

HV Substation Design: Applications and Considerations

Dominik Pieniazek, P.E.

IEEE CED – Houston Chapter
October 2-3, 2012

HV

Engineering

www.hv-eng.com



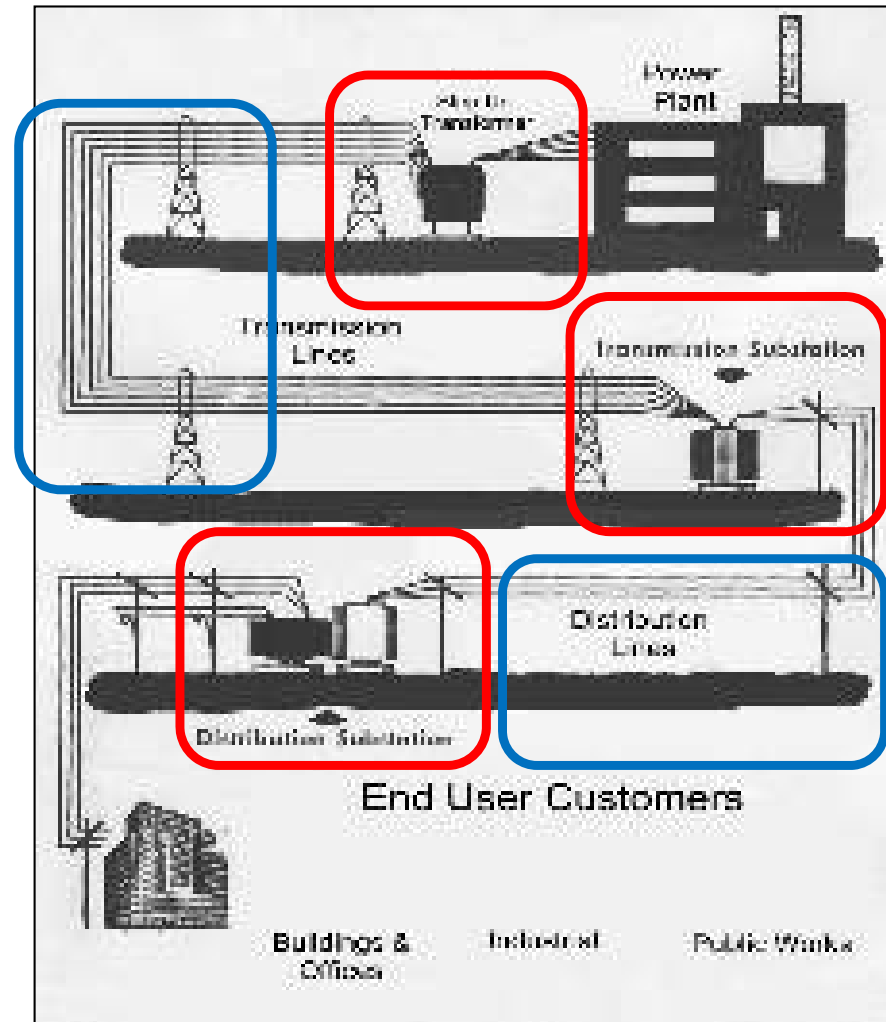
Houston Section

Agenda

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

Electrical System

- **Substation** - A set of equipment reducing the high voltage of electrical power transmission to that suitable for supply to consumers.
- **Switching Station** - A set of equipment used to tie together two or more electric circuits.



TRANSMISSION LEVEL VOLTAGES

765 kV

161 kV

500 kV

138 kV

345 kV

115 kV

230 kV

DISTRIBUTION LEVEL VOLTAGES

69 kV

15 kV

46 kV

4.16 kV

34.5 kV

480 V

23 kV



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



Typical 138 kV Substation



Typical 138 kV Substation



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



230 kV Indoor Generating Substation



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



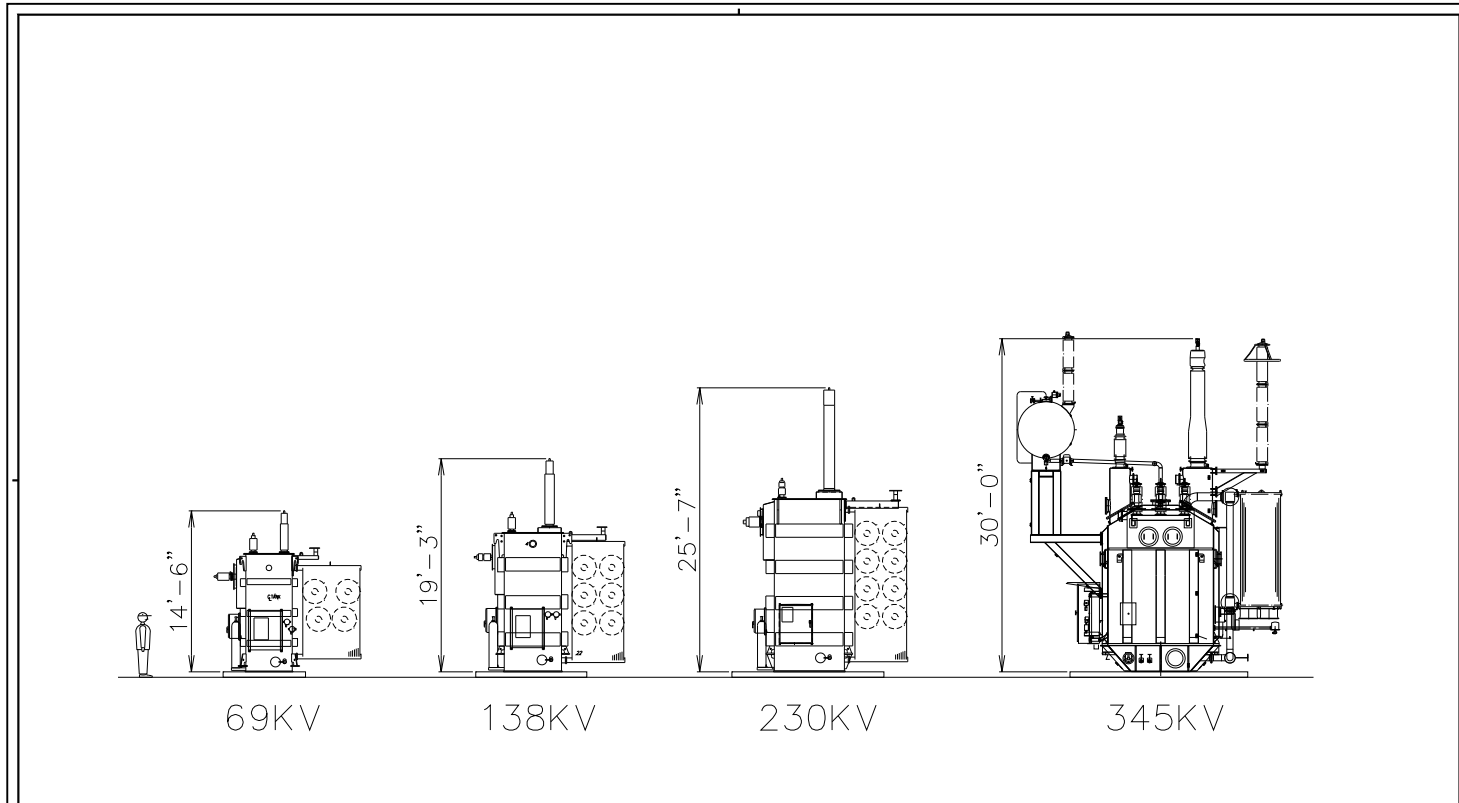
765 kV Generating Substation



765 kV Generating Substation



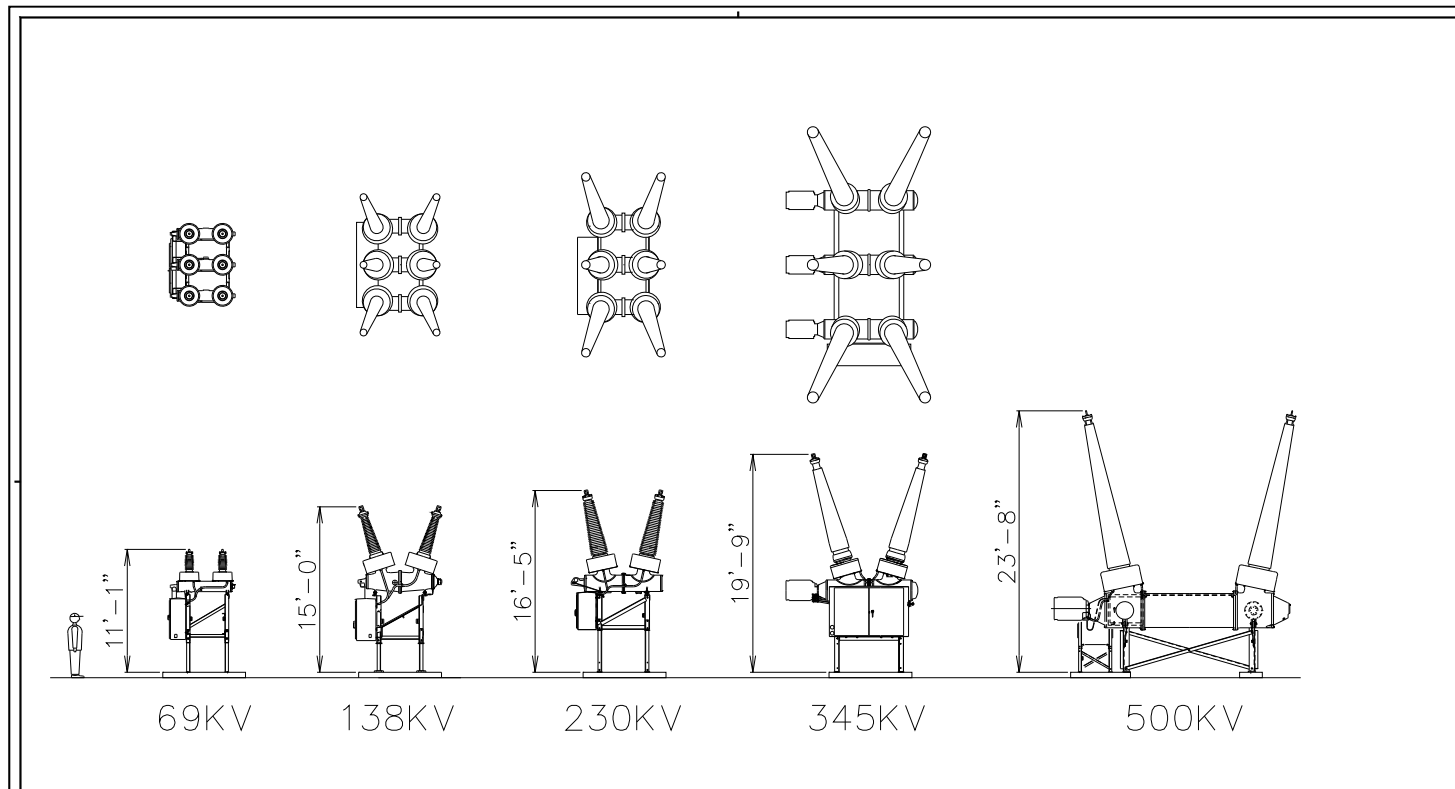
765 kV Generating Substation



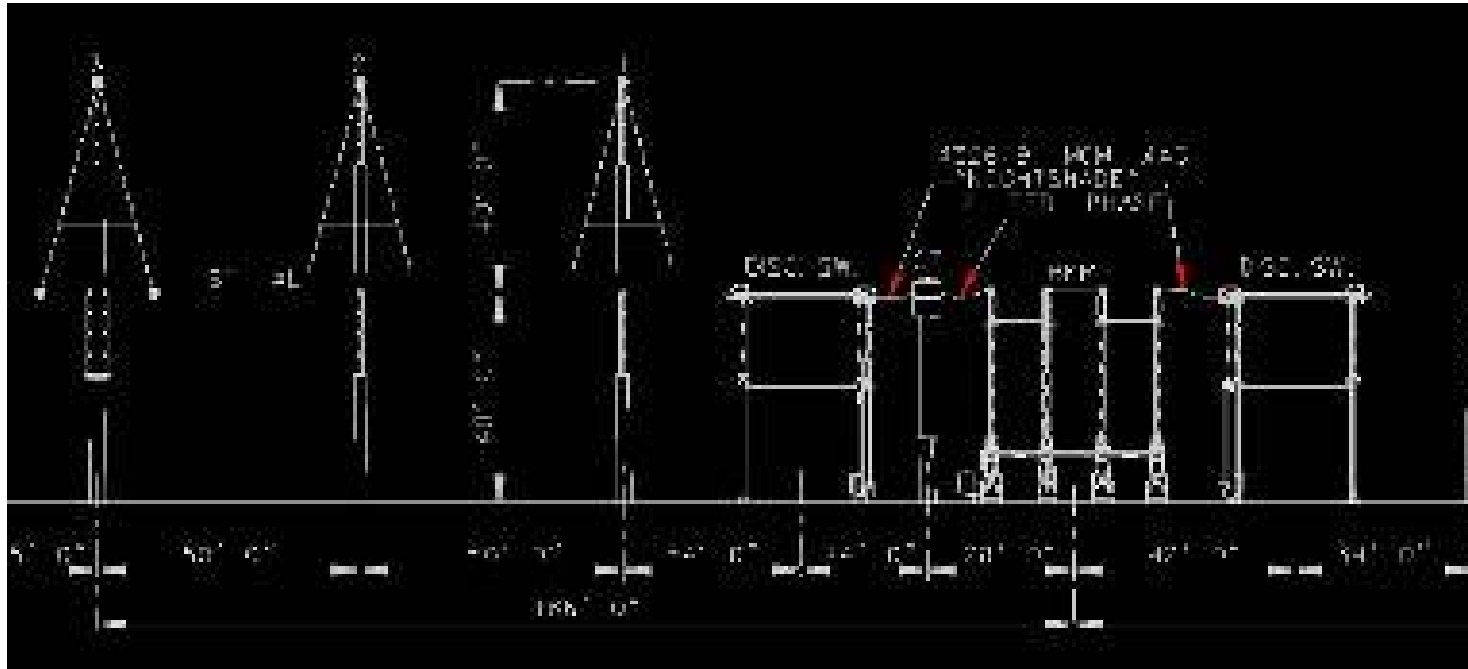
Relative Size of HV Power Transformers



Relative Size of HV and EHV Power Transformers



Relative Size of HV and EHV Gas Circuit Breakers



Dimensions for 765 kV Installation



Where Do I Start My Design?

- **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

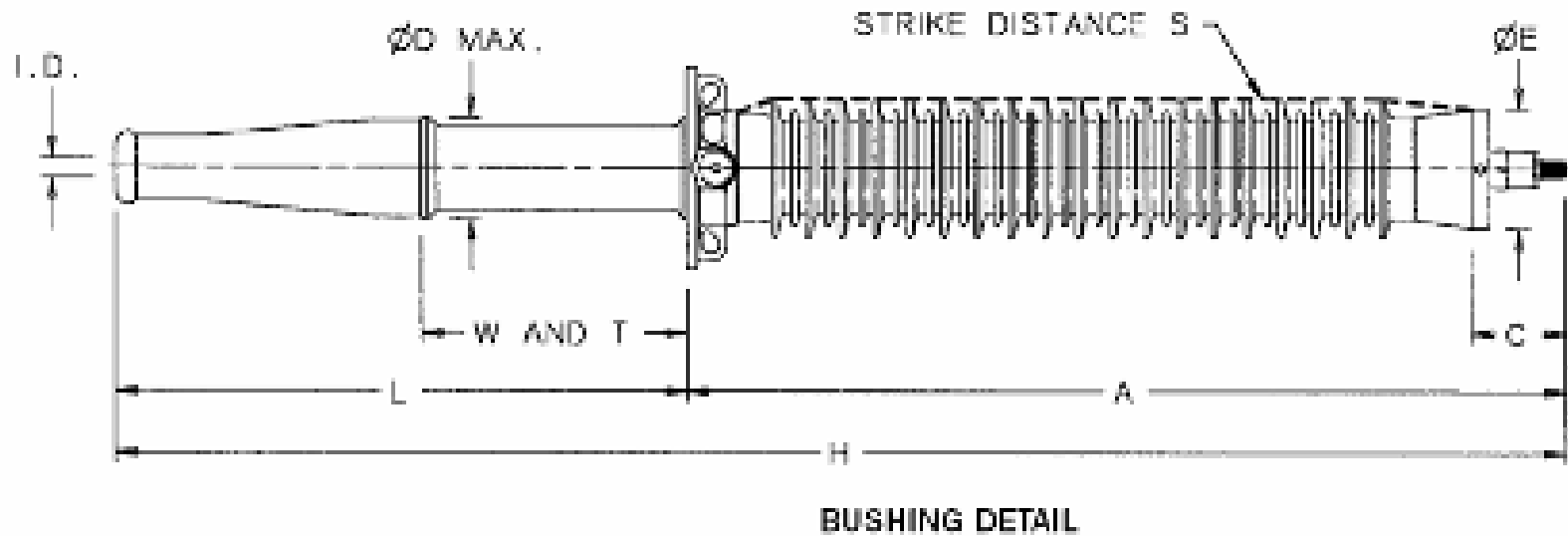
Table 1 - Bushing Data							Table 2 - Contamination Multipliers	
System Voltage		Bushing	Creepage Distance in Inches				Contamination Level	Multipling Factor
Nominal kV	Maximum kV	BIL kV	Light [1]	Medium [1]	Heavy [1]	Extra-Heavy [1]		
34.5	38.0	200	22	27	30	42	Light	20mm/kV
48	48.0	250	29	37	48	68	Medium	35mm/kV
69	72.0	300	44	56	69	80	Heavy	44mm/kV
115	121.0	500	73	91	110	141	Extra Heavy	54mm/kV
138	145.0	650	88	110	130	169		
161	169.0	750	102	120	161	190		
230	242.0	900	148	183	230	282		
345	362.0	1175	220	274	345	420		
500	550.0	1675	318	398	500	614		
765	800.0	2050	437	609	765	939		

Notes:

[1] Creepage distances shown in Table 1 are recommended values, based on IEEE standards C57.19.100-1995 & C57.010-1999.
 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

Typical Draw-Lead Bushing



Physical Questions to Address

Electrical Studies

- Power/Load Flow
- Short-Circuit / Device Evaluation
- Device Coordination
- Arc-Flash Hazard Assessment
- Motor Starting, Transient Stability
- Insulation Coordination
- Harmonic Analysis

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

Physical Questions to Address

- **Utility Requirements?**
 - Application of Utility Specifications
 - Application of Utility Standards
 - Application of Utility Protection and Control Schemes
 - SCADA/RTU Interface
 - Metering Requirements
- **Communication/Monitoring Requirements**
 - Manned or Unmanned
 - Power Management/Trending
 - Fault Recording
 - Local & Remote Annunciation
 - Local & Remote Control
 - Automation
 - Communication Protocol

Other Questions to Address

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

Other Questions to Address

- 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% 120% (with sect. breaker)
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

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

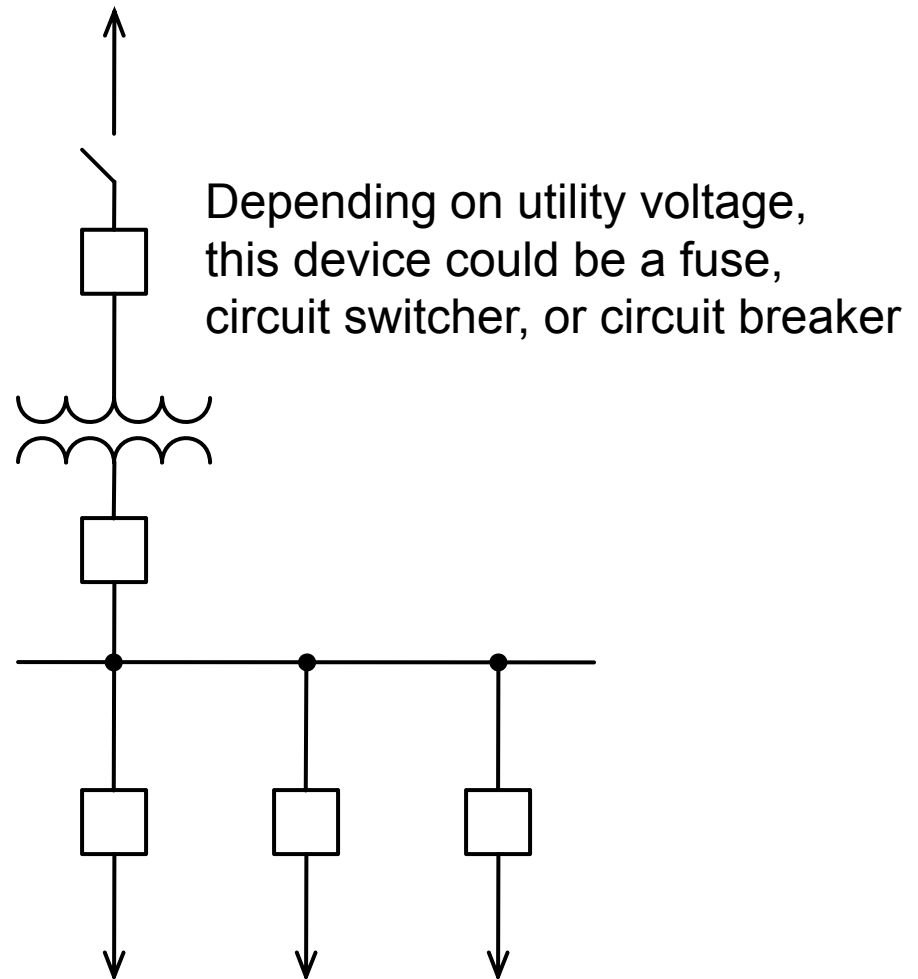
Reference: "Reliability of Substation Configurations", Daniel Nack, Iowa State University, 2005

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*"

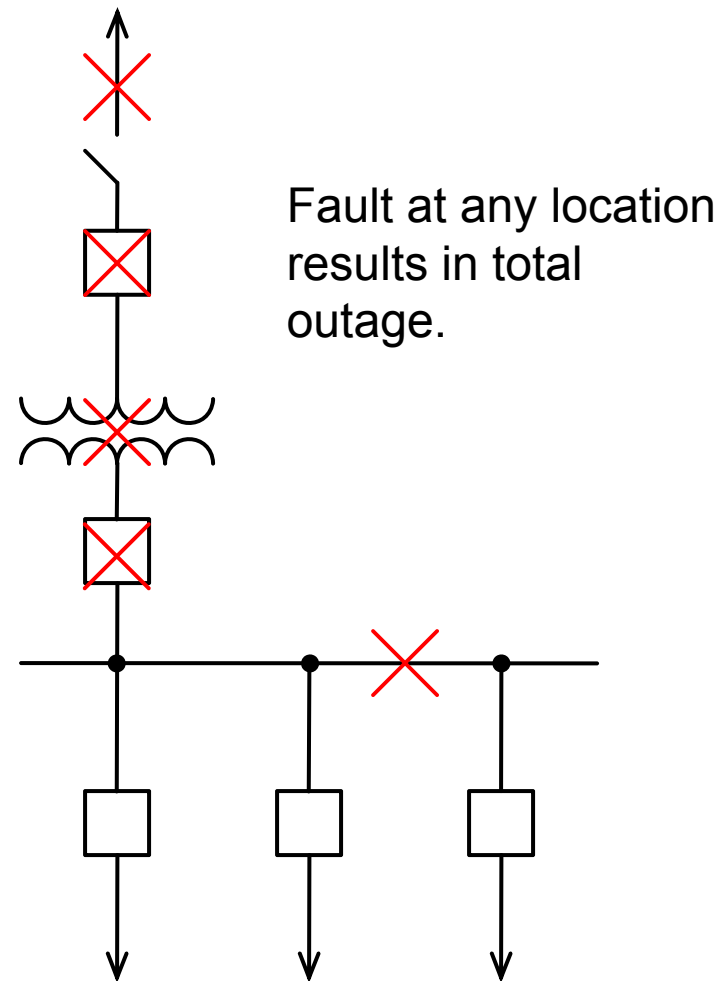
- Most Basic Design
- Tapped Line is Source of Power
- Interrupting Device Optional but Recommended
- No Operating Flexibility



