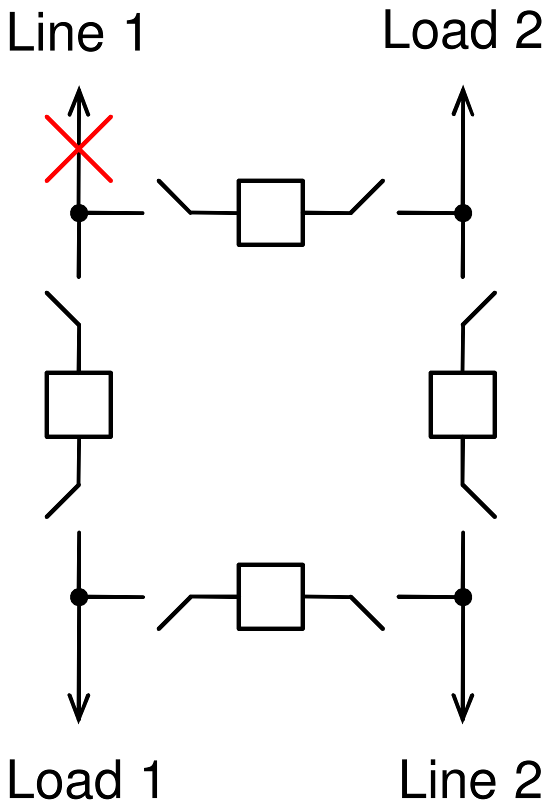


Failed Breaker

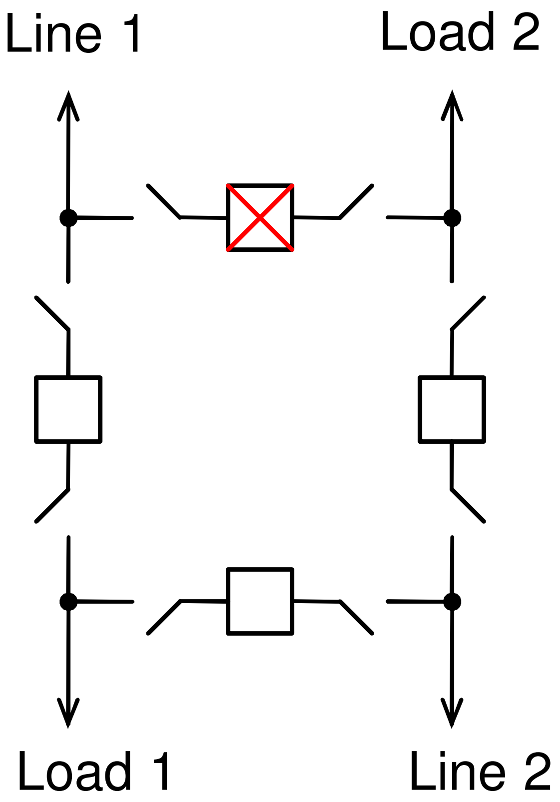


Ring Bus (line-load-line-load)

Line/Bus Fault

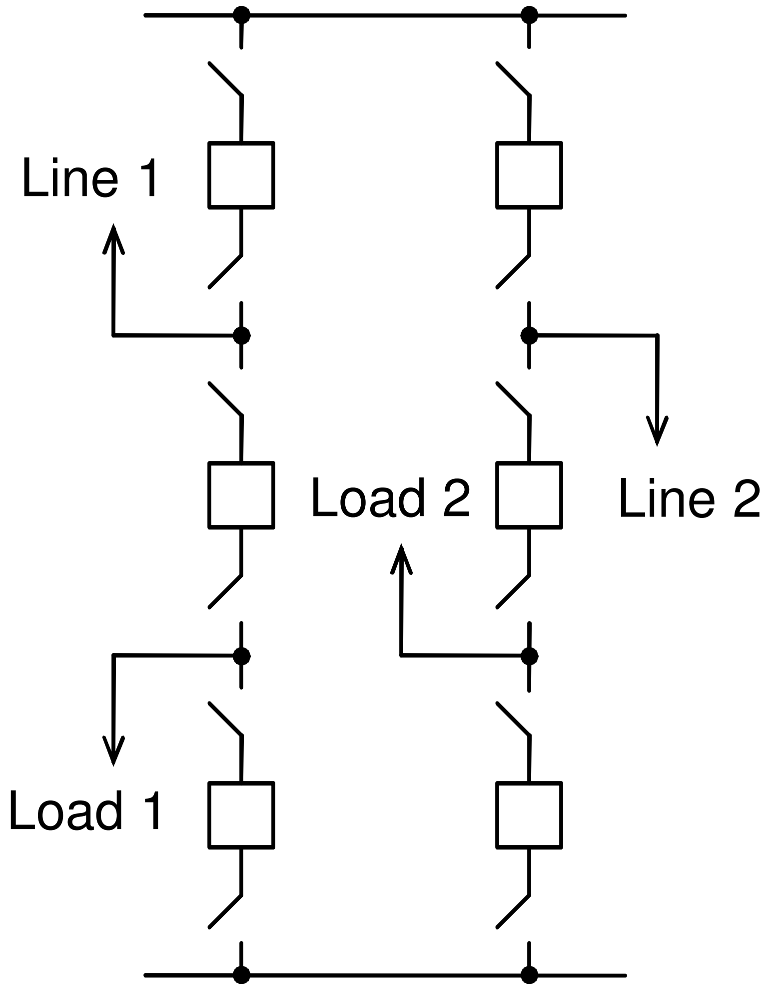


Failed Breaker



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

Pros

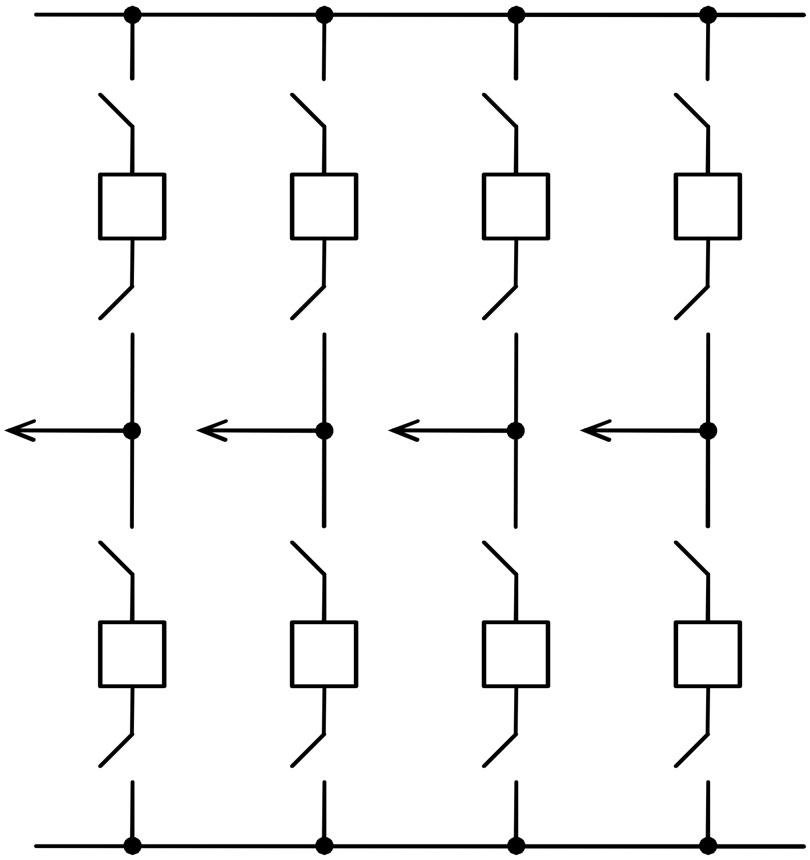
- Robust
- Highly Expandable
- Failed Outer Breakers Result in Loss of One Circuit Only
- Breaker Maintenance w/o Circuit Interruption

Cons

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

Double Breaker Double Bus

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



Double Breaker Double Bus

Pros

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

Cons

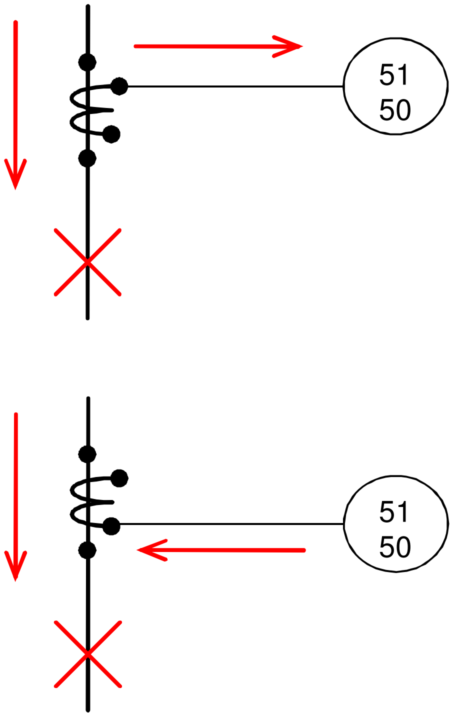
- Cost – Two Breakers & Four Switches per Circuit
- Physical Size

Protection & Control

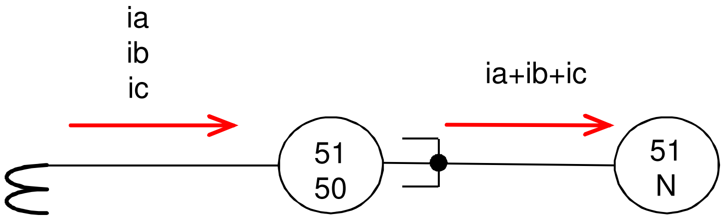
Protection & Control

- Protection
  - Fundamentals
  - Bus
  - Transformers
  - Motors
  - Primary/Back-up Systems
  - Breaker Failure

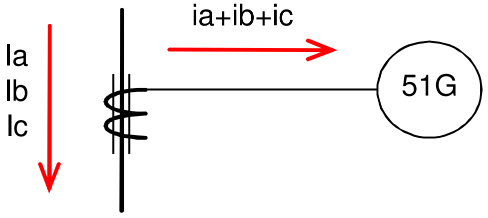
A.C. Fundamentals
Phasor Relationships



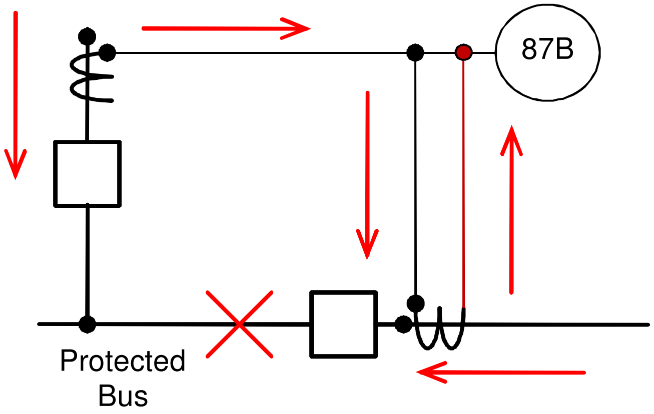
IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes - IEEE Std C37.110



