DISTRIBUTION FEEDER PROTECTION

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Chief Development Officer

Distribution Protection and Control Track
Monday, August 4, 2025
Day 1 – Session 1

COMPANY OVERVIEW

Power System Studies:
- *NERC Redundancy*
- *Stability Reviews*
- *Arc Flash*
- *Ground Fault*
- *Coordination*
- *Compliance Support*
- *Lands Survey*
- *GIS Mapping*

Power Generation:
- *Electrical Equipment Testing, Maintenance, Upgrade, Replacement*
- *Engineering Design*
- *Protection & Control Install, Test & Commission*
- *Generation Protection*
- *Switchyard Testing & Commissioning*

T&D Substation:
- *P&C Engineering Design*
- *Substation Engineering Design*
- *Structural & Civil Engineering Design*
- *Relay Testing & Commissioning*
- *Electrical Apparatus Testing & Maintenance*
- *SCADA System Commissioning*
- *Control House Design*
- *Project Management/EPC*

Distribution:
- *Distribution Design*
- *Grid Hardening*
- *Program Management*
- *Modernization*
- *Construction Management*
- *Storm Assessment/Response*
- *Data Collection and Reporting*
- *Pole Inspection and Treatment*

Digital Solutions & Advisory:
- *Systems Integration*
- *Resource Interconnection*
- *Software Solutions*
- *Outage Management System (OMS)*
- *Advanced Distribution Management*
- *Distributed Energy Resource Management*
- *Emergency Management*
- *Dynamic Line Rating (DLR) Solutions*

Renewable Collector Yard & Distributed Generation:
- *Unit Protection*
- *Engineering Design*
- *Test & Commission*
- *Battery Storage Install & Maintenance*
- *Smart Grid Implementation*
- *Renewable Siting Support*

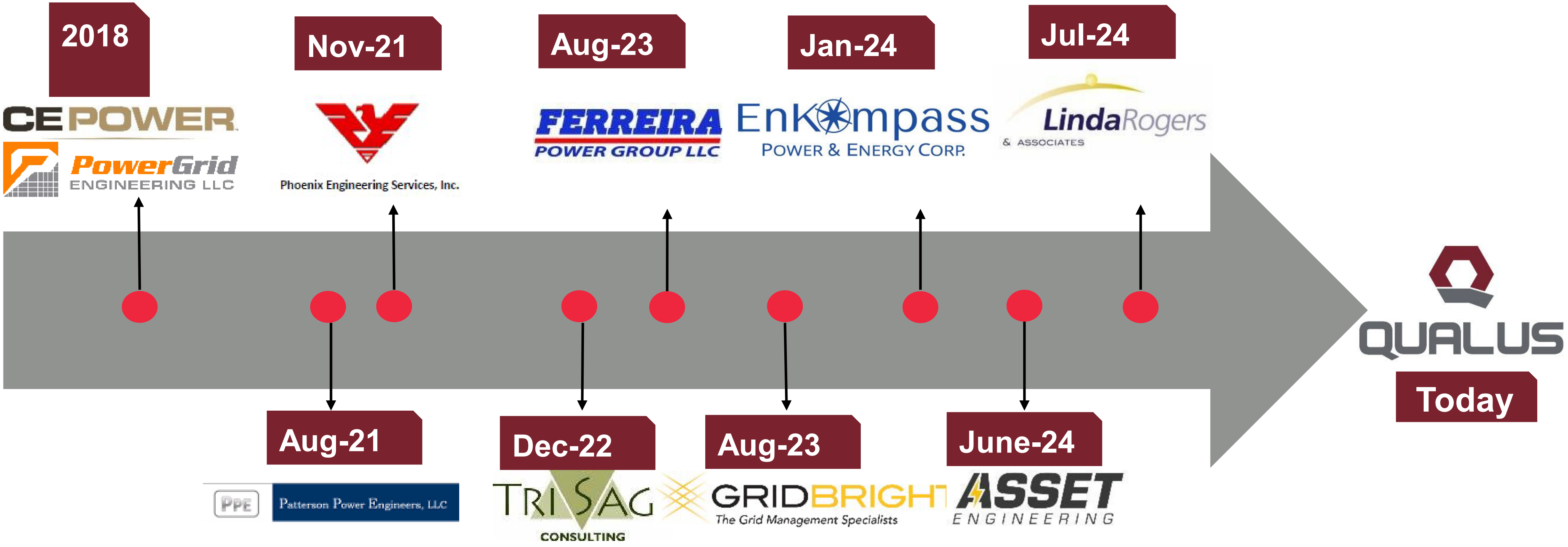
Transmission Systems:
- *Transmission Planning*
- *765, 500, 345, 230kV Systems*
- *Protective Relaying Design*
- *Protection Setting Development*
- *Communication Assisted Trips/Operations*
- *Line Differentials*
- *High Voltage T-Line Engineering*
- *EPC*

Back-Up & Emergency Power Systems:
- *Install, Test & Commission*
- *Upgrade & Replacement of Aging Equipment*
- *Electrical Design Engineering*

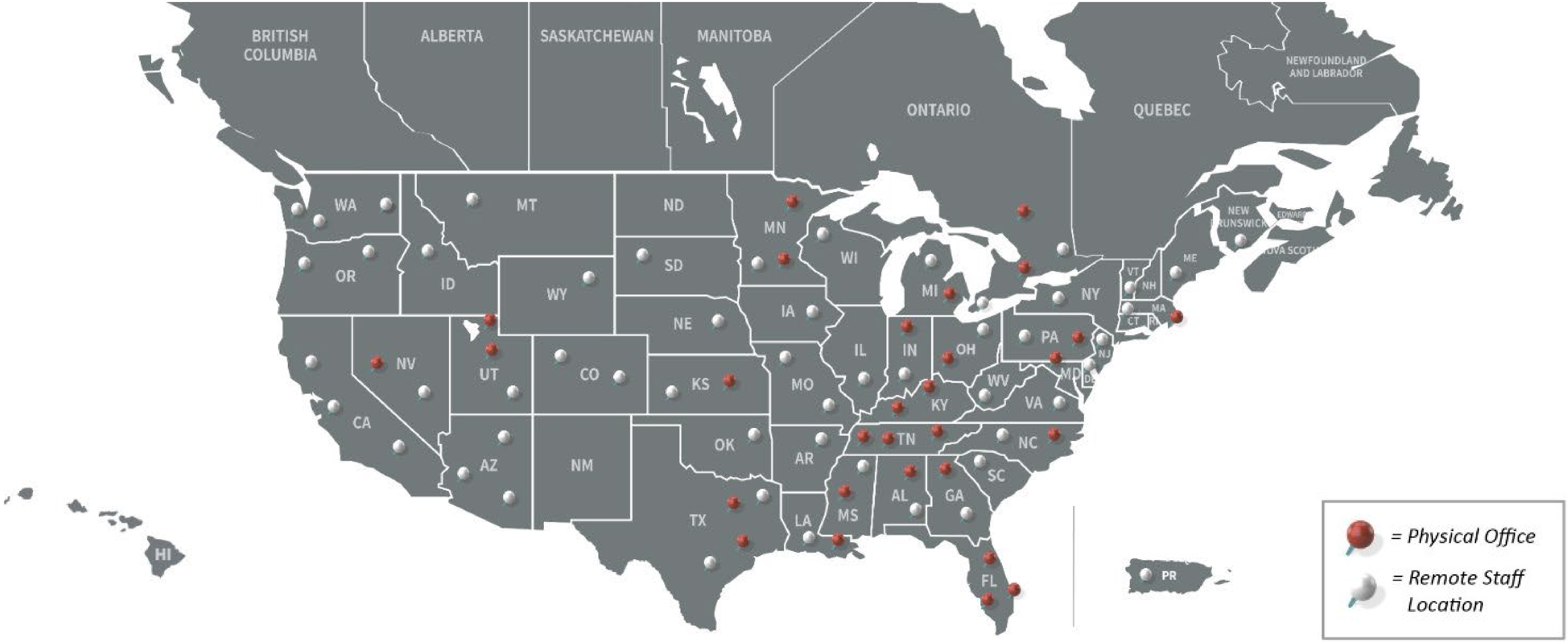
Data Centers:
- *Upfront Development/Siting*
- *Substation & Transmission Engineering*
- *Acceptance Testing & Commissioning*
- *Equipment Testing & Maintenance*
- *Protective Relay Upgrade & Replacements*
- *Project Management/EPC*

Commercial & Industrial Facilities:
- *Electrical Design Engineering*
- *Electrical Apparatus Testing, Commissioning & Maintenance*
- *Switchgear Upgrade, Replacement & Retrofil/Retrofit*
- *Protective Relay Upgrade & Replacement*
- *Motor Bus Transfer*
- *24/7 Emergency Response*
- *NETA ® Electrical Testing*

COMPANY OVERVIEW



COMPANY OVERVIEW



Over 1,000 employees throughout the U.S. and Canada and 25+ office locations

COMPANY OVERVIEW

Utility

Ameren
AEP AMERICAN ELECTRIC POWER
conEdison
Dominion
DUKE ENERGY
Entergy
EVERSOURCE
FPL
FirstEnergy
Georgia Power
Liberty
NAES
PG&E Pacific Gas and Electric Company
MIDAMERICAN ENERGY COMPANY
Southern Company
ONCOR
SRP
NV Energy
PACIFICORP
TECO TAMPA ELECTRIC
TVA
VISTRA ENERGY
Xcel Energy

Commercial & Industrial

ABM
amazon
ARCONIC Innovation, engineered.
BRIDGESTONE
Cargill
CBRE
CLIFFS
DELL EMC
Disney
DOW
EdgeCore Digital Infrastructure
Ford
Formosa Plastics
GP Georgia-Pacific
JLL
Meta
SIEMENS
switch
TESLA
USS United States Steel
TANGENT ENERGY

Renewables & Energy Storage

AMPYR
DEPCOM POWER
engie
eolus
esVOLTA
estuary POWER
NEXTera ENERGY
ORMAT
PROLOGIS
HYDROSTOR

Government

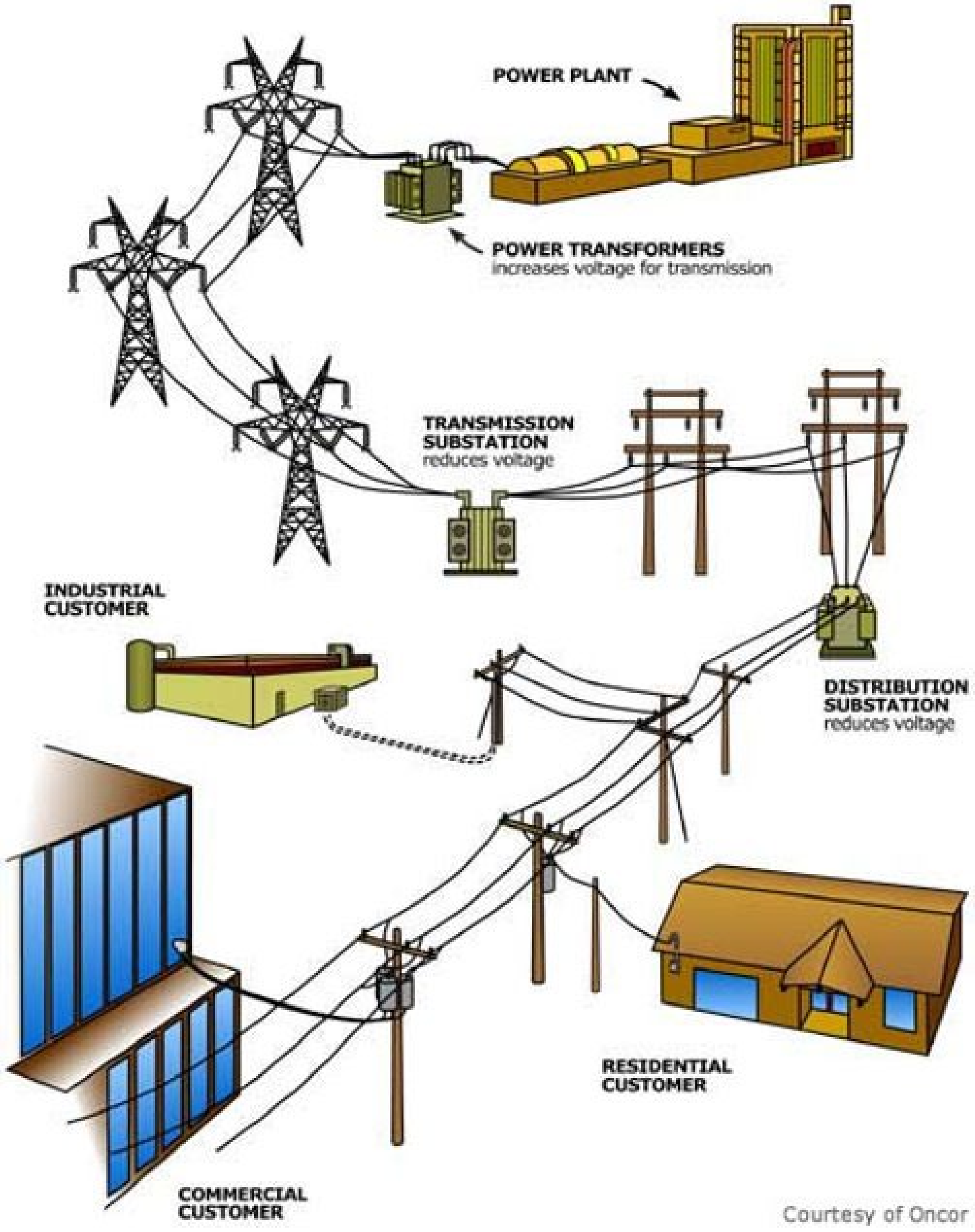
arpa-e
U.S. DEPARTMENT OF ENERGY
msd Safe, clean waterways
MDOT MARYLAND DEPARTMENT OF TRANSPORTATION
MARYLAND AVIATION ADMINISTRATION
NREL NATIONAL RENEWABLE ENERGY LABORATORY
SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy
SOCIAL SECURITY ADMINISTRATION
US Army Corps of Engineers
U.S. DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION
UNITED STATES MINT

DISTRIBUTION PROTECTION TUTORIAL OUTLINE

- Distribution System Overview
- Substation Equipment
- Substation Layouts
- Distribution Protection
- IEEE C37.230-2007
- Coordination
- Reclosing
- Distribution Automation
- Conclusion

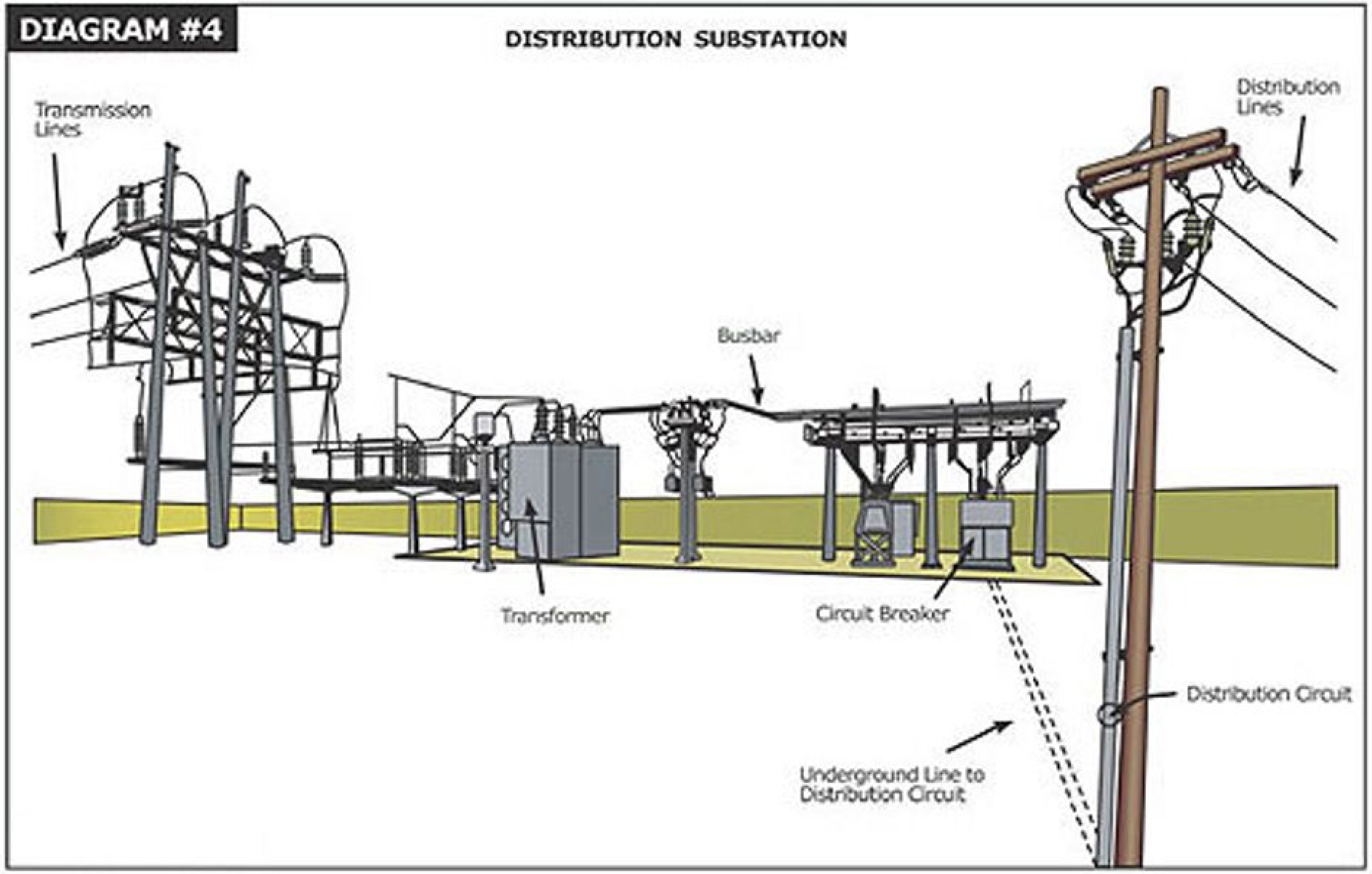
PATHWAY OF POWER

- Starts at Generators
- Step up to High Voltage
- Transmission at High Voltage
- Step down to Distribution
- Distribution to Residential, Industrial, and Commercial Customers



DISTRIBUTION SYSTEM

- Incoming Line
- Step Down Transformer
- Circuit Breakers
- Distribution Line
- Pole Top or Pad Mount Transformer to your house



SYSTEM OVERVIEW – DISTRIBUTION PROTECTION

Objective:

- Protect people (company personnel and the public) and equipment by the proper application of overcurrent protective devices.

Devices include:

- Relays operating to trip (open) circuit breakers or circuit switchers, and/or fuses blowing for the occurrence of electrical faults on the distribution system.

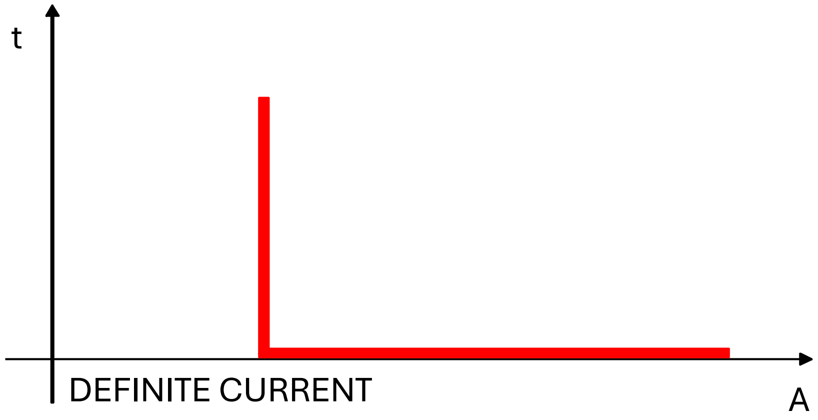
Design tools used:

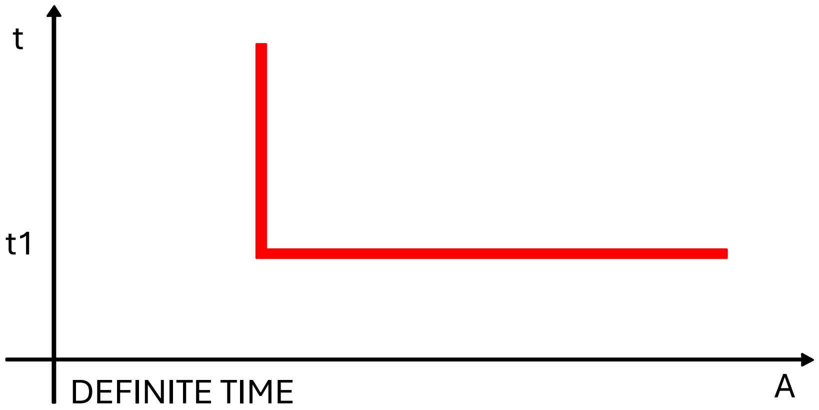
- 1 – Transformer and conductor damage curves,
- 2 - Time-current coordination curves (TCC's), fuse curves, and relay overcurrent elements based on symmetrical components of fault current.

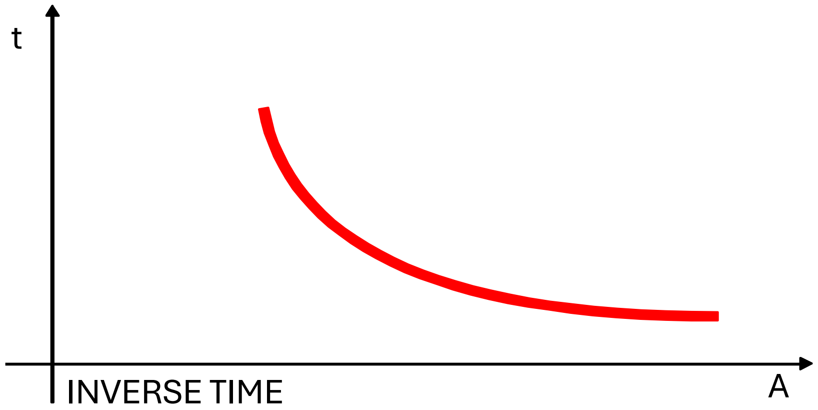
Documentation:

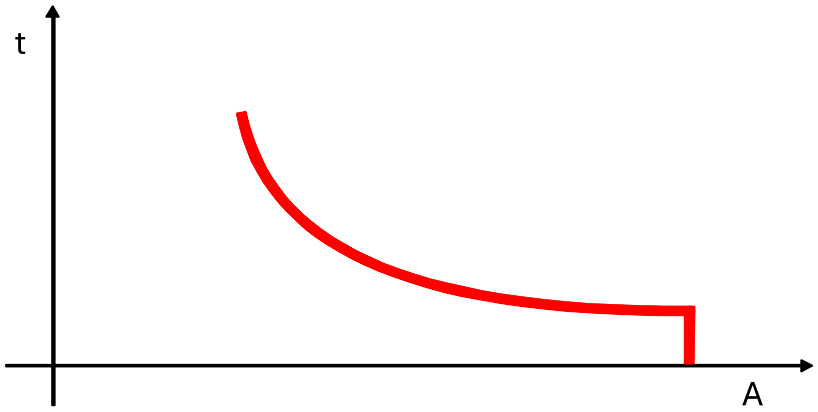
- 1 - One-line diagrams and Schematics with standardized device designations as defined by the IEEE (Institute of Electrical and Electronics Engineers) – keeps everyone on the same page in understanding how the system works.
- 2 - TCCs

Overcurrent Protection Devices









INVERSE TIME WITH INSTANTANEOUS UNIT

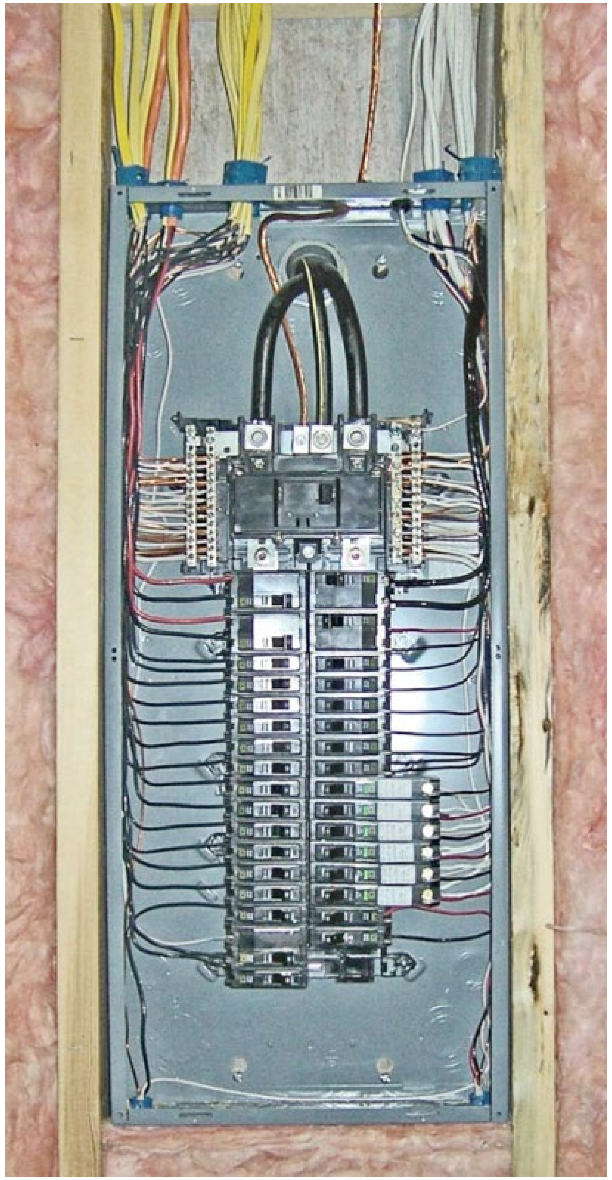
IEEE Device Designations Commonly Used in Distribution Protection

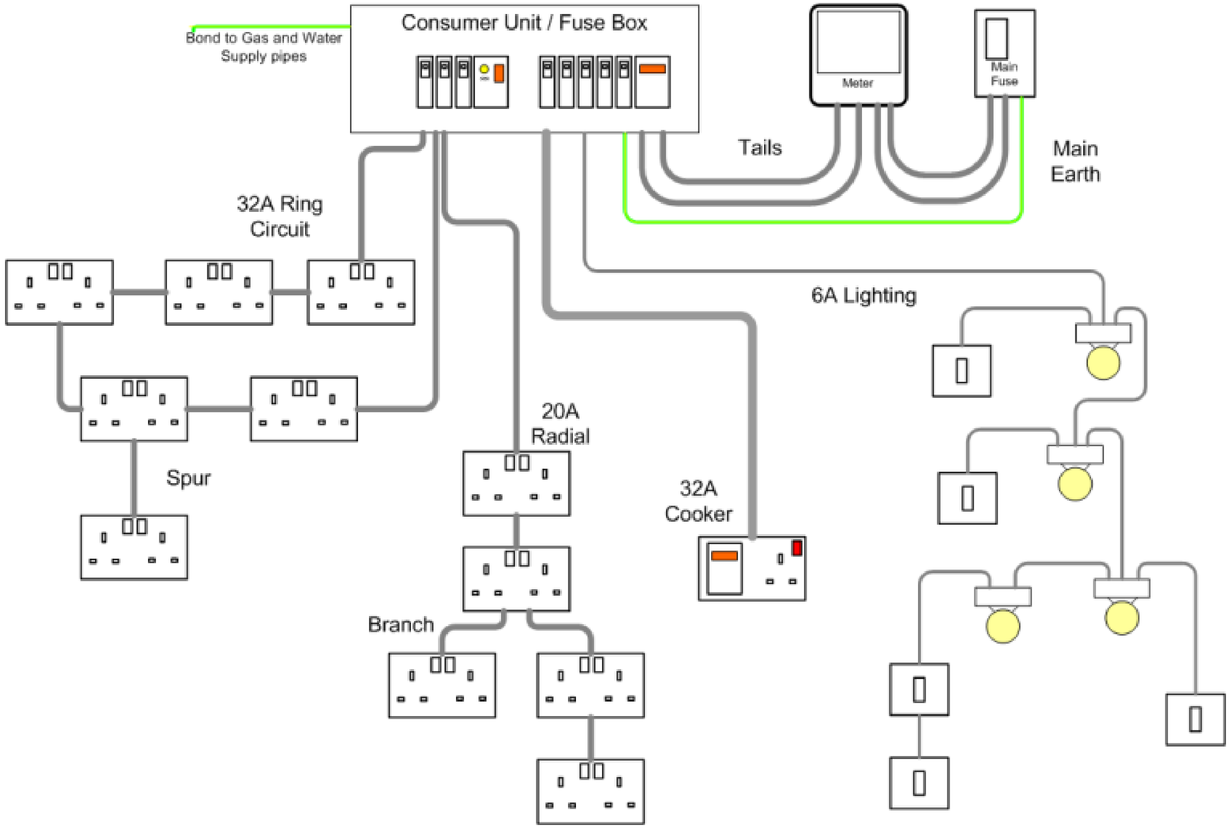
2	Time delay relay
27	Undervoltage relay
43	Manual transfer or selective device. We use these for cutting in and out instantaneous overcurrent relays, reclosing relays etc
50 (or 50P)	Instantaneous overcurrent phase relay
50N (or 50G)	Instantaneous overcurrent ground (or neutral) relay
50Q	Instantaneous Negative Sequence overcurrent relay
51 (or 51P)	Time delay overcurrent phase relay
51N (or 51G)	Time delay overcurrent ground (or neutral) relay
51Q	Time delay Negative Sequence overcurrent relay
52	AC circuit breaker
52/a	Circuit breaker auxiliary switch closed when the breaker is closed
52/b	Circuit breaker auxiliary switch closed when the breaker is open
59	Overvoltage relay
62	Time Delay relay
63	Sudden pressure relay
79	AC Reclosing relay
81	Frequency relay
86	Lock out relay which has several contacts. Avista uses 86T for a transformer lockout, 86B for a bus lockout etc
87	Differential relay
94	Auxiliary tripping relay

Many companies add letters to these, such as F for feeders, T for transformers, B for bus and BF for breaker failure.

