ECE 5984: Power Distribution System Analysis

Lecture 1: Power Distribution Systems Overview

References: Kersting, Chapter 1
Gonen, Chapters 4, 5, 6

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VirginiaTech
Invent the Future

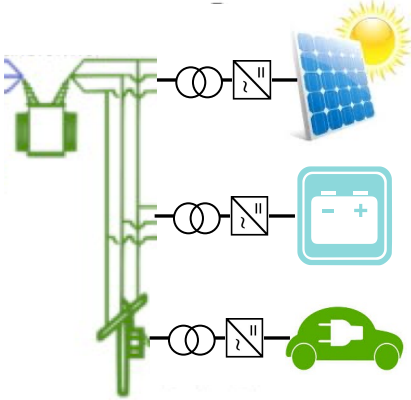
Why study distribution systems?

- Smart grid technologies connected to distribution grids



- Pressing need for efficiency and resiliency
  - demand response, TOU pricing, peak reduction
  - conservation voltage reduction
  - smart buildings and smart thermostats
  - microgrids
  - aggregators


- New monitoring and control apparatus
  - remotely controlled devices (switches, regulators, capacitors)
  - micro-PMUs and smart meters
  - smart inverters

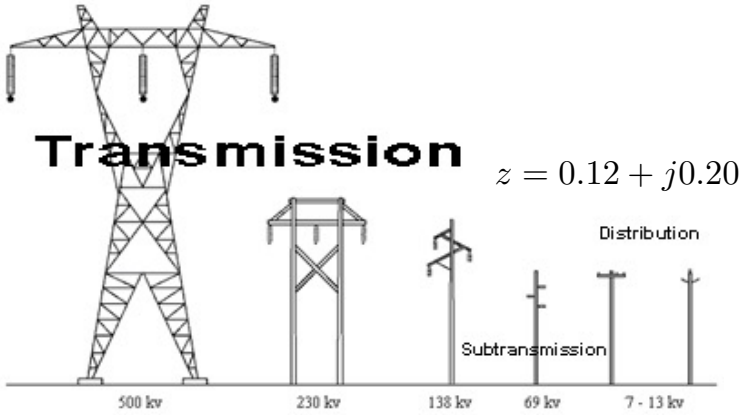



Transmission vs. distribution systems

- Imbalance and multiphase conditions
  - unbalanced load
  - untransposed lines (single- or two-phase laterals)
  - no single-phase equivalent
  - no symmetrical components
  - neutral wire and earth

- Different R/X ratios
  - fewer strands, no bundling, shorter span
  - underground cables
  - no P/theta and Q/V decoupling

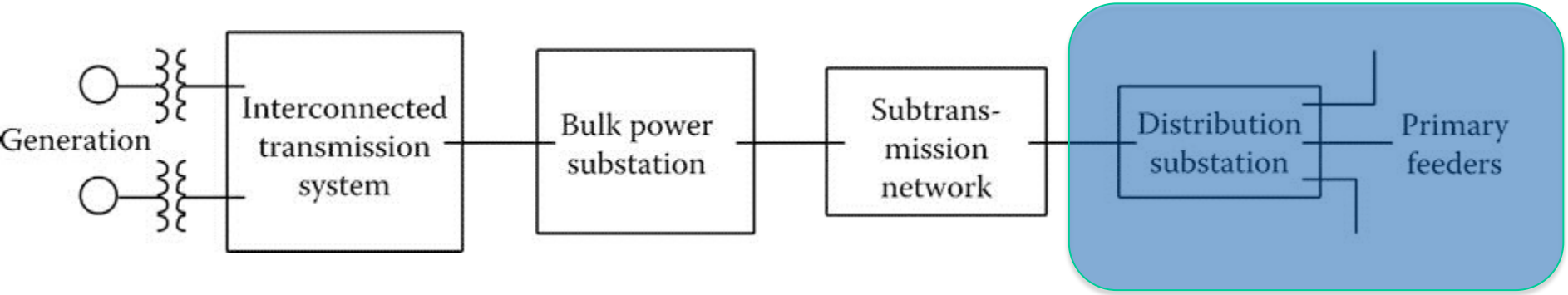
- Topologies and equipment
  - radial vs. meshed
  - regulators and capacitor banks
  - reclosers and sectionalizers



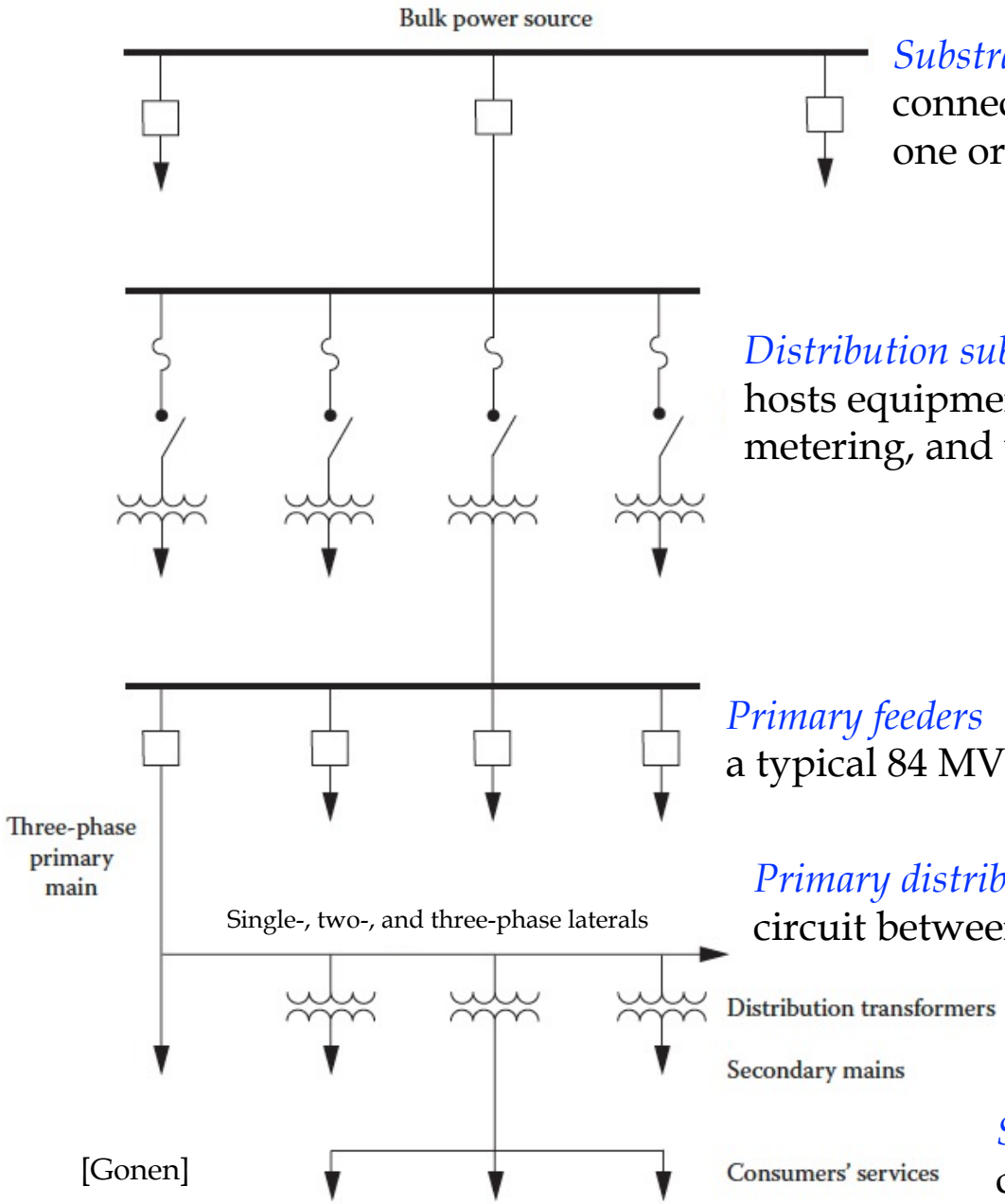
$z = 0.12 + j0.20\ \Omega/\text{mile}$

$z = 0.05 + j0.5\ \Omega/\text{mile}$

The big picture



[Kersting]



[Gonen]

Substransmission network
connects one or more distribution substations to one or more transmission substations (buses)

Distribution substation
hosts equipment for protection, switching, metering, and voltage transformation/regulation