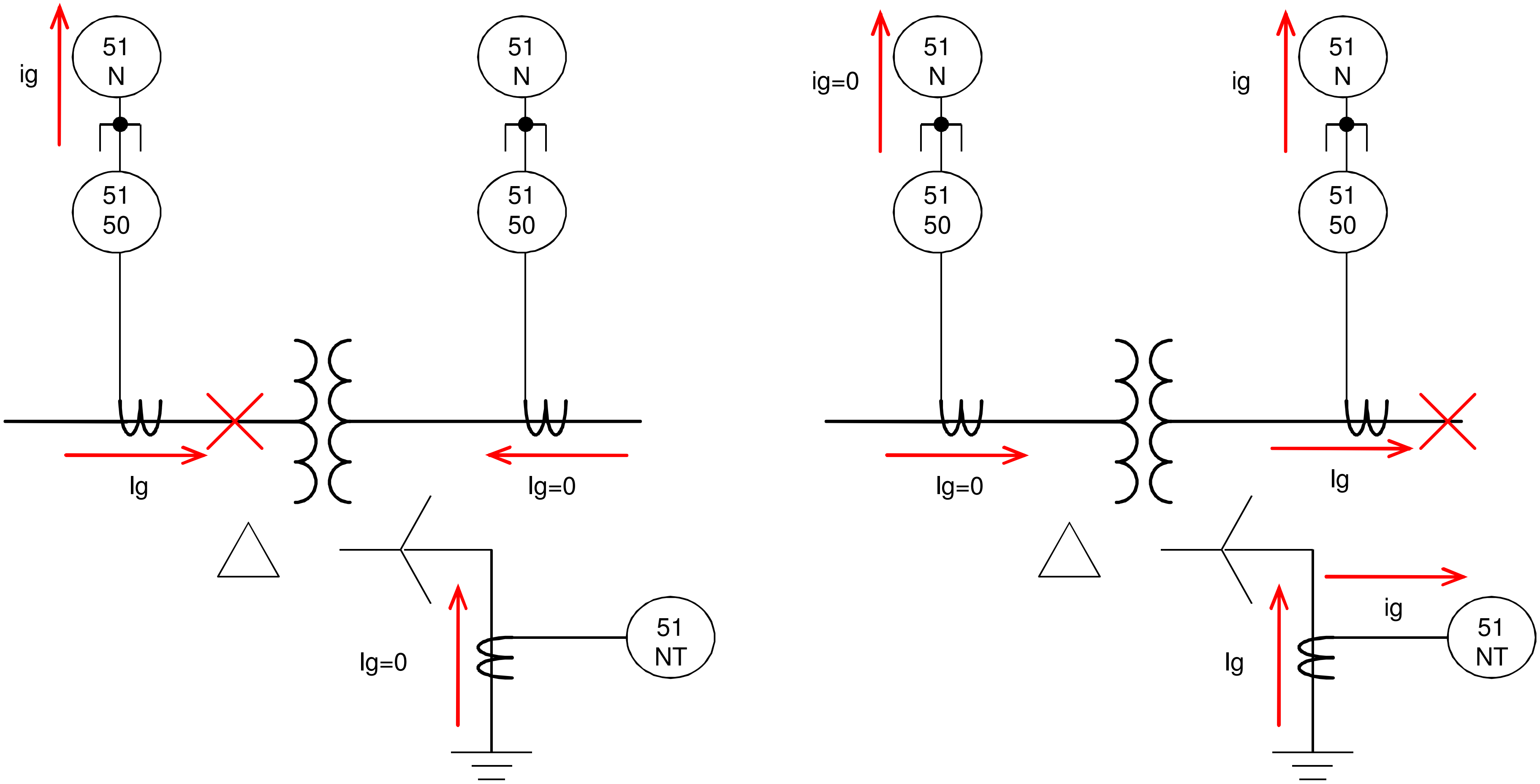
Residual CT connection



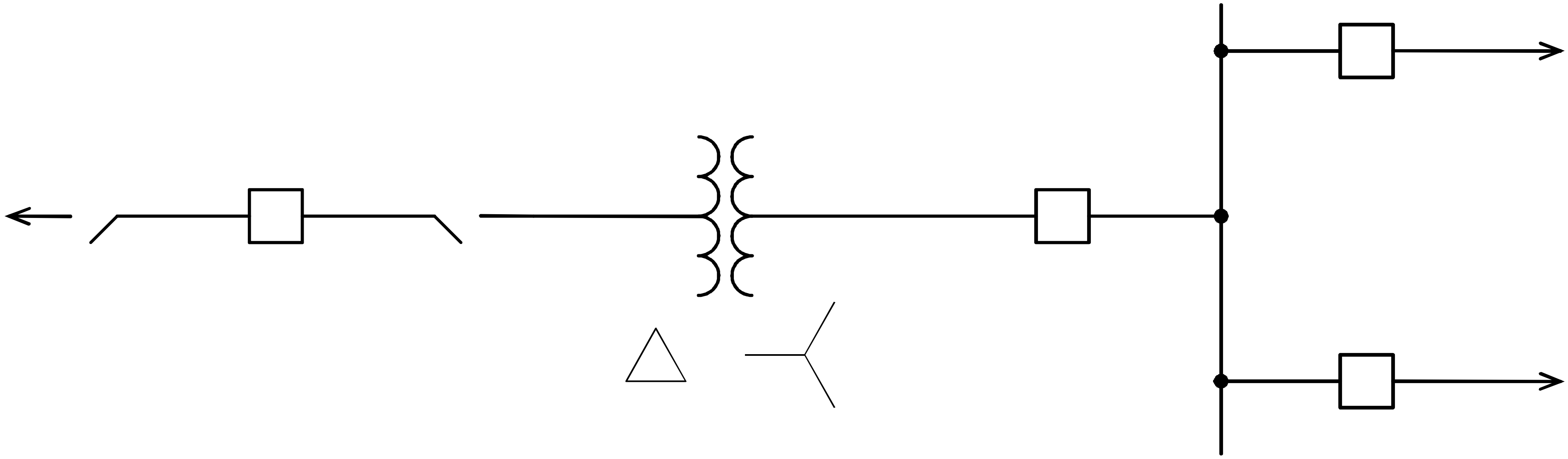
Zero sequence CT



A.C. Fundamentals



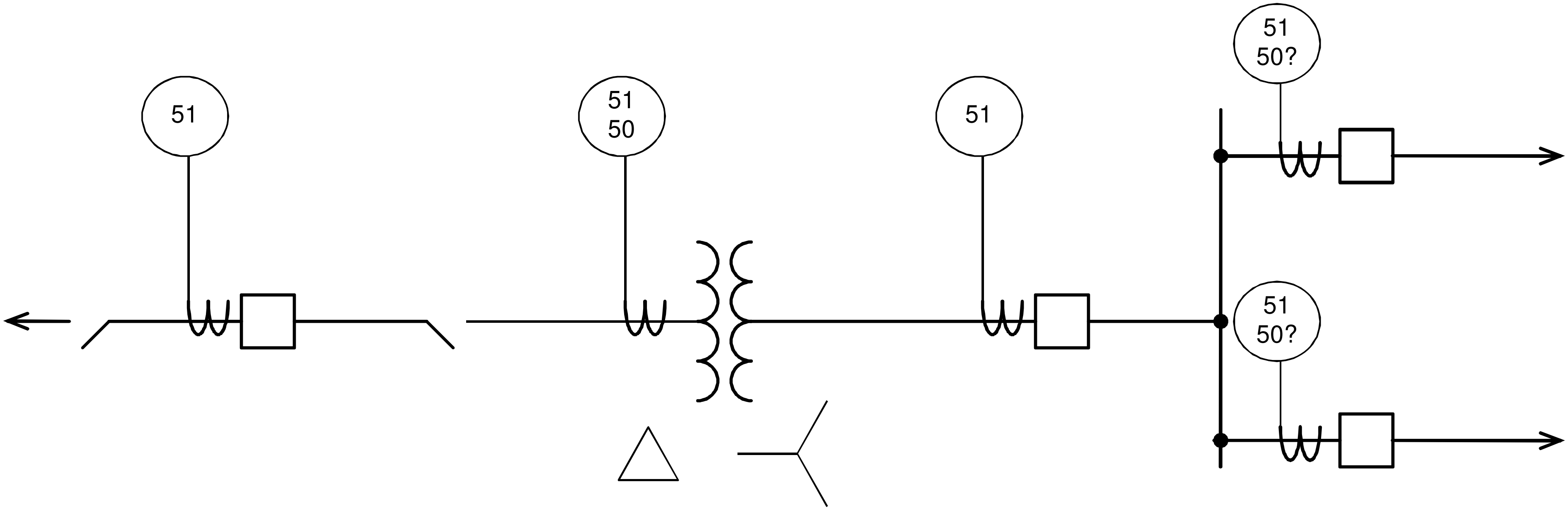
Tap Substation



Tap Substation

- Phase Protection

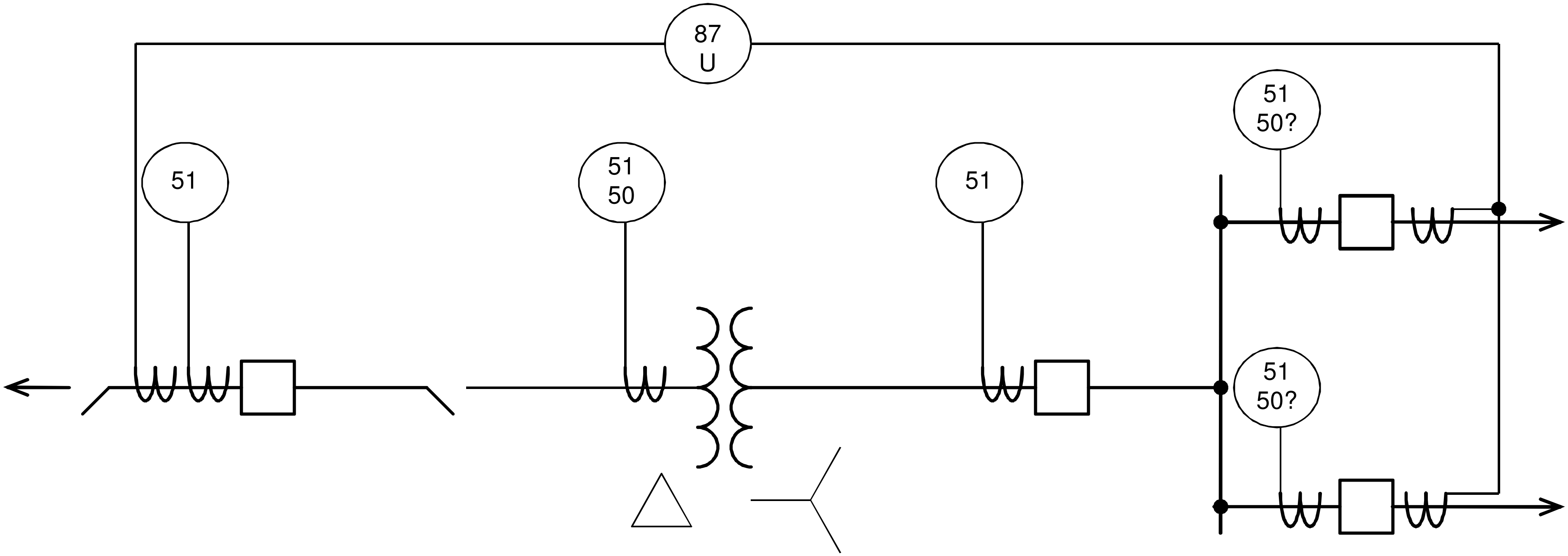
  - Overcurrent



Tap Substation

This configuration is not preferred.

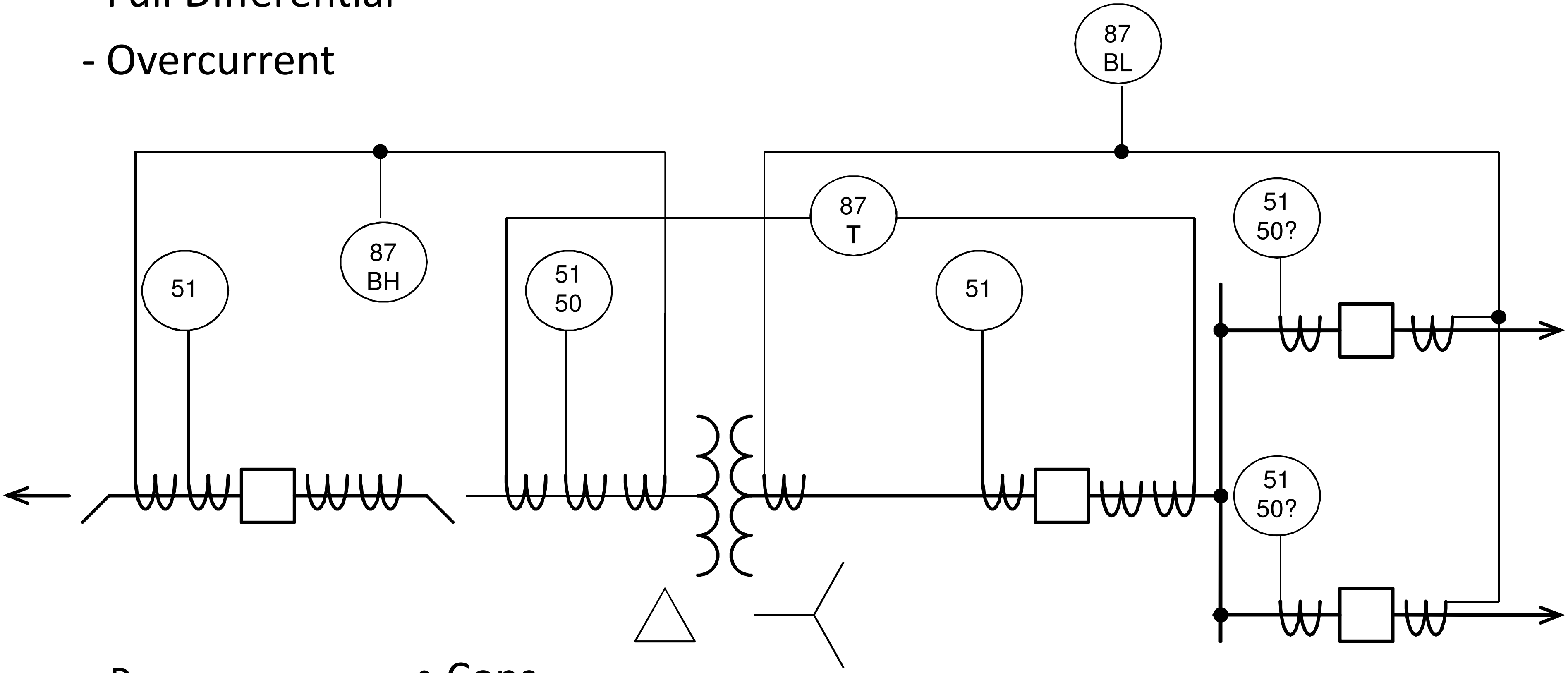
- Phase Protection
  - Unit Differential
  - Overcurrent



- Pros
  - Lower cost
- Cons
  - Lower selectivity

Tap Substation

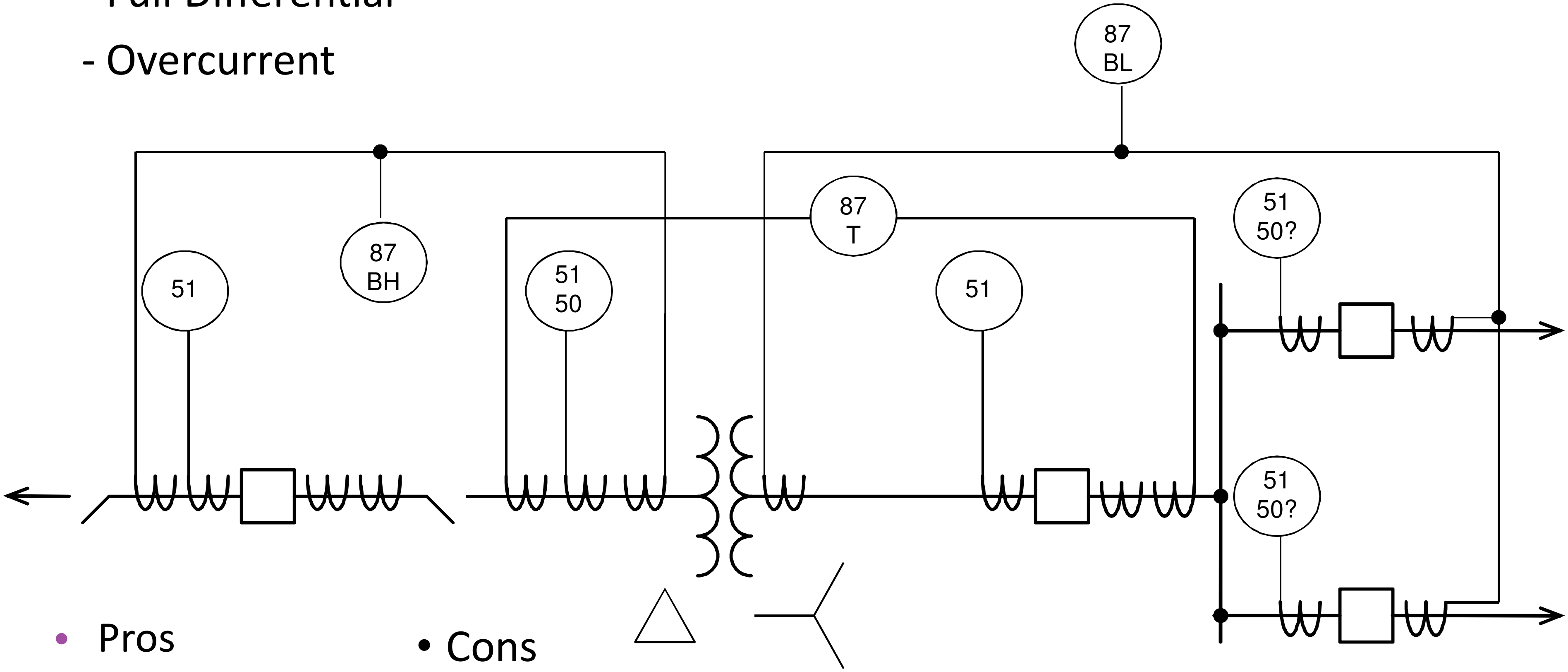
- Phase Protection
  - Full Differential
  - Overcurrent



- Pros
  - Higher selectivity
- Cons
  - Higher cost

Tap Substation

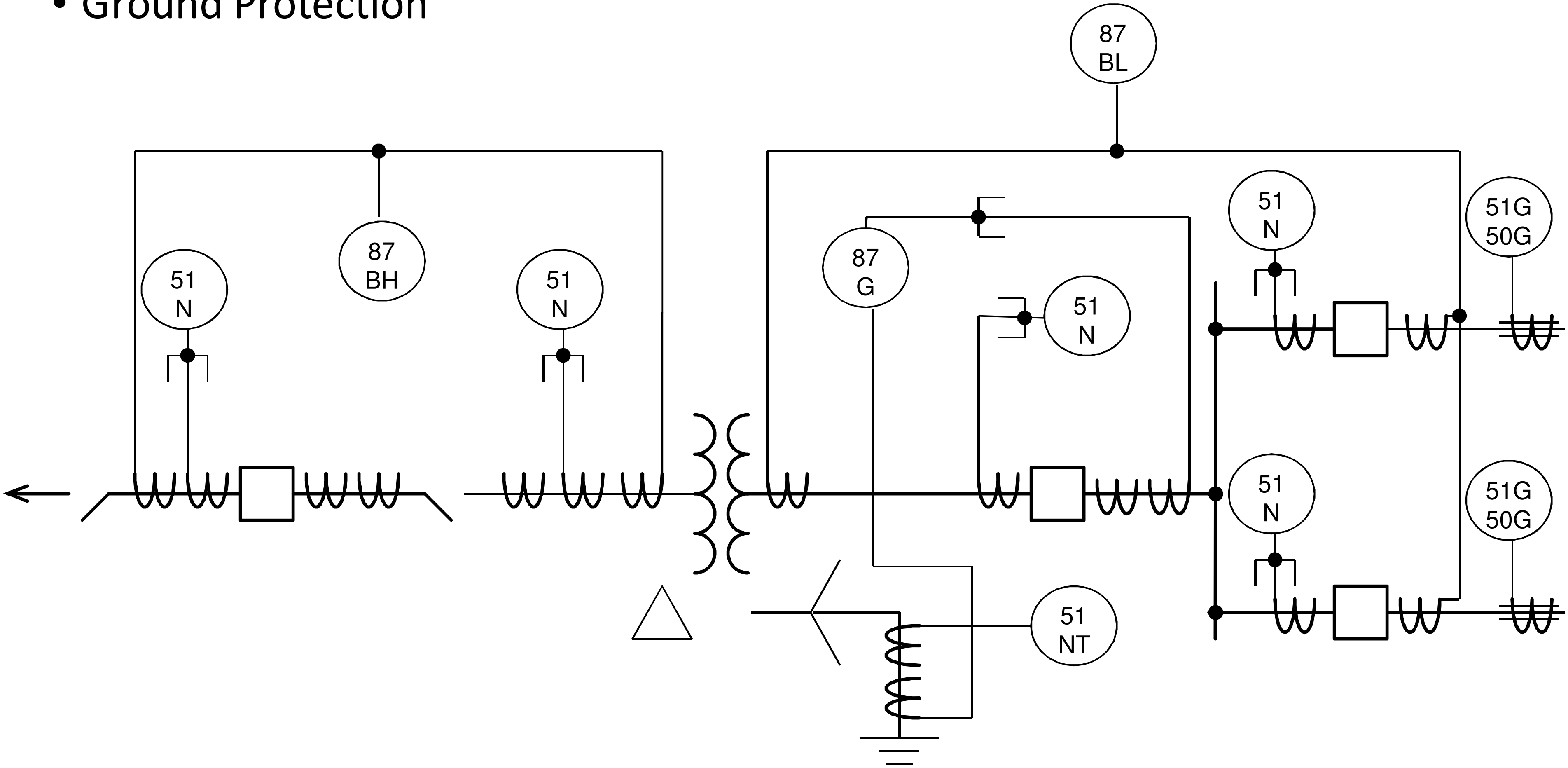
- Phase Protection
  - Full Differential
  - Overcurrent