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

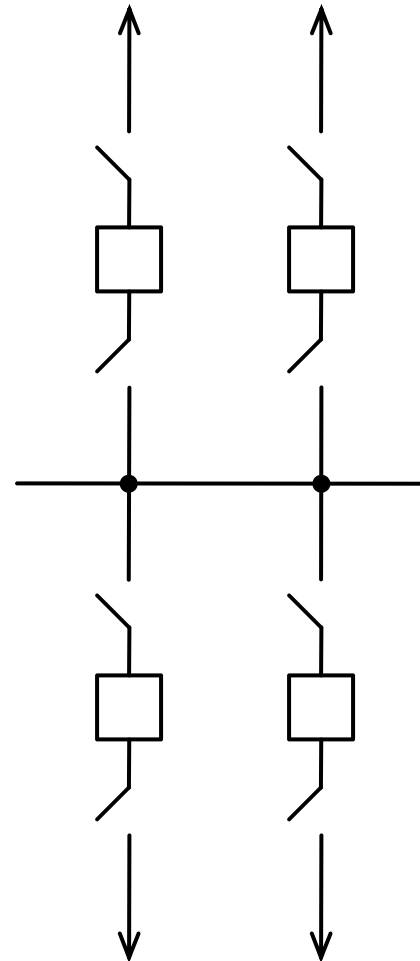
Cons

- 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

Tap Substation

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

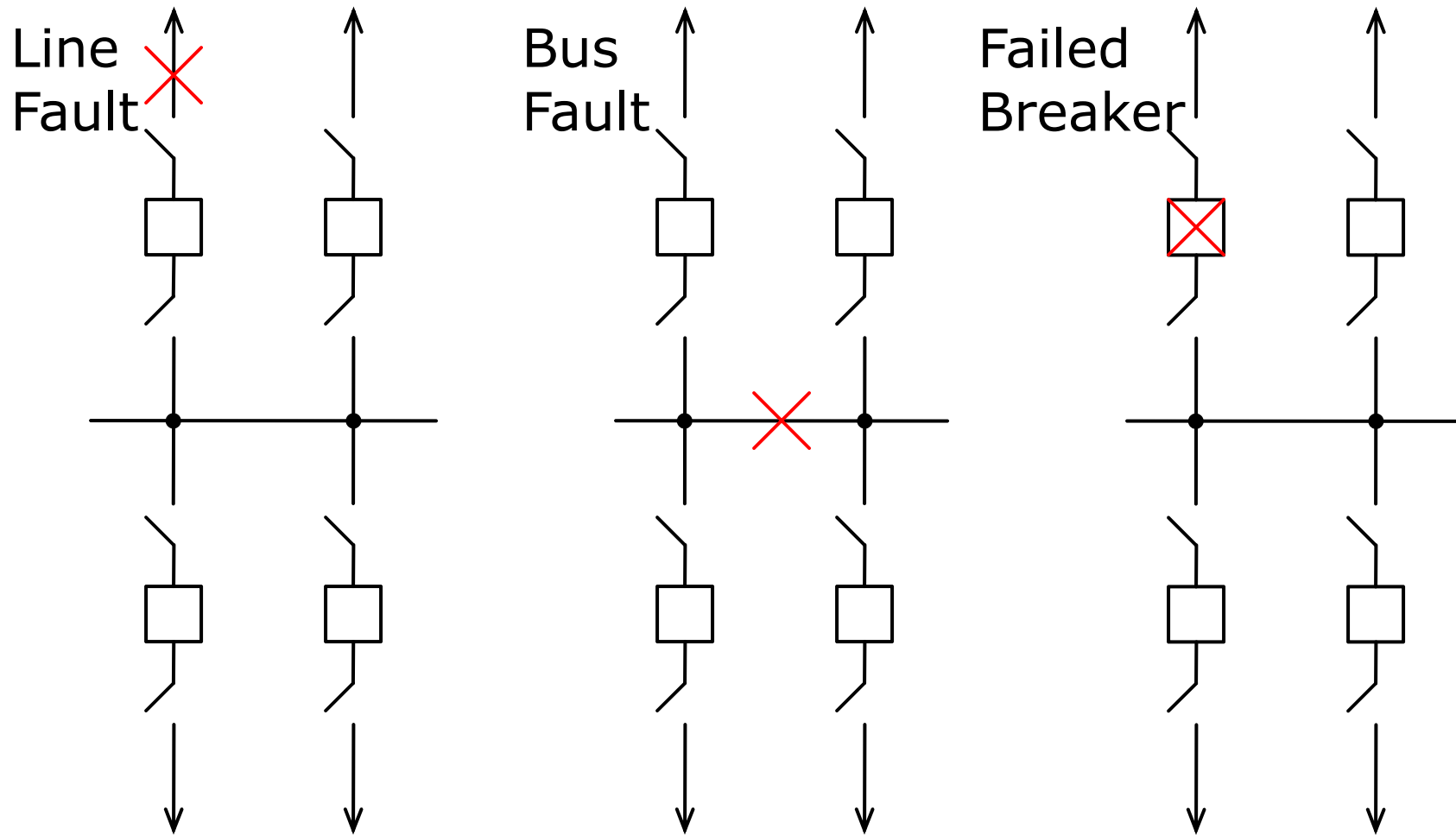
- Each Circuit has Breaker
- Only One Set of VTs Required
- Simple Design

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

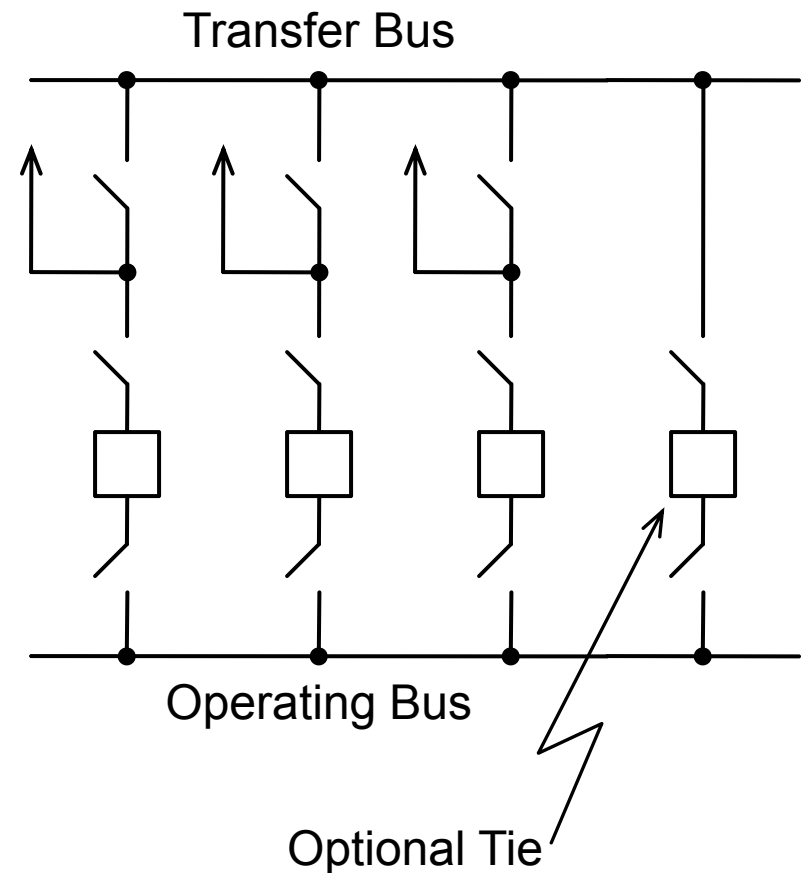
Single Breaker Single Bus

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



Pros

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

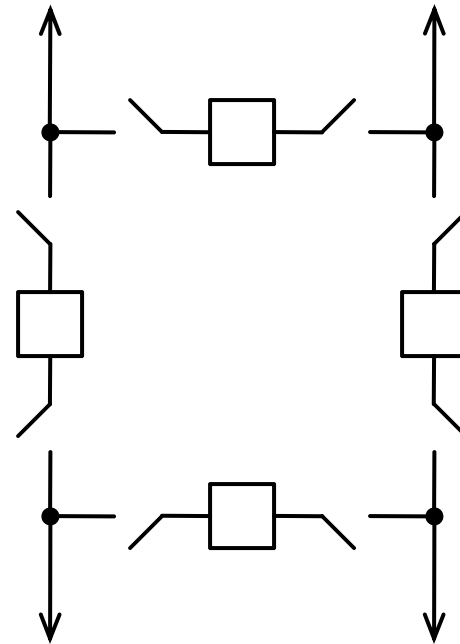
Cons

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

Operating/Transfer Buses with Single Breaker

Ring Bus

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



Pros

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

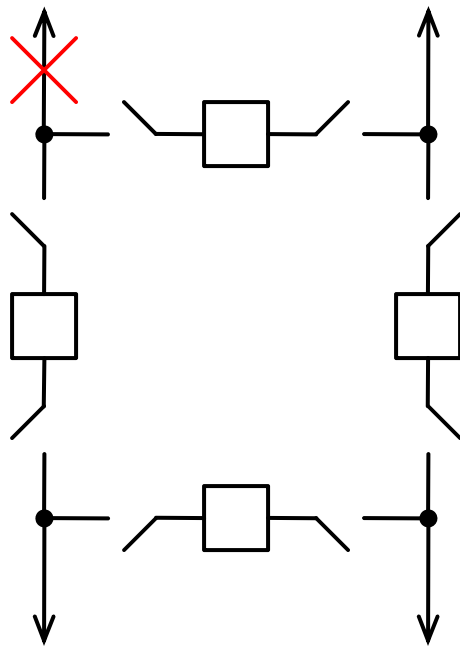
Cons

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

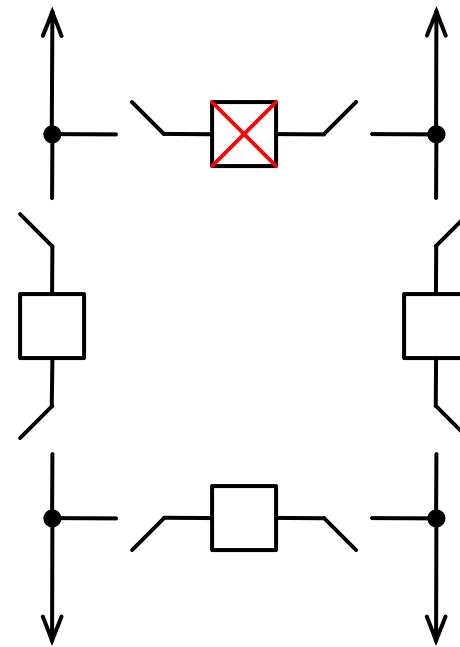
Ring Bus

Ring Bus

Line/Bus Fault

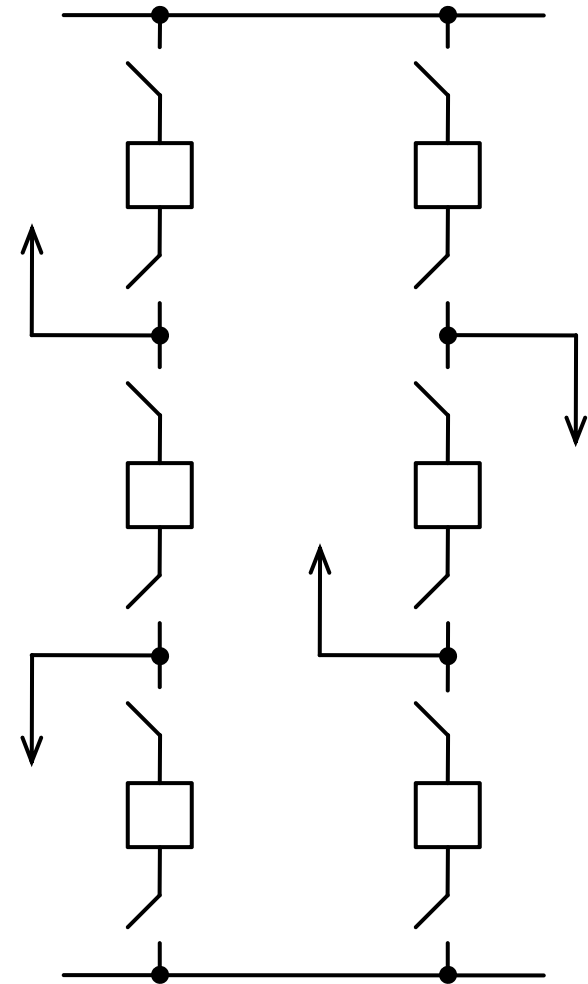


Failed Breaker



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)



Pros

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

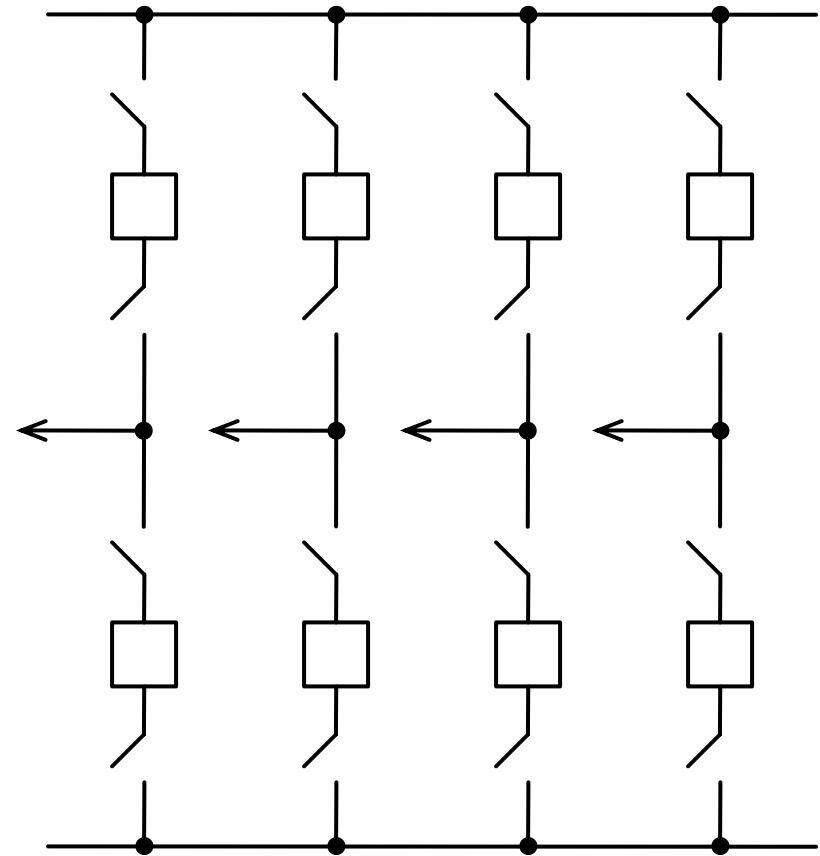
Cons

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

Breaker-And-A-Half

Double Breaker Double Bus

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



Pros

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

Cons

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

Double Breaker Double Bus

Physical Arrangement

Sh.
52

- 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 86-2
OUTDOOR SUBSTATIONS—BASIC PARAMETERS

Line No.	Rated Withstand Voltage		Minimum Medium Metal Dielectric Reference Height Supported Energized Conductors (feet) (meters)	Ground Clearances, Minimum (feet) (meters)		Tone Gap, Switch and Expansion Type (feet)	Horizontal Break Clearances, Switches	Min. Support, Vertical Dist. Overhead Switches Power Factor Corr. or other Types (feet) (meters)	Minimum Clearance Between Overhead Conductors and Ground for Personal Safety, Feet (Meters)	Withstand Vol. (kV)
	Rated Max. Vol. (kV rms)	Insulation Level 12 x 50 μ s Wave (kV rms)		Basic (kV rms)	Basic (kV rms)					
1	71	121	121	35	35	191	18	18	110	(71)
2	85.5	140	140	7 (0.10)	7.5 (0.19)	20 (0.91)	20 (0.70)	10 (0.10)	0 (2.14)	...
3	100	160	160	12 (0.30)	10 (0.25)	20 (0.91)	20 (0.70)	24 (0.71)	9 (2.74)	...
4	125	180	180	18 (0.30)	12 (0.30)	48 (1.22)	20 (0.71)	20 (0.71)	10 (3.05)	...
5	150	200	200	24 (0.40)	14 (0.34)	48 (1.22)	20 (0.71)	24 (0.71)	10 (3.05)	...
6	175	220	220	30 (0.70)	20 (0.50)	64 (2.13)	20 (0.71)	24 (0.71)	11 (3.35)	...
7	200	240	240	36 (1.00)	22 (0.60)	80 (2.44)	20 (0.71)	24 (0.71)	12 (3.66)	...
8	225	260	260	42 (1.20)	24 (0.60)	100 (3.05)	20 (0.71)	24 (0.71)	13 (3.96)	...
9	250	280	280	48 (1.50)	26 (0.60)	120 (3.66)	20 (0.71)	24 (0.71)	14 (4.27)	...
10	275	300	300	54 (1.60)	28 (0.60)	140 (4.27)	20 (0.71)	24 (0.71)	15 (4.57)	...
11	300	320	320	60 (1.80)	30 (0.70)	160 (4.88)	20 (0.71)	24 (0.71)	16 (4.88)	...
12	325	340	340	66 (2.00)	32 (0.70)	180 (5.49)	20 (0.71)	24 (0.71)	16 (4.88)	600
13	350	360	360	72 (2.10)	34 (0.70)	200 (6.10)	20 (0.71)	24 (0.71)	16 (4.88)	700
14	375	380	380	78 (2.30)	36 (0.70)	220 (6.71)	20 (0.71)	24 (0.71)	16 (4.88)	800
15	400	400	400	84 (2.50)	38 (0.70)	240 (7.32)	20 (0.71)	24 (0.71)	16 (4.88)	900
16	425	420	420	90 (2.70)	40 (0.70)	260 (7.93)	20 (0.71)	24 (0.71)	16 (4.88)	1000

NOTE: For insulation level, refer to ANSI C84.3 and C84.4.
 *Ground clearance for voltages 360 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 voltages were selected from Table 1 of IEEE Transaction Paper T82-1376 (Vol. 5, page 105), which is a report of the Transmission Substations Subcommittee. For additional switching surge values and ground clearances, refer to ANSI C84.

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 2. Recommended minimum electrical clearances for ungrounded systems where lightning impulse conditions govern^{1,2}

Maximum system voltage phase-to-phase (kV rms)	Base EFT ³ (kV rms)	Minimum phase-to-phase ⁴ clearances		Minimum phase-to-ground ^{4,5} clearances	
		min	1-in	min	1-in
15	30	24	16.7	32	21.3
	45	36	18.7	48	23.3
20	45	36	19.7	48	24.3
	60	48	21.7	64	26.3
25	60	48	20.7	64	27.3
	90	72	22.7	96	29.3
30	90	72	21.7	96	28.3
	120	96	23.7	128	30.3
35	120	96	22.7	128	29.3
	150	120	24.7	160	31.3
40	150	120	23.7	160	30.3
	180	144	25.7	192	32.3
45	180	144	24.7	192	31.3
	225	180	26.7	240	33.3
50	225	180	25.7	240	32.3
	270	216	27.7	288	34.3
55	270	216	26.7	288	33.3
	315	252	28.7	336	35.3
60	315	252	27.7	336	34.3
	360	288	29.7	384	36.3
65	360	288	28.7	384	35.3
	405	324	30.7	432	37.3
70	405	324	29.7	432	36.3
	450	360	31.7	480	38.3
75	450	360	30.7	480	37.3
	525	420	32.7	576	39.3
80	525	420	31.7	576	38.3
	600	480	33.7	672	40.3
85	600	480	32.7	672	39.3
	675	540	34.7	768	41.3
90	675	540	33.7	768	40.3
	750	600	35.7	864	42.3
95	750	600	34.7	864	41.3
	825	660	36.7	960	43.3
100	825	660	35.7	960	42.3
	900	720	37.7	1056	44.3
105	900	720	36.7	1056	43.3
	975	780	38.7	1152	45.3
110	975	780	37.7	1152	44.3
	1050	840	39.7	1248	46.3
115	1050	840	38.7	1248	45.3
	1125	900	40.7	1344	47.3
120	1125	900	39.7	1344	46.3
	1200	960	41.7	1440	48.3
125	1200	960	40.7	1440	47.3
	1275	1020	42.7	1536	49.3
130	1275	1020	41.7	1536	48.3
	1350	1080	43.7	1632	50.3
135	1350	1080	42.7	1632	49.3
	1425	1140	44.7	1728	51.3
140	1425	1140	43.7	1728	50.3
	1500	1200	45.7	1824	52.3
145	1500	1200	44.7	1824	51.3
	1575	1260	46.7	1920	53.3
150	1575	1260	45.7	1920	52.3
	1650	1320	47.7	2016	54.3
155	1650	1320	46.7	2016	53.3
	1725	1380	48.7	2112	55.3
160	1725	1380	47.7	2112	54.3
	1800	1440	49.7	2208	56.3
165	1800	1440	48.7	2208	55.3
	1875	1500	50.7	2304	57.3
170	1875	1500	49.7	2304	56.3
	1950	1560	51.7	2400	58.3
175	1950	1560	50.7	2400	57.3
	2025	1620	52.7	2496	59.3
180	2025	1620	51.7	2496	58.3
	2100	1680	53.7	2592	60.3
185	2100	1680	52.7	2592	59.3
	2175	1740	54.7	2688	61.3
190	2175	1740	53.7	2688	60.3
	2250	1800	55.7	2784	62.3
195	2250	1800	54.7	2784	61.3
	2325	1860	56.7	2880	63.3
200	2325	1860	55.7	2880	62.3
	2400	1920	57.7	2976	64.3
205	2400	1920	56.7	2976	63.3
	2475	1980	58.7	3072	65.3
210	2475	1980	57.7	3072	64.3
	2550	2040	59.7	3168	66.3
215	2550	2040	58.7	3168	65.3
	2625	2100	60.7	3264	67.3
220	2625	2100	59.7	3264	66.3
	2700	2160	61.7	3360	68.3
225	2700	2160	60.7	3360	67.3
	2775	2220	62.7	3456	69.3
230	2775	2220	61.7	3456	68.3
	2850	2280	63.7	3552	70.3
235	2850	2280	62.7	3552	69.3
	2925	2340	64.7	3648	71.3
240	2925	2340	63.7	3648	70.3
	3000	2400	65.7	3744	72.3
245	3000	2400	64.7	3744	71.3
	3075	2460	66.7	3840	73.3
250	3075	2460	65.7	3840	72.3
	3150	2520	67.7	3936	74.3
255	3150	2520	66.7	3936	73.3
	3225	2580	68.7	4032	75.3
260	3225	2580	67.7	4032	74.3
	3300	2640	69.7	4128	76.3
265	3300	2640	68.7	4128	75.3
	3375	2700	70.7	4224	77.3
270	3375	2700	69.7	4224	76.3
	3450	2760	71.7	4320	78.3
275	3450	2760	70.7	4320	77.3
	3525	2820	72.7	4416	79.3
280	3525	2820	71.7	4416	78.3
	3600	2880	73.7	4512	80.3
285	3600	2880	72.7	4512	79.3
	3675	2940	74.7	4608	81.3
290	3675	2940	73.7	4608	80.3
	3750	3000	75.7	4704	82.3
295	3750	3000	74.7	4704	81.3
	3825	3060	76.7	4800	83.3
300	3825	3060	75.7	4800	82.3
	3900	3120	77.7	4896	84.3
305	3900	3120	76.7	4896	83.3
	3975	3180	78.7	4992	85.3
310	3975	3180	77.7	4992	84.3
	4050	3240	79.7	5088	86.3
315	4050	3240	78.7	5088	85.3
	4125	3300	80.7	5184	87.3
320	4125	3300	79.7	5184	86.3
	4200	3360	81.7	5280	88.3
325	4200	3360	80.7	5280	87.3
	4275	3420	82.7	5376	89.3
330	4275	3420	81.7	5376	88.3
	4350	3480	83.7	5472	90.3
335	4350	3480	82.7	5472	89.3
	4425	3540	84.7	5568	91.3
340	4425	3540	83.7	5568	90.3
	4500	3600	85.7	5664	92.3
345	4500	3600	84.7	5664	91.3
	4575	3660	86.7	5760	93.3
350	4575	3660	85.7	5760	92.3
	4650	3720	87.7	5856	94.3
355	4650	3720	86.7	5856	93.3
	4725	3780	88.7	5952	95.3
360	4725	3780	87.7	5952	94.3
	4800	3840	89.7	6048	96.3
365	4800	3840	88.7	6048	95.3
	4875	3900	90.7	6144	97.3
370	4875	3900	89.7	6144	96.3
	4950	3960	91.7	6240	98.3
375	4950	3960	90.7	6240	97.3
	5025	4020	92.7	6336	99.3
380	5025	4020	91.7	6336	98.3
	5100	4080	93.7	6432	100.3
385	5100	4080	92.7	6432	99.3
	5175	4140	94.7	6528	101.3
390	5175	4140	93.7	6528	100.3
	5250	4200	95.7	6624	102.3
395	5250	4200	94.7	6624	101.3
	5325	4260	96.7	6720	103.3
400	5325	4260	95.7	6720	102.3
	5400	4320	97.7	6816	104.3
405	5400	4320	96.7	6816	103.3
	5475	4380	98.7	6912	105.3
410	5475	4380	97.7	6912	104.3
	5550	4440	99.7	7008	106.3
415	5550	4440	98.7	7008	105.3
	5625	4500	100.7	7104	107.3
420	5625	4500	99.7	7104	106.3
	5700	4560	101.7	7200	108.3
425	5700	4560	100.7	7200	107.3
	5775	4620	102.7	7296	109.3
430	5775	4620	101.7	7296	108.3
	5850	4680	103.7	7392	110.3
435	5850	4680	102.7	7392	109.3
	5925	4740	104.7	7488	111.3
440	5925	4740	103.7	7488	110.3
	6000	4800	105.7	7584	112.3
445	6000	4800	104.7	7584	111.3
	6075	4860	106.7	7680	113.3
450	6075	4860	105.7	7680	112.3
	6150	4920	107.7	7776	114.3
455	6150	4920	106.7	7776	113.3
	6225	4980	108.7	7872	115.3
460	6225	4980	107.7	7872	114.3
	6300	5040	109.7	7968	116.3
465	6300	5040	108.7	7968	115.3
	6375	5100	110.7	8064	117.3
470	6375	5100	109.7	8064	116.3
	6450	5160	111.7	8160	118.3
475	6450	5160	110.7	8160	117.3
	6525	5220	112.7	8256	119.3
480	6525	5220	111.7	8256	118.3
	6600	5280	113.7	8352	120.3
485	6600	5280	112.7	8352	119.3
	6675	5340	114.7	8448	121.3
490	6675	5340	113.7	8448	120.3
	6750	5400	115.7	8544	122.3
495	6750	5400	114.7	8544	121.3
	6825	5460	116.7	8640	123.3

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
71.5	350	4.89
123	550	4.47
145	650	4.48
168	750	4.46
242	900	3.72
362	1050	4.31
	1050	2.90
350	1300	3.59
	1550	2.52
500	1800	3.27
	1800	2.25
	2050	2.15
	2300	3.88

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.

