# *Basic Distribution Engineering for Utility System Operations*

An Introduction to Electric Utility Distribution System Design and Safety Concepts

April 20, 2010
George Ello

# What We Will Discuss in the Context of Safety

- System Construction and “Threats” to Feeders / Feeder Faults
- Grounding
- Touch potentials
- Protective devices
- Fault clearing
- Voltage backfeed
- Voltage swells and lightning

# A Word on Safety

*Safety in all electric operations, for utility employees and the public at large, trumps other considerations.*

*Electric utility personnel perform both live-line work and work on 'dead' facilities. Live-line work requires principles of "insulate and isolate" to keep workers from dangers; assuring facilities are 'dead' requires the workers to work between grounds applied to the electric facilities being handled.*

# Radial Distribution Feeder Conceptualization

The Essential Distribution Feeder

# Electric Utility Distribution Systems At-A-Glance

- North America:
  - 80% of distribution is “13kv”
    - Standards are: 12.47, 13.2, 13.8, and 14.4kv
  - Some use higher: 23, 27, and 33kv distribution
    - Older standards are lower voltages (e.g., 4.16kv)

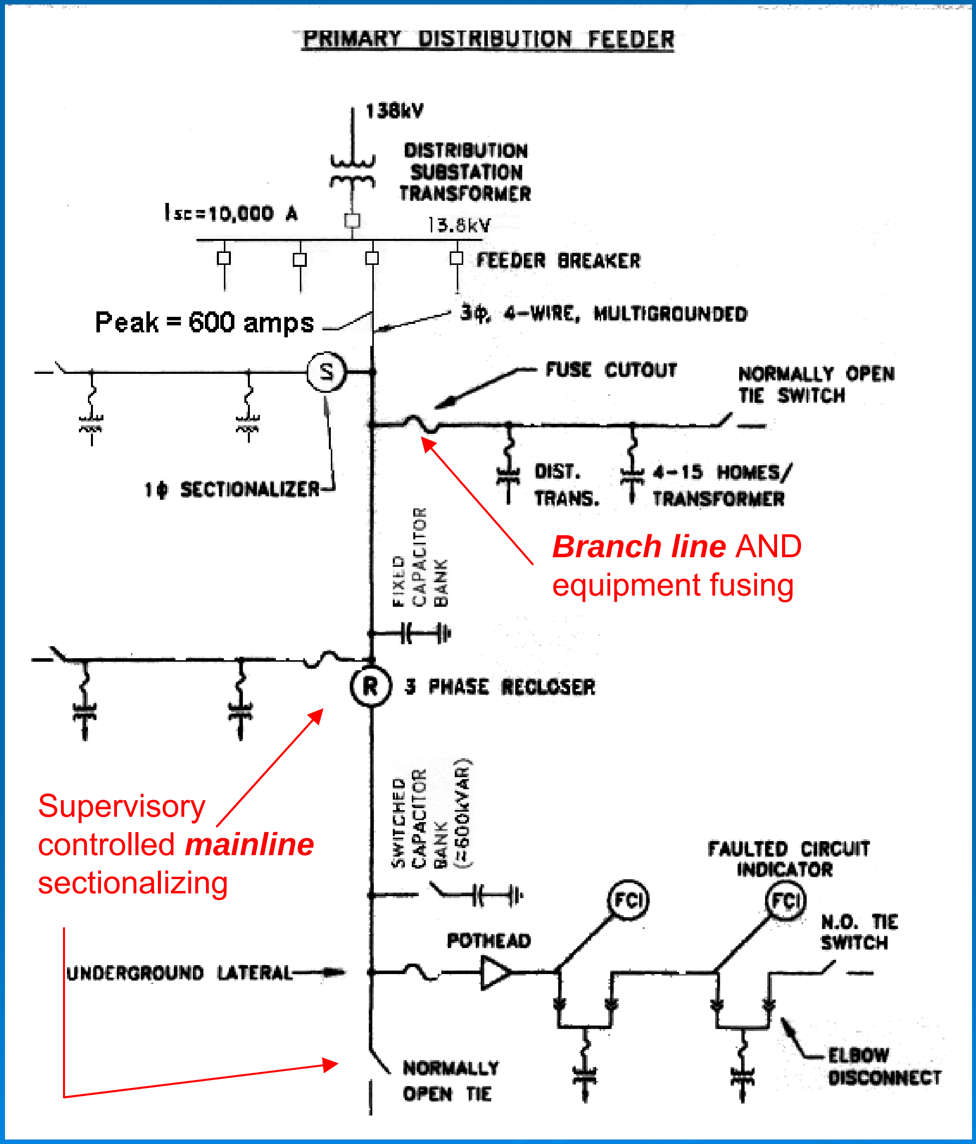
- One Local System
  - ~ 850 Feeders; 1,117,281 electric customers
  - ~<5% are all underground; Remainder are mostly overhead construction
  - >90% are 13kv; Remainder are 4kv

13kv: Up to ~4000 Electric Customers ~7MW

4kv: Up to ~1500 Electric Customers ~3MW

- Vast majority are wye-grounded

# "Normal" Distribution Design




The generic distribution feeder is one which is designed **radial** and with one supply source….the substation circuit breaker, and using fuses on most, if not all, branch taps.

Applying voltage sources elsewhere on the feeder works against this design and adequate protection to insinuate the other sources into the feeder are required.

# Threats to the Feeder

- Environmental conditions
  - Moisture intrusion damage (connectors)
  - Mechanical damage (dig in, car hit, people stunts)
  - Tree intrusion
  - Wildlife intrusion
- Weather (violent)
  - Wind (more trees into wires, wire stress)
  - Lightning
  - Ambient heat (“summer heat waves”)
- Electrical
  - Equipment failures (switches, transformers, communications)
  - Overload; carrying fault current at times
- Simple Age and Deterioration
  - Splice failures (“nothing lasts forever”)
  - Equipment failures (transformers, switches, lightning arresters, poles, cable)
- System Operations Consequences
  - Switching transients
  - Out of phase conditions
  - Emergency switching (point emergencies, pre-emergencies, load relief, construction prep)
- Anything else you can imagine

# Answers to Threats to the Feeder

- Design
  - Grounding (for fault clearing)
    - Wye-grounded distribution
    - Multi-grounded
    - NEC fold in
  - Contingency capabilities – capacity
  - VAR control (capacitance control)
- Fault Clearing
  - Voltage stability goals
  - Circuit breakers
  - Fusing ("the more fuses the better") – fault isolation
- Automated Feeder Restoration

# Customers, and Feeder Threats

- There is no guarantee of uninterruptible power.
- Momentary interruptions are a critical feature of fault clearing.
- Automatic and Supervisory re-closing is a standard practice.
- Voltage regulation issues may take time to resolve.
- Electrical protective devices protect property, but are not designed specifically for the protection of people.
- A utility's reliability statistics speak for themselves. (The bottom line)