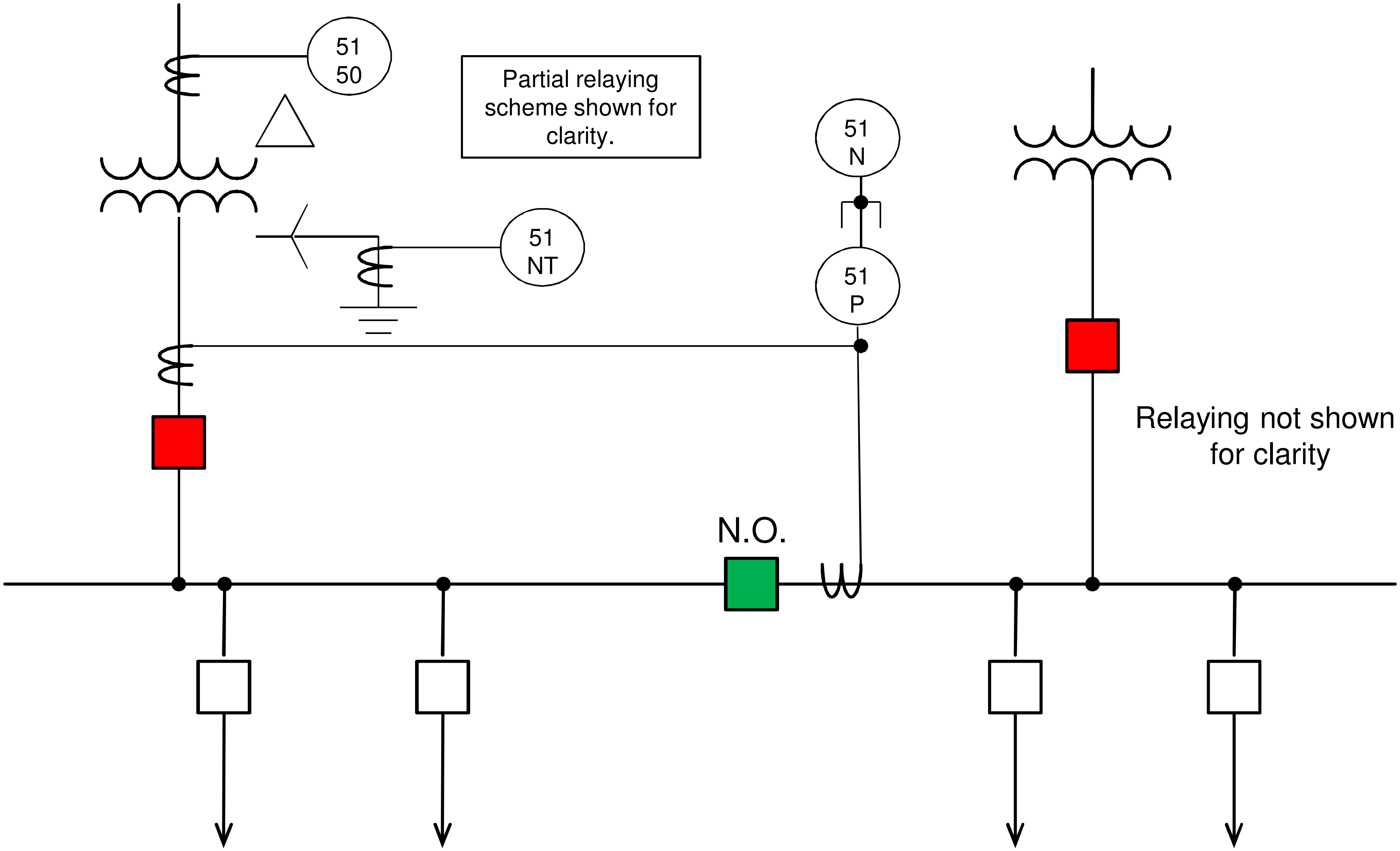
- Pros
  - Higher selectivity
- Cons
  - Higher cost

Tap Substation

- Ground Protection



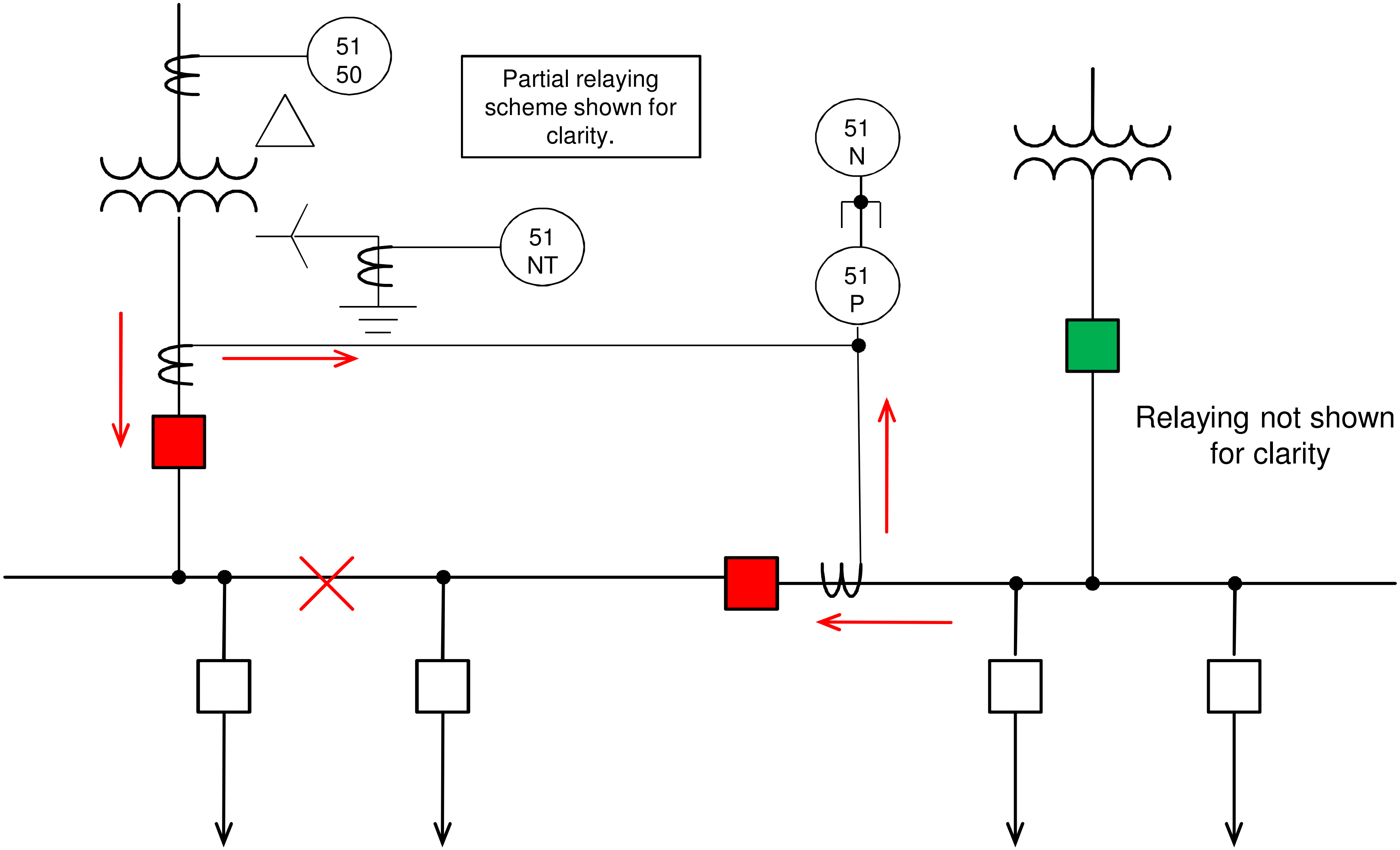
Secondary Selective Arrangement – N.O. Tie



Partial relaying scheme shown for clarity.

Relaying not shown for clarity

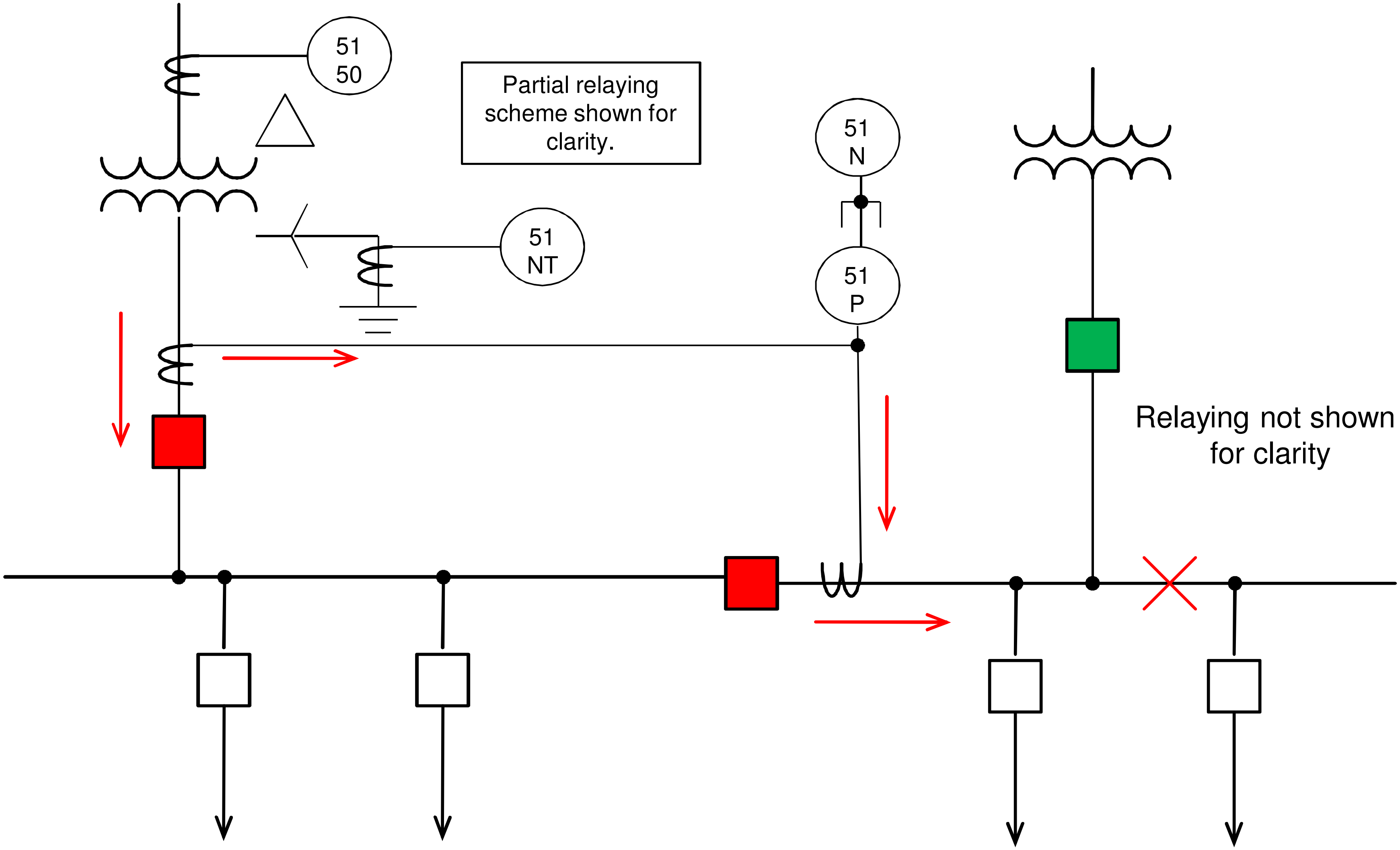
Secondary Selective Arrangement – N.O. Tie



Partial relaying scheme shown for clarity.

Relaying not shown for clarity

Secondary Selective Arrangement – N.O. Tie

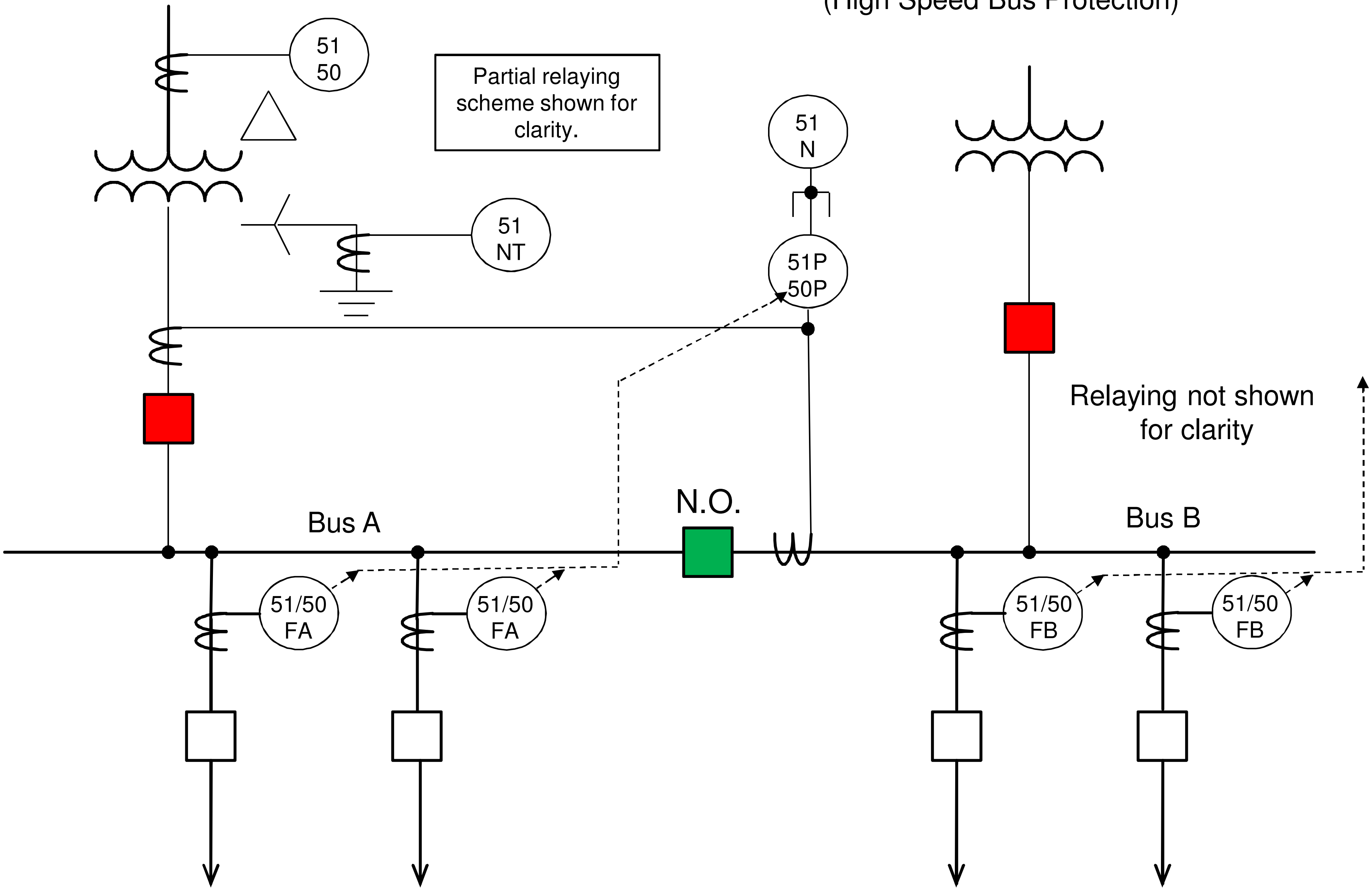


Partial relaying scheme shown for clarity.