Why we need breakers....Small Scale

Protection & Control – Small Scale





Feeder → downstream to recloser → downstream to fuse

Why we need breakers… Large Scale

Why we need breakers... Large Scale

Why we need breakers… Large Scale

- Never want to trip for normal load
- Always want to trip for faults inside of its protection zone
- Coordination
  - As fast as possible… but:
    - Must allow downstream devices to clear first
    - Must coordinate with upstream devices
    - Must protect all equipment from damage

Protection & Control – Large Scale

Substation

Breakers

Breaker Control

- Why do we have breakers?
  - Clear faults
  - Isolate parts of the system
  - Safely energize system
- A breaker is really just a big light switch
  - Turns power system on and off
- How should we control breakers?
  - Switch
  - Control House vs. local at the breaker
  - ECC - Remote
  - Automatically
    - After a trip
    - Test the line
    - Energize system (tie breaker)

- Control Switch
  - Opens Breaker
  - Closes Breaker
  - C, NAC, T, NAT (Close, Normal After Close, Normal After Trip)
  - Green Light - Open
  - Red Light - Closed
  - Newer versions are controlled by ECC
  - Currently use push buttons

Distribution Systems

- Distribution systems are responsible for delivering electrical energy from the distribution substation to the service entranc equipment located at residential, commercial and industrial consumer facilities
- Distribution voltages
  - Primary voltages between: 12.5kV & 24.9kV (in the US)
  - Some 4kV Distribution systems and some 35kV systems
  - Various other voltages such as 2.4kV delta, 4.8kV delta, 8.32 Y, 12kV delta, 13kV delta
- Distribution Equipment (not comprehensive)
  - Feeder Breakers
  - Distribution Relays
  - Poles and Wires
  - Reclosers
  - Voltage Regulators
  - Capacitor Banks
  - Switches
  - Fuses
  - Service Transformers – pad mount, pole top

Distribution Reliability

- Customers define this as the ability to keep the lights on all the time.
- Utility companies might use metrics like:
  - SAIDI – System Average Interruption Duration Index
  - SAIFI – System Average Interruption Frequency Index
  - MAIFI – Momentary Average Interruption Frequency Index
  - CMI – Customer Minutes Interrupted
- There are two facets to Distribution Reliability and you must have both to achieve it:
  - Transmission and Substation Performance (Source of Power for Distribution)
  - Distribution System Performance – Downstream of the feeder breaker
- Transmission System and Substation Performance are about keeping power provided to the distribution feeders
- Distribution System performance starts at the distribution feeder breaker and looks downstream at the poles, wires, reclosers, transformers, etc.

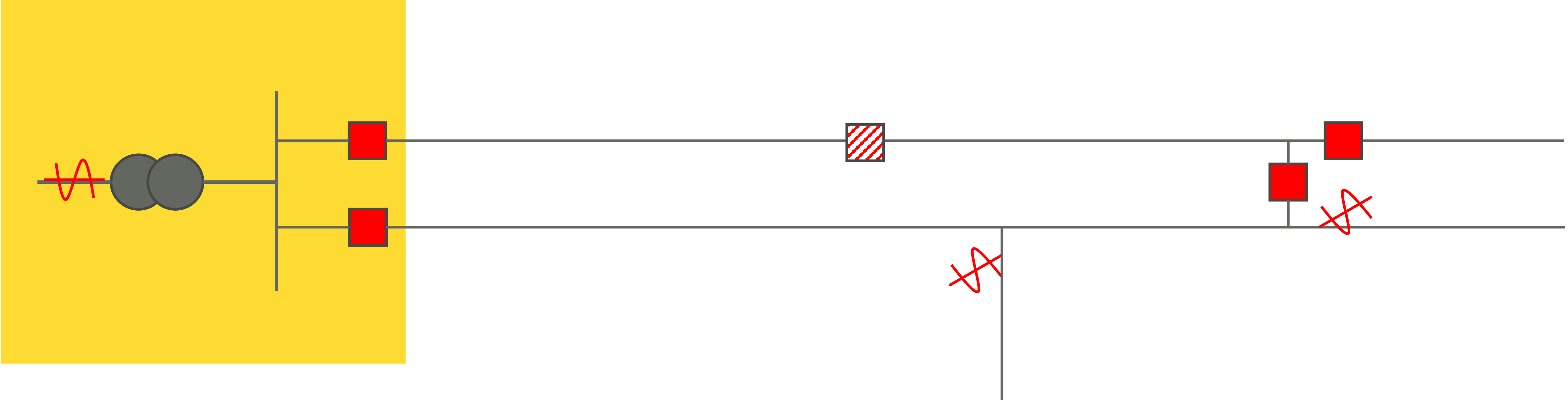
Distribution Protection Devices

Breakers/Relays

Reclosers

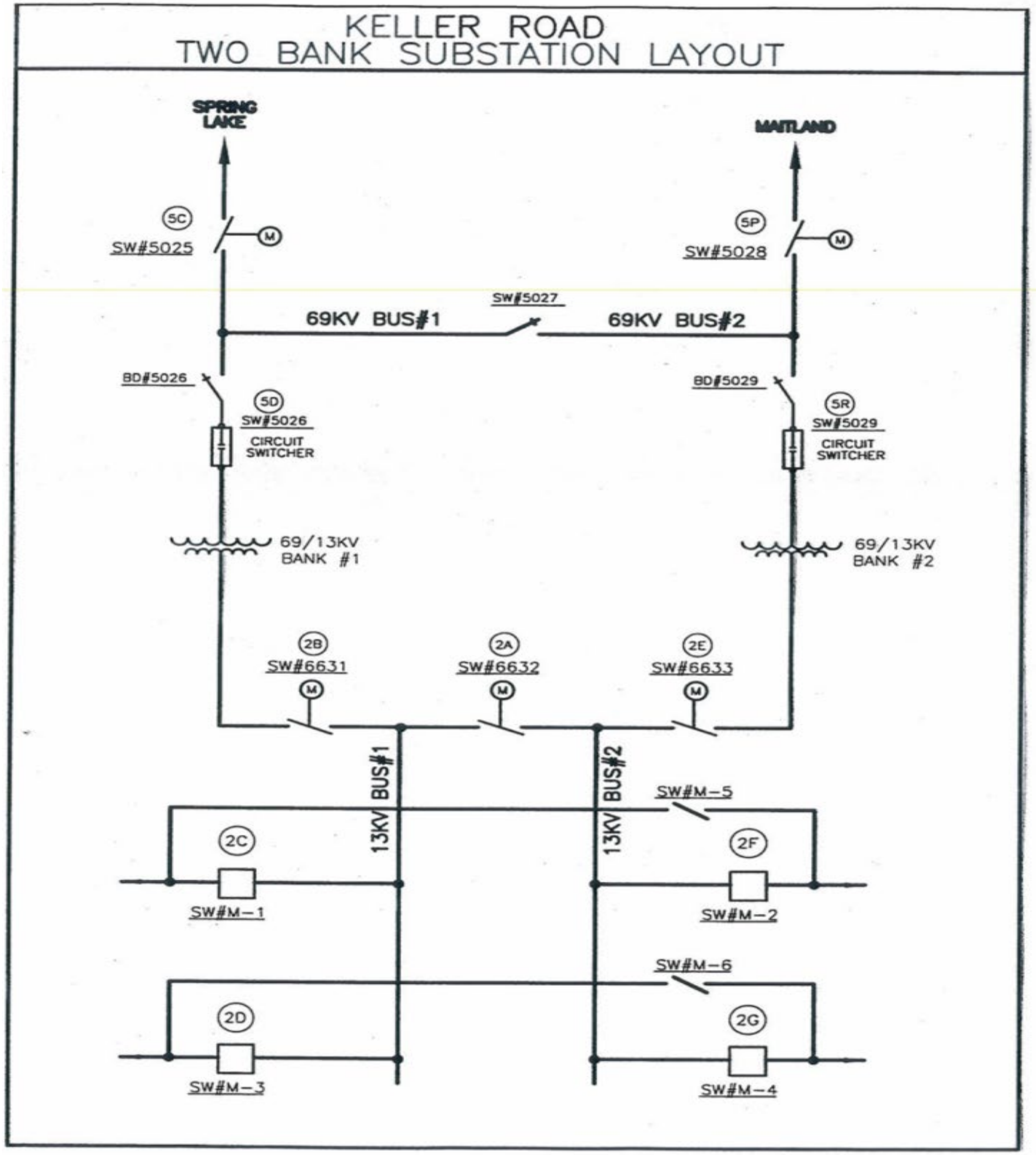
Sectionalizers

Fuses

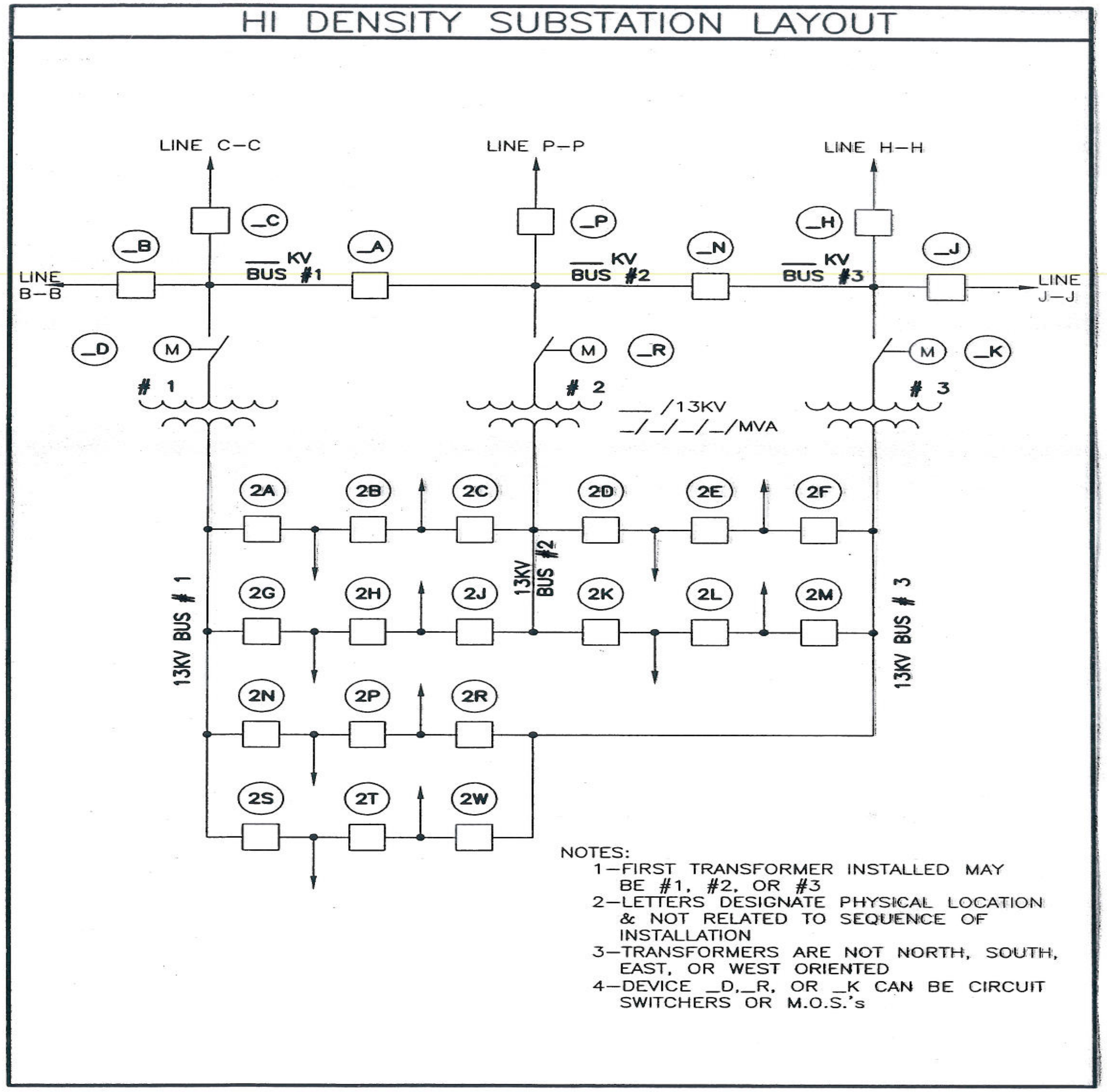


Substation Layout

- Substation Layout plays a large part in Distribution Reliability
- Substation Layouts affect the ability to keep the lights on in the event of:
  - A transmission line outage
  - Loss of a transformer
  - Required routine maintenance
- Proper substation layouts affect our ability to have redundant systems, take equipment out for maintenance, back up other substations, handle equipment failures, etc.
- Breakers allow for operational flexibility
- Let’s look at some examples


KELLER ROAD
TWO BANK SUBSTATION LAYOUT
SPRING LAKE
MAITLAND
5C
SW#5025
5P
SW#5028
SW#5027
69KV BUS#1
69KV BUS#2
BD#5026
5D
SW#5026
CIRCUIT SWITCHER
BD#5029
5R
SW#5029
CIRCUIT SWITCHER
69/13KV BANK #1
69/13KV BANK #2
2B
SW#6631
2A
SW#6632
2E
SW#6633
13KV BUS#1
13KV BUS#2
SW#M-5
2C
SW#M-1
2F
SW#M-2
SW#M-6
2D
SW#M-3
2G
SW#M-4

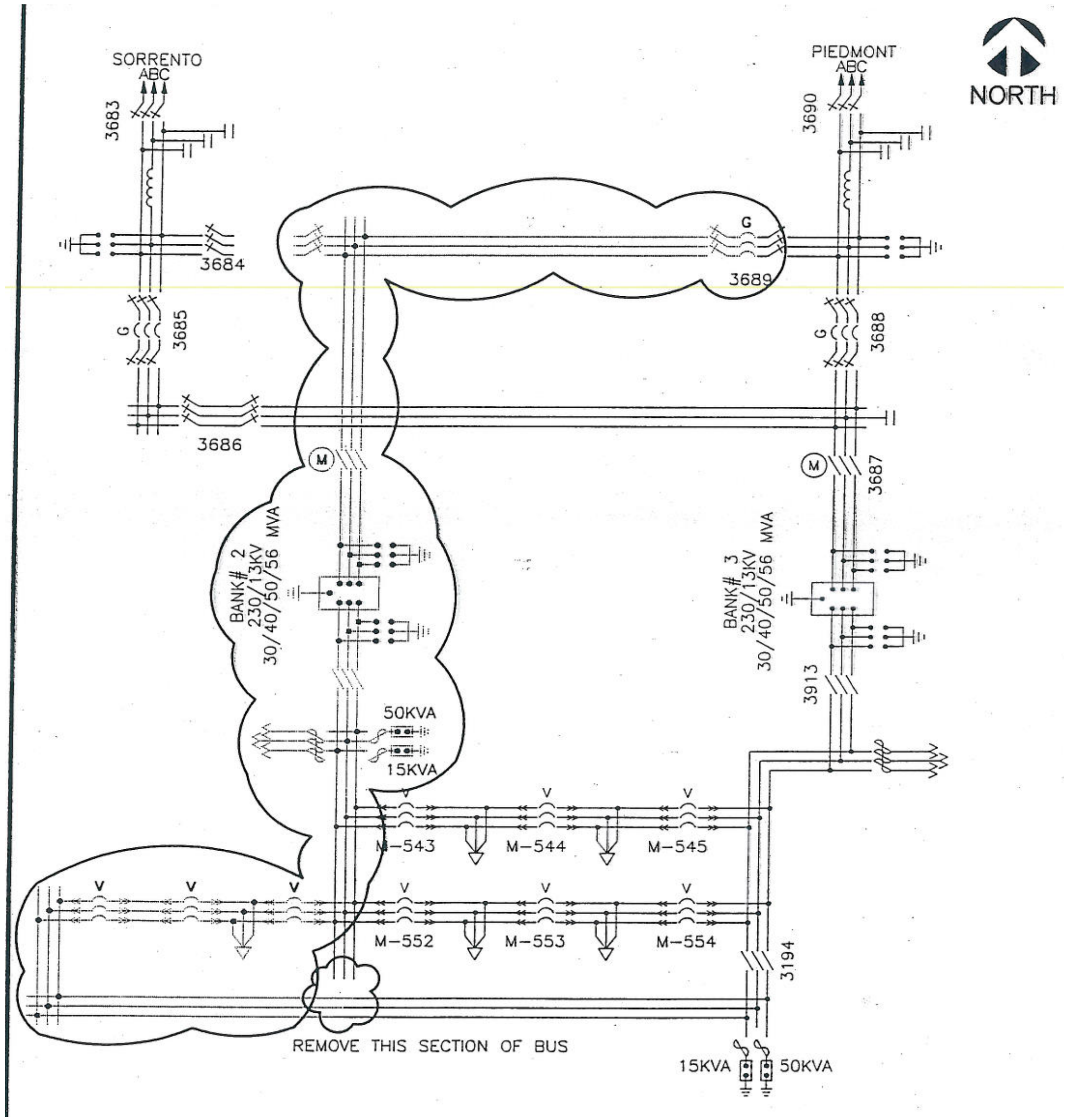
Keller Road Substation – Side View



Wekiva Substation

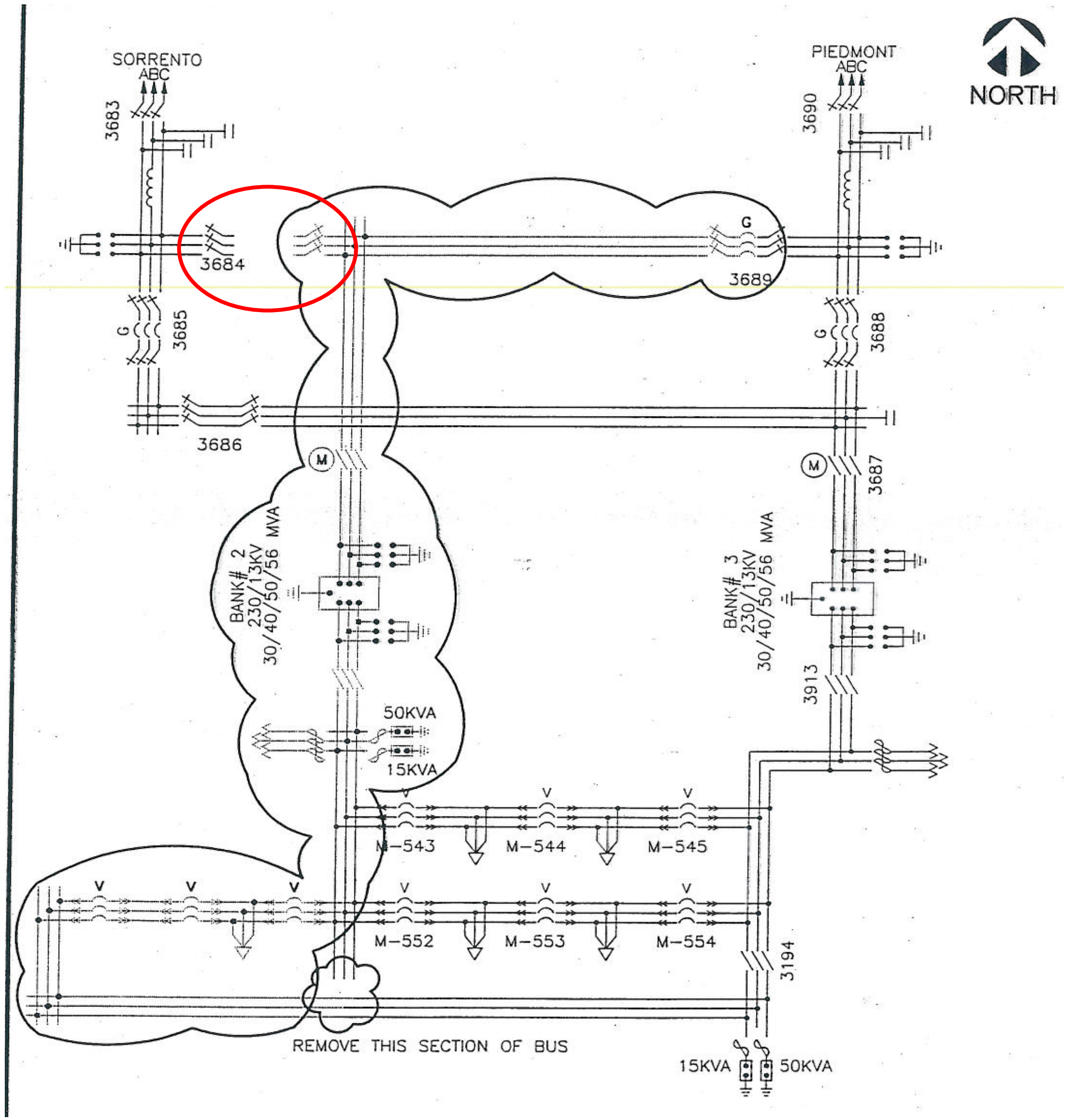
Welch Road Substation

- This “proposed” design came across my desk one day. I almost let it slip through
- What’s wrong with this picture?



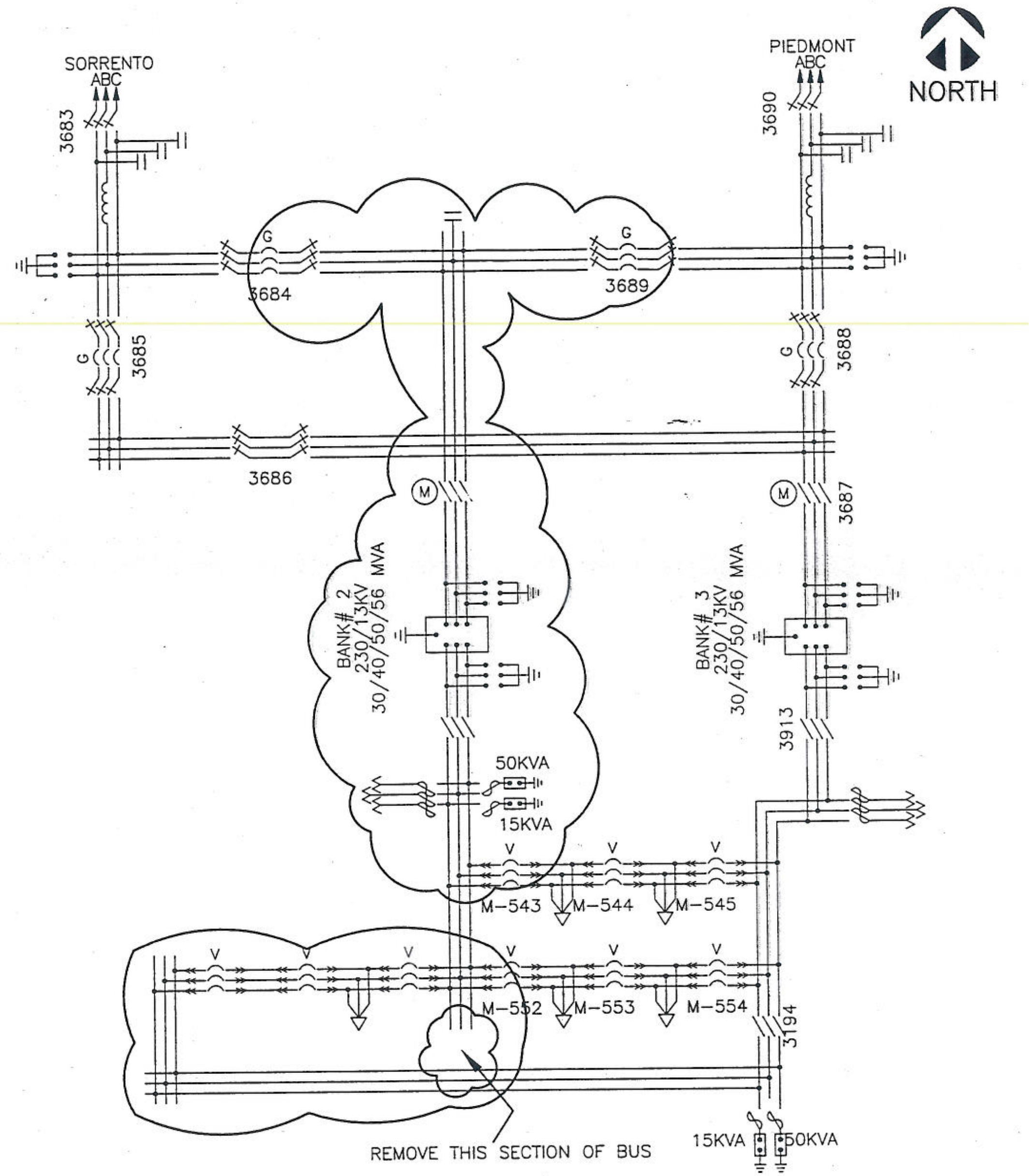
Welch Road Substation

- There is no tie breaker installed between the two
- Transmission sources

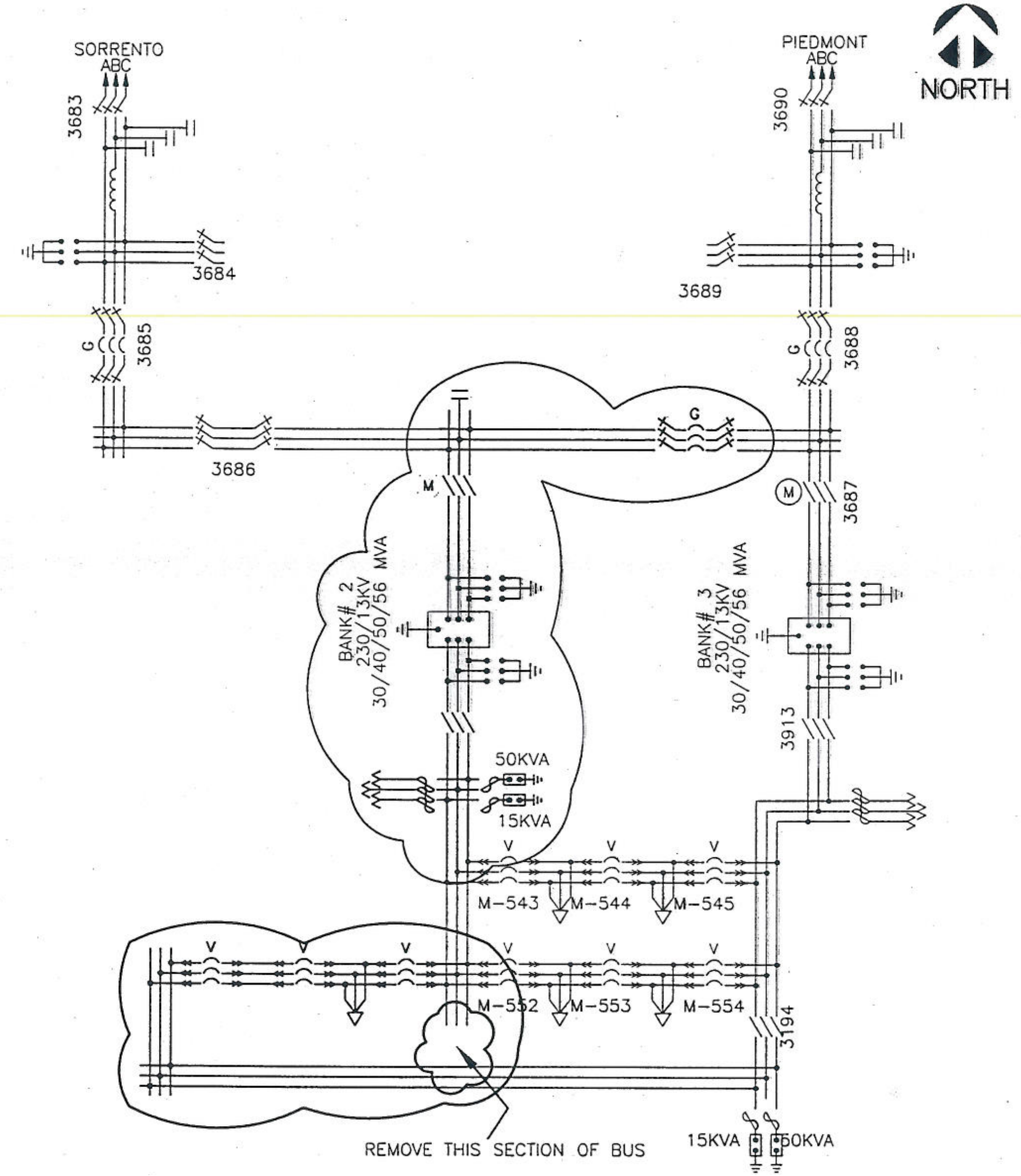


Consider this option:

- Ring bus on the 230 kV side
- Requires 2 new 230 kV breakers
- Very reliable
- Loss of any one transmission line does not affect either transformer or the distribution feeders
- Operational flexibility
- Somewhat costly due to addition of 2 new breakers

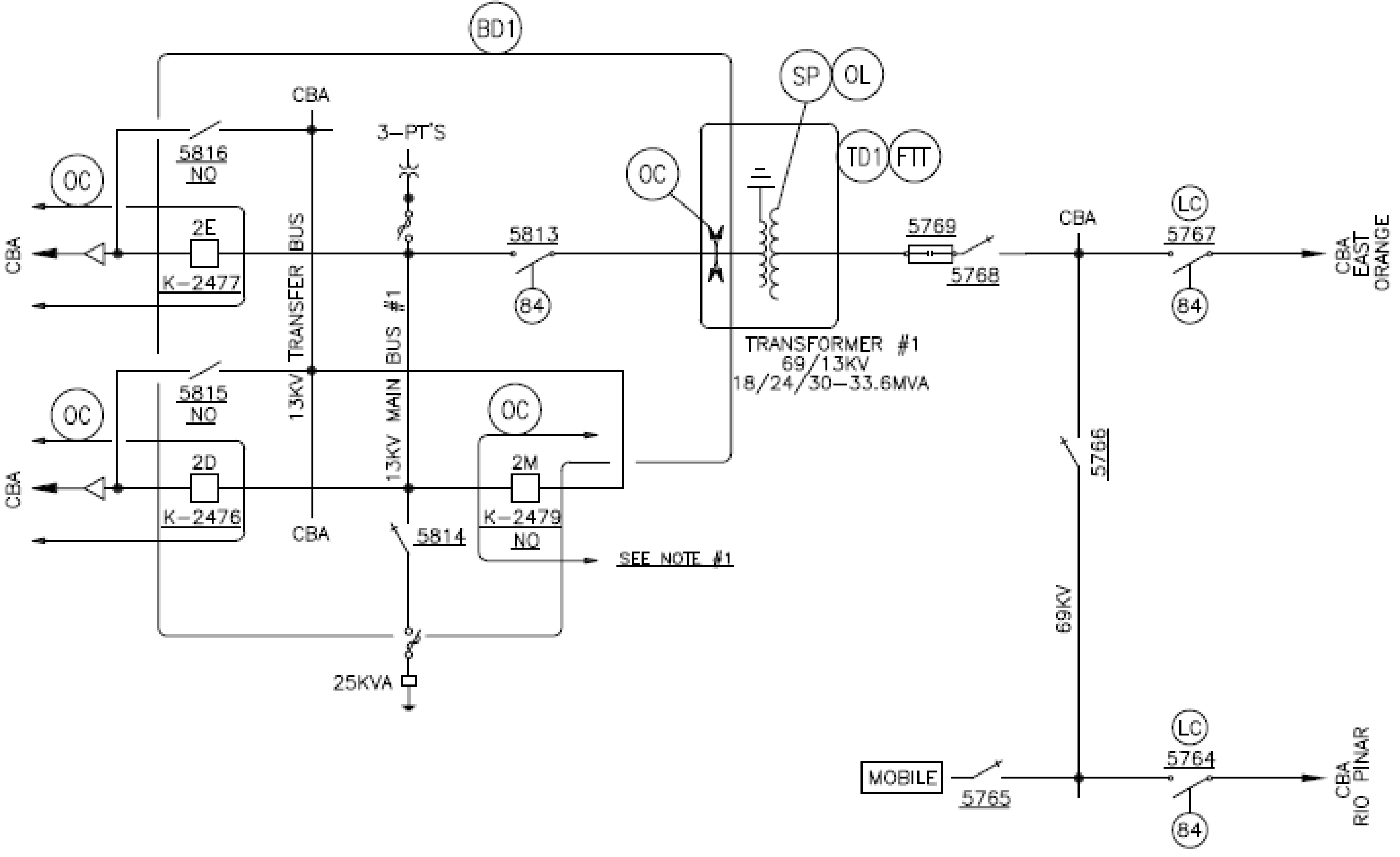


This was the final plan – a compromise

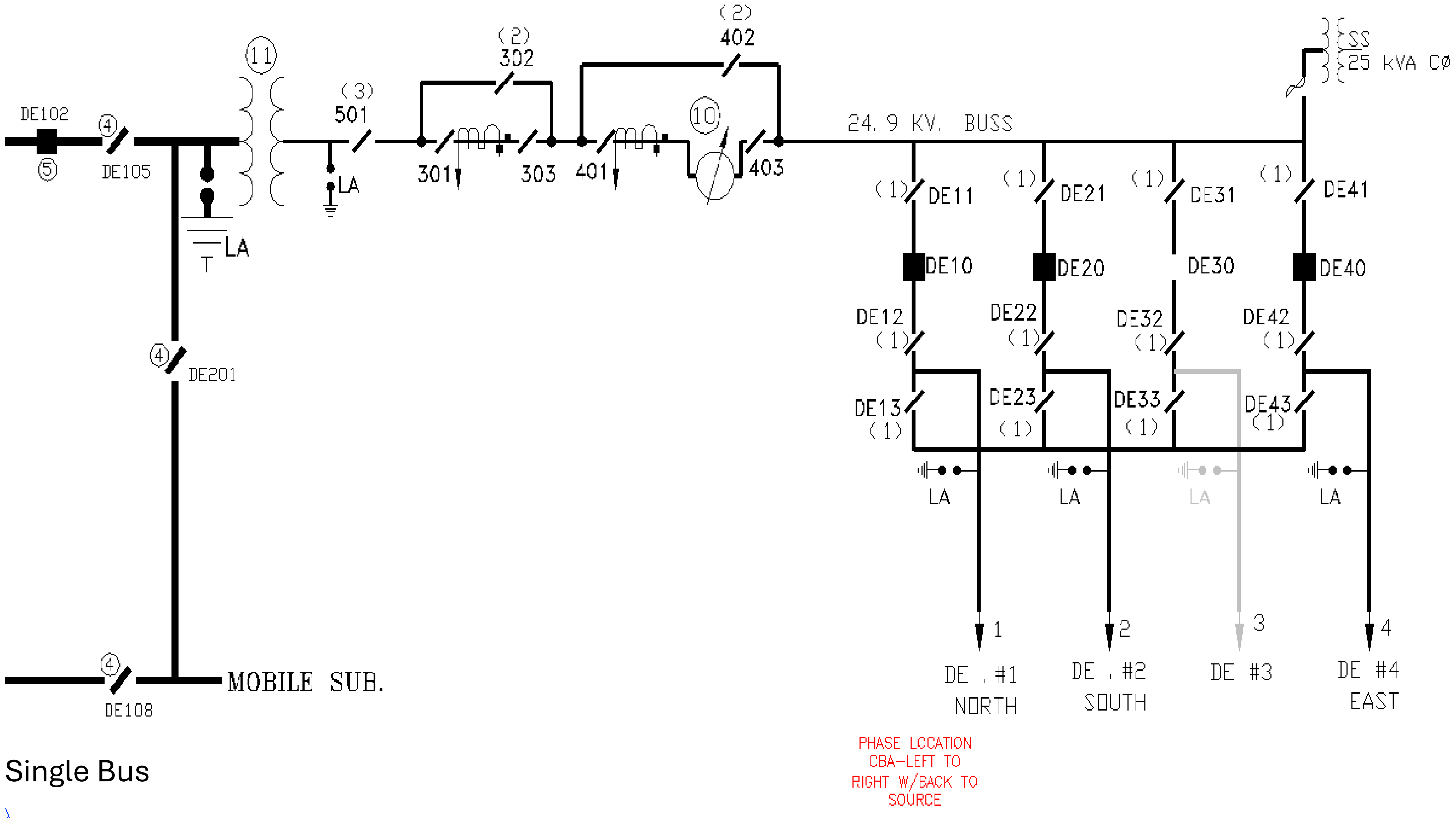


Colonial Substation

Colonial Substation PZ

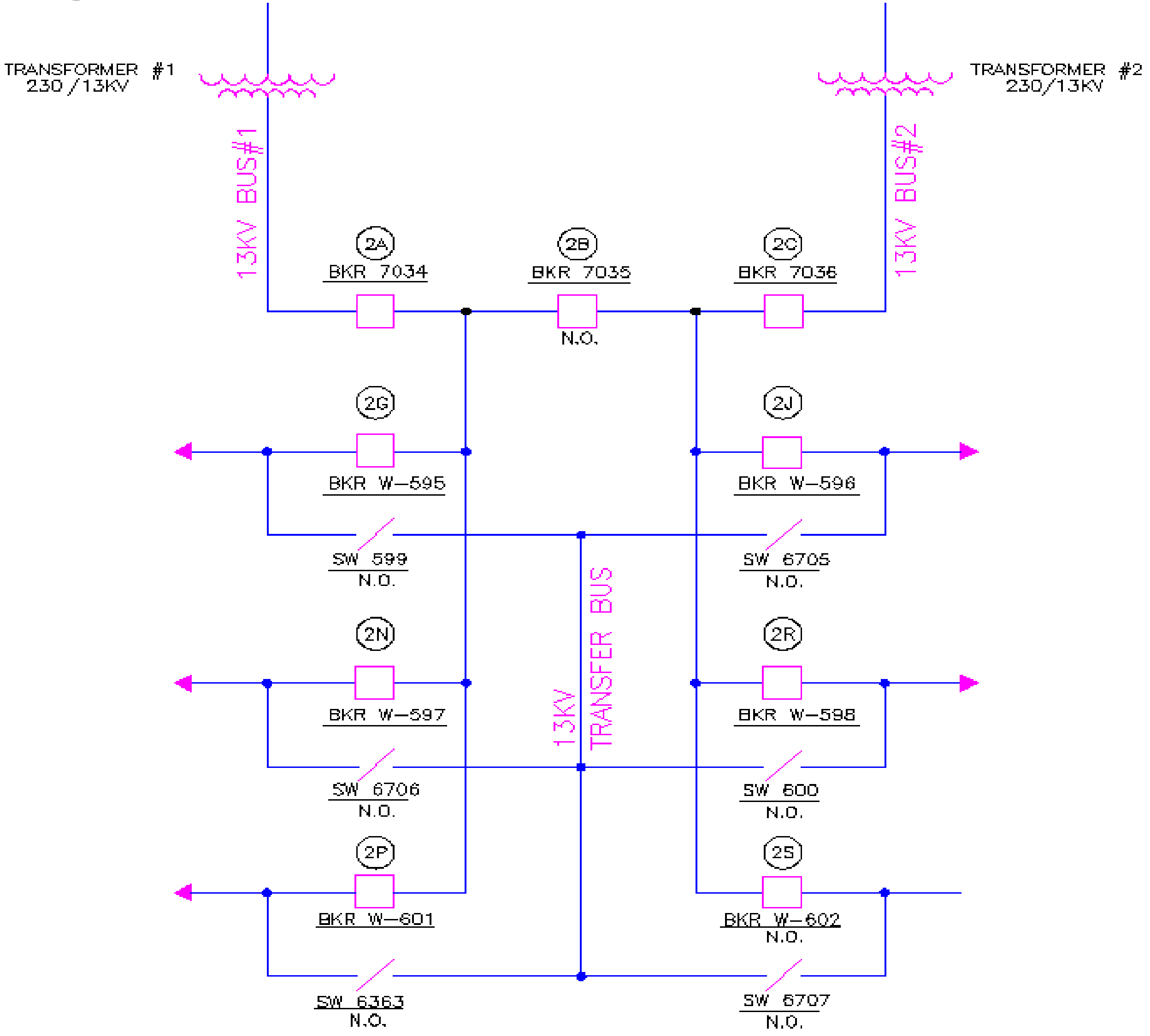


Distribution Layouts



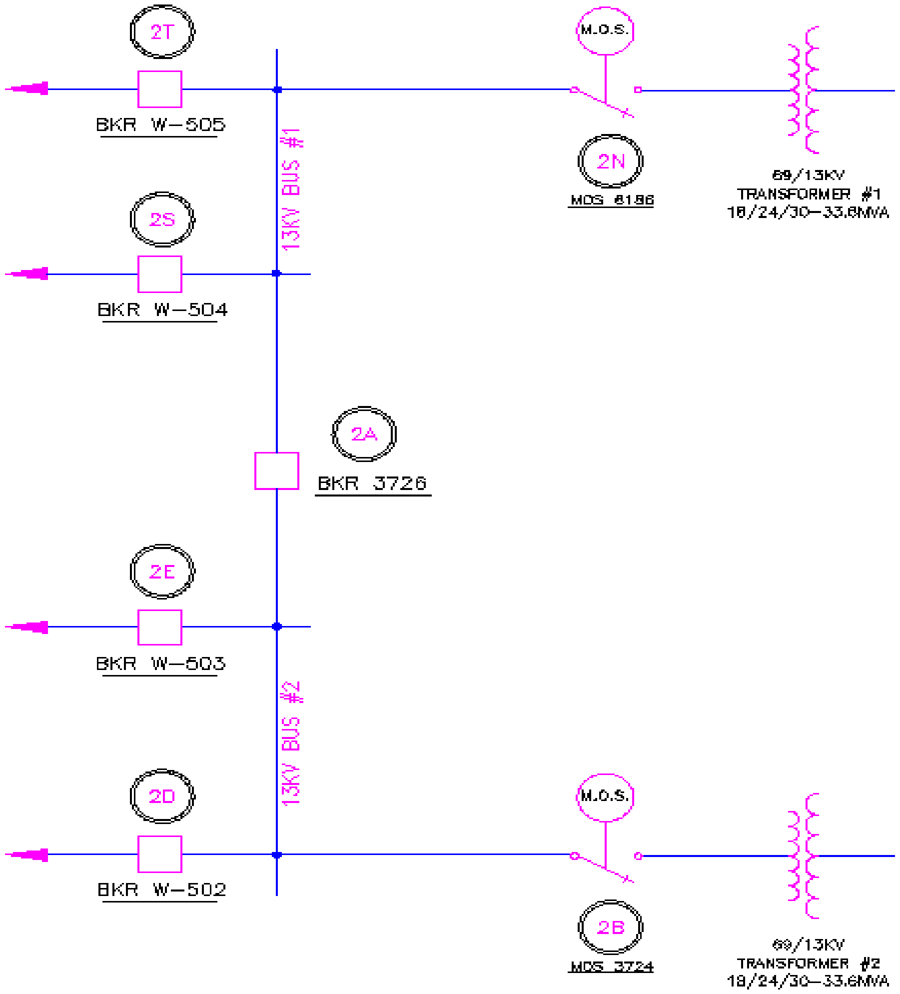
Single Bus

Distribution Layouts



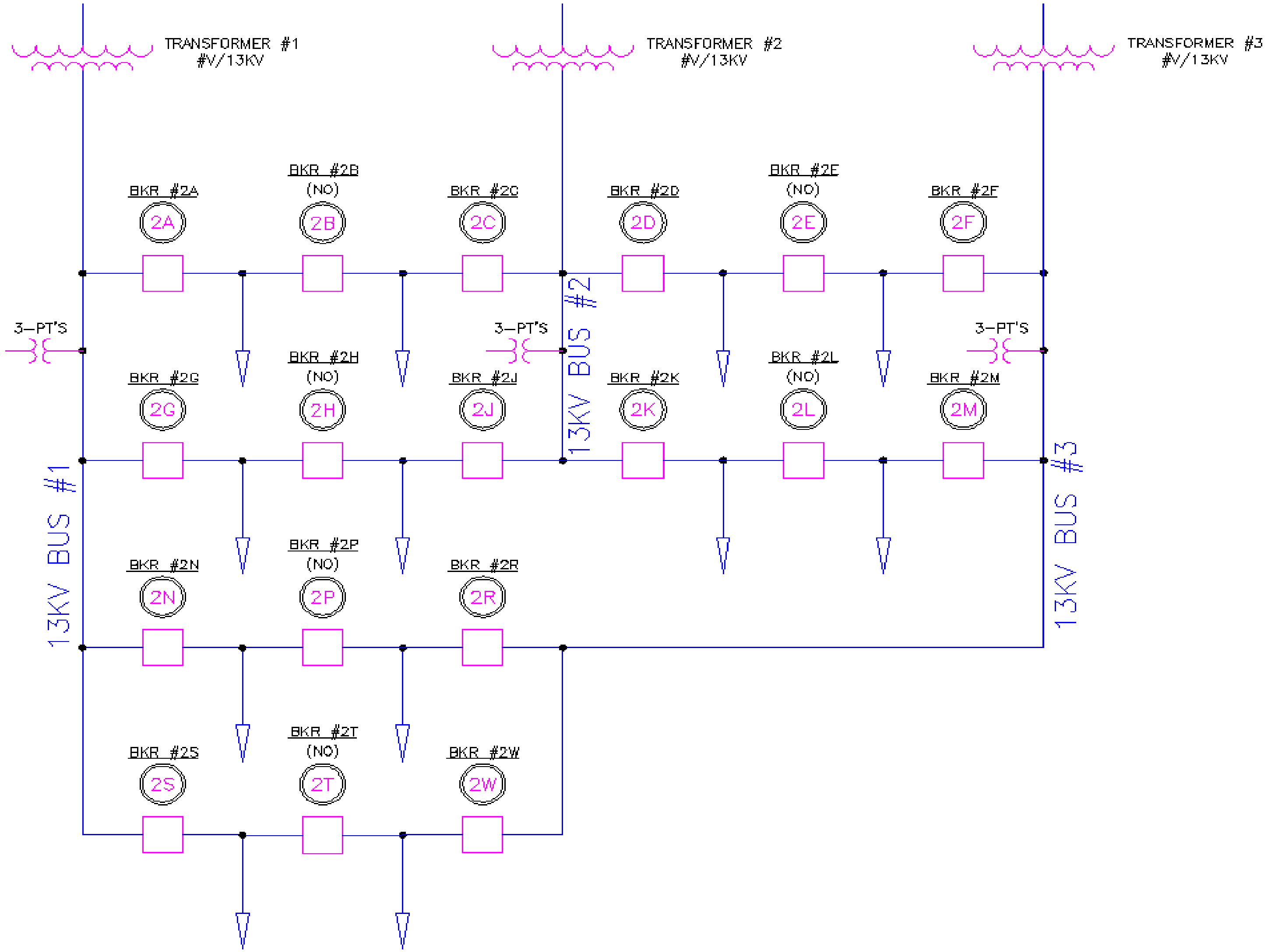
Transfer Bus & N.O. Breakers

Distribution Layouts



Single Bus with Tie Breaker

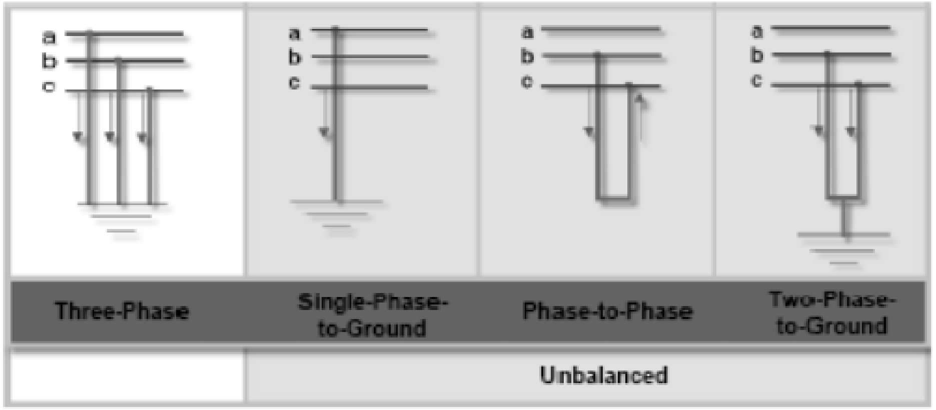
Distribution Layouts

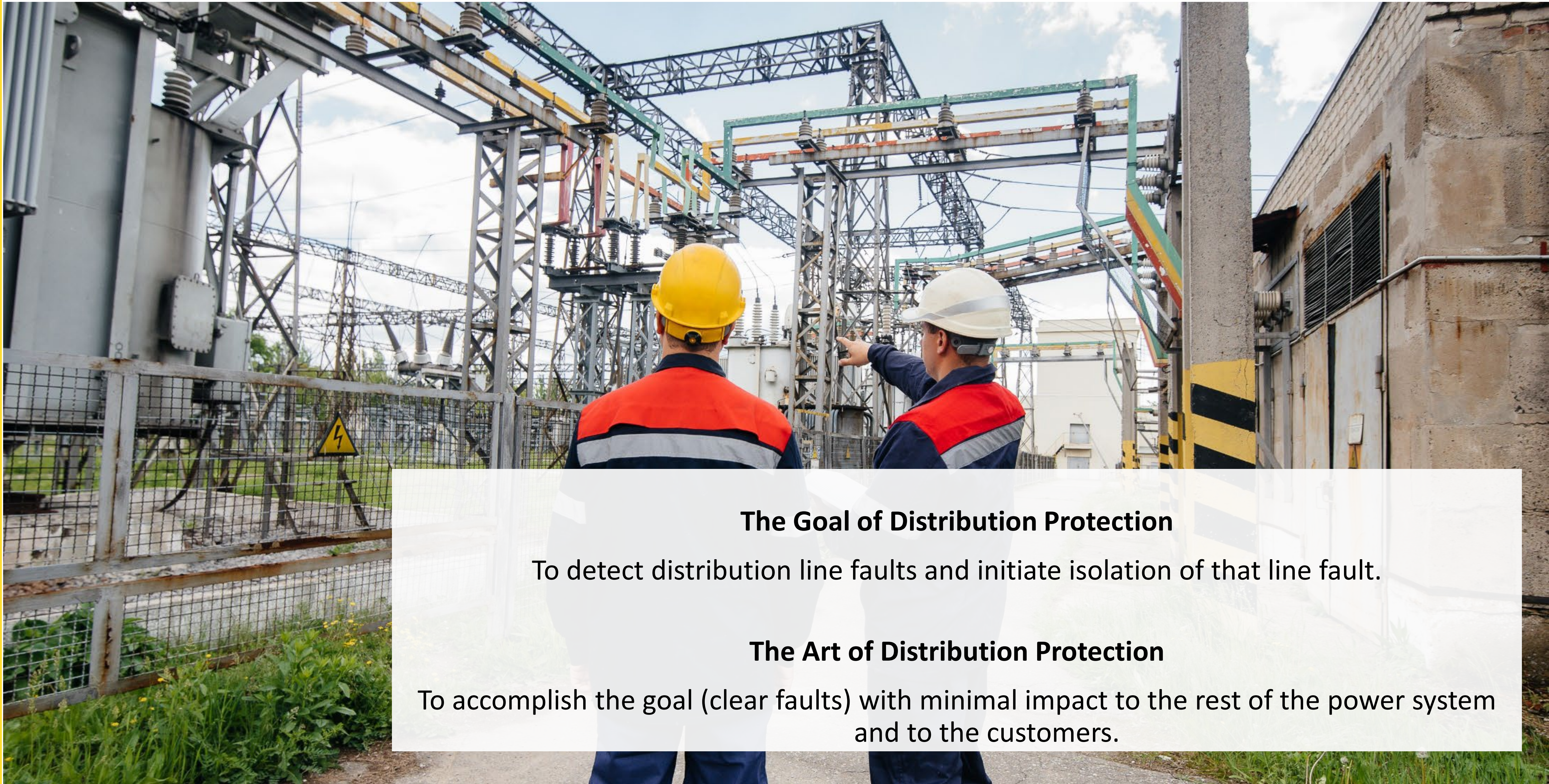


High Density

What is a fault?