# Distribution System Grounding

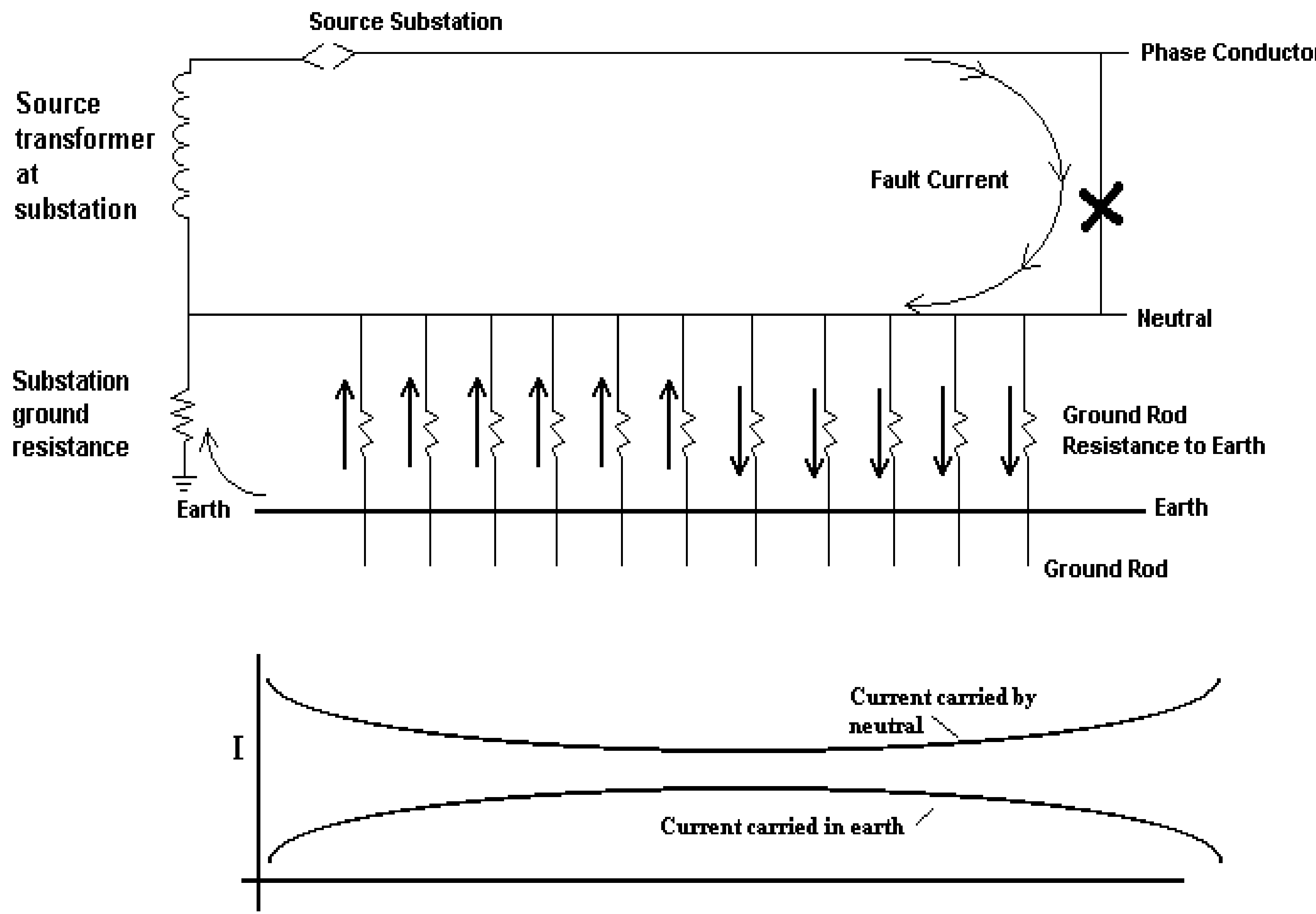
# Distribution System Grounding

- A discussion on grounding is critical when discussing utility distribution systems because:
  - Utility distribution systems are subject to a variety of stressors which result in electrical "faults."
  - "Better" grounding enables "better" fault detection.
  - Good fault detection enables successful fault clearing, which limits outages.
  - Better grounding can lead to voltage swells on unfaulted phases during phase-to-ground faults.
- Grounding generally falls into 3 categories:
  - Multi-point Grounded Systems
  - Single point Grounded Systems
  - Ungrounded Systems
- Primary fault clearing, when the fault is phase to earth, is unlikely to de-energize the phase in an ungrounded system.
- Primary distribution seldom plays a role in electrical fire events involving building structures, but secondary systems may play a critical role.
- At various points (usually many) on utility systems using multi-point grounding, the neutral and various pieces of equipment (switches, guy wires, etc.) are tied to earth through ground rods.
- Utility neutral and grounds are the same.
- By installing grounds, the ground system becomes the destination for all electric currents. Safety impacts include risk to people if they contact both ground and energized facilities.

# Distribution System Grounding

- Low ground rod resistance to earth is a good thing.
  - Corollary: Low ground rod resistance is usually very difficult to achieve (especially on Long island).

- Ground Rod Resistance Affected by:
  - **Soil resistivity**
  - **Ground rod diameter (not too much)**
  - **Ground rod length (depth)**
  - **Parallel rods**

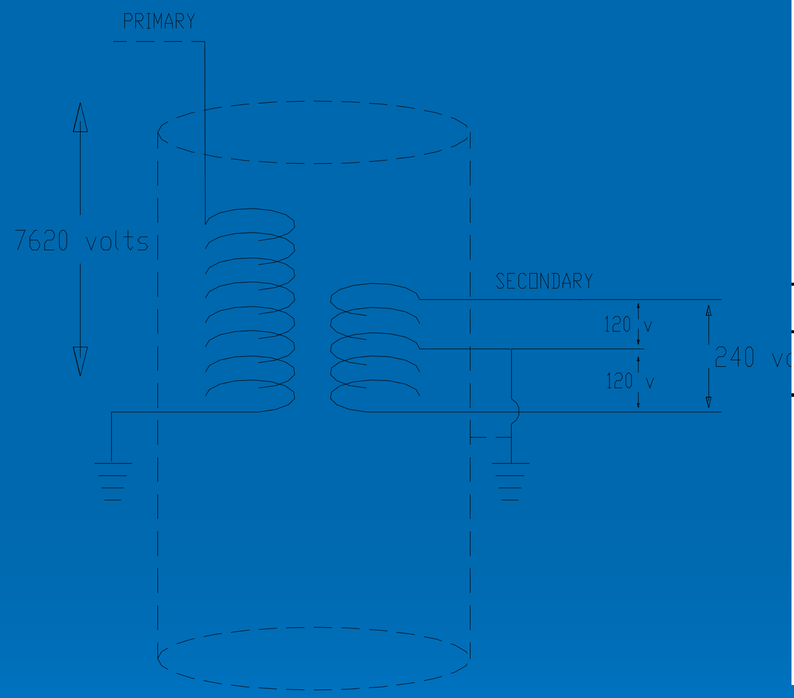


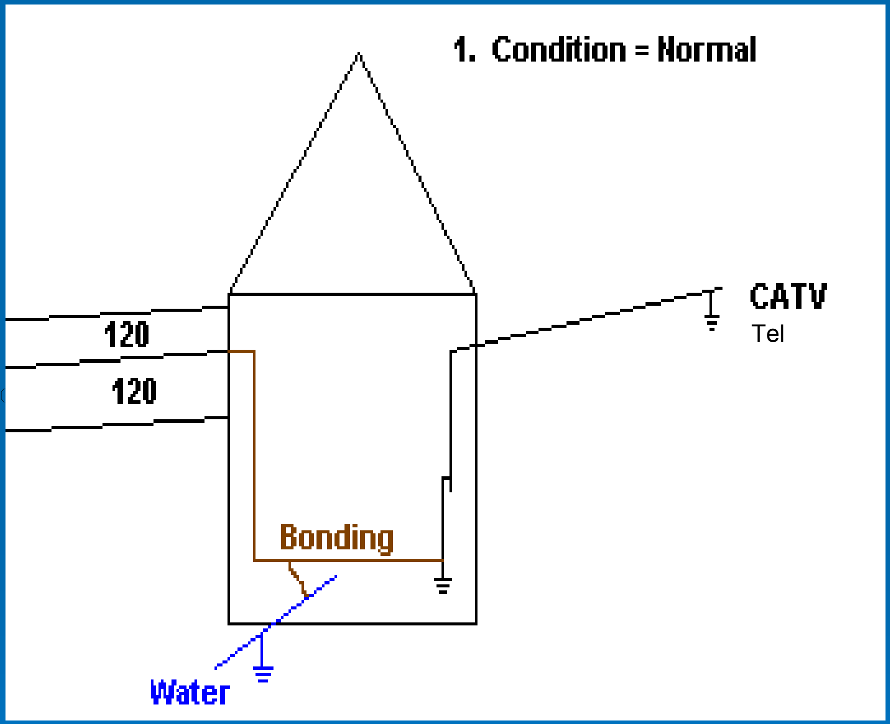
Source Substation
Phase Conductor
Source transformer at substation
Fault Current
Neutral
Substation ground resistance
Ground Rod Resistance to Earth
Earth
Earth
Ground Rod
I
Current carried by neutral
Current carried in earth

# Grounding on Secondary Systems

(This involves the building)

