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ABB Protective Relay School Webinar Series
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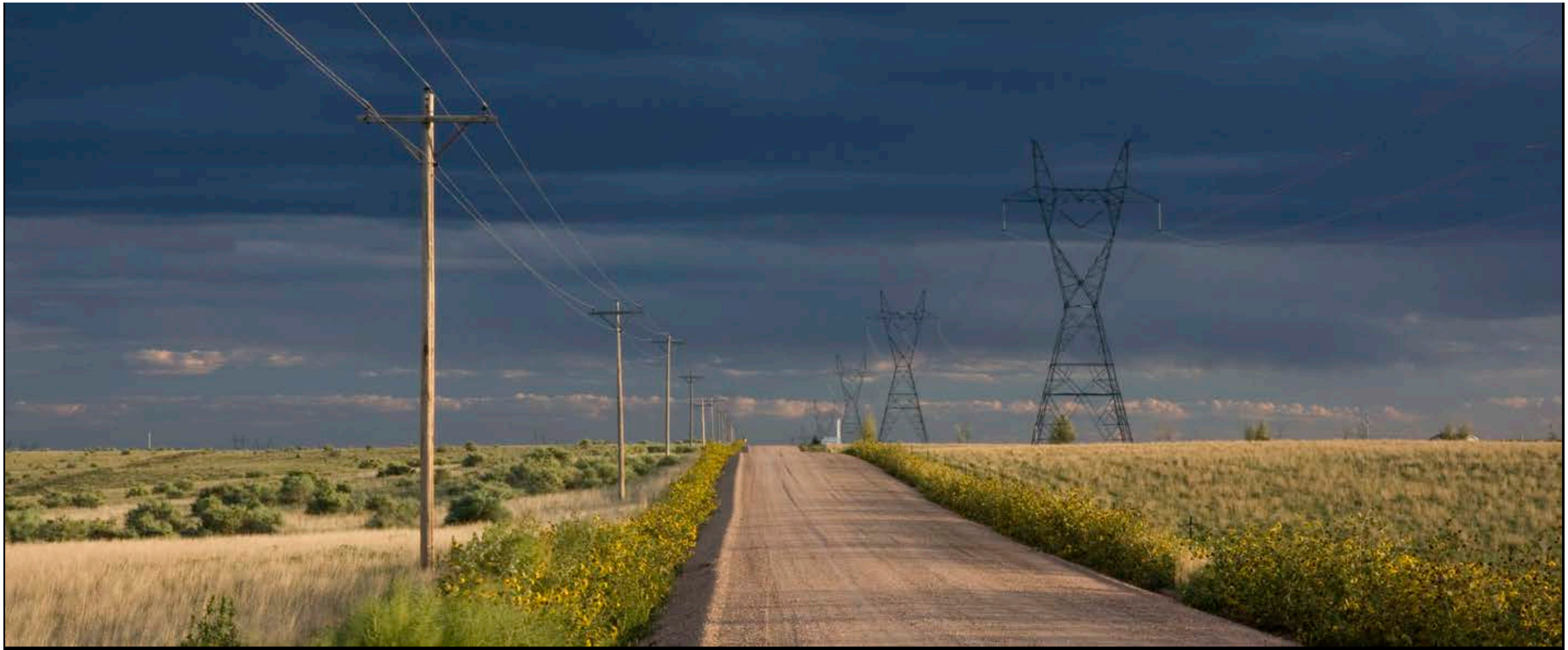


ABB Protective Relay School Webinar Series

Feeder Protection Fundamentals

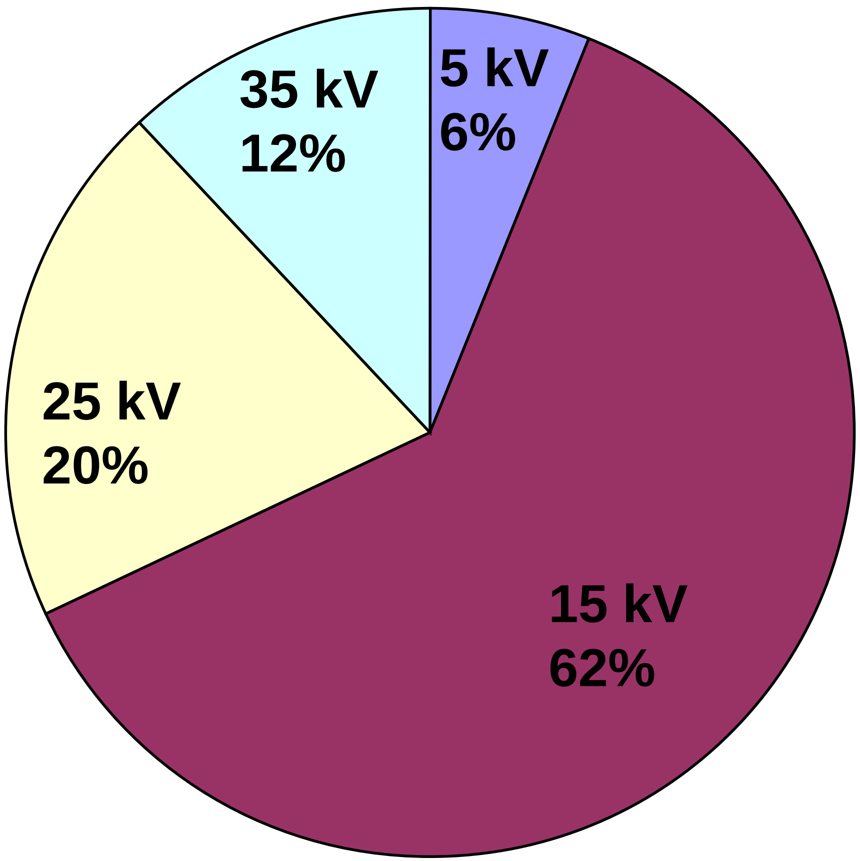
Tim Erwin

October 29, 2013

Topics

- System Overview
- Why is feeder protection necessary
- The Protection team
  - Fuses
  - Breakers/reclosers
  - Relays
  - CT’s
- Characteristics of protective devices
  - Fuses
  - Circuit breakers, relays and reclosers
- Principles of feeder coordination

Distribution System Voltage Class



Percent of Distribution Systems at the Nominal voltage Class

Trend to larger nominal voltage class

- Increasing load density
- Lower cost of higher voltage equipment

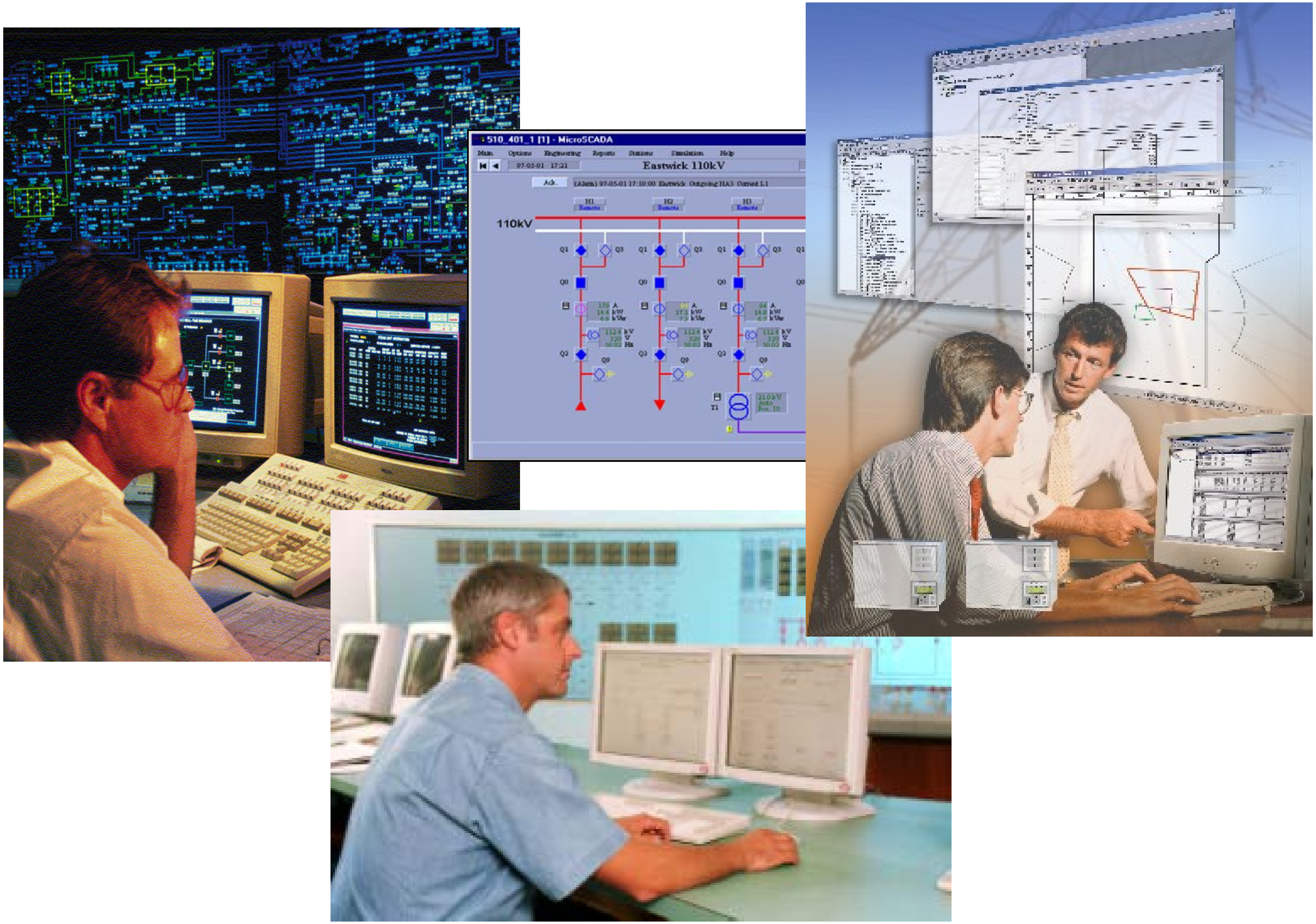
WHY IS FEEDER PROTECTION NECESSARY?

City Lights

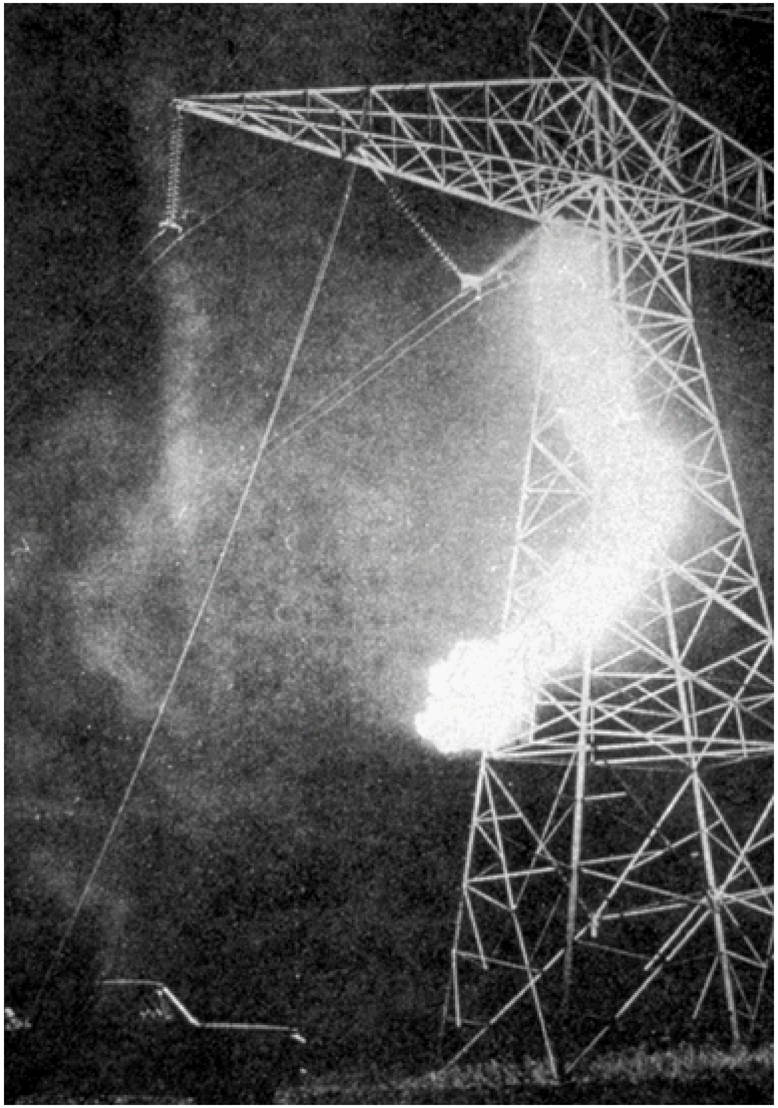
Lightning

Blackout

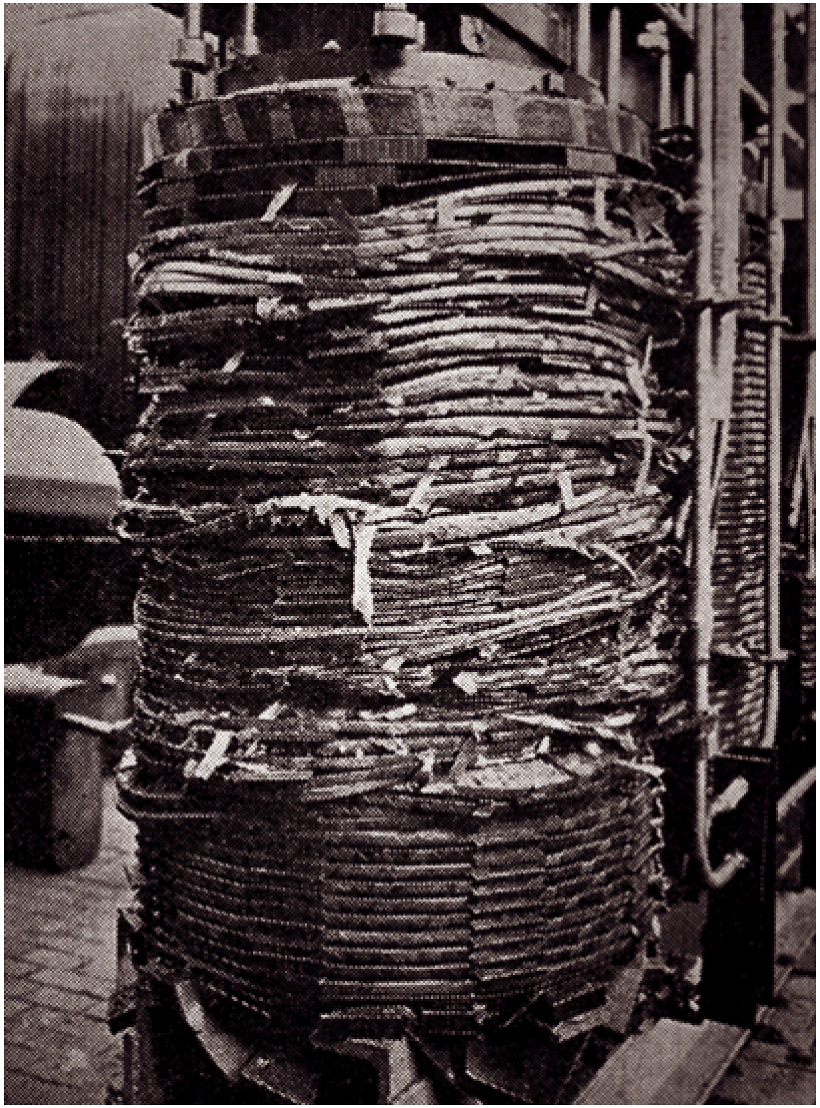
Chaos and Confusion



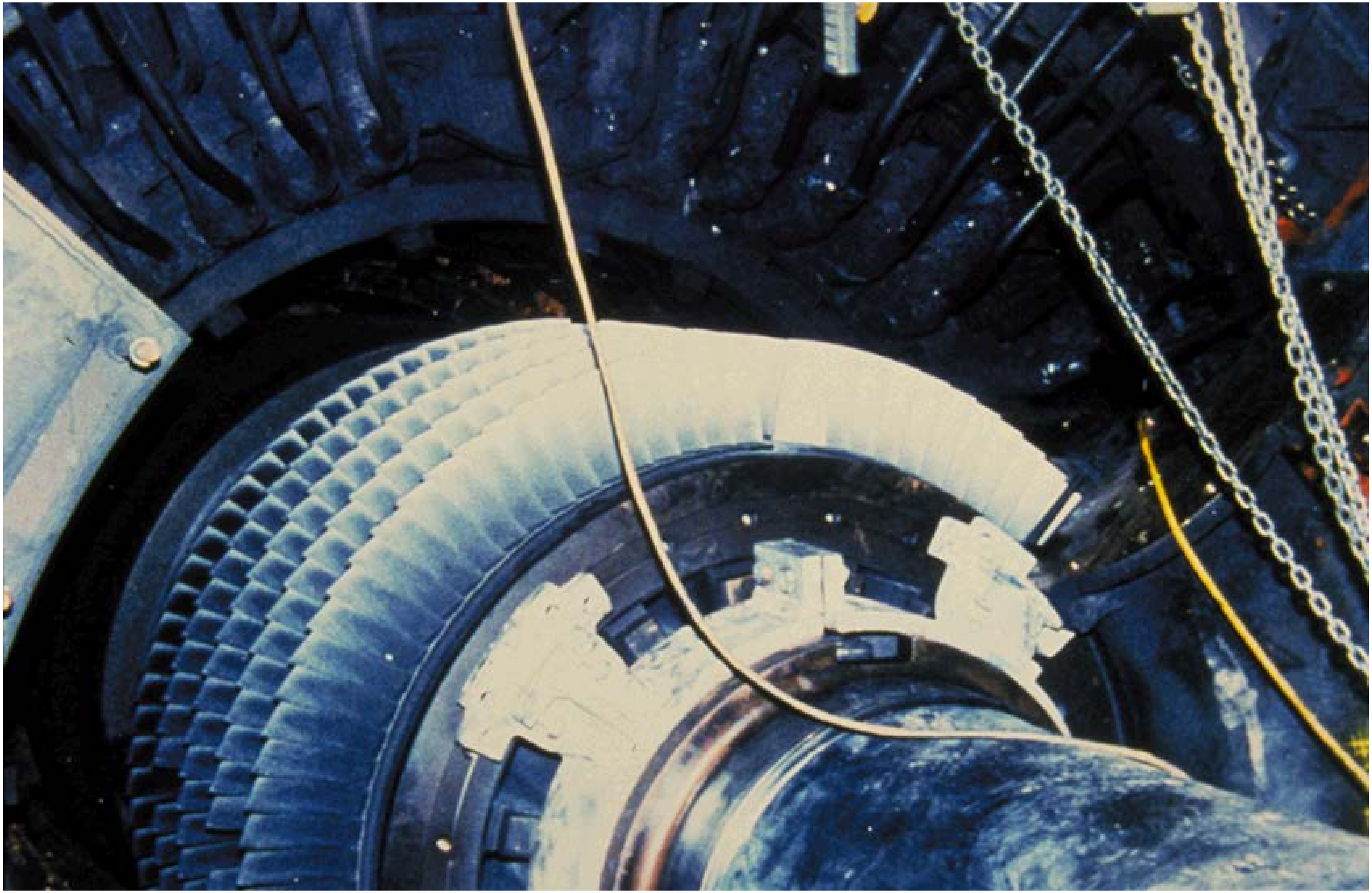
Transmission Line Tower Flashover



Transformer Failure



Generator Failure



Overhead Distribution Feeder Faults

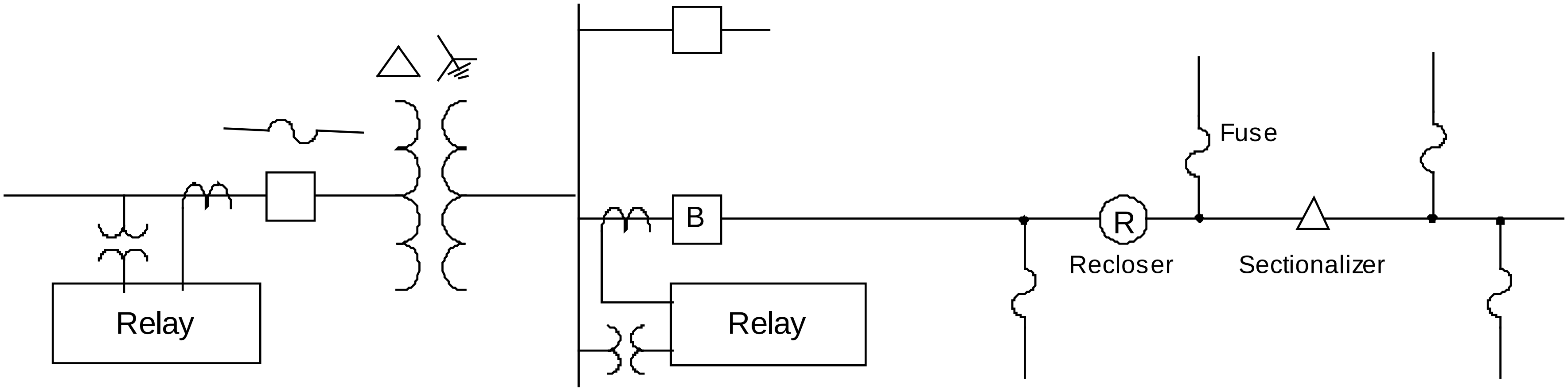
Temporary (non-persistent) – 85%

- Lightning causing flashover
- Wind blowing tree branches into line(s)

Permanent (persistent) – 15%

- Broken insulator
- Fallen tree
- Automobile accident involving utility pole

Typical Distribution Substation Feeder Circuit



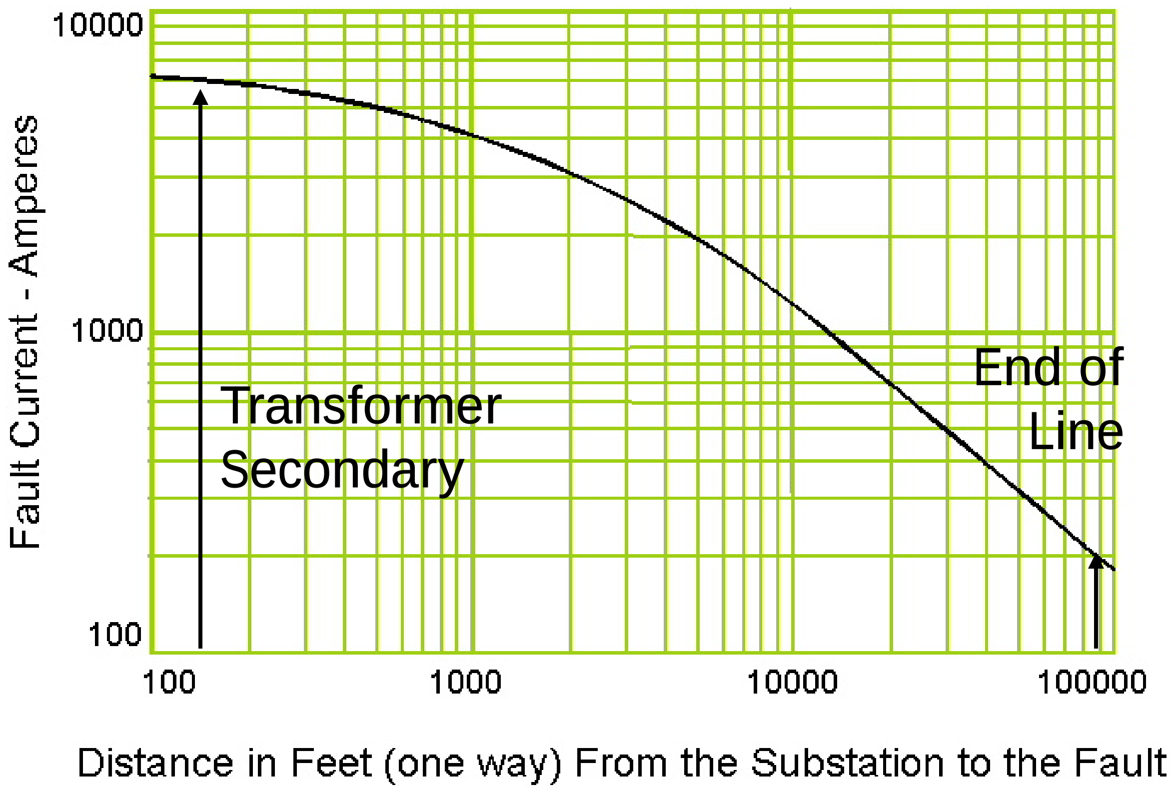
Transformer Primary

- Rural – primary fuses
- Urban – breaker or circuit switch

Feeder Circuit

- Breaker in protective zone
- Breakers controlled by protective relays
- Reclosers
- Sectionalizers
- Lateral Tapped Fuses

Fault Current Levels



Fault Current Vs. Distance to Fault on the Feeder

- Function of
  - Substation transformer size (source impedance)
  - Distribution voltage
  - Fault location
- 10kA - majority
- 10-20kA - moderate number
- 20kA - few

Application

- Protection to be applied based on exposure
- Higher voltage feeders tend to be longer with more exposure to faults
- Apply downline devices . . . reclosers, fuses, based typically on 3 to 5 MVA of load per segment

The Protection Team

Feeder protection consists
of a team of coordinated devices:

- Fuses
- Breakers/Reclosers
    - Relay(s)
    - The sensors
        - PTs
        - CTs
        - Etc.
- The interconnection

Distribution Protection

Required characteristics of protective devices are:

- Sensitivity – responsive to fault conditions
- Reliability - operate when required (dependability) and no-operation when not required (security)
- Selectivity –isolate minimum amount of system and interrupt service to fewest customers
- Speed – minimize system and apparatus damage

Reliability

DEPENDABILITY

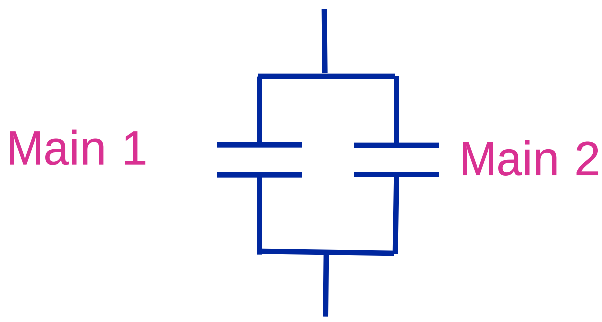
The certainty of correct operation in response to system trouble.

