Intro to Power System Protection

ELEN90060

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Last Week: Power System Faults



2016 South Australian Blackout
Source: ABC News (Tom Fedorowytsch)

Transmission Network Faults

Distribution Network Faults





Outline: Intro to Protection

1. The Need for Protection
2. Protection
   - Purpose, Design Criteria, Main Components, Main Types
3. Relays
   - Types: Magnitude, Directional, Ratio and Differential Relay
4. Impacts of Distributed Energy Resources on Protection Schemes

Note:

- Special thanks to Prof. Ochoa and Dr Arthur Goncalves Givisiez (UNICAMP)
- “Power System Analysis & Design” by J. D. Glover, M. S. Sarma and T. J. Overbye
- “Integration of Distributed generation in the Power System” by M. Bollen, and F. Hassan

Power System Protection

Fault analysis:

What currents and voltages result from the fault?

Protection:

Given those currents and voltages, what equipment should detect the fault, and which breakers should open?

1. Identify where the fault is.
2. Trip only the breakers necessary to isolate it (the closest breakers).
3. Backup acts only if needed.

If every breaker that sees a large current trips instantly, you may unnecessarily disconnect half the network.

Power System Protection

Protection detects and isolates faults.
The goal is to remove the faulted equipment quickly while disconnecting as little healthy network as possible.

Protection is fundamentally about selectivity and coordination.
Multiple relays may see the same fault. The correct/local protection should operate first; upstream protection should wait and provide backup if necessary.

Protection acts through a measurement–decision–action chain:
CT/VT → relay → circuit breaker
CTs/VTs measure, the relay decides, and the breaker physically disconnects the fault.

Power System Protection

A fault occurs

→ CTs/VTs measure the system

→ a relay decides whether the fault is in its responsibility

→ the relay commands the appropriate circuit breaker(s)

→ only the minimum necessary part of the network is disconnected

Different relays infer fault location using different information:

- Overcurrent: Is current too large?
- Directional: Is the fault in the direction I protect?
- Distance: Does V/I indicate the fault is within my reach?
- Differential: Is current entering the protected zone different from current leaving it?

Power System Protection

The network is divided into protection zones.
Equipment belongs to a zone. Breakers should open for a fault in that zone.

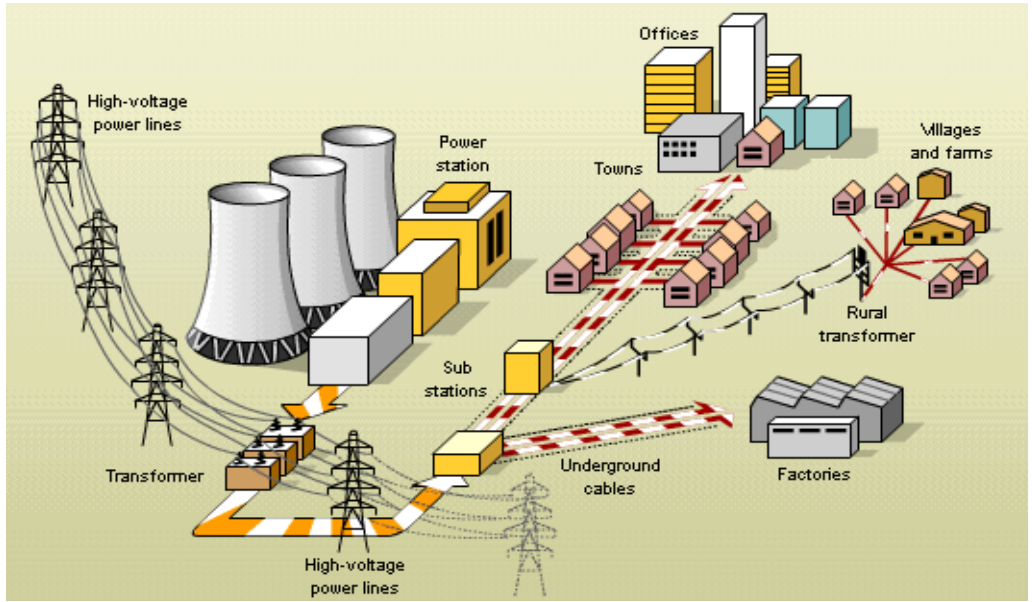
Types of Protection

Unit protection protects one clearly bounded unit/zone: a line section, transformer, busbar, generator, etc. Differential protection is the classic example.