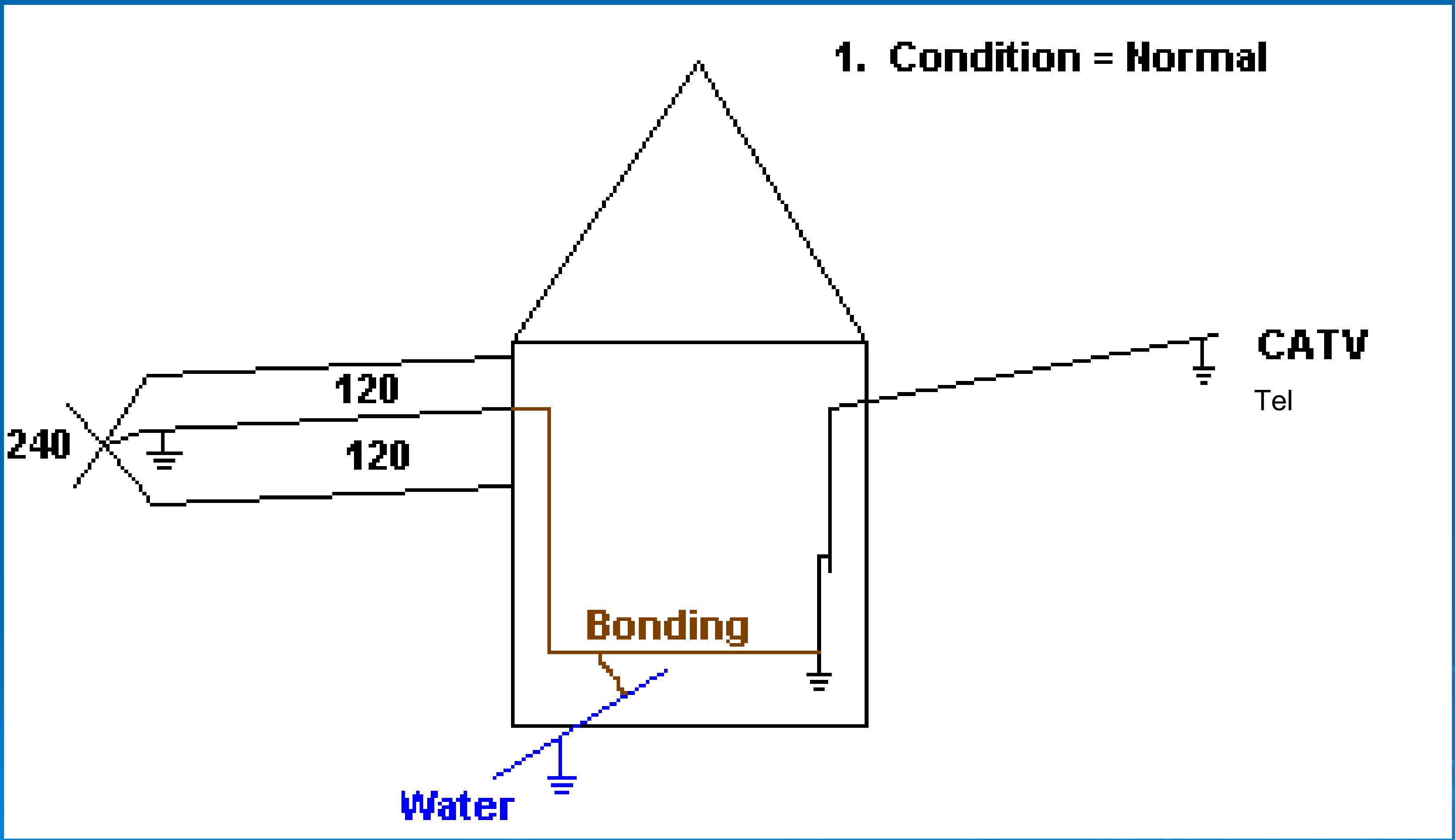
# Grounding on Secondary Systems




Such split-phase electric supply requires a well-connected neutral system. Inside buildings, per NEC, neutral and ground systems are isolated.

# Grounding on Secondary Systems



# Grounding on Secondary Systems

- A 100% metallic "city" water system is an excellent ground system with multiple ground points. <u>Under **normal** conditions, it might carry up to 50% of house load return current</u>. Smaller fractions of current will use CATV and Tel paths.
- "*Appreciable*" current levels on other utilities should prompt the electric utility to check its secondary neutral connections.

# Safety: Step & Touch Potentials

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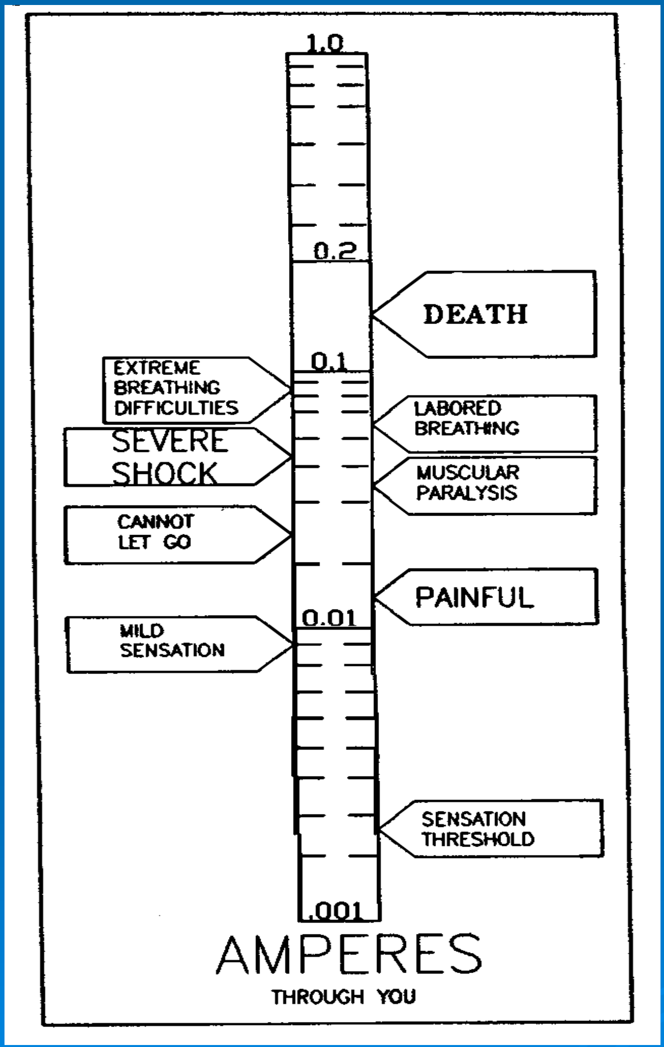



**Touch Voltage**: Caused when one part of the body touches the earth (feet, usually) and another (hand, usually) touches a piece of grounded equipment at a different potential.

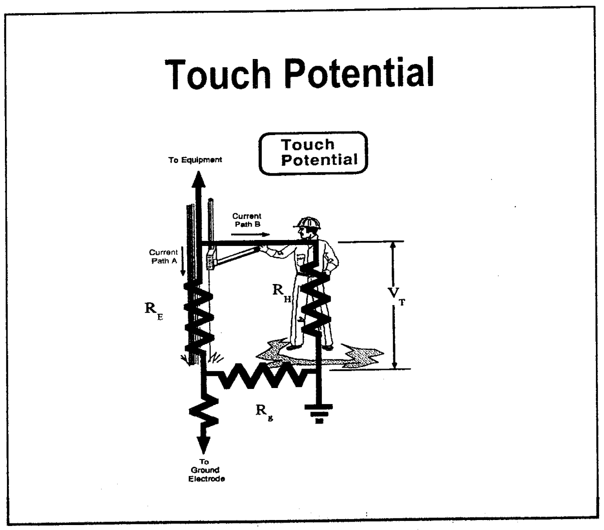
**Step Voltage**: Caused by a potential difference between two locations on the earth, spanned by the feet, and current flows through the body via the legs.

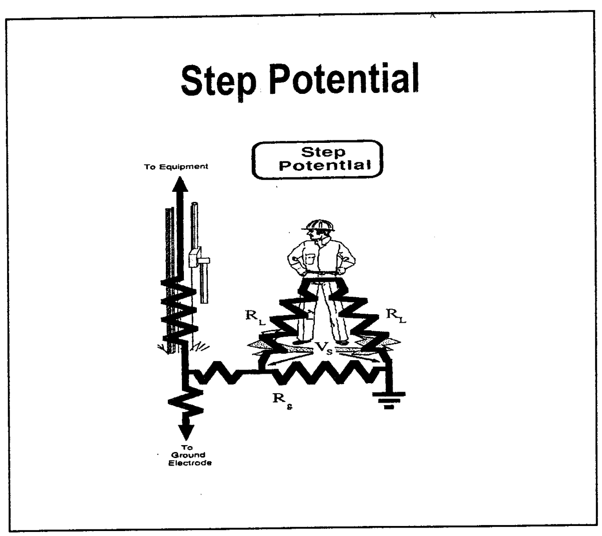
**By the way, not much current is required for cardiac injury.**

It is generally accepted that 5 milliamperes (.005 amperes) through the heart can put the cardiac muscle into ventricular fibrillation (V-fib). V-fib is a condition wherein cardiac muscle cells still "beat" but not in unison anymore. The random cell contractions result in a net pumping capacity of zero.

It is possible that another jolt of current will "reset" the cells to resume beating in unison (De-fibrillation), but this is not guaranteed. You have about 5 minutes to de-fibrillate until hypoxia (low blood oxygen) permanently damages brain tissue.

# Safety: Step & Touch Potentials




An effective way to address these concerns, i.e., to make such voltages as low as possible, is to construct a ground mesh, or tight knit grid, bonded to the ground conductor, and on or near the surface.  Standing on this conductive ground places the standee at the same potential of the device, or bridges the feet, resulting in equi-potential.

That said, such equi-potential grounding is the best way to minimize but not eliminate electric shock danger scenarios.

# Safety: Step & Touch Potentials

- A low ground resistance is not a guarantee of safety.
- There is no simple relationship between the resistance of the system grounding and the maximum shock current a person might be exposed to.
- A substation with a low ground resistance might be dangerous, and vice-versa.
- Lastly, related shock accidents/incidents can be caused by:
  - High fault current to the area of the grounding system
  - High potential gradients caused by earth resistivity and high currents
  - A person bridging 2 points of high potential difference
  - Absence of sufficient contact resistance
  - Duration of the fault.

# Safety: Step & Touch Potentials

- The worst situation to be in while exposed in a lightning storm is to be grounded (and at an altitude). Or, for that matter, while in proximity to primary or other high voltage apparatus.

- Sometimes for Step, but definitely for Touch potentials, it can be a good thing to be very wet in some circumstances. In such a case, electric current can flow through the moisture on the outside of the body, resulting in less current flow through the body and therefore somewhat greater safety in a bad electrical situation. (But, don't bet on it.)