Spacing & Clearances

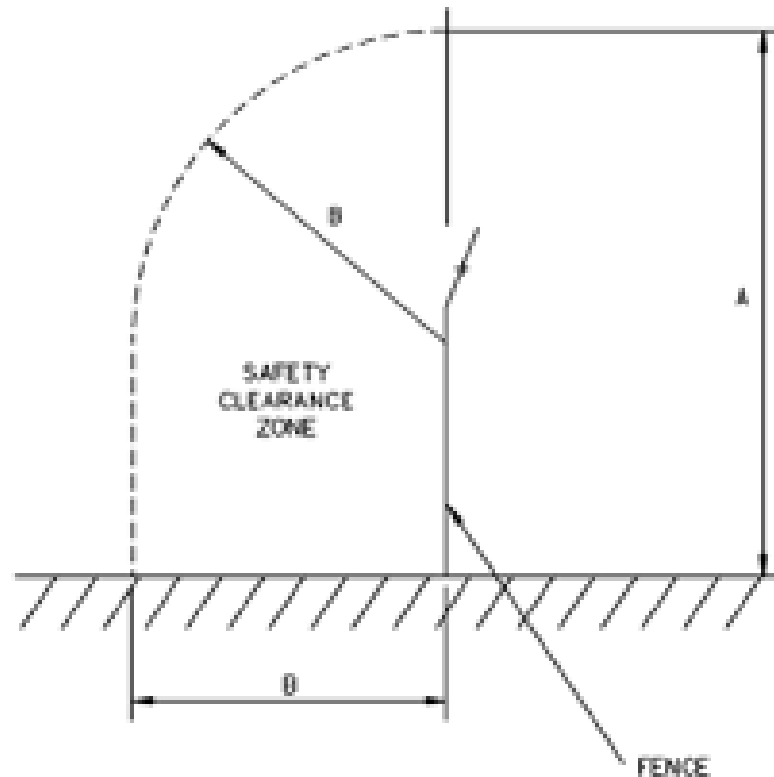
- IEEE 1427-2006 – What It Doesn't Address
 - Uprating (Discussion Only)
 - Wildlife Conservation
 - Shielding Effects
 - Contamination
 - Hardware & Corona
 - Arcing During Switch Operation
 - Mechanical Stress Due to Fault Currents
 - Safety

Spacing & Clearances

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

Spacing & Clearances

- NESC Fence Safety Clearance



Spacing & Clearances

IEEE C37.32

Table 4-8: Phase Spacing of Outdoor Air Switches. Ref. ANSI Std. C37.32-1995, Table 5.
Reproduced with permission of the National Electrical Manufacturers Association.

Centerline-to-Centerline Phase Spacing
meters (inches)

Nominal Phase-to- Phase Voltage kV	Maximum Phase-to-Phase Voltage kV	DCL 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	8.5	85	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)
25	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	48.5	250	0.533 (21)	1.22 (48)	1.52 (60)	1.83 (72)
69	72.5	350	0.762 (31)	1.52 (60)	1.83 (72)	2.13 (84)
115	121	350	1.35 (53)	2.13 (84)	2.74 (108)	3.05 (120)
138	145	450	1.83 (72)	2.44 (96)	3.05 (120)	3.66 (144)
151	169	350	1.83 (72)	2.74 (108)	3.66 (144)	4.27 (168)
160	242	600	2.29 (90)	3.35 (132)	4.87 (192)	4.87 (192)
160	242	1050	2.67 (105)	3.66 (144)	5.50 (216)	5.50 (216)
315	362	1050	2.67 (105)	3.66 (144)	5.49 (216)	5.49 (216)
315	362	1350	3.02 (119)	4.43 (174)	—	—

Notes:
(1) Values taken from ANSI C37.32 and NFMA 966.
(2) Values listed are for altitudes of 1000 meters (3300 feet) or less. For higher altitudes, the altitude correction factors listed in Table 4-3 should be applied.

Spacing & Clearances



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

Dielectric Fluids



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.¹

Liquid	FM Approval Transformer or Substation	Liquid Volume gal/m ³	Horizontal Distance ²			
			Fire Transformer (m ²)	Non-Fire Transformer (m ²)	Combustible (m ²)	Vertical Obstruction (m ²)
Listed Transformer (Approved)	Yes	NA	0 ft (0)	0 ft (0)	0 ft (0)	0 ft (0)
	No	>10,000 (378)	5 ft (1.5)	5 ft (1.5)	5 ft (1.5)	5 ft (1.5)
Unlisted Oil	NA	>100 (3.78)	5 ft (1.5)	5 ft (1.5)	5 ft (1.5)	5 ft (1.5)
		100-5,000 (3.78-189)	15 ft (4.5)	15 ft (4.5)	15 ft (4.5)	15 ft (4.5)
		>5,000 (189)	25 ft (7.5)	25 ft (7.5)	25 ft (7.5)	25 ft (7.5)

¹ FM Global Loss Prevention Data Sheet D-4, Table 2a
² All transformer components must be accessible for inspection and maintenance.

TABLE 8. FM Outdoor Fluid-Insulated Transformers Equipment Separation Distance.¹

Liquid	FM Approval Transformer or Substation	Liquid Volume gal/m ³	Distance ² (ft)
Listed Transformer (Approved)	Yes	NA	10 ft (3)
	No	>10,000 (378)	5 ft (1.5)
Unlisted Oil	NA	>100 (3.78)	5 ft (1.5)
		100-5,000 (3.78-189)	15 ft (4.5)
		>5,000 (189)	25 ft (7.5)

¹ FM Global Loss Prevention Data Sheet D-4, Table 2b
² All transformer components must be accessible for inspection and maintenance.

Spacing & Clearances

Spacing Affects Structural Design

Spacing & Clearances

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

Structural Requirements

Deflection

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

<u>Description</u>	<u>Deflection Limit</u>
Class A Structures	
Horizontal Deflection of Vertical Members	$l/100$
Vertical Deflection of Horizontal Members	$l/200$
Horizontal Deflection of Horizontal Members	$l/200$

Structural Design

Deflection

Class B: Those Structures on Which the Deflections Within the Limit Stated Do Not Affect the Performance of the Support Equipment (i.e., Bus Support, Line Termination Structures, etc.)

<u>Description</u>	<u>Deflection Limit</u>
Class B Structures	
Horizontal Deflection of Vertical Members	$L/50$
Vertical Deflection of Horizontal Members	$L/200$
Horizontal Deflection of Horizontal Members	$L/100$

Structural Design

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

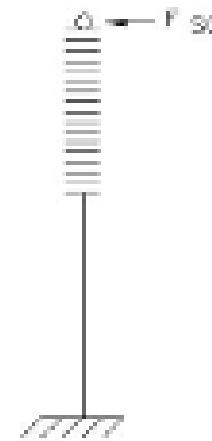
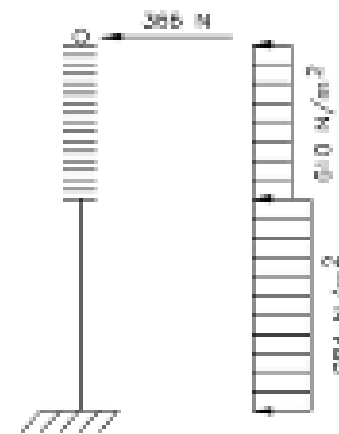


Figure 7-2: Tubular Structure—Short-Circuit Loading



Structural Design

Short-Circuit Forces

$$F_{ij} = \frac{\mu}{4\pi r^2} i_1 i_2 \mathbf{a}_1 \times (\mathbf{a}_2 \times \mathbf{r})$$

where

- μ is the magnetic permeability equal to $4\pi \times 10^{-7} \text{ V}\cdot\text{s}/(\text{A}\cdot\text{m})$
- r is the distance between the two conductor segments
- \mathbf{u} is the unit directional vector in the direction \mathbf{r}
- \mathbf{a}_1 is a vector of length a_1 in the direction of the current flow in conductor segment 1
- \mathbf{a}_2 is a vector of length a_2 in the direction of the current flow in conductor segment 2

NOTE—The symbol \otimes is the vectorial cross product

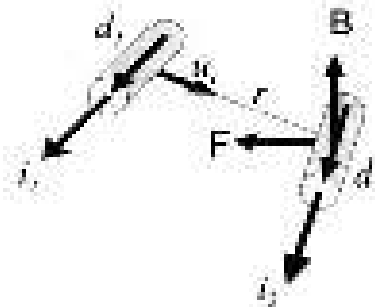


Figure 19—Illustration of two conductor segments carrying electric current

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:

$$F_w = \frac{187I_w^2}{10^3 D} \quad (14)$$

For English units:

$$F_w = \frac{3617I_w^2}{10^3 D} \quad (15)$$

where

- F_w is the fault current force by unit length, N/m (lb/ft)
- I_w is the symmetrical RMS fault current, A
- D is the conductor spacing center-to-center, m (ft)
- C is a constant based on type of fault and conductor location (Table 1)

Structural Design

Short-Circuit Forces

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

Type of short circuit	Configuration	Conductor	K
Phase to phase		A or B	1.000
Three phase		B	0.866
Three phase		A or C	0.800
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

$$F_{sc_corrected} = D_f^2 K_f F_{sc} \quad (16)$$

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	I_m	D_f	D_f^2	X/R	I_m	D_f	D_f^2
30	0.0796	0.950	0.903	30	0.0955	0.950	0.903
20	0.0731	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
3	0.0053	0.604	0.365	3	0.0064	0.604	0.365
1	0.0007	0.522	0.272	1	0.0012	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.

Structural Design

Short-Circuit Forces

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

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

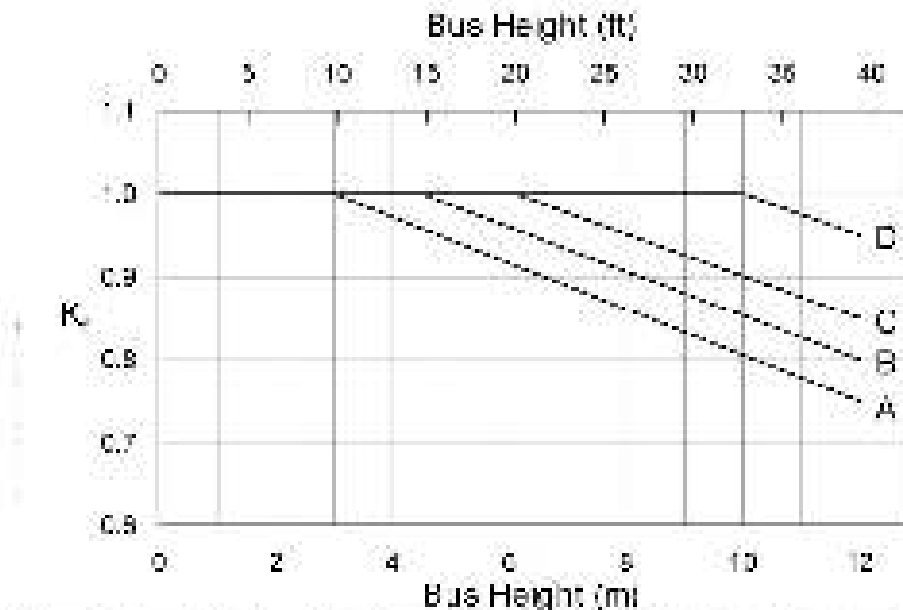


Figure 20: Flexibility factor K_f versus bus height for single-phase mounting structures.

Structural Design

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

Current Ratings

IEEE 605-2008 is a great resource:

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

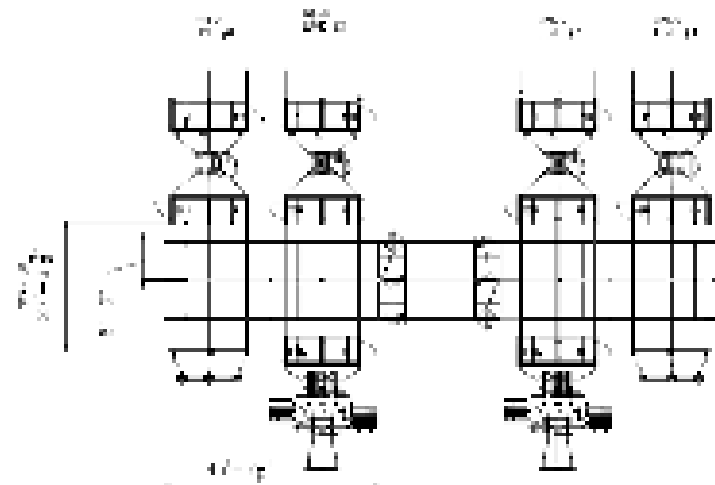


Figure H.1 General bus layout

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

- Determine the conductor size required for both ultimate strength load and ultimate flexion load (Class B and Annex C).
- Determine maximum stress on the bus and suspension (Class F and Annex D).
- Determine maximum low-voltage conductors (Class F).
- Determine conductor span length for low-voltage conductors (Class B and Annex D).
- Determine maximum required insulation string (Class B).
- Determine the maximum creepage distance (Class B).
- Determine the voltage and creepage requirements (Class B and Annex D).

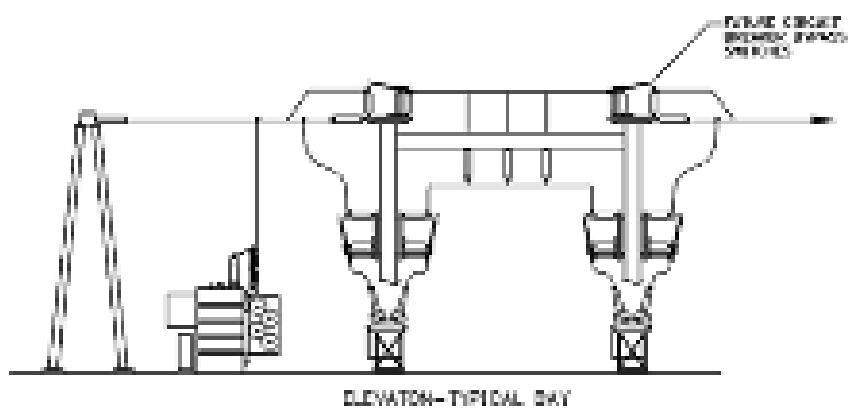
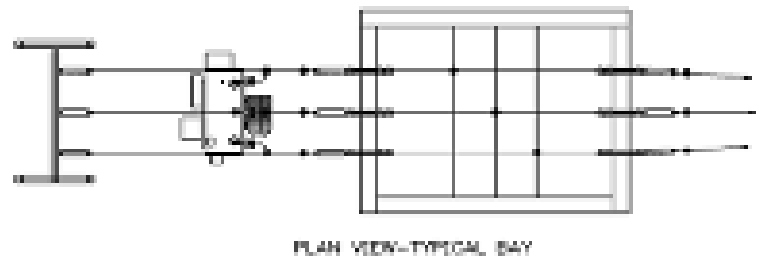
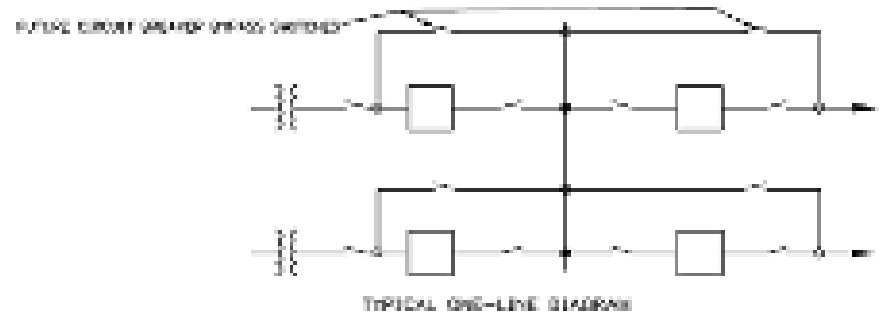
Bus Design

Types of Substation Structures

Station Physical Layout

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

Station Physical Layout





Conventional Design



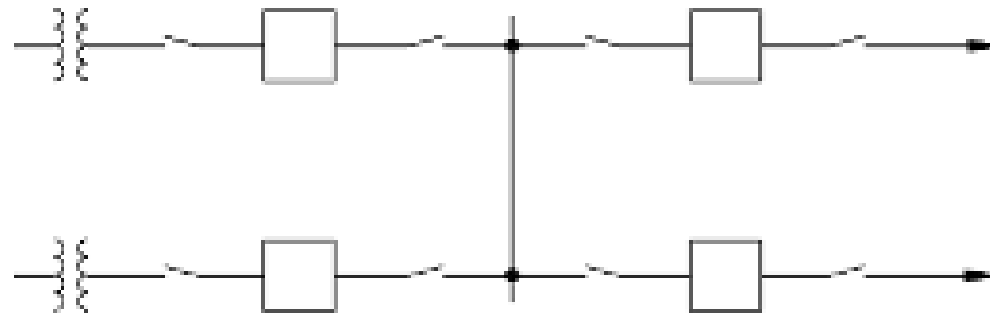
Conventional Design



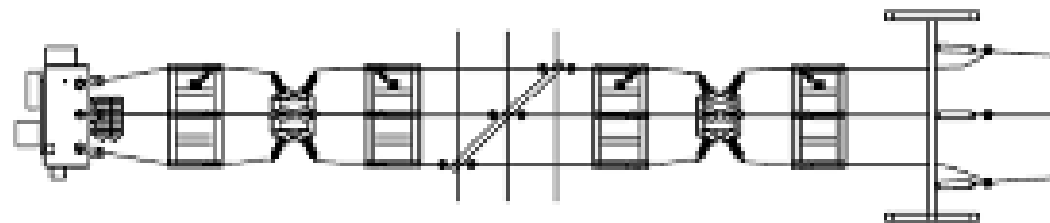
Conventional Design

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

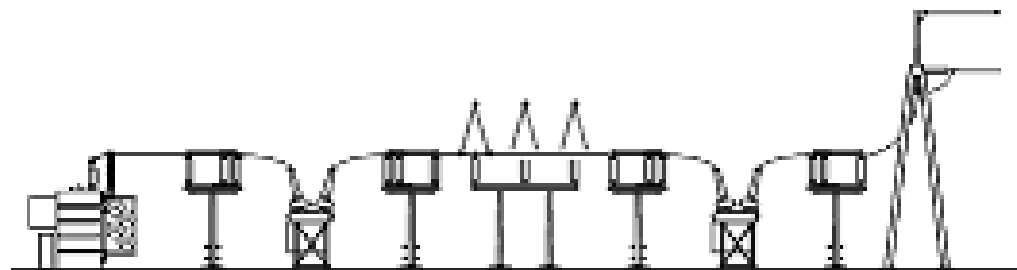
Station Physical Layout



TYPICAL ONE-LINE DIAGRAM



PLAN VIEW—TYPICAL BAY



ELEVATION—TYPICAL BAY



Low Profile (tube)

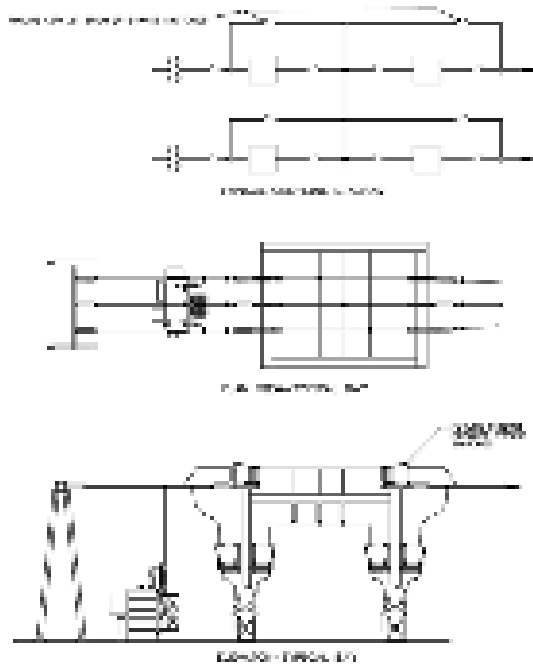


Low Profile (tube)

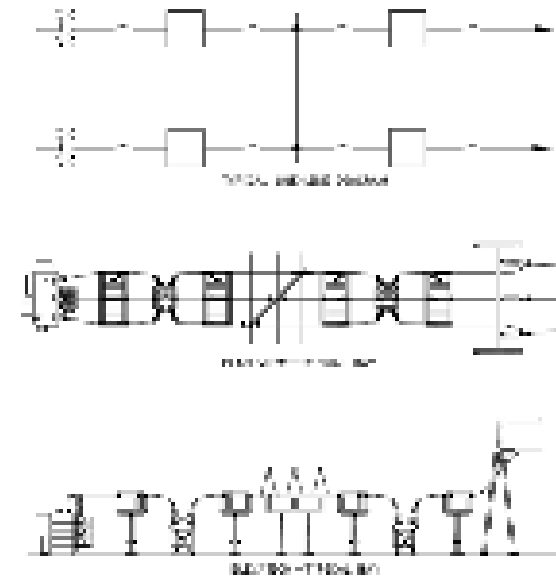


Low Profile (tube)

Conventional



Low Profile

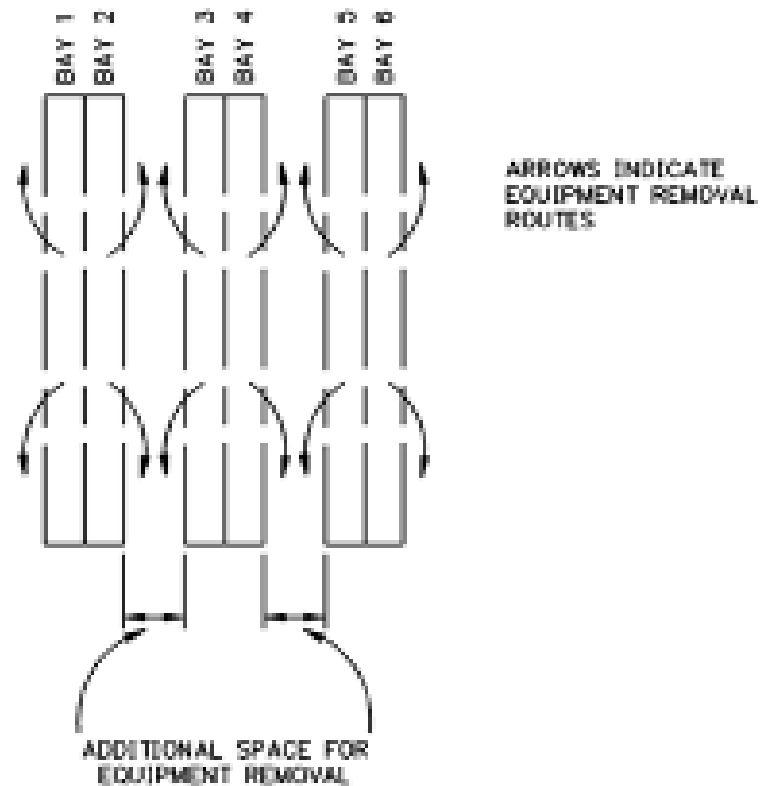


Station Physical Layout

- **GIS** (Gas Insulated Substation)

Station Physical Layout

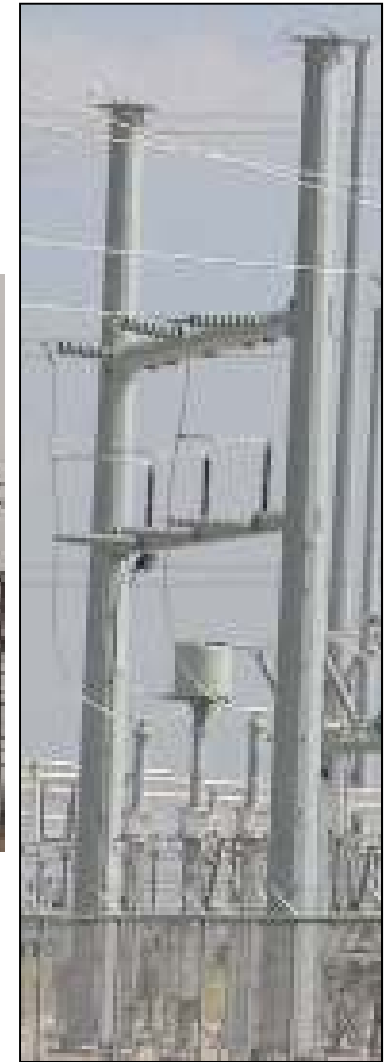
- Maintenance
- Equipment Removal
- Vehicle Mobility
- Exterior Access



Station Physical Layout

- **Common Designs**

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



Deadend Structures

Surge and Lightning Protection

Sh.
95

- **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

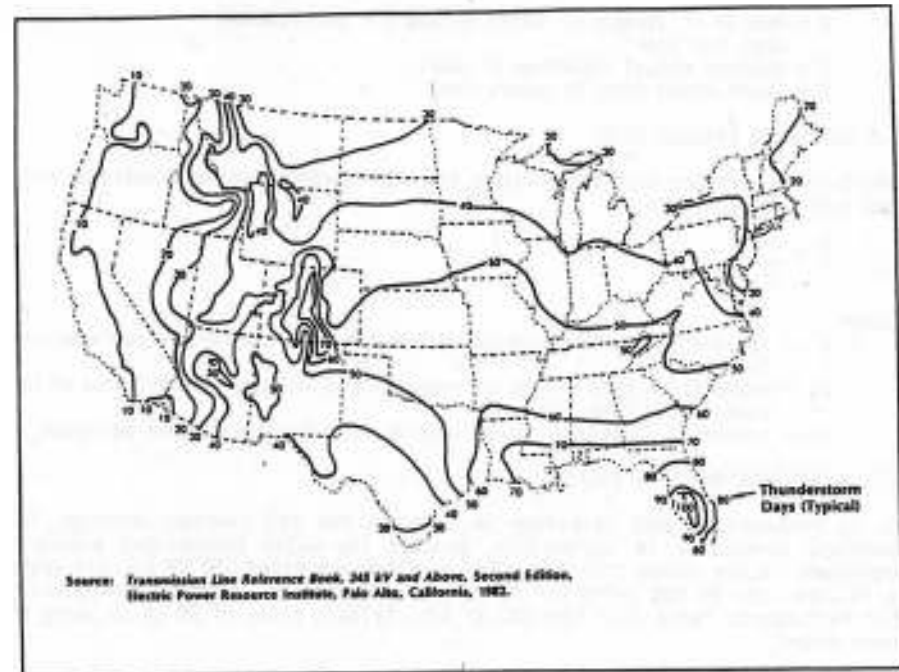


Figure 13
USA Annual Isokeraunic Map

Surge & Lightning Protection

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

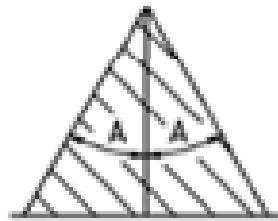
7.6 ACCEPTABLE RATES OF FAILURE

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.