- Unintentional short of an electrical circuit
  - Phase to Phase
  - Phase to Ground
- Short Circuit
- Causes High Current
- High Current Causes Damage due to Heat
  - $P_{heat} = I^2 \times R$
- Need to clear faults from the system
- We LOVE fault current!!! Why?
  - It is an easy way for us to determine if there is a problem (short or fault) on our power system





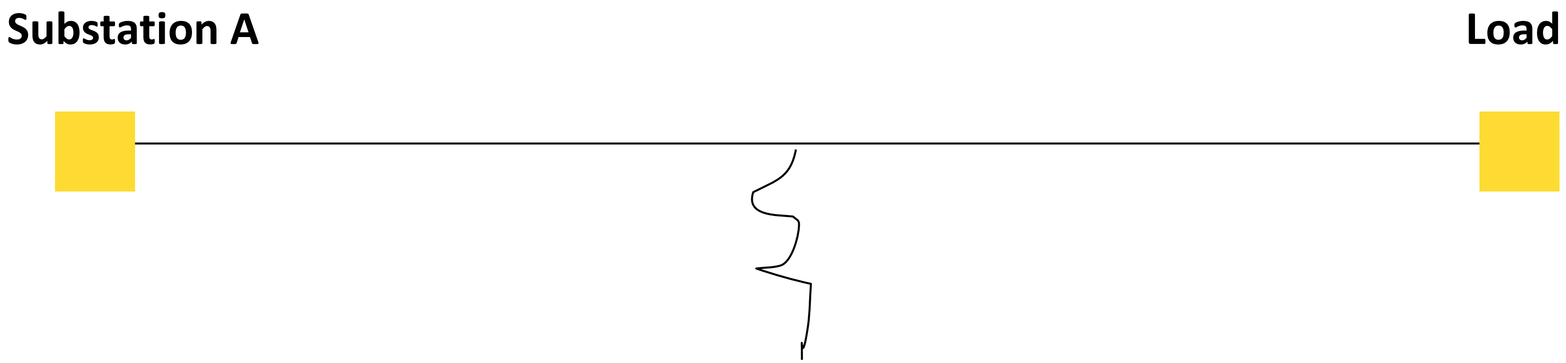
The Goal of Distribution Protection

To detect distribution line faults and initiate isolation of that line fault.

The Art of Distribution Protection

To accomplish the goal (clear faults) with minimal impact to the rest of the power system and to the customers.

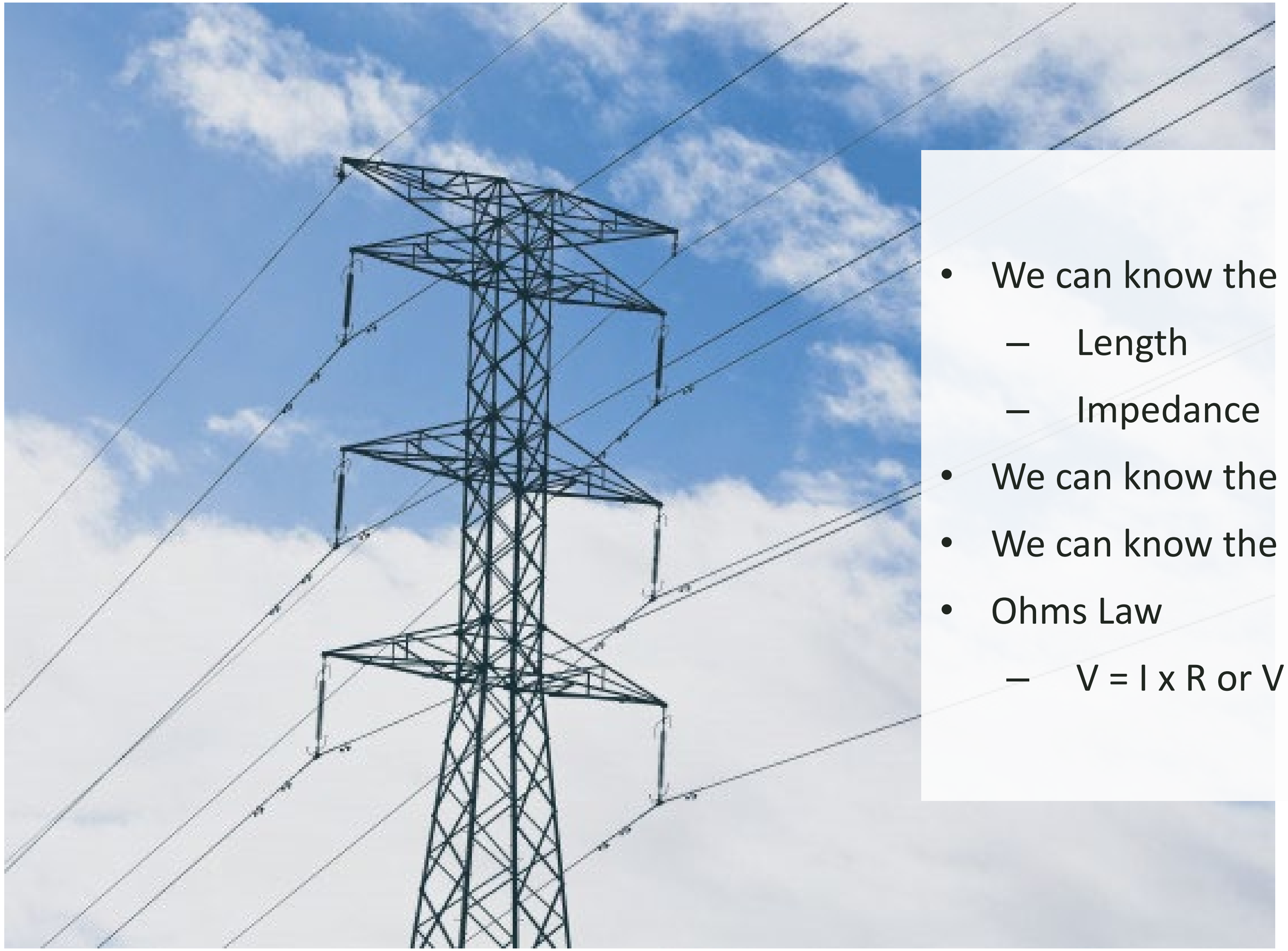
Typical Distribution Line



- Finite Length
- Specified Material Properties

- System Characteristics
  - Voltage
  - Current

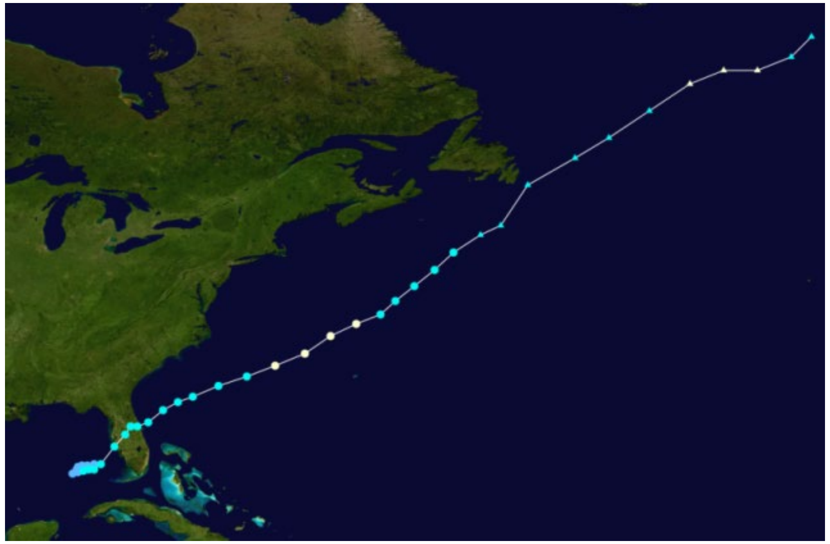
What information can we get about the line to know if it has a FAULT?



- We can know the properties of the transmission line
  - Length
  - Impedance
- We can know the current on the line from the substation
- We can know the voltage on the line bus at the substation
- Ohms Law
  - V = I x R or V = I x Z (for Impedance)

Distribution System Faults

- The next few slides are graphs from a data set feeder fault data set compiled by a Florida based utility for the year 2001
- The utility had about 250 Distribution class substations in 2001
- 1126 total distribution system trips from 1/1/2001 through 12/31/2001
- This data was not every TRIP but every feeder fault event that went to lockout (not necessarily permanent but required human intervention)
- Hurricane Gabrielle hit Florida in mid-September causing anomalies in the statistics



Distribution System Faults

Most common source of outages?

- Unknown

Second most common source of outages

- Squirrels

Honorable Mention

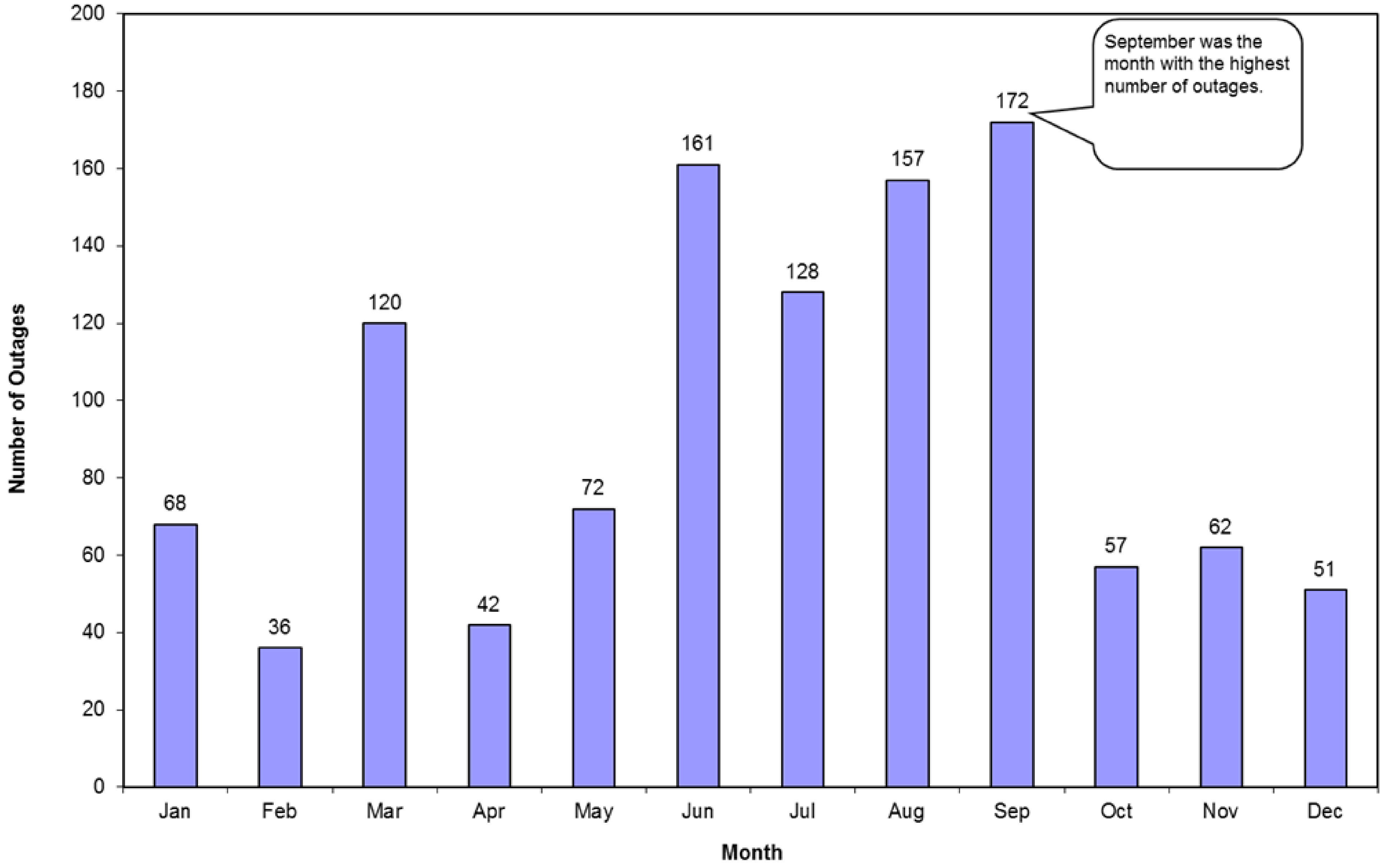
- Vegetation

Before

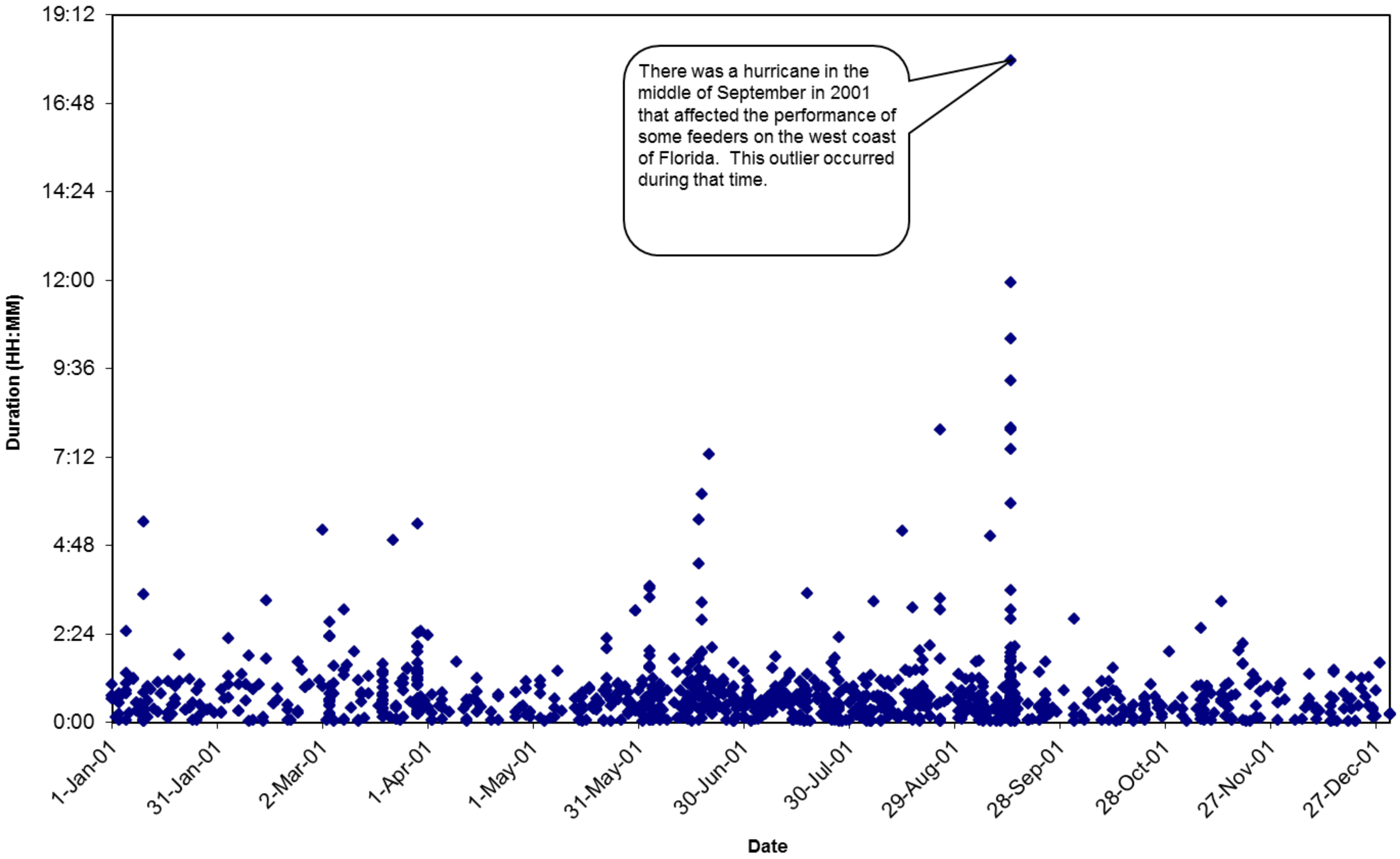
During

After

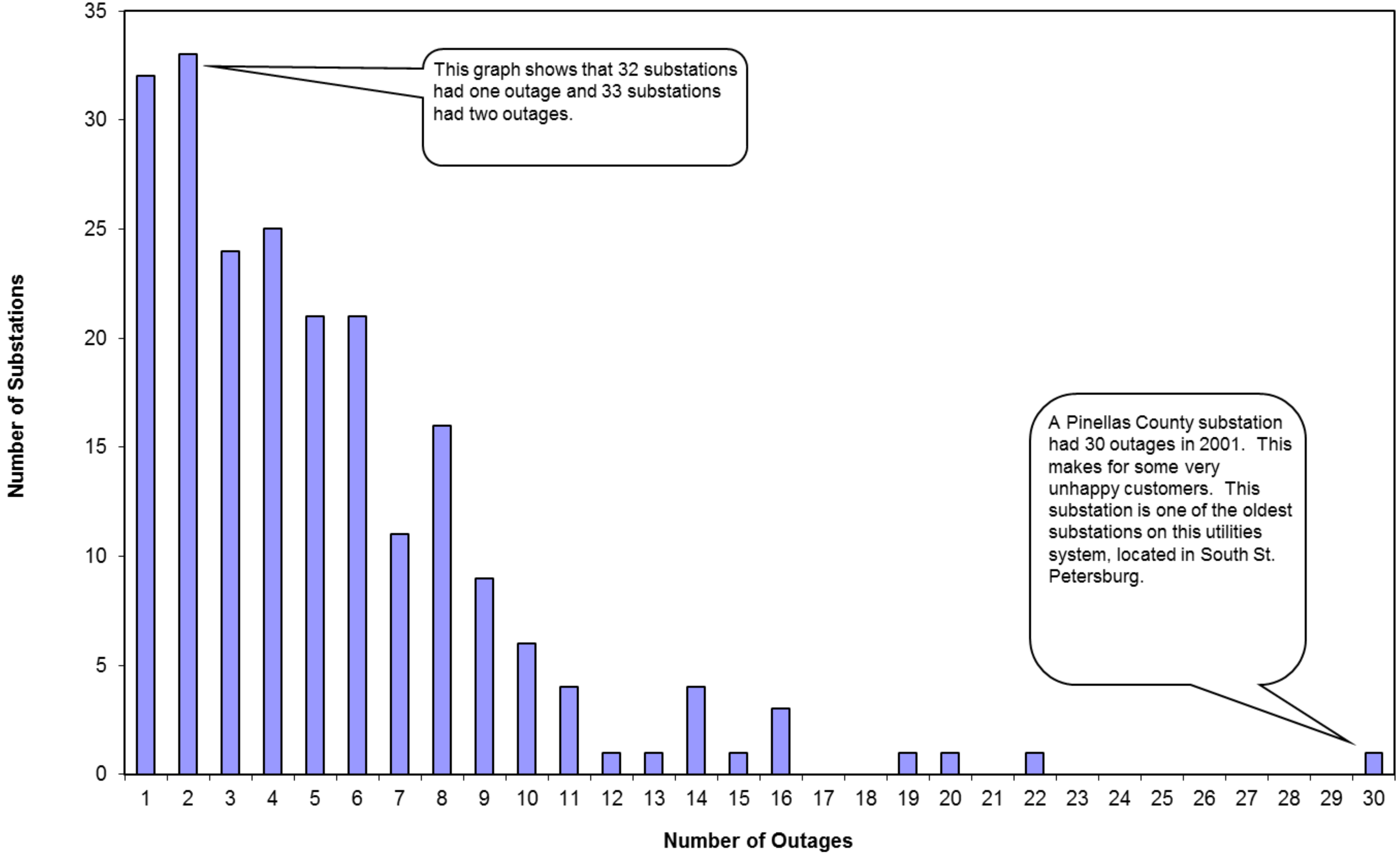
2001 Monthly Outage Frequency



2001 Feeder Outage Durations per Month



Number of Outages per Substation



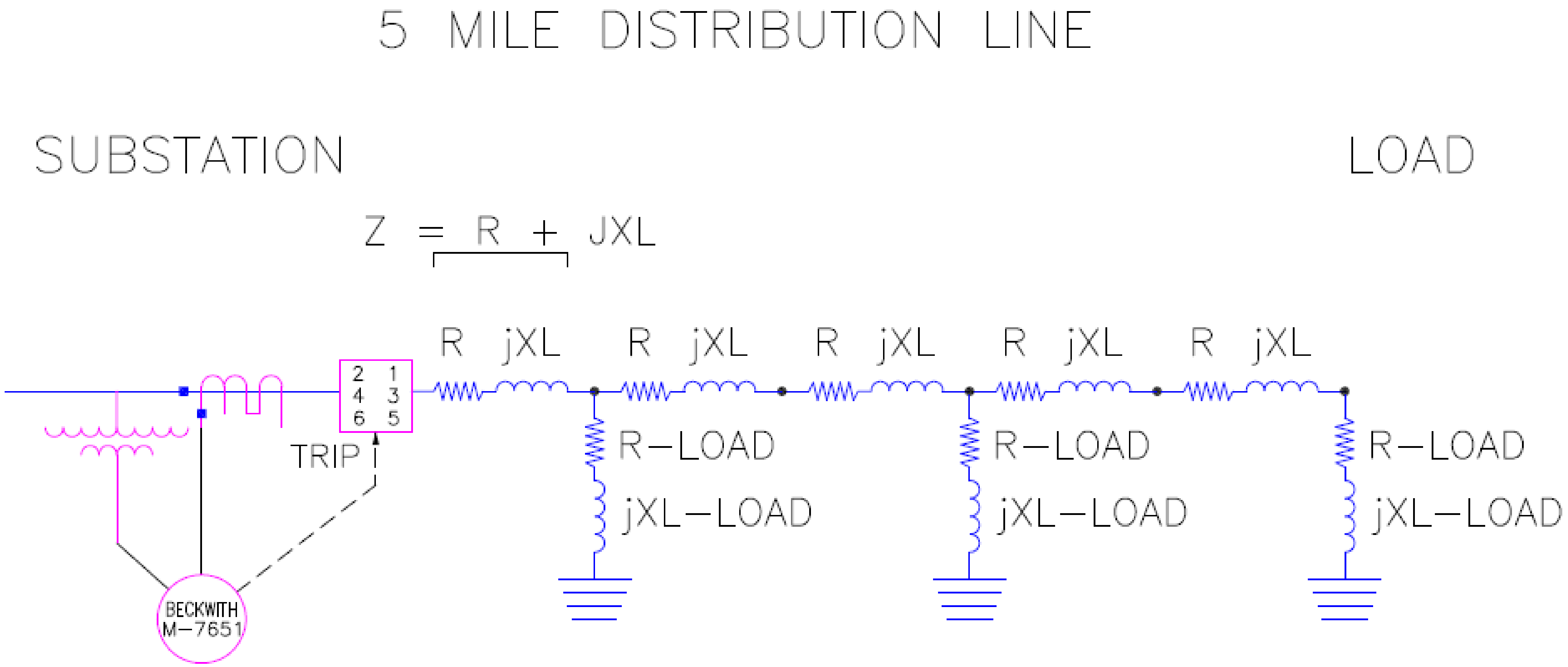
Inputs to a Feeder Protection Relay

- Current – required for most protection, 50, 51, 67, 46, 32, metering, DTF
- Voltage – required for some protection – 67, 32, 27, 47, 59, 81, metering, DTF
- Needed to make distance decision
- Z = V/I
  - If the relay knows the voltage and the current, it can calculate the impedance.
  - The impedance represents the distribution line which has an Ohm's per Mile number that comes from the manufacturer
- Distance to Fault (DTF)
  - Does it work???
  - It did for me during….
    Hurricane Jeanne, 9/26/2004

Overcurrent Protection

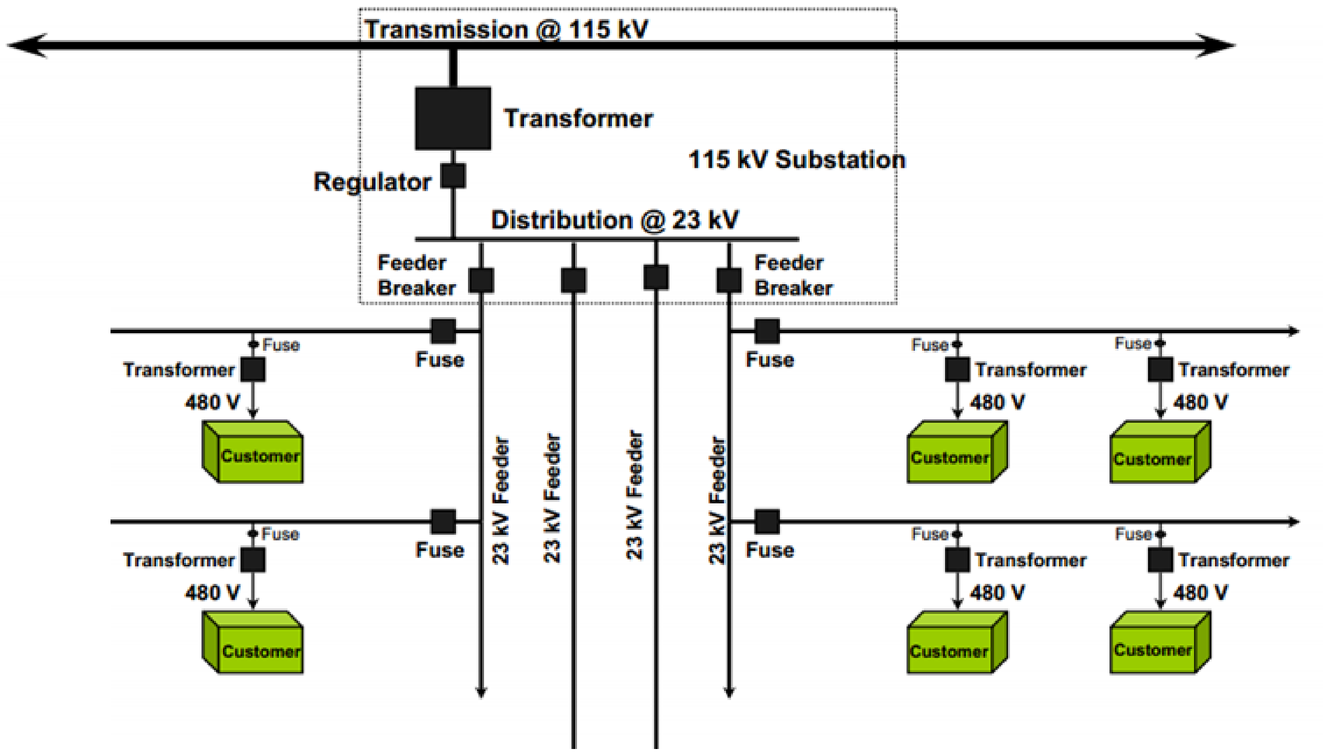
- Detects a high current
- Does not care what direction the current is flowing
- Must be provided a set point
  - 20 amp fuse – used in substations
  - 30 amp breaker – used in your house
  - Set point is pretty clear
- Relays can do this too…
  - But they need to be told what the set point is
- Issues for calculating set points
  - Never want to trip for normal load
  - Always want to trip for faults inside of its protection zone
  - Coordination
    - As fast as possible…but
    - Must allow downstream devices to clear first
    - Must coordinate with upstream devices
    - Must protect all equipment from damage