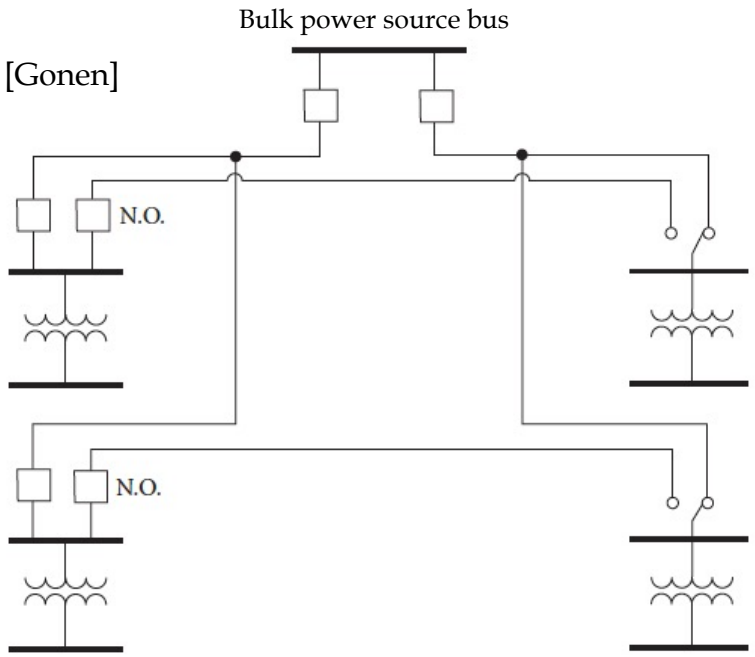
Primary feeders
a typical 84 MVA transformer may be serving 3 feeders

Primary distribution network
circuit between substation and dist. transformers

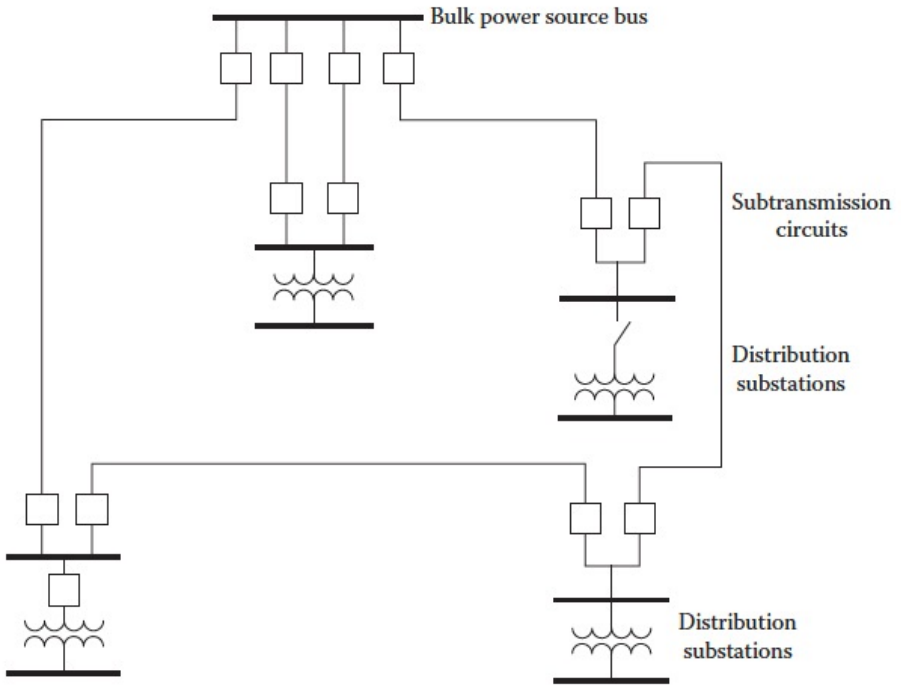
Secondary distribution network
circuit between dist. transformers and customers

Sub-transmission network

- Network of overhead (OH) or underground (UG) subtransmission lines operating in 69/115/138 kV; transmission bus may be at 230 kV



Radial-type sub-transmission network

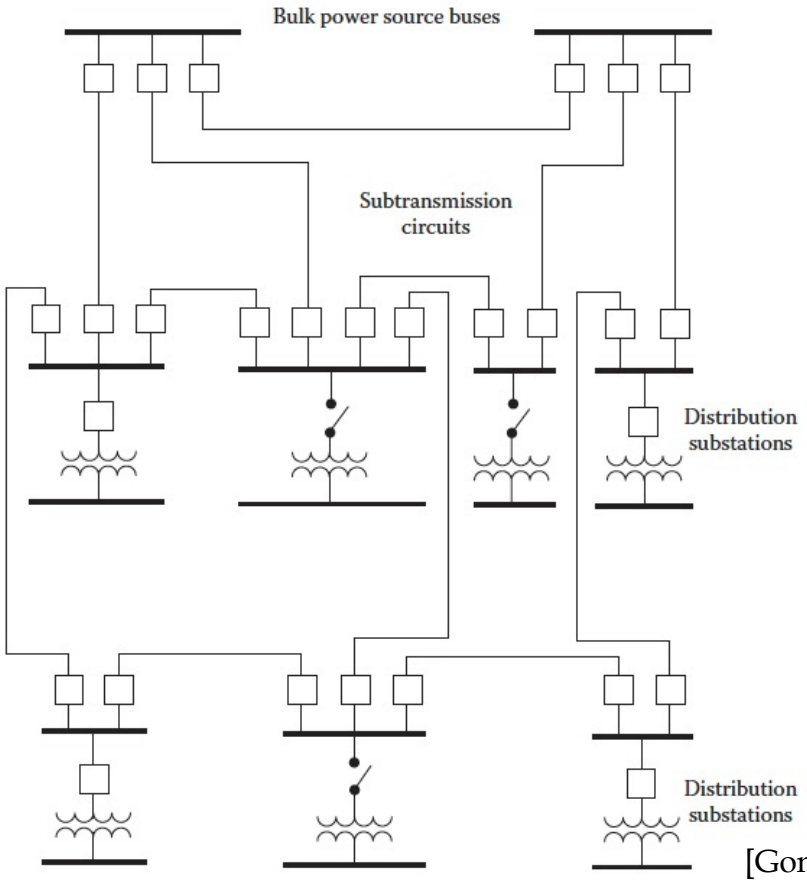


Loop-type sub-transmission network

- What does *radial or tree* structure mean?

Meshed sub-transmission network

- For increased reliability, subtransmission may involve multiple transmission buses and have a meshed architecture

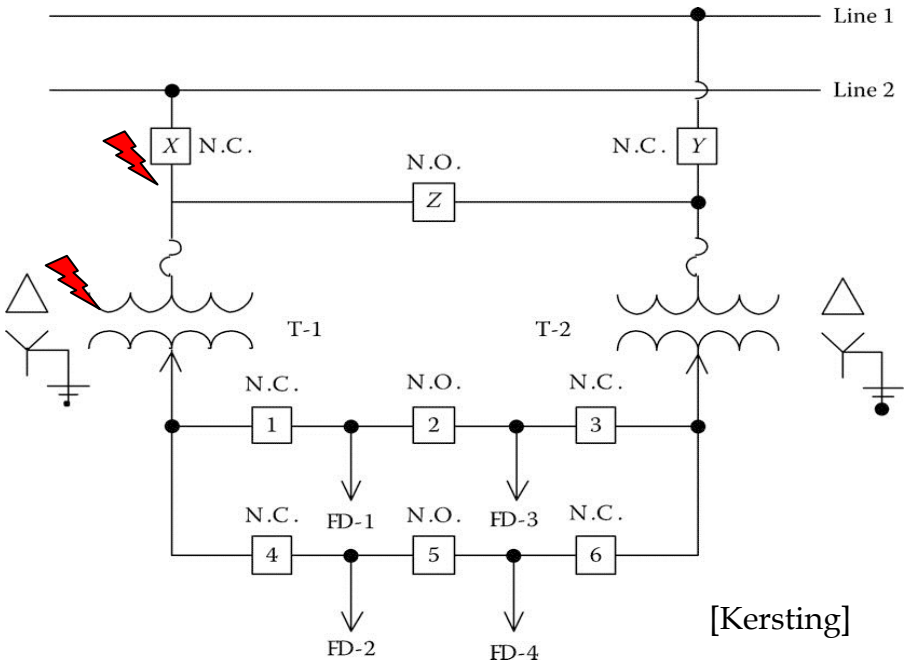


[Gonen]