# Faults On Primary and Secondary Systems

……….And Fault Clearing

# What is a Fault?

- A “fault,” in utility terms, is a problem with any energized conductor that either falls, fails in service, or is touched by a foreign entity.  It is not necessarily a “short circuit,” but can be.
  - Is a wire down a fault?
  - Flashover – high heat generation from arc in a gas (air) plasma
  - Animal/tree contact
- Faults are either transient or permanent.
- Whether a fault exists is independent of whether high fault current flows.

# Faults

- Available fault current levels are rarely reached.
- Actual fault current values are dependent upon the impedance of the fault.
- It is BEST to characterize fault impedances as either “high” or “low.”
- The tap wire length to transformers (and other distribution equipment) should be as short as possible.  Long lead lengths have higher impedance values and, when fault current flows through them (say, to a lightning arrester), the voltage built up by the impedance severely limits fault current flow.  This could inhibit the effectiveness of fault clearing.

# Primary System Faults

- Permanent vs. Transient
- Overhead vs. Underground
- Arc (on non-bolted faults) maintains the fault
- Fault-clearing is dependent upon high current levels
- An Arc is a low-current, high-heat event in which the current path is ionized air
- Core arc temperatures approach $9000^{o}F$

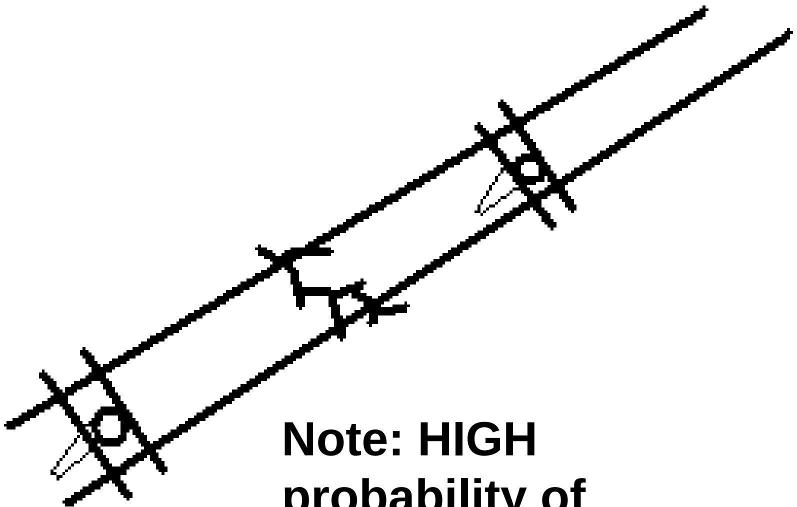
Think of all faults as being either high resistance or low resistance.

# Typical Primary System Faults

- Result in phase to ground or phase to phase faults; sometimes, result in simple loss of a phase with no fault current.
- Wires burn down due to flashover and tree contacts, as well as mechanical damage.
    - Electrically, bare conductors burn down less often than covered conductors since a bare conductor will allow a traveling arc to proceed down the line until it elongates and extinguishes. If such an arc encounters insulated wire covering, it stops but still burns and may burn through the conductor. So, conductor thickness plays a role in burn down events also.
- Connector failure
- Flashover
    - Flashover is a temporary conduction from any phase to another, or to ground.
    - Usually induced by another fault: Something contacts phase to phase or phase to ground, or lightning.
- Equipment failure

If a primary wire comes down, what are the chances it will end up dead?

50% falls hot x 50% fault clearing success = 25% chance it is dead



Note: HIGH probability of flashover.

**Tree Limb on Phases:**

- Electric current through limb dries it out and, therefore, the amount of current through the limb goes down, i.e., the limb's conductivity is reduced.

- As the limb carbonizes, its conductivity rises and carbon tracking occurs.

- This is usually not fault current....the limb burns clear (self-trims)....or,

- The heat of the current flow at the wire-limb contact resistance may cause the wire to burn down.

# Primary System Faults: Flashover

- Flashover is a conduction through air between phases or from phase to ground. They can be cleared, or self clear, or become "better" or "worse."
- Some things that affect flashover probability:
  - **Feeder geometry:** Greater distances between phases is a good thing. Close proximity of phases or phases to neutral/ground raises the probability of flashover in any given event.
  - **Pole BIL:**
    - Wood has good BIL, about 75kv/ft. dry and about half that wet
    - Metal cross arm braces tend to short out BIL
    - Guy wire placement can short out wood BIL also
    - 8' wood crossarms are better than 4' wood crossarms, which are better than armless construction.
  - Pole arrester location and rating

# Primary System Faults:  Flashover

# Transformer Failures

- Most utility transformers are oil filled.
- Internal intermittent arcs on coils can point-boil oil, evolving gases in the tank. Gases include hydrogen and acetylene. Failure can be violent.
- Environmental (oil, oil additives, burning by-products)

# Primary Fault Clearing

# Primary Fault Clearing

- Distribution protective devices have, as their main purpose, the isolation of system damage for purposes of protecting utility equipment. <u>Their main function is not personal safety</u> of either utility workers or the general public, though clearing of the fault if successful lends to overall safety.

# Primary Fault Clearing: Fuses

- Fuses are the most wide-spread and the most consistently reliable form of line protection in use today.  They are cost-effective, and can remain in service for many years without operating, yet still function when needed.
- Fuses are either expulsion fuses or current limiting fuses.  (Current limiting fuses are used on the output of 277/480Y network protectors.)

# Primary Fault Clearing: Fuses

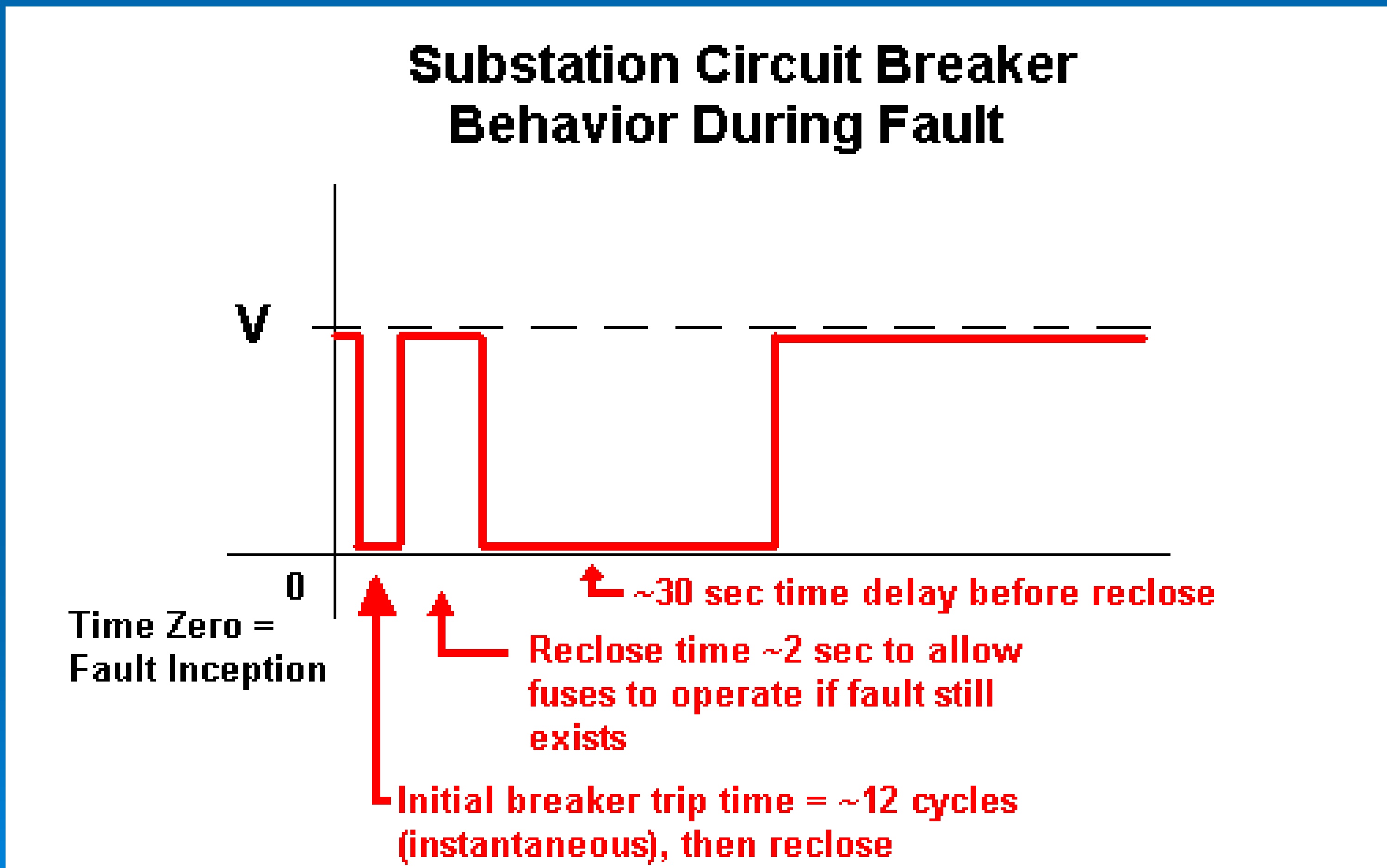
- Fuses must be coordinated to each other if in series, as well as being coordinated to the substation circuit breaker.