Distribution System Impedance

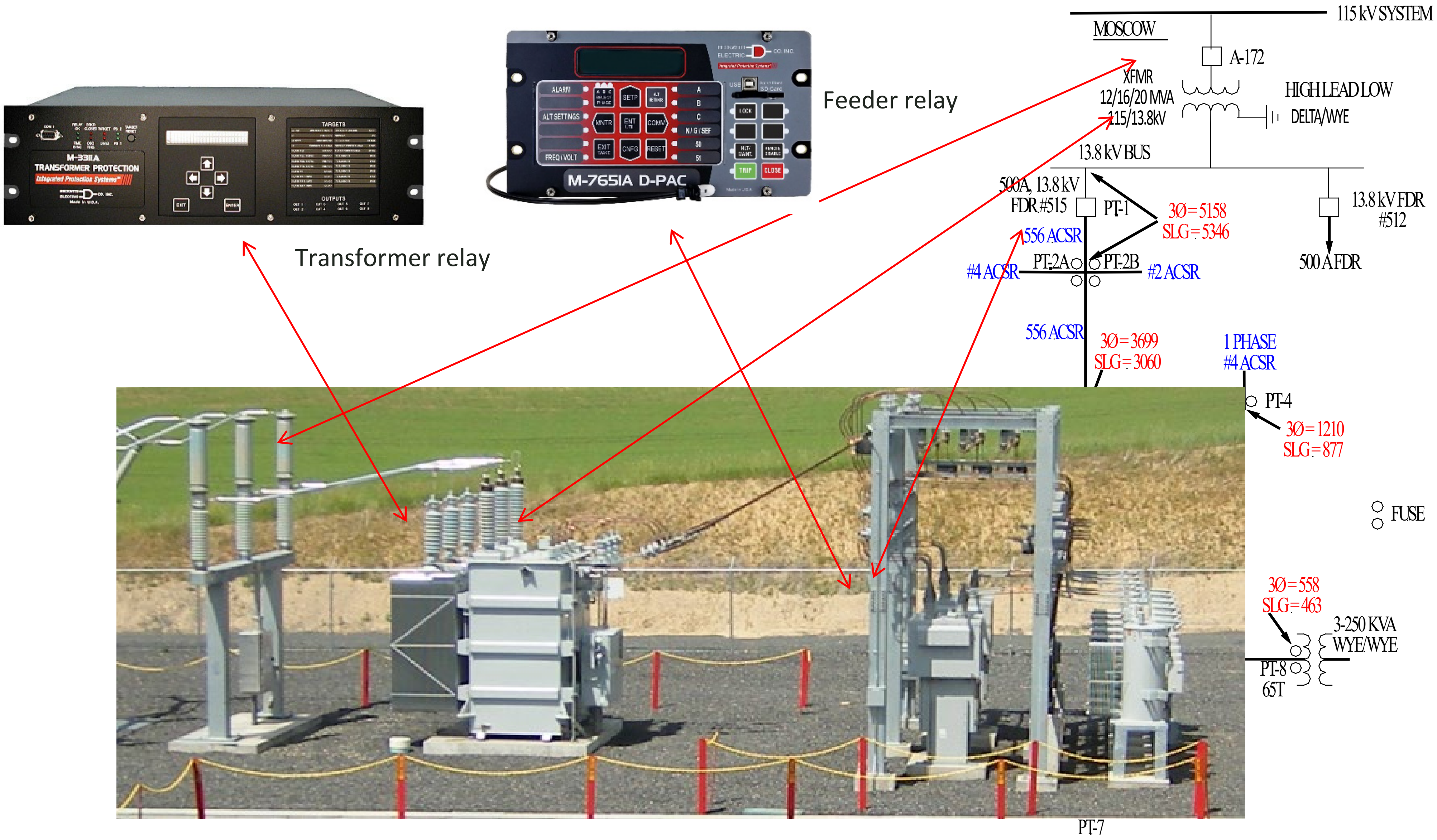


Radial System

- Most distribution systems are radial
- Power flows in one direction only
- Note the fused taps

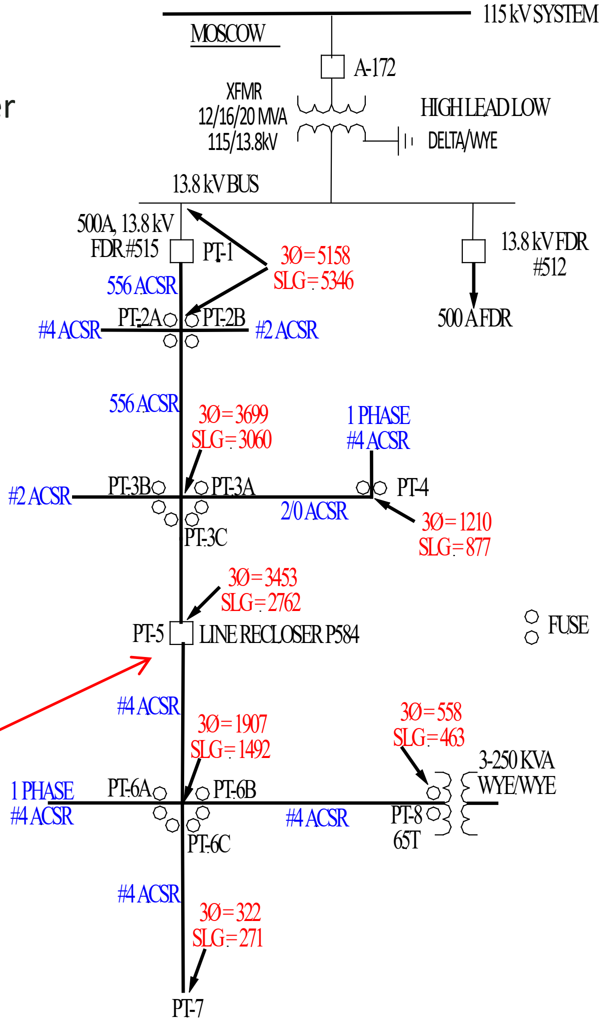


System Overview – Inside the Substation Fence

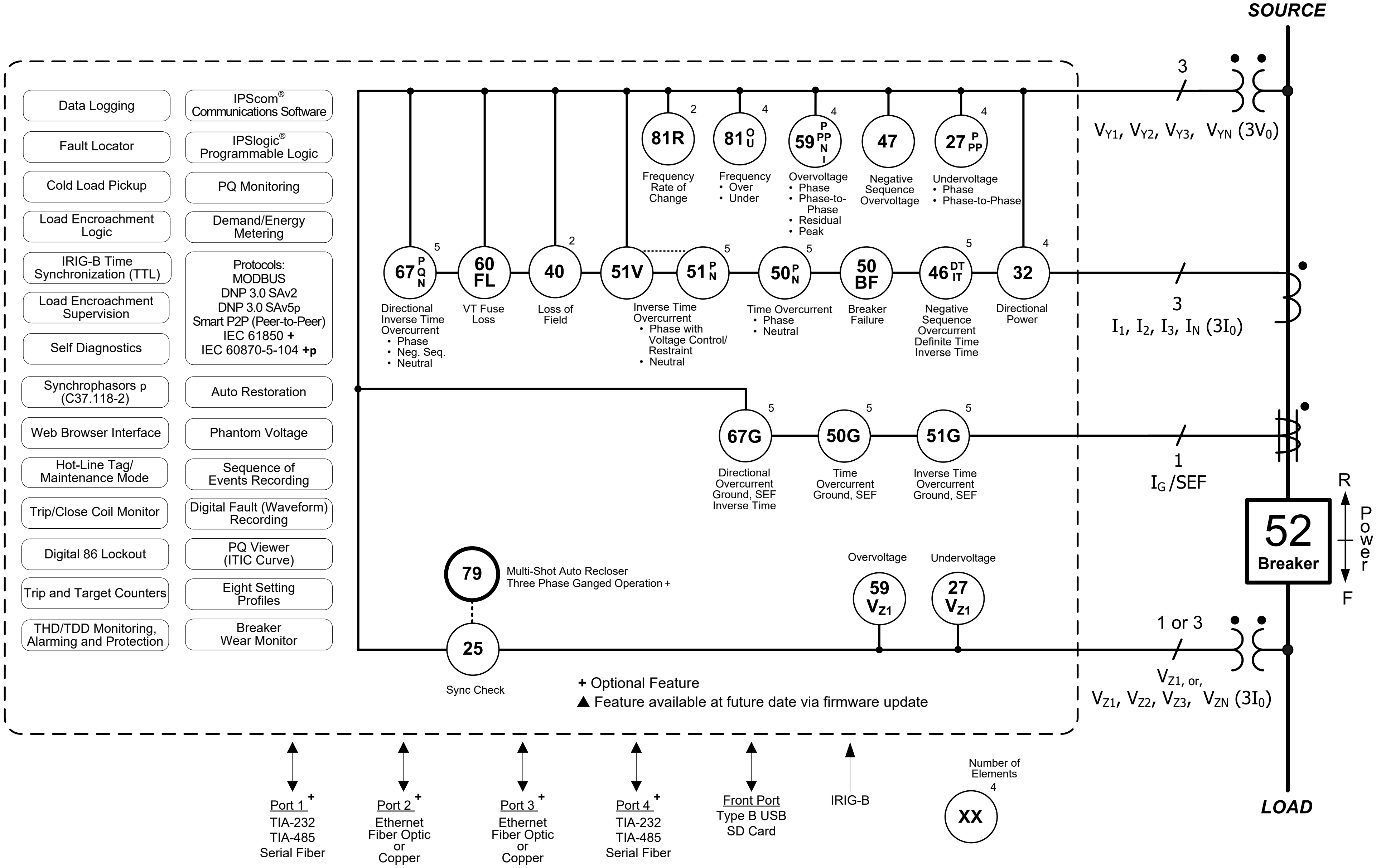


System Overview – Outside the Substation Fence

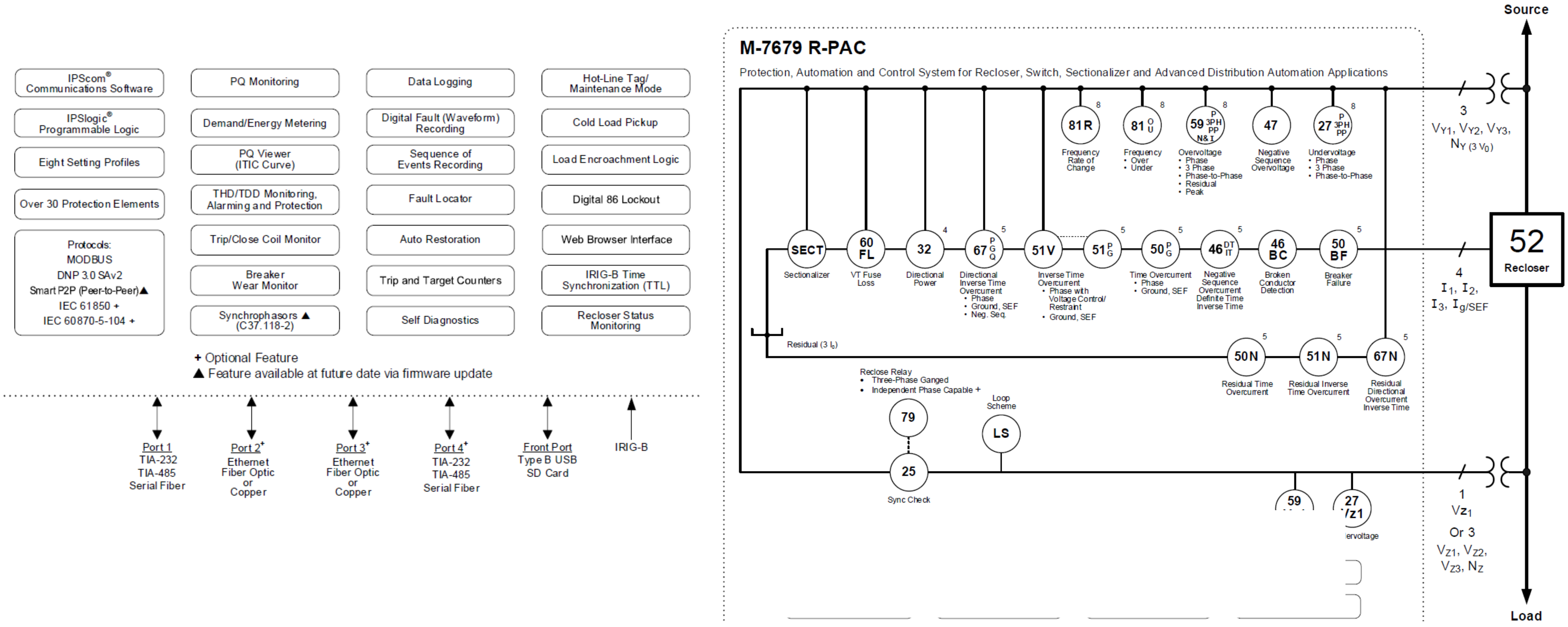
Midline recloser relay



Beckwith Feeder Relay M-7651 One Line Diagram

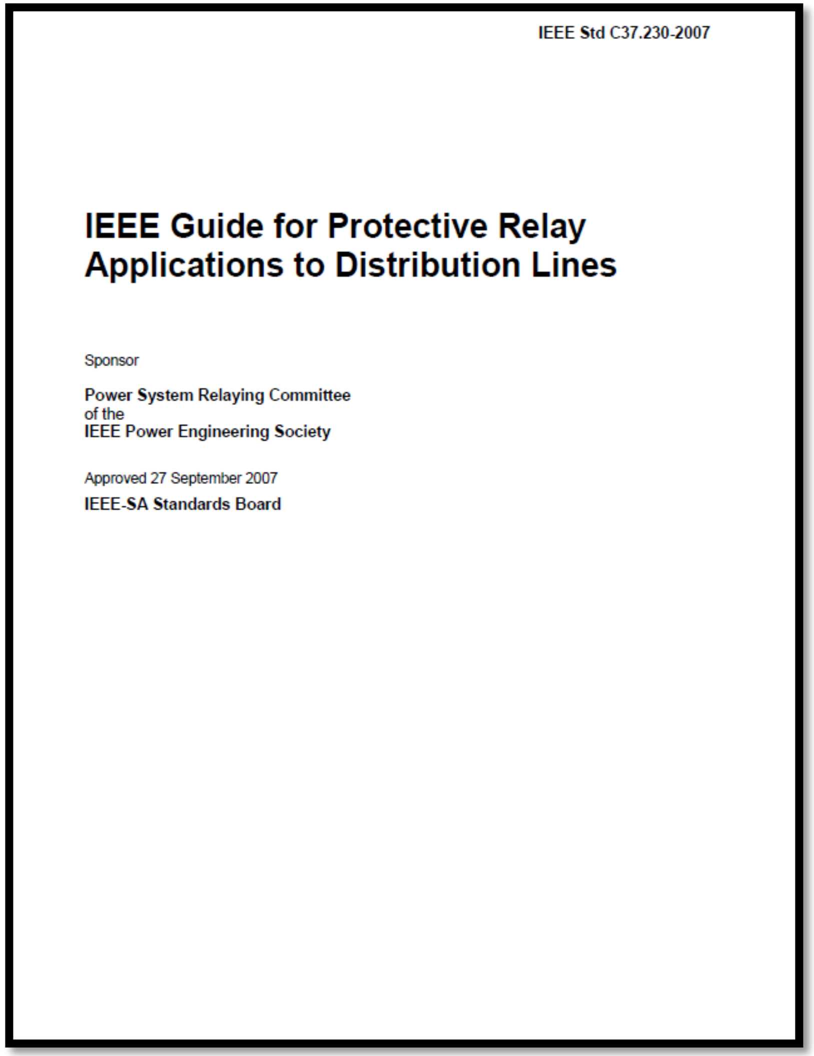


Beckwith Recloser Control Relay M-7679 One Line Diagram



IEEE Std C37.230-2007

IEEE Guide for Protective Relay Applications to **Distribution Lines**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IEEE Guide for Protective Relay Applications to Distribution Lines

Sponsor

Power System Relaying Committee
of the
IEEE Power Engineering Society

Approved 27 September 2007

IEEE-SA Standards Board

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- Weather
- Equipment Failure
- Forestry Contact
- Public Contact (Pole, overhead, underground)
- Animal Contact
- Vandalism
- Vehicle Accidents
- Three Phase
- Phase-to-phase
- Phase-to-ground or single-line-to-ground
- Two-phase-to-ground

- Temporary Faults (most)
  - Wildlife
  - Wind
  - Lightning
- Permanent
  - Equipment failure
  - Dig-ins
- Faults can evolve

Section 4 – Fundamentals

Types of Distribution Faults

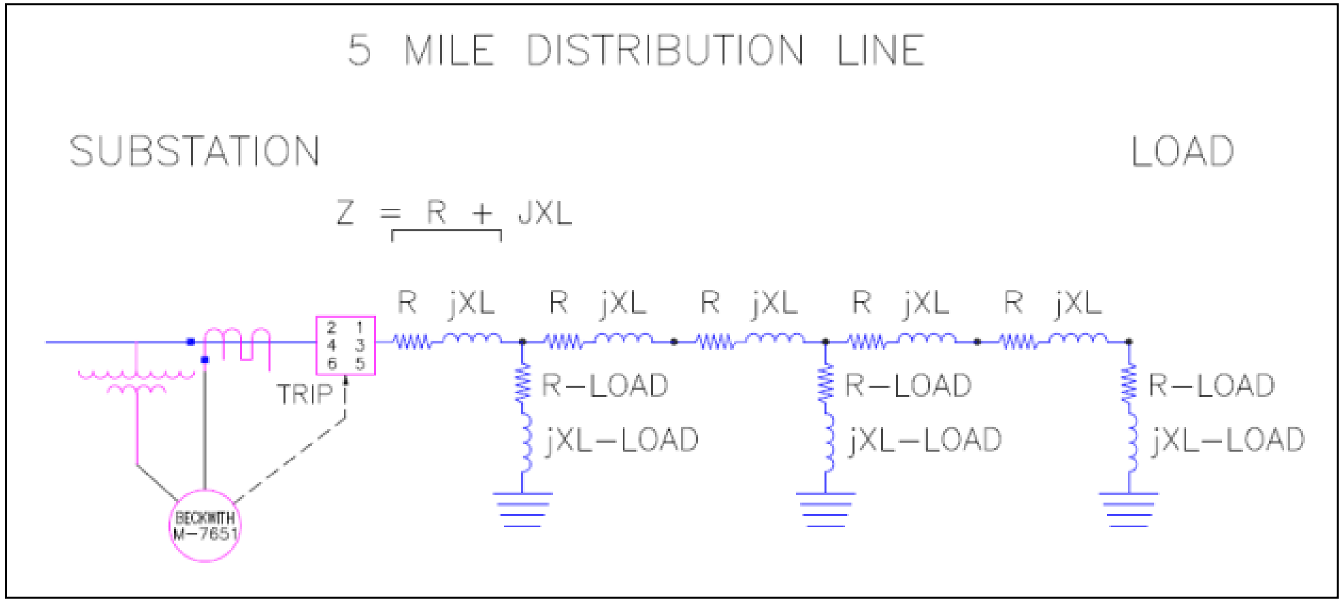
- OH faults are mostly temporary in nature
- UG faults are more commonly permanent
- Faults can evolve from one type to another
  - SLG fault arcing over to involve another phase
- Faults' currents can and will change during faults
  - When fault arc is established
  - When initiating item burns away
- Simultaneous faults can occur specifically on shared structures

Section 4 – Fundamentals

Types of Distribution Faults

- Distribution fault current will vary depending on the system design
- Most distribution lines are radial
  - Max fault current is the fault current at the substation bus
  - Fault current decreases the further down the feeder a fault occurs due to impedance of the conductors
  - Max fault currents are typically limited to allow for distribution class equipment to be installed on the circuits
- Rule of thumb – distribution fault current should be kept below 10,000 amps

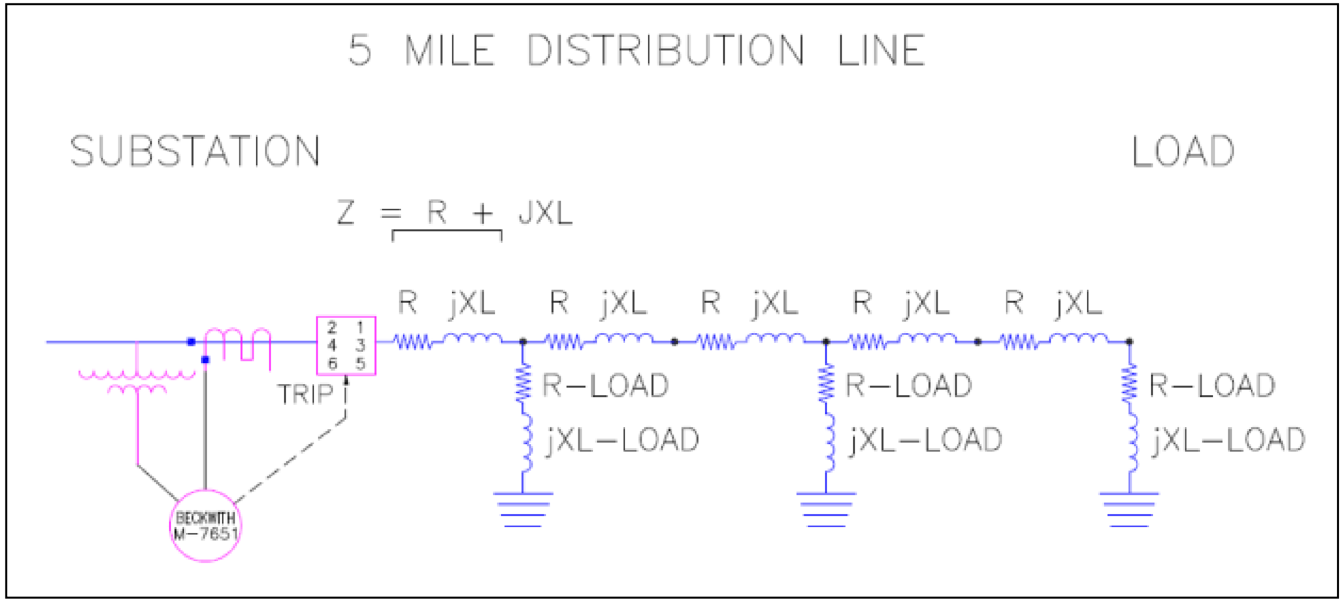
- To limit distribution fault current:
  - NOT parallel distribution transformers (keep tie breakers normally open)
  - Spec transformers with internal impedance that limits fault current
  - Use grounding impedance



Section 4 – Fundamentals

High-impedance Faults

- All faults have some impedance
- Some faults have high impedance
  - A Phase conductor falls on B Phase – only the impedance of the conductors
  - A Phase conductor makes contact with a dry tree branch – very high impedance
- A high-impedance fault
  - Might not be detectable (might look like normal load)
  - Presents a challenge
  - Special protection for this is not in this guide



Section 4 – Fundamentals

Load Characteristics

Need to understand load characteristics to accurately model the system

- Load Flow Study
- Short Circuit Study
- Stability
- Electromagnetic Transients

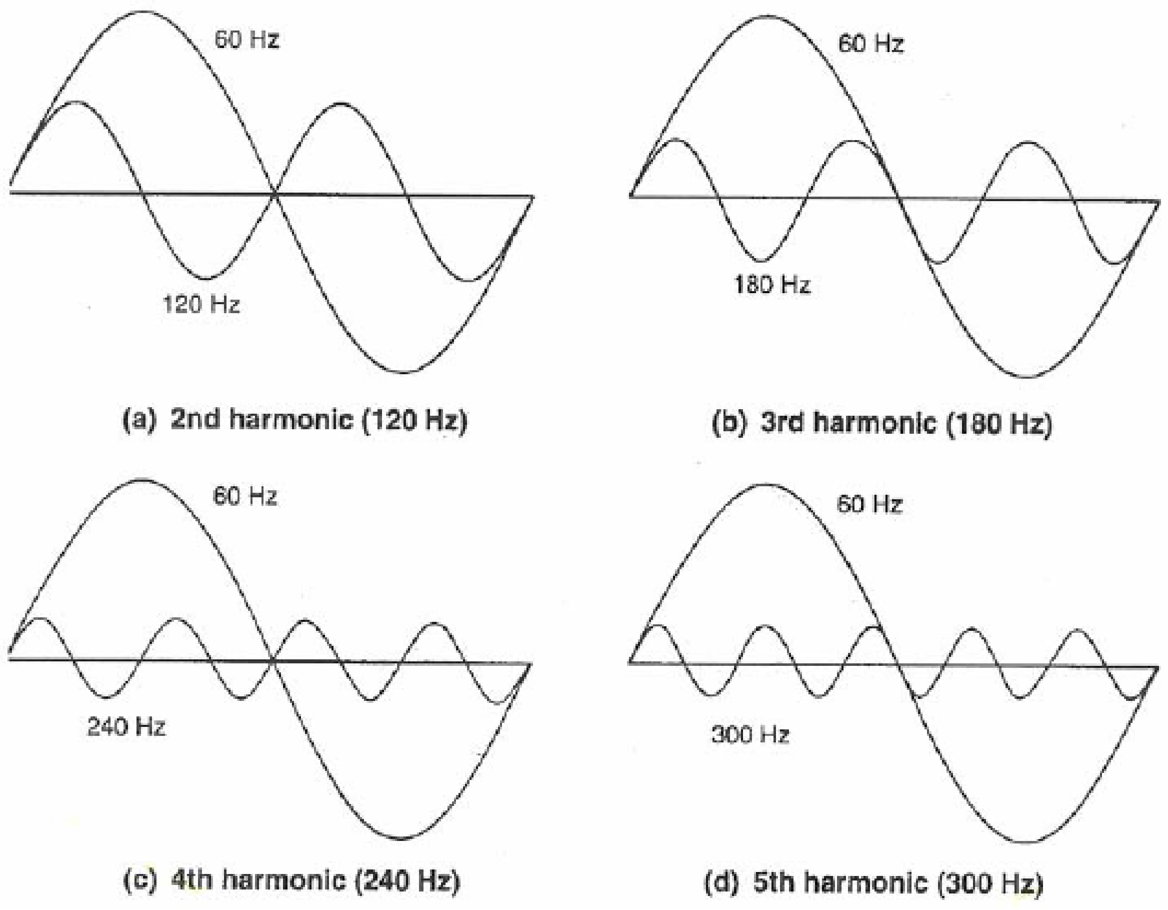
This is not in the scope of this guide

- B30 – “System load dynamics-simulation effects and determination of load constants”
- B11 - “Representation of loads”
- B17 - “Incorporation of load modeling in load flow studies”
- B14 - “A fault locator for radial sub-transmission and distribution lines”

Section 4 – Fundamentals

Distribution System Harmonics

- A harmonic is defined as a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency.
- h = n x 60 Hz
  - h is the harmonic frequency
  - n is the harmonic number
- Example – a 60 Hz waveform and its second, third, fourth, and fifth harmonics



Section 4 – Fundamentals

Distribution System Harmonics

- Non-linear loads and power electronic devices are the largest source of harmonics that appear in power systems.
- Example devices that cause harmonics
  - Single phase static and rotating AC/DC converters
  - Three phase static AC/DC converters
  - High Phase order static converters
  - Battery Chargers
  - Electric Arc furnaces
  - Fluorescent lighting
  - Pulse modulated devices
  - Adjustable speed motor drives
  - Transformers
- Harmonics tend to show up in power system neutrals
- Harmonics effect the performance of electromechanical relays more so than microprocessors which have a good 60 Hz filter

Section 4 – Fundamentals

Distribution System Harmonics

- Harmonics affect symmetrical components

Table 4-1—Similarity between a harmonic quantity and a sequence component

Order	Sequence	Order	Sequence	Order	Sequence
1	Positive	6	Zero	11	Negative
2	Negative	7	Positive	12	Zero
3	Zero	8	Negative	13	Positive
4	Positive	9	Zero	14	Negative
5	Negative	10	Positive	15	Zero

Section 4 – Fundamentals

Distribution System Harmonics

- Why do we care about harmonics?
- Moderate levels of harmonics typically do not affect the performance of protective relays.
- If harmonic distortion is great, the total RMS current can be significantly greater than the fundamental frequency component alone.
- The true RMS current can be found by using the equation:

$$\text{RMS} = \sqrt{\sum_{n=1}^{\infty} i_n^2}$$

  - Where *i* is the RMS value of a particular harmonic current.
  - *n* is the harmonic number.
- This will affect electromechanical relays or other relays without 60 Hz filters.
- Most microprocessors have a 60 Hz filter in their protection algorithms and are practically immune to the effects of harmonics.