Grid- or network-type subtransmission

Distribution substation

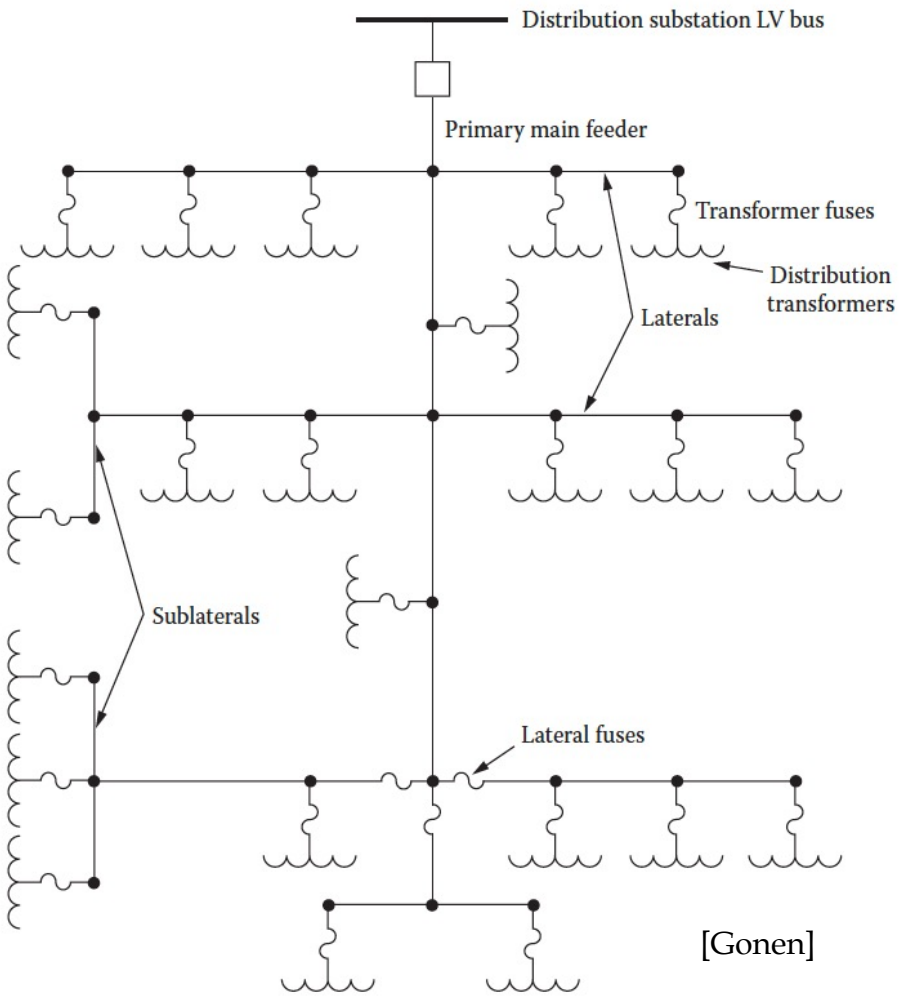
- Voltage transformed from sub-trans. to primary distribution (e.g., 115 to 34.5 kV)
- Substation may be hosting multiple transformers



Breaker-and-a-half [why?] substation scheme

- Each transformer may be serving multiple primary feeders
  e.g., 84-MVA transformer serving 3 feeders at 34.5 or 12.47 kV

Primary distribution feeders



Radial-type primary feeder

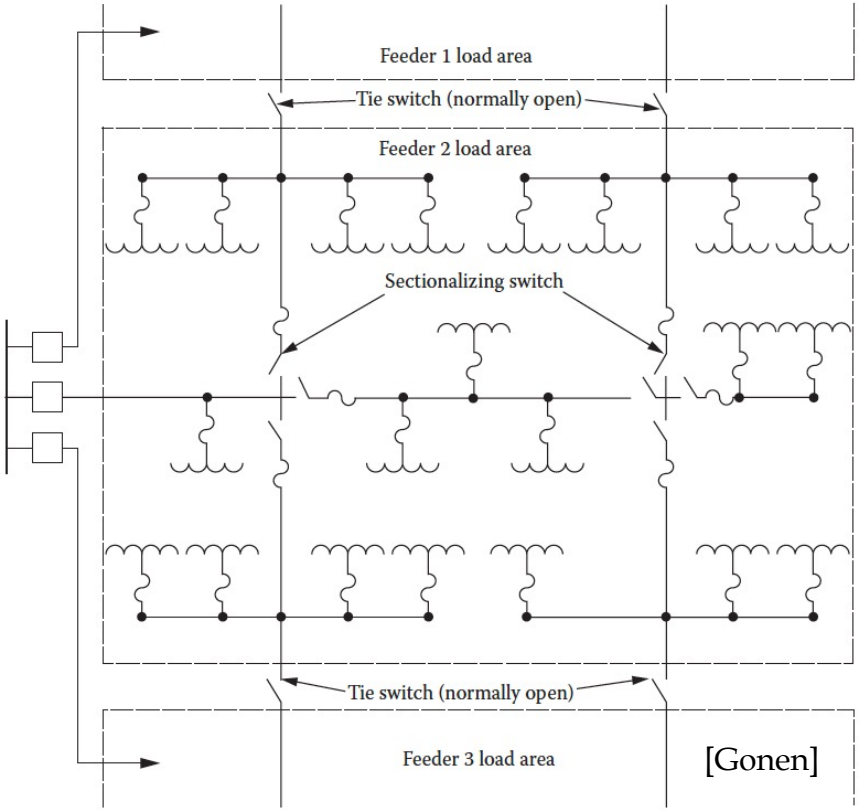
Typical Primary Voltage Levels [Gonen]

Class, kV	3φ Voltage	
2.5	2,300	3W-Δ
	2,400[a]	3W-Δ
5.0	4,000	3W-Δ or 3W-Y
	4,160[a]	4W-Y
	4,330	3W-Δ
	4,400	3W-Δ
	4,600	3W-Δ
	4,800	3W-Δ
8.66	6,600	3W-Δ
	6,900	3W-Δ or 4W-Y
	7,200[a]	3W-Δ or 4W-Y
	7,500	4W-Y
	8,320	4W-Y
15	11,000	3W-Δ
	11,500	3W-Δ
	12,000	3W-Δ or 4W-Y
	12,470[a]	4W-Y
	13,200[a]	3W-Δ or 4W-Y
	13,800[a]	3W-Δ
	14,400	3W-Δ
25	22,900[a]	4W-Y
	24,940[a]	4W-Y
34.5	34,500[a]	4W-Y

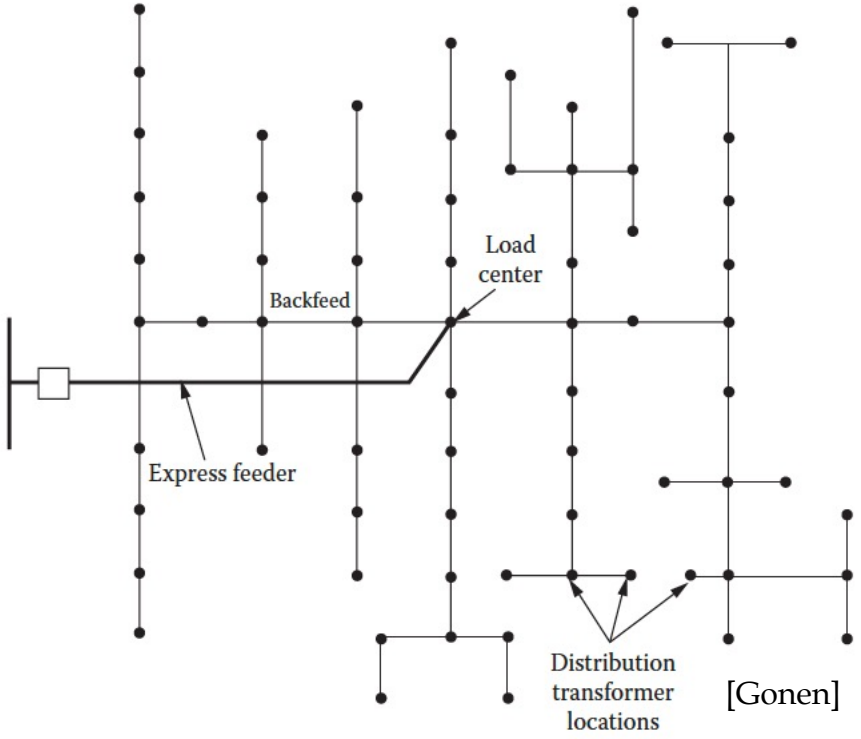
[a] Most common voltage in the individual classes.