- Greater fault current clears the fault faster but makes fuse coordination somewhat more difficult.
  - The 100T and 65T “cross” at 4000 amps…..At 4000 amps, the 65T will not necessarily clear the fault before the 100T

# Primary Fault Clearing: Substation Circuit Breakers

- **"Quickly"** clearing faults on the main line prevents outages and wire burn downs. Quickly clearing faults on fused taps not only saves the fuse, where possible, preventing a field repair, but prevents branch line outages. The substation circuit breaker serves a critical role in this fault clearing process.

# Primary Fault Clearing: Substation Circuit Breakers




utilities
eral
han
lock-out.

# Primary Fault Clearing: Substation Circuit Breakers

- 600A rating at 13kv
- “Typical fault current ~1800A
  - Fault current could range from ~8kA near the substation to <1kA further out on the feeder
  - Power dissipation in millions of watts
- Older, electromechanical relays in the breakers coordinate so the breaker at first is faster than an intervening fuse, then slower. Attempts to save the fuse.
- Digital relays are both faster, more controllable (down to cycles), more consistent, and programmable. If fault current is very high, the breaker can allow a fuse to blow, saving the momentary interruption. At lower fault current levels, can attempt to save the fuse.

# Primary Fault Clearing: ASUs

ASU (Automatic Sectionalizing Unit)

- 600 Amp Continuous
- Senses fault (Over-current and loss of voltage) on Main line (load side wire)
- Allows substation breaker to trip to clear the fault on the instantaneous (allowing for fuse operation), yet prevents lockout for faults downstream of the ASU.
- Before the third trip of the substation breaker, the ASU will open
  - Isolates fault side customers
  - Keeps customers on line side energized
  - Does not reclose automatically after fault; can be restored w/supervisory controls

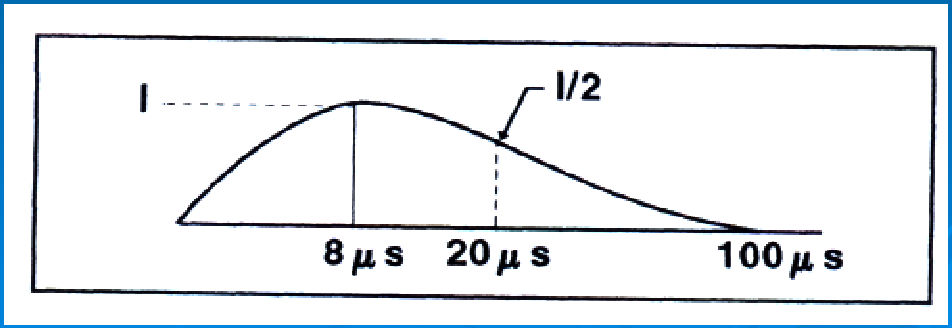
From DPE

# Upshot:

- Reclosing, either automatic or manual through supervisory control, is critical to proper and prudent electric utility operations.

# Primary Fault Clearing: Lightning Arresters

- Lightning is very fast
- About half are multiple strokes
- A lightning hit directly onto an arrester will fail the arrester.
- It has less energy than you may think because of its short duration
  - Average duration is 43 μs (microseconds, = $10^{-6}$ seconds)
  - Most are less than a couple of hundred microseconds
- In 90% of cases, the earth is positively charged, and the cloud is negatively charged.
- Velocity is about 100 ft/μs
- Duration is from 1/1500sec (high current, short duration, explosive effects without much burning) to 1/50 sec (less current, more burning, melting, etc.)
- 70% of lightning >30 ka
  - Industry standard is a 10 ka stroke – what we design for:



# How Primary Faults Affect Other Voltages

- Voltage Backfeed
  - Backfeed onto the “dead” phase
- Voltage Swells
  - Voltage rise on unfaulted phases

# Voltage “Backfeed”

# Voltage “Backfeed”

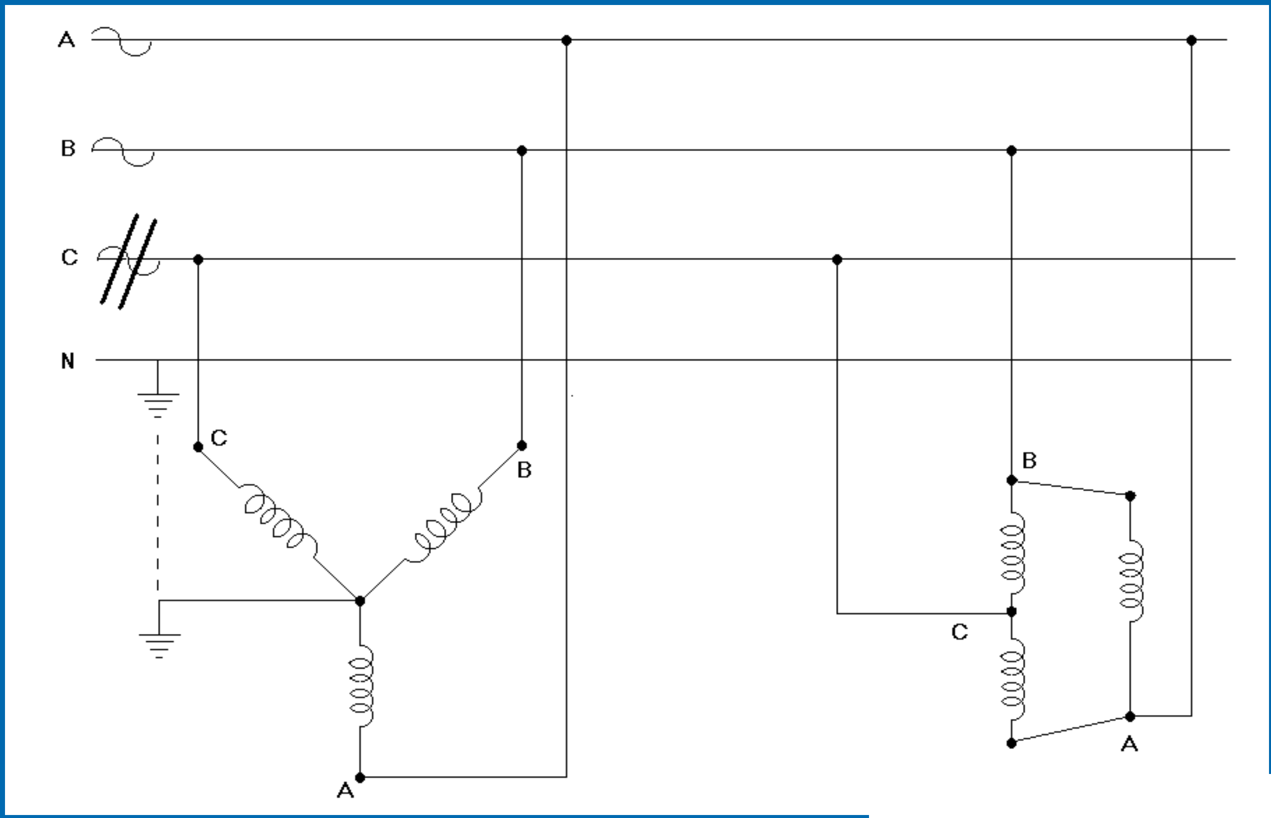
- The induced voltage when the normal source has been interrupted
- These risks are addressed by work methods and safety practices. The most important of these are: Apply grounds before working on facilities, work between grounds, and use high voltage tools and rubber protection appropriately.
- In no other situation is it more true than in backfeed situations: *If it’s not grounded, it’s not dead!*

# Voltage "Backfeed"

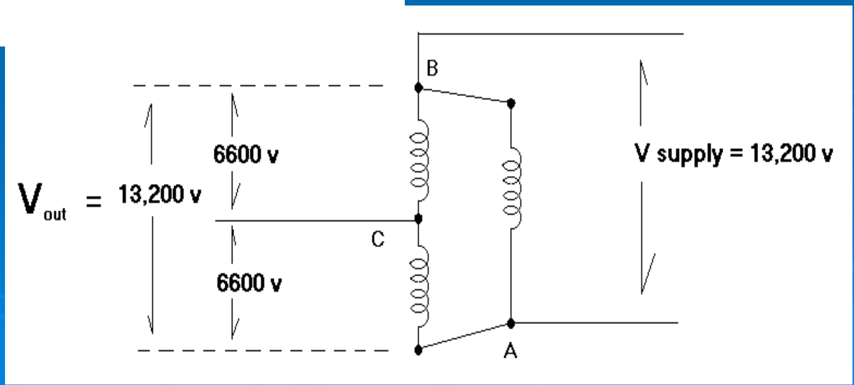
Three common sources of voltage backfeed aside from erroneous customer generation include:

- **Backfeed involving network transformers**: If a network protector on a transformer remains closed when a primary feeder is de-energized, the energized network secondary will backfeed the de-energized circuit.
- **Backfeed involving delta primary connections** on feeders: One of the more common sources of backfeed results from a delta connection on a grounded-wye circuit. This backfeed has appreciable power and will readily feed customer loads (though with improper voltage).
- **Backfeed when 3-phase transformers, all with Y-grounded 5-legged-core primary coils, exist and a phase becomes de-energized but not solidly grounded (a high resistance fault)**. This backfeed voltage is induced by the magnetic flux currents in the transformer ferrous core (which is common to all 3 the phases). The capacitance of underground cable usually plays a key role in the LC circuit resulting in the backfeed. This backfeed voltage can be quite high, higher than the normal phase-to-ground voltage, but has little power behind it: The voltage will collapse when grounded, with a bolted fault current of under 10 amperes.