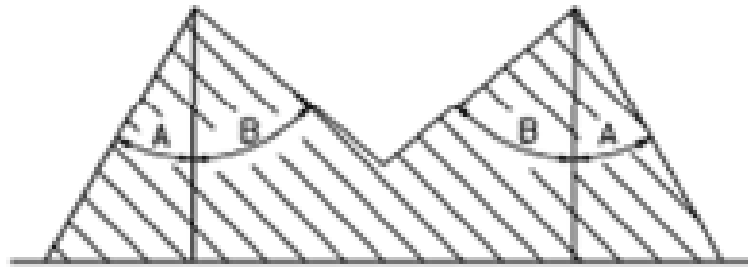
Surge & Lightning Protection

- Fixed Angle Method

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



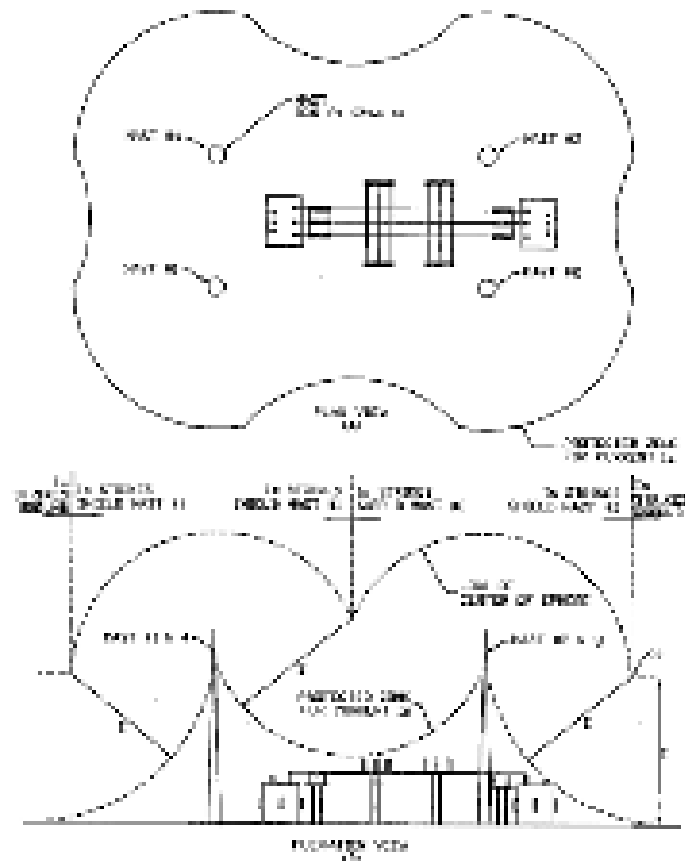
SINGLE MAST OR SHIELD WIRE



TWO MASTS OR SHIELD WIRES

Surge & Lightning Protection

Rolling Sphere Method



Source: Adapted from [874]

Figure 6-7 — Multiple structural protection for stroke current I_s

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]:

$$R_c = r \ln \left(\frac{2.3 \times 10^6}{R_c} \right) \cdot \frac{V_c}{E_0} \quad (C.1)$$

where

- R_c is the corona radius in meters
- r is the average height of the conductor in meters
- V_c is the allowable insulation voltage for a negative polarity surge having a 50 μ s front in kilovolts ($V_c = 0.8E_0$ 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_b [B4] is taken as follows:

$$R_b = R_c + R_0 \quad (C.2)$$

where

- R_0 is the value for a single conductor as given by Eq. C.1
- R_b is the equivalent radius of the bundle.

The calculation method of R_0 is given in C.2.

Surge & Lightning Protection

Grounding Considerations

Sh.
105

- 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

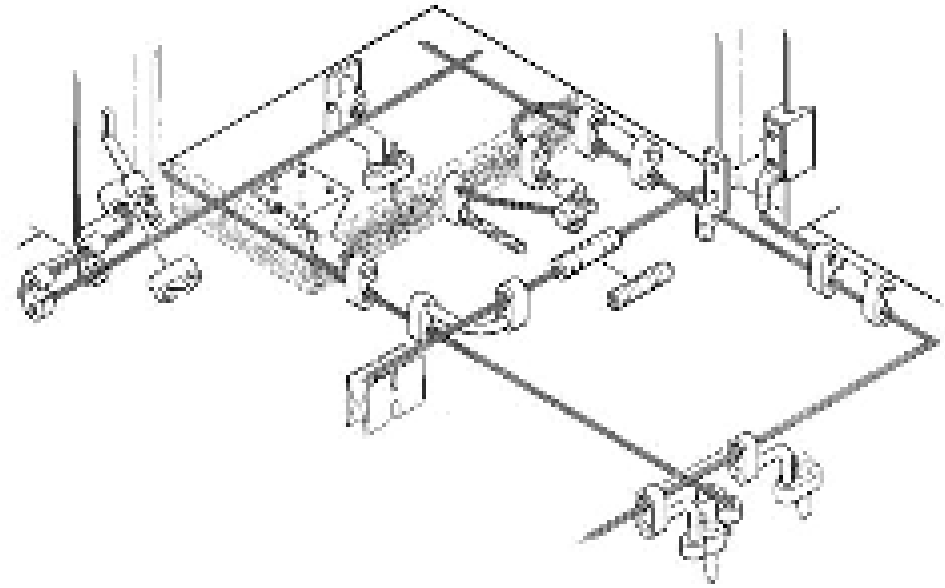
Grounding



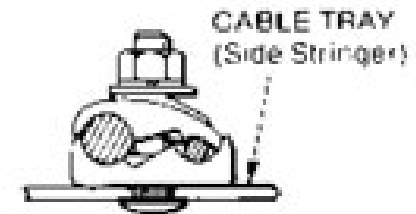
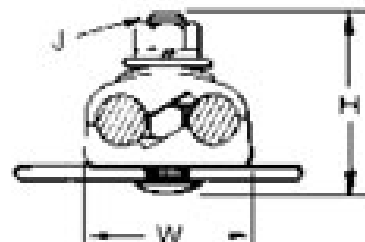
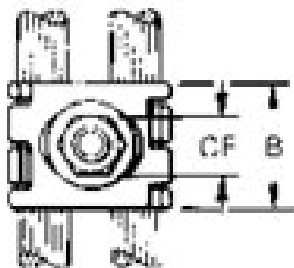
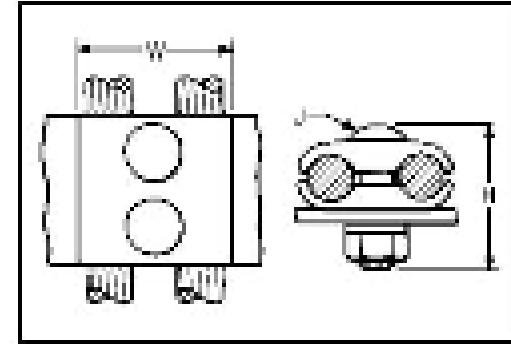
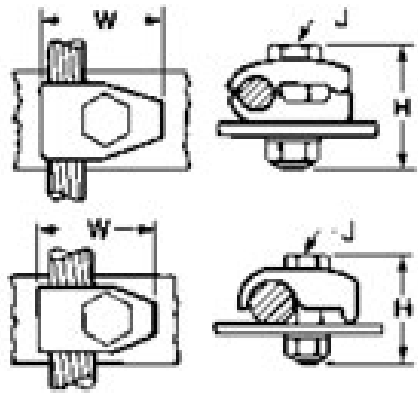
Grounding – Exothermic



Element B



Grounding – Compression



Grounding – Mechanical

OBJECTIVES

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

Grounding Design

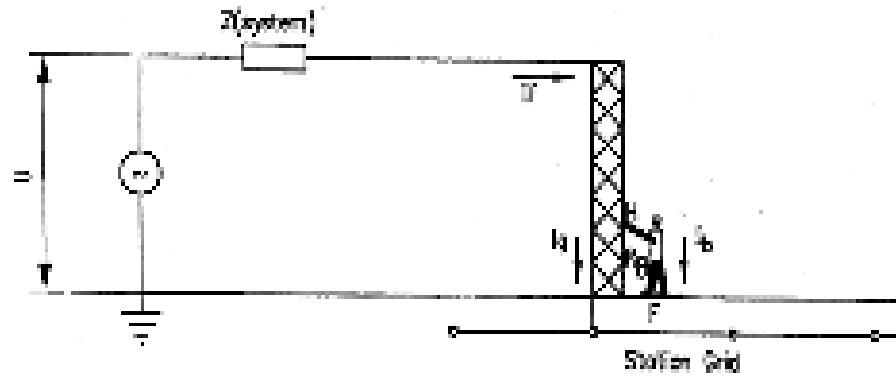
1. **Assure that persons in or near any substation are not exposed to electric shock above tolerable limits.**
2. **Provide means to dissipate normal and abnormal electric currents into the earth without exceeding operating or equipment limits.**

Grounding Objectives

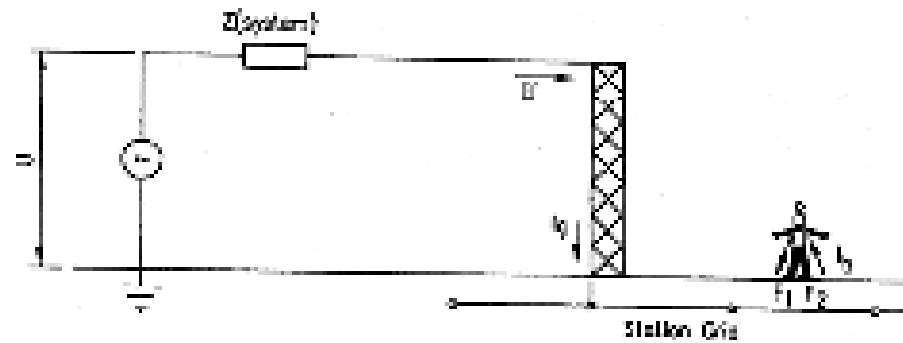
- 1. High fault current to ground**
- 2. Soil resistivity and distribution of ground currents**
- 3. Body bridging two points of high potential difference**
- 4. Absence of sufficient contact resistance**
- 5. Duration of the fault and body contact**

Cause of Electric Shock

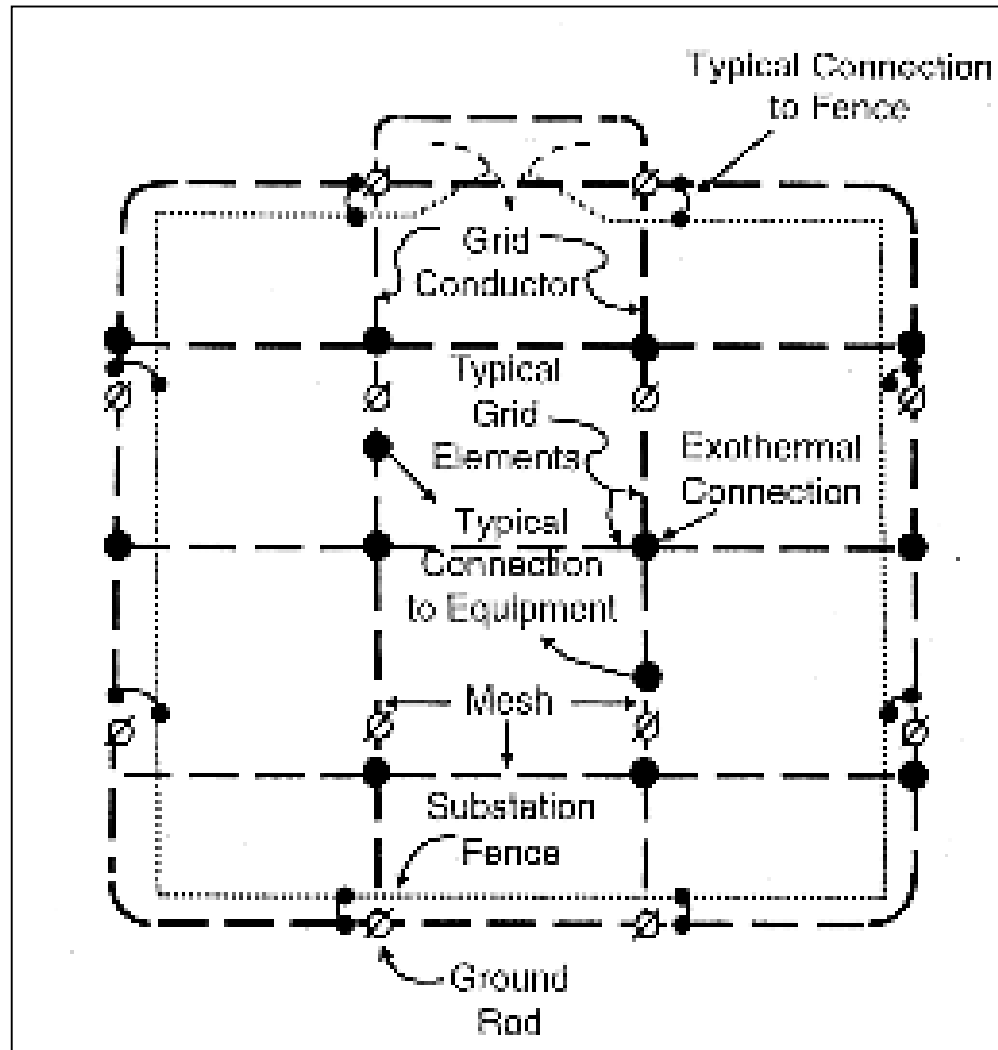
Exposure to Touch Voltage



Exposure to Step Voltage



Basic Shock Situations



Simple Grid Design

Protection & Control

One-Line Diagrams

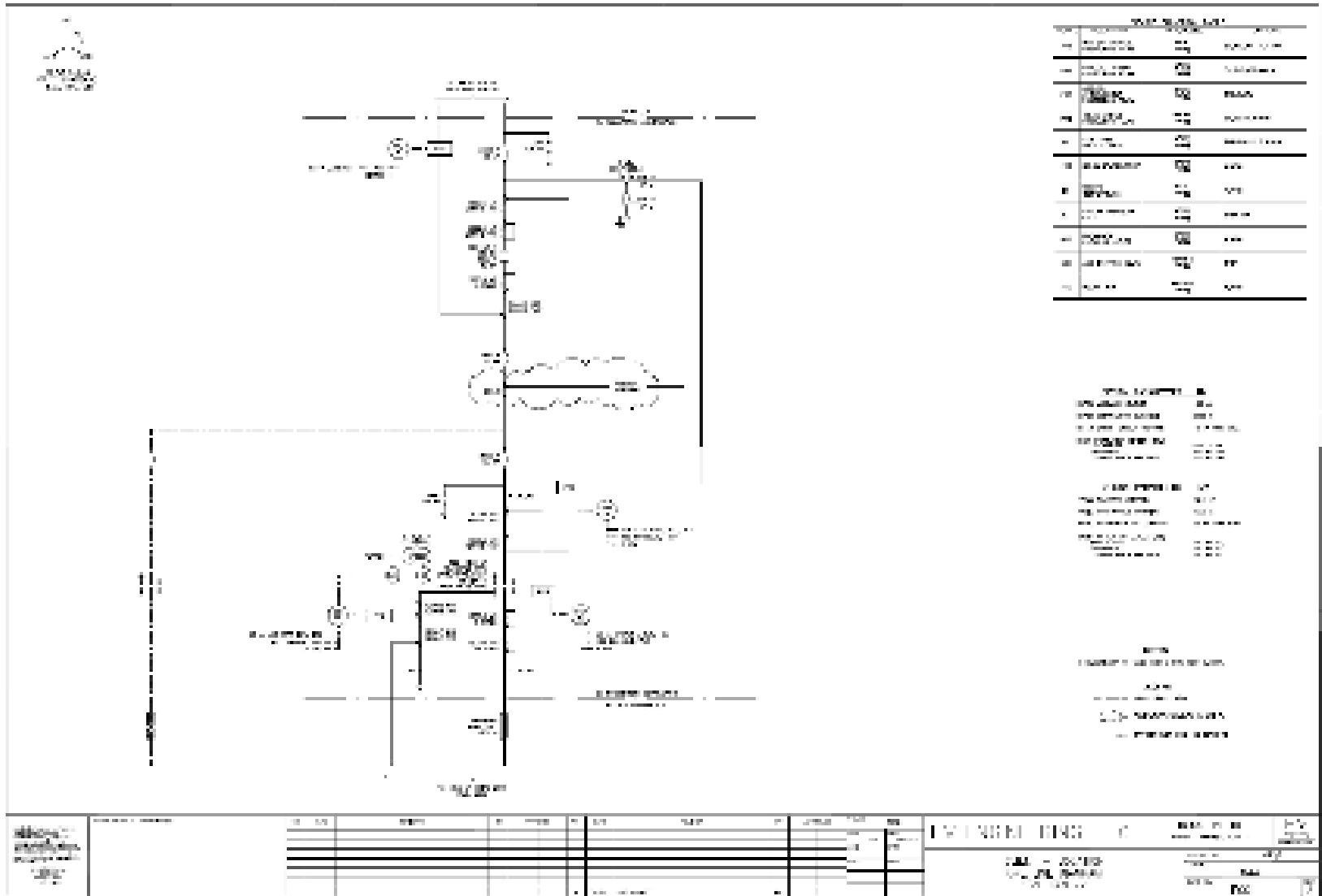
- The one-line diagram is probably the single most important document in the substation design package.
- The one-line diagram defines the design parameters and scope of the design...a road map

One-Line Diagrams

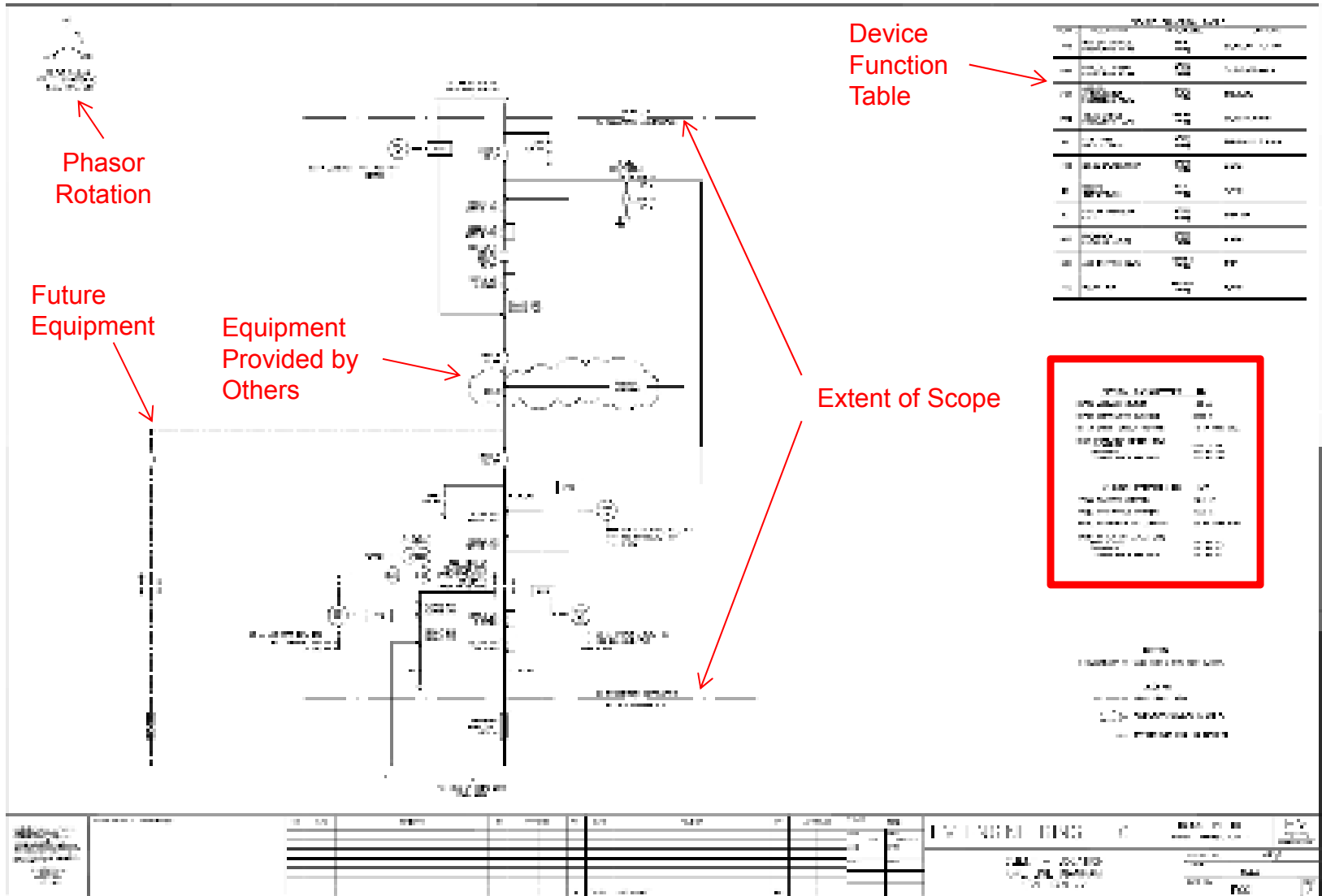
Key elements that should be included on relaying one-lines

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

One-Line Diagrams



One-Line Diagrams



One-Line Diagrams

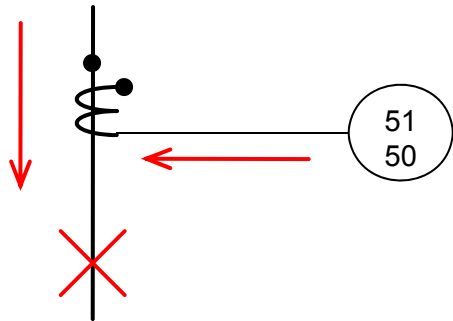
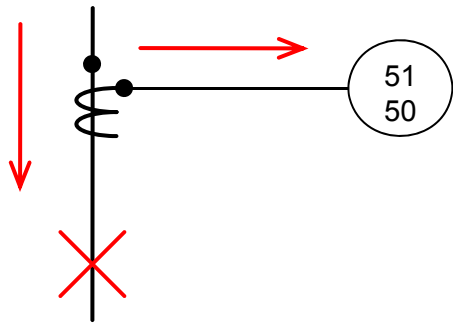
- Modern microprocessor relays are fairly complex
- Functionality typically can not be adequately illustrated between the one-line diagram and schematic diagrams
- Creating Logic Diagrams is strongly recommended.