- In-line transformers could be lowering voltage from say 12.47 to 4.16 kV

Other radial feeders

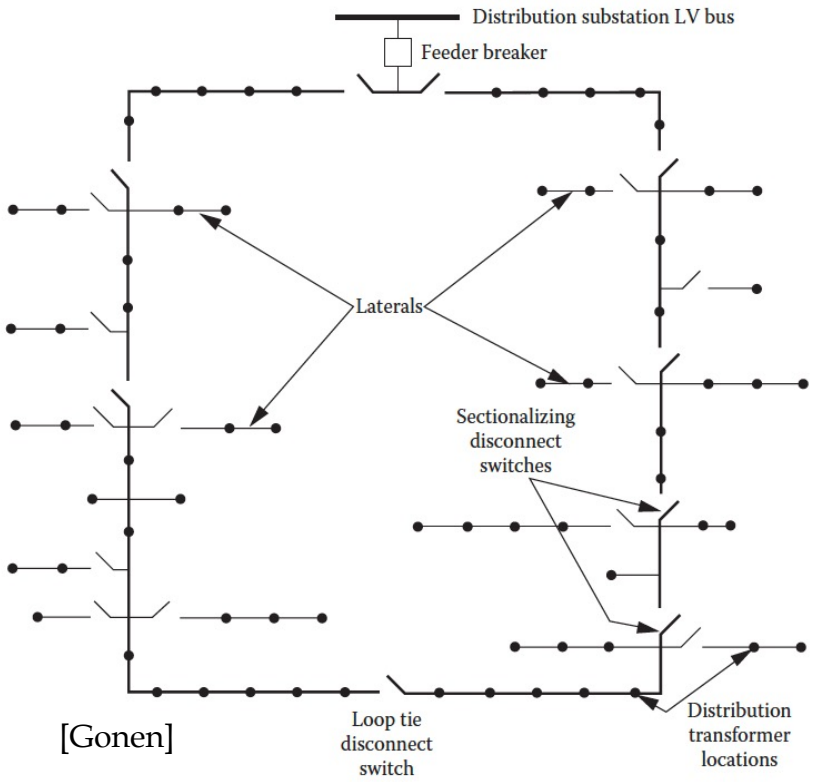


Radial feeder with tie switches



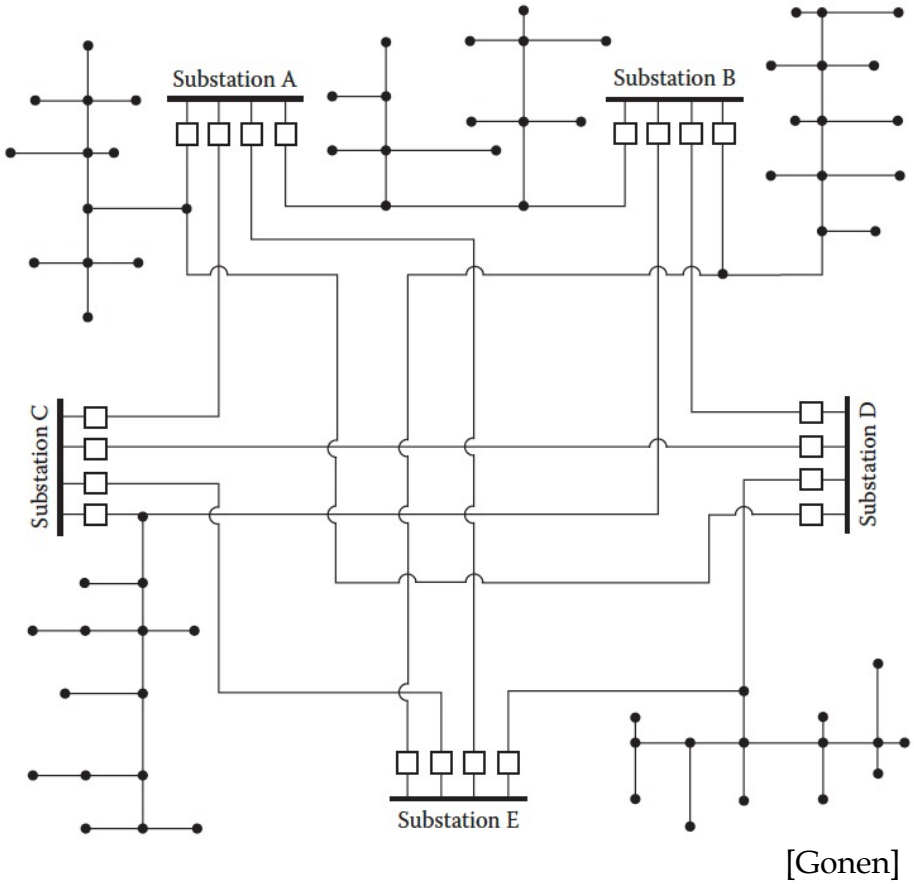
Radial feeder with express feeder and backfeed

Meshed primary feeders



[Gonen]

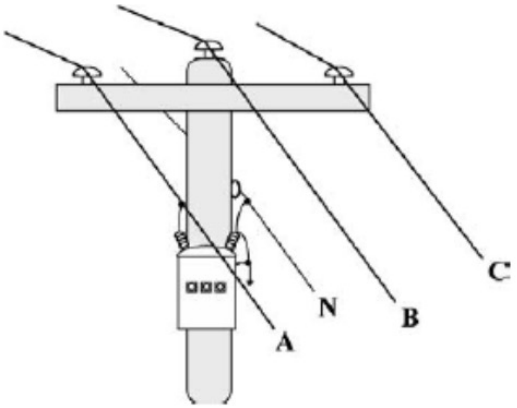
Loop-type feeder
(loop tie disconnect can be NO or NC)



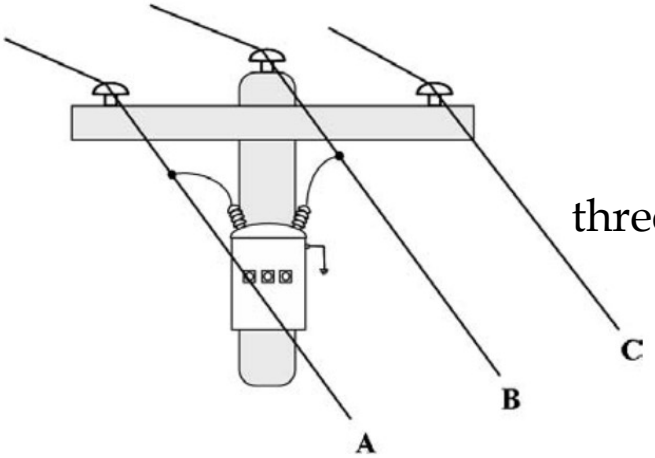
[Gonen]

Network-type primary system

Distribution lines



three-phase four-wire multi-grounded Y



three-phase Delta (under replacement)