Relaying not shown for clarity

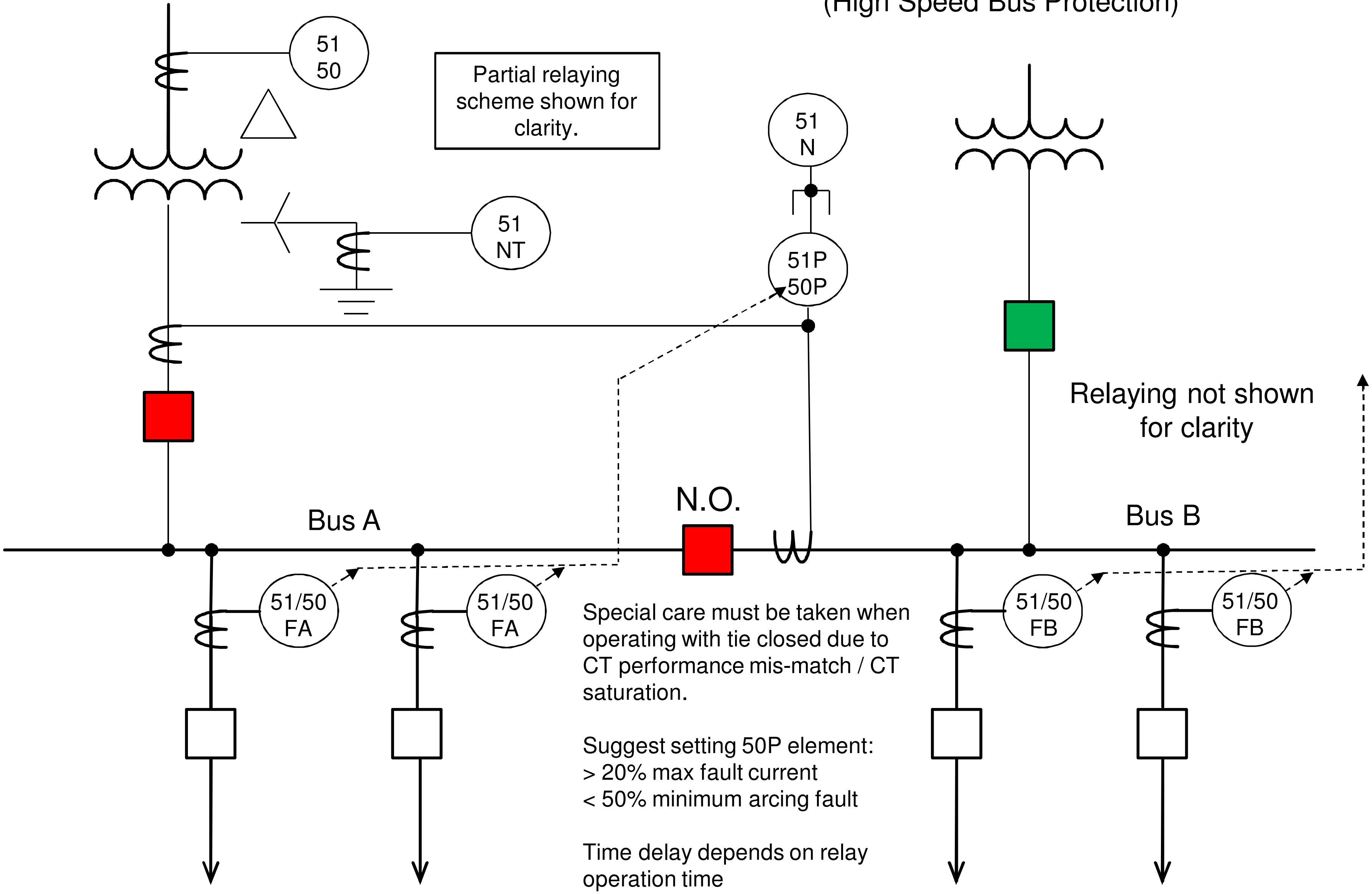
Secondary Selective Arrangement – N.O. Tie w/ ZSI

(High Speed Bus Protection)



Secondary Selective Arrangement – N.O. Tie w/ ZSI

(High Speed Bus Protection)



Partial relaying scheme shown for clarity.

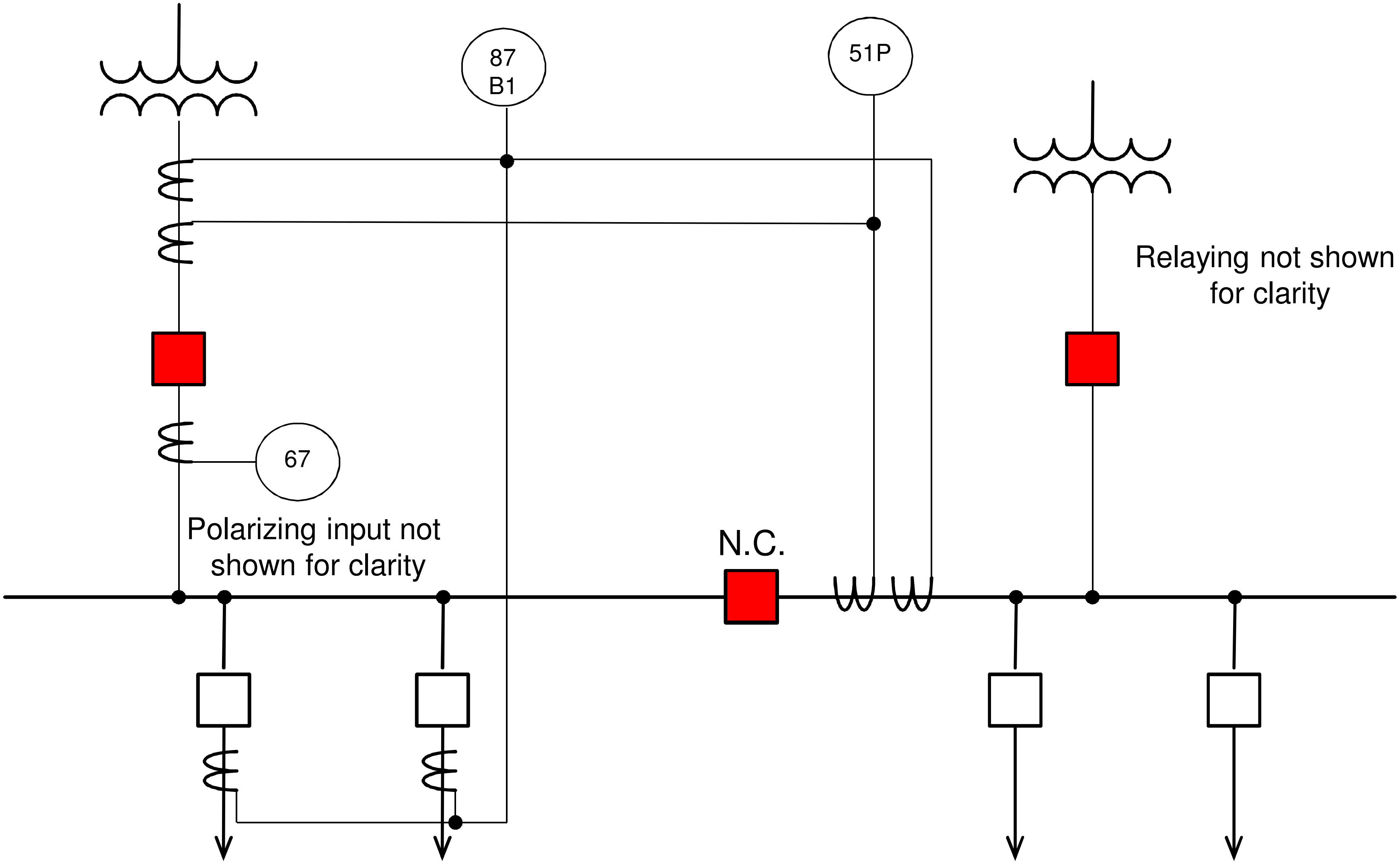
Relaying not shown for clarity

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

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

Time delay depends on relay operation time

Secondary Selective Arrangement – N.C. Tie



Relaying not shown for clarity

Polarizing input not shown for clarity

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

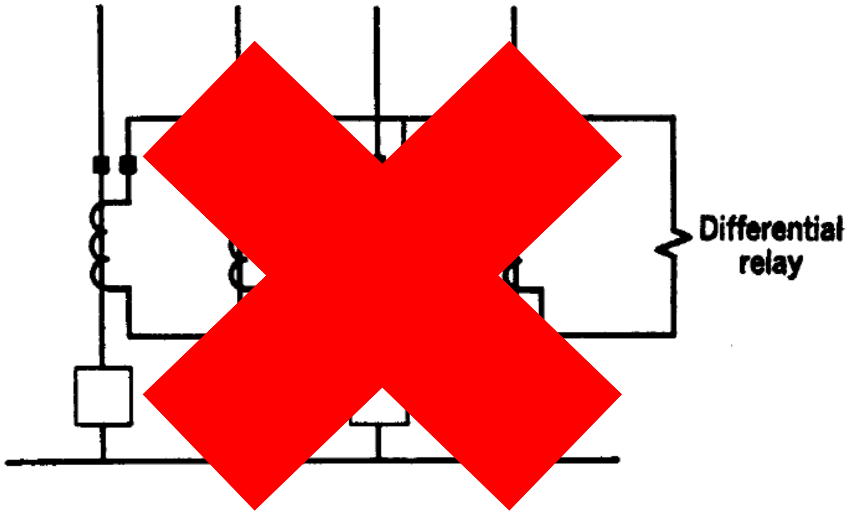
Bus Protection

- Concerns
  - Large number of circuits and different fault levels
  - Different levels of DC saturation
- Differential Protection
  - Most sensitive and most reliable
  - Linear couplers – do not saturate (no iron core)
  - Multi-restraint differential – use restraint and variable percentage slopes to overcome iron core deficiencies at high currents
  - High impedance differential – forces false differentials through CTs and not relay

Bus Protection

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

Bus Protection

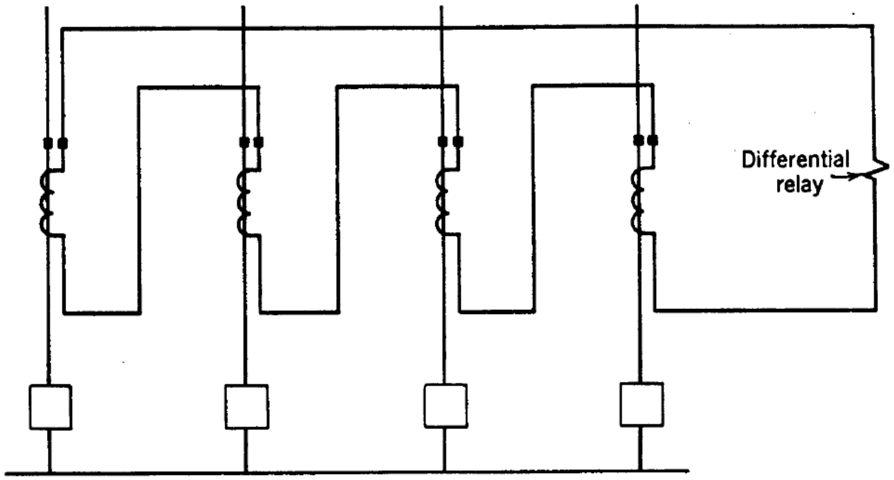


Current Differential

Not Recommended

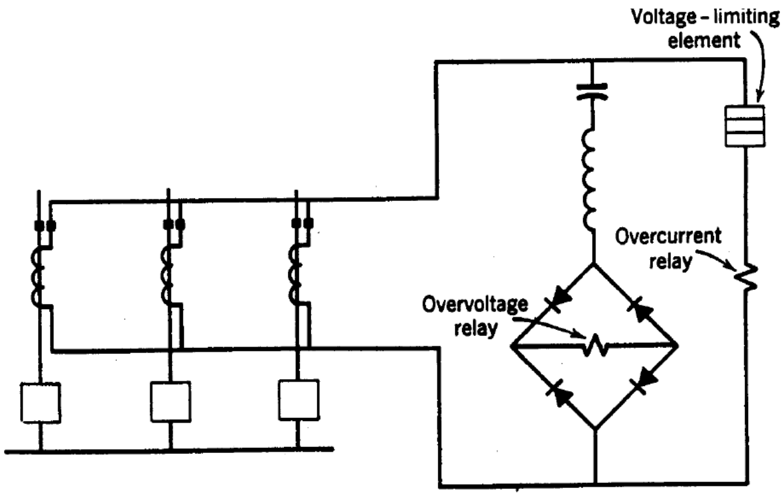
Linear couplers are like CTs except no iron in the core and number of secondary turns is much higher.

No saturation due to air core design



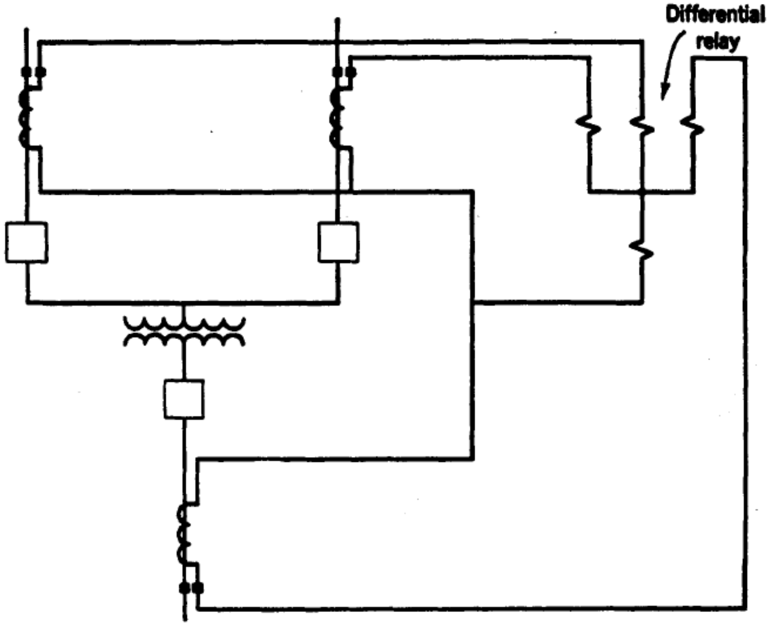
Voltage Differential – Using Air Core CTs called “Linear Couplers”

Bus Protection



Voltage Differential using CTs

Main draw back is the inability to share the CT with different circuits.



Current Differential with Restraint Elements

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

(10+Main + Tie) x 3 = 36 current inputs!

Bus Protection

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

Transformer Protection

- Considerations
  - Differential Protection
    - Different Voltage Levels Including Taps
    - Mismatch Due to CT Ratios
    - 30° Phase Shift on Delta-Wye Connections
    - Magnetizing Inrush
  - Overcurrent Protection
    - CT Performance During High-Current Faults
  - Transformer Type
    - Delta-Wye
    - Zig-Zag Grounding Transformer
    - Autotransformer with Delta Tertiary
    - Phase-Shifting Transformer
- IEEE Std C37.91 – IEEE Guide for Protective Relay Applications to Power Transformers

Motor Protection

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

Motor Protection

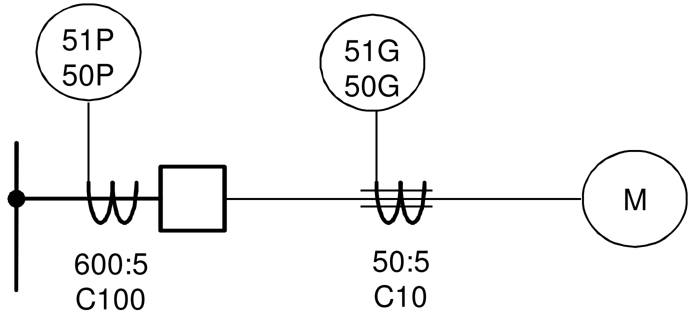
- Abnormal Conditions
  - Faults in Windings
  - Excessive Overloads
  - Reduction or Loss of Supply Voltage
  - Phase Reversal
  - Phase Unbalance
  - Out-of-step Operation (Synchronous Machines)
  - Loss of Excitation (Synchronous Machines)

Motor Protection

- Phase Fault Protection
  - Differential
  - Core Balance CT
  - Instantaneous Overcurrent
- Ground Fault Protection
  - Zero Sequence CT
  - Residually connected phase CTs
  - Internally calculated neutral current
- Locked Rotor Protection
  - Time Overcurrent – Set below rotor damage curve
  - Distance Relay (Large Machines)
- Overload Protection
  - Time overcurrent – Set below stator damage curve
- Thermal Protection – RTDs

Motor Protection

- Typically Zero Sequence CT
  - 50:5, C10

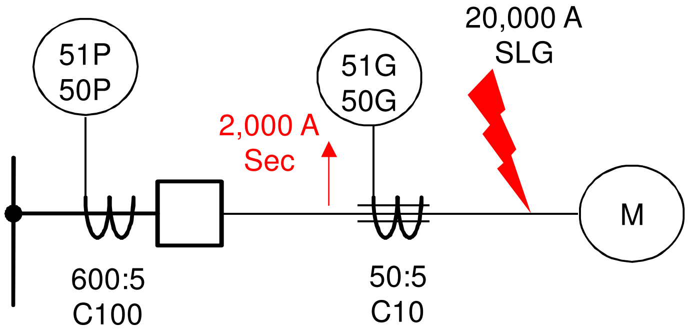


Motor Protection

- Typically Zero Sequence CT
  - 50:5, C10

…but rarely is the system grounding considered.