Protection & Control

- Protection
 - Fundamentals
 - Bus
 - Transformers
 - Motors
 - Generators
 - Line & Circuits
- Control
 - Primary/Back-up Systems
 - Breaker Failure
 - Reclosing
 - Pilot Systems & Communication Channels

A.C. Fundamentals

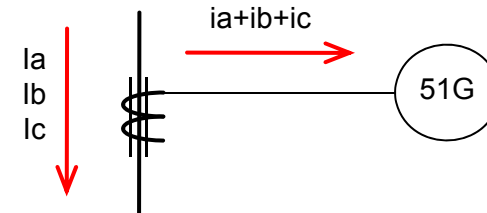
Phasor Relationships



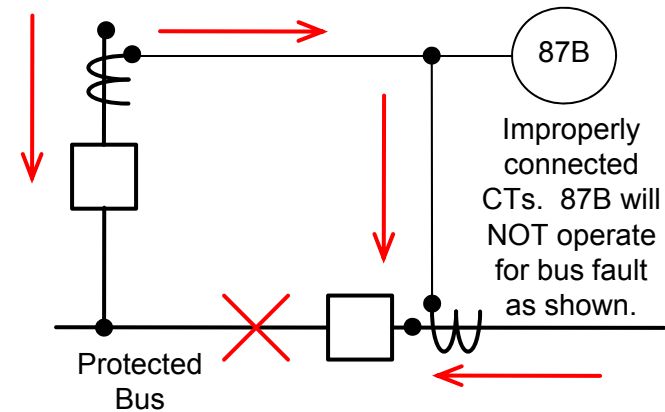
IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes - IEEE Std C37.110



Residual CT connection

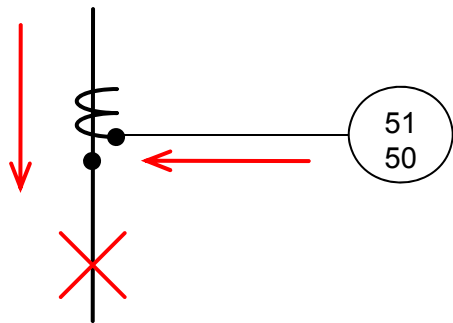
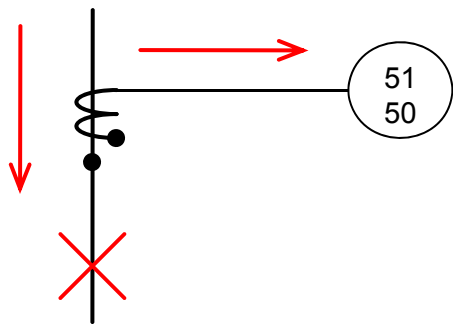


Zero sequence CT

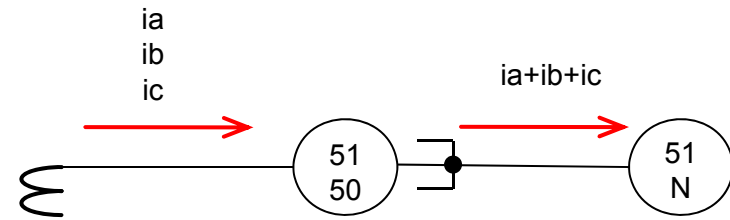


A.C. Fundamentals

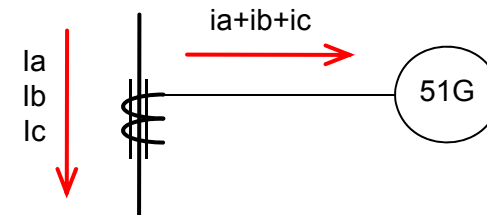
Phasor Relationships



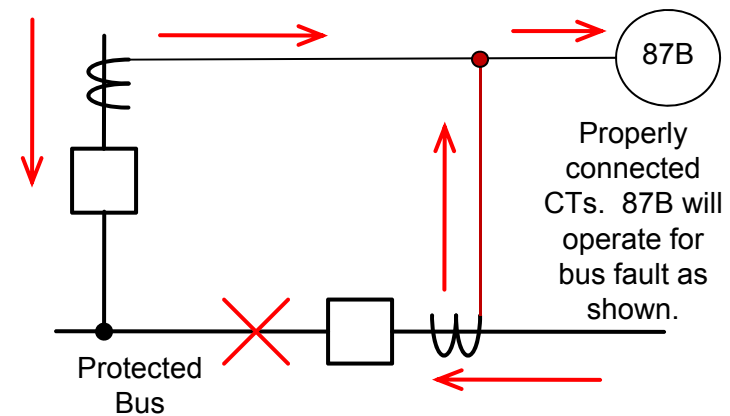
IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes - IEEE Std C37.110



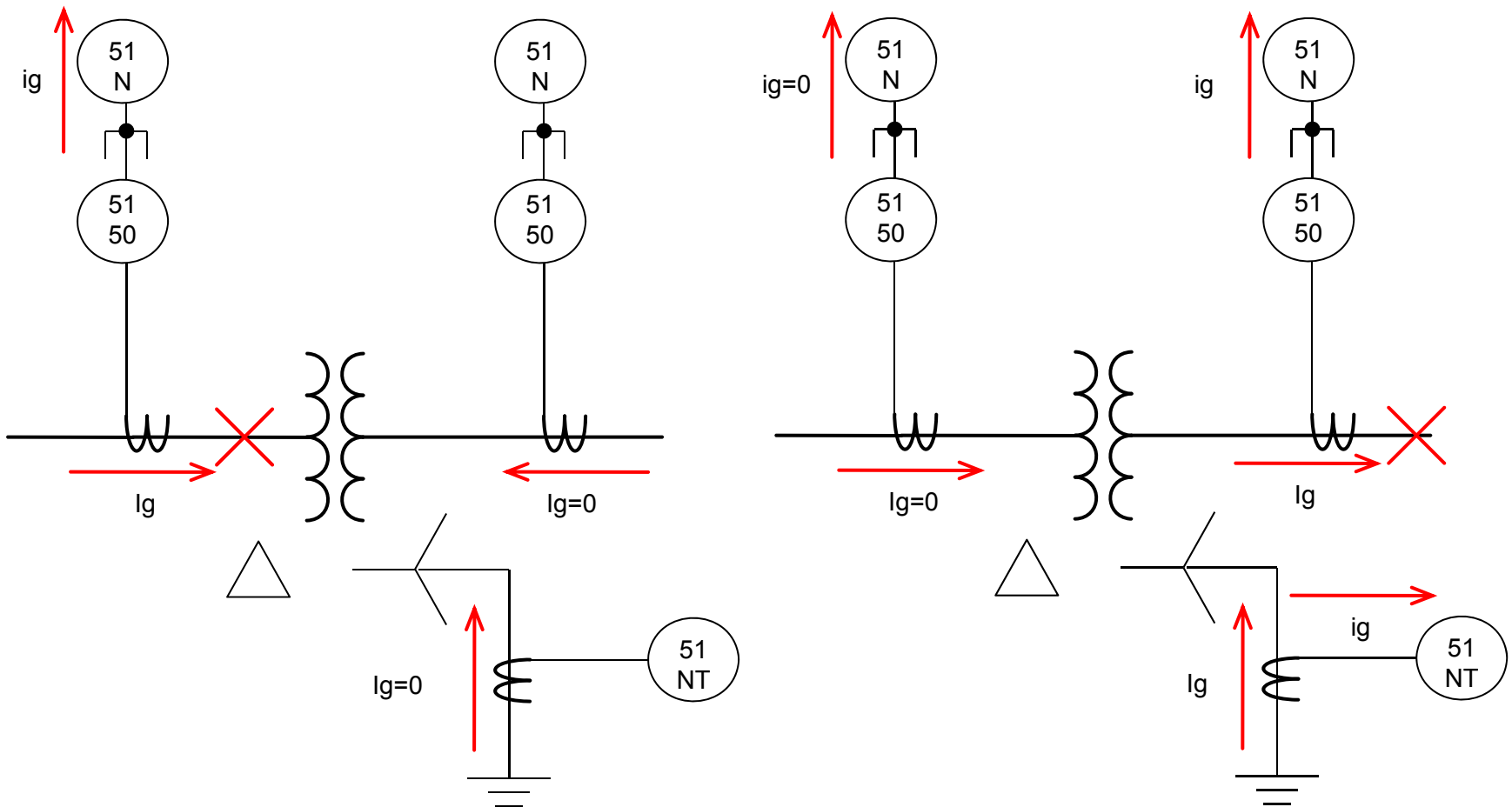
Residual CT connection



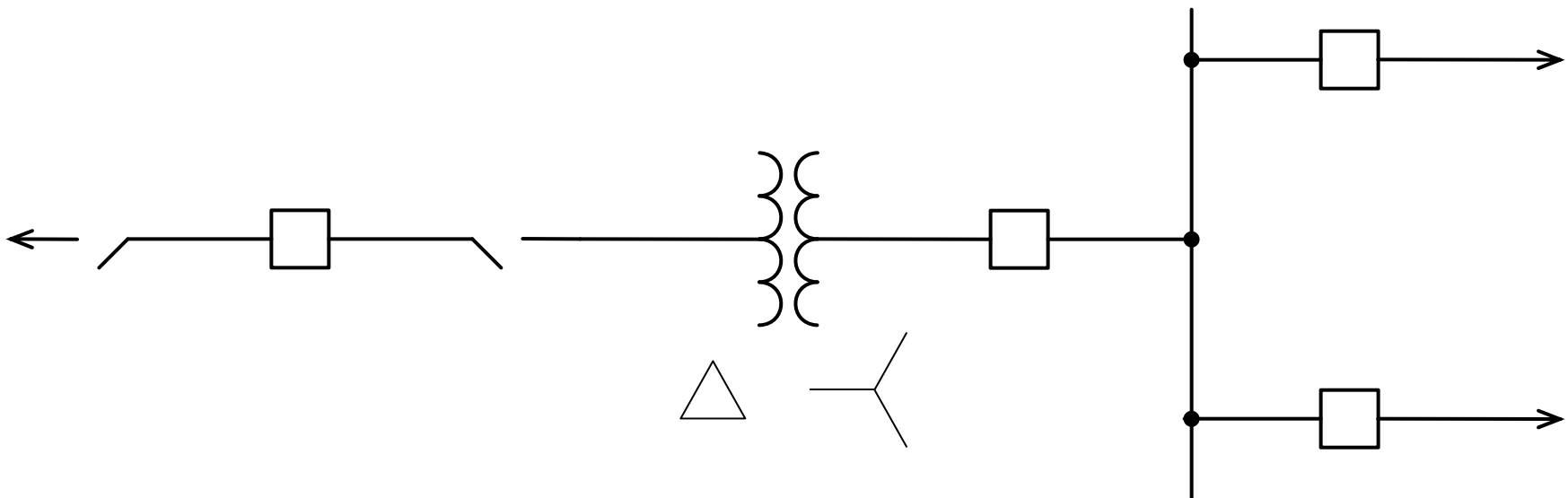
Zero sequence CT



A.C. Fundamentals



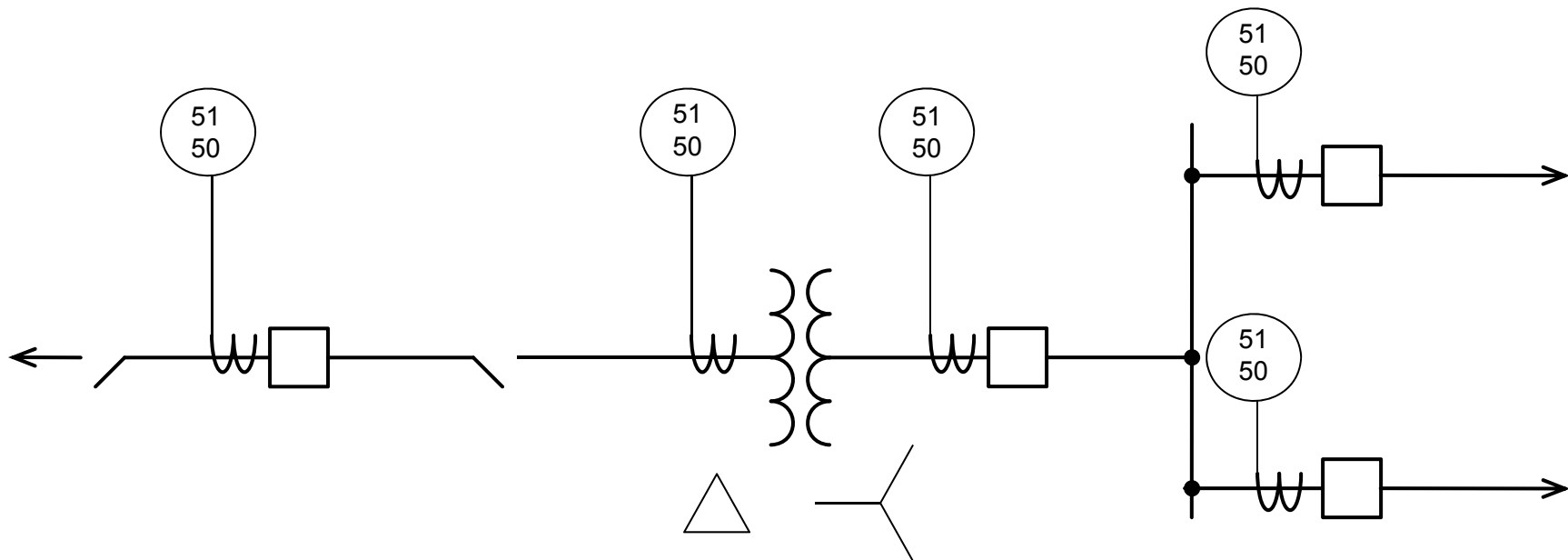
Tap Substation



Tap Substation

- Phase Protection
- Overcurrent

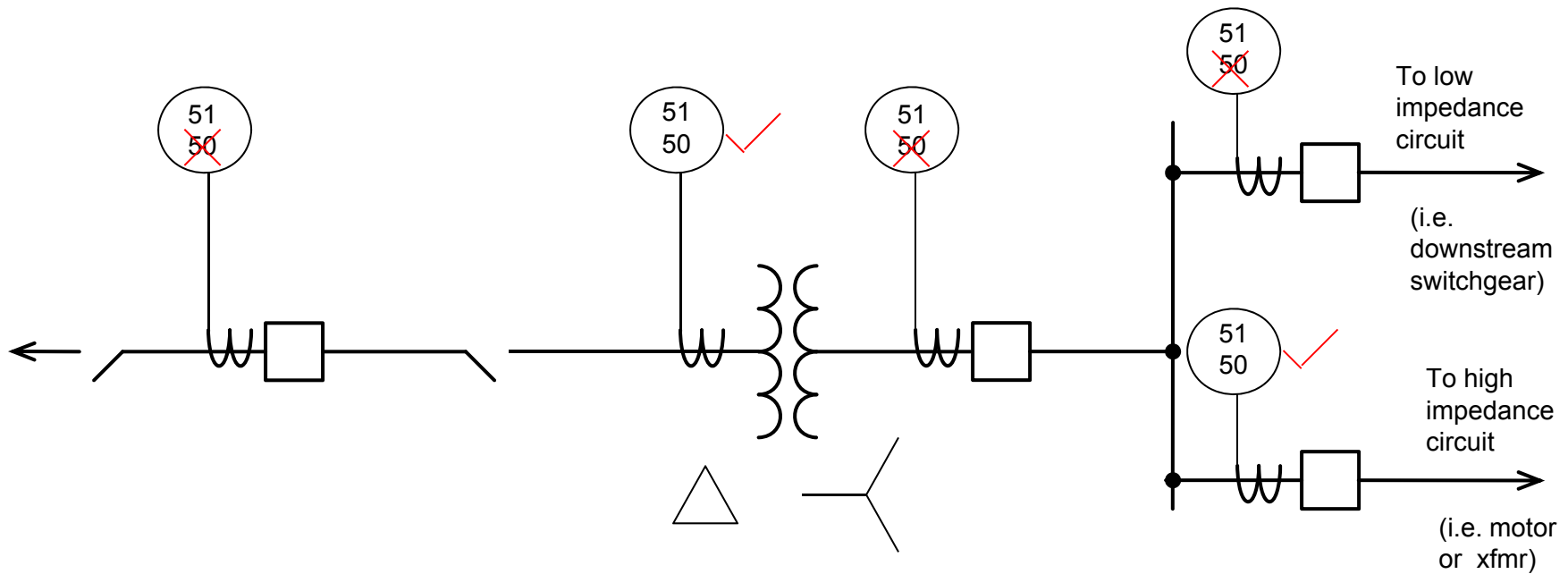
Should 50 elements be set on all relays?



Tap Substation

- Phase Protection
- Overcurrent

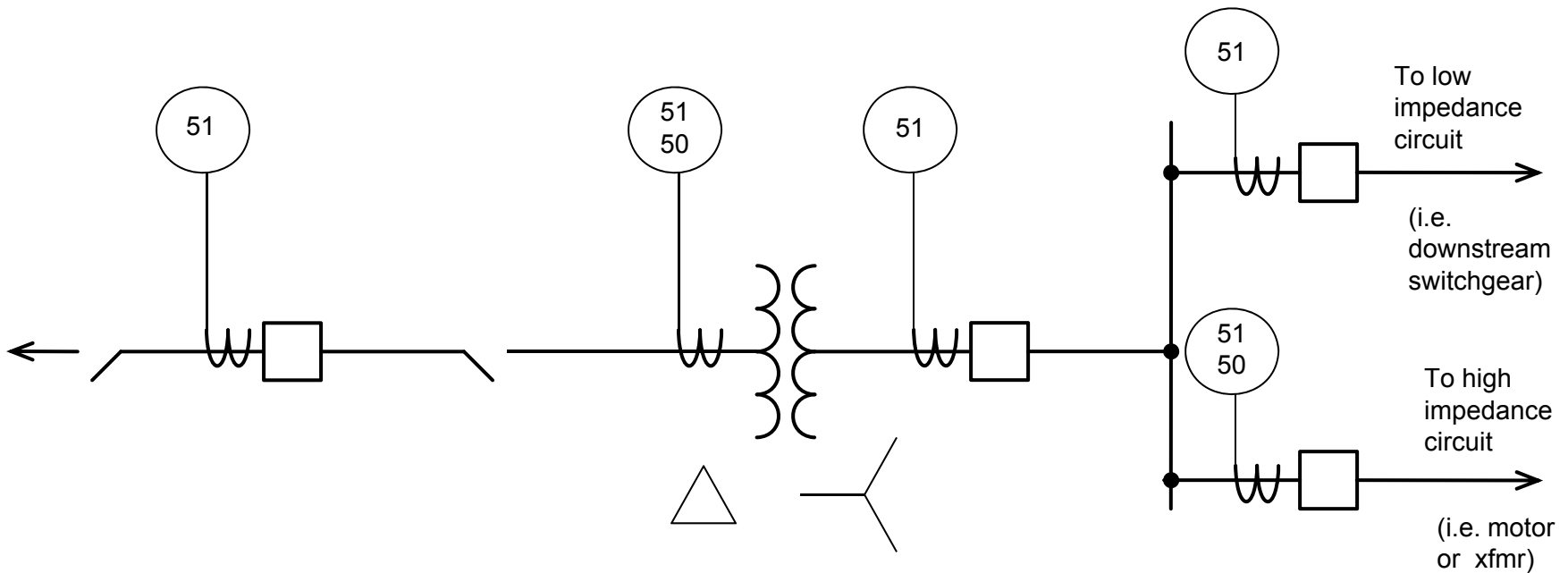
Should 50 elements be set on all relays?



Tap Substation

- Phase Protection
- Overcurrent

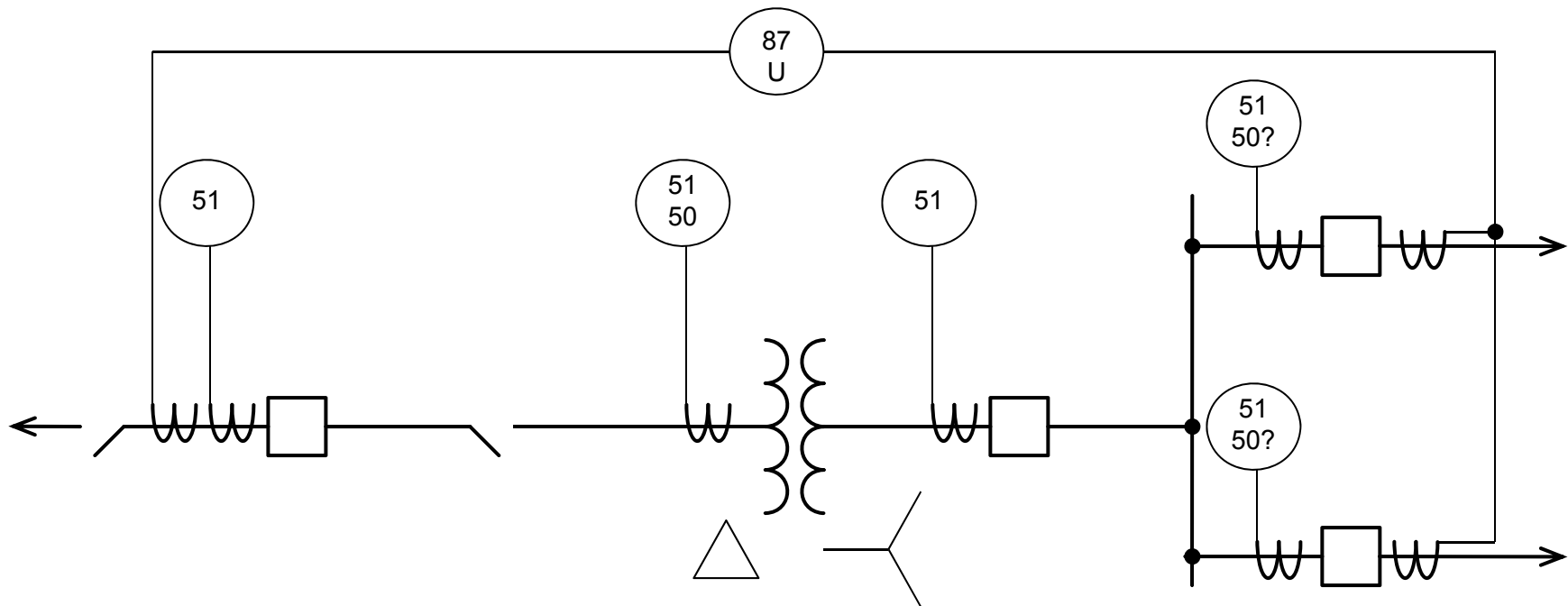
Should 50 elements be set on all relays?



Tap Substation

- Phase Protection
 - Unit Differential
 - Overcurrent

This configuration is not preferred.