SECURITY

The ability of the system to avoid undesired operations with or without faults.

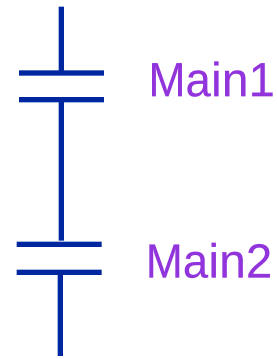
Reliability

DEPENDABILITY



The certainty of operation in response to system trouble

SECURITY

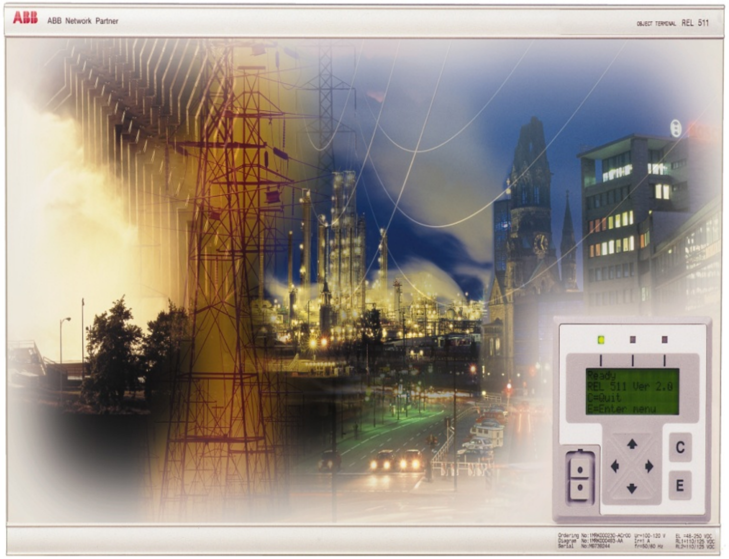


The ability of the system to avoid misoperation with or without faults

General Relaying Philosophy

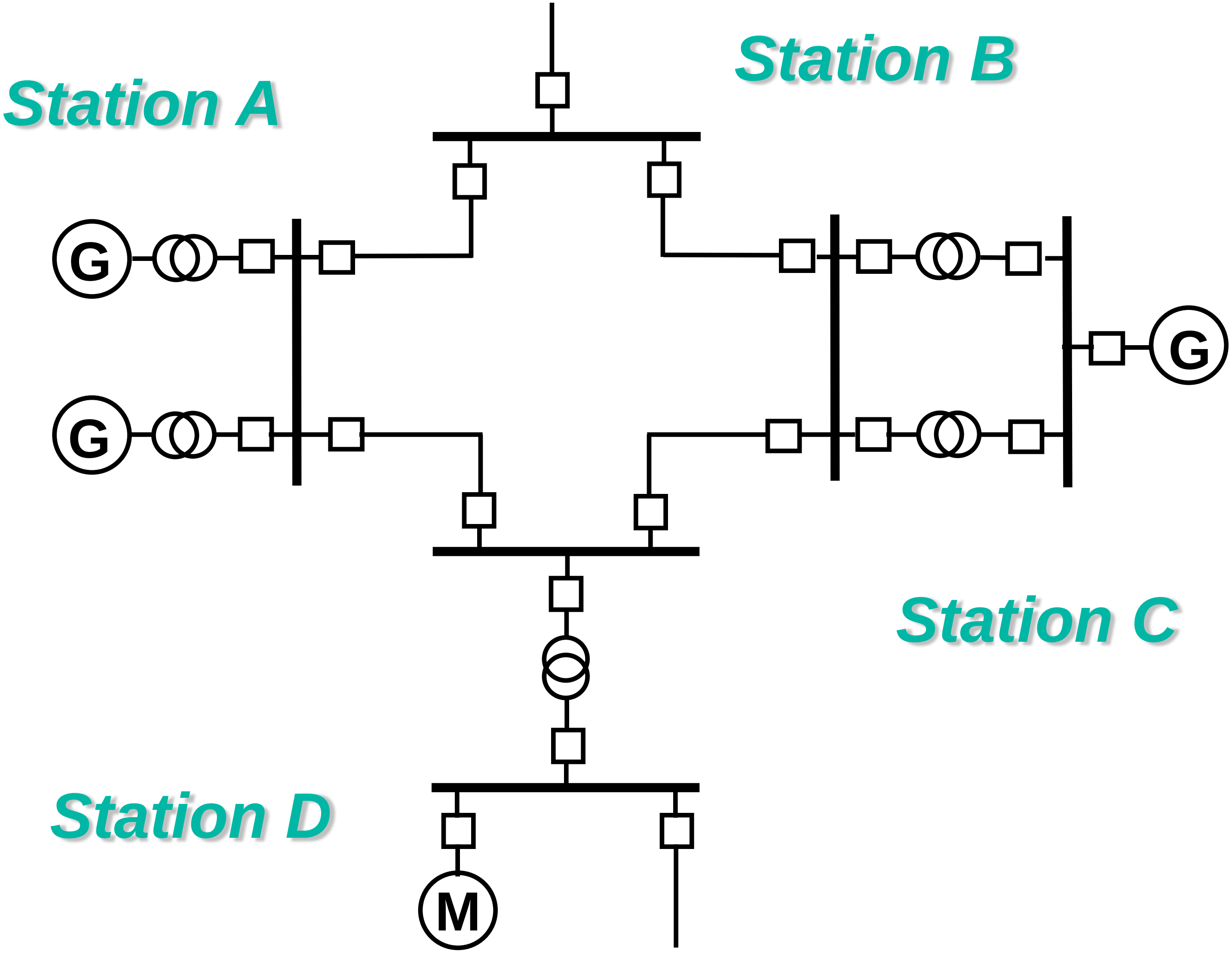
"Zone Protection"