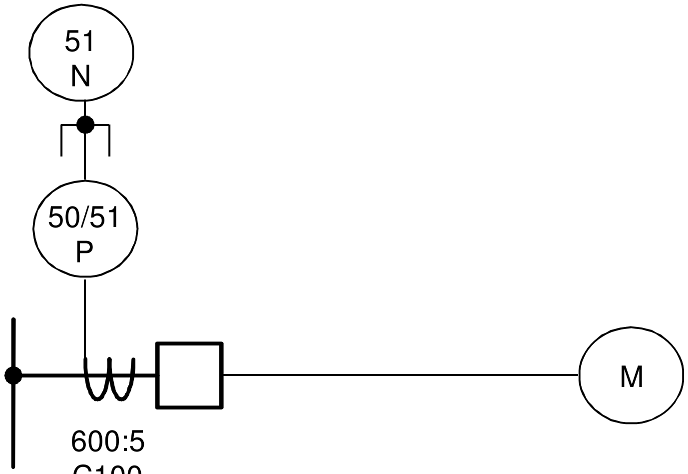
This configuration works well on a low resistance grounded system (LRG), but what if the system is effectively grounded??



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

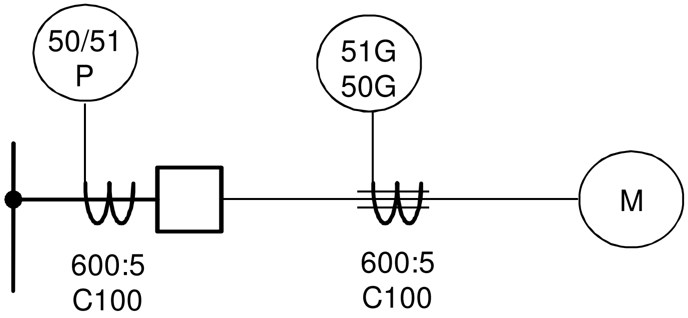
Motor Protection

- An option is to use residually connected CTs or have the relay calculate the residual current
- This works well but often does not allow setting of an instantaneous trip because the CTs will see different currents during LRA and may saturate differently



Motor Protection

- Consider a larger GFCT
- Reduce secondary current from 2,000 A to 166 A
- Increase the accuracy class to ensure CT does not lay down



Primary & Back-up Protection

- Primary/Back-up Protection Philosophy
  - Each protected component has two sets of protection
  - Each protection set is independent of the other
  - Failure of any one component must not compromise protection
- DC Battery Systems
  - Single Battery System
    - Primary protection on different circuit from back-up protection
    - Blown fuse or open DC panel breaker cannot compromise protection
    - Battery itself is a single point of failure
  - Dual Battery System
    - Primary protection on different battery than back-up
    - Battery is no longer single point of failure

Breaker Failure Protection

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

Other Considerations

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

Physical Arrangement

Spacing & Clearances

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

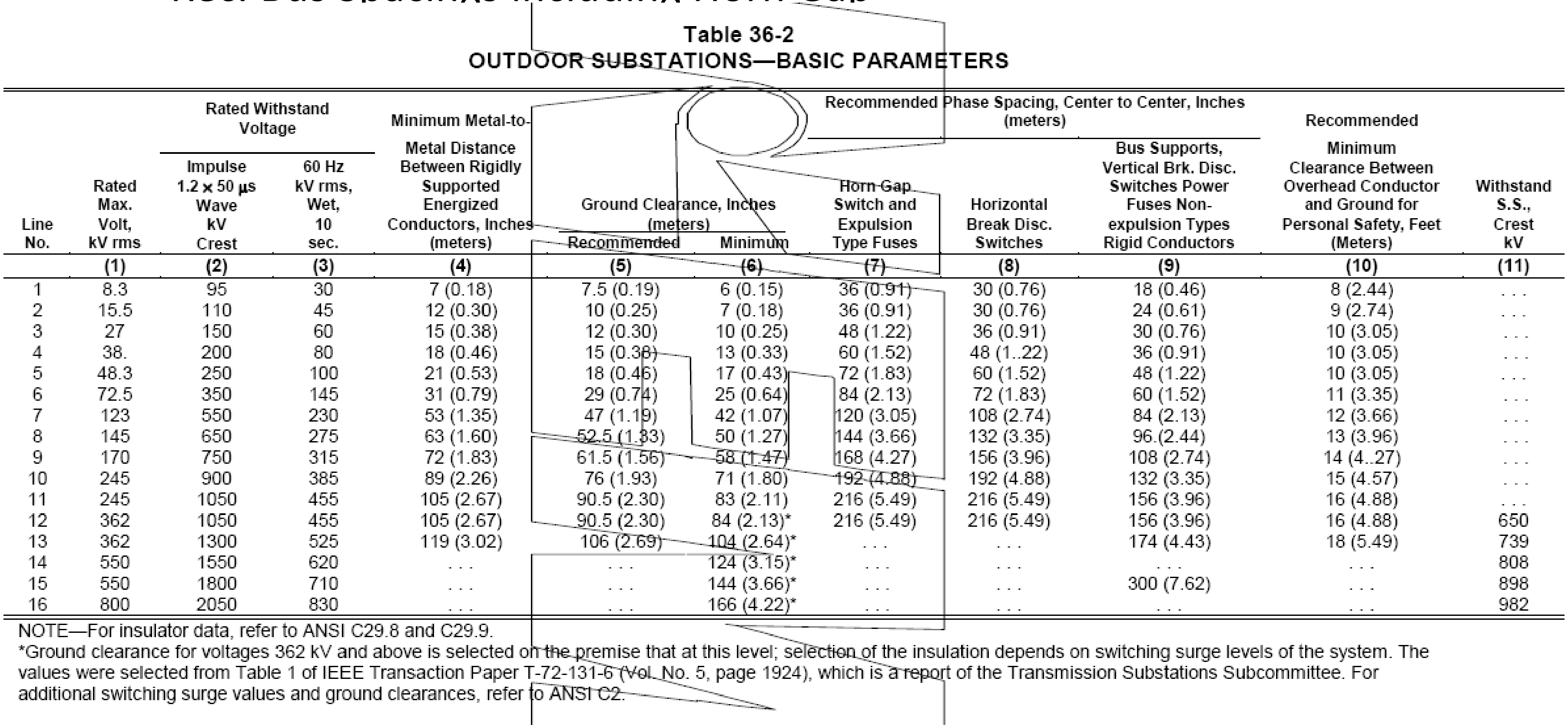


Table 36-2
OUTDOOR SUBSTATIONS—BASIC PARAMETERS

Line No.	Rated Max. Volt, kV rms	Rated Withstand Voltage		Minimum Metal-to-Metal Distance Between Rigidly Supported Energized Conductors, Inches (meters)	Ground Clearance, Inches (meters)		Recommended Phase Spacing, Center to Center, Inches (meters)			Recommended Minimum Clearance Between Overhead Conductor and Ground for Personal Safety, Feet (Meters)	Withstand S.S., Crest kV
		Impulse 1.2 × 50 µs Wave kV Crest	60 Hz kV rms, Wet, 10 sec.		Recommended	Minimum	Horn Gap Switch and Expulsion Type Fuses	Horizontal Break Disc. Switches	Bus Supports, Vertical Brk. Disc. Switches Power Fuses Non-expulsion Types Rigid Conductors		
	(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.

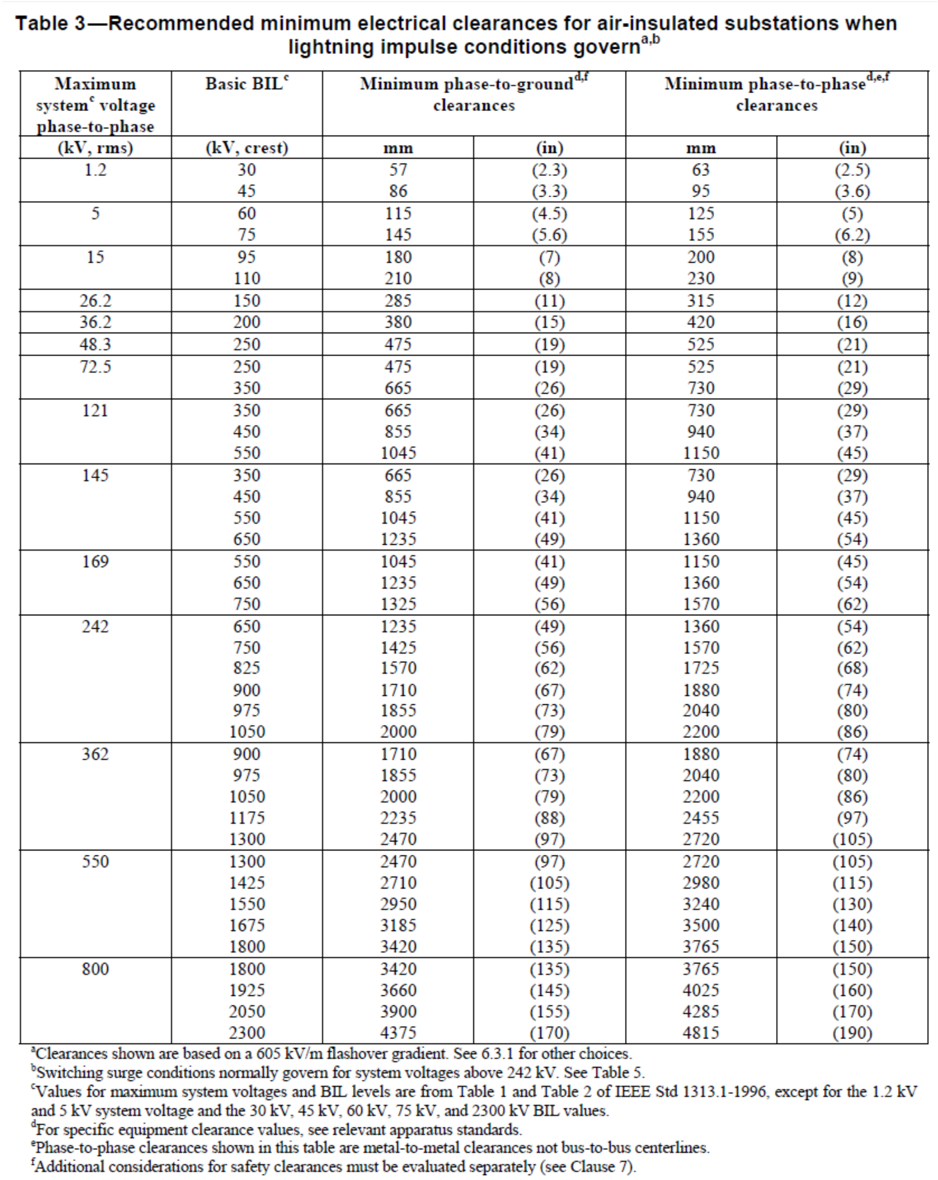


Table 3—Recommended minimum electrical clearances for air-insulated substations when lightning impulse conditions govern[a,b]

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).

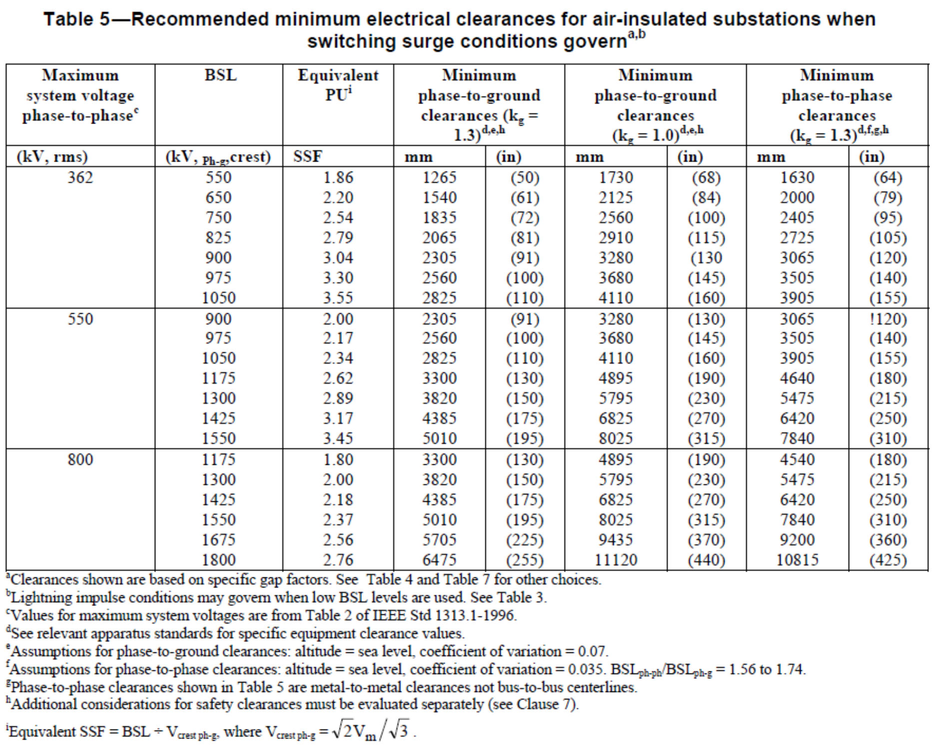


Table 5—Recommended minimum electrical clearances for air-insulated substations when switching surge conditions govern[a,b]

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.

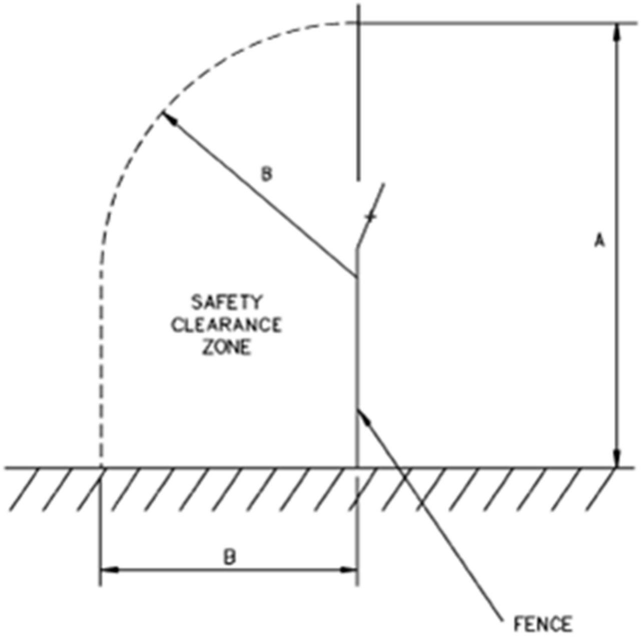
[h] Additional considerations for safety clearances must be evaluated separately (see Clause 7).

[i] Equivalent SSF = BSL ÷ $V_{crest\ ph-g}$, where $V_{crest\ ph-g} = \sqrt{2}V_m/\sqrt{3}$.