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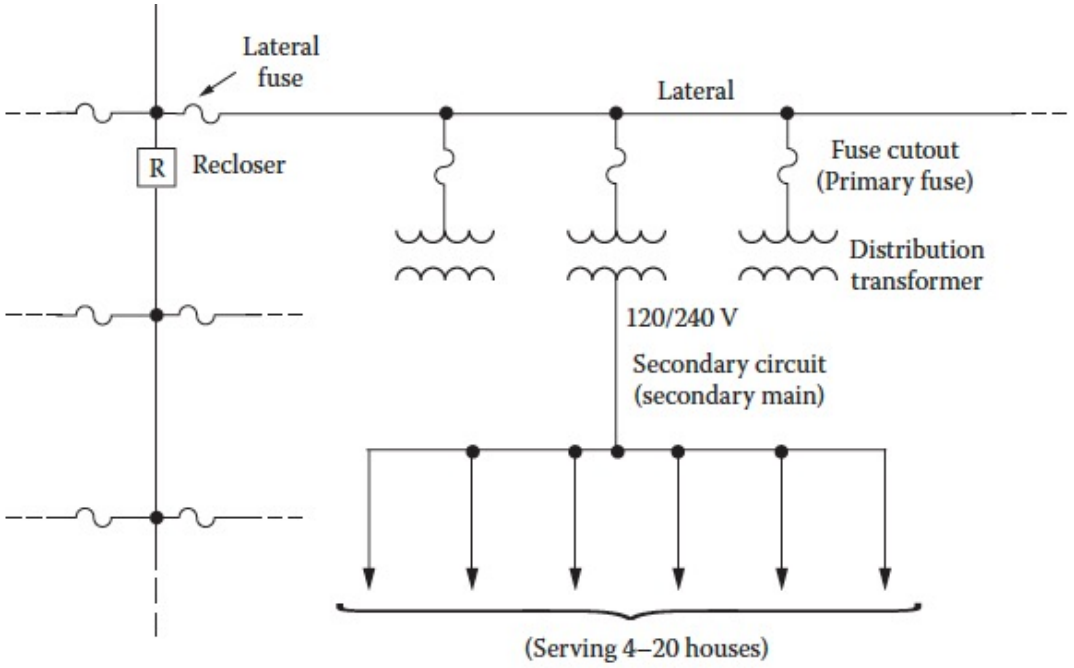
Secondary distribution network

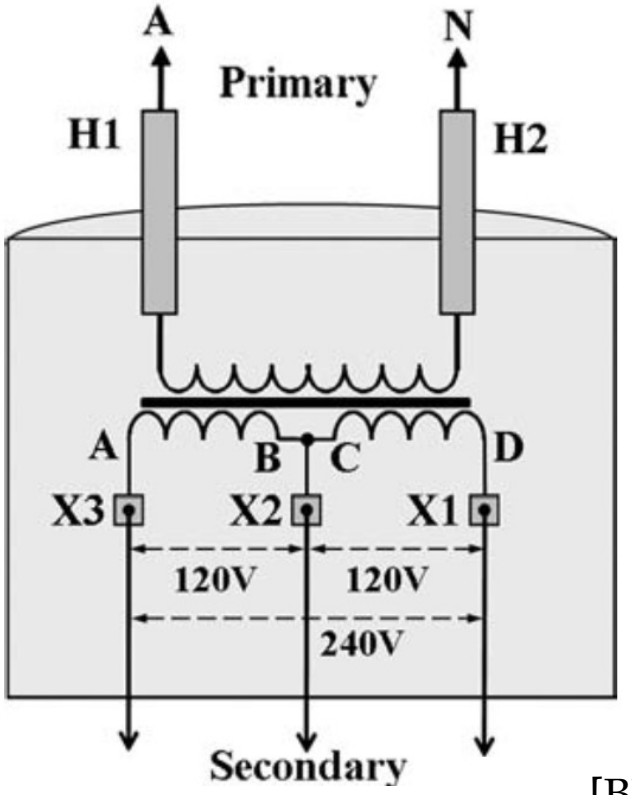
- Distribution XFMRs form the boundary between primary and secondary distribution



- Secondary distribution voltages

Voltage	# Phases	# Wires	Application
120/240 V	Single-phase	Three	Residential
208Y/120 V	Three-phase	Four	Residential/Commercial
480Y/277 V	Three-phase	Four	Commercial/Industrial/High Rise

240/120 V single-phase distribution transformers



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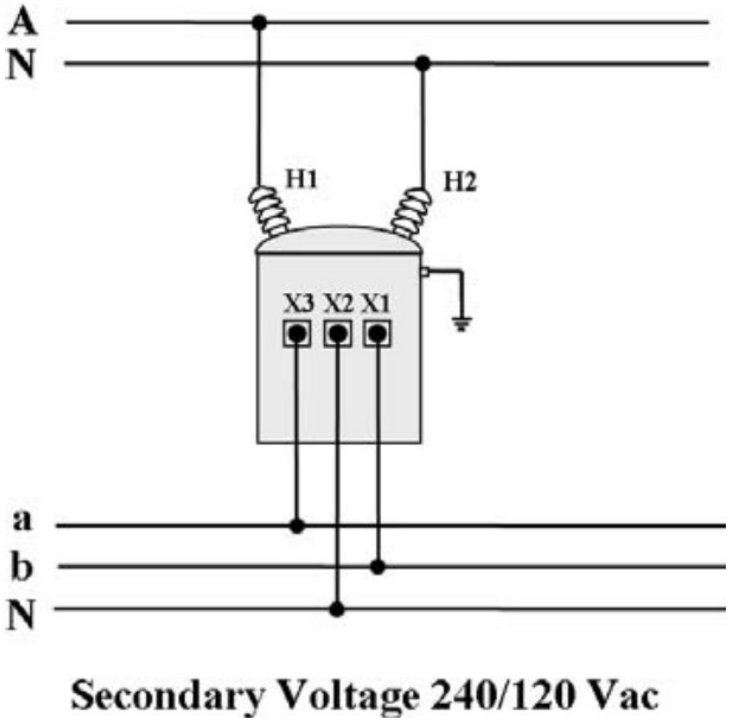

208/120 V three-phase distribution transformers

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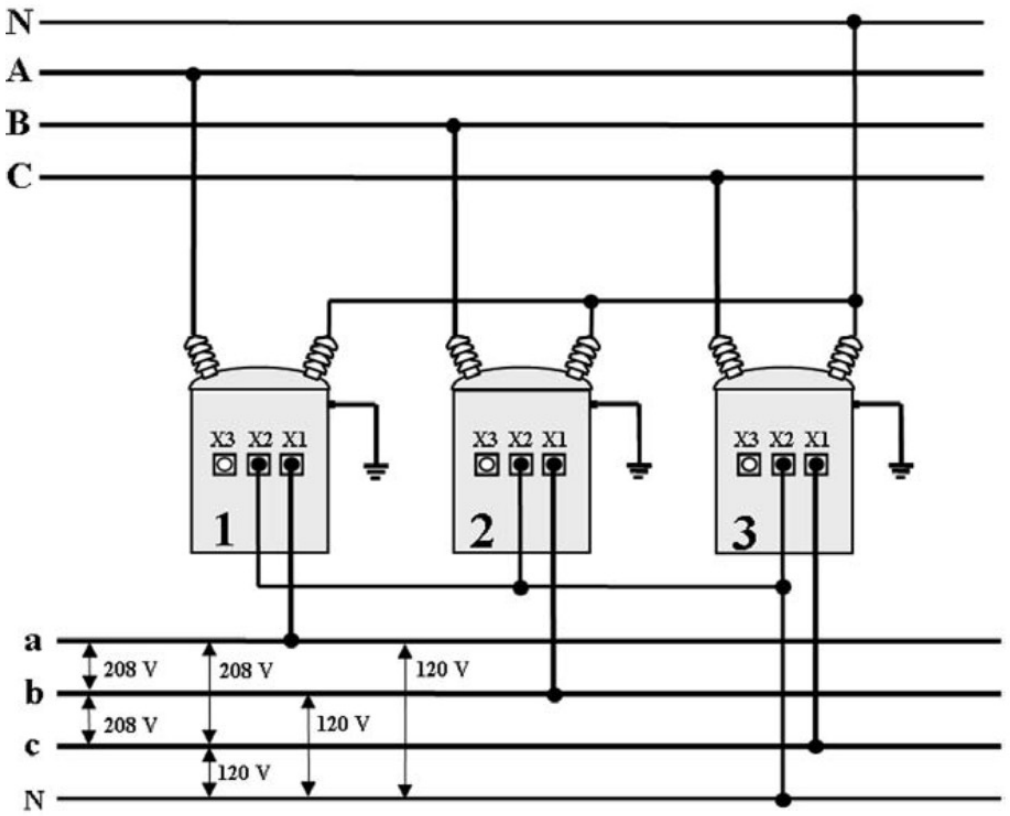
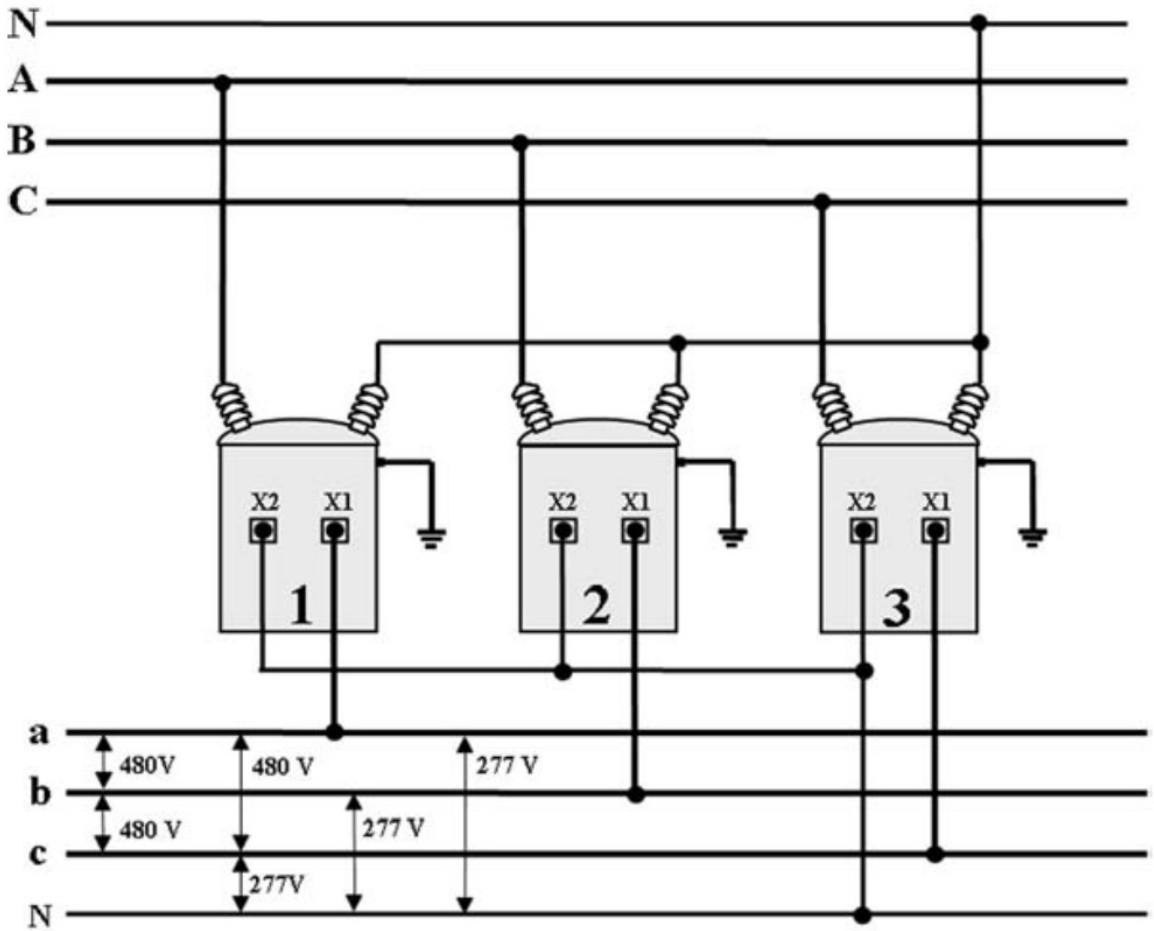