# Voltage "Backfeed"

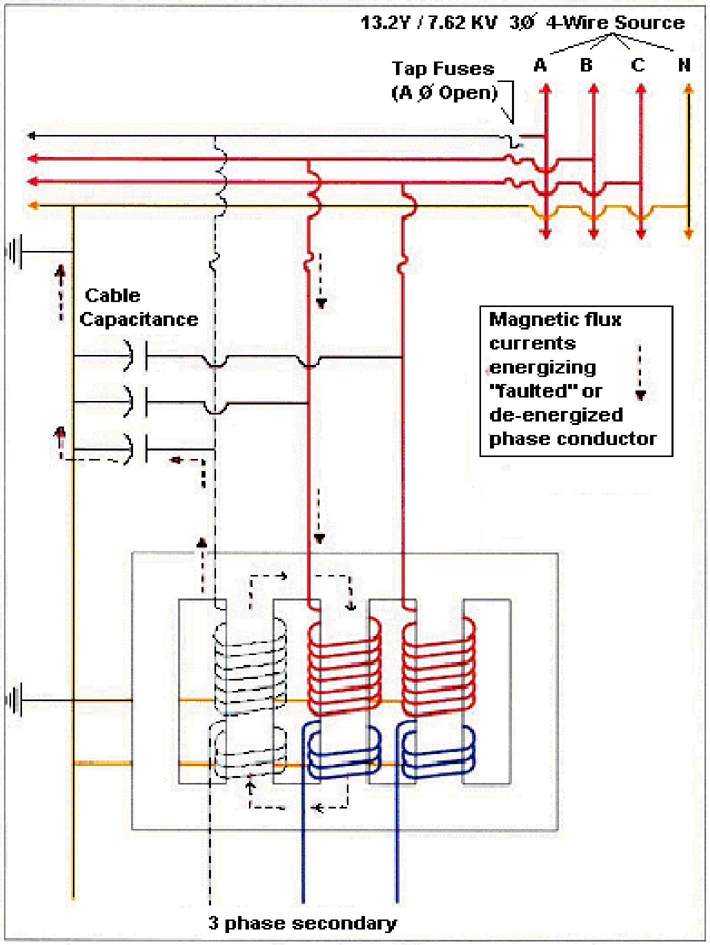



Backfeed from a Delta Connection

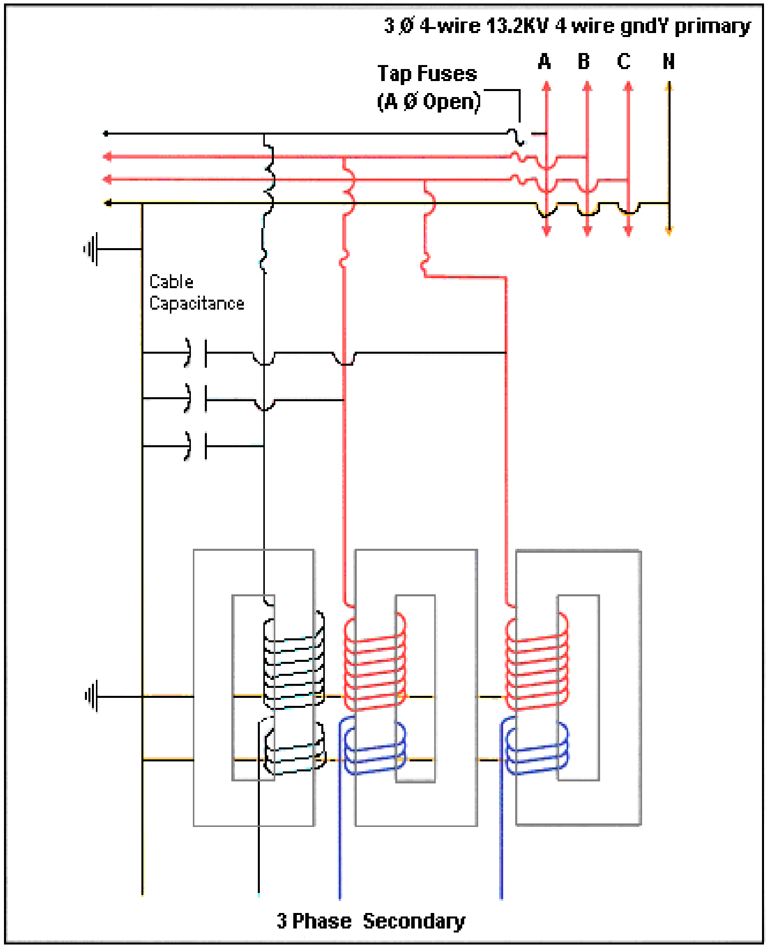


# Voltage "Backfeed"

## Backfeed on Wye-Grounded Systems




Primary side ferroresonance between cable capacitance and stray flux in a grounded wye -- grounded wye transformer.



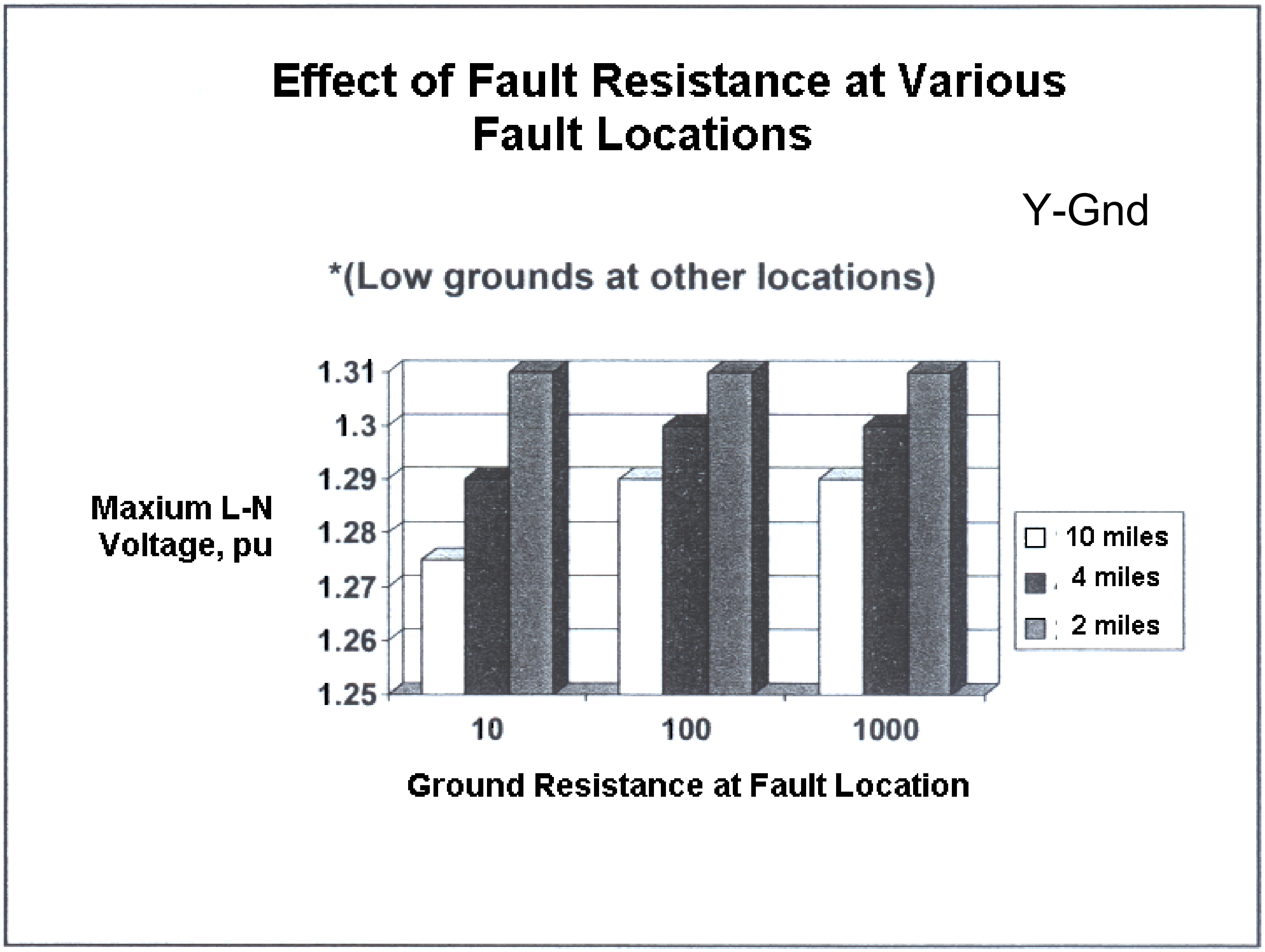

3 Phase primary grounded wye -- grounded wye triplex core transformer, with no ferroresonance induced in the dead phase (no magnetic flux currents)

# Voltage Swells

# Voltage Swells

- A voltage swell is a rise in voltage which exists during a phase-to-ground fault on another phase. It is approximately 1.35 p.u. on wye-grounded systems and 1.73 (or more) p.u. on delta systems.
- The higher voltage will be seen by customers supplied from the unfaulted phases
- The voltage swell will vary as fault current flow varies
- Successful fault clearing will cease the voltage swell

# Voltage Swells



# Voltage Swells

- Effects of Voltage Swells:
  - Customer equipment could be affected
  - If backfeed is from a delta supply onto the wye system, and voltages of 1.73 p.u. are impressed on the unfaulted phases, lightning arresters will fail unless fault clearing is prompt. (it is not)

# Fault Clearing on Secondary Systems

# Fault Clearing on Secondary Systems

- Exactly what fault protection is on secondary systems?
- What are CSP transformers supposed to protect?
- Do we “fuse” secondary supplies? Why or why not?