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

Spacing & Clearances

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



Contamination Levels

Multiplier applied to
phase-to-ground voltage

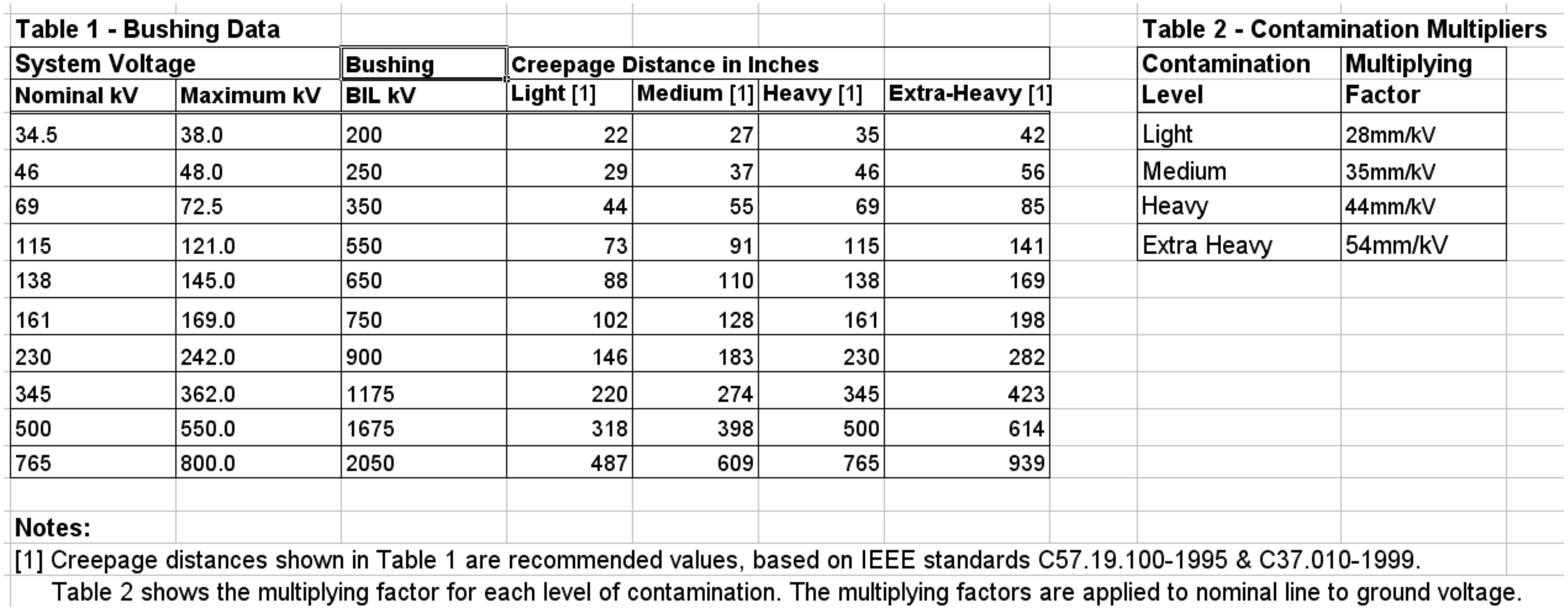


Table 1 - Bushing Data

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

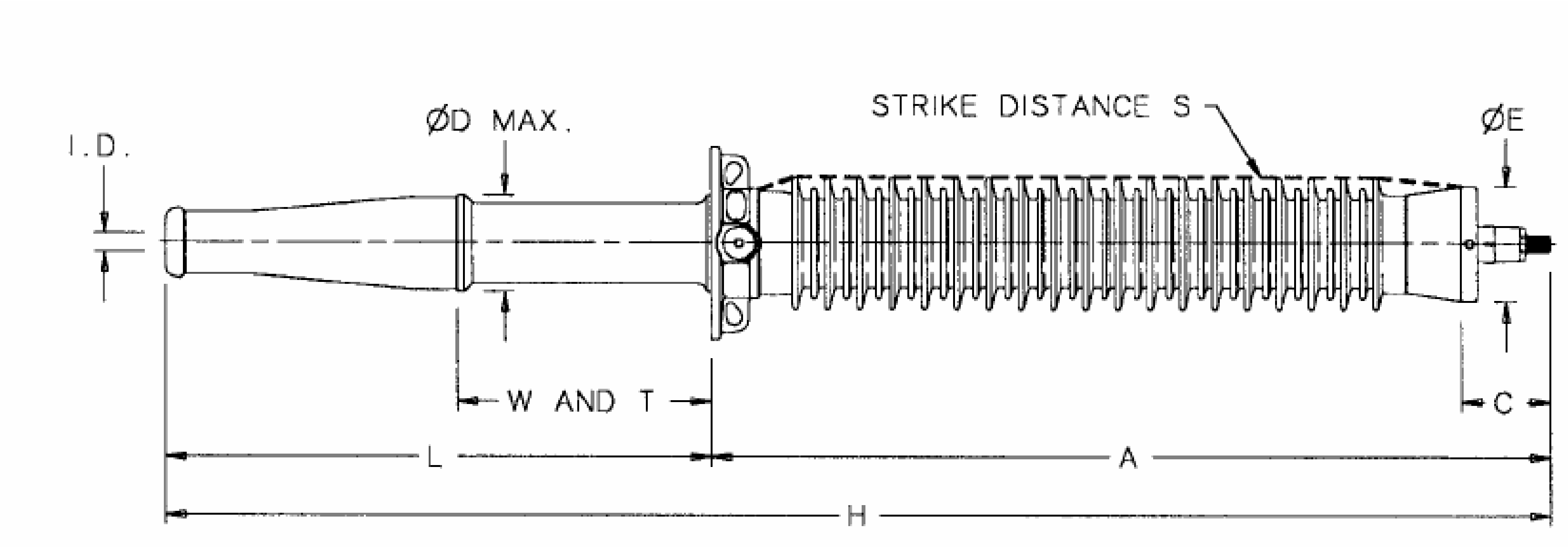
Table 2 - Contamination Multipliers

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.

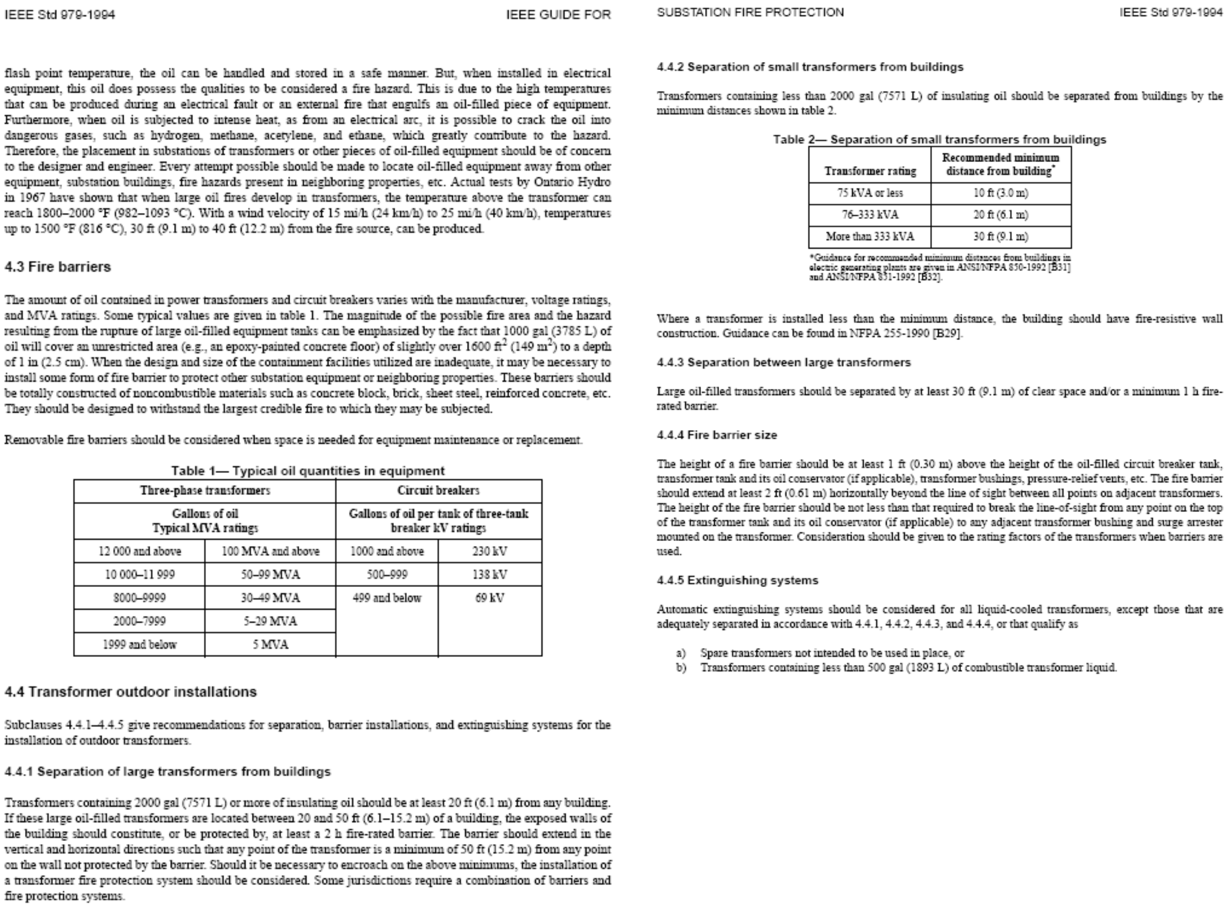
BIL vs Creep



Typical Draw-Lead Bushing

Spacing & Clearances

- IEEE 979 – Substation Fire Protection



IEEE Std 979-1994 IEEE GUIDE FOR

flash point temperature, the oil can be handled and stored in a safe manner. But, when installed in electrical equipment, this oil does possess the qualities to be considered a fire hazard. This is due to the high temperatures that can be produced during an electrical fault or an external fire that engulfs an oil-filled piece of equipment. Furthermore, when oil is subjected to intense heat, as from an electrical arc, it is possible to crack the oil into dangerous gases, such as hydrogen, methane, acetylene, and ethane, which greatly contribute to the hazard. Therefore, the placement in substations of transformers or other pieces of oil-filled equipment should be of concern to the designer and engineer. Every attempt possible should be made to locate oil-filled equipment away from other equipment, substation buildings, fire hazards present in neighboring properties, etc. Actual tests by Ontario Hydro in 1967 have shown that when large oil fires develop in transformers, the temperature above the transformer can reach 1800–2000 °F (982–1093 °C). With a wind velocity of 15 mi/h (24 km/h) to 25 mi/h (40 km/h), temperatures up to 1500 °F (816 °C), 30 ft (9.1 m) to 40 ft (12.2 m) from the fire source, can be produced.

4.3 Fire barriers

The amount of oil contained in power transformers and circuit breakers varies with the manufacturer, voltage ratings, and MVA ratings. Some typical values are given in table 1. The magnitude of the possible fire area and the hazard resulting from the rupture of large oil-filled equipment tanks can be emphasized by the fact that 1000 gal (3785 L) of oil will cover an unrestricted area (e.g., an epoxy-painted concrete floor) of slightly over 1600 ft^2 (149 m^2) to a depth of 1 in (2.5 cm). When the design and size of the containment facilities utilized are inadequate, it may be necessary to install some form of fire barrier to protect other substation equipment or neighboring properties. These barriers should be totally constructed of noncombustible materials such as concrete block, brick, sheet steel, reinforced concrete, etc. They should be designed to withstand the largest credible fire to which they may be subjected.

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

Table 1— Typical oil quantities in equipment

Three-phase transformers		Circuit breakers	
Gallons of oil Typical MVA ratings		Gallons of oil per tank of three-tank breaker kV ratings	
12 000 and above	100 MVA and above	1000 and above	230 kV
10 000–11 999	50–99 MVA	500–999	138 kV
8000–9999	30–49 MVA	499 and below	69 kV
2000–7999	5–29 MVA		
1999 and below	5 MVA		

4.4 Transformer outdoor installations

Subclauses 4.4.1–4.4.5 give recommendations for separation, barrier installations, and extinguishing systems for the installation of outdoor transformers.

4.4.1 Separation of large transformers from buildings

Transformers containing 2000 gal (7571 L) or more of insulating oil should be at least 20 ft (6.1 m) from any building. If these large oil-filled transformers are located between 20 and 50 ft (6.1–15.2 m) of a building, the exposed walls of the building should constitute, or be protected by, at least a 2 h fire-rated barrier. The barrier should extend in the vertical and horizontal directions such that any point of the transformer is a minimum of 50 ft (15.2 m) from any point on the wall not protected by the barrier. Should it be necessary to encroach on the above minimums, the installation of a transformer fire protection system should be considered. Some jurisdictions require a combination of barriers and fire protection systems.

SUBSTATION FIRE PROTECTION IEEE Std 979-1994

4.4.2 Separation of small transformers from buildings

Transformers containing less than 2000 gal (7571 L) of insulating oil should be separated from buildings by the minimum distances shown in table 2.

Table 2— Separation of small transformers from buildings

Transformer rating	Recommended minimum distance from building*
75 kVA or less	10 ft (3.0 m)
76–333 kVA	20 ft (6.1 m)
More than 333 kVA	30 ft (9.1 m)

*Guidance for recommended minimum distances from buildings in electric generating plants are given in ANSI/NFPA 850-1992 [B31] and ANSI/NFPA 851-1992 [B32].

Where a transformer is installed less than the minimum distance, the building should have fire-resistive wall construction. Guidance can be found in NFPA 255-1990 [B29].

4.4.3 Separation between large transformers

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

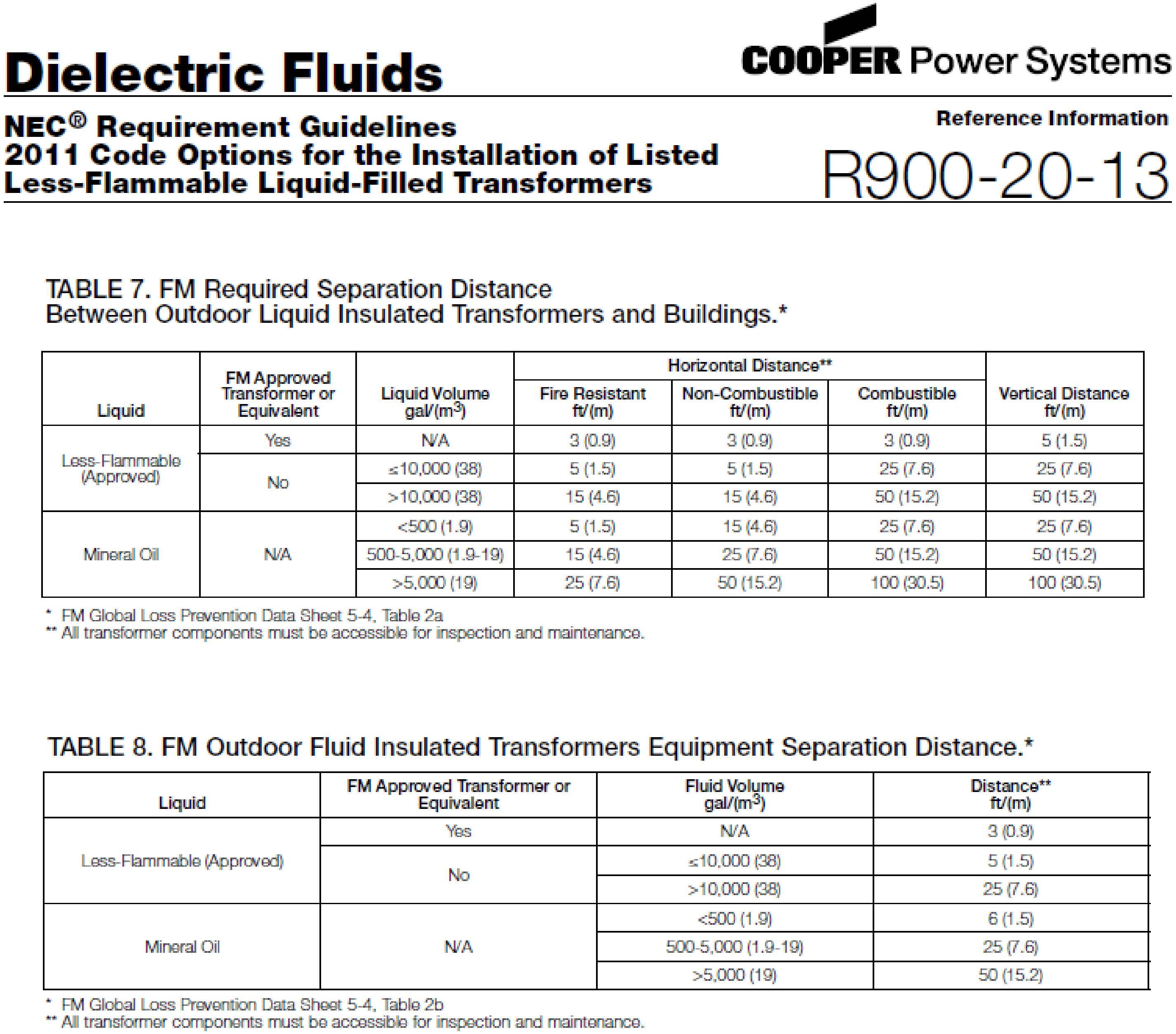
4.4.4 Fire barrier size

The height of a fire barrier should be at least 1 ft (0.30 m) above the height of the oil-filled circuit breaker tank, transformer tank and its oil conservator (if applicable), transformer bushings, pressure-relief vents, etc. The fire barrier should extend at least 2 ft (0.61 m) horizontally beyond the line of sight between all points on adjacent transformers. The height of the fire barrier should be not less than that required to break the line-of-sight from any point on the top of the transformer tank and its oil conservator (if applicable) to any adjacent transformer bushing and surge arrester mounted on the transformer. Consideration should be given to the rating factors of the transformers when barriers are used.

4.4.5 Extinguishing systems

Automatic extinguishing systems should be considered for all liquid-cooled transformers, except those that are adequately separated in accordance with 4.4.1, 4.4.2, 4.4.3, and 4.4.4, or that qualify as

a) Spare transformers not intended to be used in place, or
b) Transformers containing less than 500 gal (1893 L) of combustible transformer liquid.