480/277 V three-phase distribution transformers



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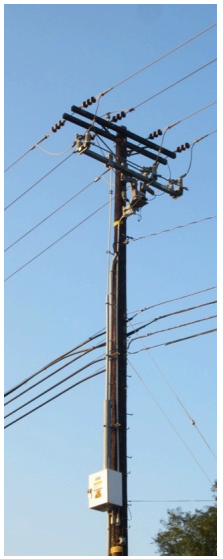
Small single-phase transformers provide 120 V from 480 V for lighting/office use

Switches and circuit breakers

Switches

- located at substation or feeder
- isolate equipment for maintenance or reconfigure feeders
- cannot interrupt faults
- manual or remote control



[K. Schneider]

[K. Schneider]

Circuit breakers

- similar to switches, but can break fault currents
- used for protection rather than switching
- located at substation (due to size and rating)

Fuses

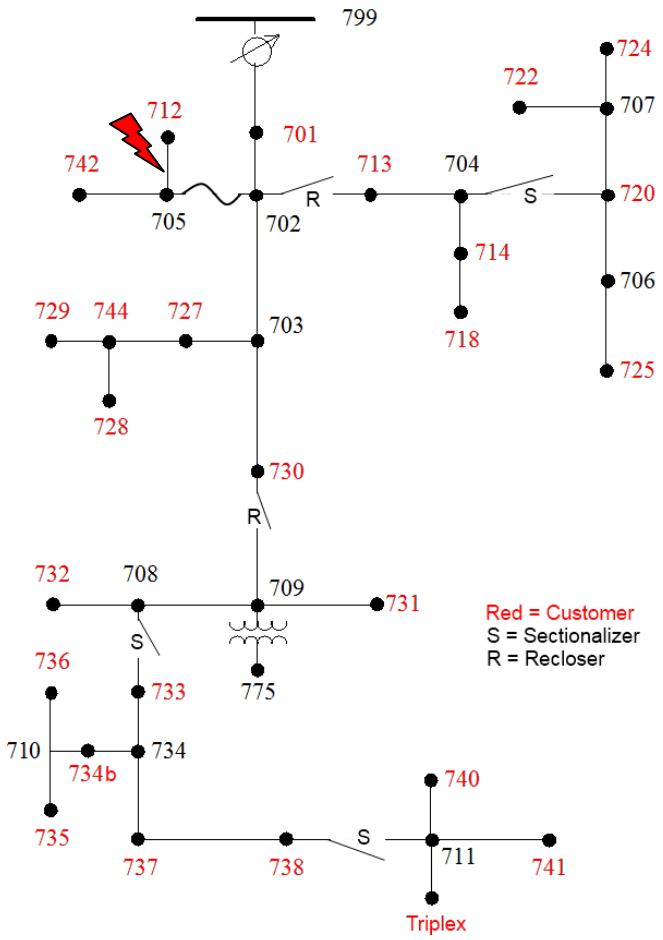
- Low-cost devices used to interrupt fault currents
- Once fuse interrupts overcurrent, it has to be manually replaced by a line crew
- *Fuse coordination*: the practice of selecting fuse sizes so that fuse closest to the fault blows first
- Fuse coordination requires knowledge of system load and gets complicated with distributed resources

Photo courtesy of K. Schneider

- Operate on an inverse time curve:
  the higher the fault current, the quicker the fuse will blow

Example of fuse protection

- Permanent line to ground fault on line 705-712
- Fuse blows due to overcurrent, thus isolating single-phase lateral
- Customers at 712 and 742 call in to report power outage
- Utility dispatches a line crew to investigate
- Line crew locates fault and repairs condition
- Line crew replaces blown fuse with a new one
- Single-phase lateral is back to service



Courtesy of K. Schneider

Protection relays

- Use local measurements to generate control signals
- Fuses measure only current; relays measure voltage and current so can also estimate
  - real and reactive power
  - sequence components
  - phasor measurements
- They can be accessed remotely for maintenance and updates

Courtesy of K. Schneider

Reclosers

- Designed to minimize number of customers affected by momentary fault
- Not needed in transmission or underground distribution systems

Courtesy of K. Schneider

Operation

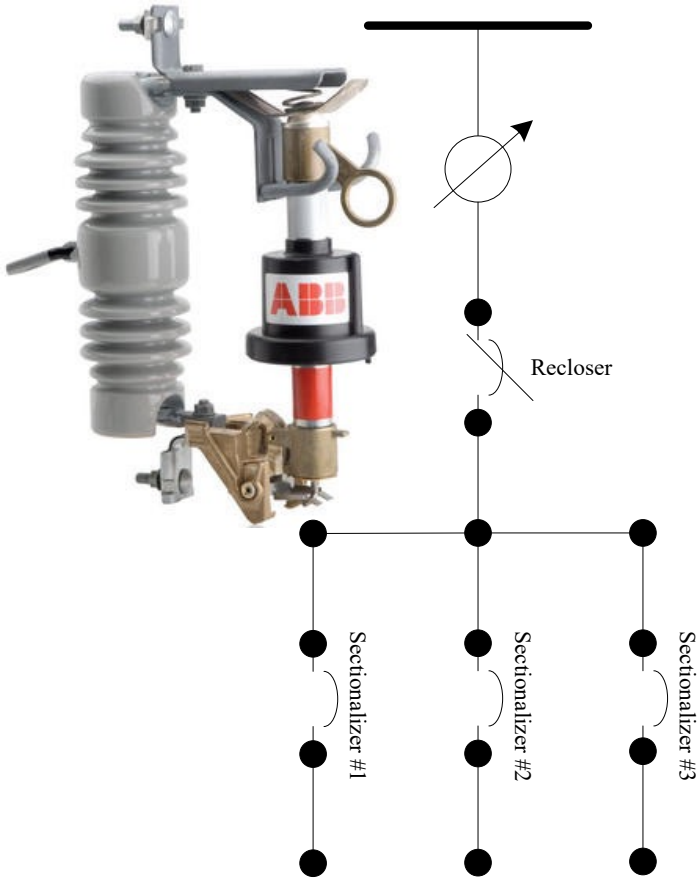
1. Fault occurs
2. Recloser interrupts fault current and remains open for a time period (1-2 sec) to allow momentary faults to clear
3. Recloser closes back into fault and sees if fault has cleared
4. If fault has cleared, recloser stays closed; otherwise, recloser reopens
5. Number of tries to reconnect is user-configurable (usually 3)
6. After final 'shot', recloser locks open
7. Utility crew must locally reset the unit