# Fault Clearing on Secondary Systems

- Faults on secondary systems are expected to burn clear
- Any fusing or breaker protection in transformers is there to protect the transformer
- Secondary pattern and building service entrance cables are unfused

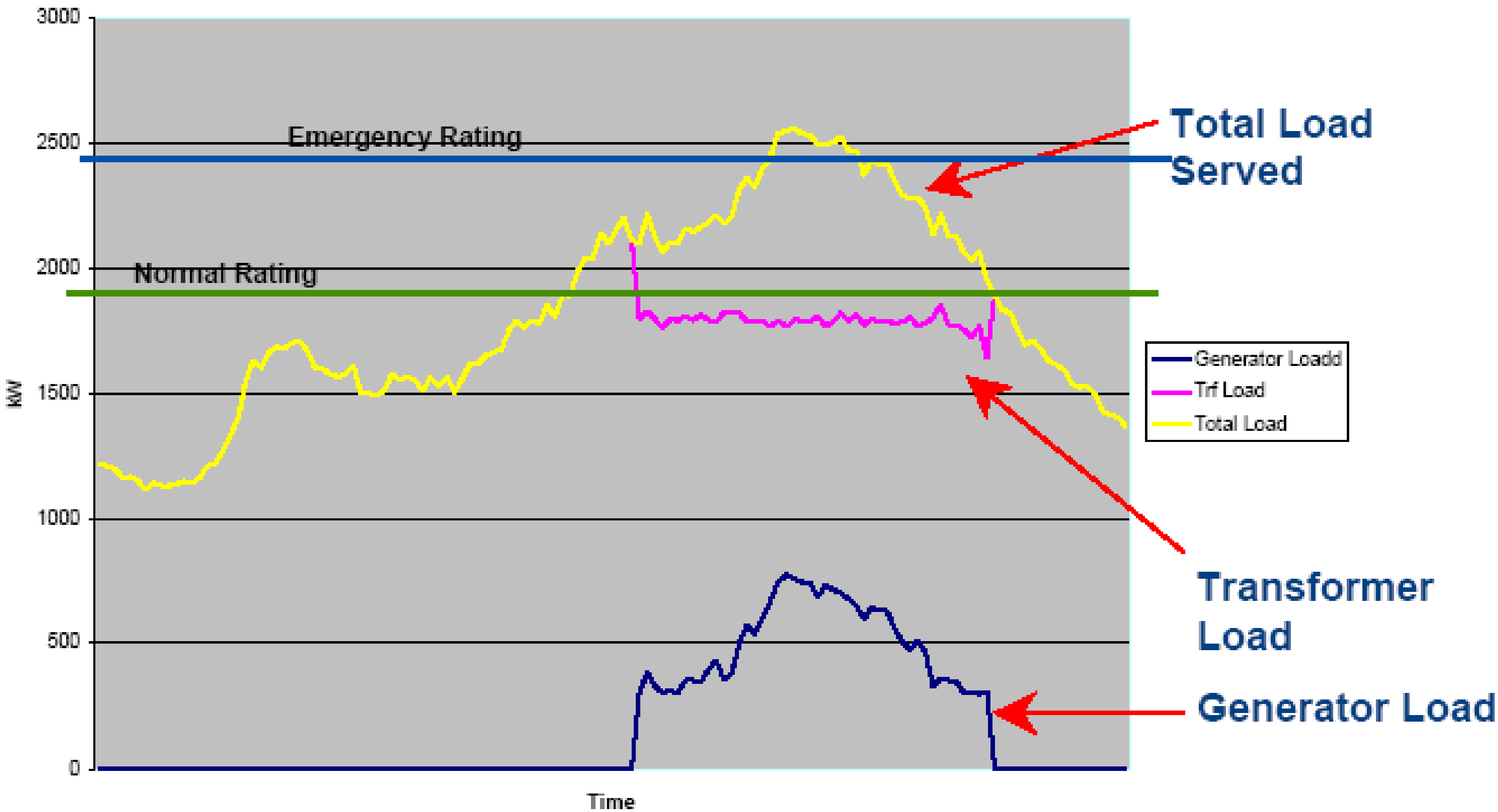
# Distributed Generation

# Distributed Generation

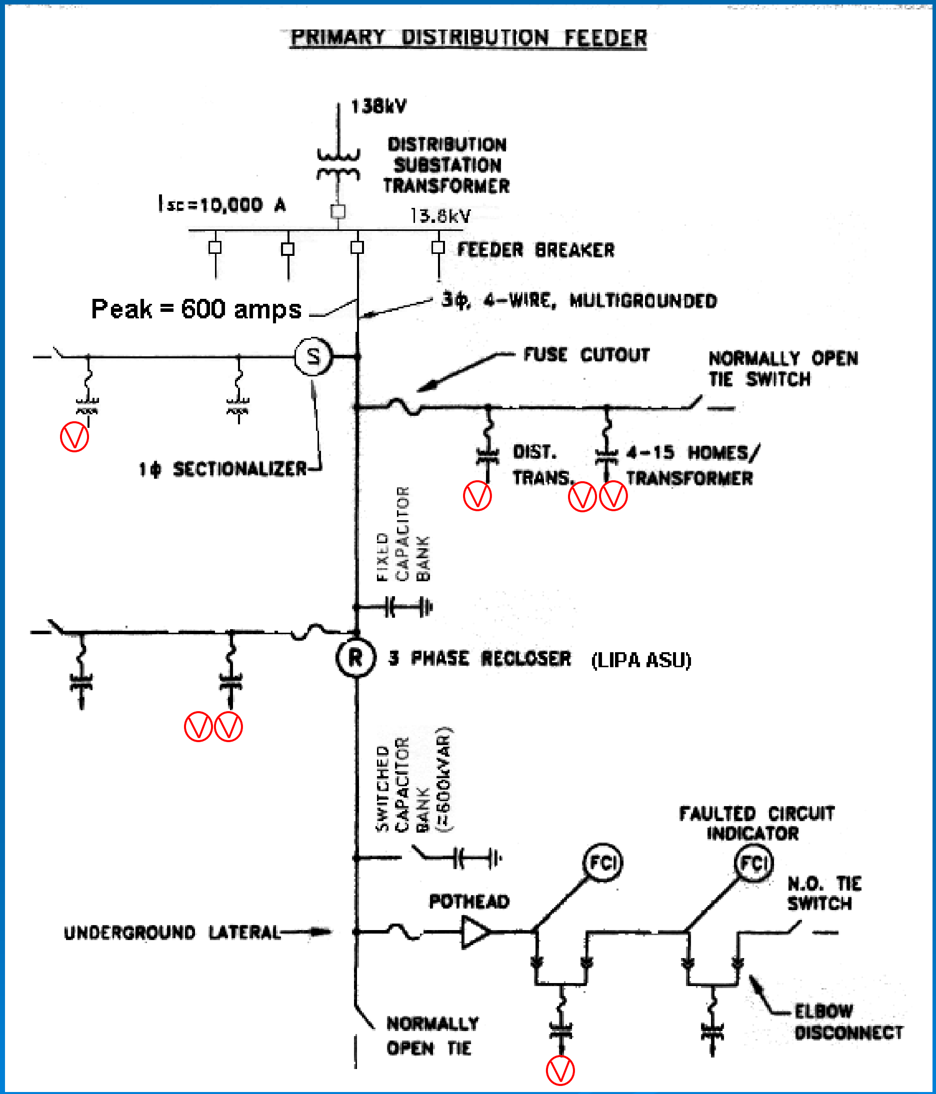
- Distributed generation ("DG") can be loosely defined as the interconnection of electric generating apparatus to the utility distribution system by utility customers, and others, where the functioning of the generator is, by and large, outside of the utility's control.
- To a large extent, laws and other regulations (e.g., PSC rulings, net metering, etc) allow for DG interconnections into utility distribution systems. However, because the utility retains responsibility of service levels to other, non-DG customers, the utility has the duty to specify adequate relay and protection it deems necessary to protect service quality to those other customers.
- The engineering inexperience with DG at all utility systems has resulted in as many interconnection requirements as there are utilities.
- The utility bears responsibility for controlled voltage supply to all customers. Unless PSCs/PUCs modify this to offer some tort protection, a utility's reasonable interconnection requirements should withstand regulatory scrutiny.