- Generator
- Transformer
- Bus
- Transmission Lines
- Motors

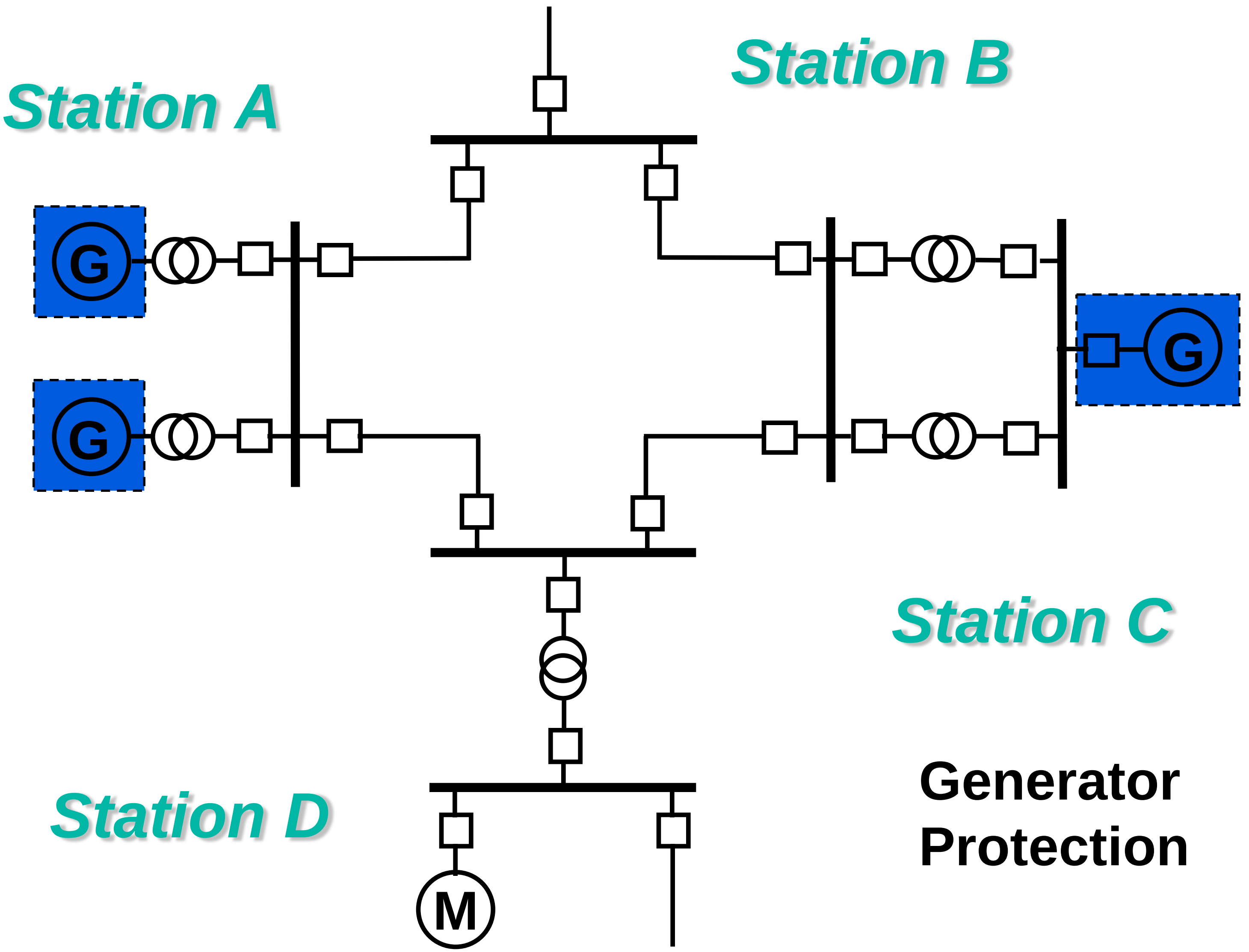


ABB

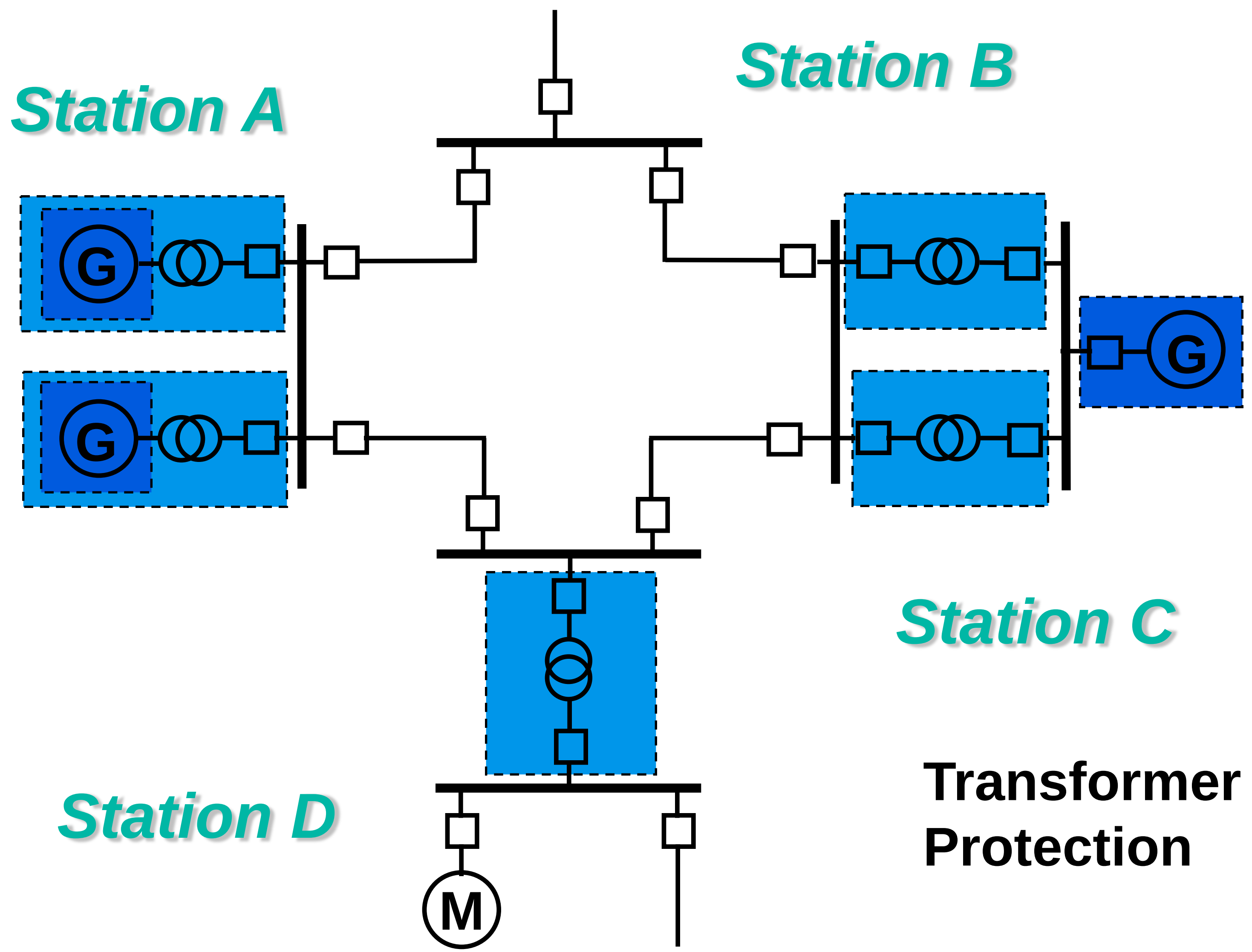
Zones of Protection



Zones of Protection

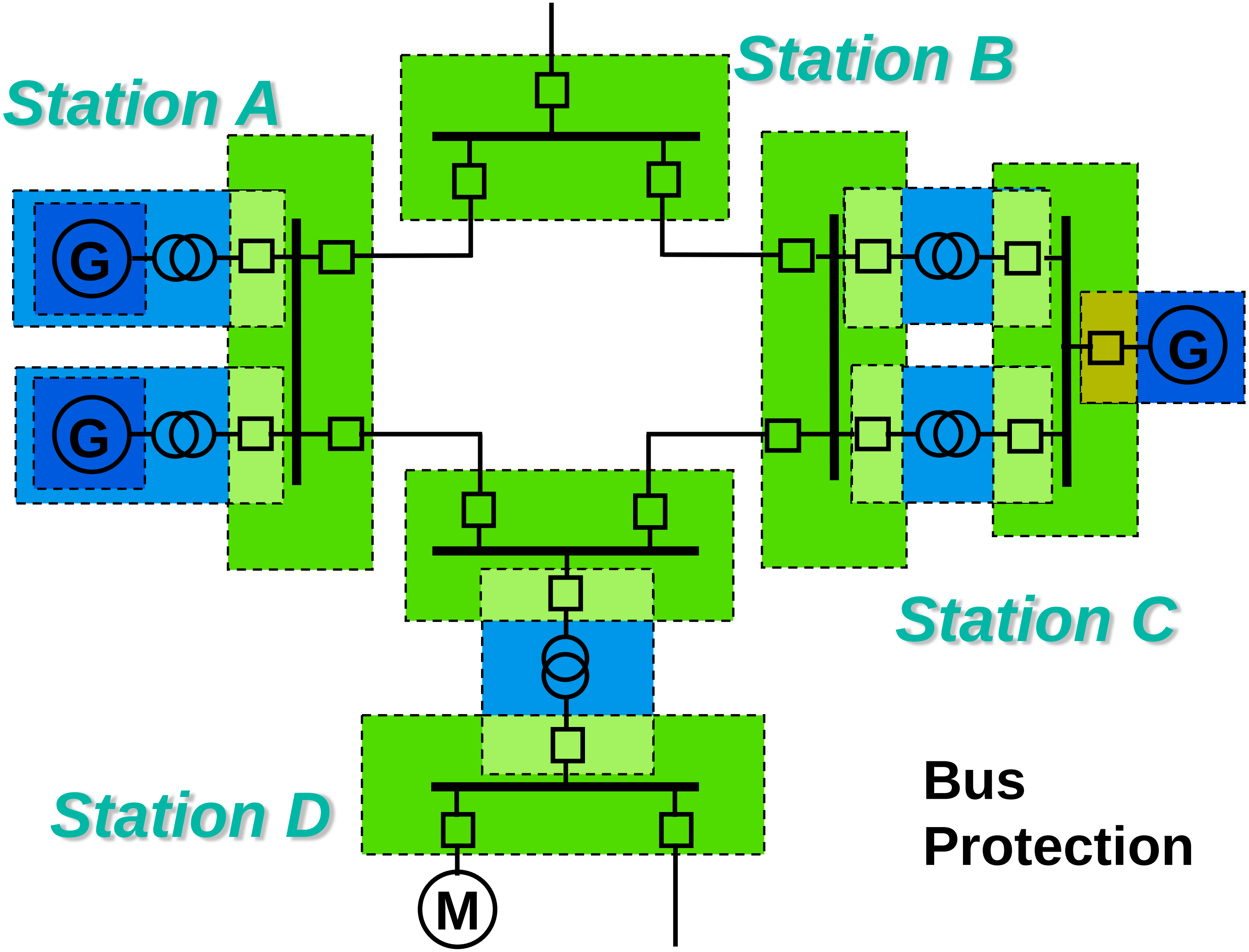


Zones of Protection



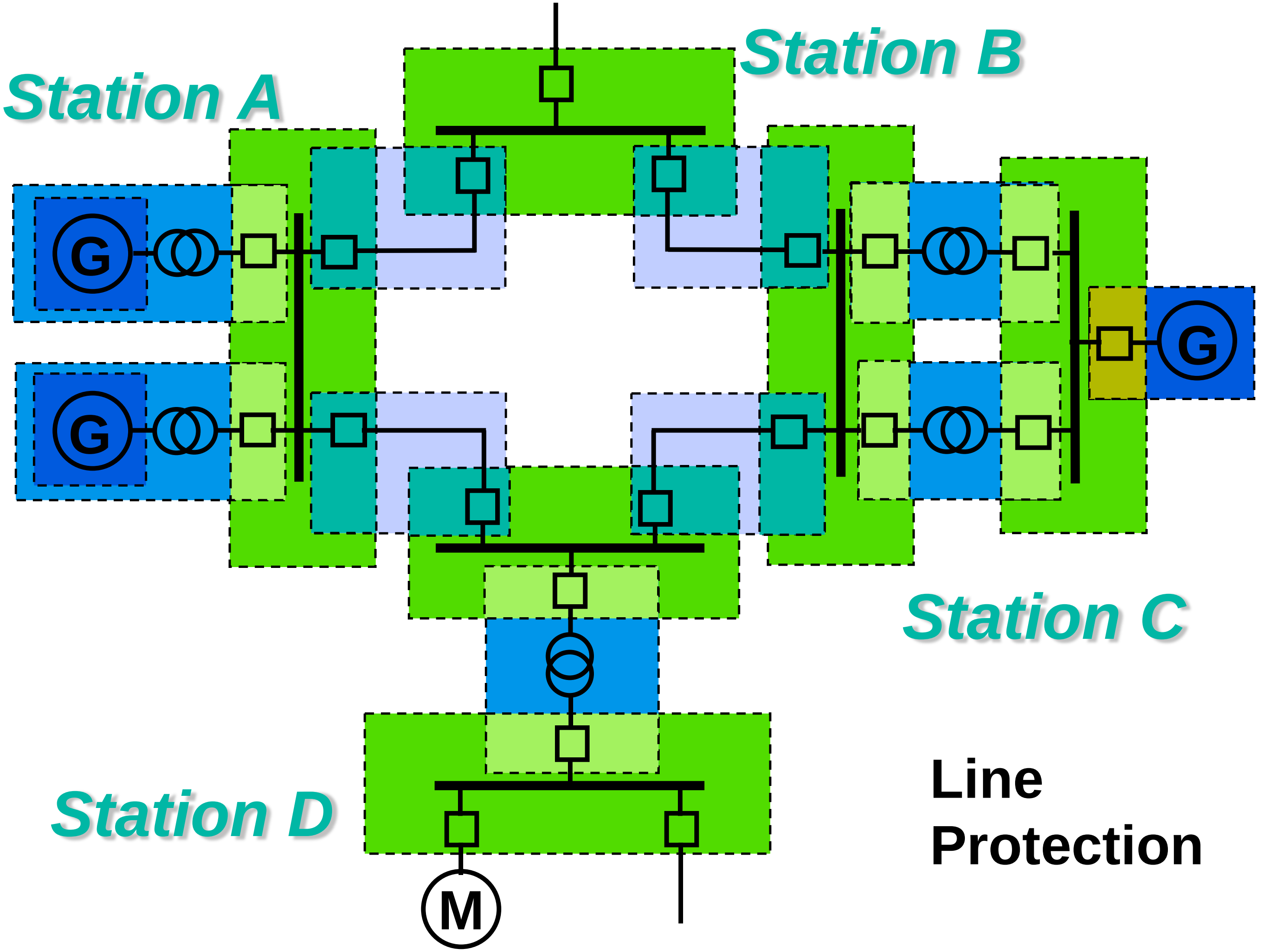
Transformer Protection

Zones of Protection

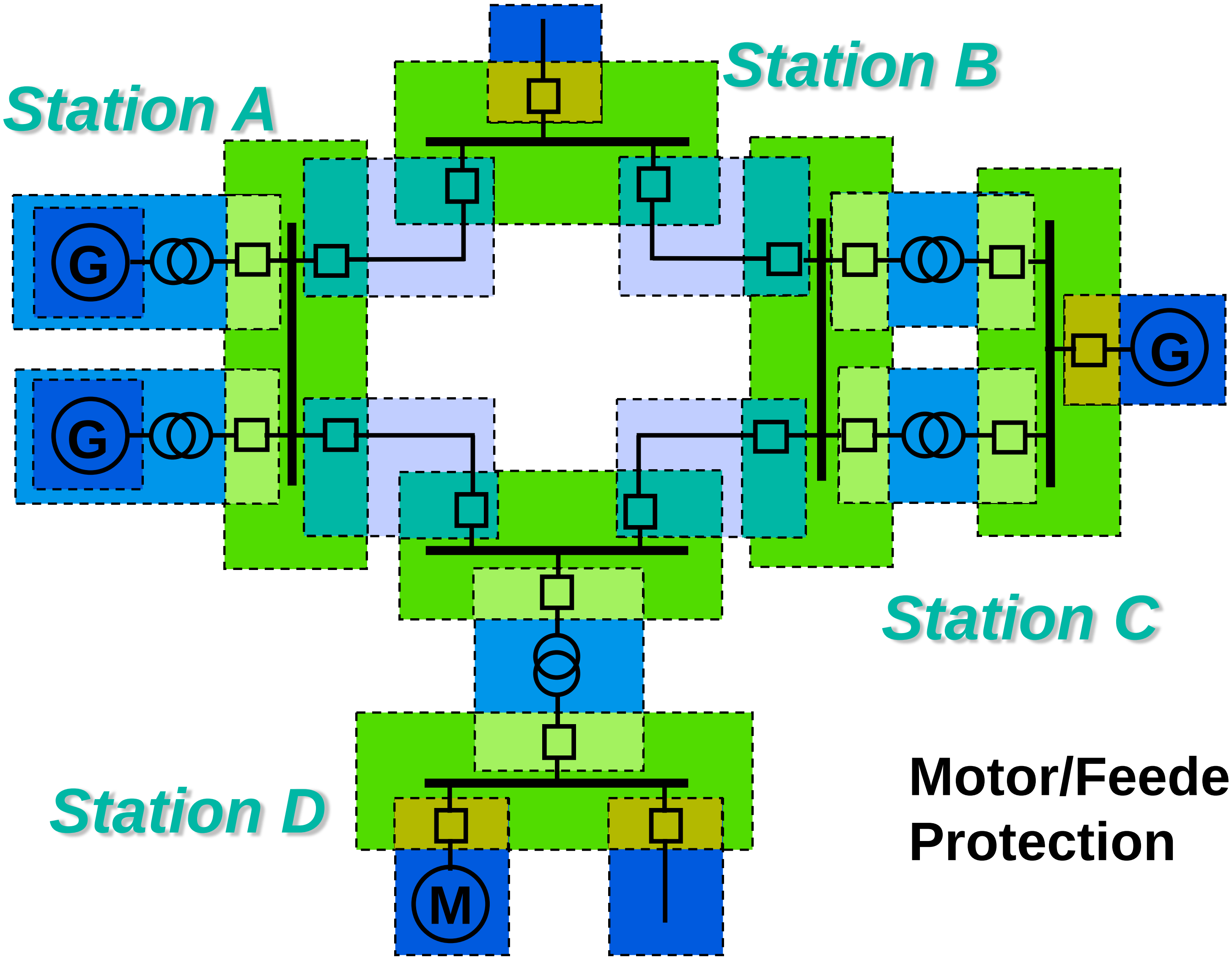


Bus Protection

Zones of Protection



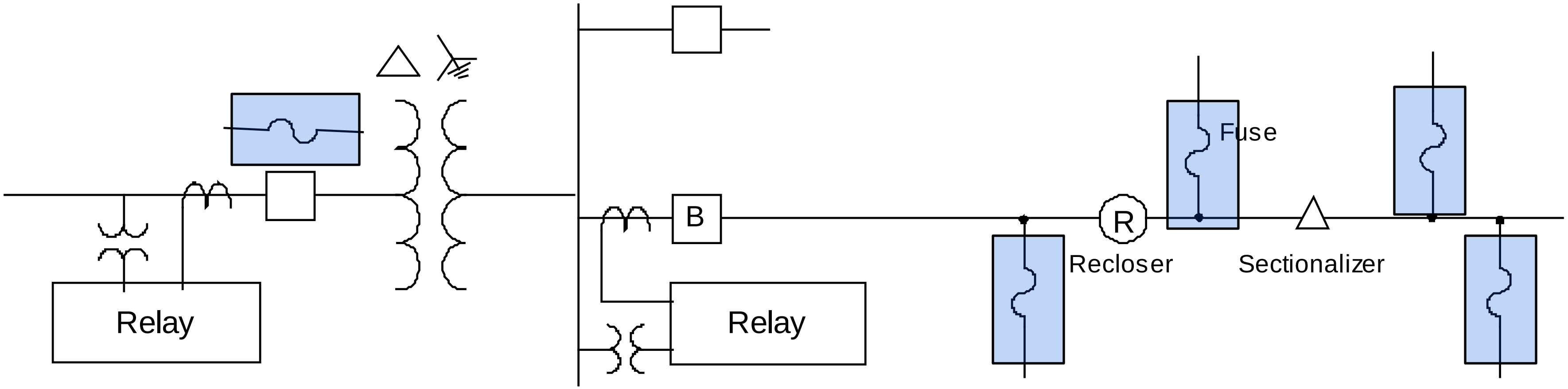
Zones of Protection



Motor/Feeder Protection

Distribution Fuses

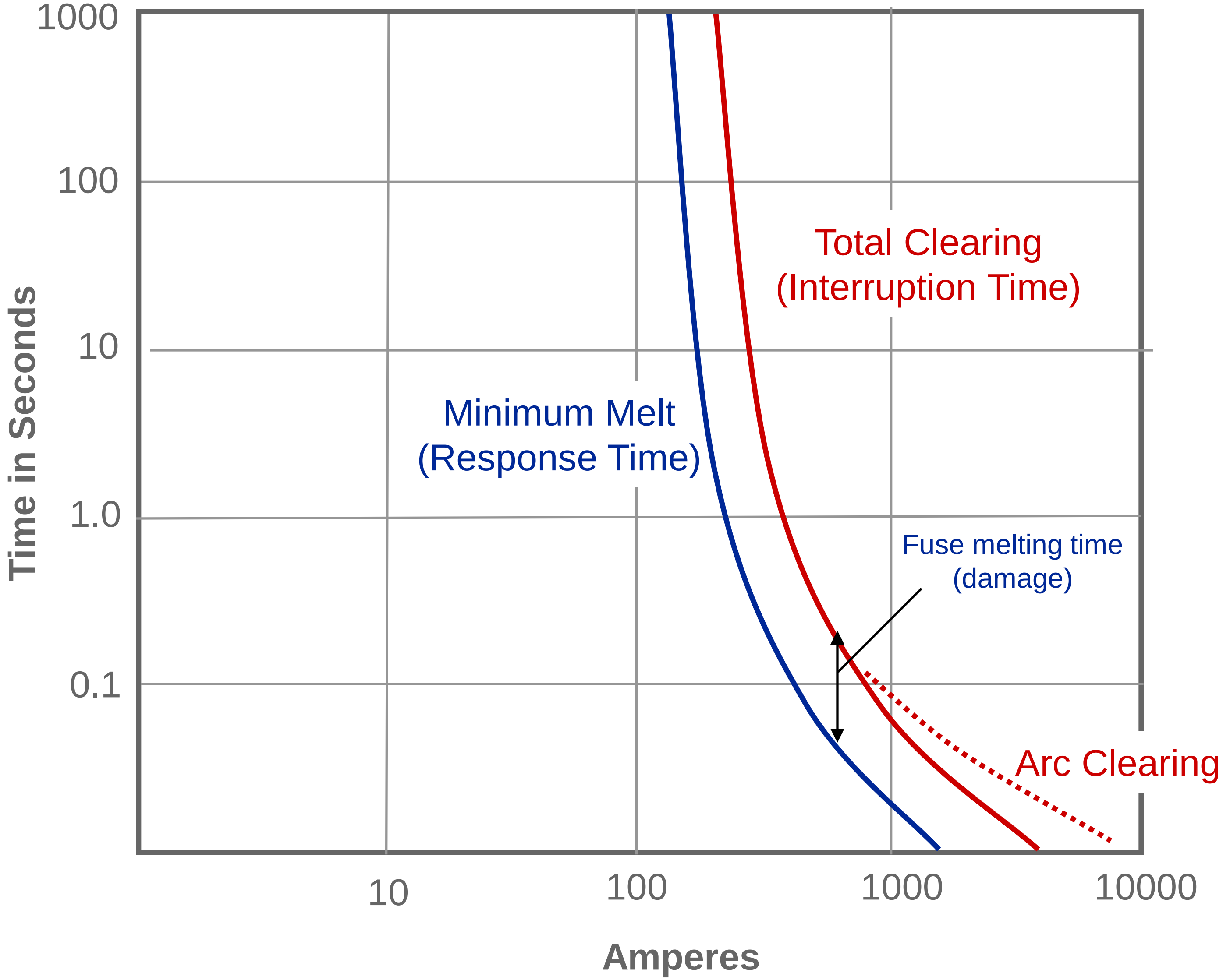
Typical Distribution Substation Feeder Circuit: Fuses



Distribution Fuses

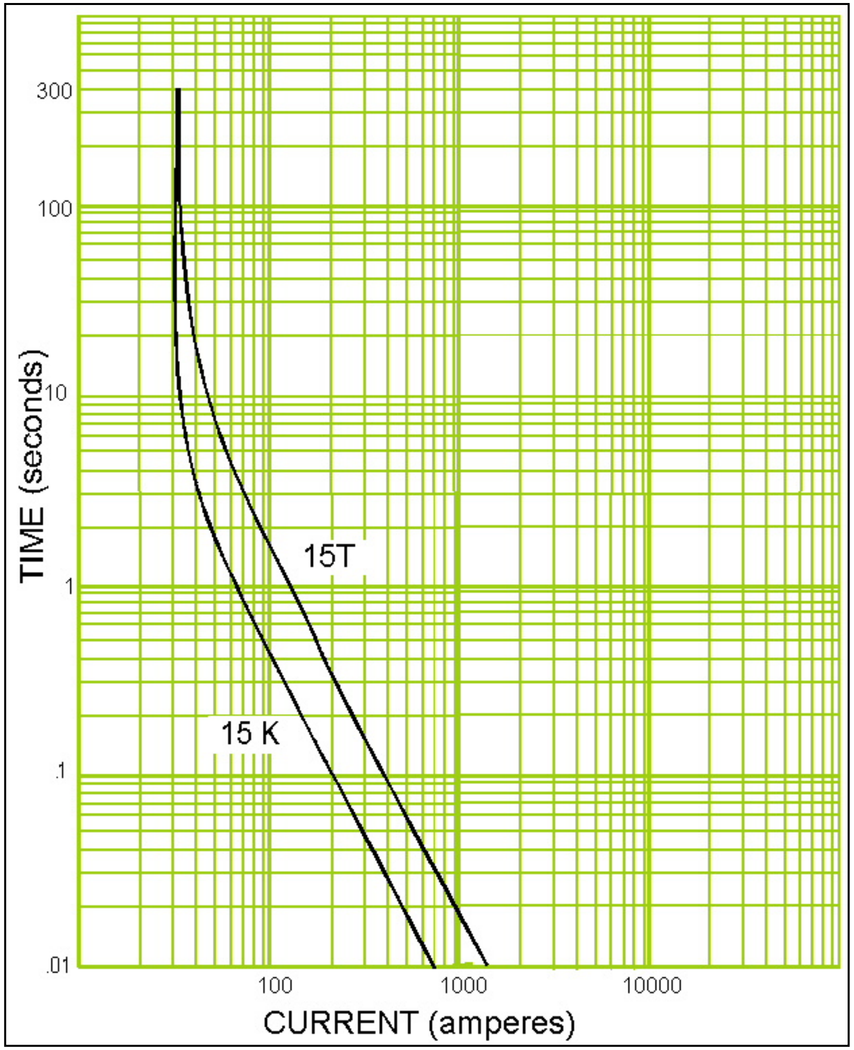
- Continuous current rating
- Interruption rating
- Curve characteristics
  - Minimum melt
  - Total clearing

Fuse Characteristic



Distribution Fuses - Expulsion

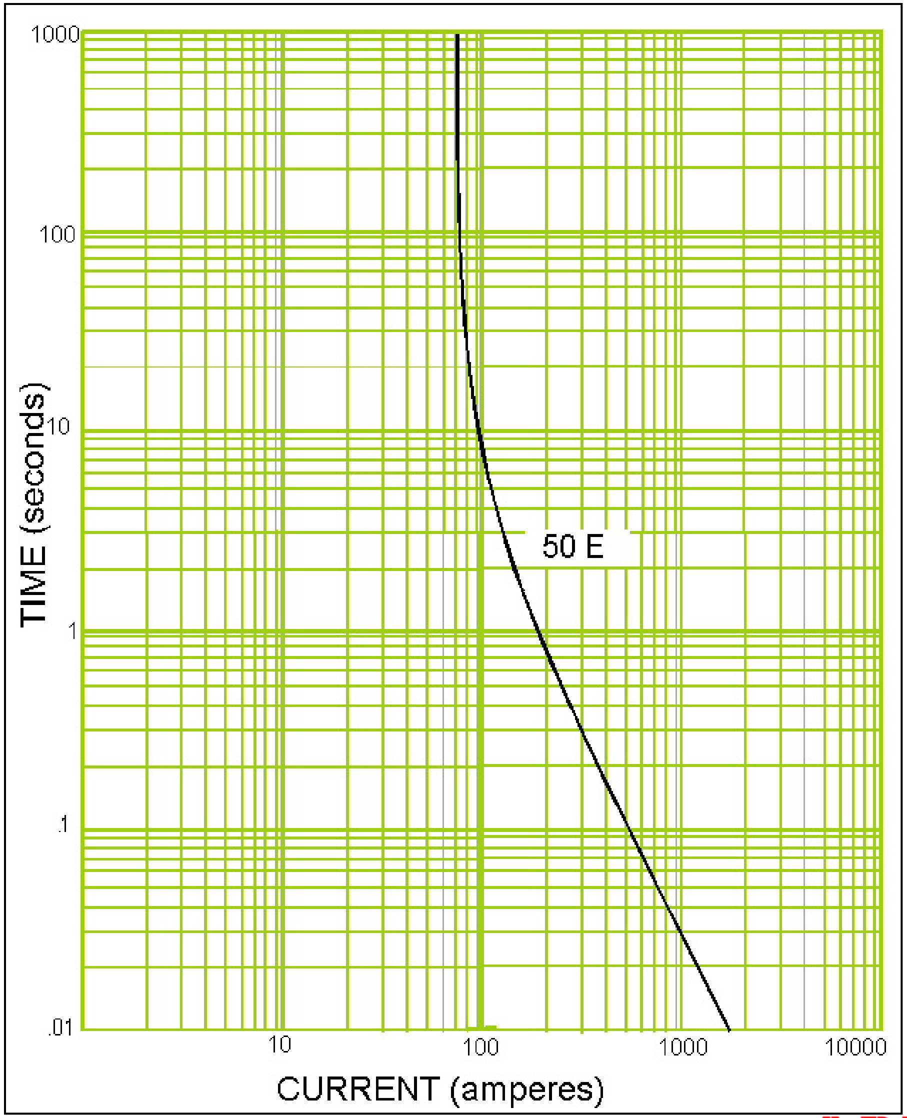
- K link
- T link (slower clearing at high current)
- Common low current clearing time based on fuse rating
- 300 sec <=100 A rating
- 600 sec >   100 A rating



Distribution Fuses – Current Limiting

General purpose

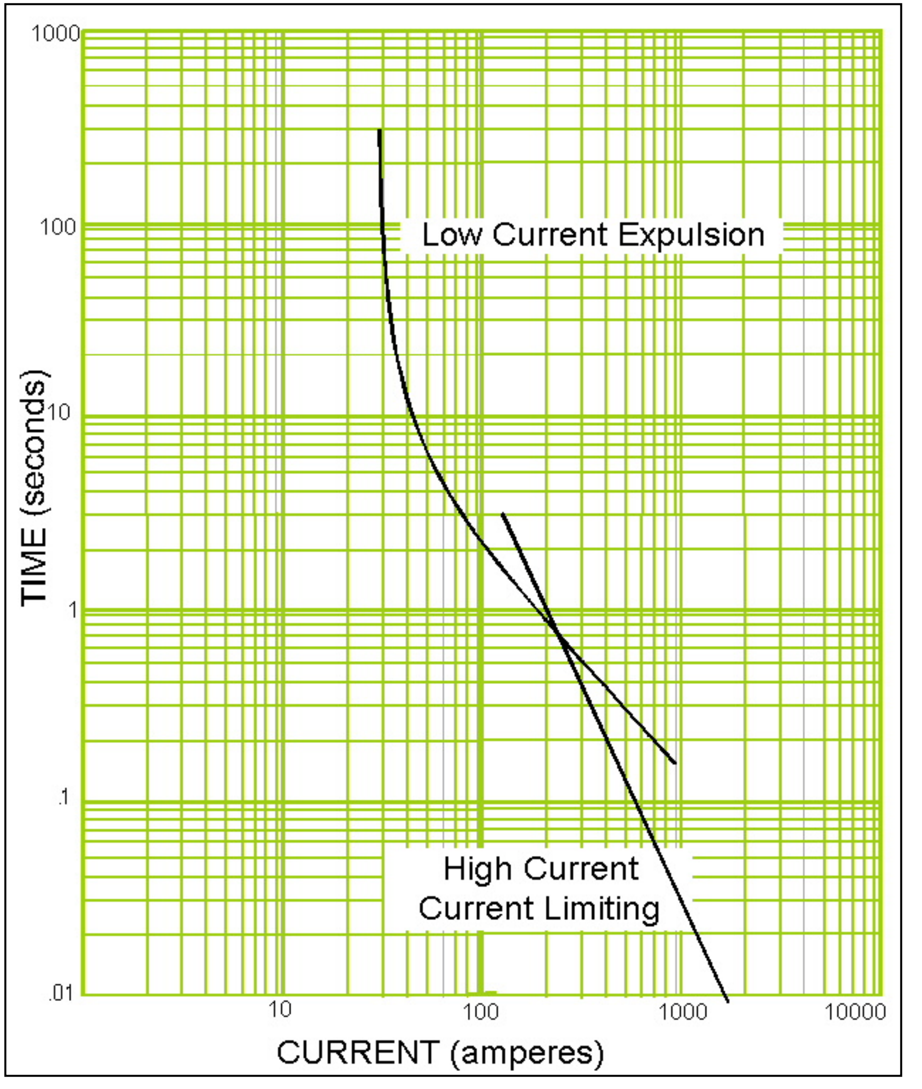
- Rated maximum interrupting down to current that causes melting in one hour
- Melting - 150% to 200%



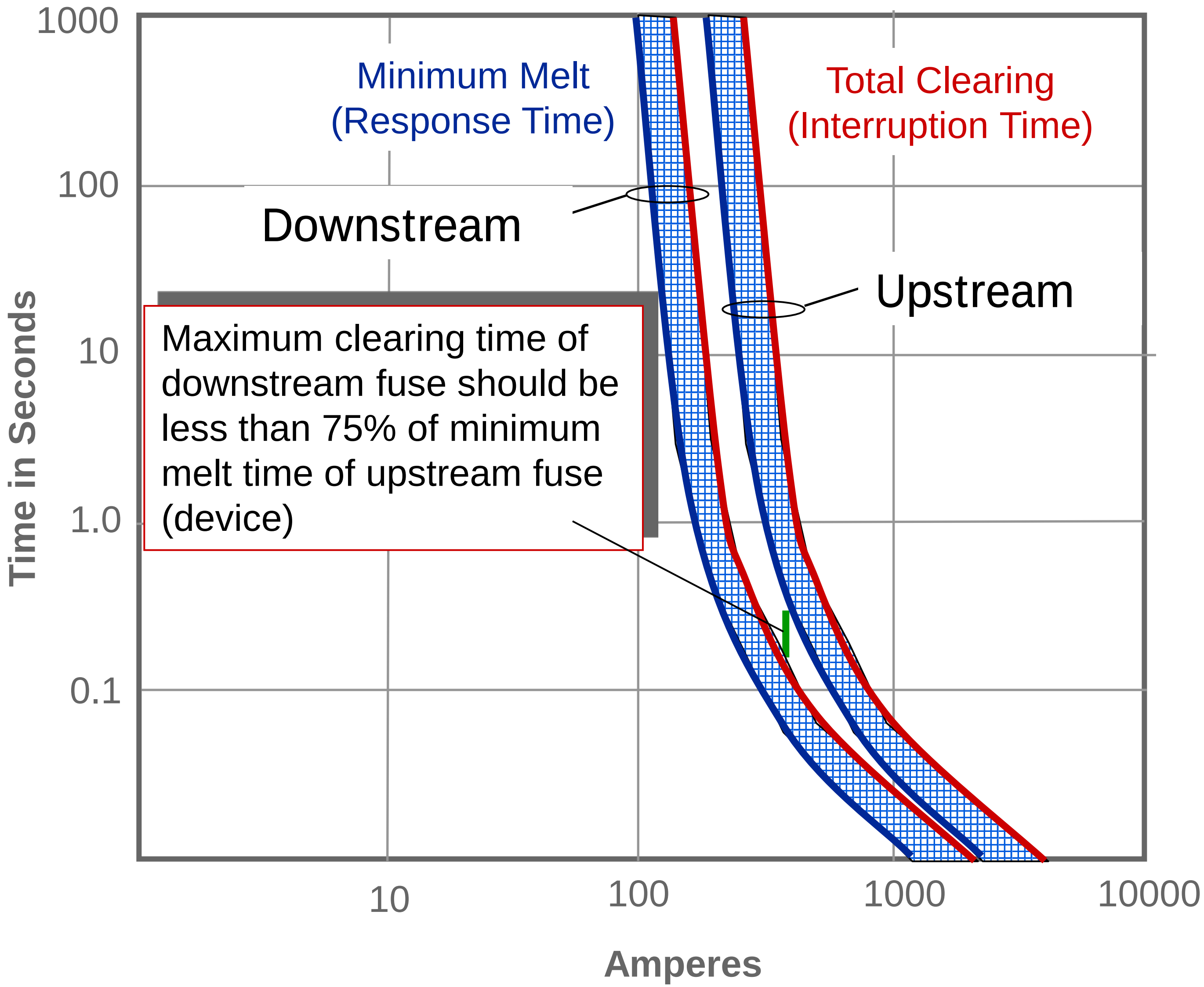
Distribution Fuses – Current Limiting

Backup

- Rated maximum interrupting down to rated minimum interrupting
- Requires application with expulsion fuse for low current protection