Sectionalizers

- Operate on local measurements and with proper coordination of upstream reclosers
- Combination of reclosers and sectionalizers is ideal for system with permanent and temporary faults

Operation

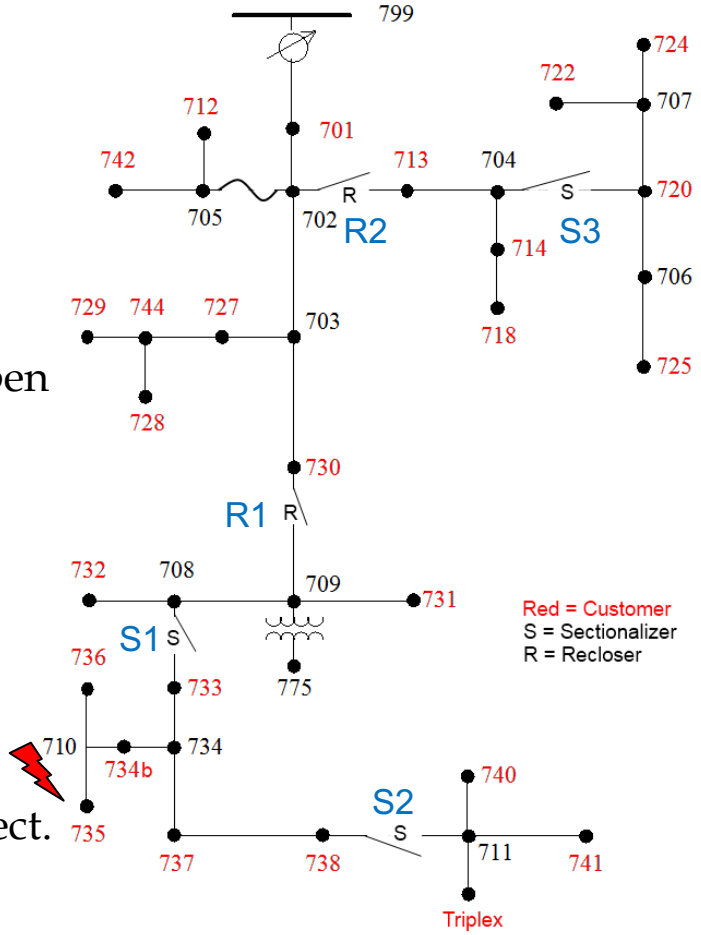
1. Sectionalizer detects overcurrent but cannot interrupt fault
2. It starts counting recloser shots
3. During the second/third recloser shots, the sectionalizer opens under no load



Courtesy of K. Schneider

Example of sectionalizer protection

- Permanent line to ground fault on line 710-735
- Overcurrent causes R1 to open
- S1 detects overcurrent and prepares to open
- S2 does not detect overcurrent
- R1 waits and closes back in; repeats 3x before locking open
- S1 opens on 3rd shot during no load
- R1 closes back in, sees no fault, and remains closed
- Customers downstream of 708 report power outage and utility dispatches line crew
- Line crew locates fault; repairs condition; and recloses sect.
- Lateral back to service

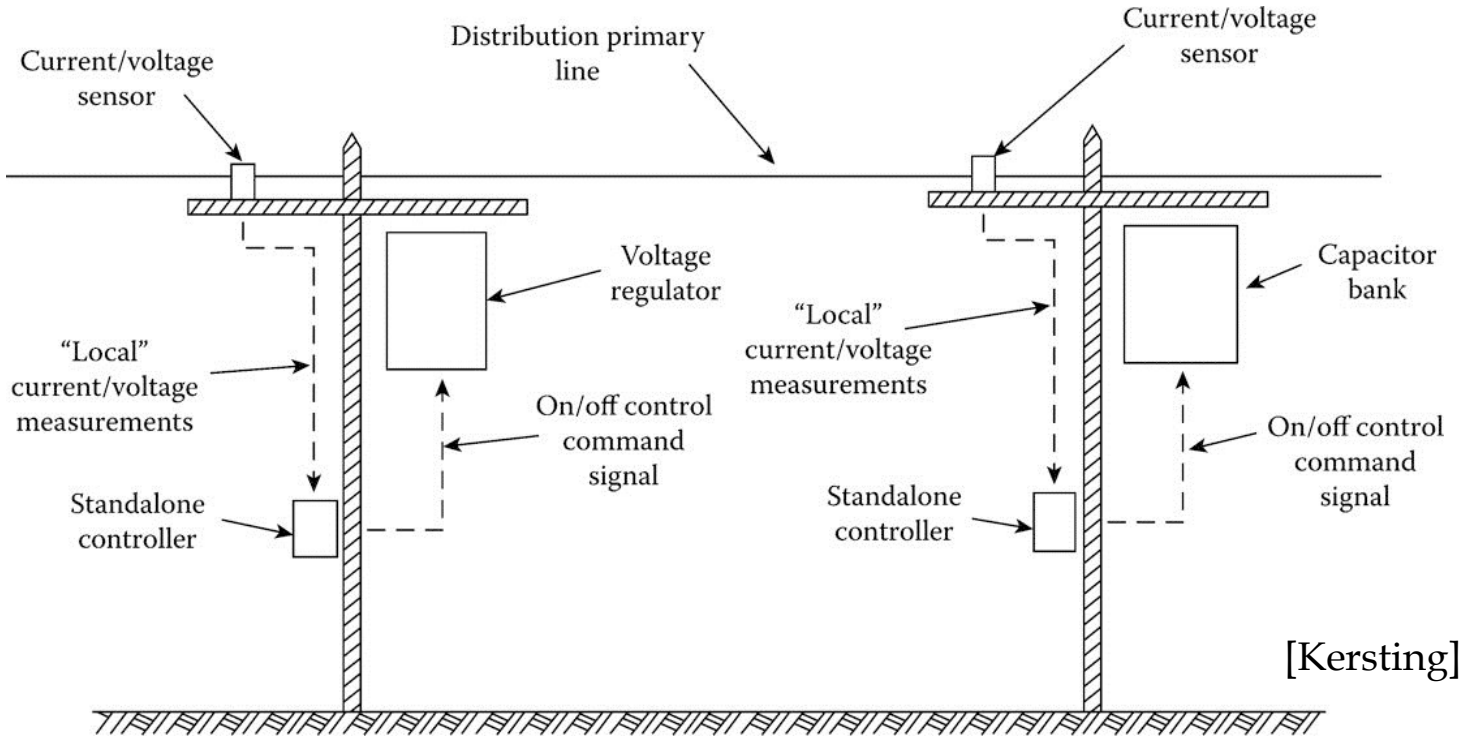


Courtesy of K. Schneider

What is the sequence for fault on 741?