Section 4 – Fundamentals

Distribution System Transients

- What is a transient?
  - Spike or surge in a power line
  - Sudden, short-lived oscillation in the current flowing through a circuit
  - Pulse, damped oscillation or other temporary phenomenon occurring in a power system prior to reaching a steady state condition
- Distribution line protective relays can be negatively affected by power transients.
- Calculating settings should consider the transient effect.
- Causes of transients:
  - Capacitor bank switching
  - System switching
  - Transformer Inrush
- Typically, time overcurrent relays are not affected by transients since the transient will be dampened out much faster than the relay operating time.

Section 4 – Fundamentals

Interrupting Ratings

- The interrupt rating is the maximum symmetrical current that the device is capable of interrupting.(some equipment is rated in assymetrical current)
- When circuit breakers, reclosers, and fuses are called upon to interrupt a fault, it is imperative that their interrupt rating is not exceeded.
- When applied to reclosers and breakers, the interrupt current rating must be greater than the maximum expected symmetrical fault current at the device's point of application.
- The X/R ratio at that location must be equal to or less than that at which the recloser is tested, at the maximum interrupting current, during the operating duty test.
- No uprating for symmetrical fault currents occurring at X/R ratios less than these maximums for which the recloser is tested should be allowed.

Section 5 – System Configuration & Components

Distribution System Grounding

- Grounding system and fault type must be understood to model and calculate fault current.
- Three Types of Grounding Systems
  - Ungrounded or Delta Systems
  - Impedance Grounded – resistance or reactance
  - Solidly Grounded
- Current and voltage characteristics during fault conditions will differ from non-faulted conditions, and will vary depending on the grounding system applied.

Section 5 – System Configuration & Components

Distribution System Grounding

- Some faults have impedance and should be considered
  - Solid fault – broken phase conductor contacts neutral wire
  - Varying impedance – insulator flashover whose impedance will vary with the length of the arc
  - High impedance – tree limb making contact with a phase
- Depending on the grounding system, fault characteristics will vary
- Grounding does not affect normal operation but comes into play for phase to ground type faults

Section 5 – System Configuration & Components

Distribution System Grounding - Ungrounded System or Delta Connected

- Used in marine vessels
- A single phase to ground fault does not cause overcurrent
- Ground faults cause a voltage rise in the un-faulted phases
- Voltage approaches SQRT (3) times nominal
- Insulation level of feeders should be designed to accommodate this
- Ground references can be applied through a grounding transformer
- Relay should be installed to detect a phase to ground fault and at minimum alarm so system operators can locate and repair as necessary
- Phase to phase faults are unaffected by an ungrounded system

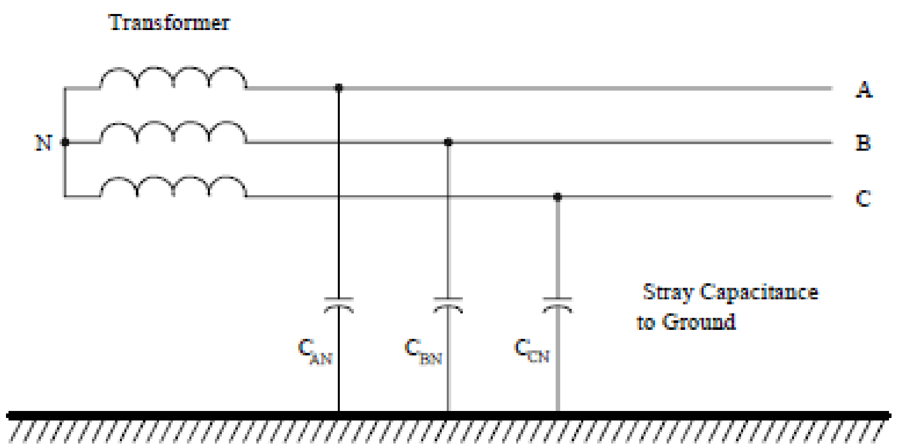


Figure 5-1—Ungrounded system

Section 5 – System Configuration & Components

Distribution System Grounding - Ungrounded System or Delta Connected

- Under normal conditions and balanced loads, phase-to-ground voltages are equal in magnitude and 120° apart.
- Therefore, there is no voltage difference between neutral and ground.
- In the case of a phase-to-ground fault, the fault current will flow from the source to the fault location and returns through the stray capacitance-to-ground of the two unfaulted phases of that feeder and the unfaulted phases of all other feeders connected to the same power transformer.
- Therefore, ground fault current magnitudes depend not only on the faulted feeder parameters, but also on the size (i.e., stray capacitance) of the rest of the system.

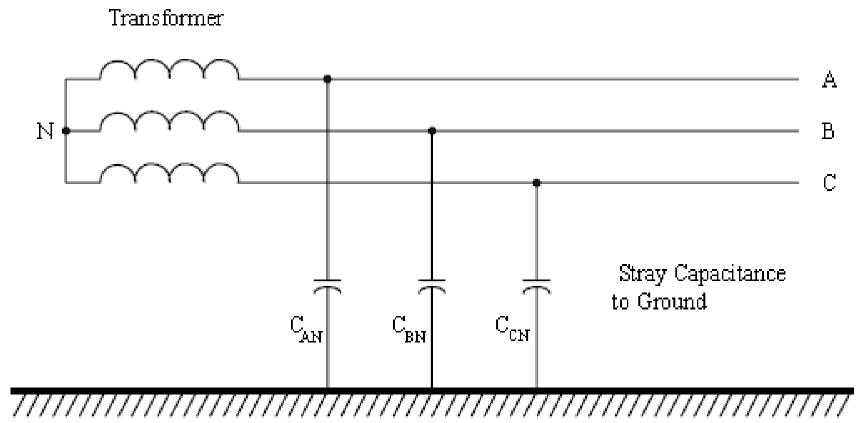


Figure 5-1—Ungrounded system

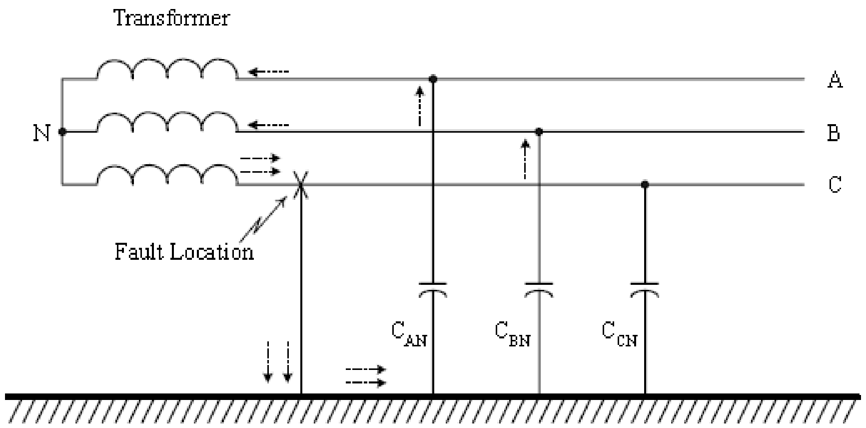


Figure 5-2—Ground fault in ungrounded system

Section 5 – System Configuration & Components

Distribution System Grounding - Uni-Grounded System

- Solidly grounded at the substation
- Can be 3 wire with no neutral conductor or 4 wire with insulated neutral
- Ground current can be as high as phase current
- Ground fault currents flow back to the source through earth
- High voltages can occur between the faulted point and reference ground

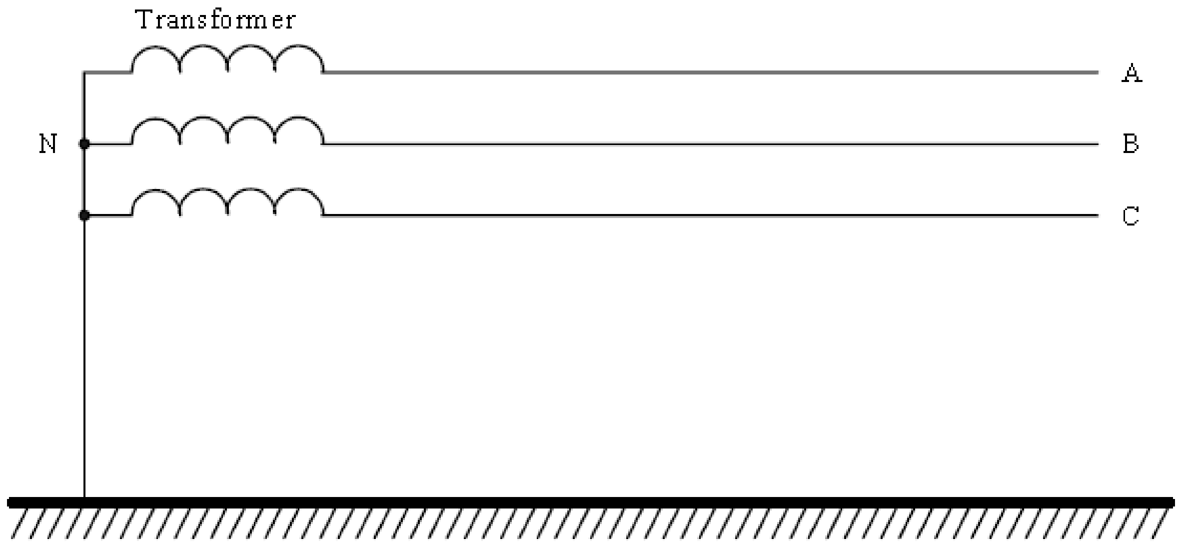
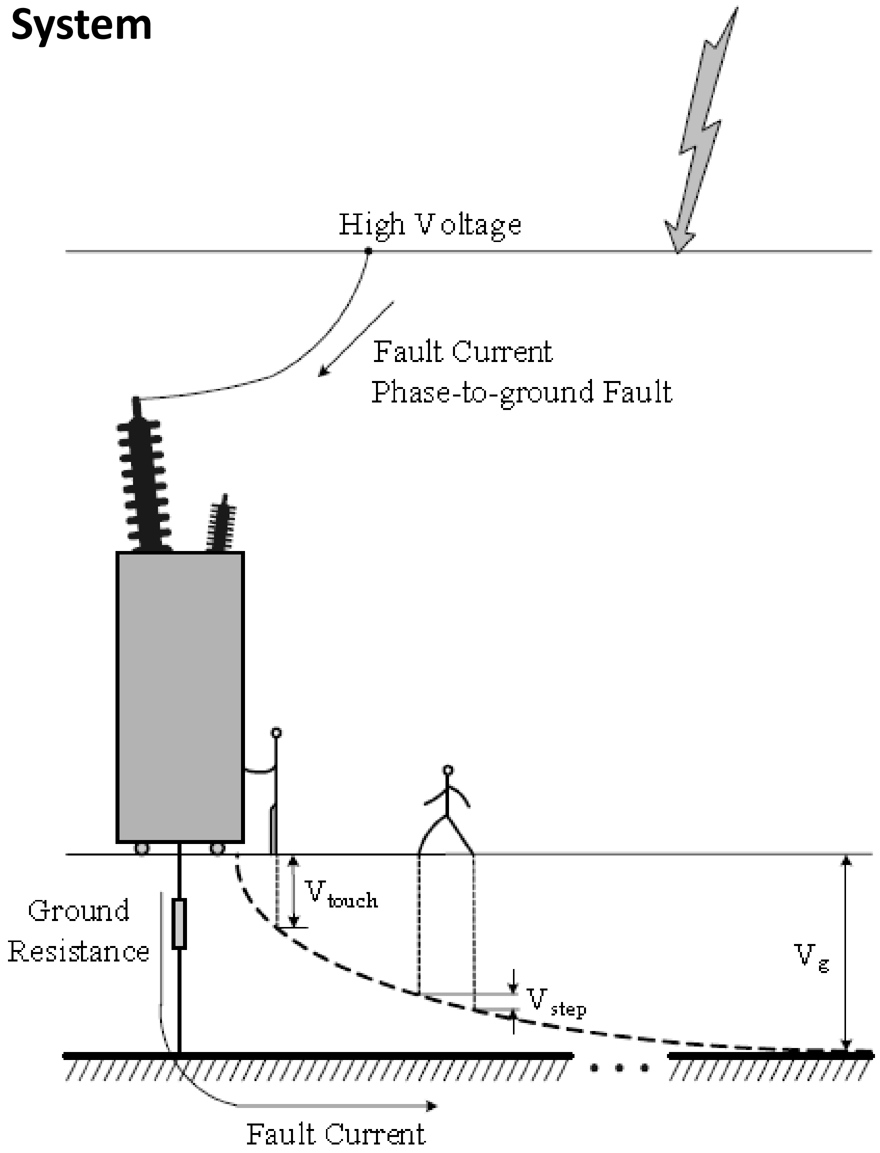


Figure 5-4—Solidly uni-grounded system

Section 5 – System Configuration & Components

Distribution System Grounding - Uni-Grounded System

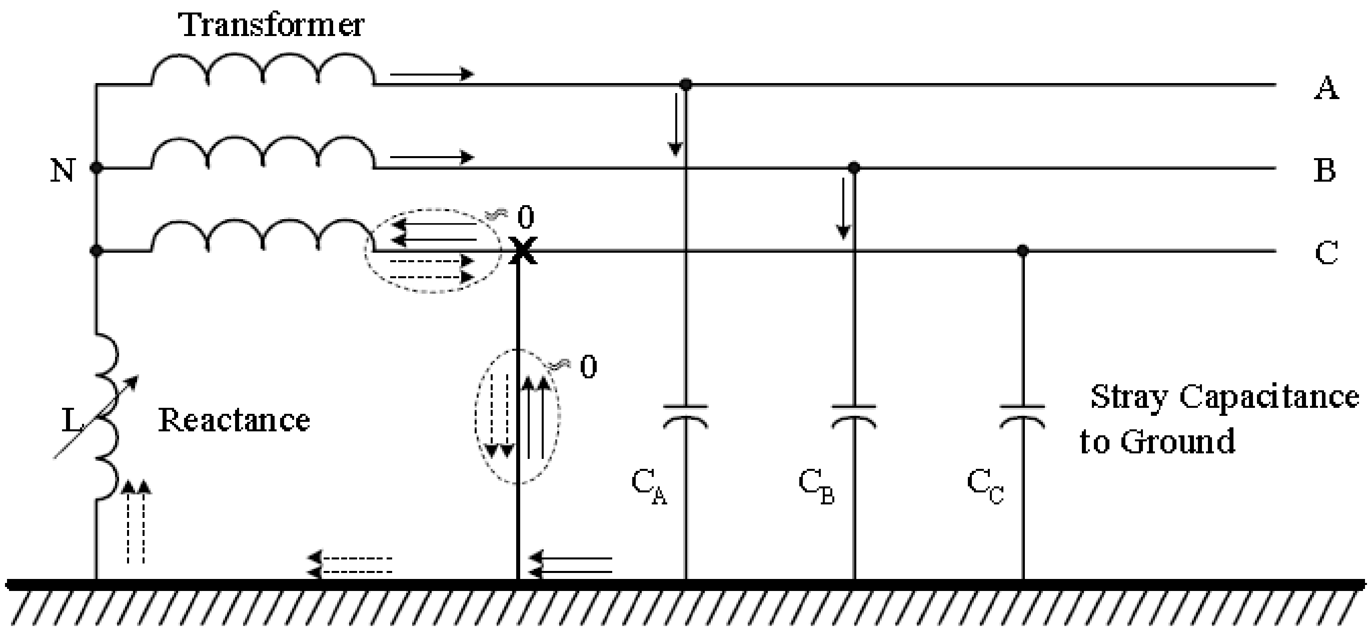
Touch and Step Voltages



Section 5 – System Configuration & Components

Distribution System Grounding - Resonant-Grounded System

- Most often applied in Europe
- Transformer neutral is ground through a reactance called a Peterson Coil
- The reactance is resonantly tuned to the fundamental frequency with the stray capacitance of all feeders connected to the same transformer
- If tuned properly, the neutral reactor and the stray capacitance will cause the same amount of fault current to flow in opposite directions through the point of the fault, canceling each other



Section 5 – System Configuration & Components

Distribution System Grounding - Resonant-Grounded System

- Advantages of a resonant-grounded system include the following:
  - Ground fault currents are small.
  - Arcs are self-extinguished.
  - Touch and step voltages are small.
  - Intermittent ground faults are avoided
- Disadvantages of a resonant-grounded system include the following:
  - Phase-to-ground voltages can be high due to resonance.
  - Arrester protective levels are higher.
  - Insulation may need to be increased due to neutral shifting during transients.
  - It is not effective in case of arcing cable faults.
  - Cables can produce repetitive and harmful restrikes.
  - Tuning can be difficult to adjust for varying system configurations such as those associated with distribution system

Section 5 – System Configuration & Components

Distribution System Grounding - Resonant-Grounded System

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  - Tuning can be difficult to adjust for varying system configurations such as those associated with distribution system

Section 5 – System Configuration & Components

Distribution System Grounding – Resistive or Reactive Grounded System

- Advantages of a resistive or reactive grounded system include the following:
  - Ground-fault currents, touch, and step voltages are reduced.
  - Overvoltages are smaller compared to ungrounded systems.
  - Intermittent arc voltages are avoided.

- Disadvantages of a resistive or reactive grounded system include the following:
  - The use of neutral resistance or reactance increases neutral voltages during ground faults and requires higher insulation of the transformer neutral.
  - Overvoltages can be high when higher resistance values are used.

Section 5 – System Configuration & Components

Distribution System Grounding

- Figure 5-10 shows a 12.47 kV feeder supplying power to a 5 MVA constant impedance, delta connected load.
- The source voltage was increased 5% to obtain 0.99 p.u. voltage at the load.
- A ground fault on phase C, with a fault resistance of 1 Ω, was simulated.
- For different load types and connections, the results will be different.

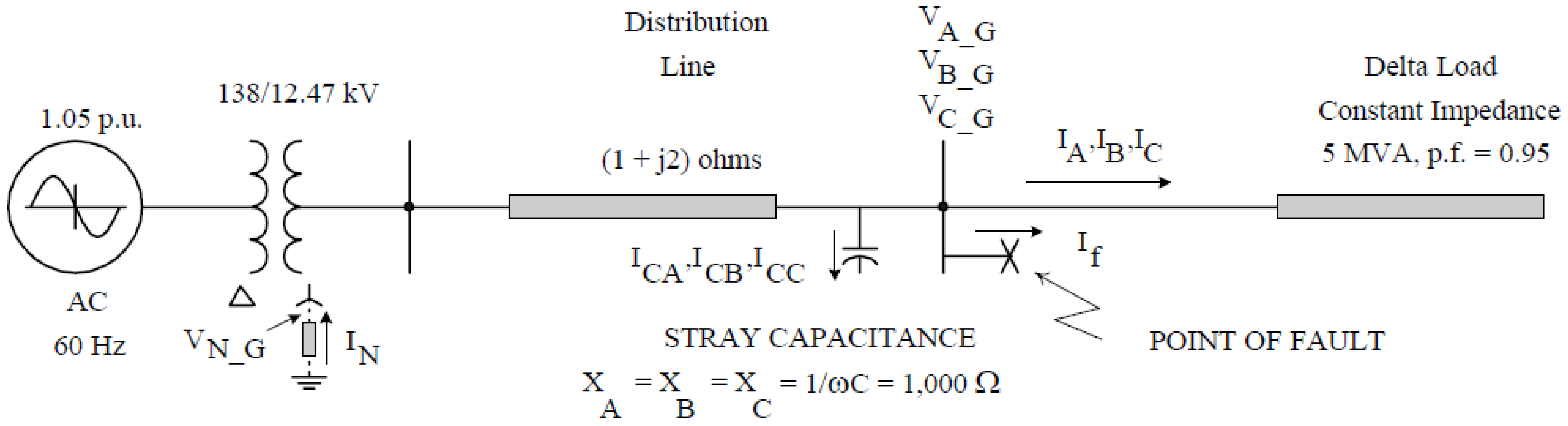


Figure 5-10—A typical distribution system with a radial feeder

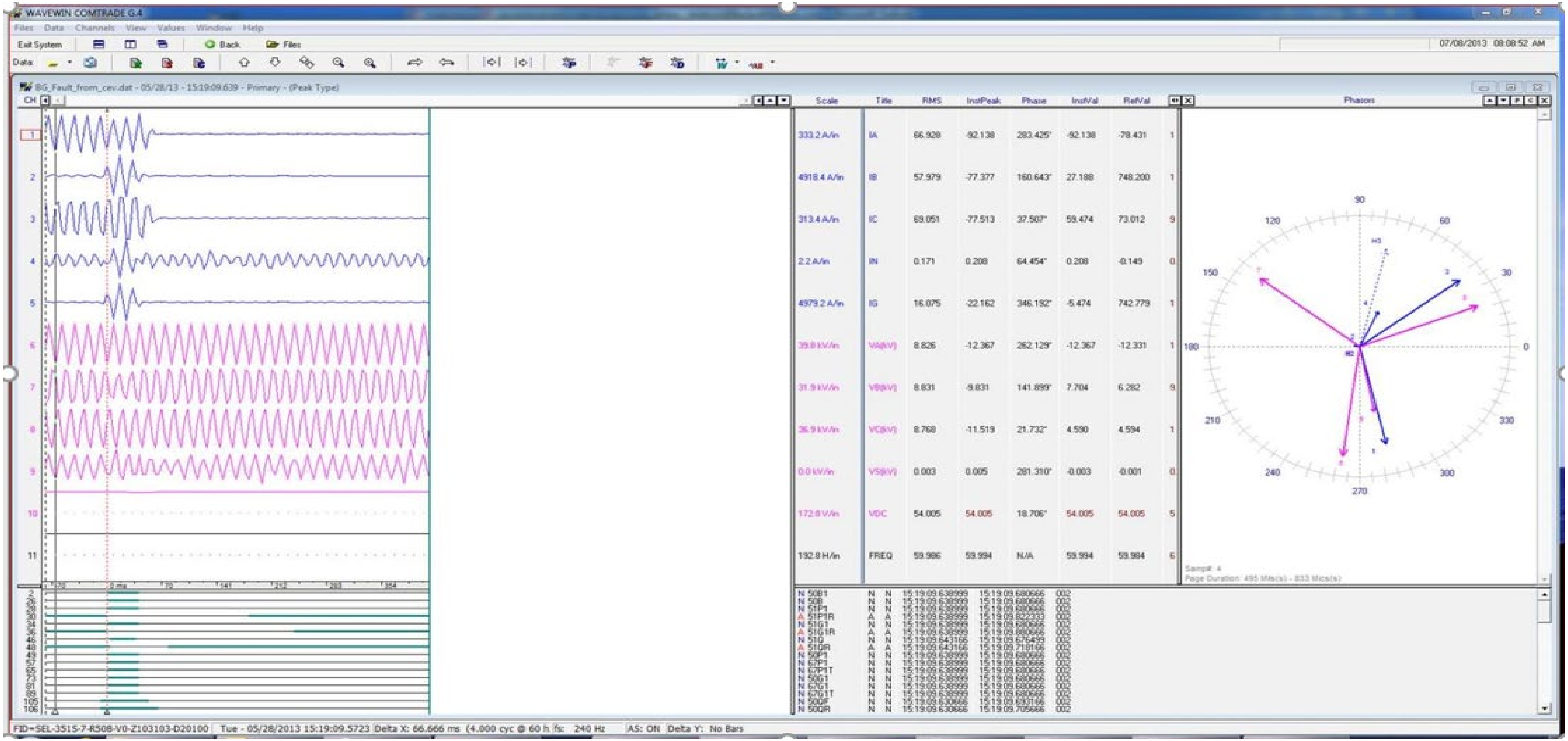
Section 5 – System Configuration & Components

Distribution System Grounding

- System Voltages and Currents during SLG Faults for Different Neutral Treatments

Neutral impedance (Ω)		Normal operation	Single-phase-to-ground fault (refer to Figure 5-10)				
			Solidly grounded	Ungrounded	Resonant grounded	Resistor grounded	Reactor grounded
			0.1 Ω	10 000 Ω	1 000/3 Ω	10 Ω	10 Ω
Voltage at fault	V_{AG} [V]	7 159	7 276	12 430	12 400	10 480	11 610
	V_{BG} [V]	7 163	7 252	12 480	12 400	11 860	10 580
	V_{CG} [V]	7 161	2 062	22	0	578	542
Load currents	I_A [A]	230	114	231	230	212	198
	I_B [A]	230	223	231	230	238	219
	I_C [A]	230	190	230	230	213	226
Xformer neutral	V_{NG} [V]	0	207	7 197	7 141	5 795	5 601
	I_N [A]	0	2 067	0	21.4	579	560
Fault current	I_f [A]	0	2 062	22	0	578	542
Capacitive currents	I_{CA} [A]	7.2	7.3	12.4	12.4	10.5	11.6
	I_{CB} [A]	7.2	7.3	12.5	12.4	11.9	10.6
	I_{CC} [A]	7.2	2.1	0	0	0.6	0.5

Example B Phase to Ground Fault

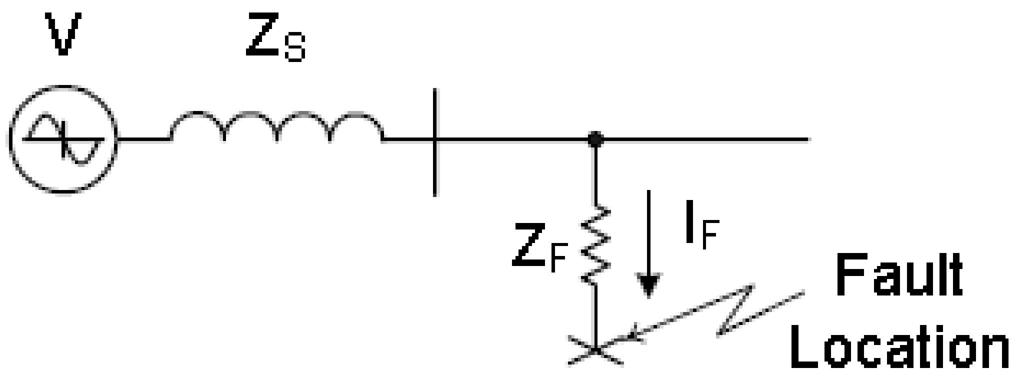


Section 5 – System Configuration & Components

Fault Studies

For Faults on Radial Systems

- Max fault currents are influenced by:
  - Low source impedances
  - Maximum generation conditions
  - Zero fault impedance
- Minimum fault current levels are influenced by:
  - High source impedances
  - Minimum generation conditions
  - Non-zero fault impedance



Section 5 – System Configuration & Components

Bus Configurations

- The bus configuration designs take into consideration requirements such as load characteristics, the necessity for maintaining continuity of service, flexibility of operation, maintenance, and cost.

- The designs vary from the simplest single-circuit layout to the involved duplicate systems installed for metropolitan service where the importance of maintaining continuity of service justifies a high capital expenditure.

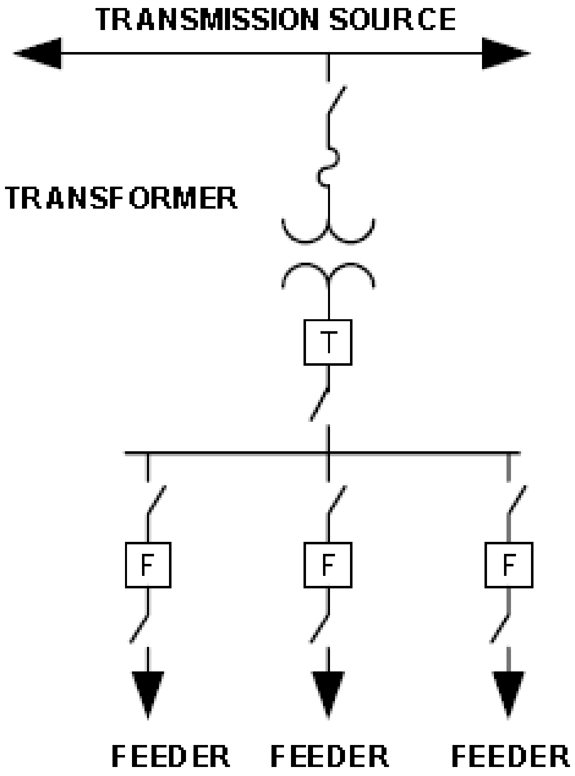
- Bus configuration for distribution buses may differ radically from the layout of transmission buses.