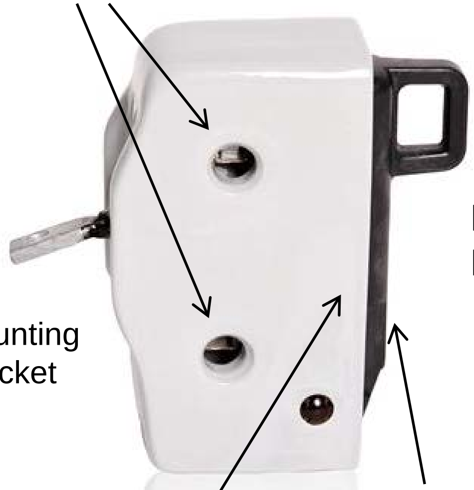


Fuse Coordination - Rule of Thumb

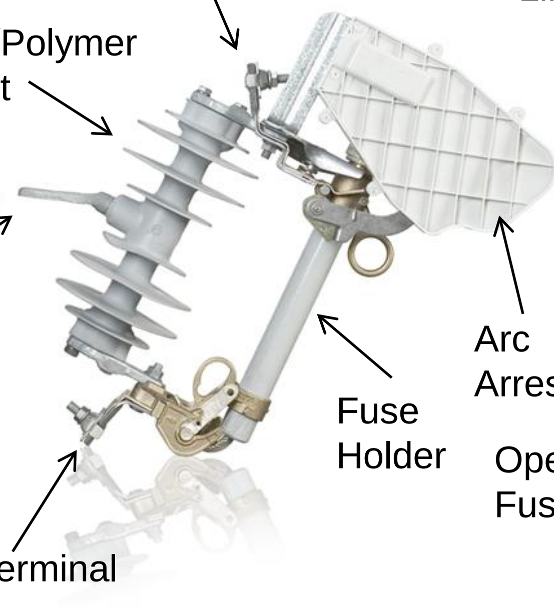


Fused Cutouts

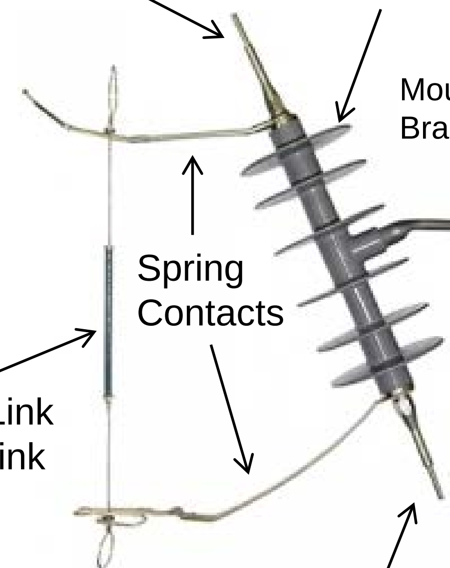
Enclosed



Fused Cutout

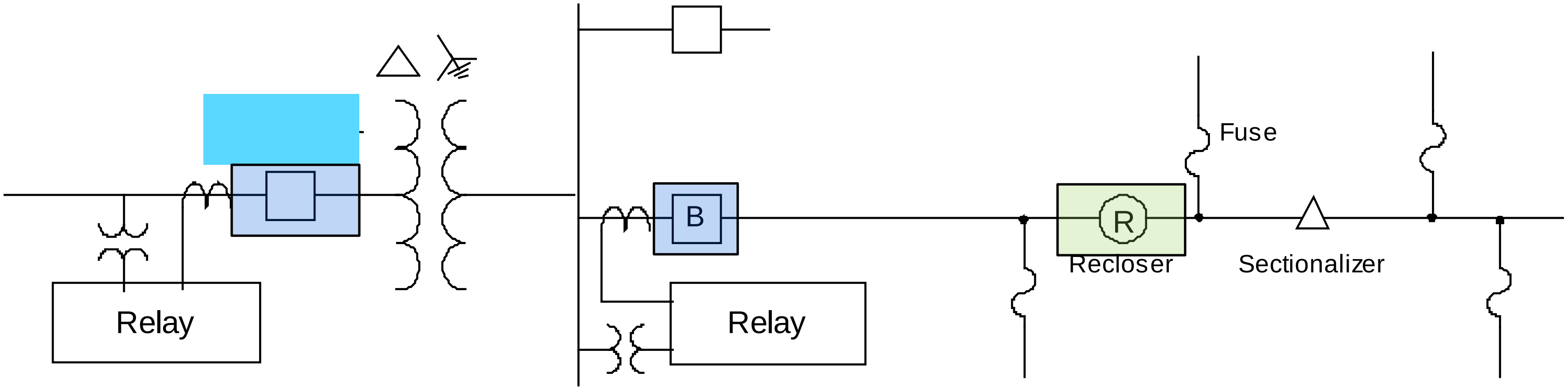


Open Link



Distribution Circuit Breakers and Reclosers

Typical Distribution Substation Feeder Circuit: Breakers and Reclosers



Distribution Circuit Breaker / Recloser

Interruption medium

- Oil
- Vacuum under oil
- Vacuum

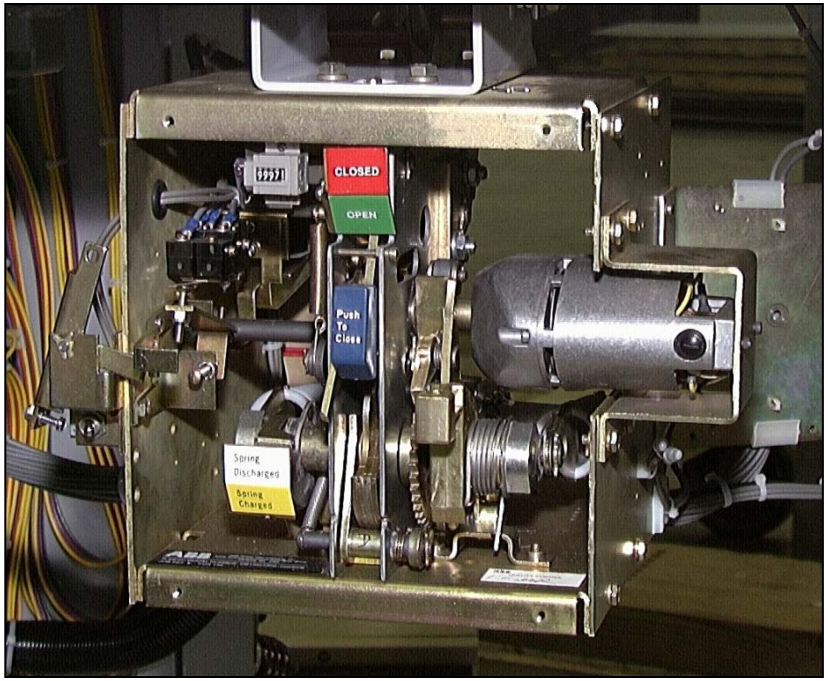
Operating mechanism

- Electromechanical (spring charging)
- Magnetic actuator

Fault sensing and control

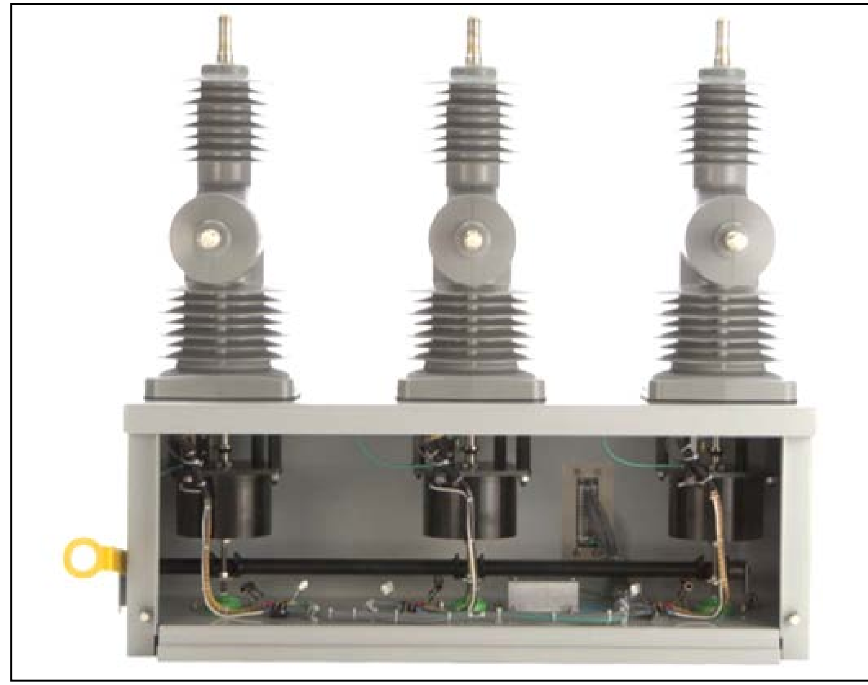
- Electromechanical
- Solid state
- Microprocessor

Operating Mechanisms: ESV (spring charge) vs. OVR



Spring charged mechanism

- Over 300 total parts
- Many moving parts
- 2000 Operation
- Three phase operation only



Magnetic actuator

- One moving part
- No maintenance
- 10,000 Operation
- Single and three phase

Oil Reclosers vs. Solid Dielectric

Oil

- Lower interrupting ratings
- Clearing time / coordination can vary depending on temperature and condition of oil
- Reclosing must be delayed on older units without vacuum bottles to allow for out gassing
- 2000 Operations or less
- Requires 5 – 7 year maintenance schedule

Magnetic Actuation, Solid Dielectric

- High fault interrupting capability
- High load current rating
- One size fits all amp rating (interchangeability)
- Low maintenance costs
- Environmentally friendly

Medium Voltage Vacuum Breakers

- 15kV/27kVBreaker
  - Single Bottle design
  - 15kV & 27kV
  - Stored Energy or magnetic Mechanism
- 38 KV Breaker
  - 38kV
  - Two bottle per phase design
  - Stored Energy or Magnetic Mechanism
- Vacuum Interruption
- Definite purpose rated – ANSI C37.06 – 2000 Table 2A

MV Breaker Ratings

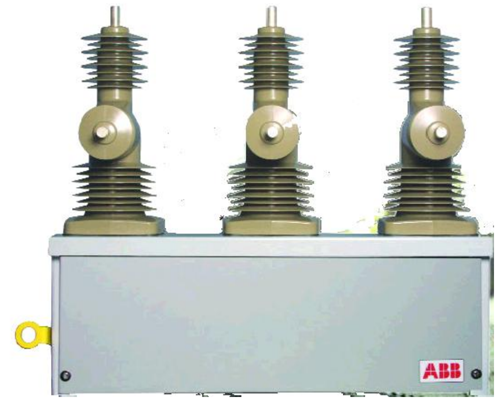
	Type X	R-MAG	Type R	R-MAG	Type V
Voltage , kV	15	15	27	27	38
Continuous Current, A	600 / 1200 / 2000 / 3000	600 / 1200 / 2000 / 3000	1200 / 2000	1200 / 2000	1200 / 2000
Interrupting, kA	12 - 25	12 - 25	12 - 20	12 - 25	25 - 40
BIL	110	110	125 - 150	125 - 150	150 - 200

BIL (Basic Impulse Level): Impulse withstand voltage

Type V two bottle design allows for back-to-back capacitor switching up to 1200 A

Automatic Recloser

- Improve reliability of service
- Pole-top mounting - eliminates need to build substation
- Three-phase unit can replace breaker in substation for lower current ratings



Three Phase


Single Phase

- Breakers and Reclosers provide the physical interruption

- Both require a protective relay to signal when to operate

Distribution Circuit Protective Relays

WHAT IS RELAYING

Relays

Relays are electromechanical, solid-state (static) or microprocessor-based (digital/numerical) devices that are used throughout the power system to detect abnormal and unsafe conditions and take corrective action

Classification of Relays - Defined in IEEE C37.90

Classification by Function

- **Protective** - Detects intolerable conditions and defective apparatus.
- **Monitoring** - Verify conditions in the protection and/or power system.
- **Reclosing** - Establish closing sequences for a circuit breaker following a protective relay trip.
- **Regulating** - Operates to maintain operating parameters within a defined region.
- **Auxiliary** - Operates in response to other [relay] actions to provide additional functionality
- **Synchronizing** - Assures that proper conditions exist for interconnecting two sections of the power system.

Classification of Relays

Classification by Input

- Current (Generator, Motor, Transformer, Feeder)
- Voltage (Generator, Motor, Transformer, Feeder)
- Power (Generator, Motor, Transformer, Feeder)
- Frequency (Generator, Motor, Feeder)
- Temperature (Generator, Motor, Transformer)
- Pressure (Transformer)
- Flow (Generator, Motor, Transformer, Feeder)
- Vibration (Generator, Motor)

Classification of Relays

Classification by Performance Characteristics

- Overcurrent
- Over/under voltage
- Distance
- Directional
- Inverse time, definite time
- Ground/phase
- High or slow speed
- Current differential
- Phase comparison
- Directional comparison

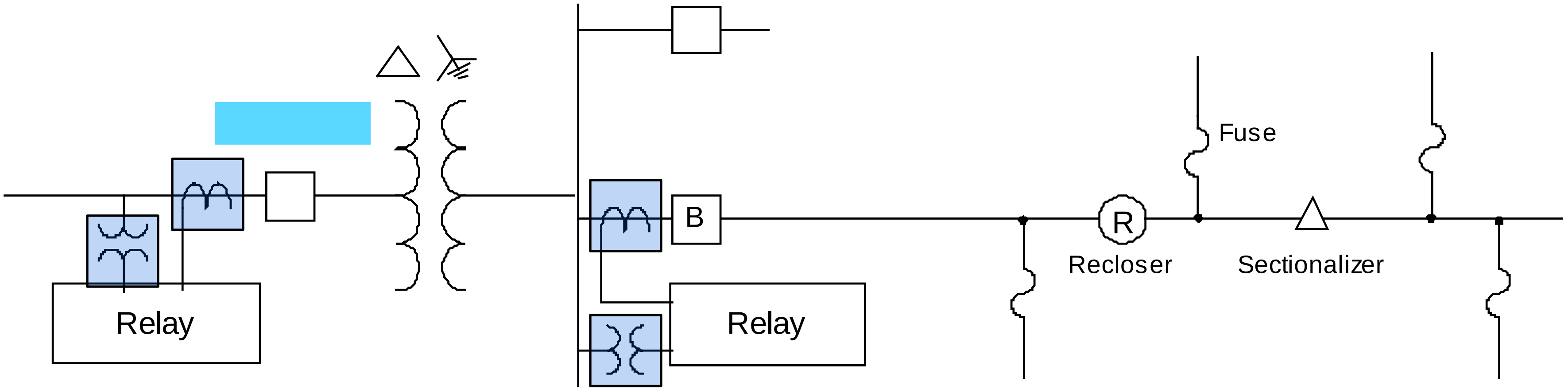
Classification of Relays

Classification by Technology

- Electromechanical
- Solid state (Static)
- Microprocessor-based (Digital/Numerical)

Relay Input Sources

Typical Distribution Substation Feeder Circuit



Purpose

- Provide input signal (replica of power system voltage and current) to Relays
  - Reduce level - suitable for relays (typically 120V and 69V depending on line-line or line to neutral connection)
  - Provide isolation

Types

- Voltage transformation
  - Electromagnetic voltage transformer
  - Coupling capacitance voltage transformer
  - Optical voltage transformer
- Current transformation
  - Electromagnetic current transformer
  - Optical current transformer
  - Rogowski coil

Voltage (potential) Transformer (VT/PT)

- Do not differ materially from constant-potential power transformers except
  - Power rating is small
  - Designed for minimum ratio & phase angle error

Current Transformer Basics

- Current or series transformer primary connected in series with the line
- Ratio of transformation is approximately inverse ratio of turns. i.e 2000/5
- Differs from constant-potential transformer
  - Primary current is determined entirely by the load on the system and not by its own secondary load

Current Transformer Basics

- Secondary winding **should never** be open-circuited
  - Flux in the core, instead of being the difference of the primary & secondary ampere-turns, will now be due to the total primary ampere-turns acting alone
  - This causes a large increase in flux, producing excessive core loss & heating, as well as high voltage across the secondary terminals

$$V_{CD} = V_S = I_L(Z_L + Z_{lead} + Z_B)$$

$$V_{CD} = V_S = I_L(Z_L + Z_{lead} + \infty)$$

Where Z_B is the load presented to the CT by the relay.

Steady State Performance of CT

- ANSI accuracy classes
  - Class C indicates that the leakage flux is negligible and the excitation characteristic can be used directly to determine performance. The Ct ratio error can thus be calculated. It is assumed that the burden and excitation currents are in phase and that the secondary winding is distributed uniformly.

Steady State Performance of CT

- ANSI accuracy classes

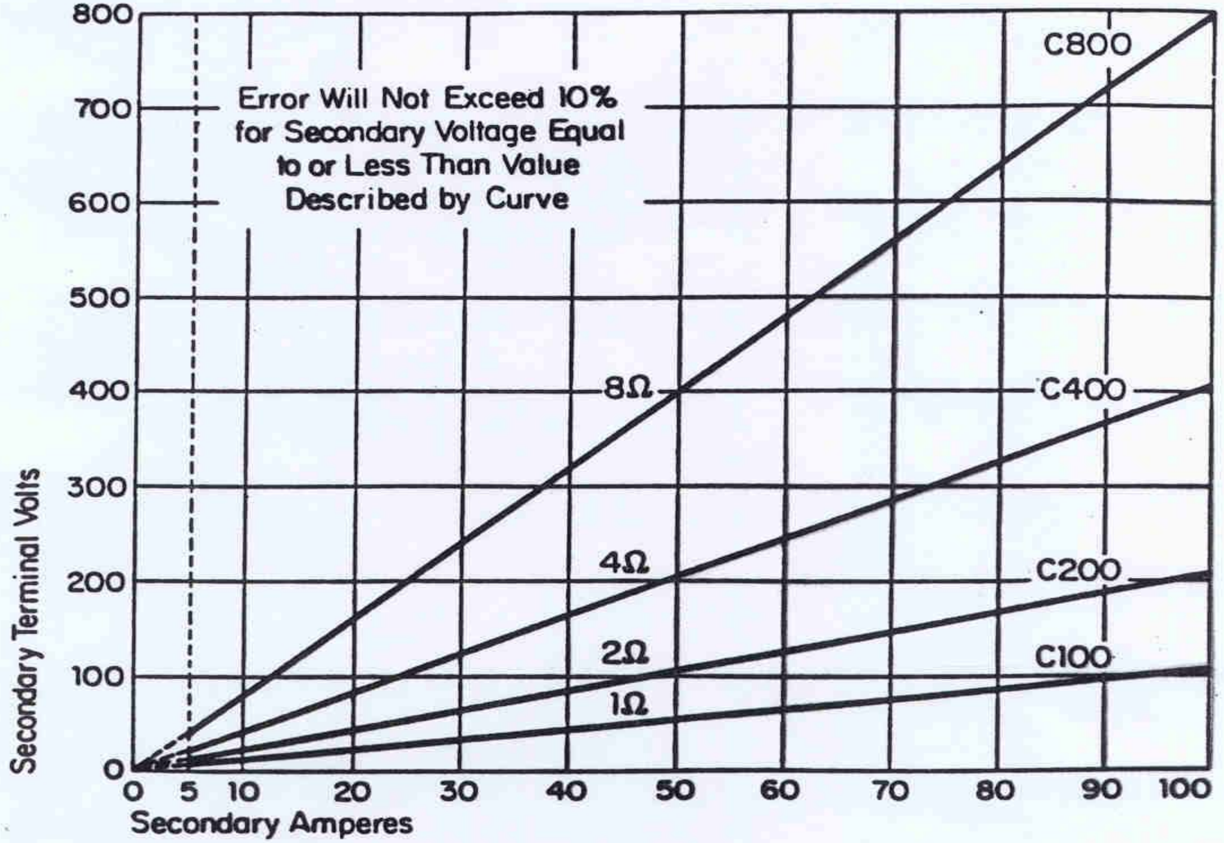


Figure 5-6 ANSI accuracy standard chart for class C current transformers.

D.C. Saturation of a CT

Saturation of a CT may occur as a result of any one or combination of:

- Off-set fault currents (dc component)
- Residual flux in the core

D.C. Saturation Effect in Current

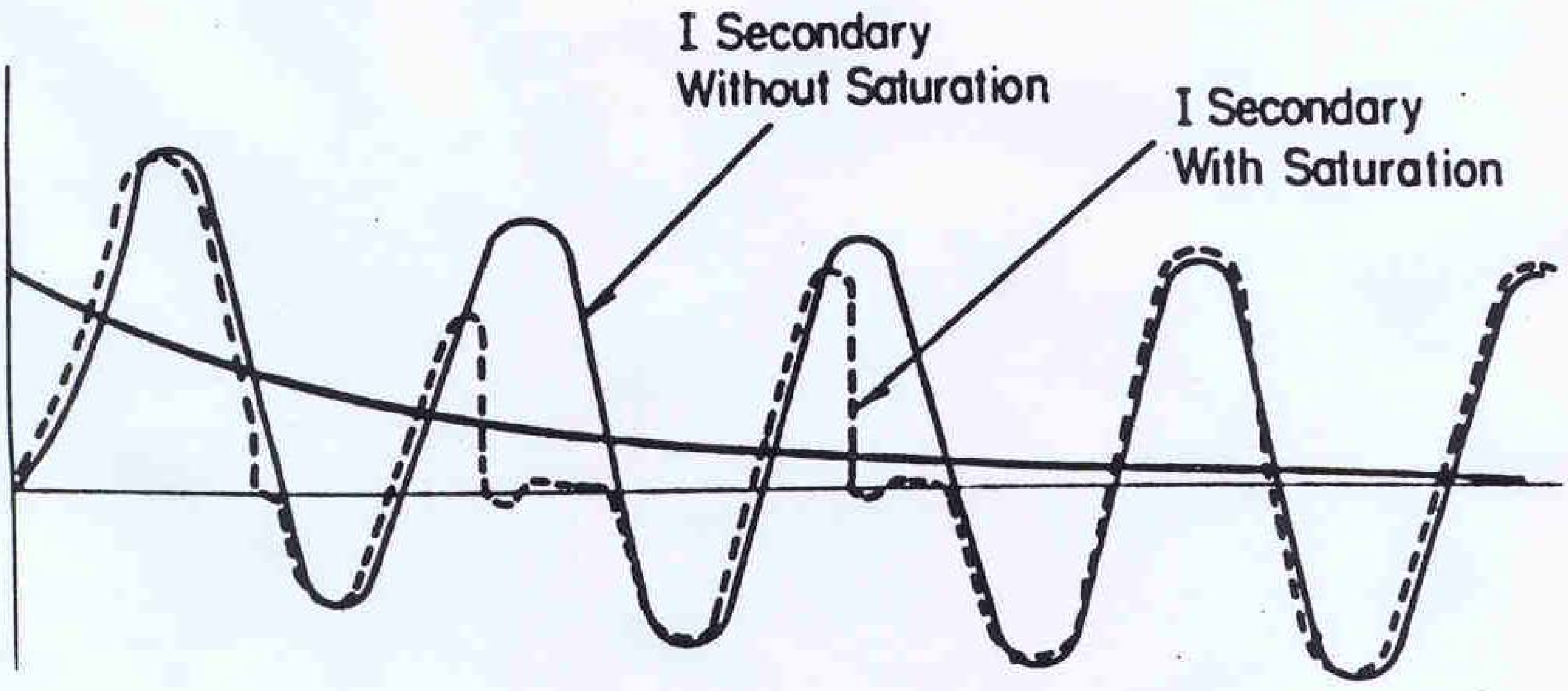
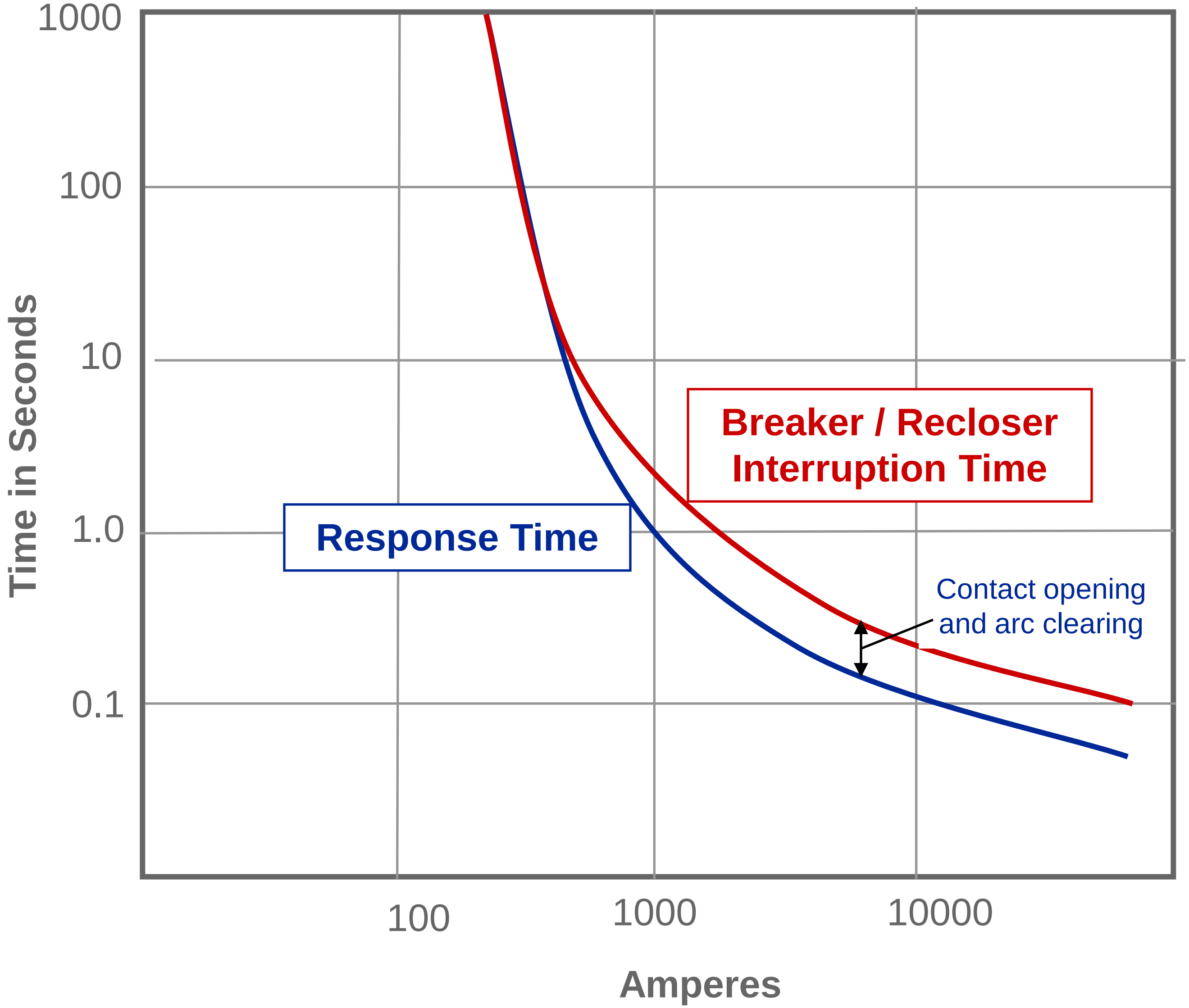


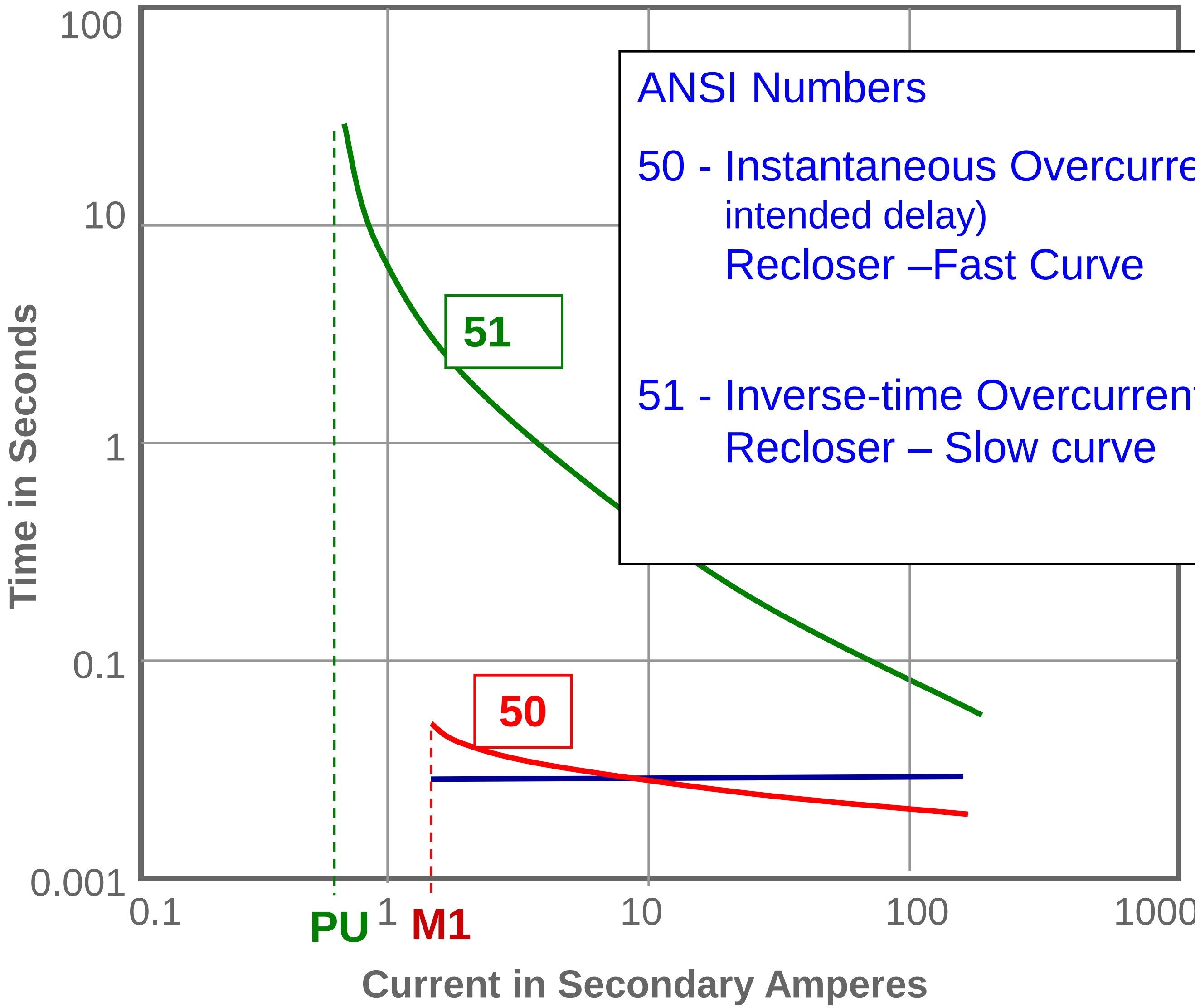
Figure 5-9 Dc saturation of current transformer.