Voltage regulation

- Voltage magnitude should lie within ±5% of nominal (114-126 V for 120 V)
- *Voltage regulators*: special transformers that change turns ratios depending on load conditions to maintain voltage on secondary side within range
- *Capacitors*: can switch on/off depending on load to regulate voltage via PF correction



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Voltage transformers

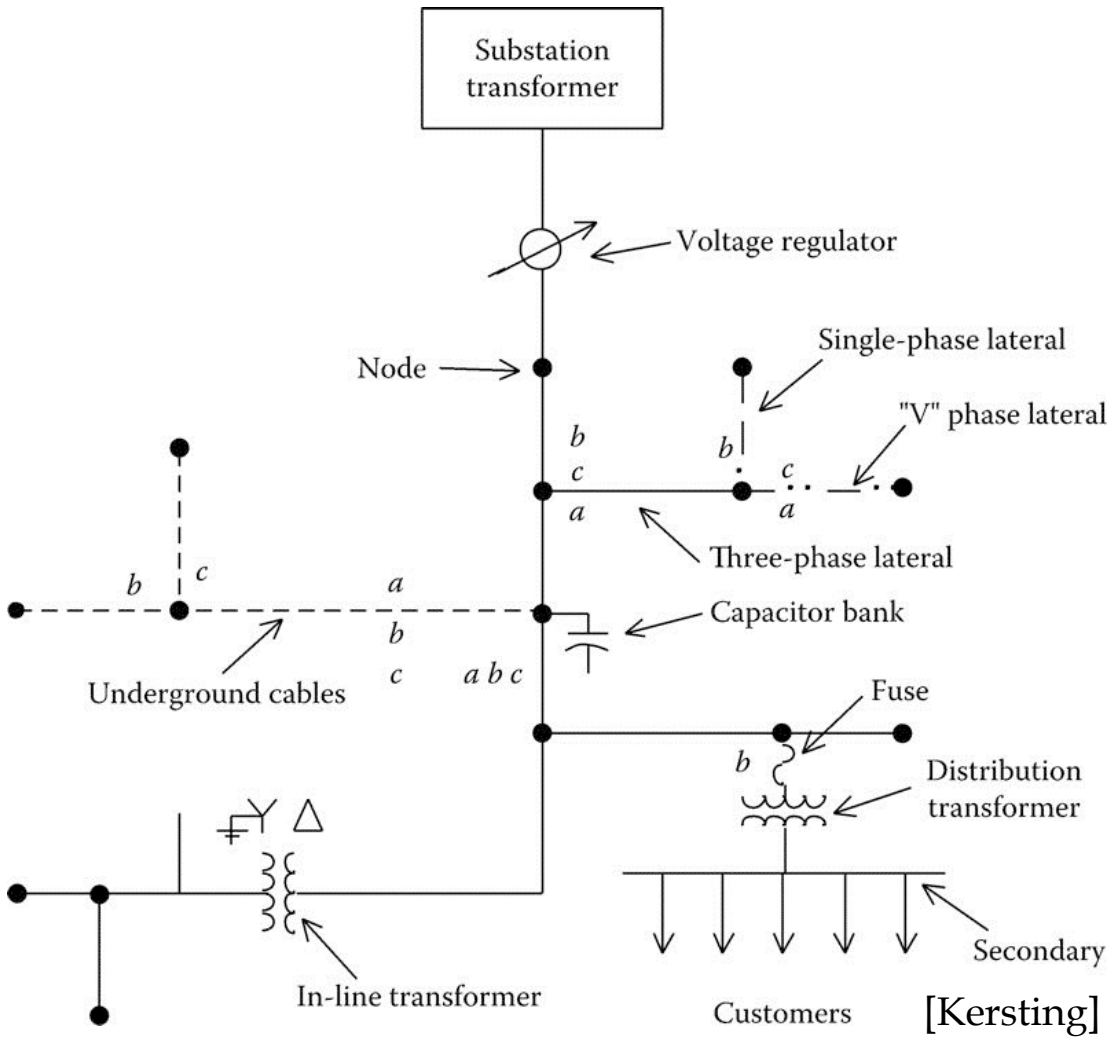
On-Load Tap-Changing (OLTC) transformer

- a.k.a. Tap Changing Under-Load Transf. (TCUL)
- located at the substation; can serve multiple feeders
- maintains constant low-voltage side under varying distribution load or transmission-side conditions
- can be substituted with transformer & regulator

In-line transformers and regulators

Distribution transformers

Radial feeders



[Kersting]

primary 'main' feeder:
2-30 MVA @ 2-34 kV

secondaries:
5-500 kVA @ 120-480 V

3, V, single-phase laterals

in-line transformers

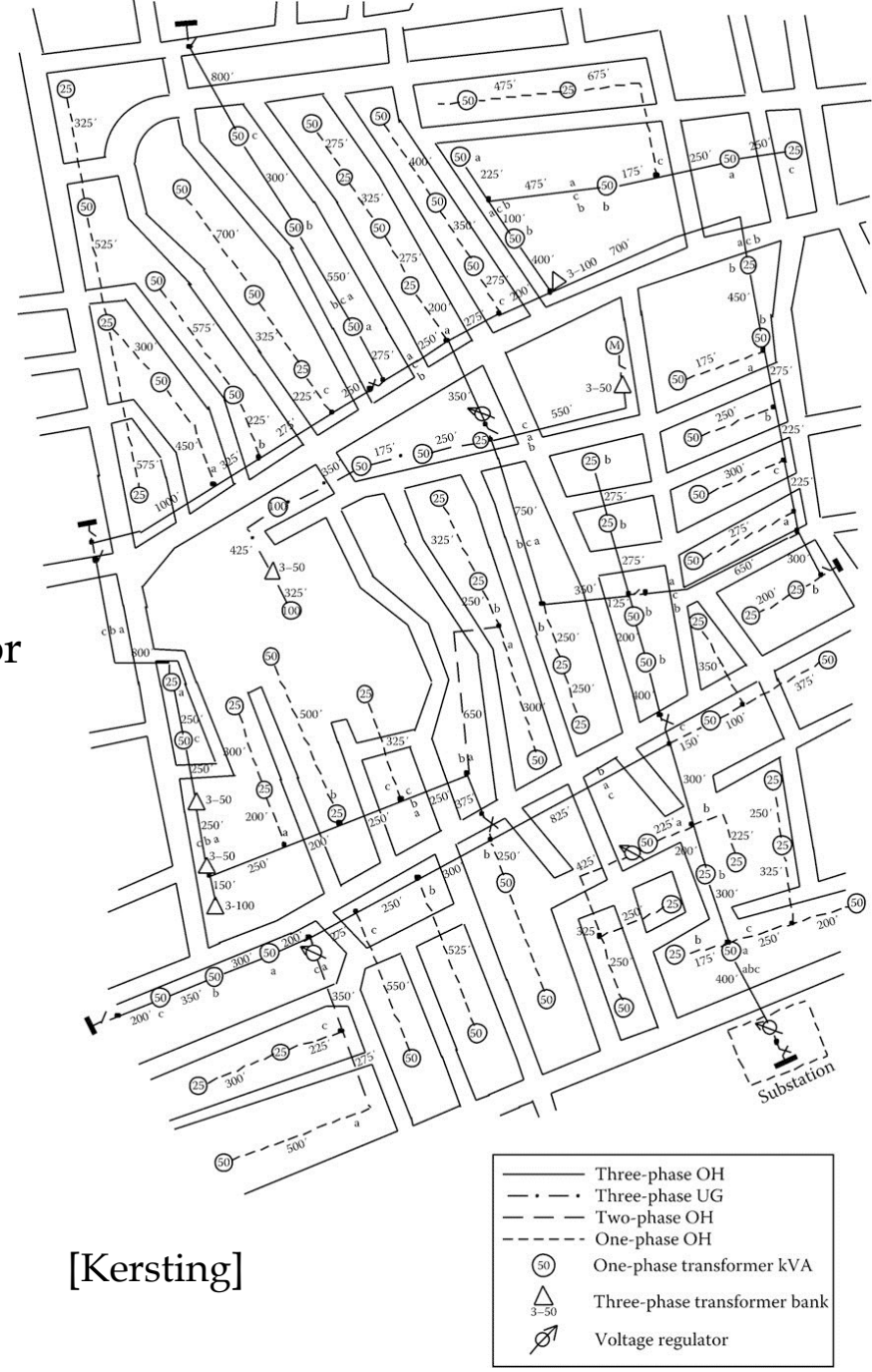
distribution transformers
240/120 V 1-phase (split-phase)
208/120 V 3-phase
480/277/120 V 3-phase
400/230 V 3-phase (Europe)

regulators and cap banks

protection devices

Distribution feeder map

- Transformers (kVA rating, connection)
- Shunt capacitors (kVAR rating, phase)
- Voltage regulators (phase, ratios, compensator settings)
- Lines (OH/UG, distance, conductor, phase)
- Switches (NO/NC)
- Geographical distances
- Conductors (radius, diameter, resistance)



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