- In some metropolitan developments supplying underground cable systems, segregated-phase layouts are employed to secure the maximum of reliability in operation.

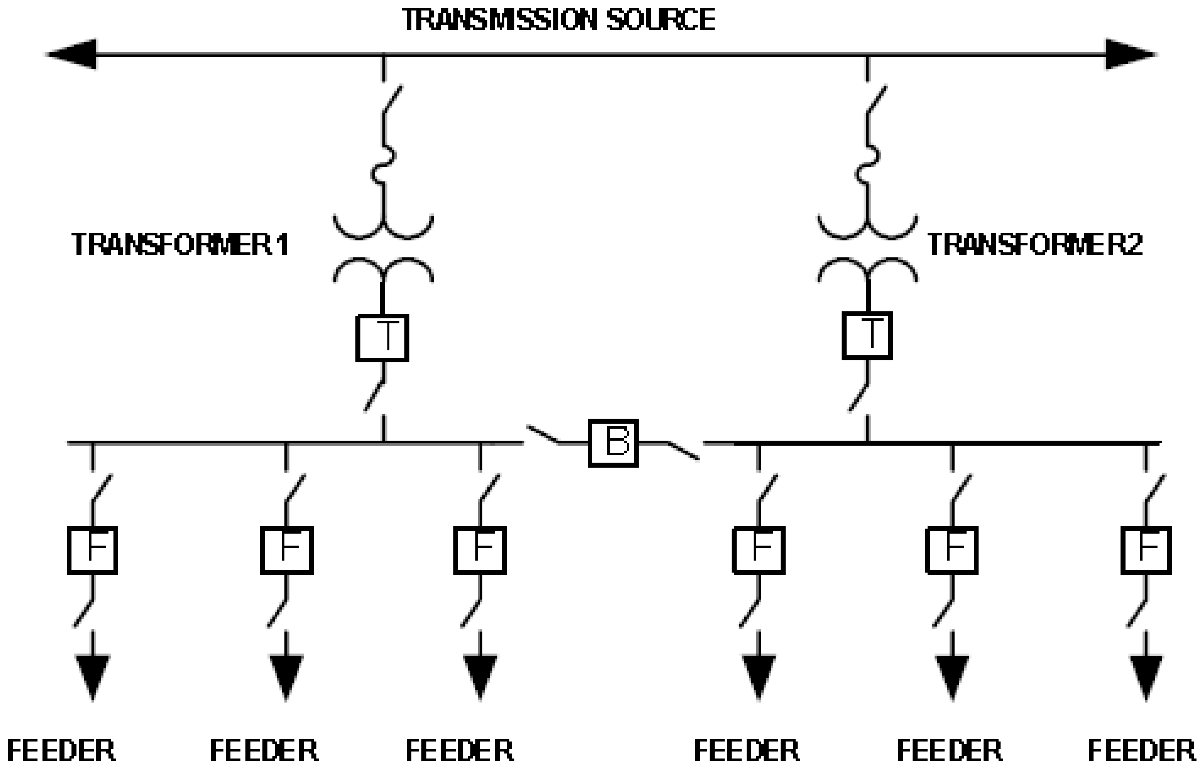
- The following are some commonly used distribution substation bus arrangements and a description of the protective relay issues that these bus arrangements create.

Section 5 – System Configuration & Components

Bus Configurations



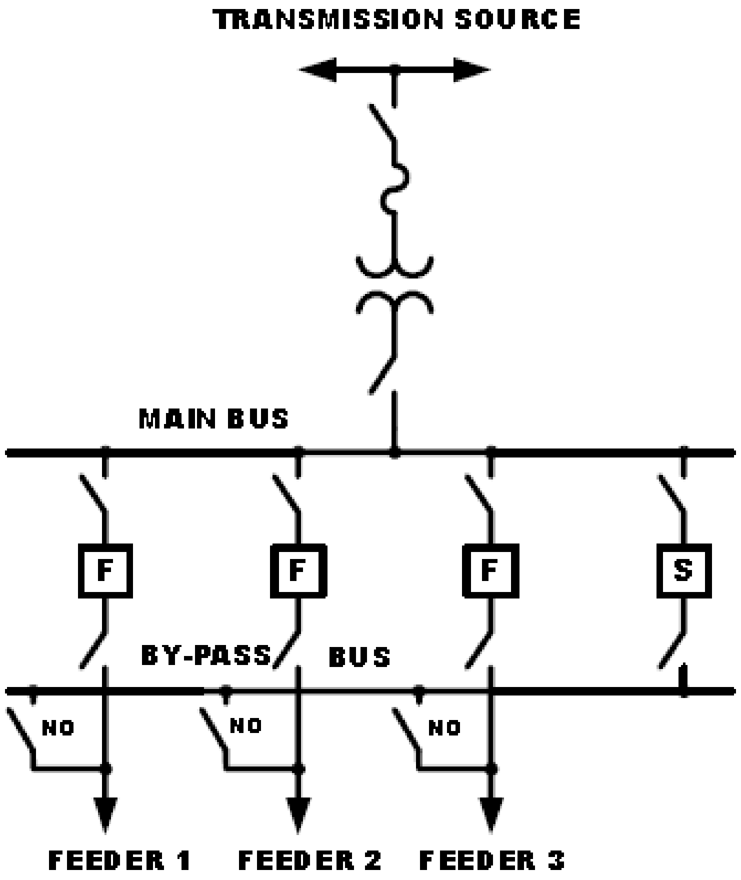
Single Transformer
Distribution Bus



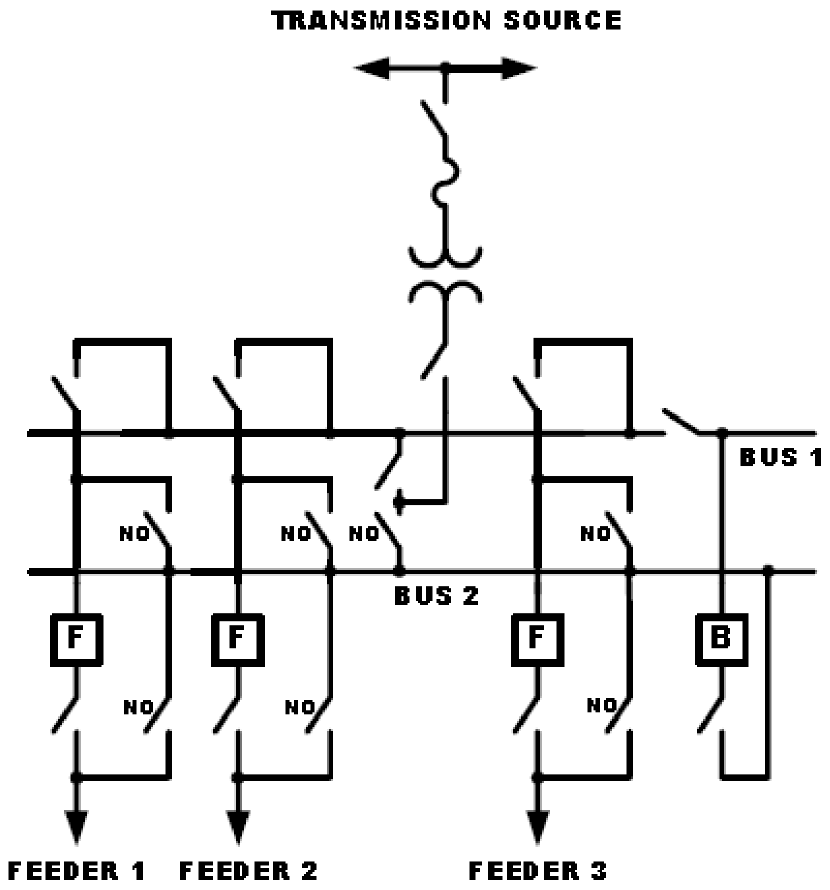
Two Transformer
Distribution Bus

Section 5 – System Configuration & Components

Bus Configurations



Main-Bypass Bus

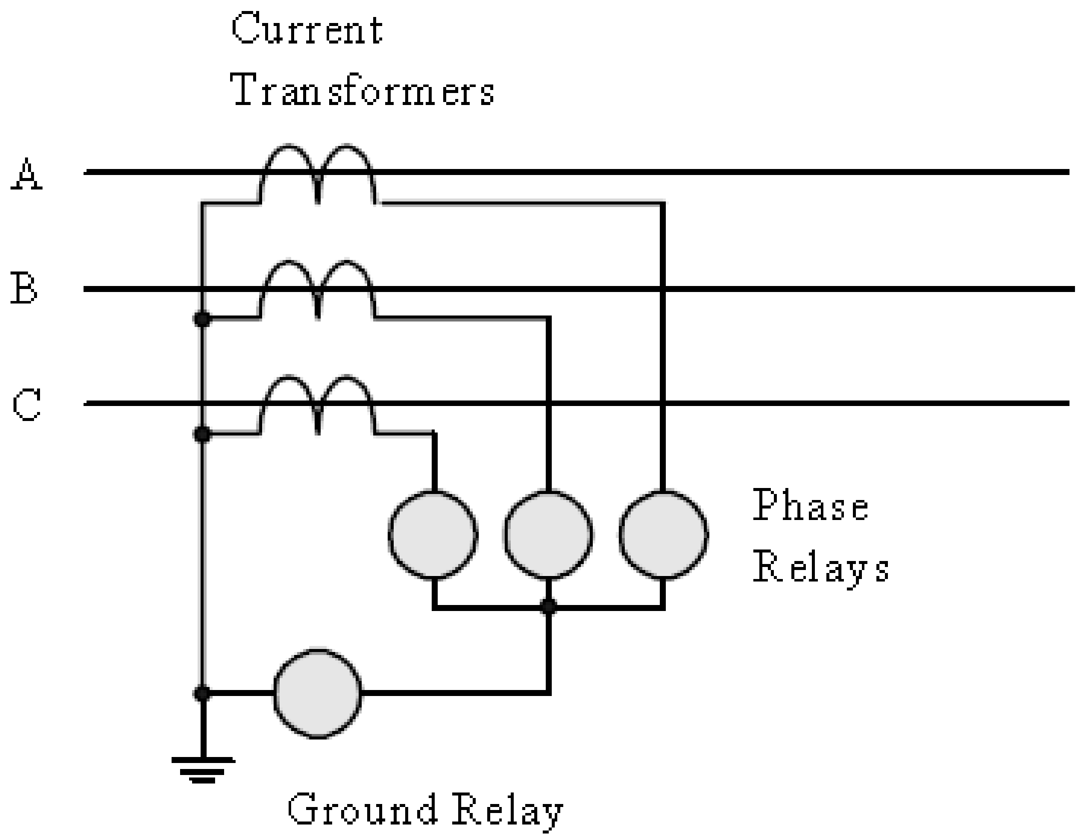


Dual Operation Distribution Bus

Section 5 – System Configuration & Components

Neutral versus Residual Ground CT's

- Ground fault protection can be designed using ground relays
- OC relays (50/51) used for ground-fault protection are typically the same as for phase-fault protection
- Ground-fault relays require a more sensitive range of minimum operating currents
- Ground relay settings should allow for system unbalanced (residual) currents to flow without tripping



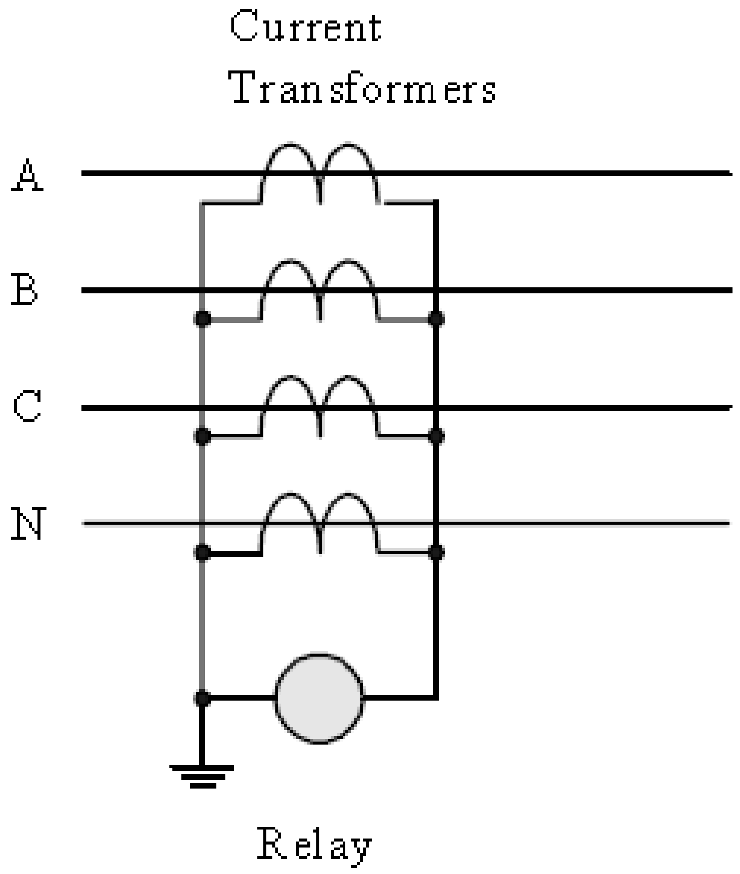
Typical Phase & Ground Relay Connections

Section 5 – System Configuration & Components

Neutral versus Residual Ground CT's

- On a four wire system with an insulated neutral conductor (common in US), an additional CT installed in the neutral conductor removes the residual load currents from the ground relay.

- Most common in low voltage systems.



Ground Relay and Residually Connected CTs

Section 5 – System Configuration & Components

Instrument Transformers – CTs

- Single & Three phase
- Rectangular & Toroidial

Applications:

- LV & MV Switchgear
- Switchboards
- Motor Control Centers
- Generators
- UPS systems
- Utility Metering and Relaying
- Pad-mount Transformers

Section 5 – System Configuration & Components

Instrument Transformers – Zero Sequence/Core Balance CTs

Applications:

- Detection of ground/earth fault currents in 3 or 4 wire systems.
- For low or solidly grounded systems a 5A secondary CT should be used. Typical primary ratings are 50A and 100A.

Section 5 – System Configuration & Components

Instrument Transformers – Bushing CTs

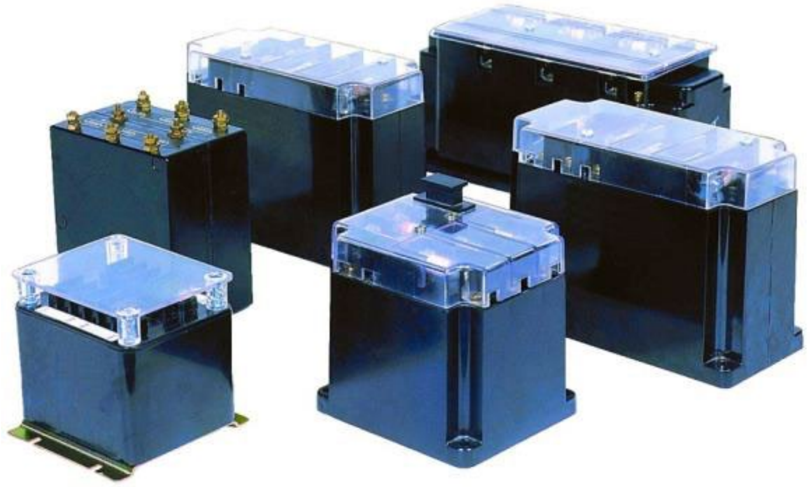
- 600V Class
- For mounting over HV bushings

Applications:

- Power Transformers
- Generators
- HV Circuit Breakers
- Outdoor Distribution Breakers

Section 5 – System Configuration & Components

Instrument Transformers – LV Potential Transformers (LV VT)



- Single & Three phase

Applications:

- LV & MV Switchgear
- Switchboards
- Motor Control Centers
- Generators

Section 5 – System Configuration & Components

Instrument Transformers – MV Potential Transformers (MV VT)

- 5 KV to 38 KV

Applications:

- MV Switchgear
- MV Motor Control
- MV Generators
- Utility Metering

Section 5 – System Configuration & Components

Instrument Transformers – MV/HV Substation Current and Potential Transformers (MV/HV VT; MV/HV CT)

Free Standing Outdoor VT

Free Standing Outdoor CT

Section 5 – System Configuration & Components

Transformer Ground Source Connections

- Additional transformers may be added to provide a ground reference on systems where no ground connection exists, like a delta connected transformer.
- Two commonly used transformer arrangements are as follows:
  - Grounded-wye with closed delta
  - Zigzag

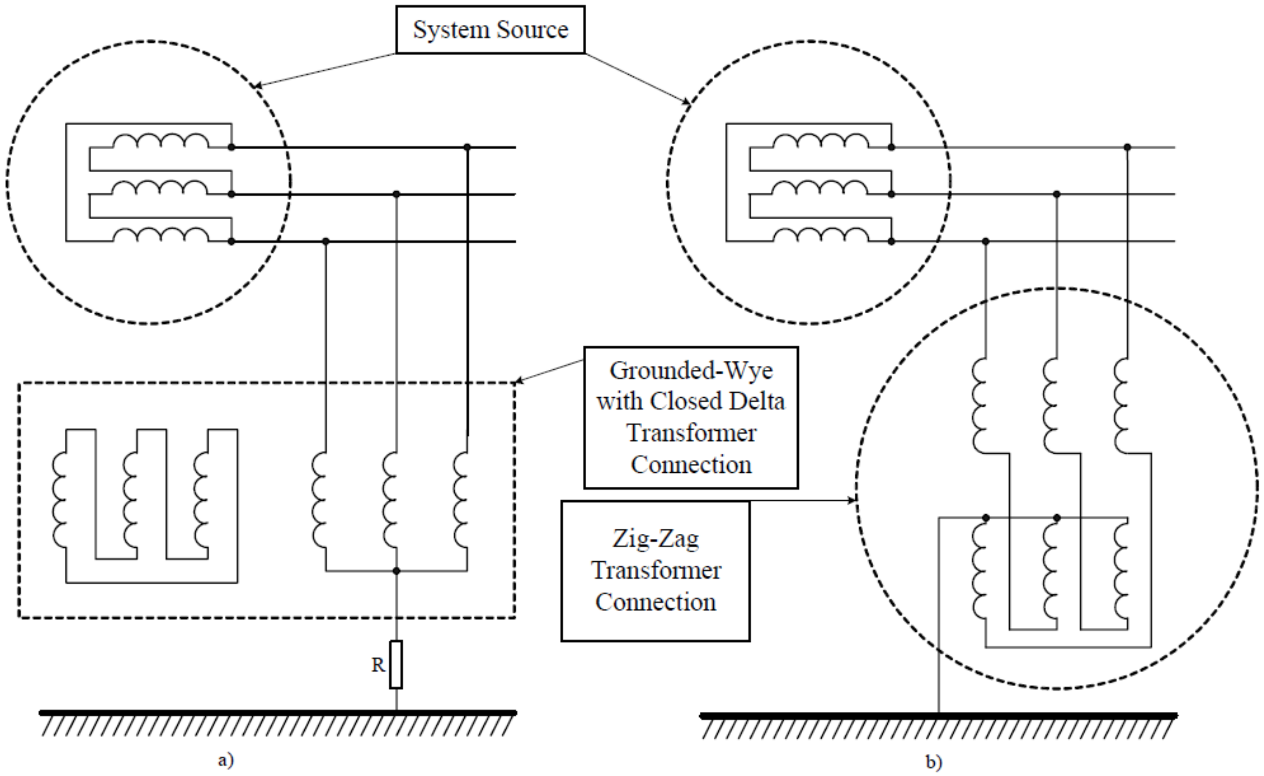


Figure 5-27—Grounding transformers

Section 5 – System Configuration & Components

Transformer Ground Source Connections

- Both connections have high positive-sequence impedance, but low zero-sequence impedance.
- The zigzag transformer is more commonly used since it provides more effective use of transformer material.
- To limit ground-fault currents to a level satisfying the criteria for resistance grounded systems, a resistor between the primary neutral and ground can be installed.

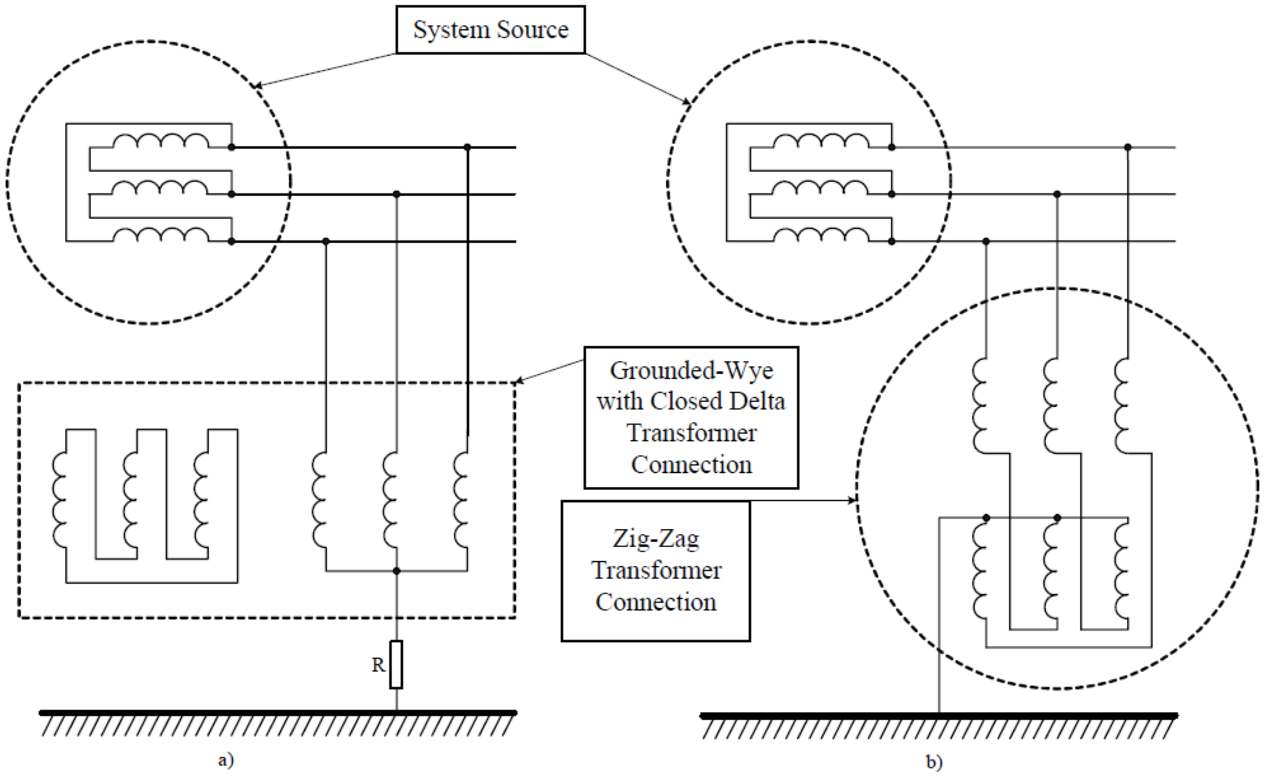


Figure 5-27—Grounding transformers

Section 5 – System Configuration & Components

Lines

- This guide does not go into detail about the lines themselves, their design, or application. This guide briefly discusses what should be considered in regard to protection.
- Protection & Coordination – Where to begin?
  - Damage curves for both lines and transformers
  - Every conductor has a maximum current limit before it is damaged
  - Protection should always be set so as to clear faults before a conductor (or transformer) is damaged
- Conductor damage curves or (I squared t) curves can be found from conductor manufacturers

Section 5 – System Configuration & Components

Transformers – Distribution Substation

- Transformer damage curves are based upon
  - I^2t of the windings (which are really just big conductors)
  - Mechanical bracing of the windings for through faults
- Common practice in North America is to operate 3 phase distribution systems in a 4-wire grounded-wye mode
- This practice dictates that the transformer LV or secondary winding is connected in wye and solidly grounded at the common wye connection
- It is also common practice that the primary HV winding be connected in delta
- This provides advantages for the application of protective relays on the primary supply system

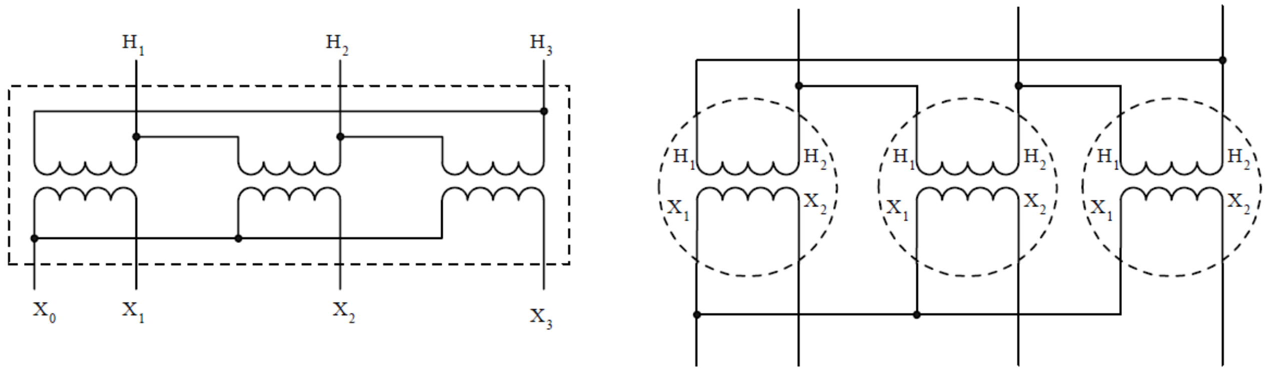


Figure 5-28—Three-phase and single-phase transformer connections

Section 5 – System Configuration & Components

Transformers – Distribution Substation

- Transformer are built with impedance
- Preferred standard values of transformer impedance are provided in Table 10 of ANSI C57.12.10-1997 [B3], which is shown as Table 5-2.
- Variation from these values may be required in some applications to limit distribution bus fault magnitudes.