Over Current Relay Characteristics

Recloser or Breaker Relay Characteristic



Overcurrent Current Device Characteristics

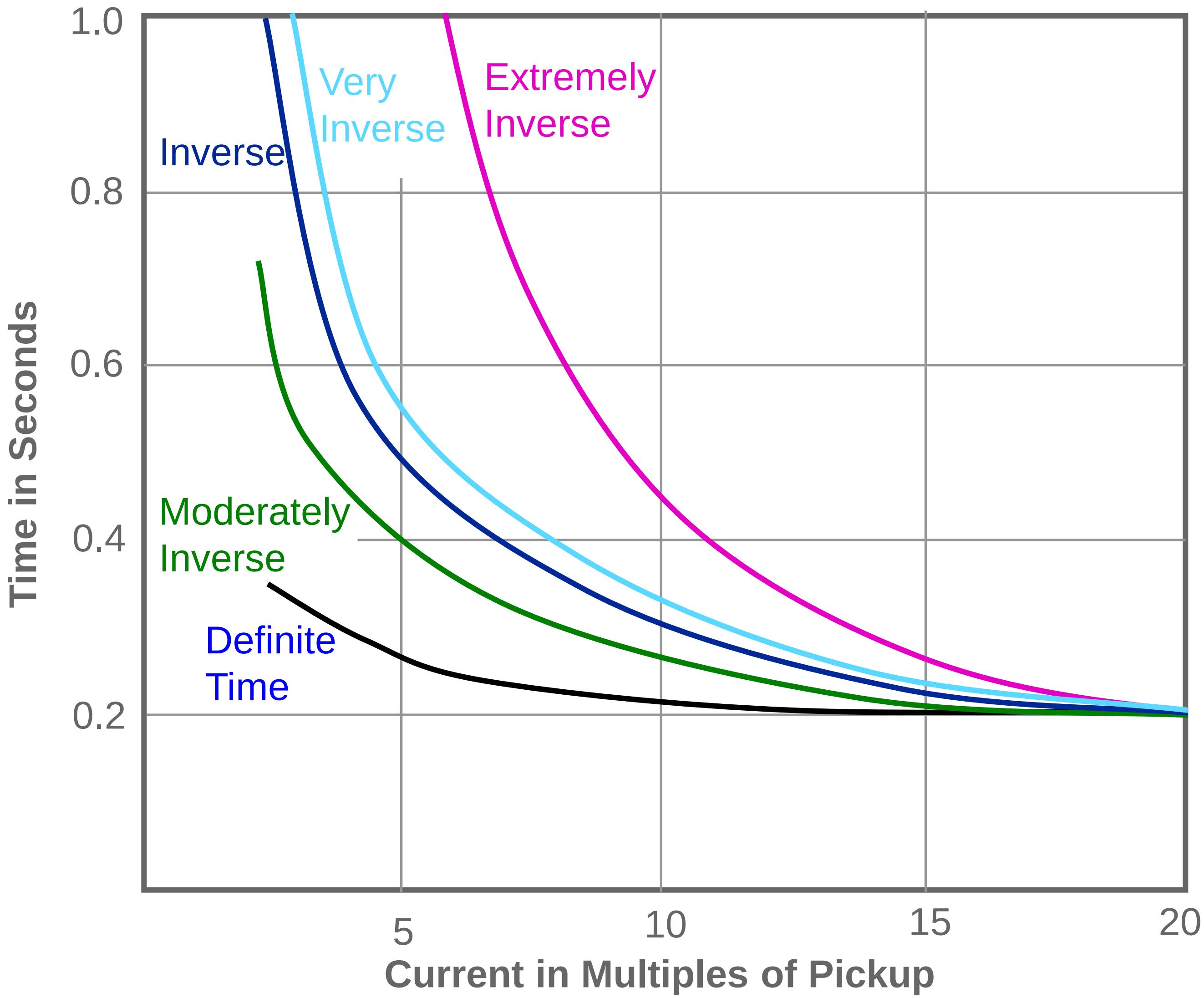


ANSI Numbers

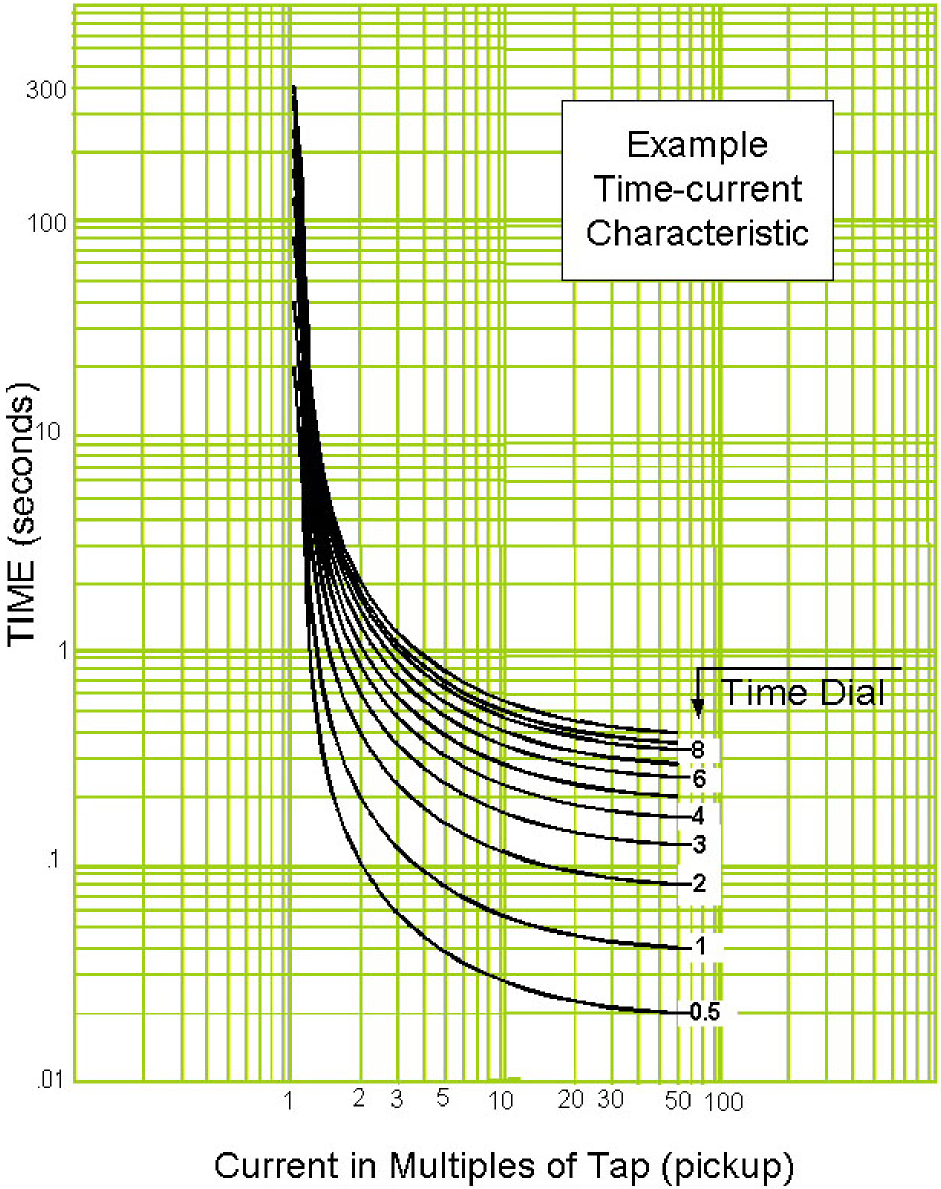
50 - Instantaneous Overcurrent (No intended delay)
Recloser –Fast Curve

51 - Inverse-time Overcurrent
Recloser – Slow curve

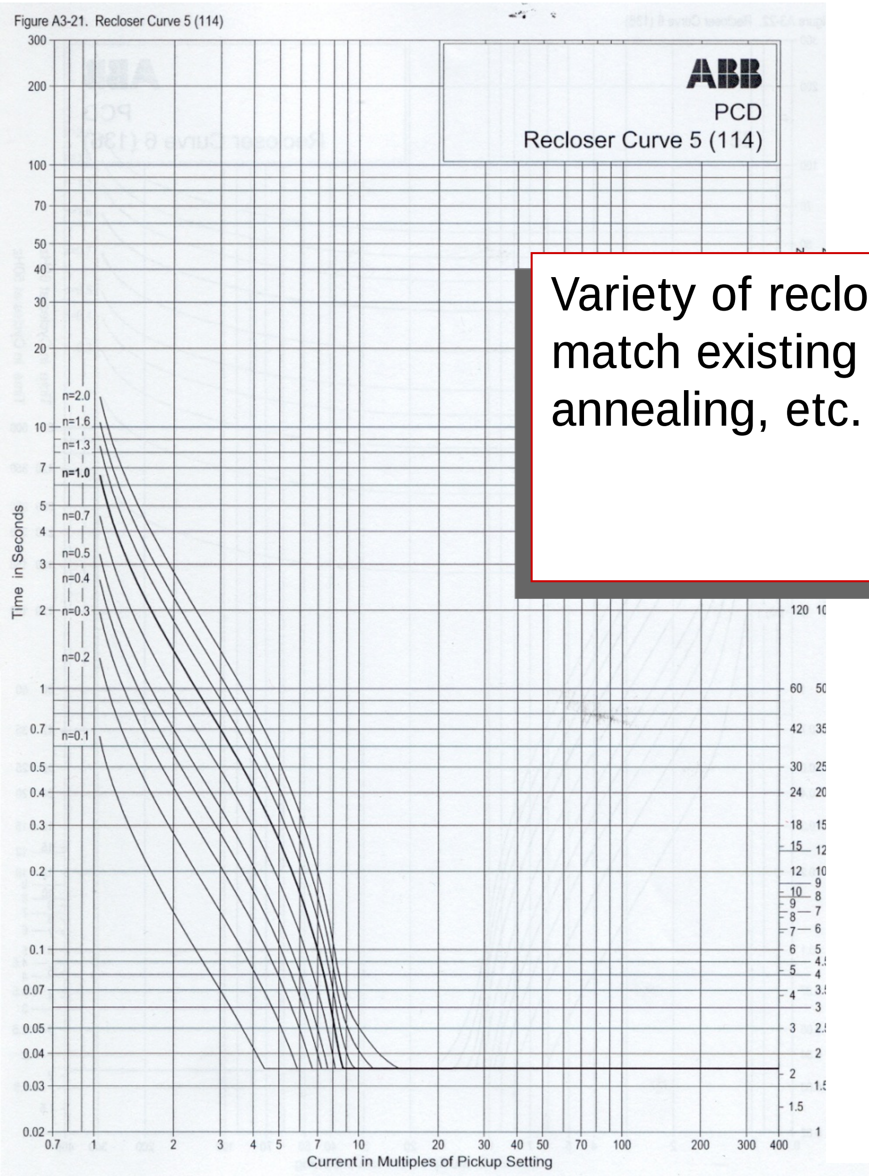
Time Overcurrent Curves

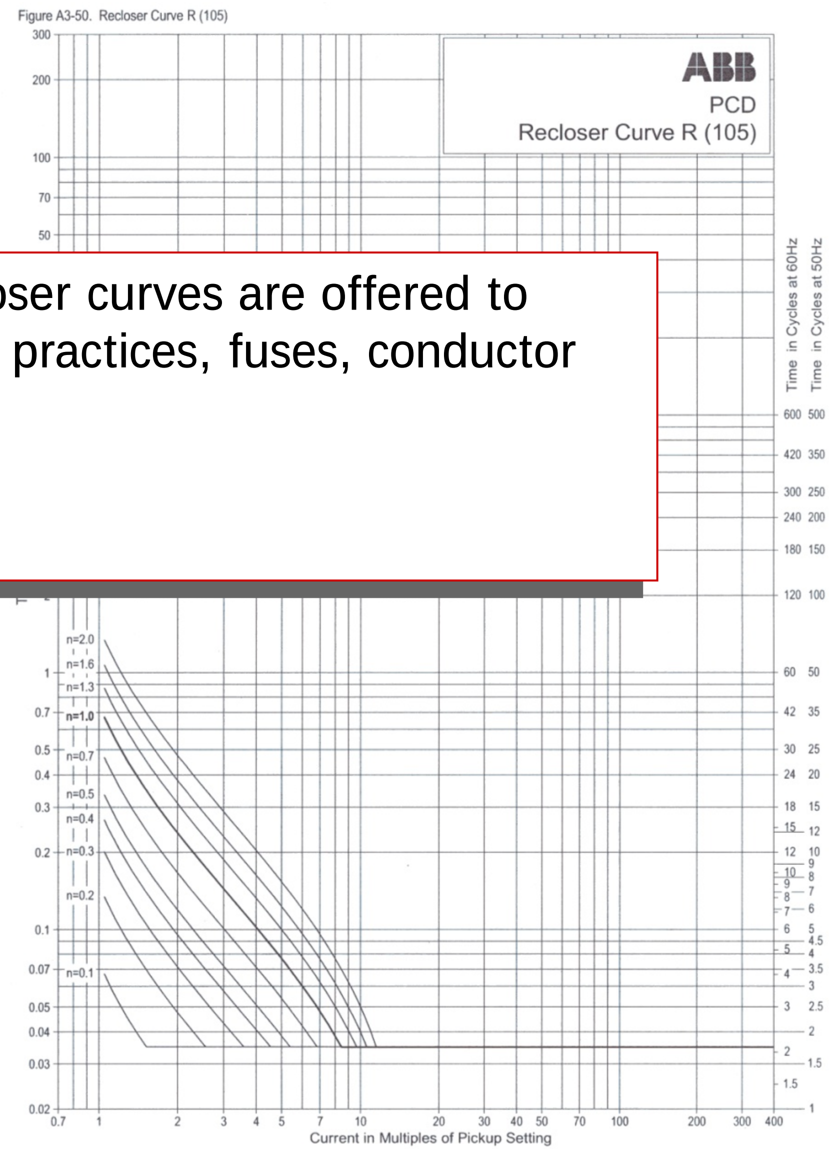


Time Overcurrent Curve – Time Dial



Recloser Curves





Variety of recloser curves are offered to match existing practices, fuses, conductor annealing, etc.

Distribution Feeder Phase Protection

- Pickup tap setting typically is 2, but never less than 1.5, times the normal maximum load interruption rating
- Or 1.25 times the short-time maximum load rating of the feeder

Distribution Feeder Ground Protection

Pickup commonly based on one of the following

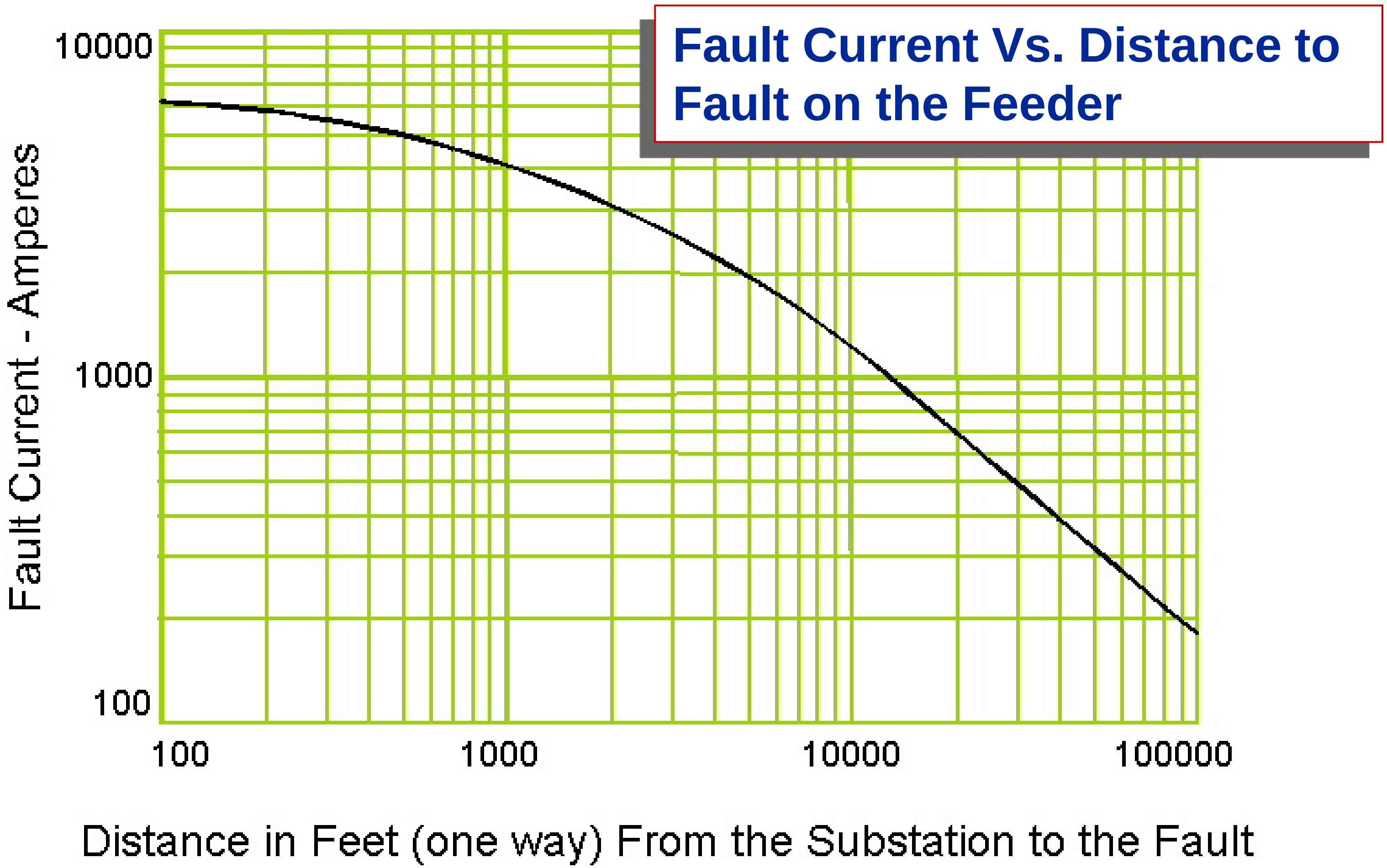
- % Above estimated normal load unbalance
- % Above estimated load unbalance due to switching
- % Of the phase overcurrent pickup
- % Of the feeder emergency load rating
- % Of the feeder normal load rating

Permissible Unbalance

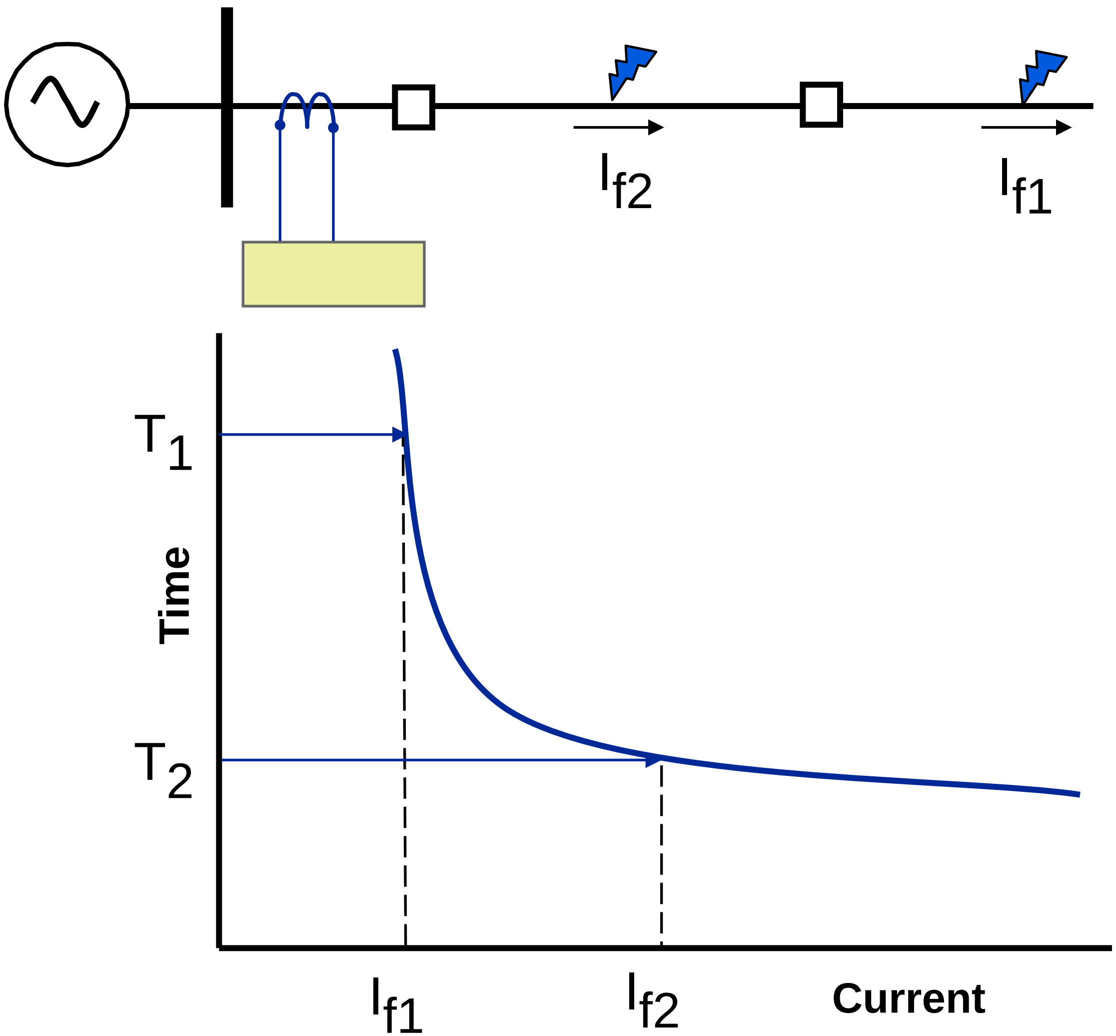
- Not above 25% of load current is typical rule-of-thumb, but some allow up to 50%
- Pickup setting of ground element to be 2 - 4 times the permissible unbalance