- Pros
 - Lower cost

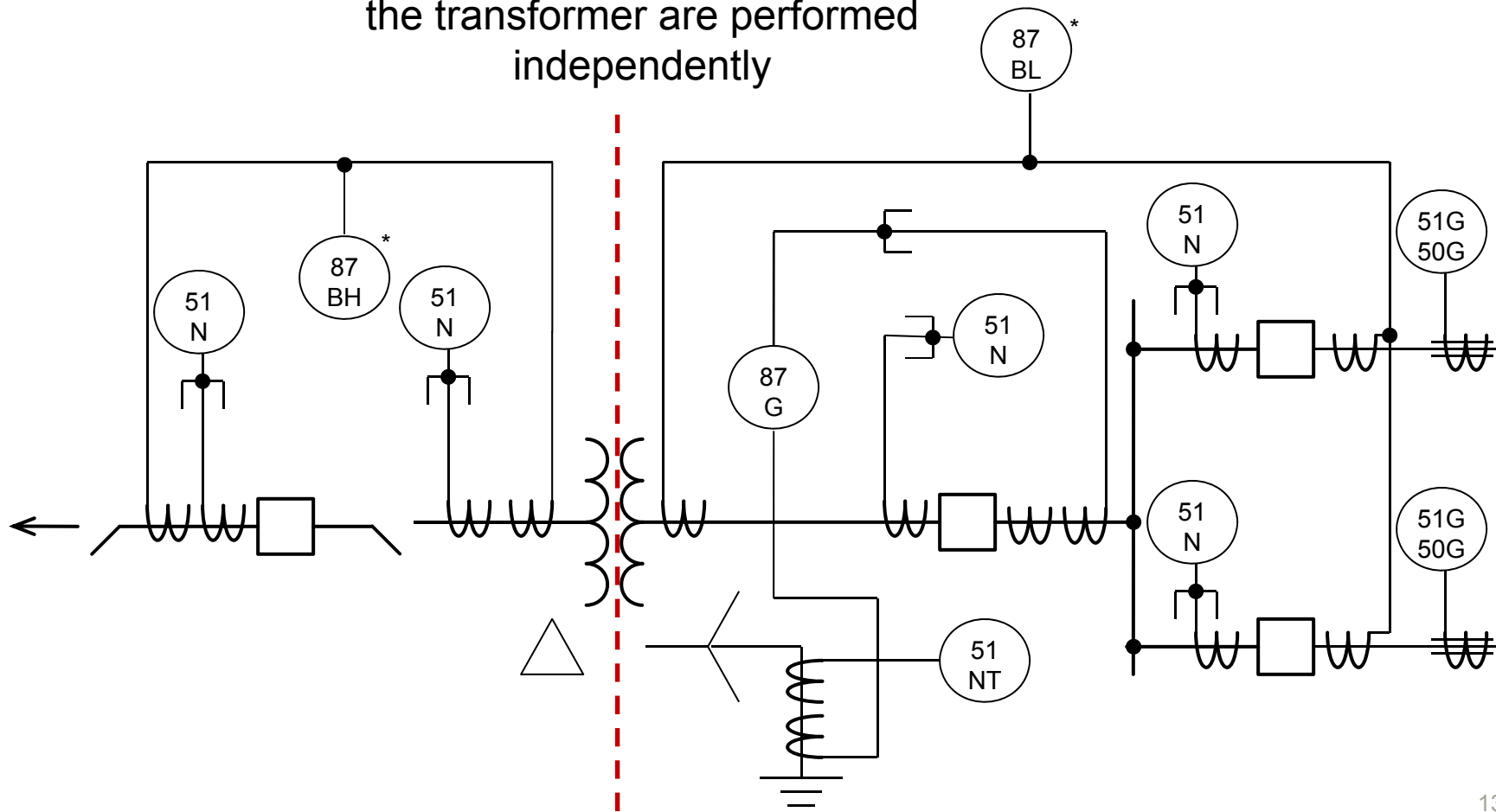
- Cons
 - Lower selectivity

Tap Substation

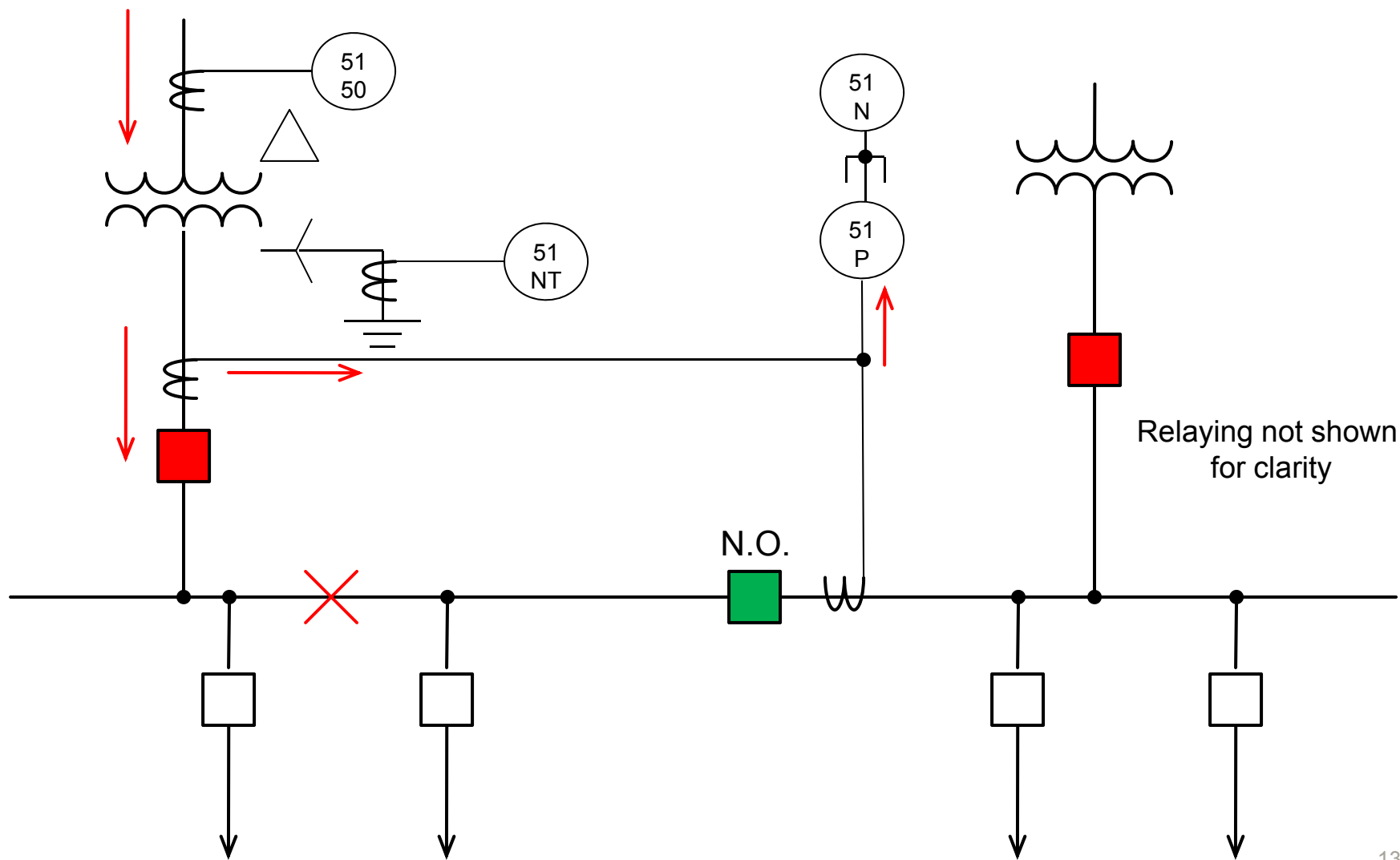
- Ground Protection

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

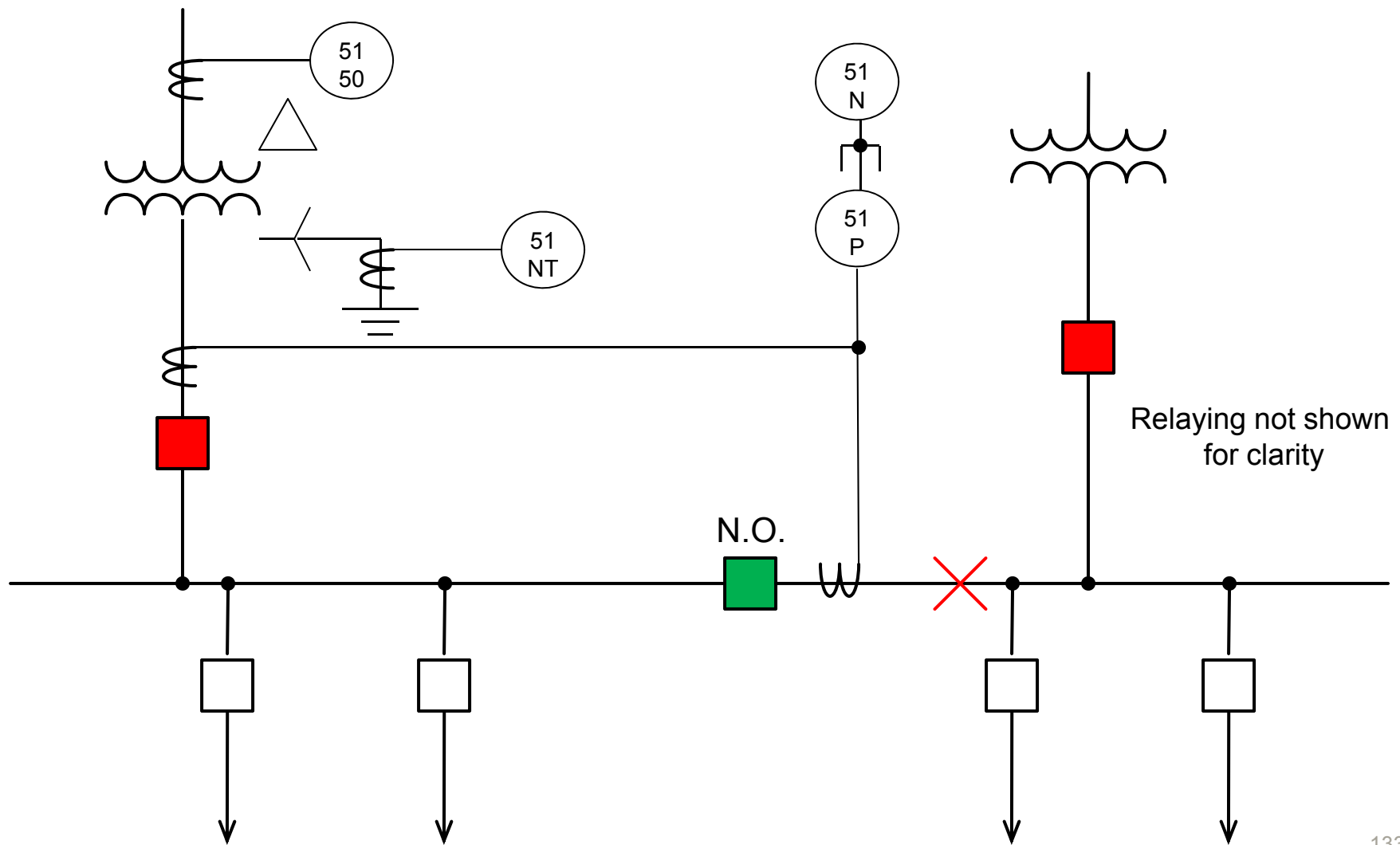
Ground coordination on each side of the transformer are performed independently



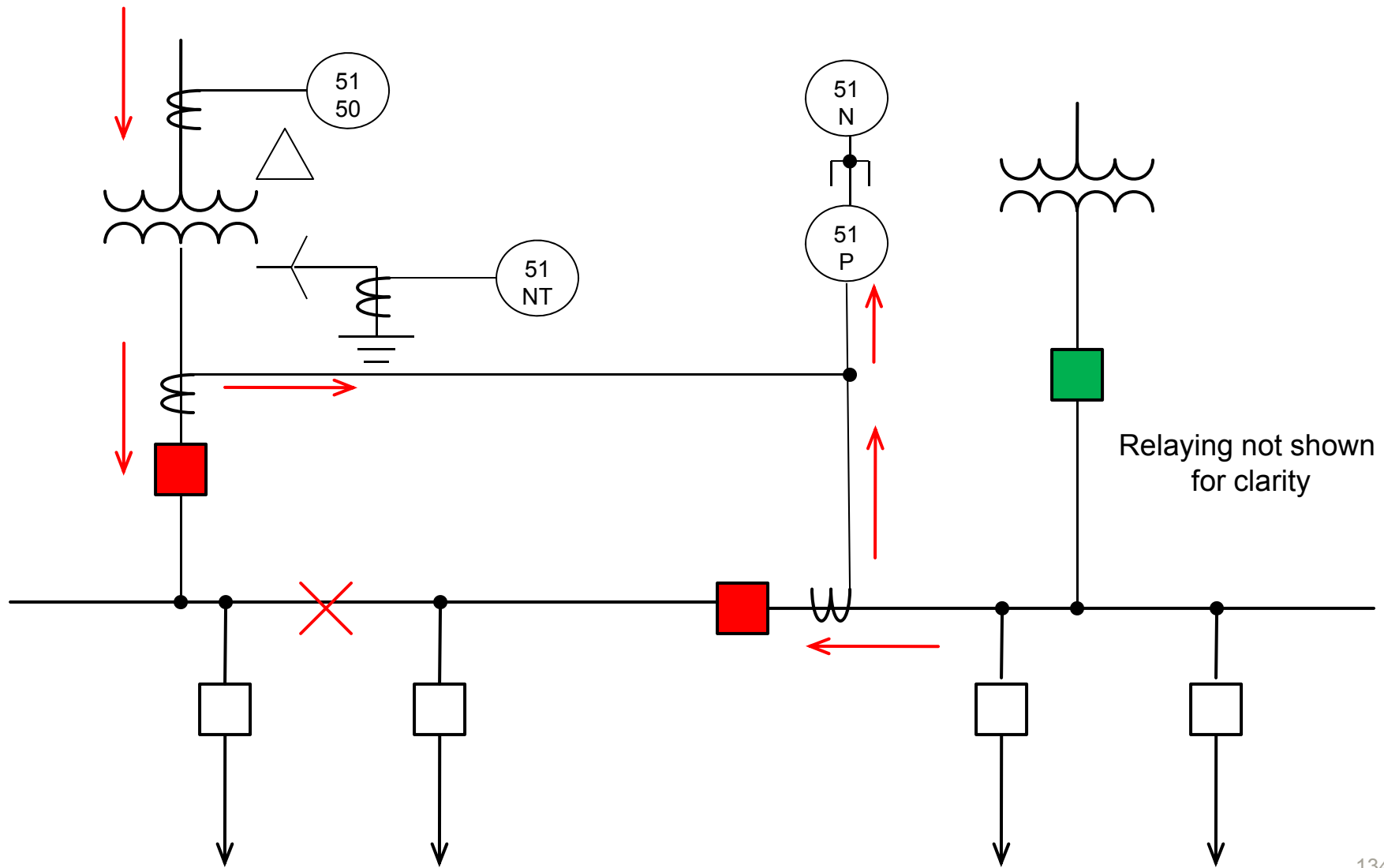
Secondary Selective Arrangement – N.O. Tie



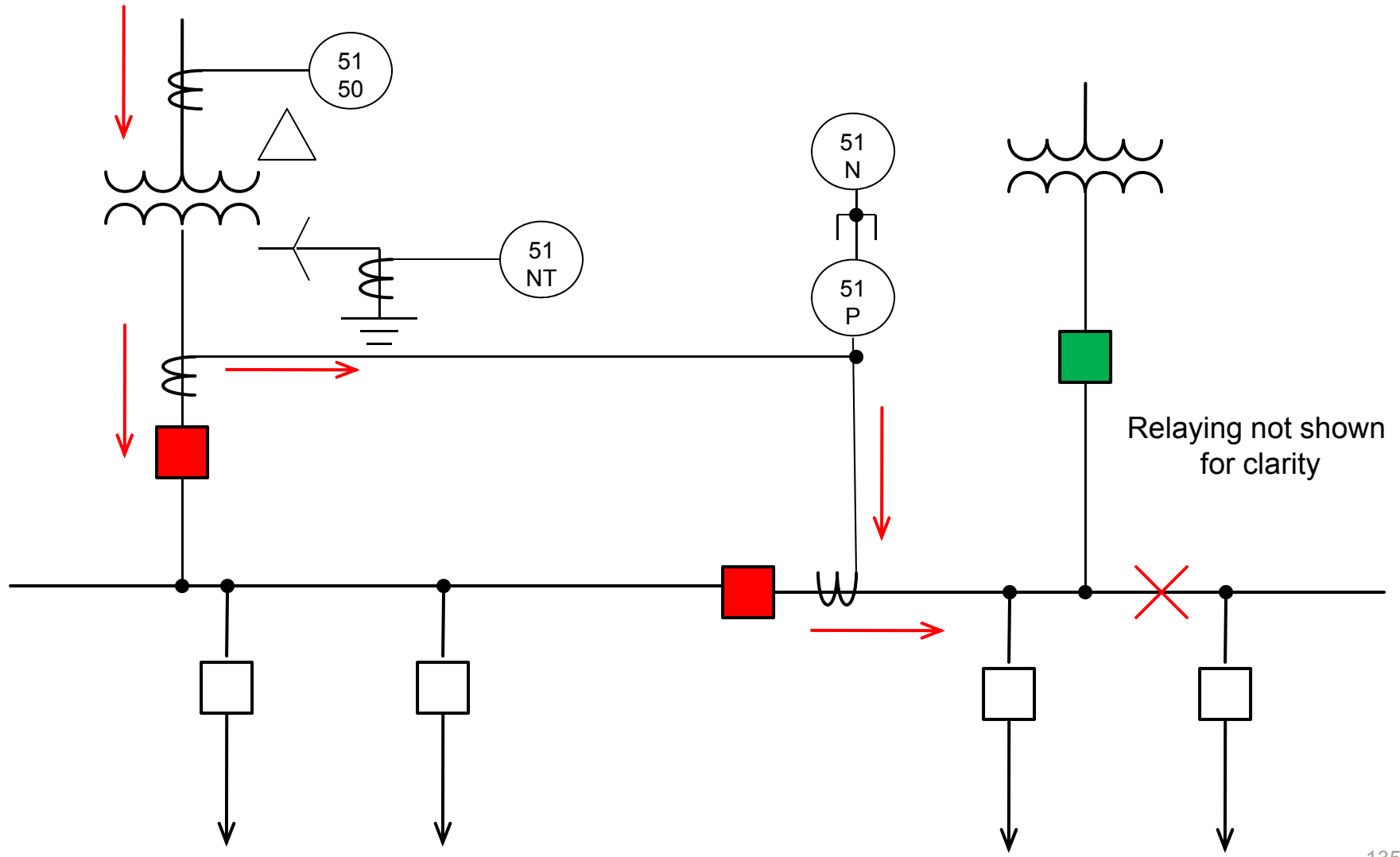
Secondary Selective Arrangement – N.O. Tie



Secondary Selective Arrangement – N.O. Tie

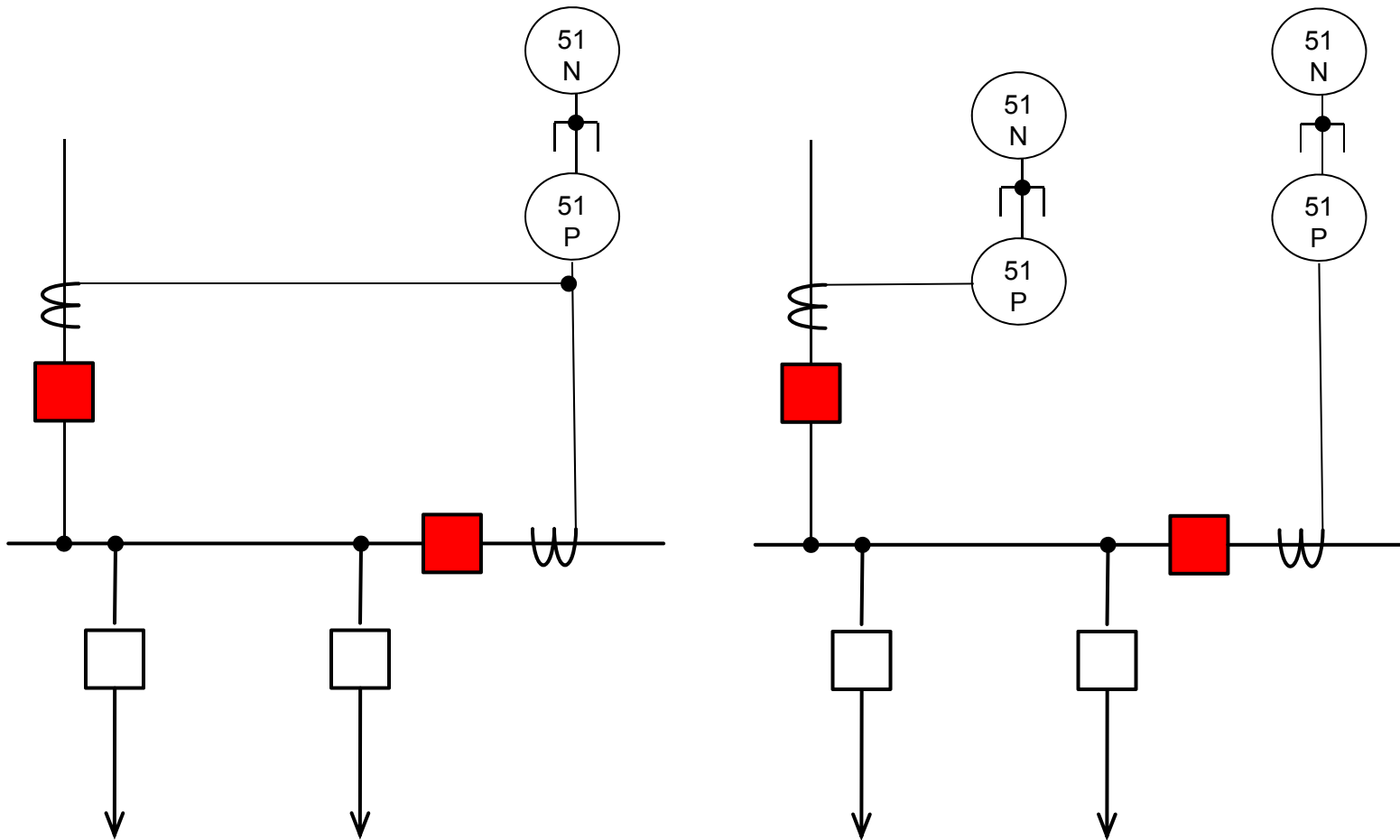


Secondary Selective Arrangement – N.O. Tie



Secondary Selective Arrangement – N.O. Tie

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



Secondary Selective Arrangement – N.O. Tie

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

Pros:

Use one (1) less relay

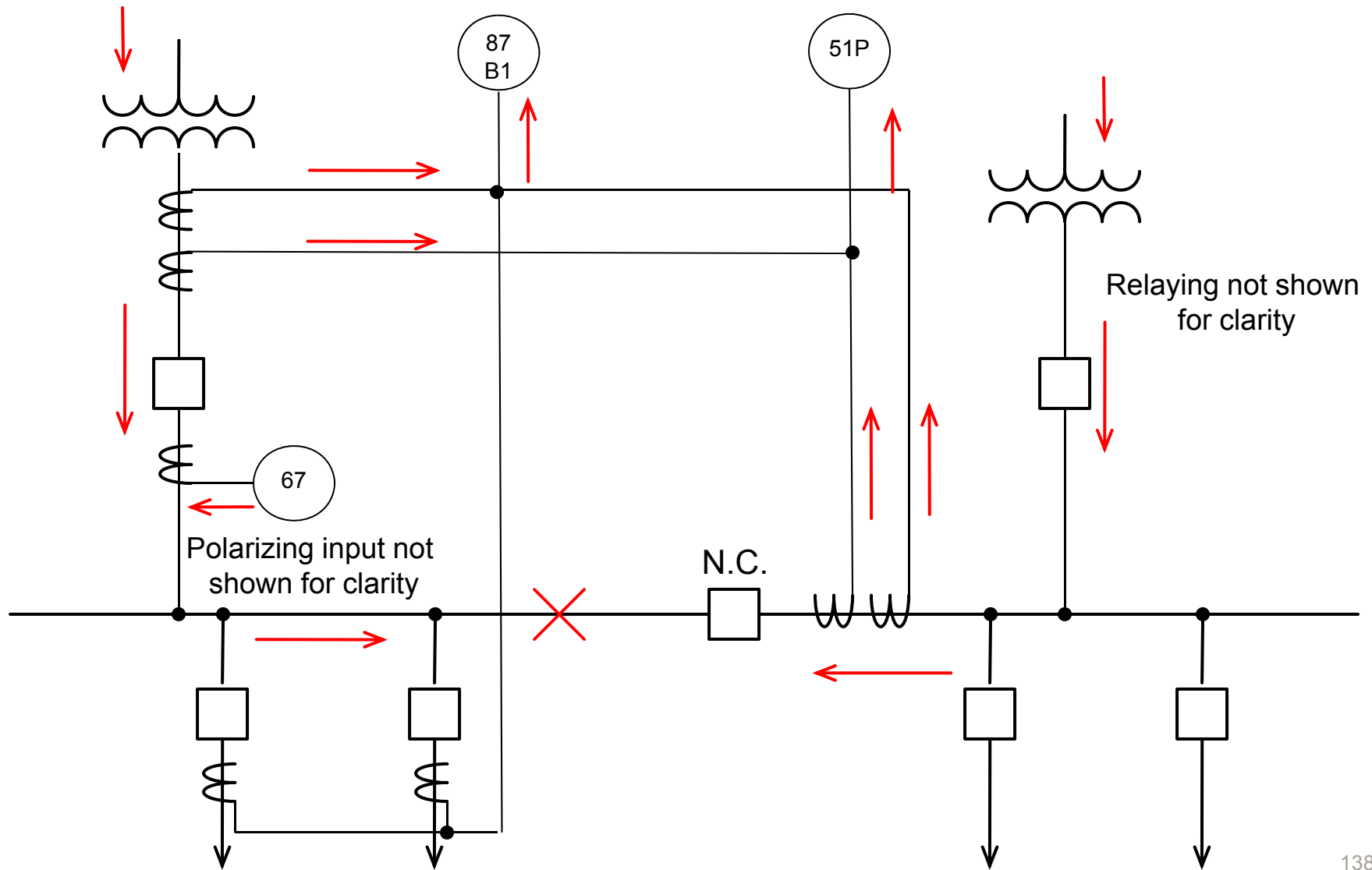
Eliminate one (1) level of coordination

Cons:

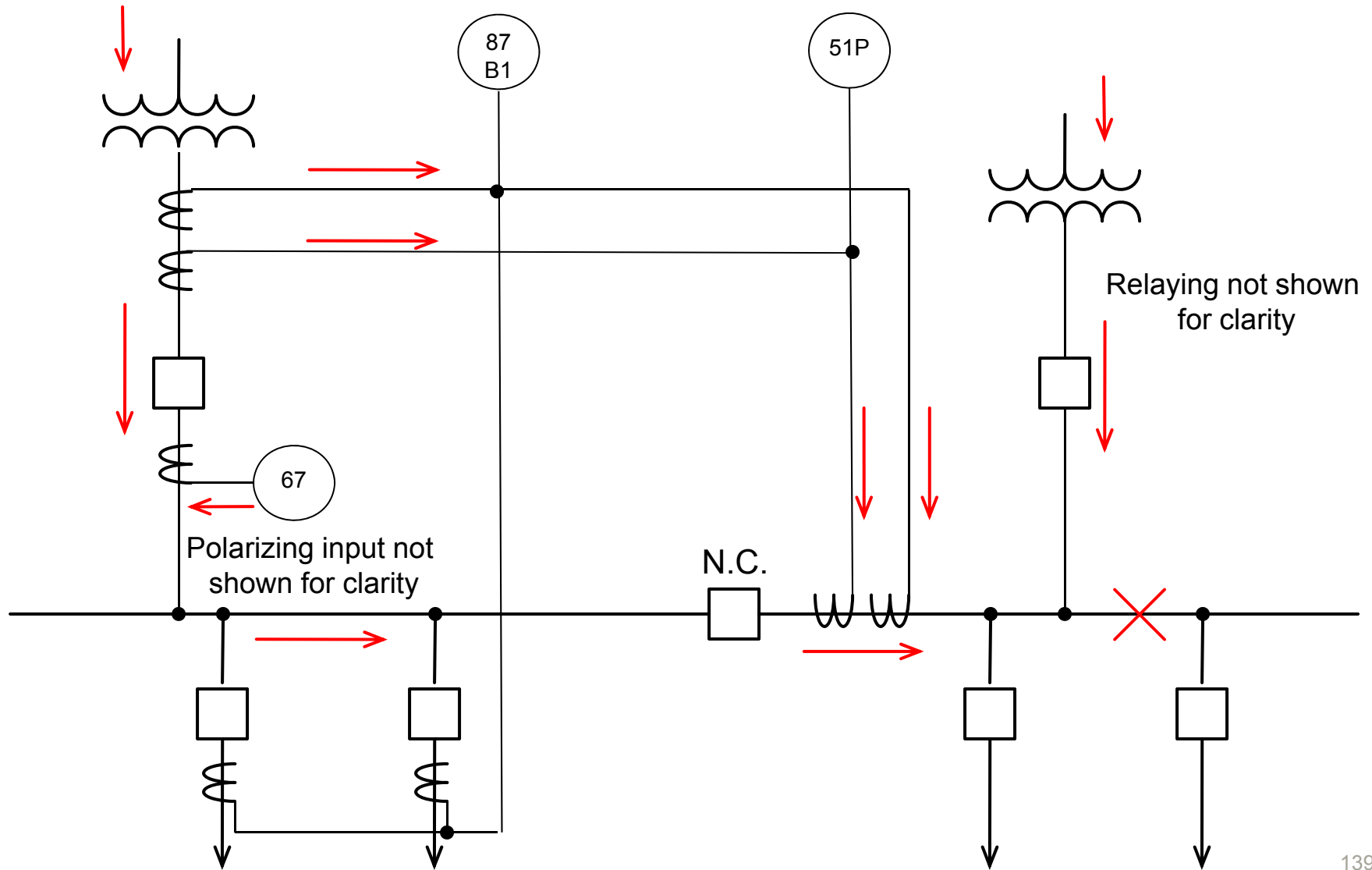
Require one (1) extra set of CTs on the tie breaker

Can not set 67 element on mains because currents are summed before the relay

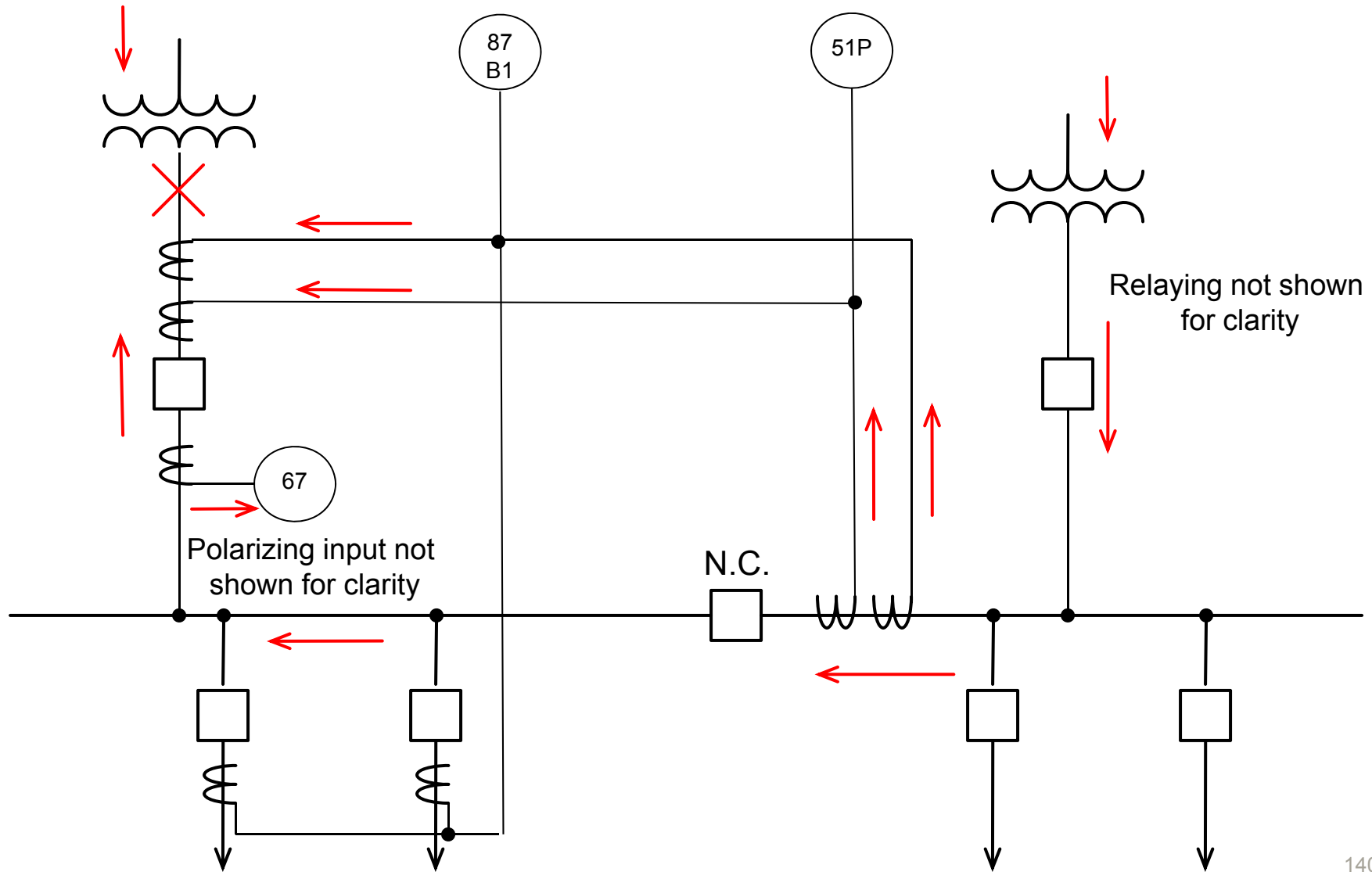
Secondary Selective Arrangement – N.C. Tie



Secondary Selective Arrangement – N.C. Tie



Secondary Selective Arrangement – N.C. Tie



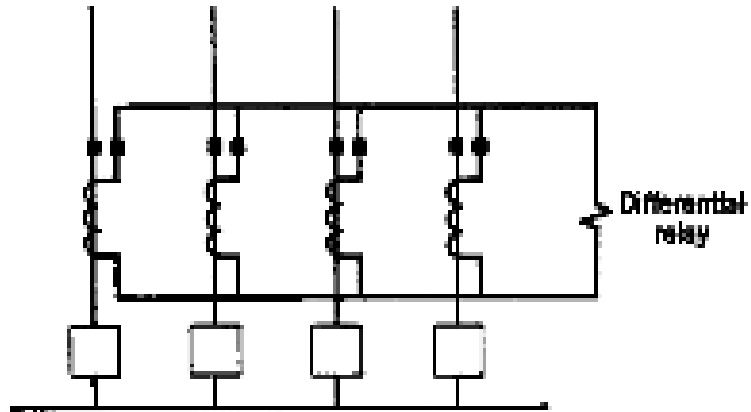
Bus Protection

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

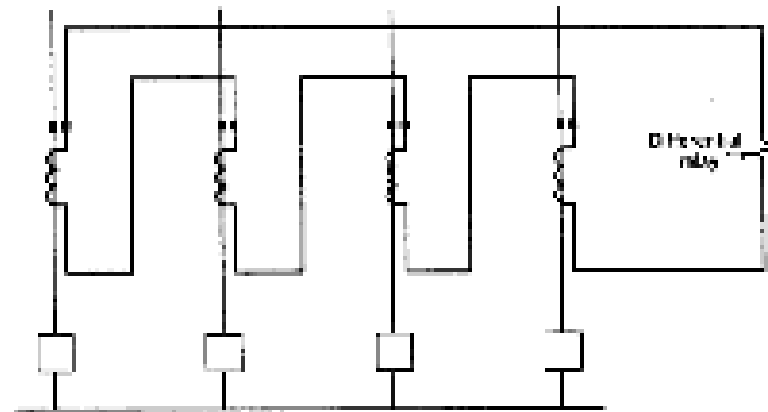
Bus Protection

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

Bus Protection

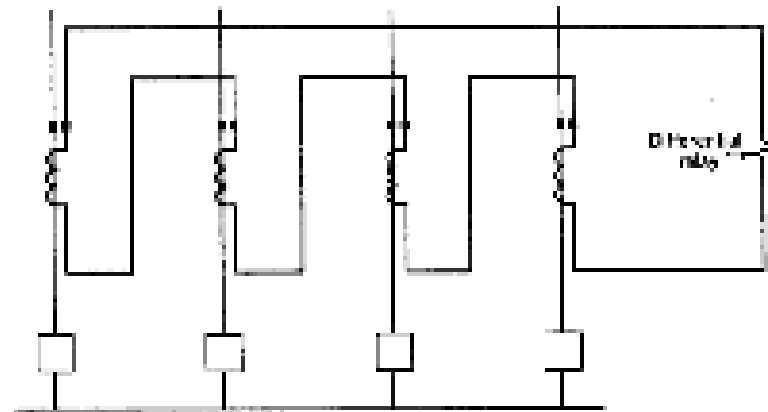
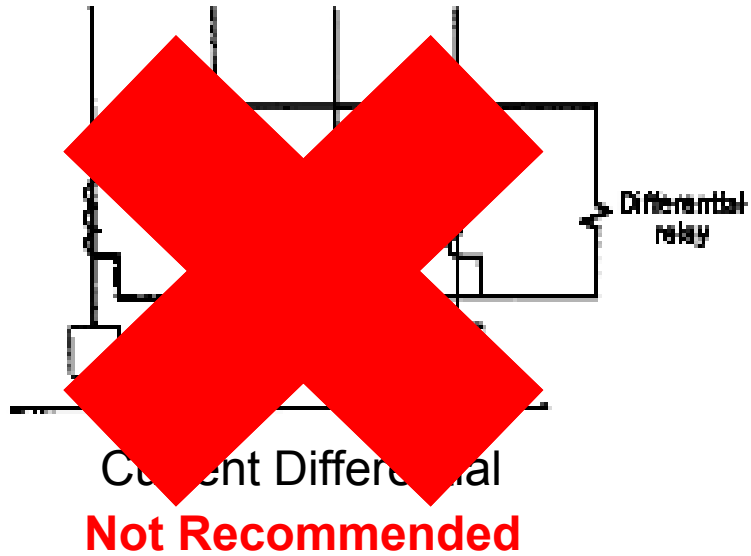


Current Differential
Not Recommended



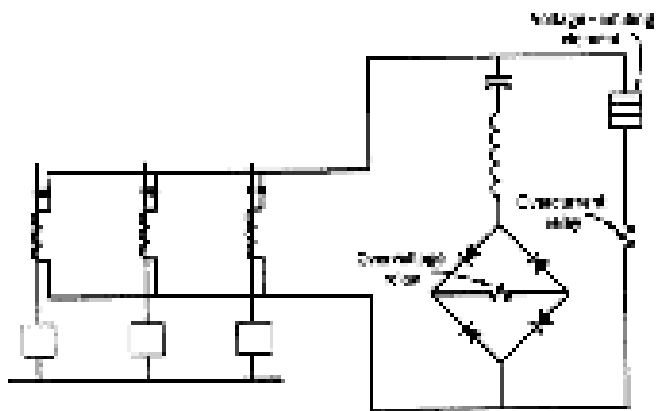
Voltage Differential – Using Linear Couplers

Bus Protection



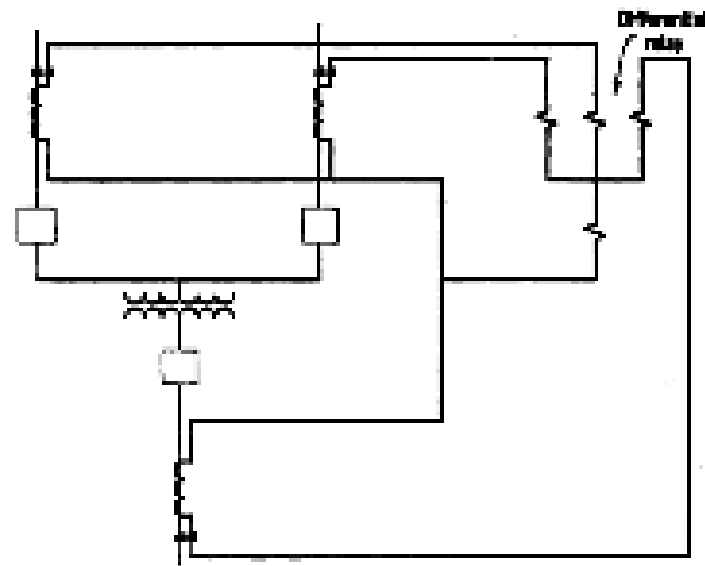
Voltage Differential – Using Linear Couplers

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:

$$(10 + \text{Main} + \text{Tie}) \times 3 = 36 \text{ current inputs!}$$

Transformer Protection

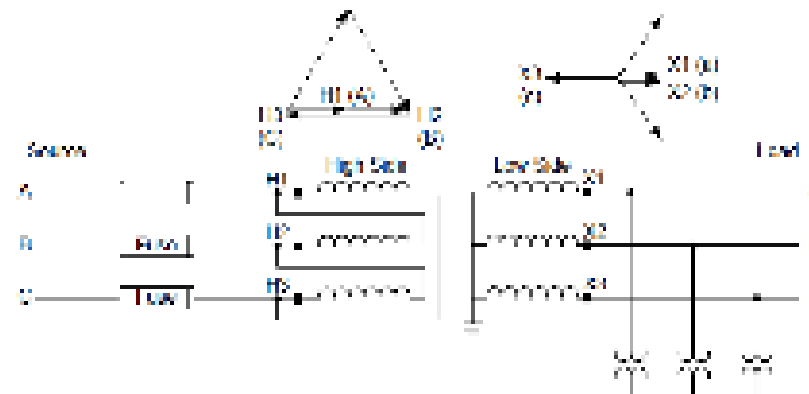
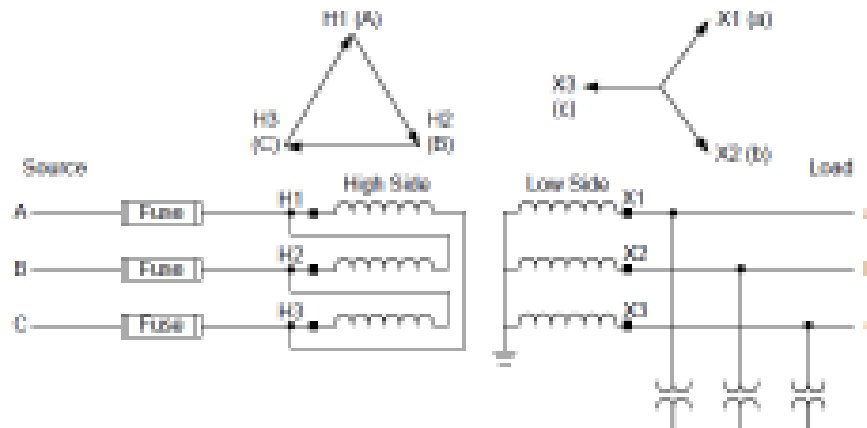
- Considerations
 - Differential Protection
 - Different Voltage Levels Including Taps
 - Mismatch Due to CT Ratios
 - 30° Phase Shift on Delta-Wye Connections
 - Magnetizing Inrush
 - Overcurrent Protection
 - CT Performance During High-Current Faults
 - Transformer Type
 - Delta-Wye
 - Zig-Zag Grounding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

Motor Protection

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

Motor Protection

Source:
Schweitzer
SEL651A
Application
Guide



5V12 = (27YAD1 OR 17YDC1 OR 27YCA1) AND (55YAD1 OR 55YDC1 OR 59YCA1). The selected generic SEL651A control equation variable combines any phase-to-phase undervoltage and any phase-to-phase overvoltage to detect a high-side blown fuse/open-phase condition.

Motor Protection

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

Motor Protection

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

Primary & Back-up Protection

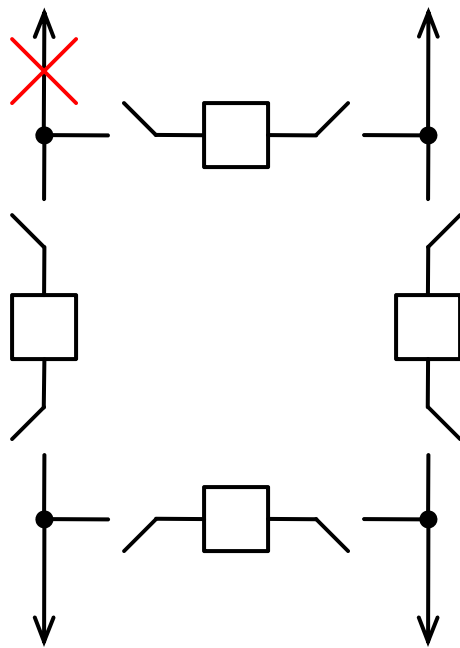
- Primary/Back-up Protection Philosophy
 - Each protected component has two sets of protection
 - Each protection set is independent of the other
 - Failure of any one component must not compromise protection
- DC Battery Systems
 - Single Battery System
 - Primary protection on different circuit from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

Breaker Failure Protection

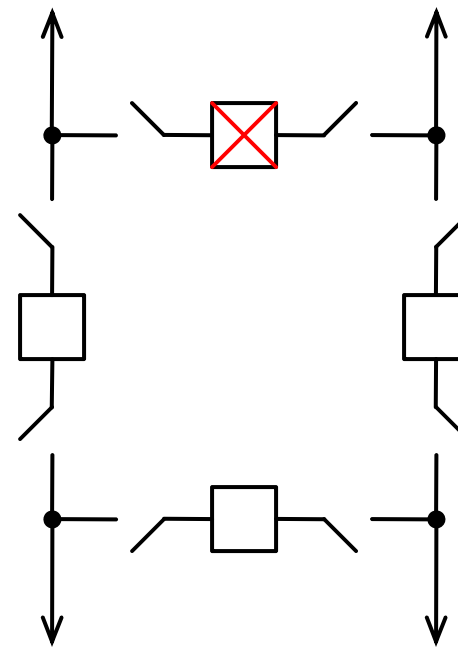
- More common at high voltage
- Communication assisted tripping required for line breakers (i.e. direct transfer trip)
- Typical Protection Logic
 - Trip signal received by breaker
 - Identical signal starts breaker failure timing
 - After a pre-set amount of time (6 cycles is common) and if current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

Breaker Failure Protection

Line/Bus Fault



Failed Breaker



Some considerations for protective relay applications...

Recommended References:

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 Protection - ANSI/IEEE Std C37.109
Transmission Line Protection – IEEE C37.113
Breaker Failure Protection of Power Circuit Breakers – IEEE C37.119
IEEE Buff Book
IEEE Brown Book
Applied Protective Relaying - Westinghouse