Table 5-2—BILs and percent impedance voltages at self-cooled (OA) rating

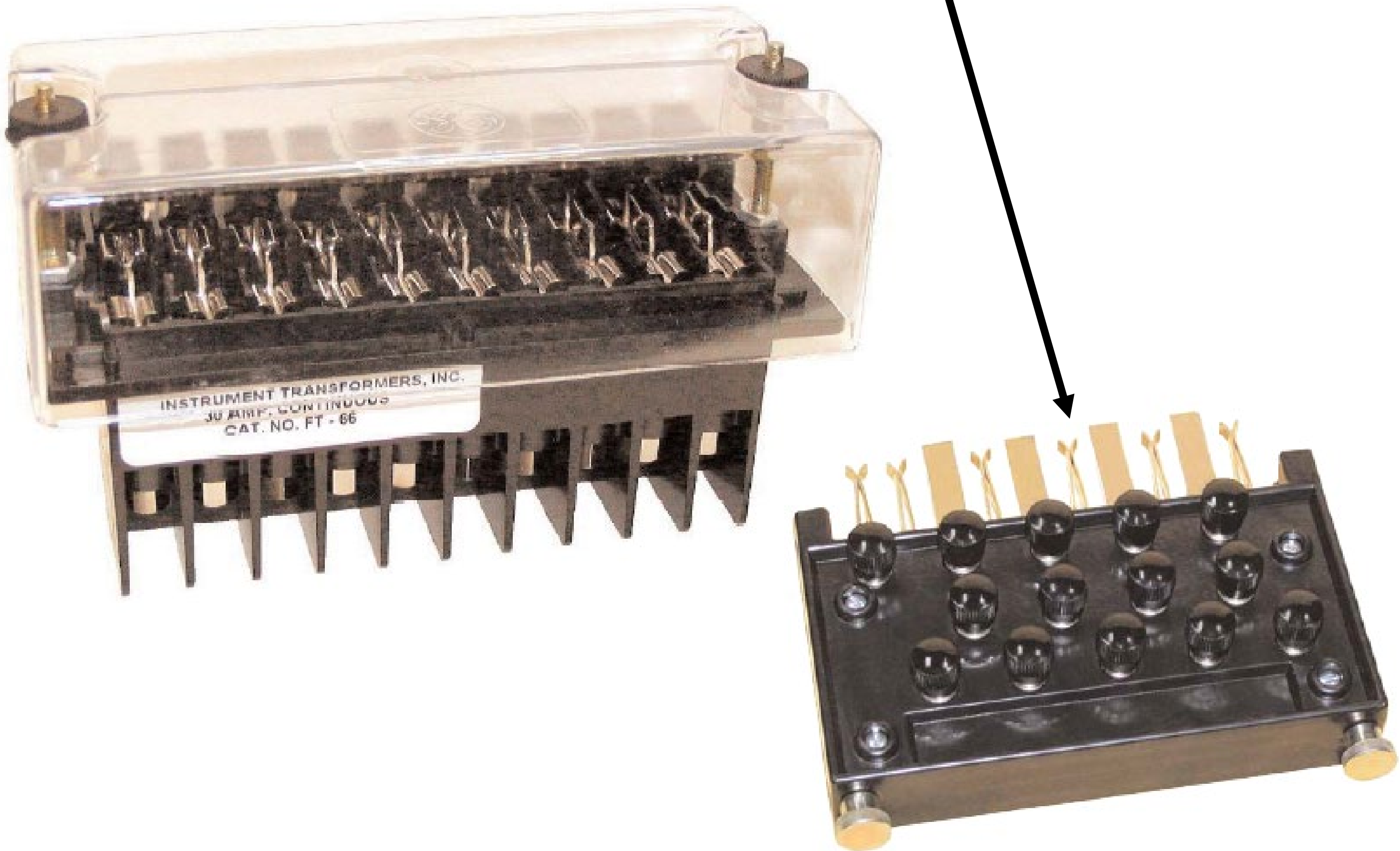
	Without load tap changing		With load tap changing
High-voltage BIL (kV)	Low voltage 480 V	Low voltage 2400 V and above	Low voltage 2400 V and above
60–110	5.75 [a]	5.5 [a]	—
150	6.75	6.5	7.0
200	7.25	7.0	7.5
250	7.75	7.5	8.0
350	—	8.0	8.5
450	—	8.5	9.0
550	—	9.0	9.5
650	—	9.5	10.0
750	—	10.0	10.5

[a] For transformers greater than 5000 kVA self-cooled, these values shall be the same as those shown for 150 kV HV BIL.

Source: ANSI C57.12.10-1997 [B3].

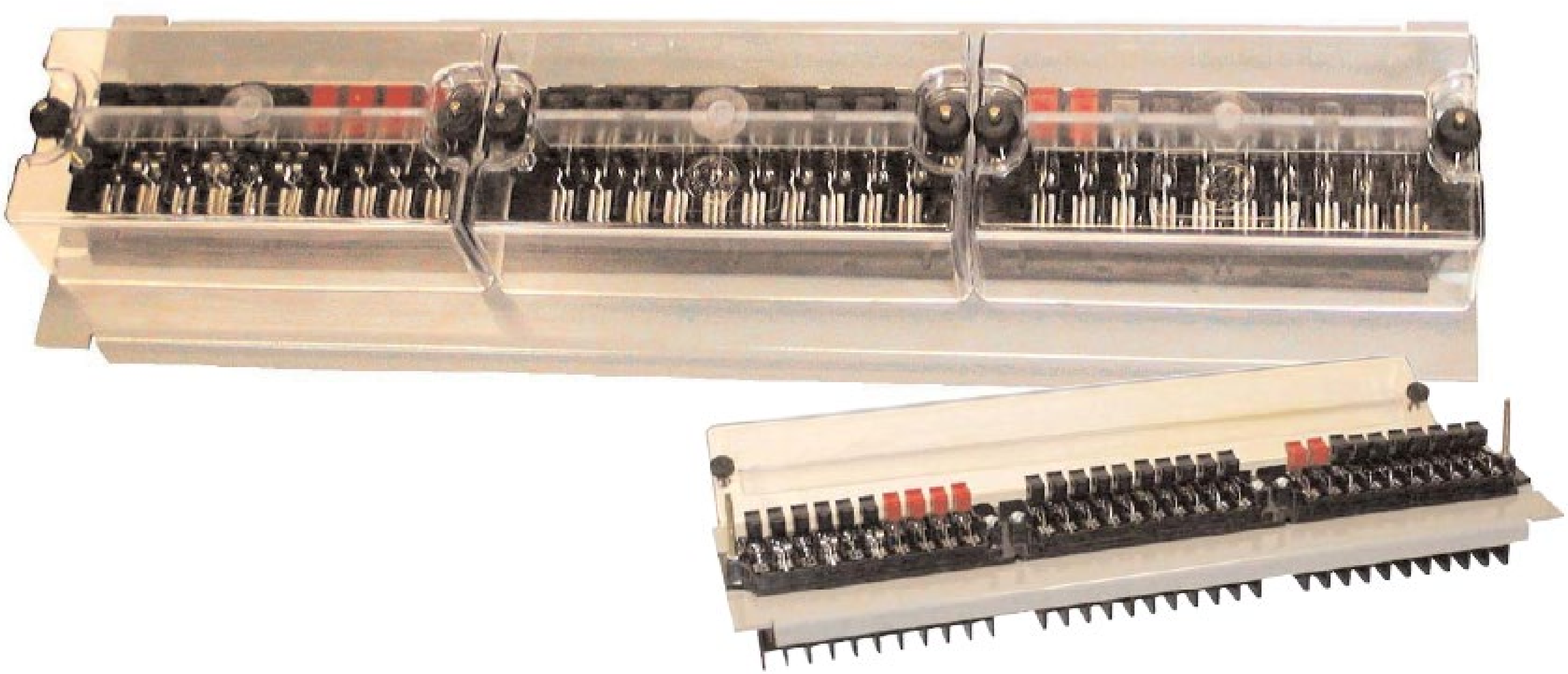
Section 5 – System Configuration & Components

Test Switches and Test Plugs



Section 5 – System Configuration & Components

Rack Mount Test Switch



Section 5 – System Configuration & Components

Test Switch Operation

Potential Circuits (VT or PT)

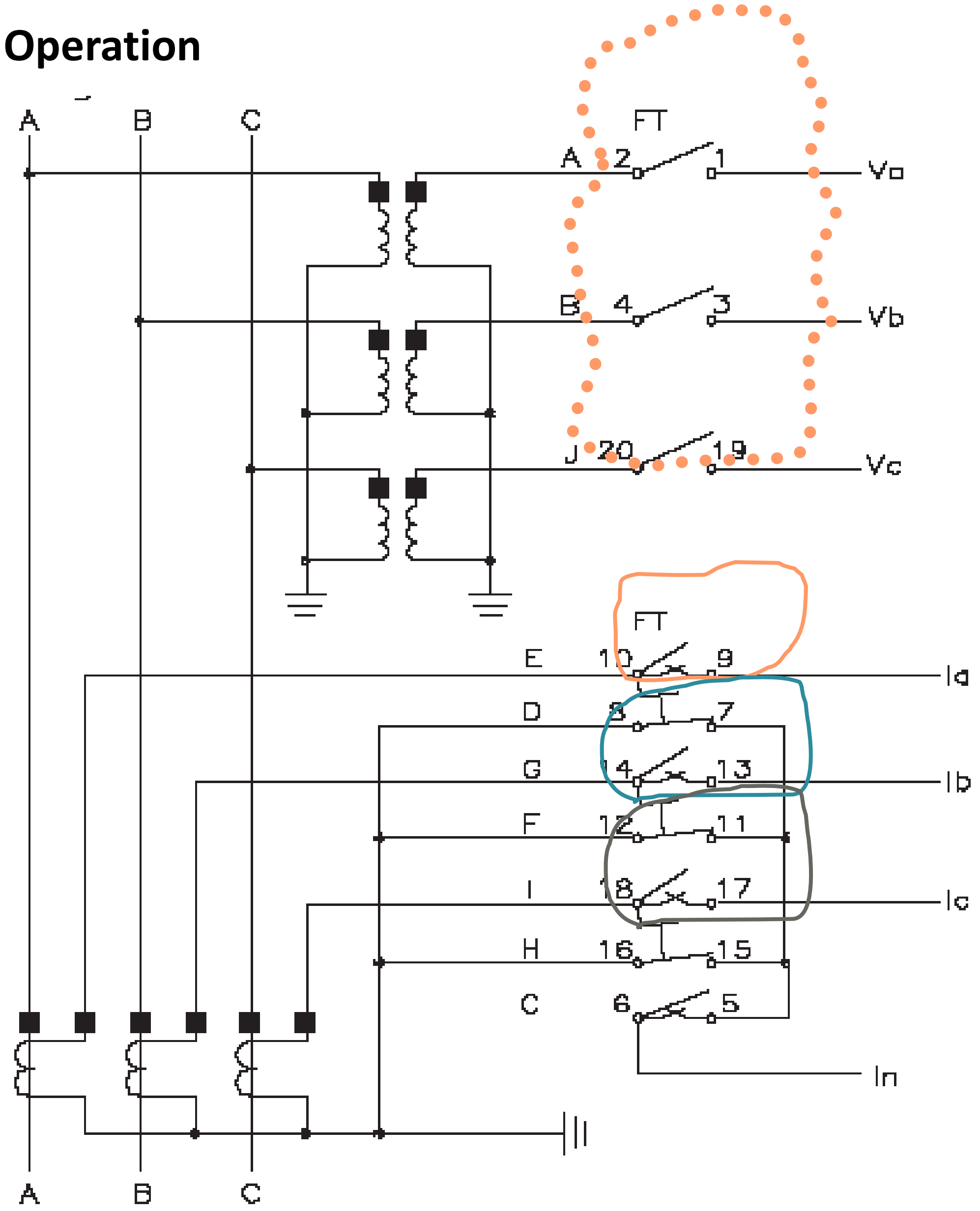
- Open to Relay
- Open to Instrument Transformer

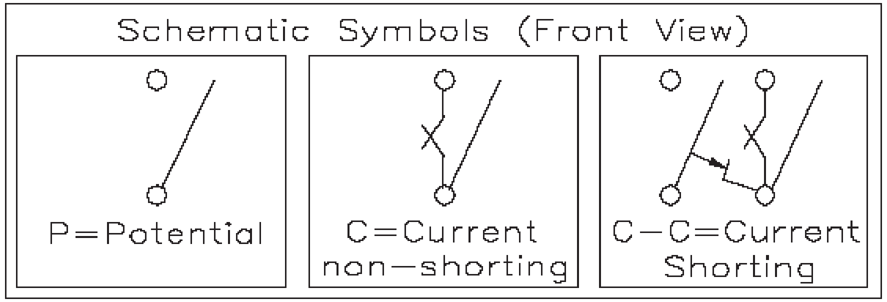
Current Circuits (CT)

- Open to Relay
  - Circuit from Switch to Relay becomes ungrounded
  - Circuit to Instrument Transformer secondary shorts
    - Ground maintained in IT secondary

Section 5 – System Configuration & Components

Test Switch Operation





Section 6 – Protective Schemes

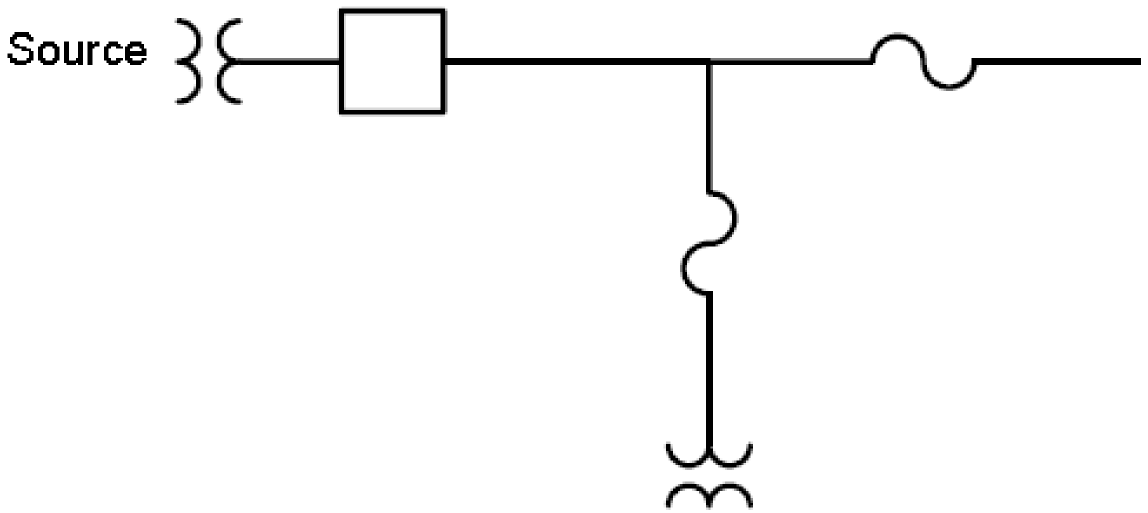
Distribution Protective Schemes

- Overcurrent Protection – Three types
  - Phase Overcurrent
  - Ground Overcurrent
  - Negative Sequence Overcurrent
- OC protection must be coordinated
  - Upstream devices – Transformer protection, main breaker OC
  - Downstream devices – Reclosers, fuses
- Overcurrent protection can be non-directional (50/51) or directional (67)
- Non-directional can be used for radial distribution
  - Load and fault current can only go in one direction
- Directional OC can be used for networked or looped systems
  - Current could theoretically go in either direction based upon system conditions.
  - Requires a voltage input

Section 6 – Protective Schemes

Distribution Protective Schemes

- Fuse Save vs Fuse Blow
- Overcurrent Protection schemes can fall into 2 categories:
  - Fuse Saving Schemes
  - Fuse Blowing Schemes
- Distribution fuses require physical replacement after a fault clearing operation.
  - Fuses are one time use
  - Results in extended outage times



Section 6 – Protective Schemes

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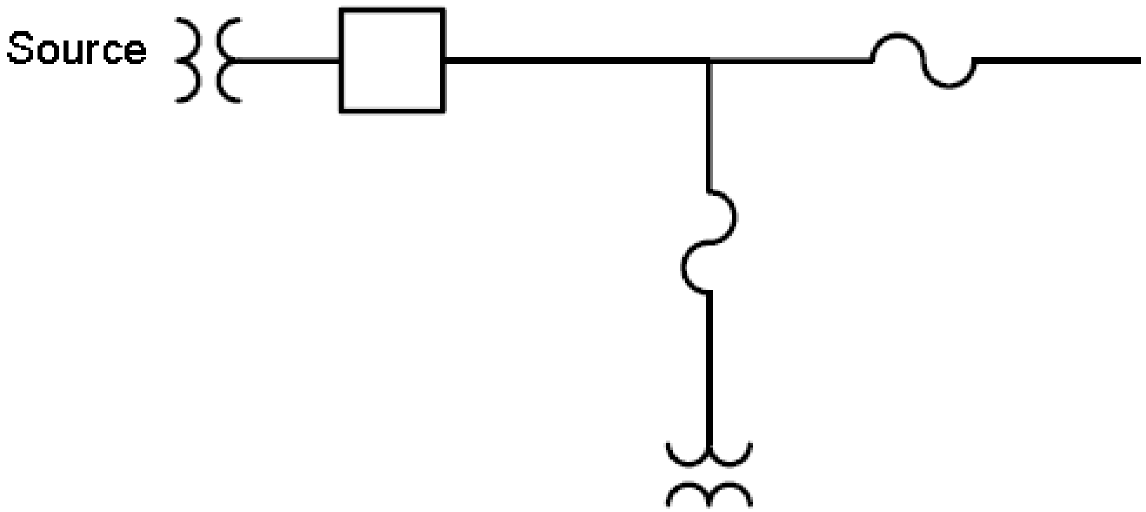
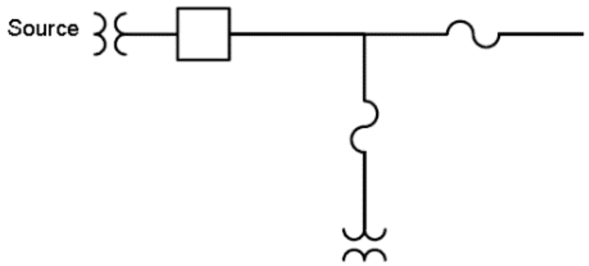


Section 6 – Protective Schemes

Distribution Protective Schemes – Fuse Blow

- Used where loads are sensitive to momentary outages, it will limit the number of main feeder trip-reclose cycles
- Used on systems where faults are more often permanent (like UG)
- Fuses operate first (traditional coordination), before a breaker or recloser
- Causes a longer outage on the system downstream of the blown fuse
- Eliminates momentary outages on system upstream of the blown fuse



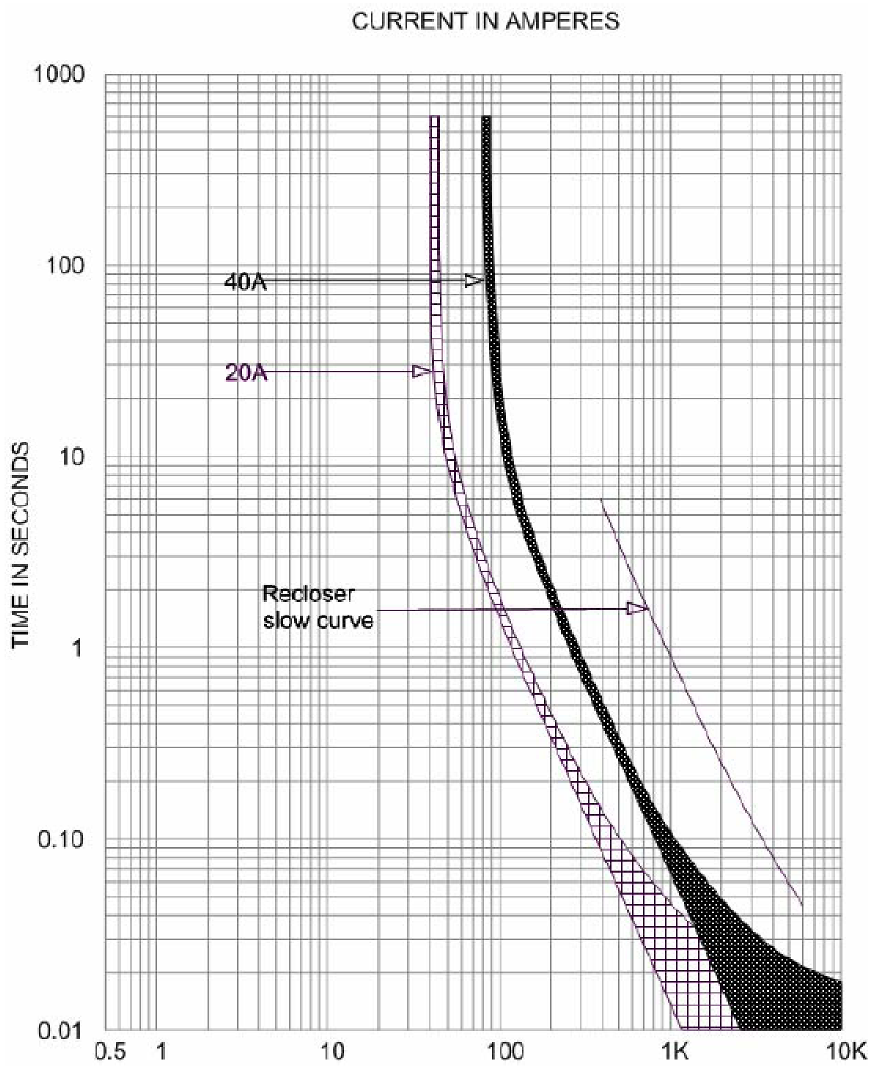
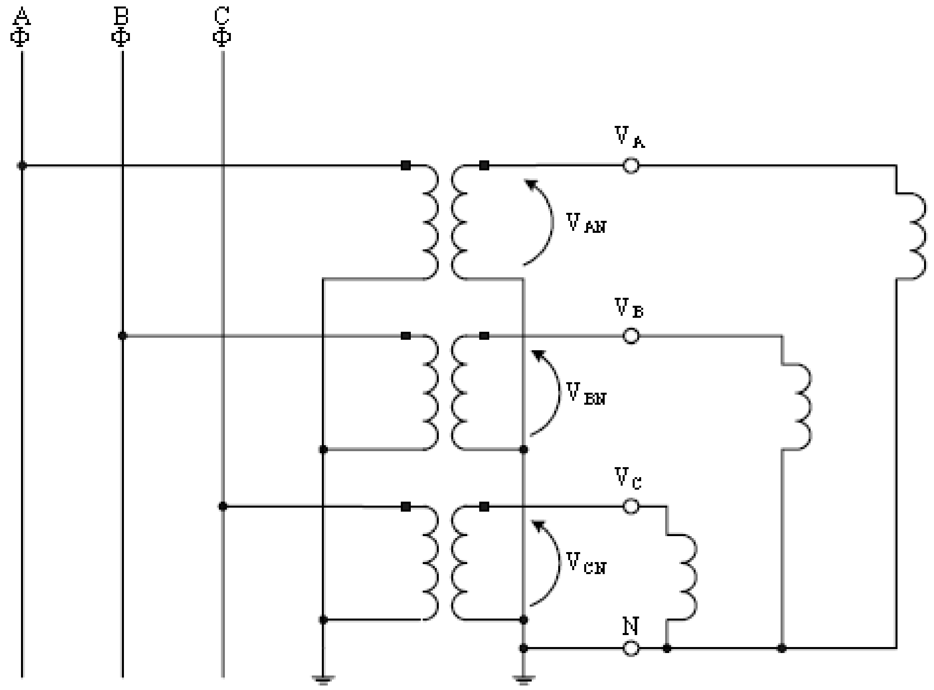


Figure 6-3—Time-current curve showing fuse blowing scheme

Section 6 – Protective Schemes

Distribution Protective Schemes – Voltage Schemes

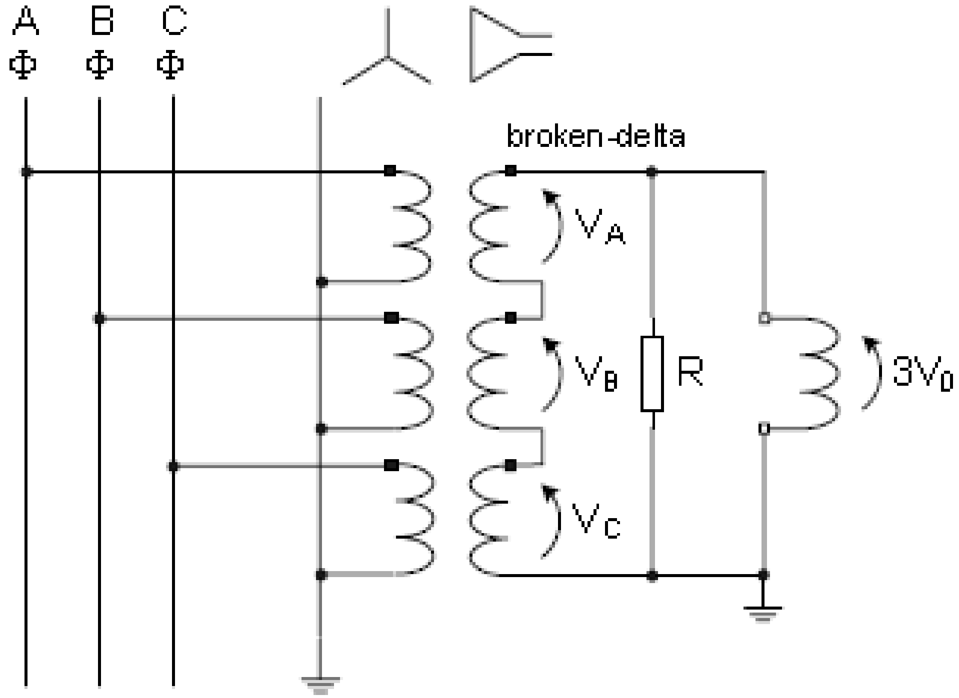
- Used to protect equipment from damage
- To determine if a supply source is healthy or not
- To detect ground faults on normally ungrounded systems
- To supervise automatic or manual reclosing of circuit breakers
- To determine whether a single breaker pole is open or closed undesirably
- To detect unbalanced voltage due to a blown fuse
- To supervise or restrain OC elements for fault detection near generation sources
- Can be over voltage (59) or under voltage (27) depending on the application



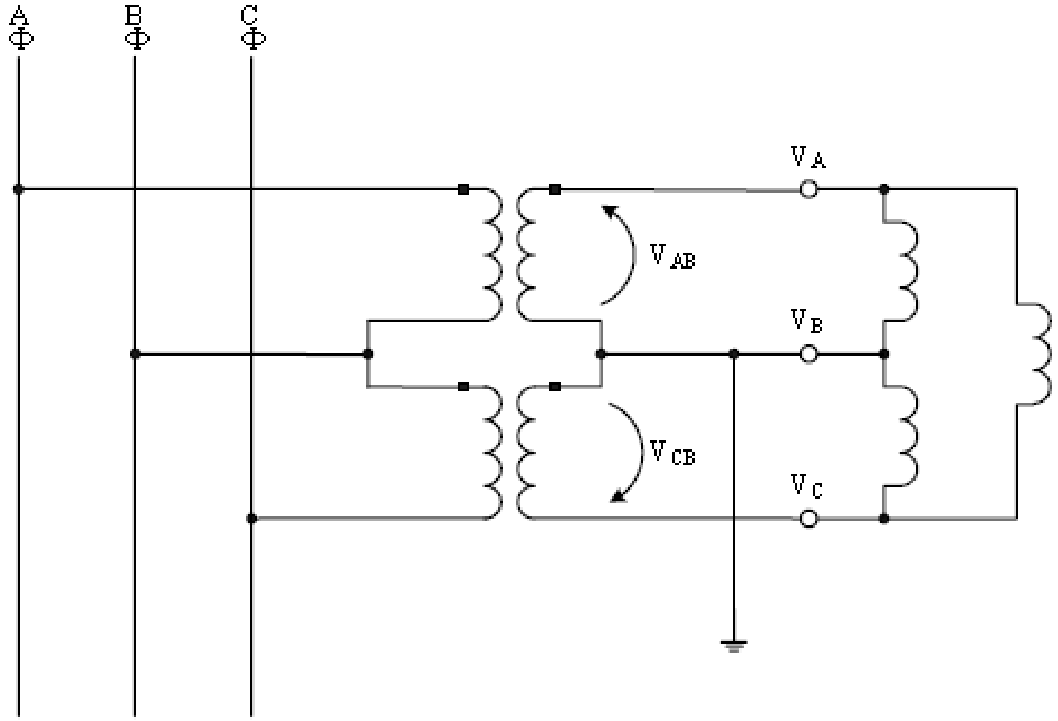
Three Phase, Four Wire VT’s

Section 6 – Protective Schemes

Distribution Protective Schemes – Voltage Transformer Connections



Wye-Broken Delta Connected VTs – Looking for 3 V_0



Three Phase, Three Wire VTs Open Delta

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