Principles of Feeder Coordination

Principles of Feeder Coordination

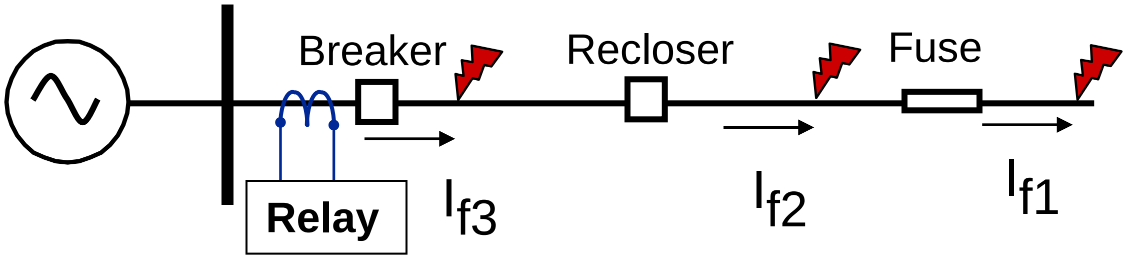


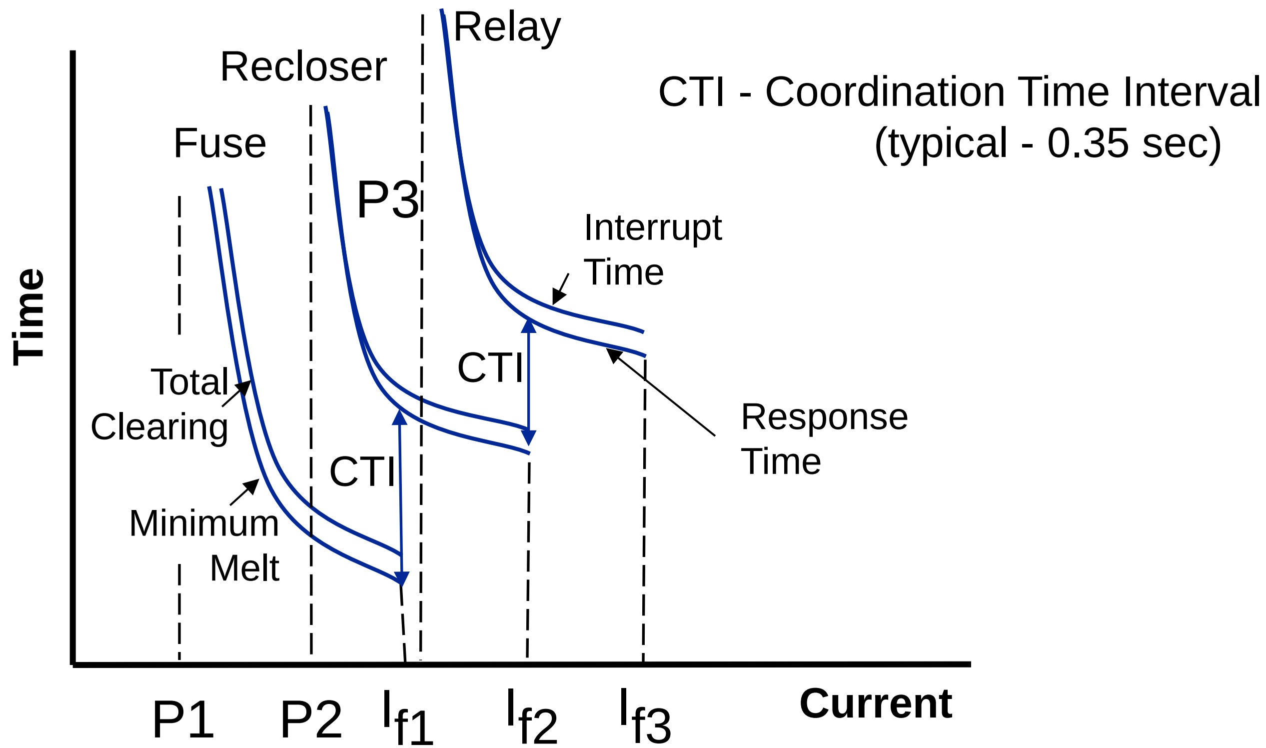
Principles of Feeder Coordination



51 – Inverse time-overcurrent characteristic

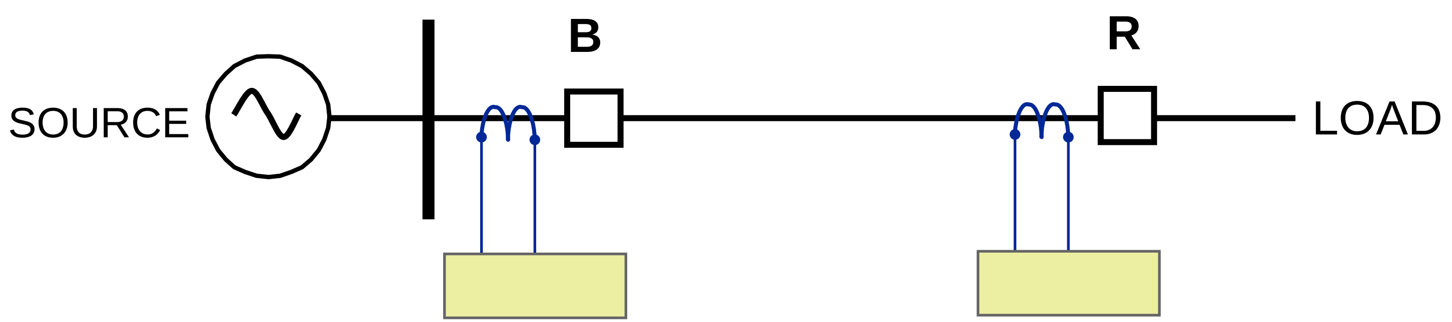
Principles of Feeder Coordination





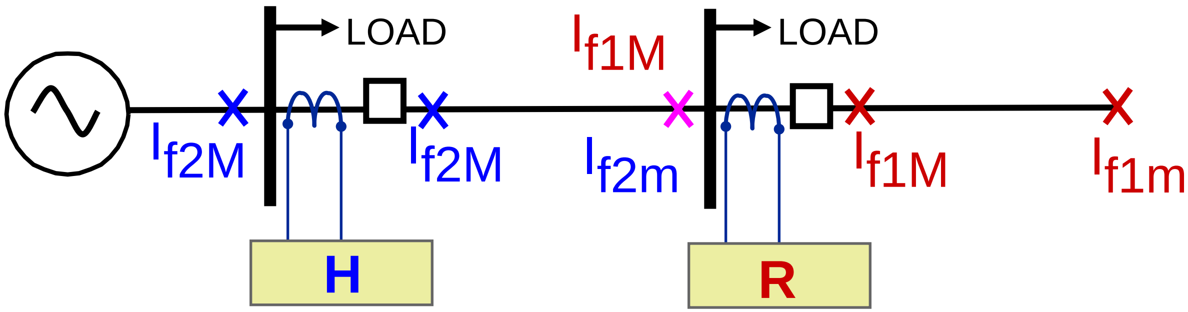
Principles of Feeder Coordination

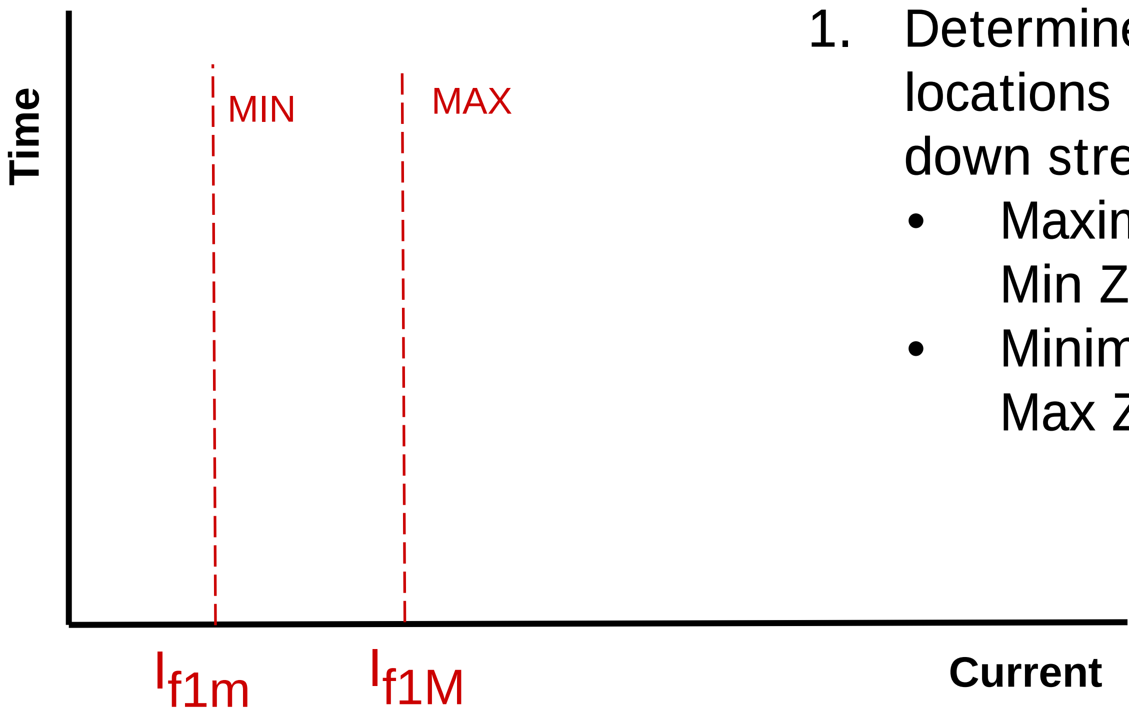
Coordination Terminology



Upstream	Downstream
Source-side	Load-side
Protected	Protecting
Backup	Down-line
	Local (where you are)

Principles of Feeder Coordination





1. Determine critical fault current locations and values of most down stream device, and plot
   - Maximum – I_{f1M}
     Min Zs, at device
   - Minimum – I_{f1m}
     Max Zs, end of segment

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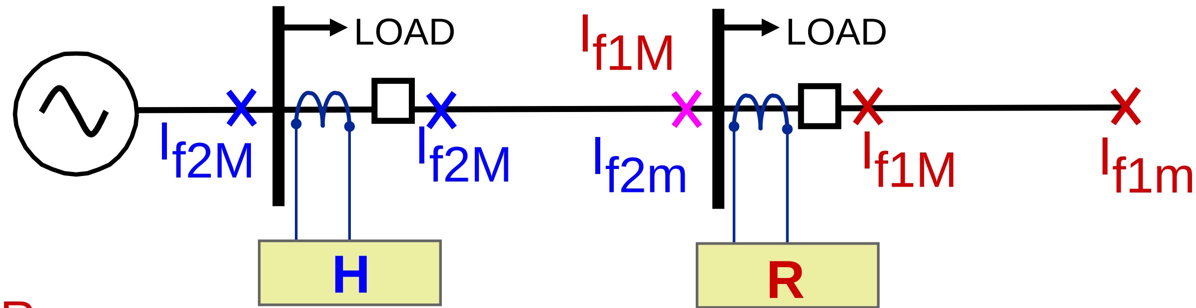

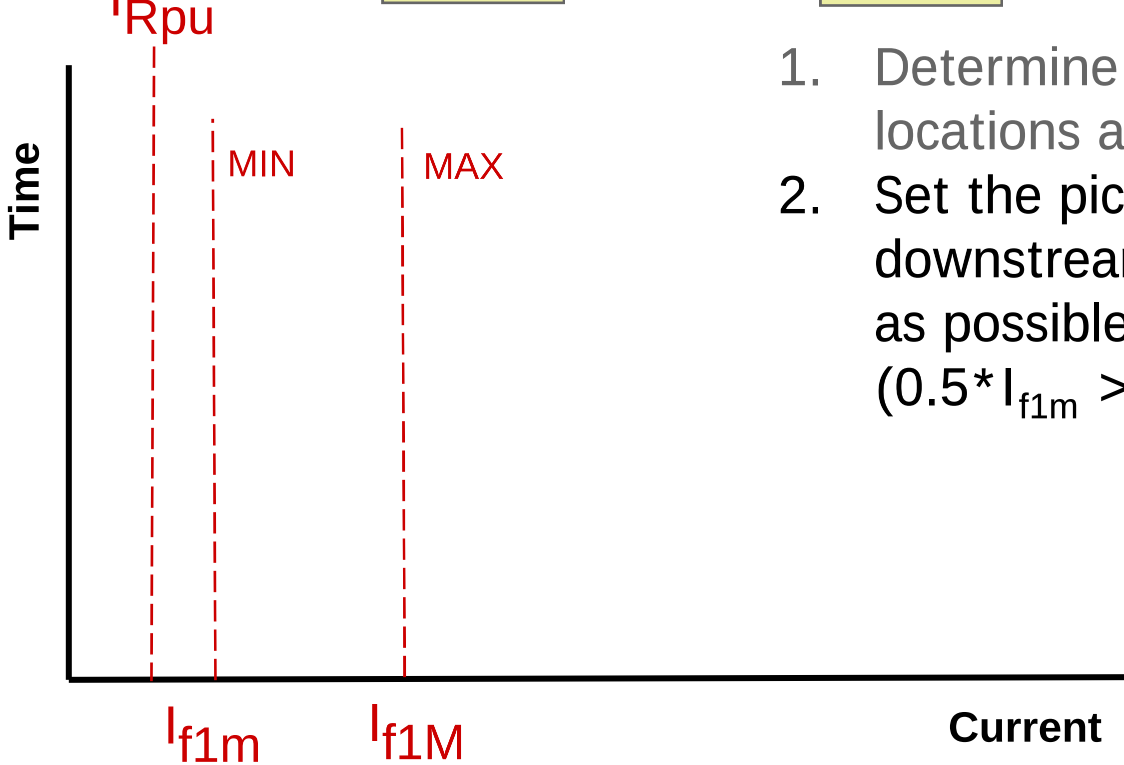

1. Determine critical fault current locations and values, and plot.
2. Set the pickup of the most downstream device as sensitive as possible
   ($0.5 * I_{f1m} > I_{Rpu} > 2 * LOAD$)

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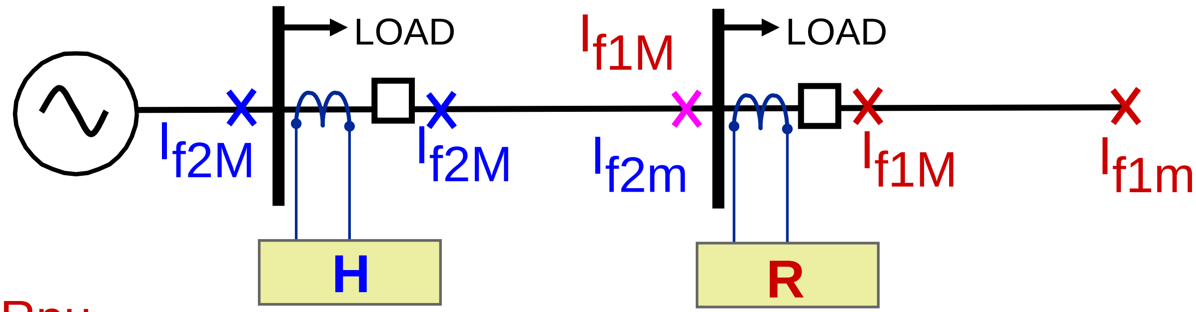

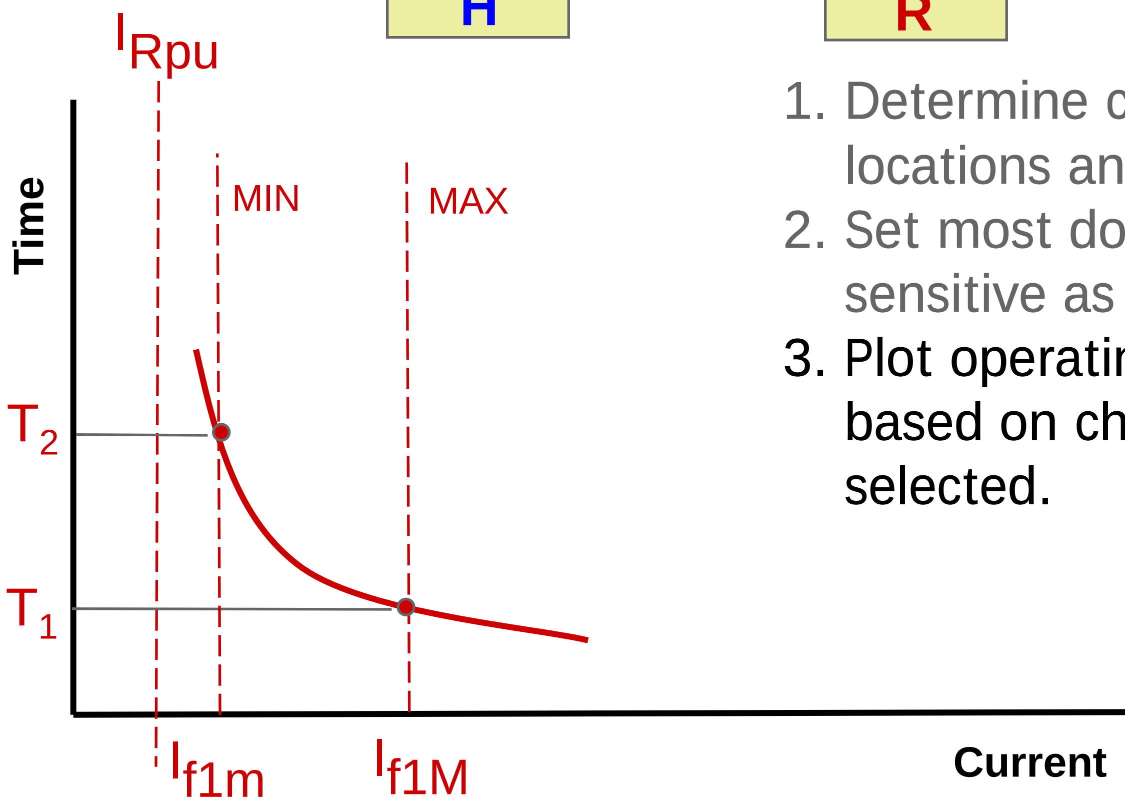

1. Determine critical fault current locations and values, and plot.
2. Set most downstream device as sensitive as possible.
3. Plot operating times of Relay R based on characteristic of device selected.

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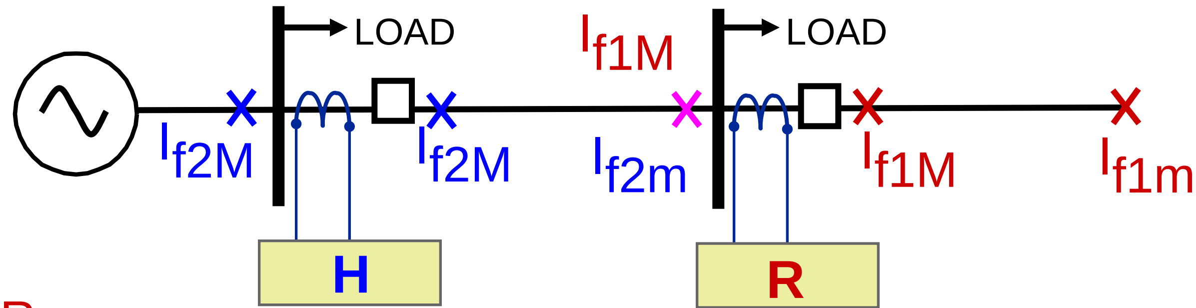
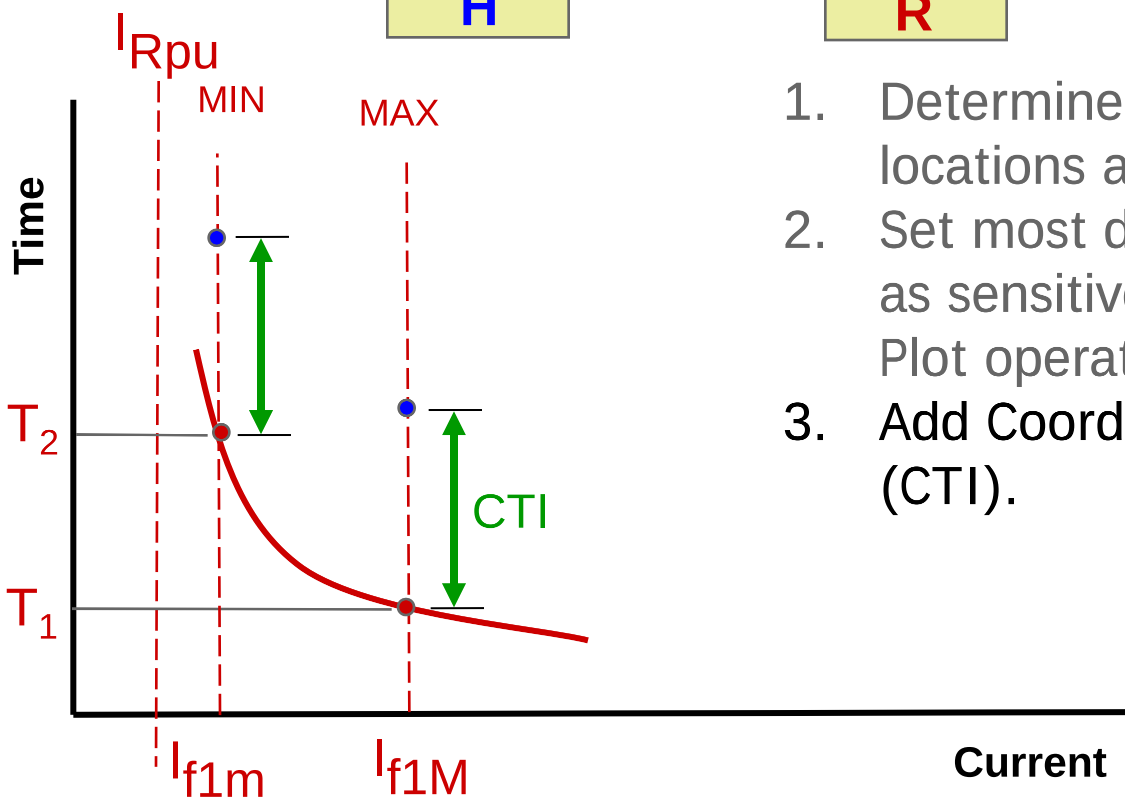
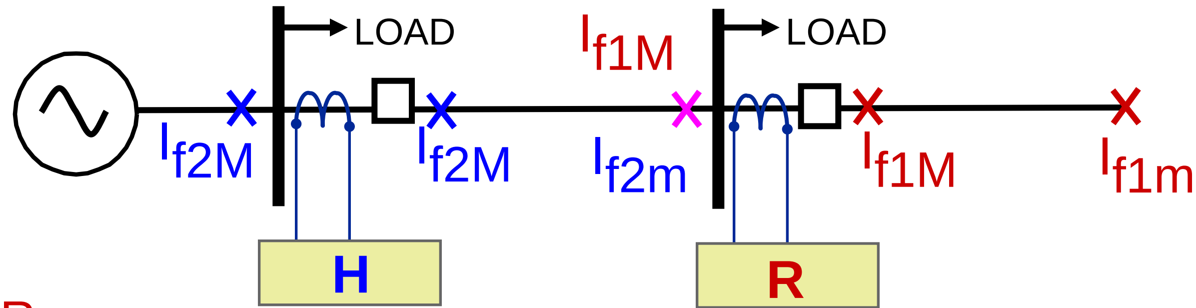
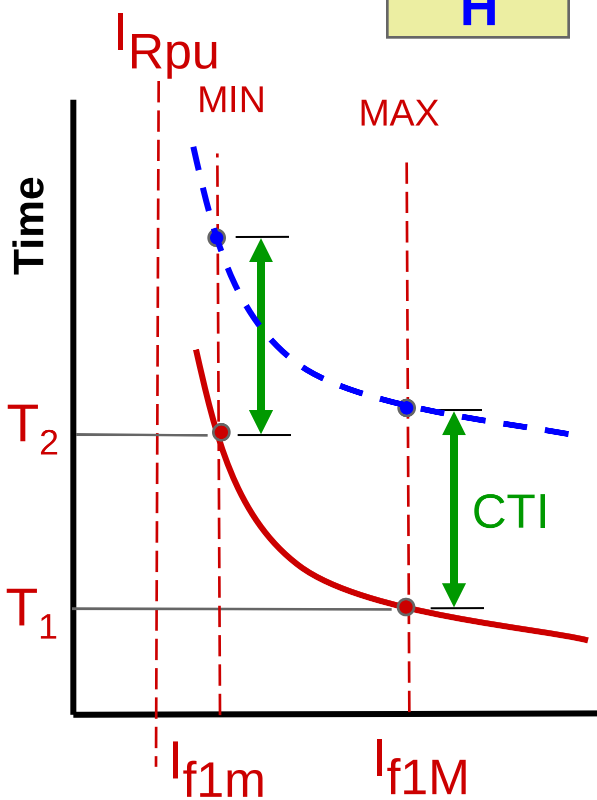




1. Determine critical fault current locations and values, and plot.
2. Set most downstream device as sensitive as possible.
   Plot operating times of Relay R.
3. Add Coordination Time Interval (CTI).

Principles of Feeder Coordination





Coordination Time Interval

CTI is the minimum time interval added to the local device (relay/breaker, fuse) that permits coordination with the next remote upstream device. Coordination is achieved where the remote device will not [normally] operate for faults downstream of the local device, but will operate for all faults between the two.