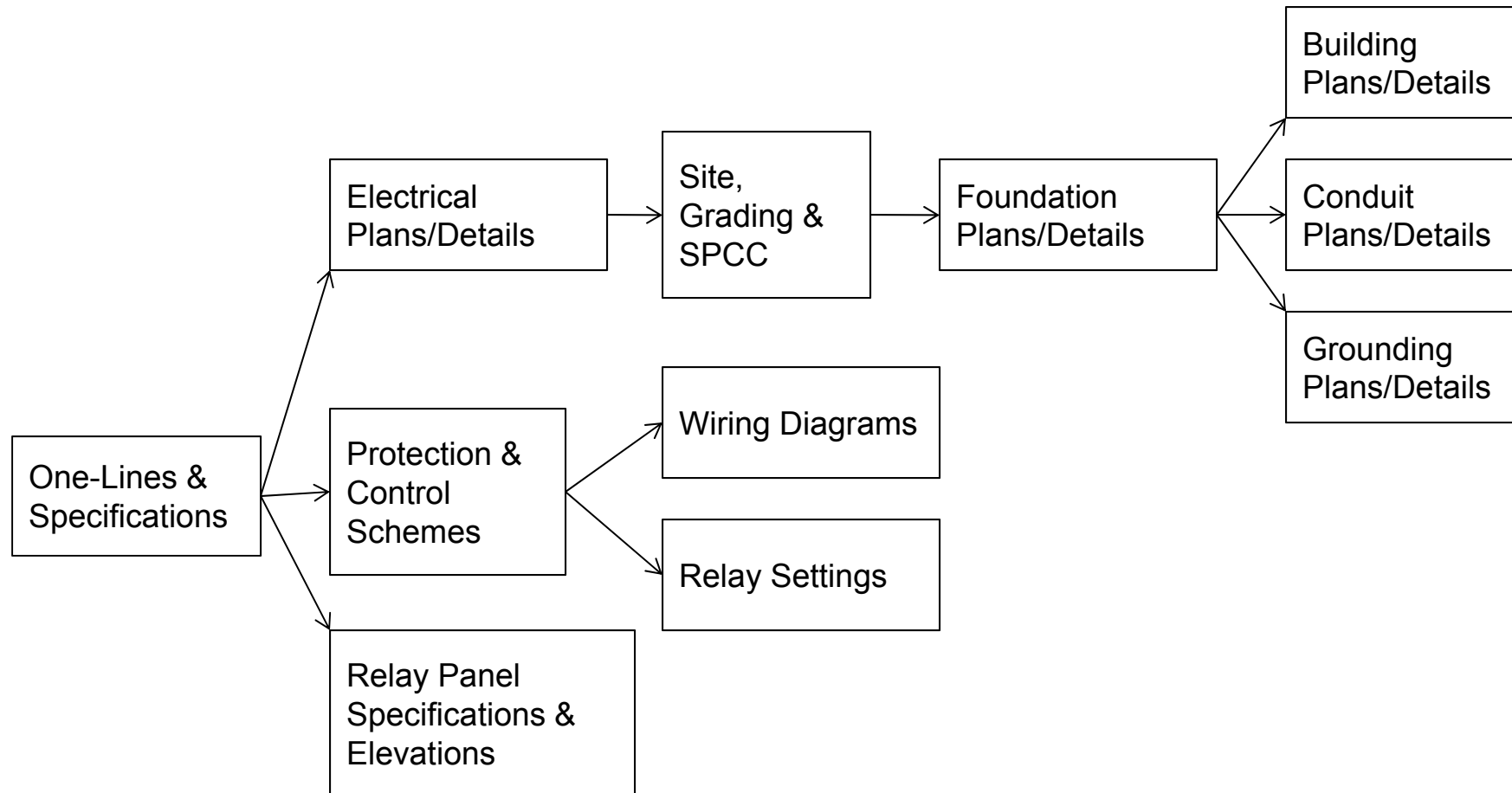
Other Considerations

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

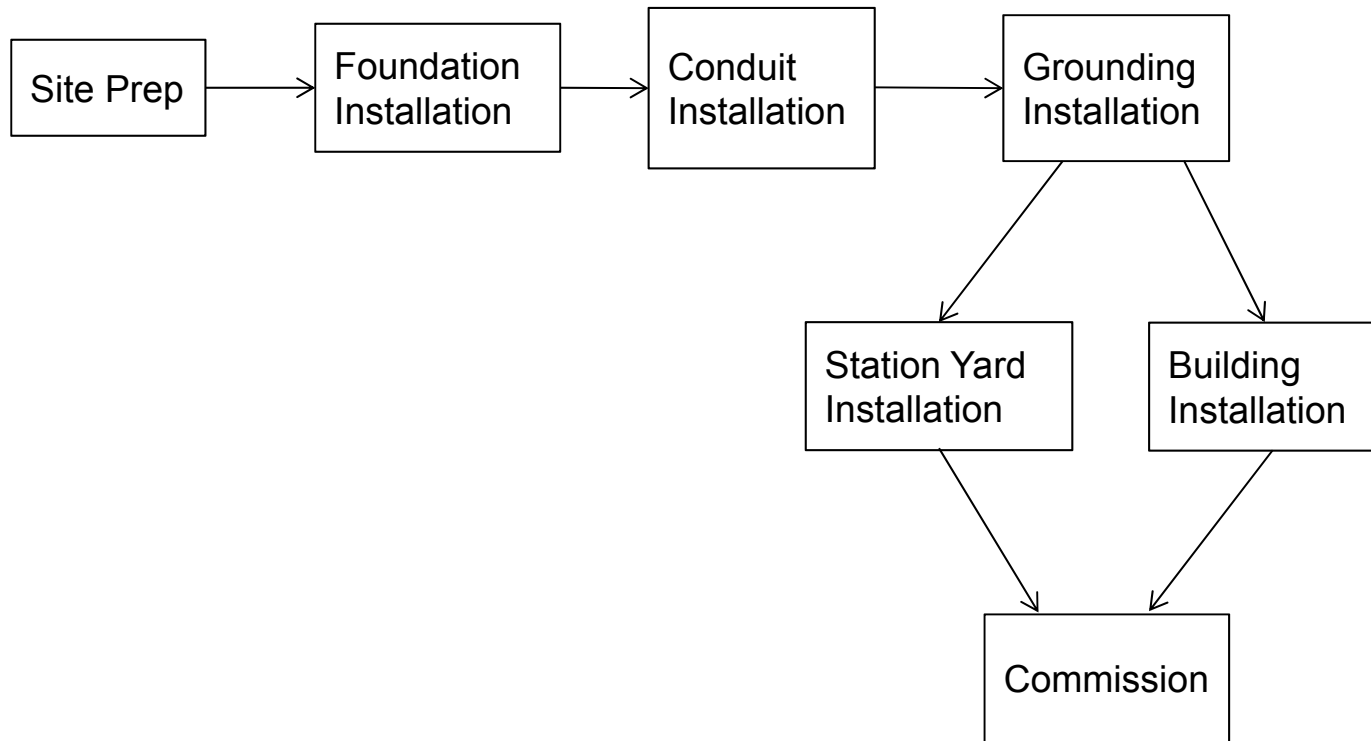
Engineering & Construction Coordination

Sh.
156

Engineering Process



Construction Process



Supplemental Topics

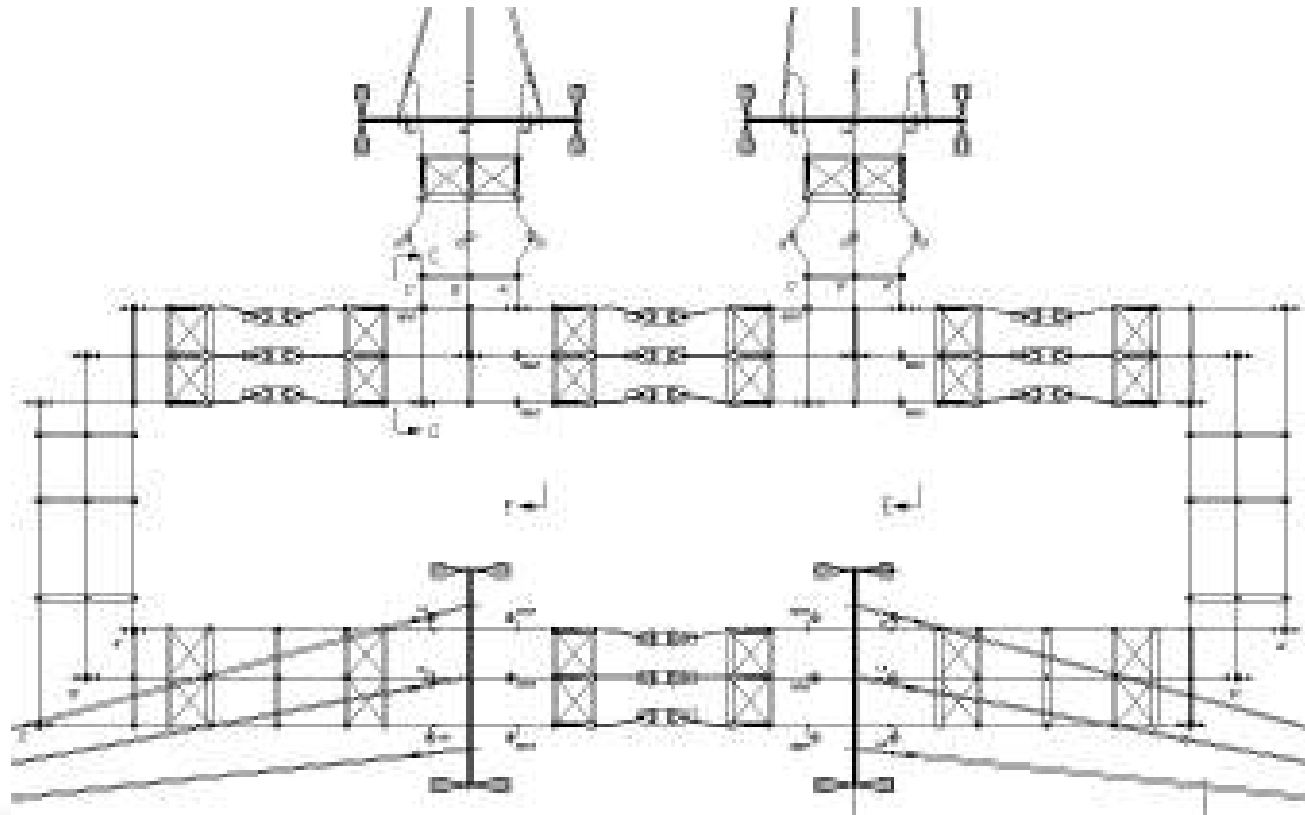
Sh.
159

Future Expansion Possibilities

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

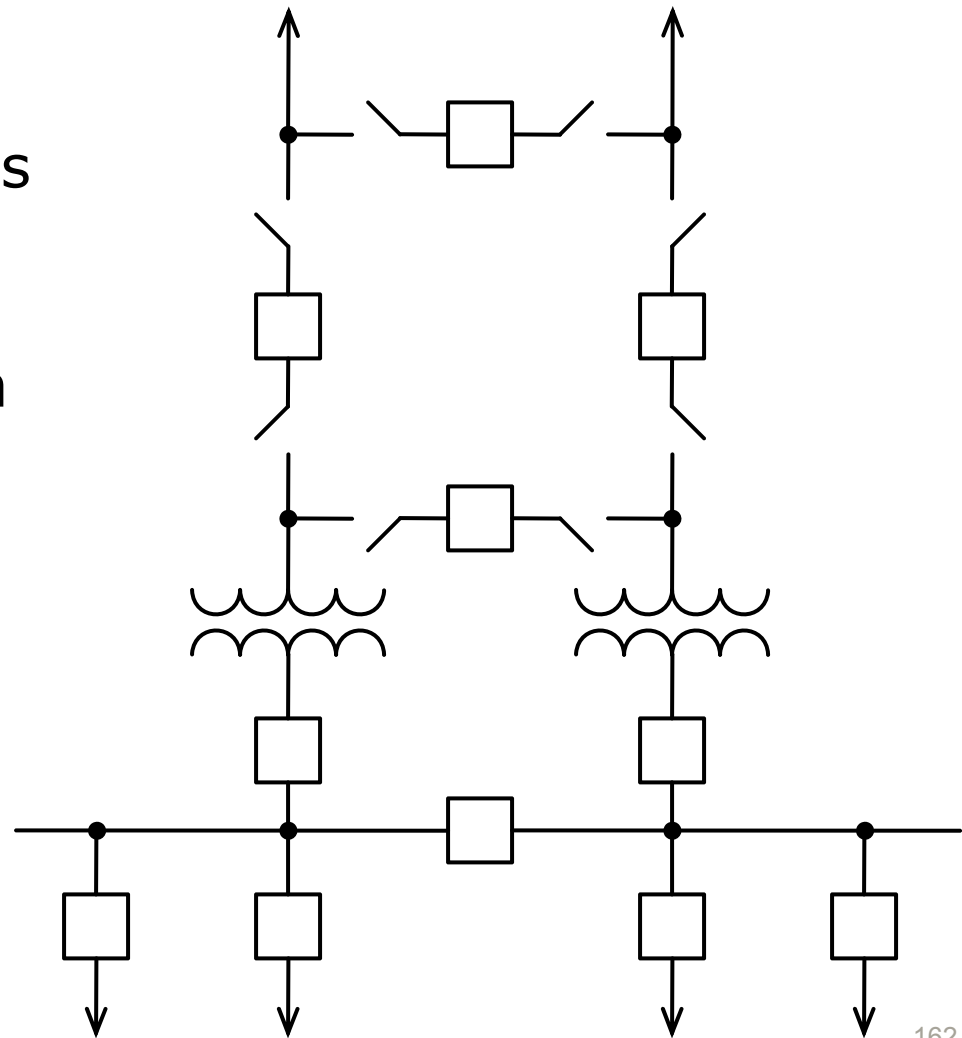
Future Expansion Possibilities

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



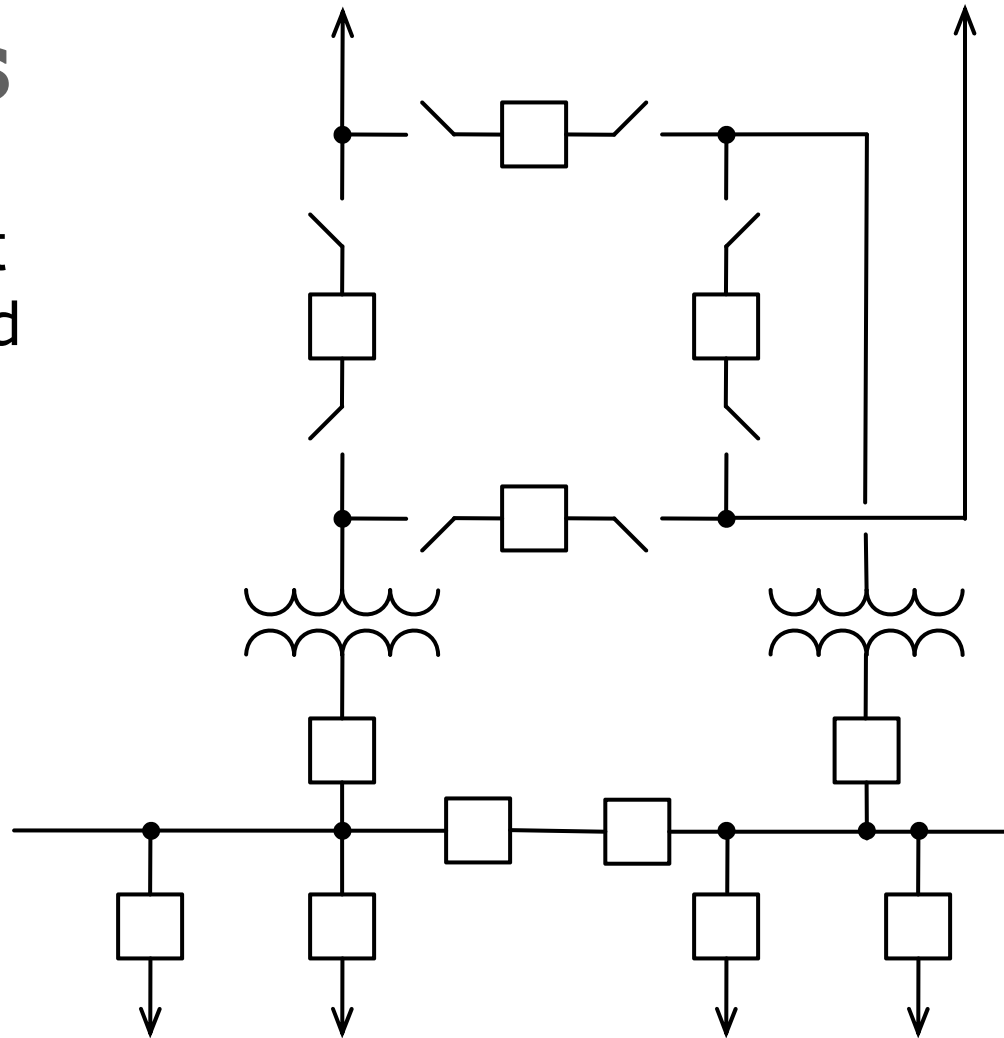
Mixing Bus Arrangements

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



Variations

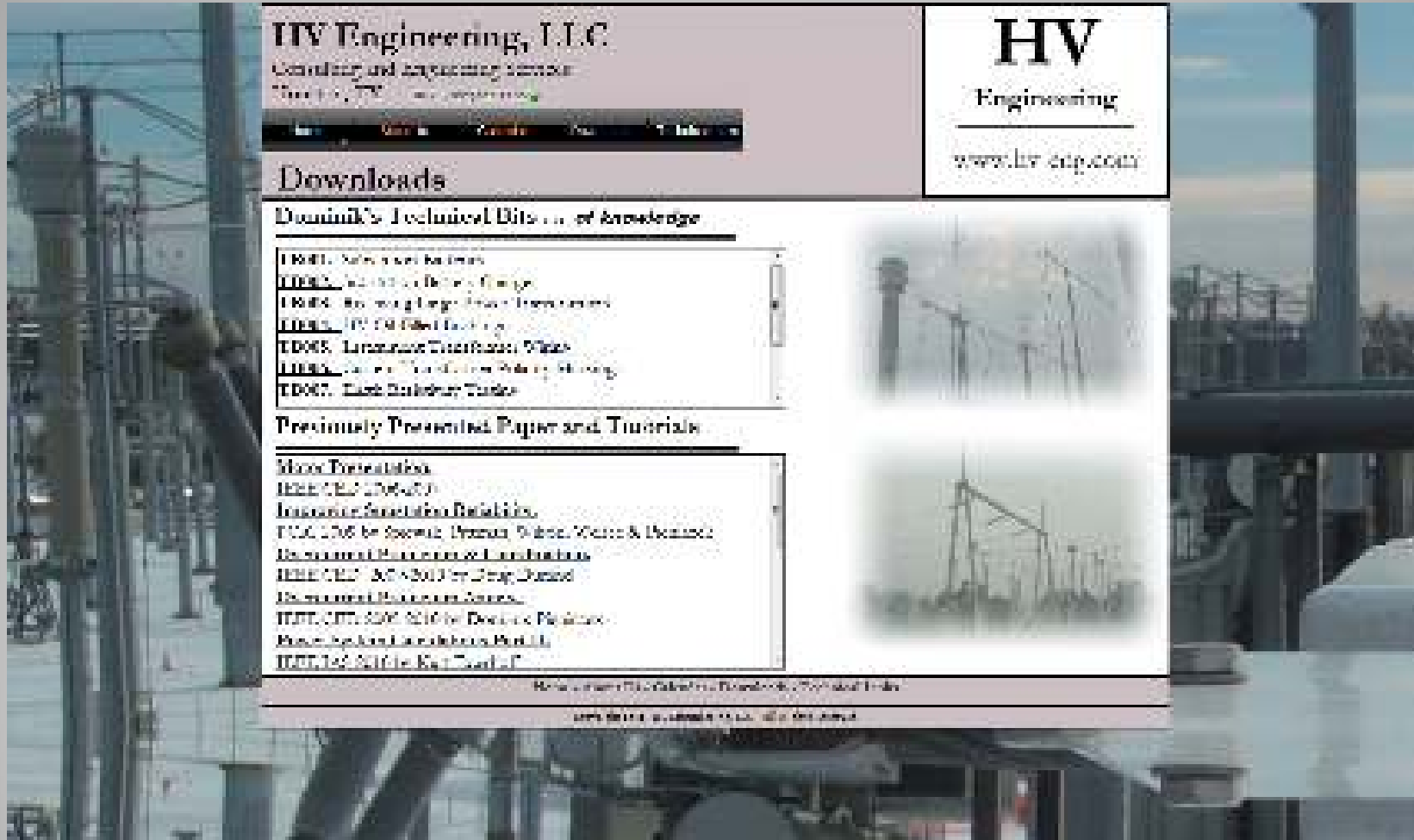
- Variations Exist
 - Swap Line and Transformer Positions
 - Add 2nd Tie Breaker



- **Single Breaker Designs**
 - Breaker maintenance requires circuit outage
 - Typically contain multiple single points of failure
 - Little or no operating flexibility
- **Multiple Breaker Designs**
 - Breaker maintenance does not require circuit outage
 - Some designs contain no single points of failure
 - Flexible operation
 - In general, highly adaptable and expandable

Conclusion

Questions?



HV Engineering, LLC
Consulting and Engineering Services
Houston, TX
www.hv-eng.com

HV Engineering
www.hv-eng.com

Downloads

Dominik's Technical Bits ... of Knowledge

- [TD001 - Substation Relaying](#)
- [TD002 - Substation Relaying Change](#)
- [TD004 - Relaying Large Power Transformers](#)
- [TD005 - HV Cable Faults](#)
- [TD005 - Lightning Transients: What](#)
- [TD005 - Lightning Transients: Why](#)
- [TD007 - Earth Electrode Ties](#)

Previously Presented Paper and Tutorials

More Presentations

- [IEEE CIGRE 2006-07](#)
- [Insulation Coordination Reliability](#)
- [IEEE 2006 for Special Voltage \(300kV, 500kV & 765kV\)](#)
- [Insulation Coordination of Substations](#)
- [IEEE CIGRE 2004-05 for High Voltage](#)
- [Insulation Coordination Considerations](#)
- [IEEE CIGRE 2004-05 for Design Practices](#)
- [Power System Reliability Part II](#)
- [IEEE 2004-05 for Key Topics](#)

Home | About | Contact Us | Feedback | Privacy Policy

© 2006 HV Engineering, LLC. All rights reserved.

www.hv-eng.com

Sh.
165

Appendix

www.hv-eng.com

Sh.
166

Example of low profile substation using lattice structures



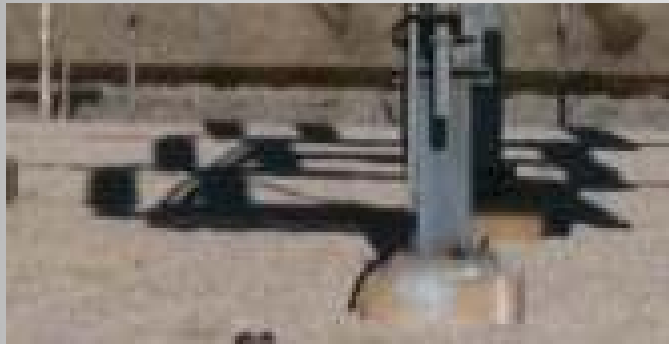
Sh.
167

Example of conventional design



Sh.
168

Base plates with grout



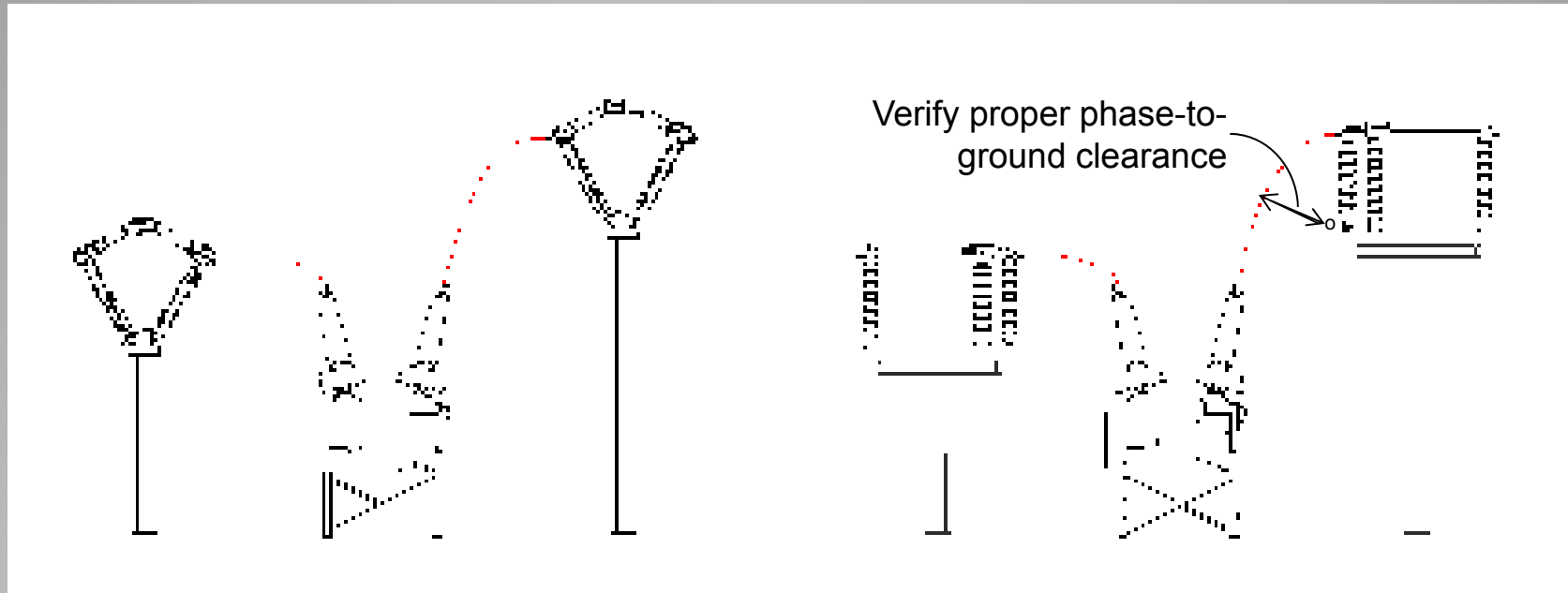
Installation leads to rusting at base of support

Base plates without grout



Preferred Installation Method*

* Structural engineer should confirm base plate and anchor bolts are sized properly



Vee Break vs. Vertical Break

**Table 15—
Preferred rated switching currents for interrupter switches***

Line Number	Rated maximum voltage (kV) max	Low-voltage loop current (amps)	Unloaded Transformer current (amps)	Line-charging current		Delayed capacitor bank current (amps) †	Table-charging current (amps)
				Capacitor bank (amps) ‡	Table-charging (amps) ‡		
1	33.9	RCC (3)	See Note 1†	10	10	100	10
2	15.0, 15.5	RCC (3)	See Note 2	10	10	400	15
3	27.6, 27.6	RCC (3)	See Note 2	10	10	400	20
4	33.0	RCC (3)	See Note 1†	10	10	150	25
5	48.3	RCC (3)	10	10	10	250	30
6	72.5	RCC (3)	10	10	10	400	30
7	121.0	RCC (3)	10	10	15	500	40
8	110.0	RCC (3)	0	0	10	100	100
9	180.0	RCC (3)	0	0	10	400	100
10	300.0	RCC (3)	0	0	100	100	115
11	400.0	RCC (3)	0	0	100	100	115

NOTES:

1. RCC = rated continuous current from Tables 3, 5 or 12 in 200, 400, 600, 1000, 1500, 2000, 3000, 4000, 5000 and 6000 amps.

2. These switches are capable of switching currents that transcend a value of 7000 A or less, provided the switches have demonstrated the ability to switch the rated load current for longer than 1000 cycles or switch for an hour at load switching ratings, as applicable.

*Interrupter switches may have one or more specifically assigned switching ranges. To be in compliance with the above, interrupter switches should provide the rated clearances, foot-candle ratings for disconnector clearances and be fully established, closed and locked.

† These devices are typically high-velocity reciprocating devices, having significant mass with stored kinetic energy and are usually mounted in the air during the opening process.

‡ These devices are either open air type, vacuum, or oil type interrupters.

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
25.0, 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
180.0	0.61	120	73.2	20.0
242.0	0.87	170	147.9	22.3
362.0	1.31	250	327.5	-

Switch Interrupter Selection Guide

Product	Load Breaking	Loop Splitting	Line/Cable Dropping	Transformer Magnetizing
Standard Arcing Horn			X	X
Quick Break Whip			X	X
High Speed Whip HSW			X	X
MAG I™		X	X	X
Load and Line Switchers (LLS®)	X	X	X	X



Arcing Horn



Quick Break Whip



High Speed Whip



Magnetic Interrupter



Load and Line Switcher