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

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

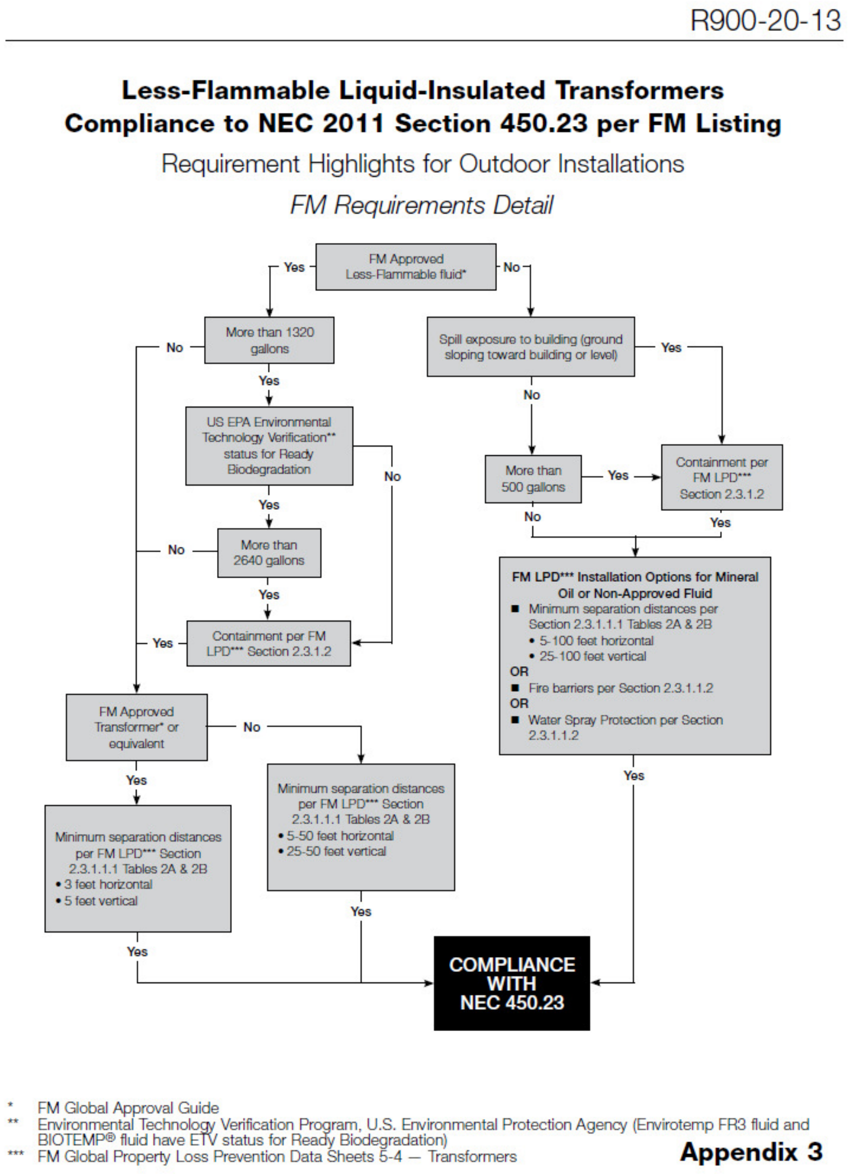
Liquid	FM Approved Transformer or Equivalent	Liquid Volume gal/(m^3)	Horizontal Distance**			Vertical Distance ft/(m)
			Fire Resistant ft/(m)	Non-Combustible ft/(m)	Combustible ft/(m)	
Less-Flammable (Approved)	Yes	N/A	3 (0.9)	3 (0.9)	3 (0.9)	5 (1.5)
	No	≤10,000 (38)	5 (1.5)	5 (1.5)	25 (7.6)	25 (7.6)
		>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.



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

Requirement Highlights for Outdoor Installations

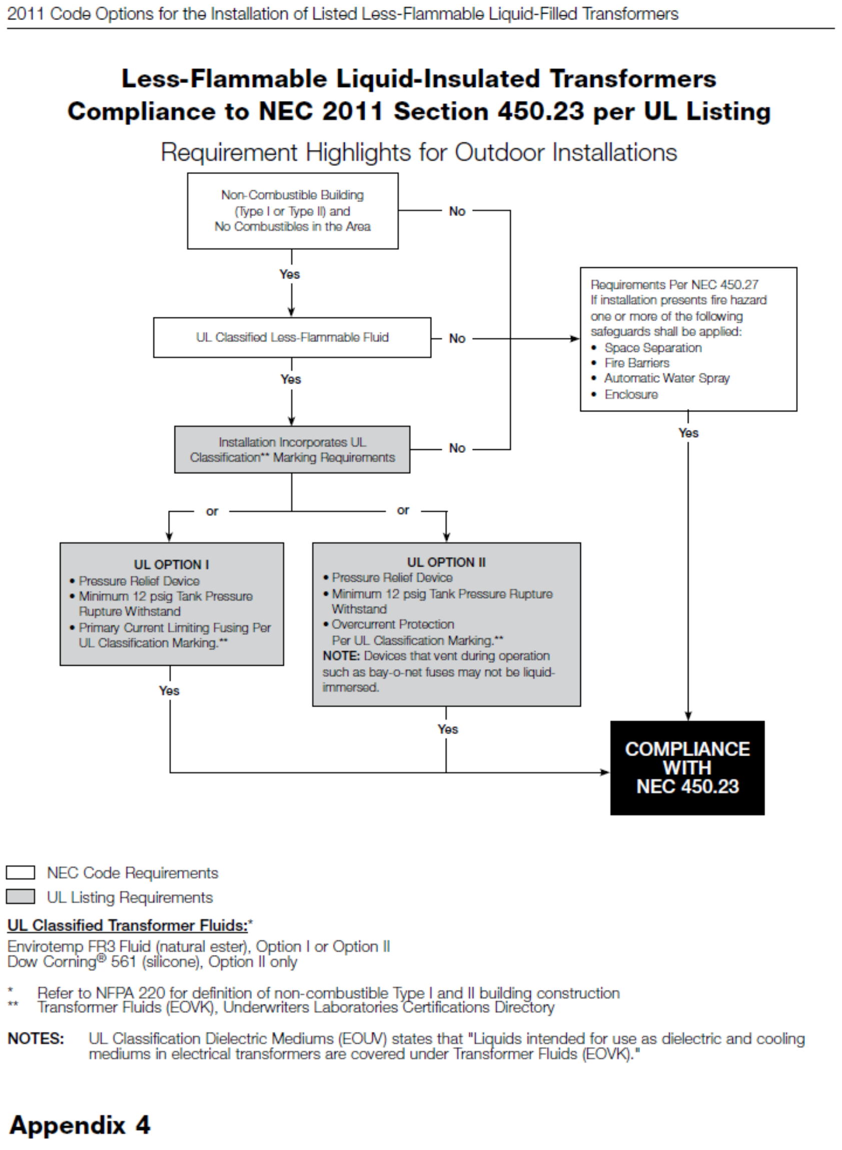
FM Requirements Detail

* 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

Structural Requirements

- Applied Forces
  - Wind
  - Ice
  - Forces from Short-Circuit Faults
- Design Considerations
  - Insulator strength to withstand forces from short-circuit faults
  - Structural steel strength under short-circuit fault forces (moments)
  - Foundation design under high moments
  - Ice loading, bus bar strength, and bus spans
  - Thermal expansion and use of expansion joints
- IEEE 605 – IEEE Guide for Design of Substation Rigid-Bus Structures

Station Design

- **Conventional** (Lattice Structures)
  - Angle (Chord & Lace) Members
  - Minimum Structure Weight
  - Requires Minimum Site Area
  - Stable and Rigid Construction
  - Requires Considerable Bolting & Erection Time
- **Low Profile** (Tubular / Folded Plate Structures)
  - Polygonal Shapes > Four Sides
  - Common Shapes
    - Octagon – Eight Sides
    - Dodecagon – Twelve Sides
  - Short Erection Time
  - Aesthetical Pleasing
  - Requires Greater Site Area
  - Shapes are not Readily Available

Station Design

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

Typical Ring Bus Substation Installation

Station Design - Conventional

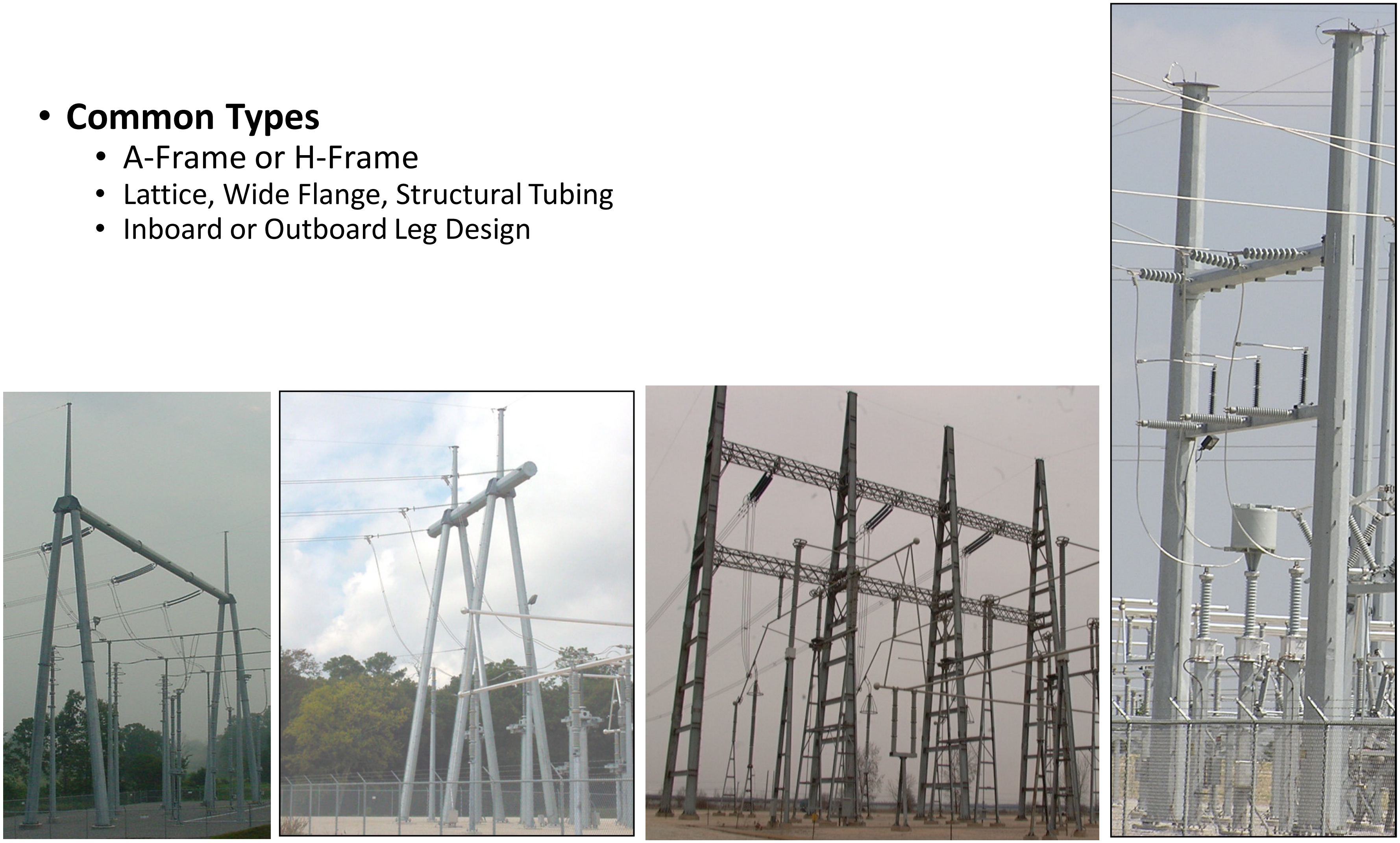
Station Design – Low Profile (tube)

Station Design – Low Profile (tube)

Station Design – Low Profile (tube)

Deadend Structures

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



Deadend Structure

Prefab Switchgear Building

Surge & Lightning Protection

- Surge Protection (Arresters)
  - Use Arresters (Station Class)
  - Transformer Protection (High Z Causes High V Reflected Wave)
  - Line Protection (Open End Causes High V Reflected Wave)
  - Systems above 169 kV Require Special Attention
  - IEEE C62.22 – IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems
- Lightning Protection
  - Strokes to Tall Structures; Strokes to Ground
  - Frequency – Isokeraunic Levels at Station Location
    - The keraunic (or ceraunic) level was the average number of days per year when thunder was heard in a given area

Surge & Lightning Protection

- Lightning Protection (cont’d)
  - Design Methods
    - Fixed Angles (good at or below 69 kV, generally applied up to 138 kV)
    - Empirical Curves (not used widely)
    - Whitehead’s EGM
    - Revised EGM
    - Rolling Sphere
- Combination of Surge Arresters and Lightning Shielding Provides Acceptable Levels of Protection
- IEEE 998 – IEEE Guide for Direct Lightning Stroke Shielding of Substations

OPGW Installation

Considerations:

1. Ensure OPGW is suitable for available short circuit
2. Ensure proper grounding
3. Ensure safe installation

OPGW Installation

OPGW / Static Wire Installation

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

$$Z = 2\pi \times f \times L$$

L steel structure >> L copper ground wire

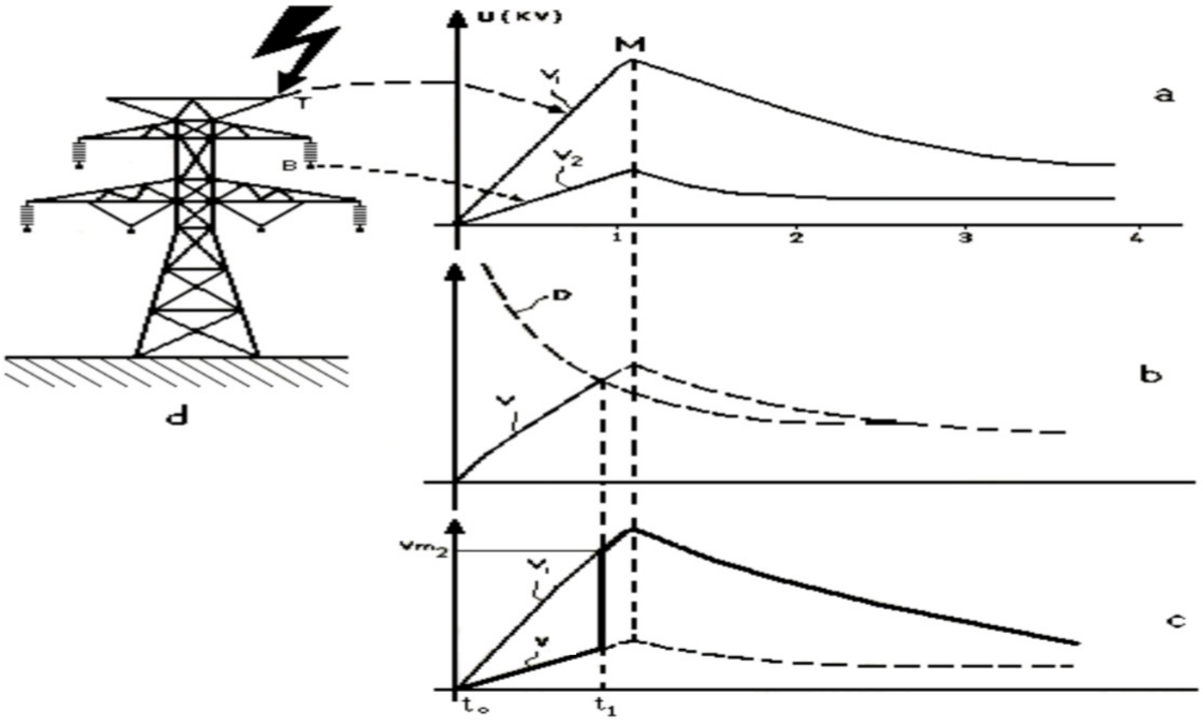
Z steel structure >> Z copper ground wire

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

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

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

OPGW / Static Wire Back Flashover (BFO)



V1 = Direct stroke of lightning to a transmission tower produces a voltage surge on the tower structure

V2 = Surge voltage with same waveform and lower amplitude induces on the phase conductors. The coupling factor between V1 and V2 may be variable from 15% to 25%.

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

D = illustrates insulation strength of line insulator.

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

Ref: “Back Flashover Phenomenon Analysis in Power Transmission Substation for Insulation Coordination” by Saeedollah Talaei Mobarakei, Taghi Sami, and Babak Porkar, IEEE 2012.