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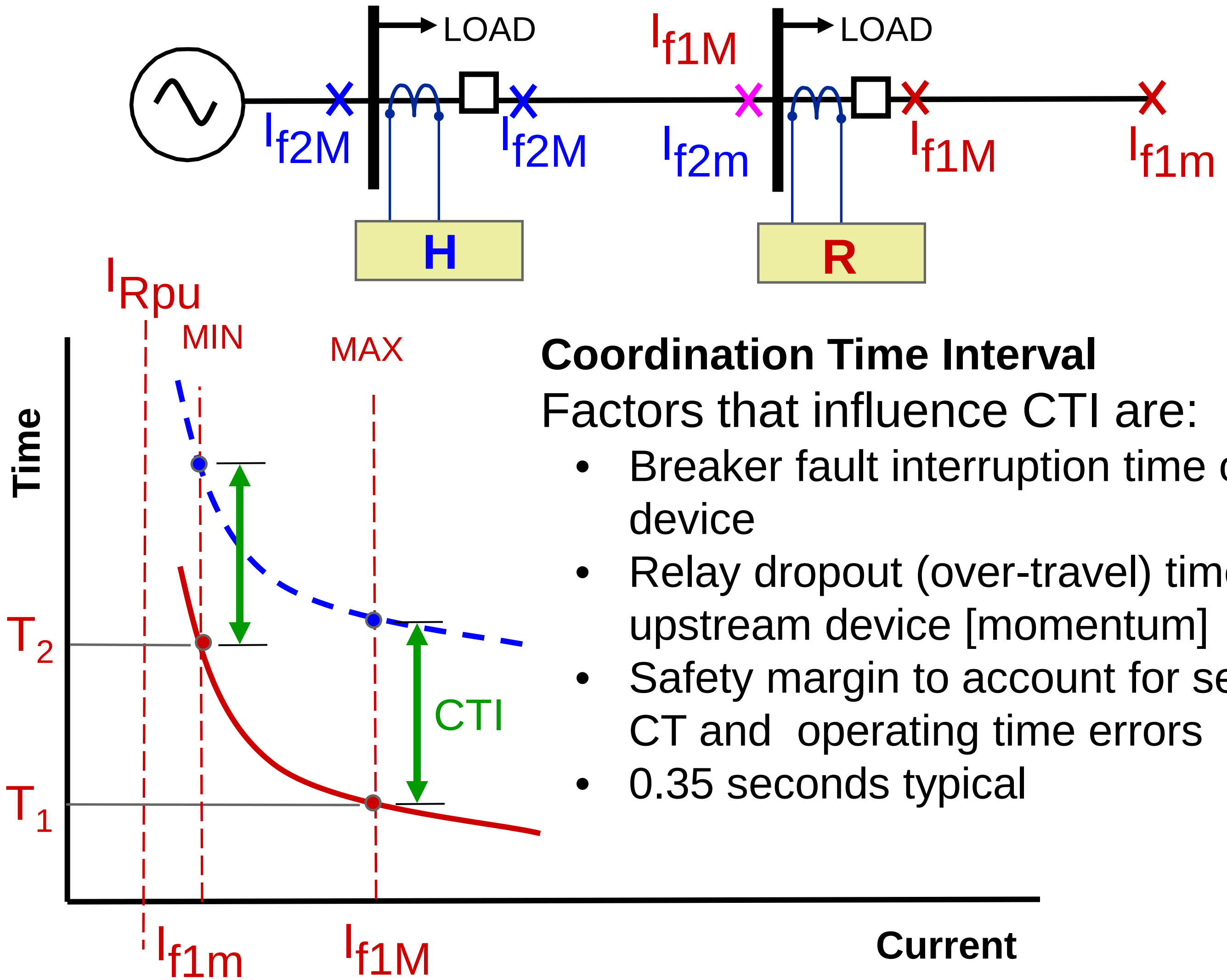

Coordination Time Interval

Factors that influence CTI are:

- Breaker fault interruption time of upstream device
- Relay dropout (over-travel) time of upstream device [momentum]
- Safety margin to account for setting, tap, CT and operating time errors
- 0.35 seconds typical

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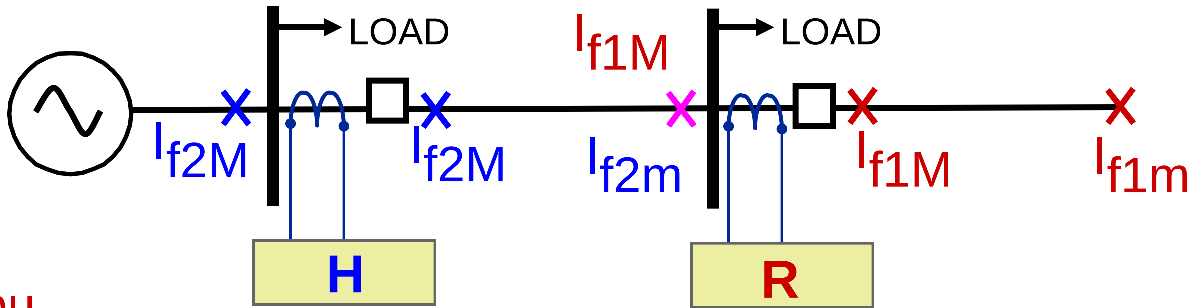

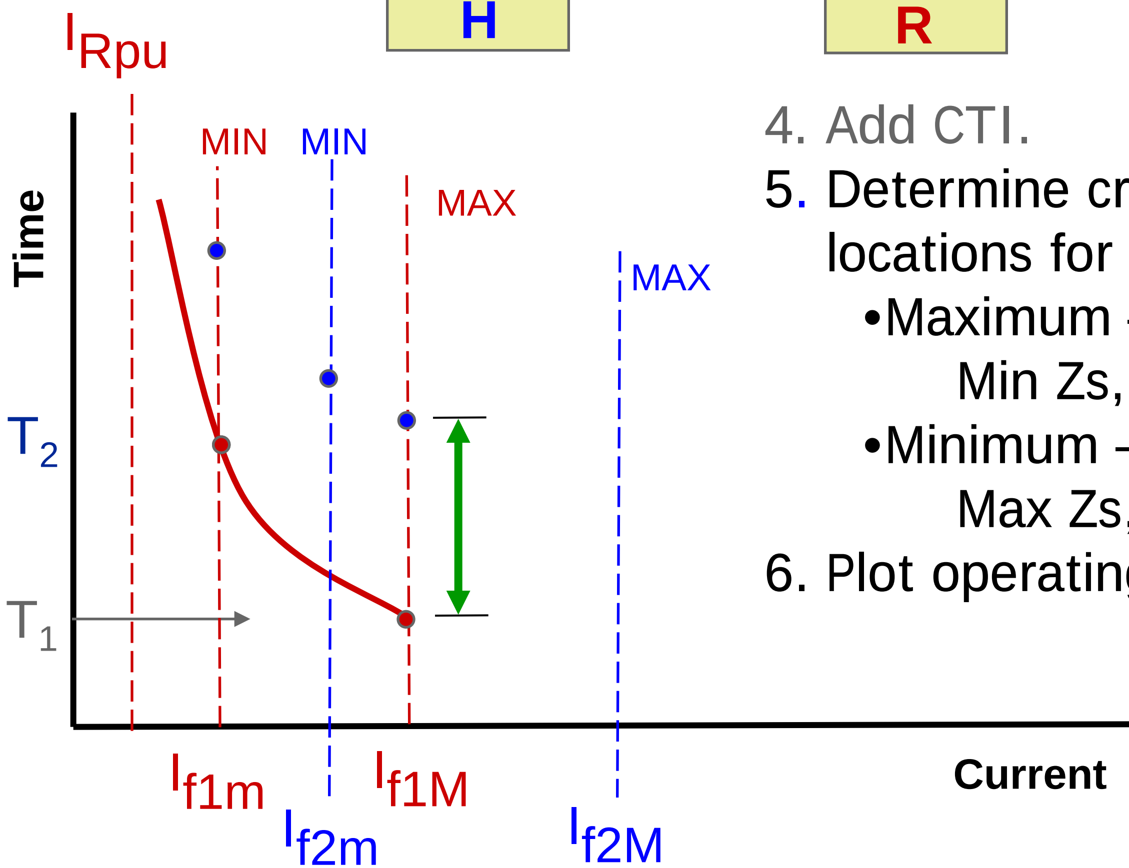

4. Add CTI.
5. Determine critical fault current locations for device H, and plot
   - Maximum – I_{f2M}
     Min Zs, at device
   - Minimum – I_{f2m}
     Max Zs, end of segment.
6. Plot operating times for H.

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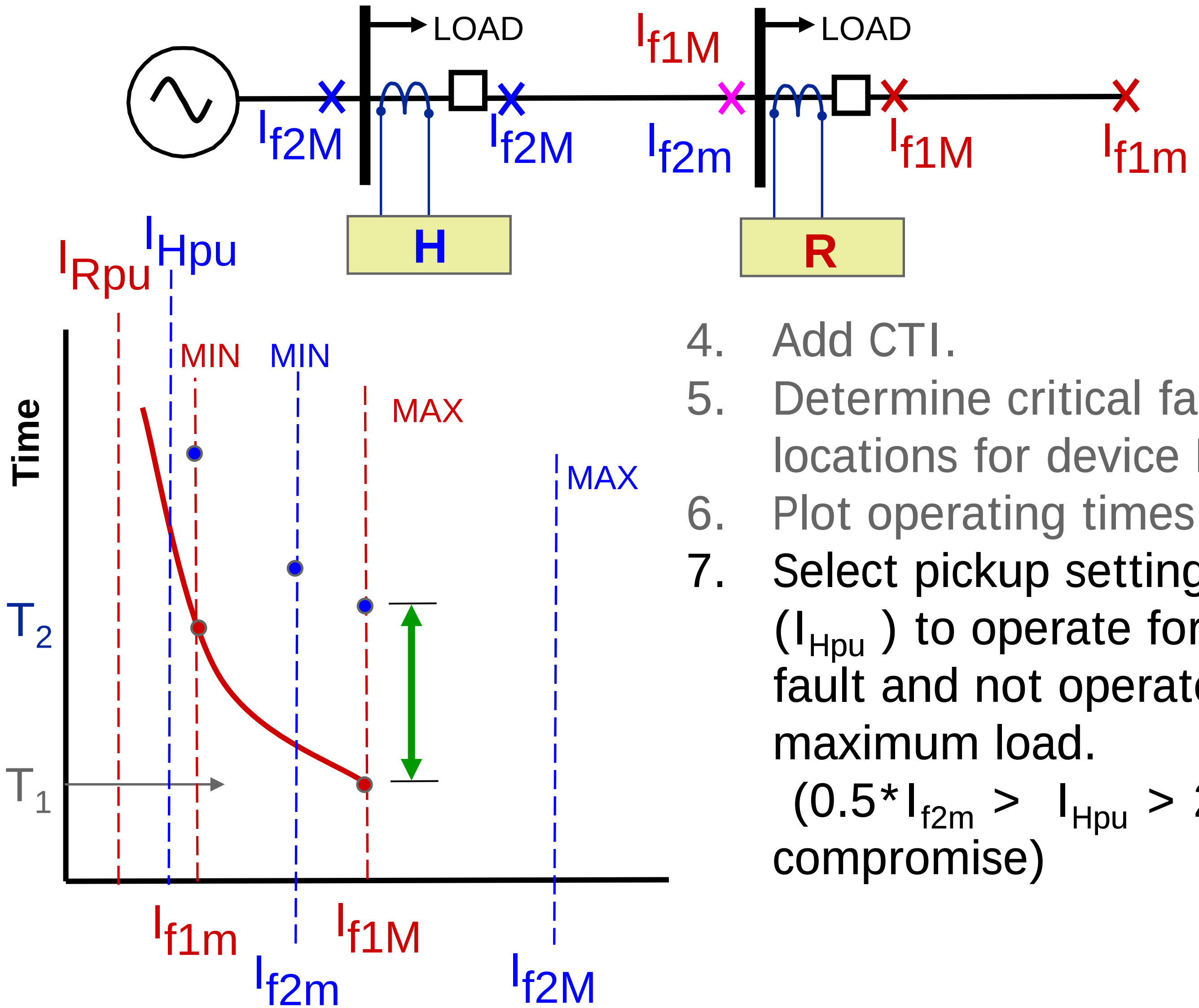
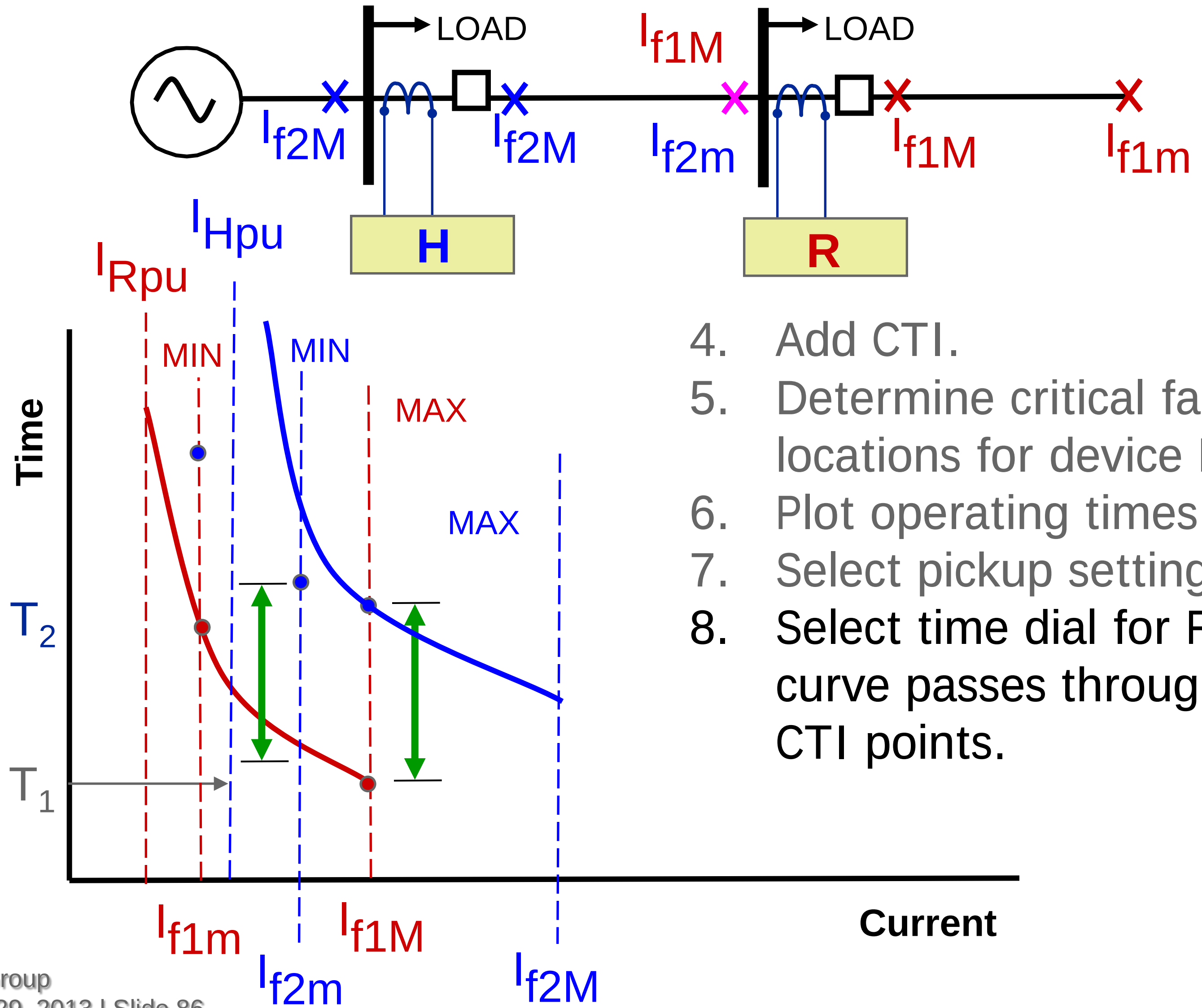


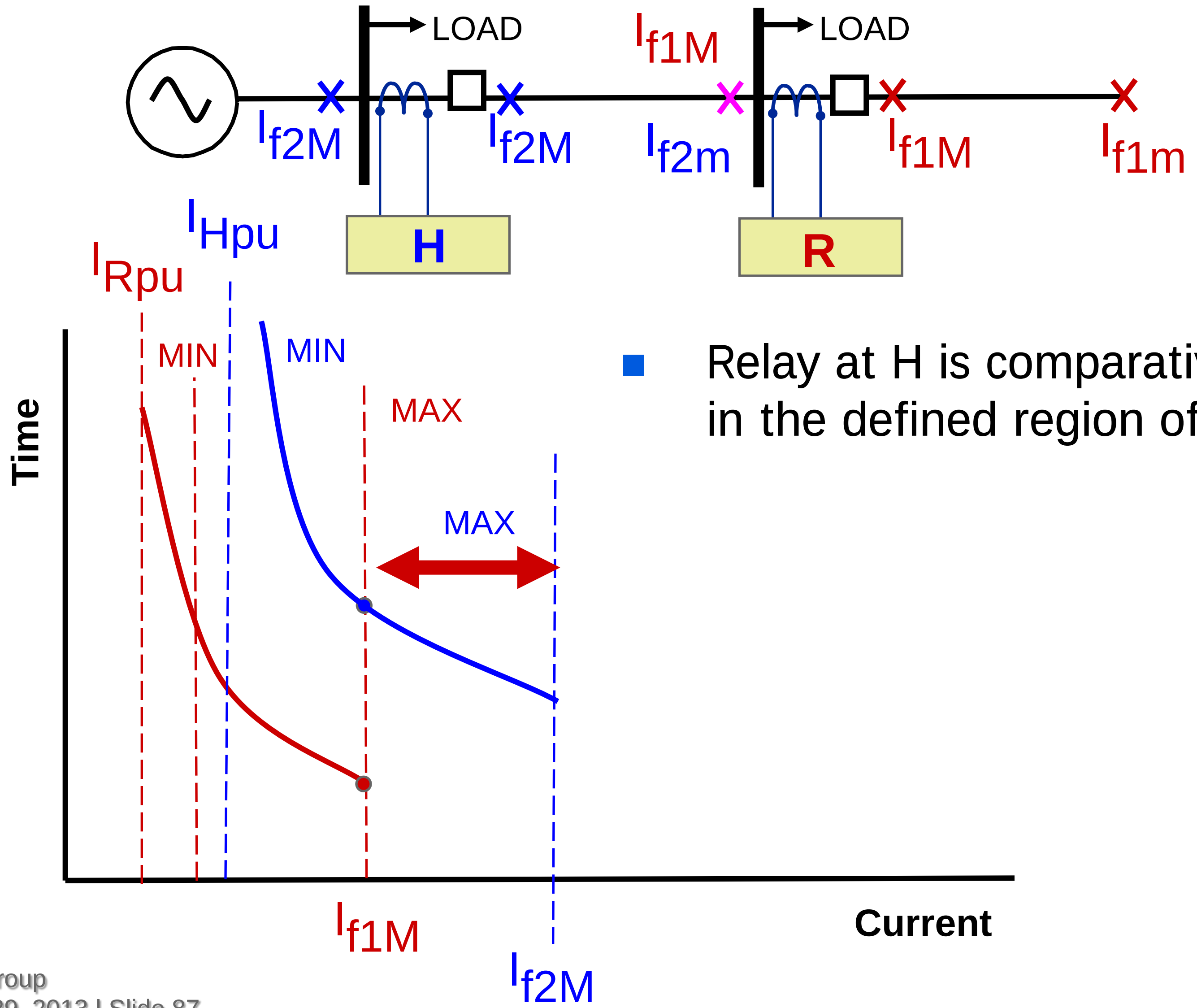
4. Add CTI.
5. Determine critical fault current locations for device H, and plot.
6. Plot operating times of Relay H.
7. Select pickup settings for Relay H (I_{Hpu}) to operate for minimum fault and not operate on maximum load.
 ($0.5*I_{f2m} > I_{Hpu} > 2*$ Load or compromise)

Principles of Feeder Coordination



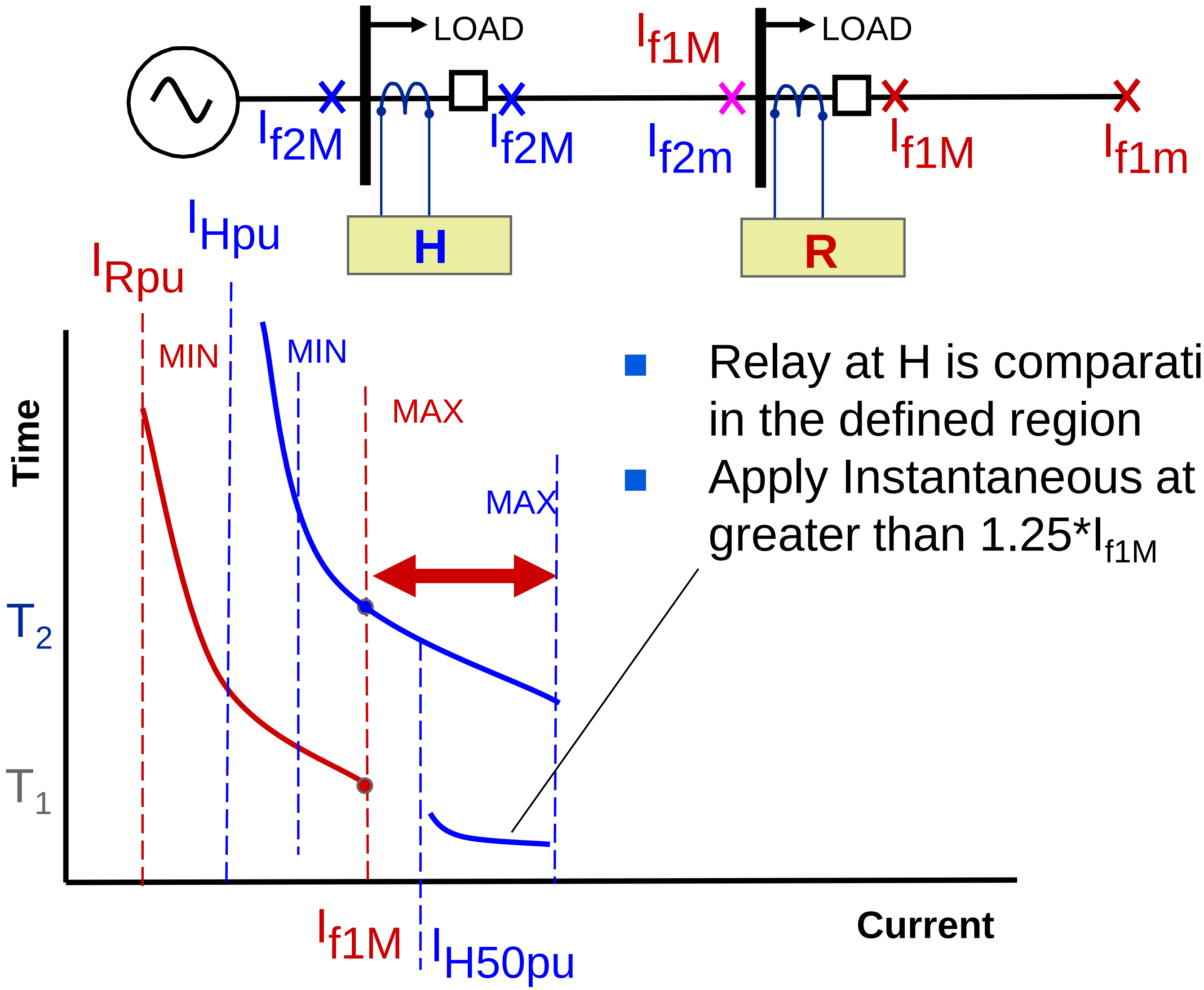
4. Add CTI.
5. Determine critical fault current locations for device H.
6. Plot operating times of Relay H.
7. Select pickup settings for Relay H.
8. Select time dial for Relay H so curve passes through or above all CTI points.