# Distributed Generation

DG in an ideal world…………



# Normal Distribution Voltage Supply



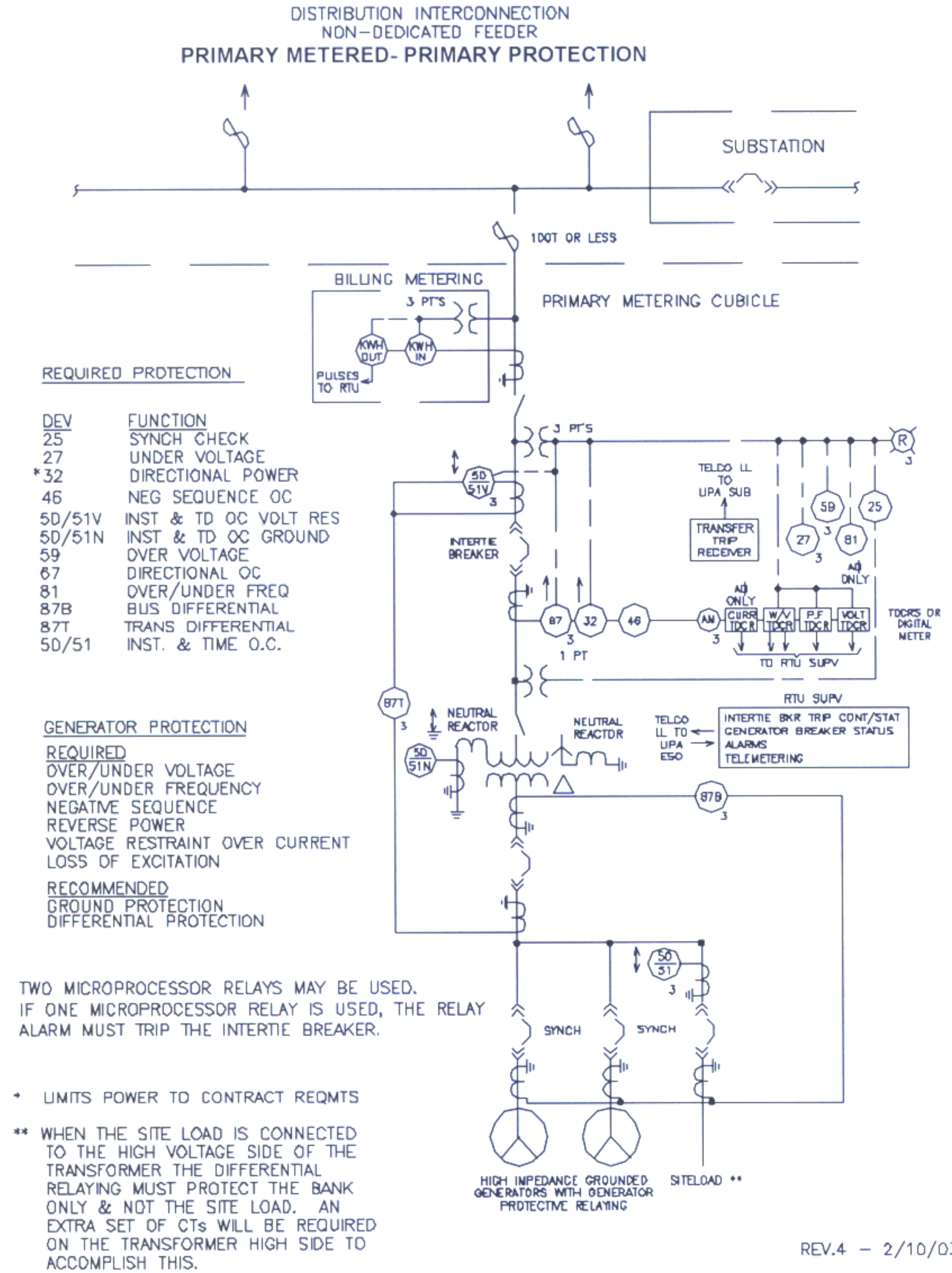

= Distribution Generation Unit

# Distributed Generation

Possible Impact on system protection:

- Defeat utility fault-clearing schemes.
- False setting of the utility voltage regulator.
- Voltage swings when the substation breaker does trip and reclose.
- DG into secondary networks can interfere with protector operation and load flows..
- DG Direct Transfer Trip (DTT) is to the wrong feeder breaker when loads are moved to other circuits by Distribution System Operators.

# Typical DG protection and interconnect one-line diagram




George Ello

# Distributed Generation:
## Closed Transition Generator Switching

- Involves temporary paralleling of generators so customer can avoid the momentary interruption of generator switching
- Switches are widely available (ASCO, Russelectric)
- What if there is a feeder fault while paralleling?

# CABLE

Properties, Testing and Fault Locating

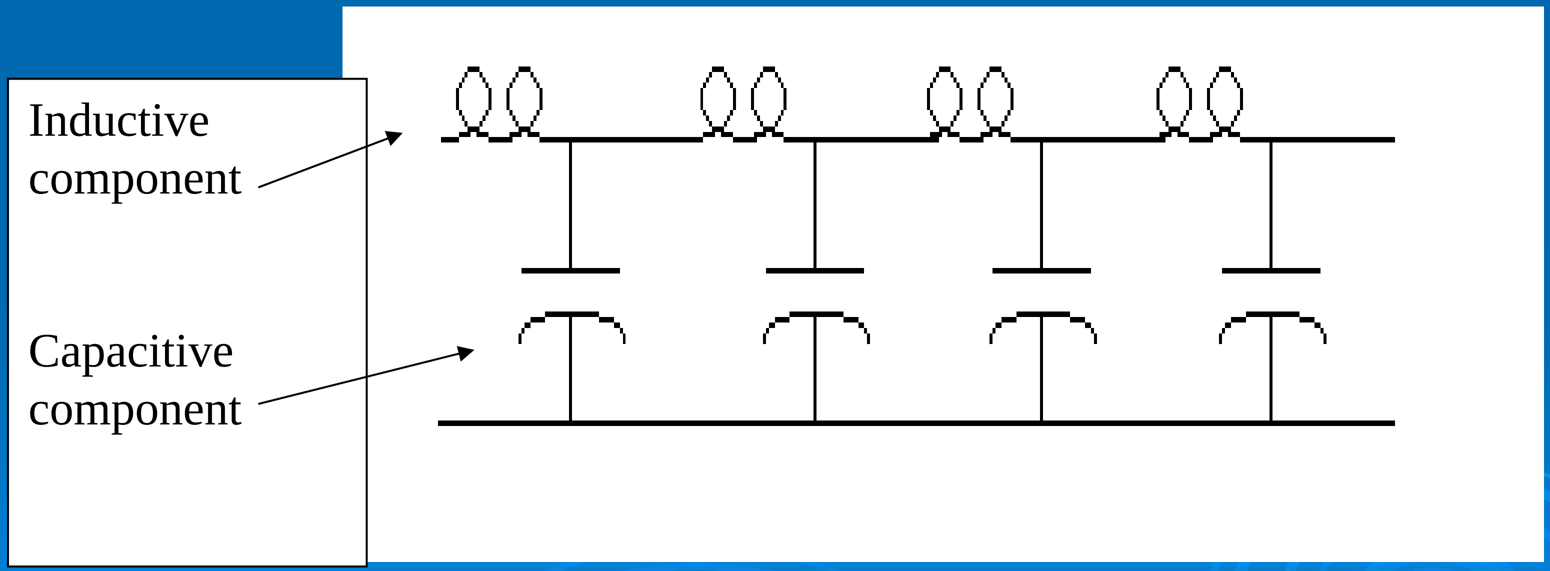
# Major Primary Cable Insulations

- Paper-Insulated, Lead Covered (PILC)
- Cross-linked Polyethylene (XLPE, TRXLPE)
- Ethyl-propylene Rubber (EPR)

- All cable construction wraps the insulation around the energized conductor with the neutral or ground wrapped around the insulation. (There are exceptions!)

# Primary Cable Properties

- Because of its construction, cable acts as a capacitor:



# Primary Cable Failures

- Insulation tracking ("trees") in XLPE (cross-linked polyethylene) and EPR (ethyl propylene rubber) cables
- "Dig in" by others
- Cable termination failure (pothead, elbow)
- Physical cable stress (compression by earth, rocky backfill, etc)
- Damage during cable storage and/or installation
- Water intrusion into the cable
- Age deterioration of the insulation (Leads to Partial Discharge)
- Heat due to overload
- Application of over voltage

# Primary Cable Failures

- When primary cable failures occur, the fault's electrical resistance can and will vary. It will be either "high" or "low" resistance most of the time. High resistance faults can be high enough such that system voltage can be re-applied to the cable, but it will fail again shortly. Low resistance faults will impede the build up of any voltage on the cable. This range in fault resistances is what creates such challenges to cable fault locating.

The End…………?

Trekkies do it with Synchrophasors….