OHGW / Static Wire Installation

OHGW / Static Wire Installation

OHGW / Static Wire Installation

GROUND

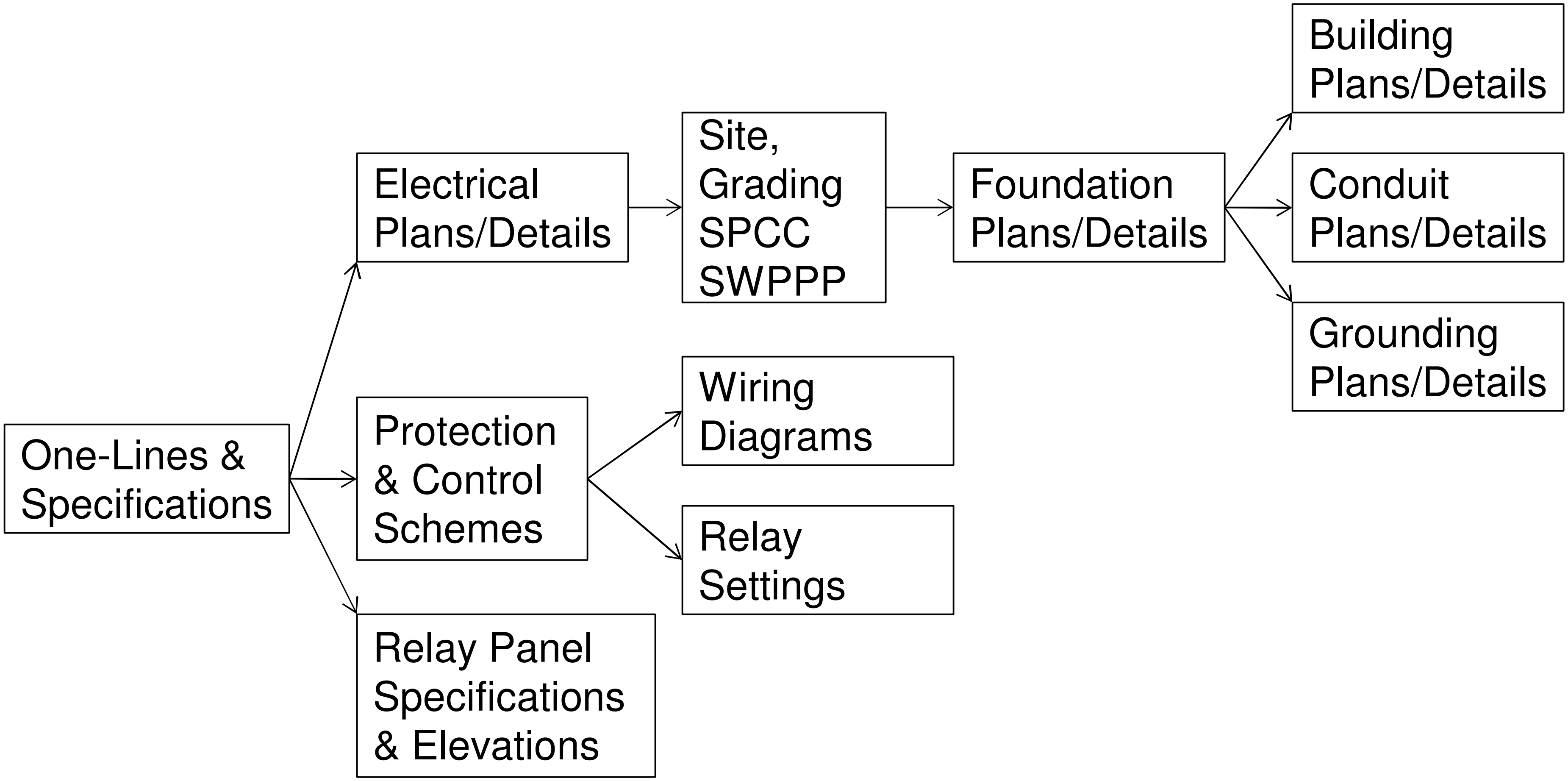
Grounding Considerations

Grounding

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

Engineering & Construction Coordination

Engineering Process



One-Lines & Specifications

Electrical Plans/Details

Protection & Control Schemes

Relay Panel Specifications & Elevations

Site, Grading SPCC SWPPP

Wiring Diagrams

Relay Settings

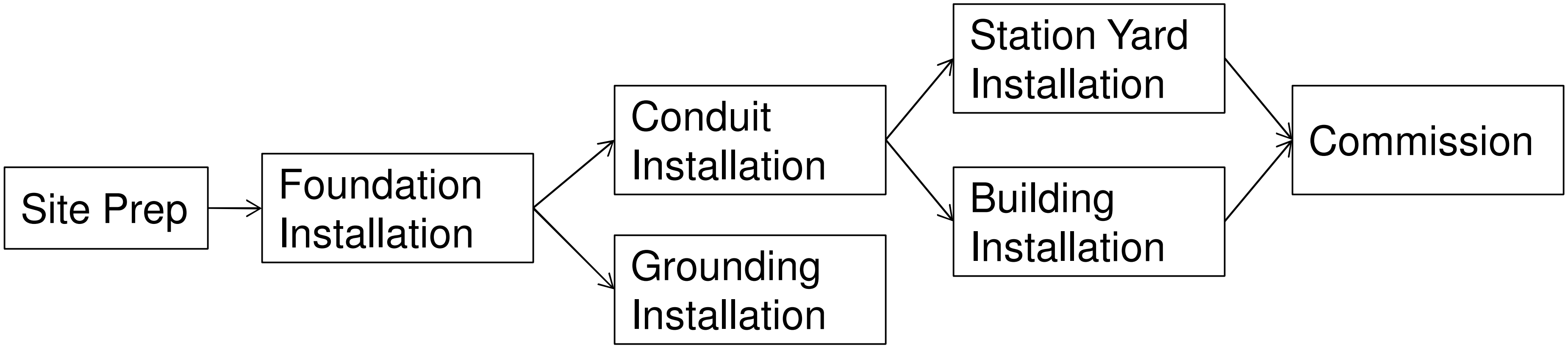
Foundation Plans/Details

Building Plans/Details

Conduit Plans/Details

Grounding Plans/Details

Construction Process


Site Prep

Foundation Installation

Conduit Installation

Grounding Installation

Station Yard Installation

Building Installation

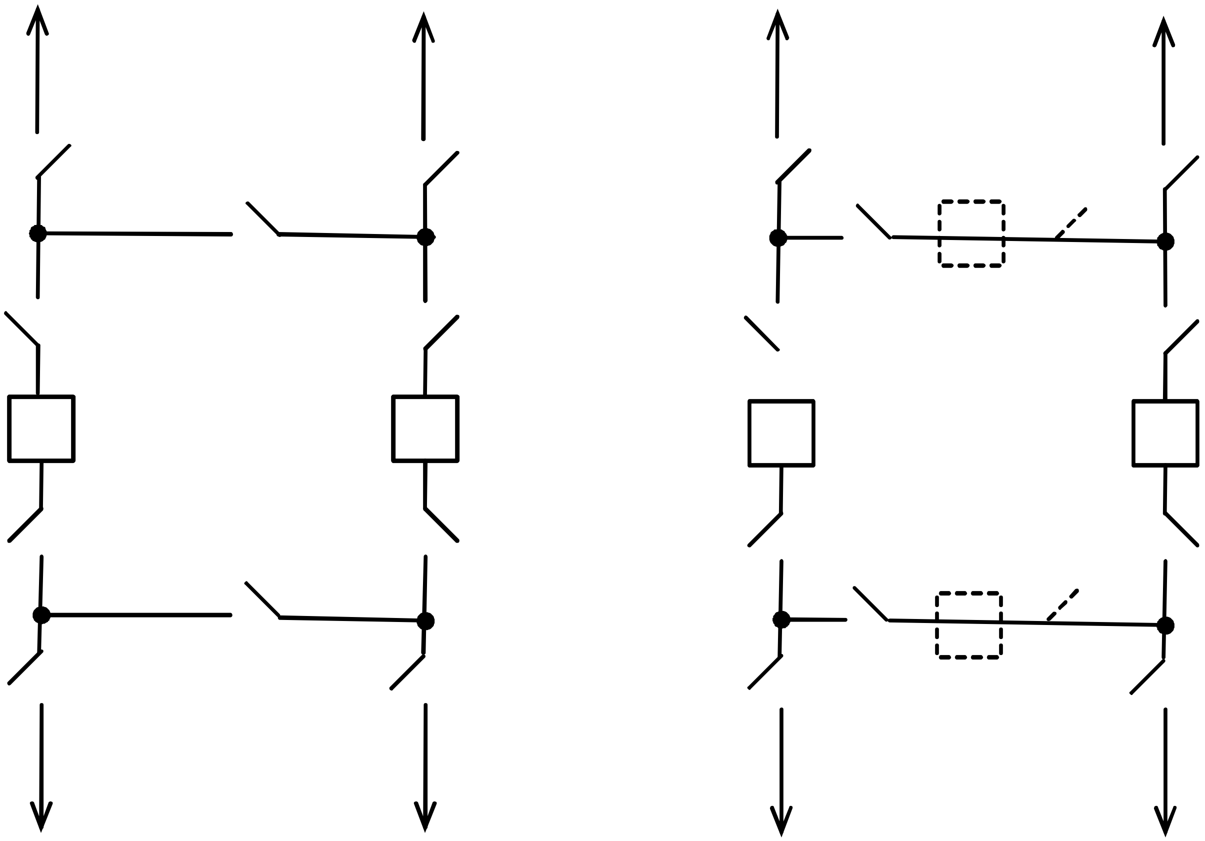
Commission

Supplemental Topics

Future Expansion Possibilities

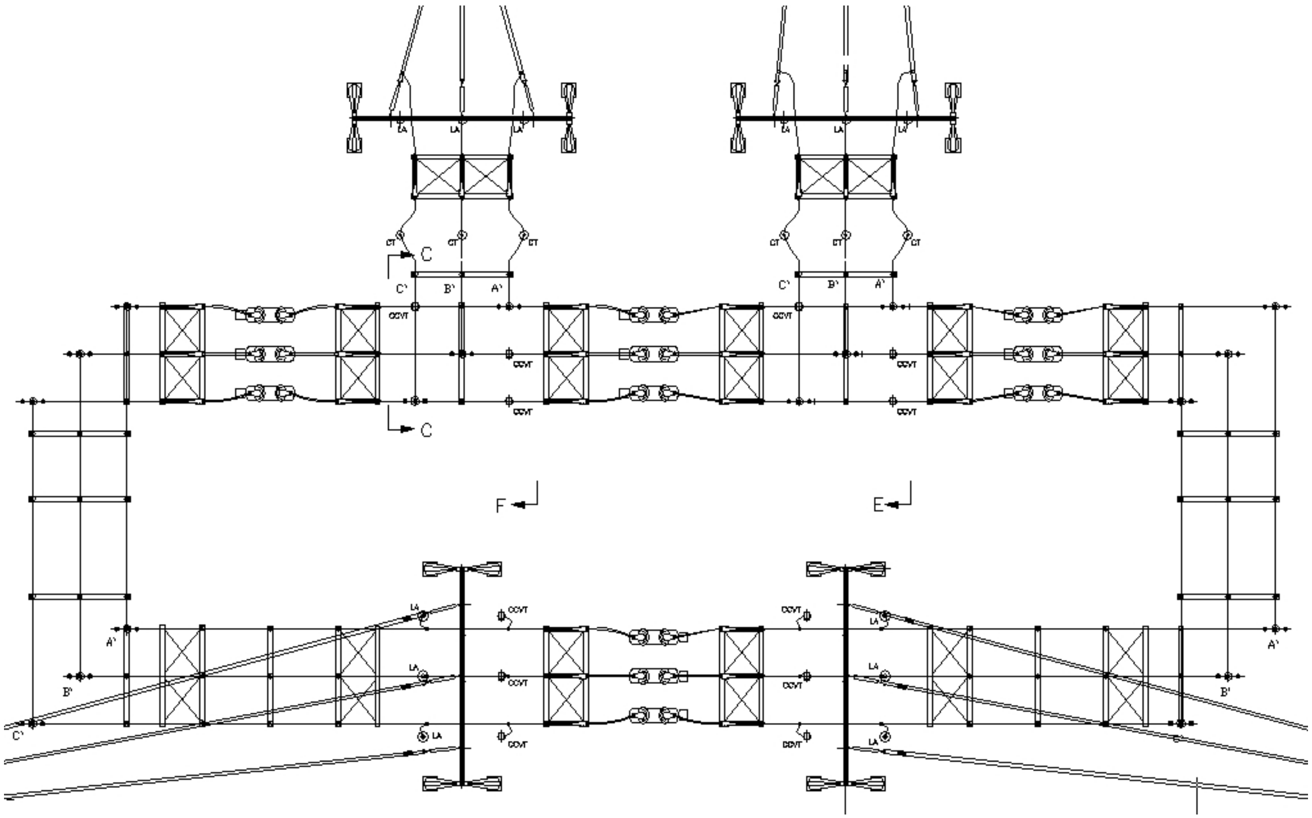
- Tap to Ring
  - Build as “Loop Tap”
  - Add switches to facilitate expansion
  - Initial layout considerate of final ring bus configuration

CenterPoint Tap Substation Configuration



Future Expansion Possibilities

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

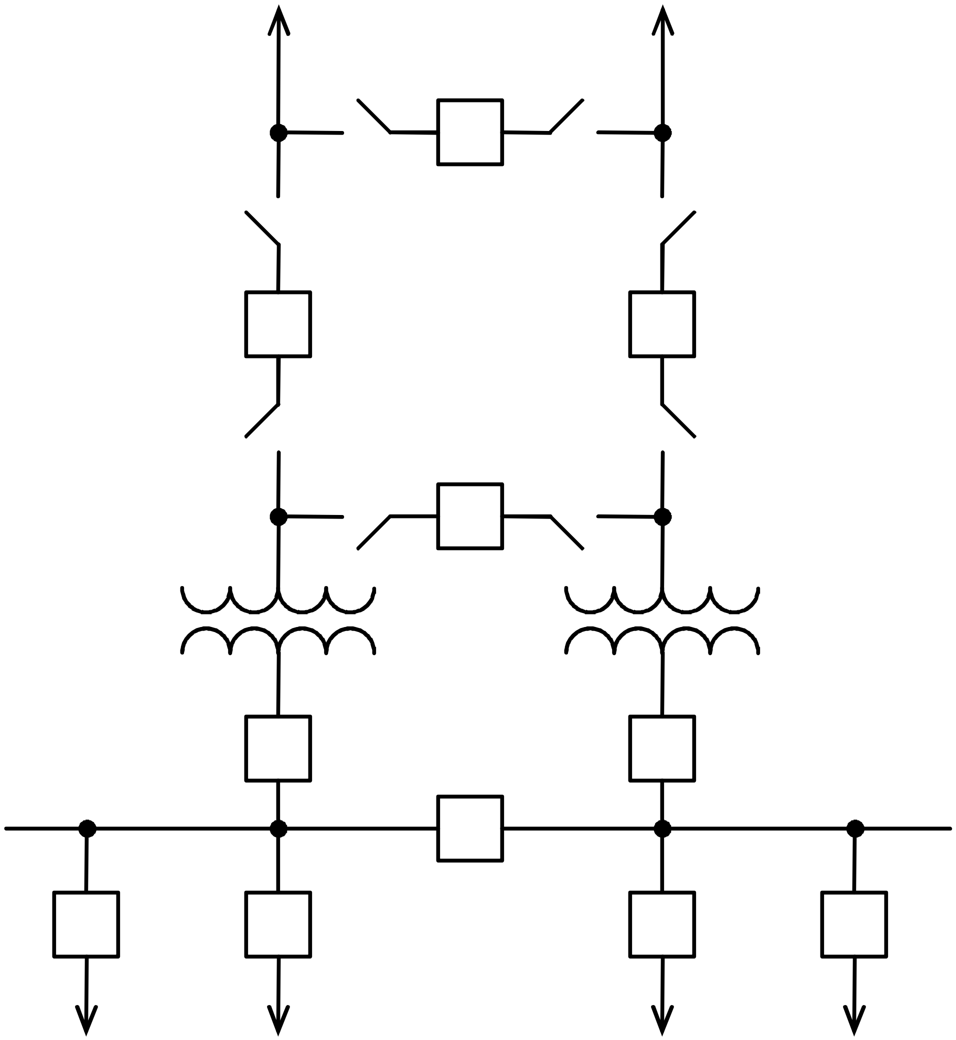


Future Expansion Possibilities

- Others
    - Ring Bus with Offset Lines
    - Expandable Bus

Mixing Bus Arrangements

- Example: Industrial
  - High-Voltage Ring Bus
  - Two Single Breaker Single Bus Medium-Voltage Systems with Tie Breaker (a.k.a. Secondary Selective)
- Variations Exist
  - Swap Line and Transformer Positions
  - Add 2nd Tie Breaker



Questions?