Principles of Feeder Coordination



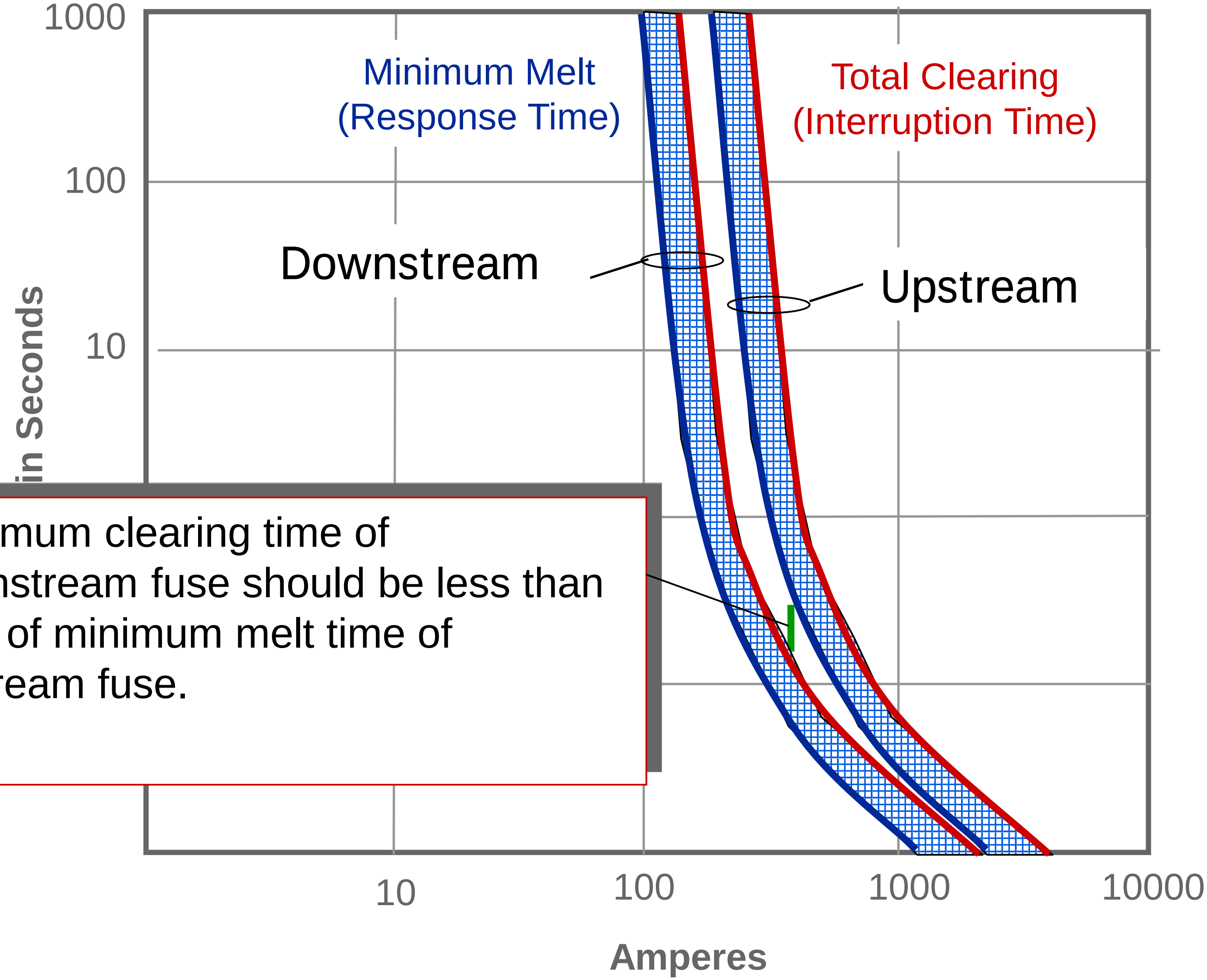
- Relay at H is comparatively slow in the defined region of $I > I_{f1M}$

Principles of Feeder Coordination



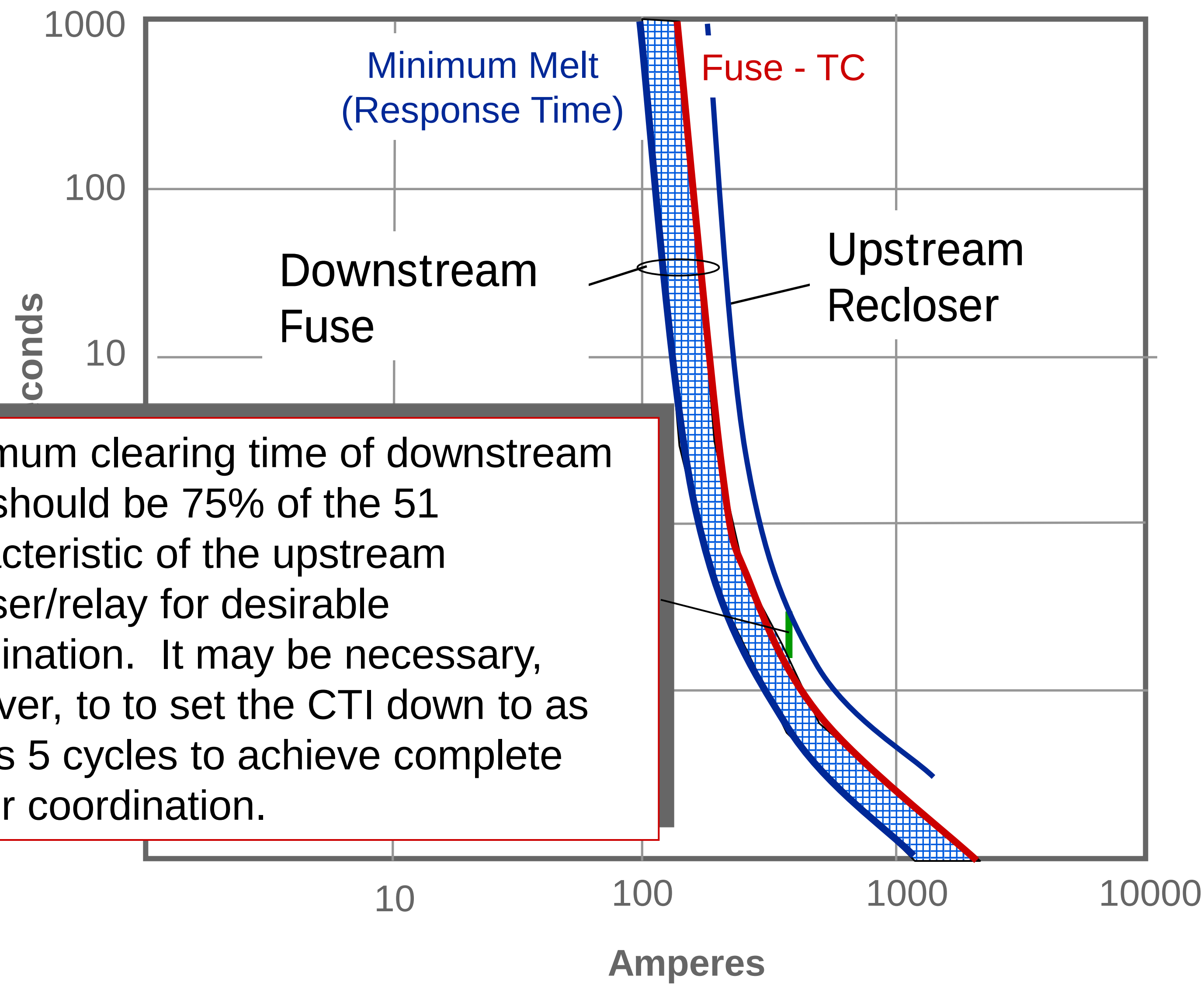
- Relay at H is comparatively slow in the defined region
- Apply Instantaneous at H at value greater than $1.25*I_{f1M}$

Fuse Coordination - Rule of Thumb



Maximum clearing time of downstream fuse should be less than 75% of minimum melt time of upstream fuse.

Fuse Coordination - Rule of Thumb



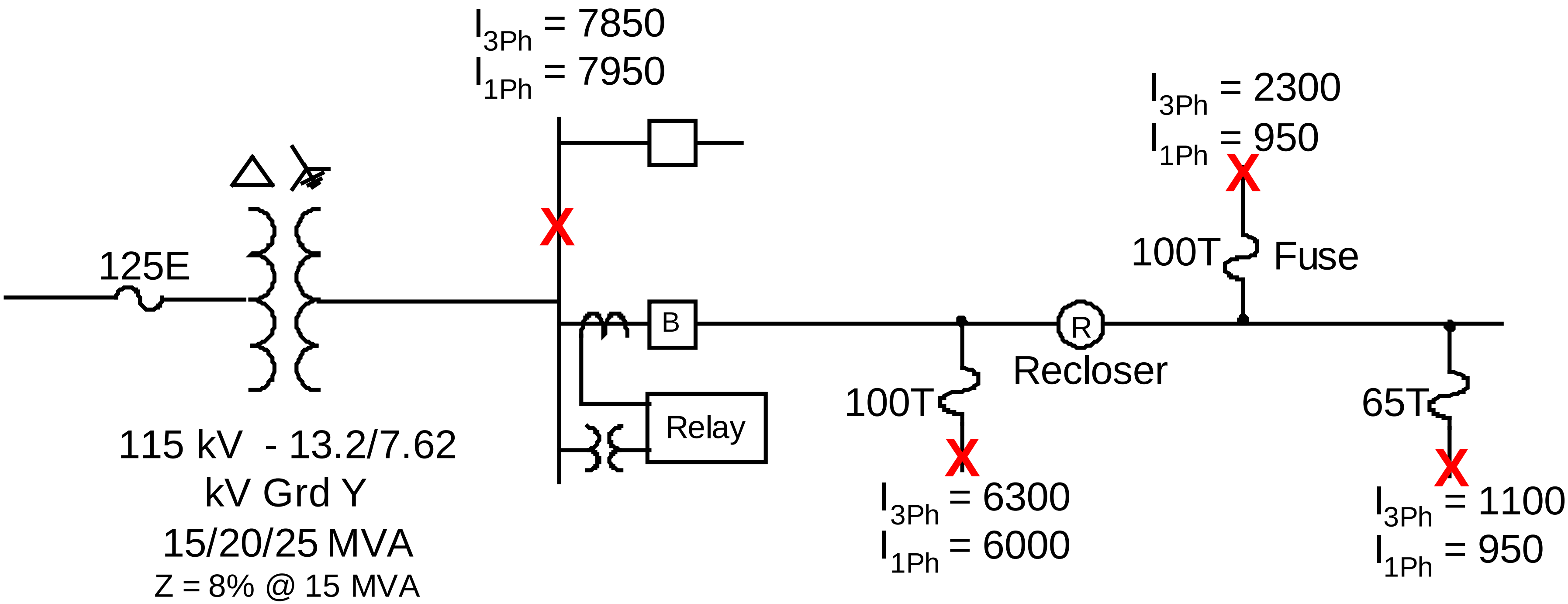
Maximum clearing time of downstream fuse should be 75% of the 51 characteristic of the upstream recloser/relay for desirable coordination. It may be necessary, however, to to set the CTI down to as low as 5 cycles to achieve complete feeder coordination.

Principles of Feeder Coordination

- Most utilities require complete coordination between phase time-overcurrent elements down through customer owned protective devices

- Those who allow miscoordination only permit it at high current levels where the result is likely to be simultaneous fuse blowing and feeder tripping

Typical Feeder Coordination



Feeder Coordination Example

Typical Feeder Coordination

- Time-Current Curves drawn based on the 13.2kv system currents

Assumptions

  - Maximum load through recloser = 230A
  - Maximum load at feeder breaker = 330A
  - 65T and 100T fuses used at lateral taps

Typical Feeder Coordination

- With 230A maximum load, select 560A phase pickup setting for the recloser (240%)
  - for both phase time and instantaneous units
- Select 280A pickup for ground overcurrent element (50% of phase pickup)
  - for both ground time and instantaneous units
- Select ground time-curve of recloser to coordinate with the 100T fuse

Typical Feeder Coordination

- Assuming 400:5 ct ratio for the substation relays, 330A max load = 4.125A secondary

- Select 9A tap for phase relays = 720A pickup
- Select 4A tap for ground relay = 320A pickup

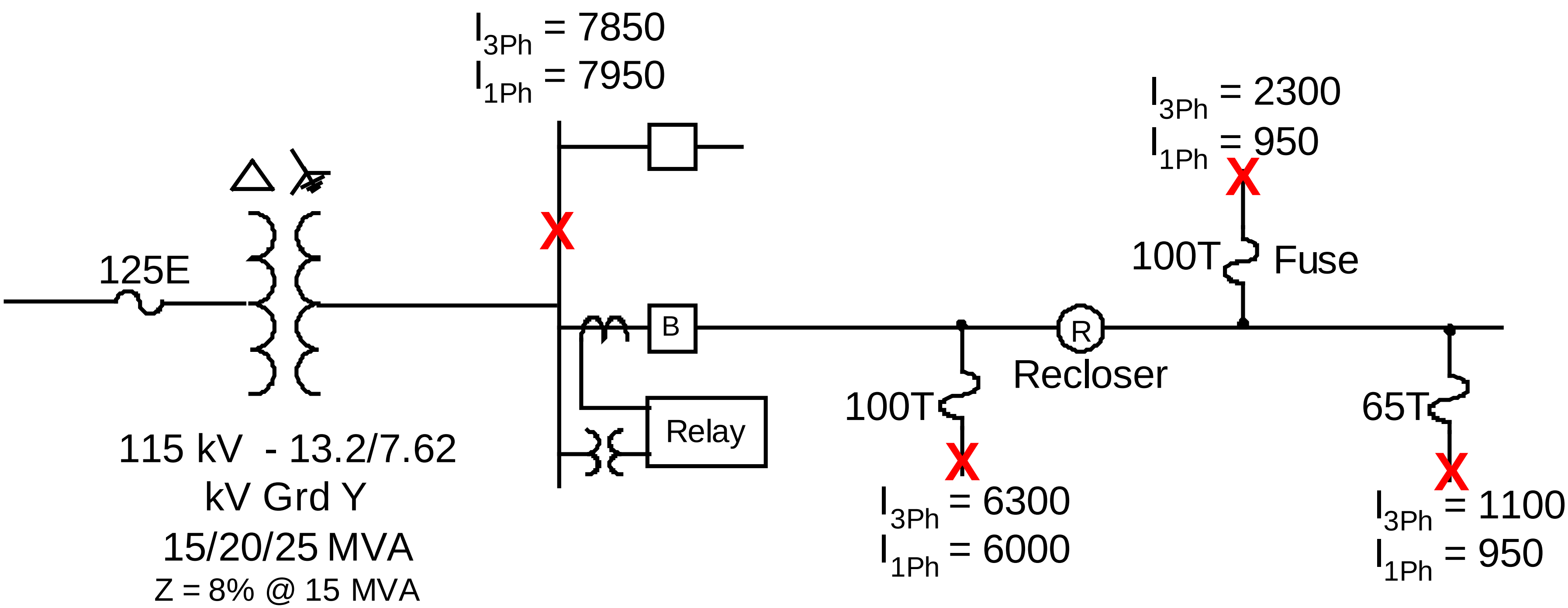
- Select ground relay time-dial to coordinate with recloser ground curve. Select phase relay time dial to coordinate with recloser phase curve

Typical Feeder Coordination

- Phase overcurrent relay curve must also coordinate with transformer primary side fuses and transformer frequent-fault capability

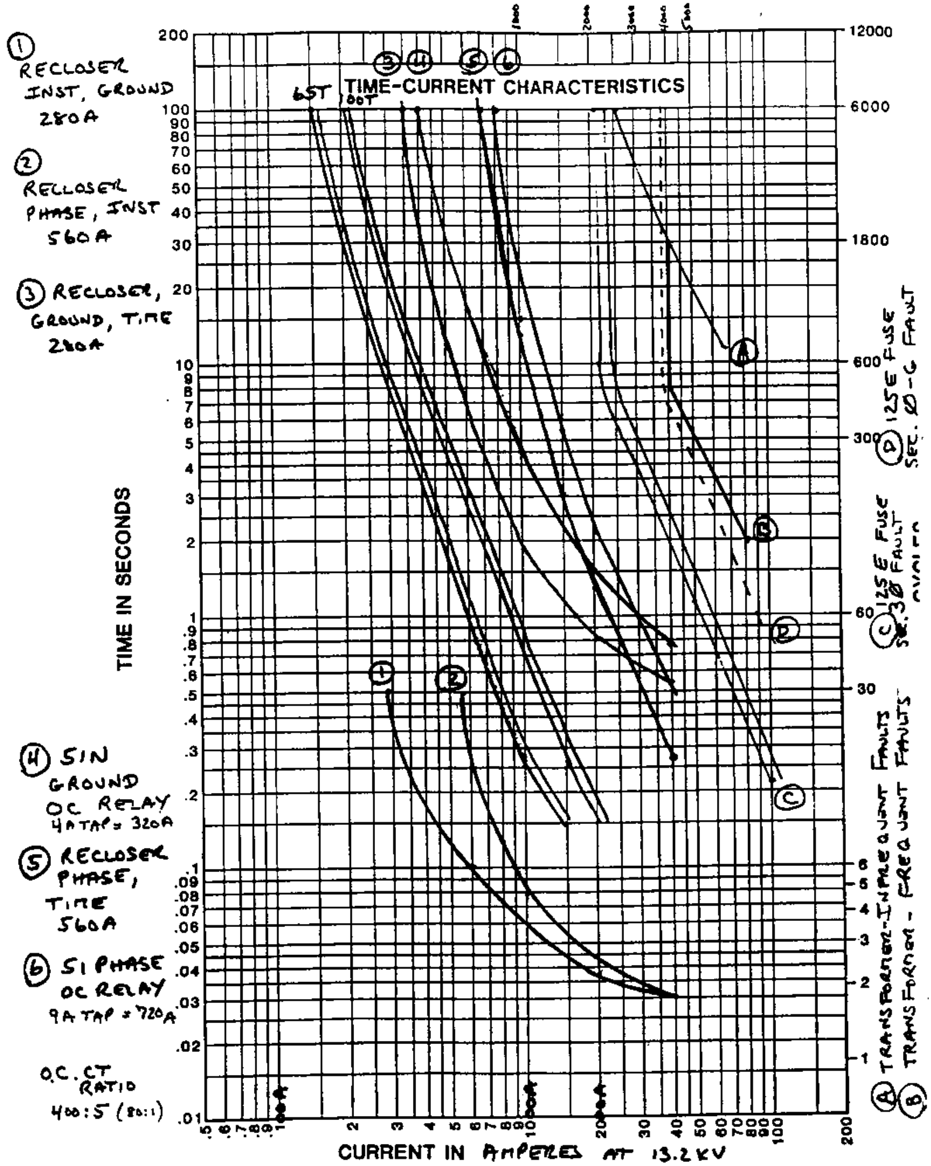
- Primary side fuse must protect transformer per transformer infrequent-fault capability curve

Typical Feeder Coordination



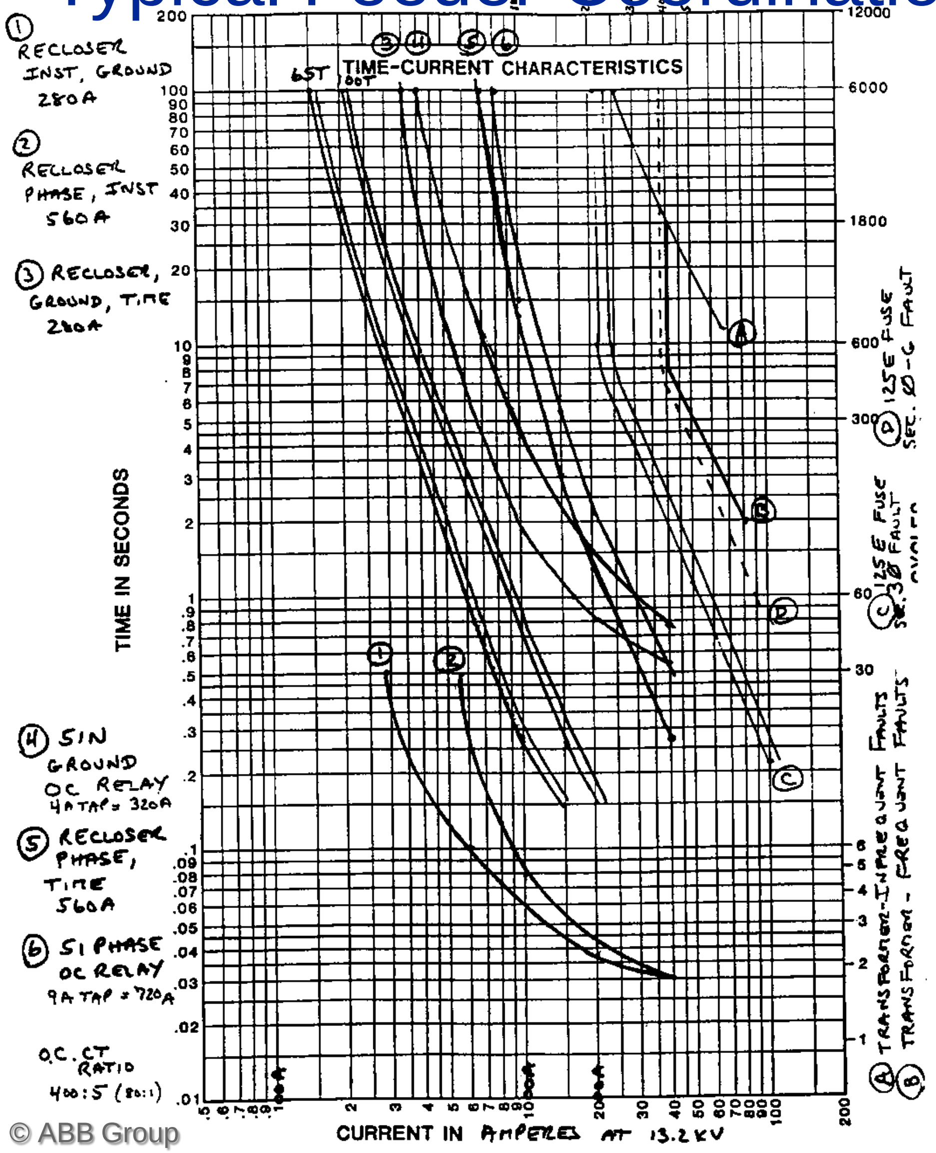
Feeder Coordination Example

Typical Feeder Coordination



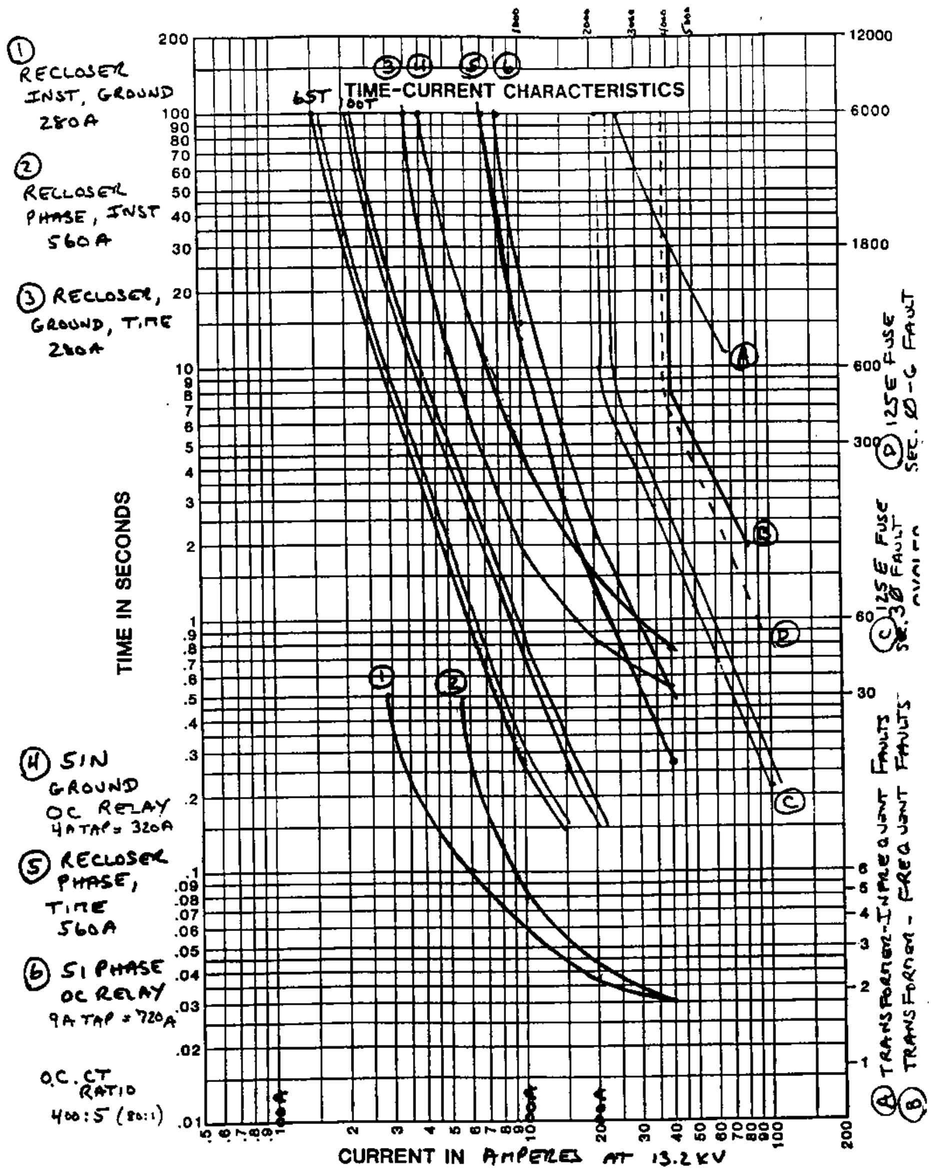
- Transformer fuse is the slowest (C&D)
- OC Relay and Recloser slow curves faster than 65T and 100T Fuses (3,4,5 & 6)

Typical Feeder Coordination



- Recloser fast curves faster than 65T and 100T Fuses
- Recloser is operating in a "fuse save" mode:
  - Fast curve (1&2) will open recloser before down stream fuses open
  - This will allow a transient fault on a fused tap to be cleared before blowing the fuse
  - After a pre-determined number of operations, usually one or two, the fast curves are blocked and the recloser allows the fuse to blow if the fault is in the fuse's zone of protection.
  - If the fault is on the feeder the recloser will operate again, typically going to lockout after one or two more operations.
  - Each recloser operation will have a longer open time to allow the fault to clear
  - This **reduces the outage time** on the taps for transient faults, saving the fuse and not having to dispatch a crew to replace the fuse.

Typical Feeder Coordination



The breaker is operating in a fuse blowing mode:

- If the fault is on the tap above the recloser the 100T fuse will open before the breaker
- This **reduces the number of customers affected** by the outage to only those on the tap.

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