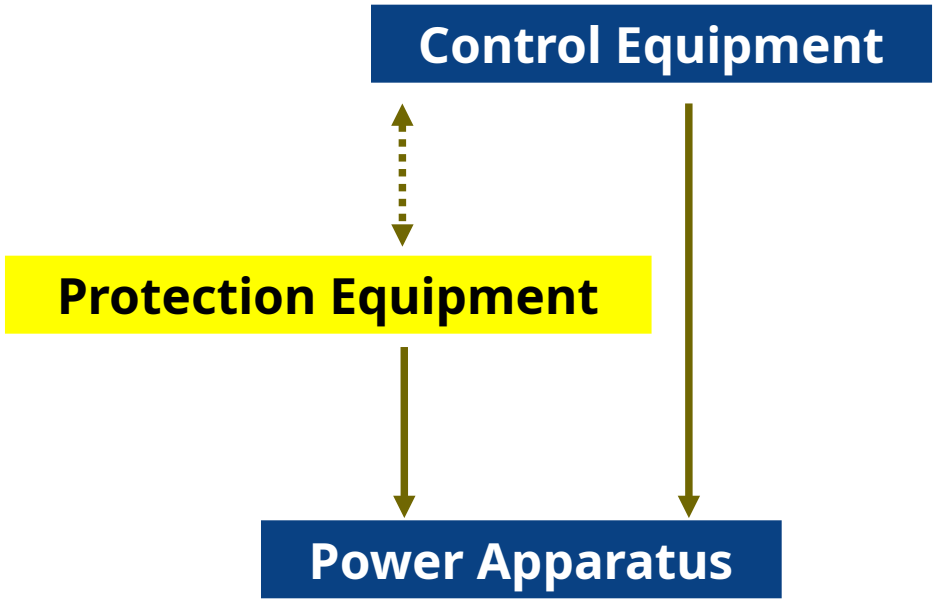
Non-unit protection does not have a precise physical boundary. It responds to quantities such as current or impedance, so it relies on coordination and time grading for selectivity and backup.

	Unit	**Non-unit**
Boundary	Precisely defined	Not intrinsically fixed
Selectivity	Built into the scheme	Achieved by coordination/settings
Backup downstream	Generally no	Yes
Example	Differential	Overcurrent, distance

The power system is made up of three types of interconnected equipment



Physical Structure



Functional Structure

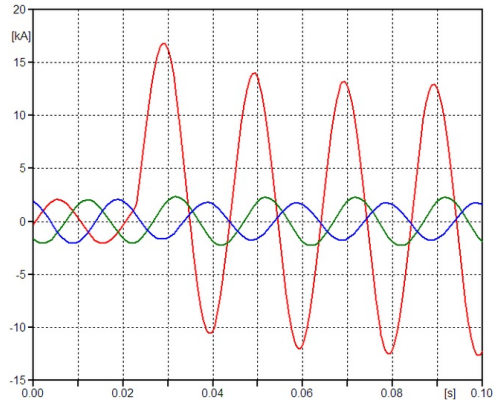
Main Effects of Faults

Faults in power systems can cause:

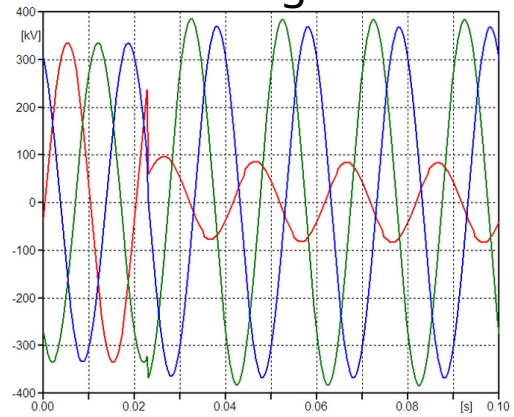
- **Personal harm** (fires, explosions)
- **Equipment Damage** (fires, explosions)
- **Unnecessary Tripping** of essential loads and generators
- **Network instability/blackouts**
  - **Blackouts** cost society millions/billions of dollars per year

Single-line-to-ground fault

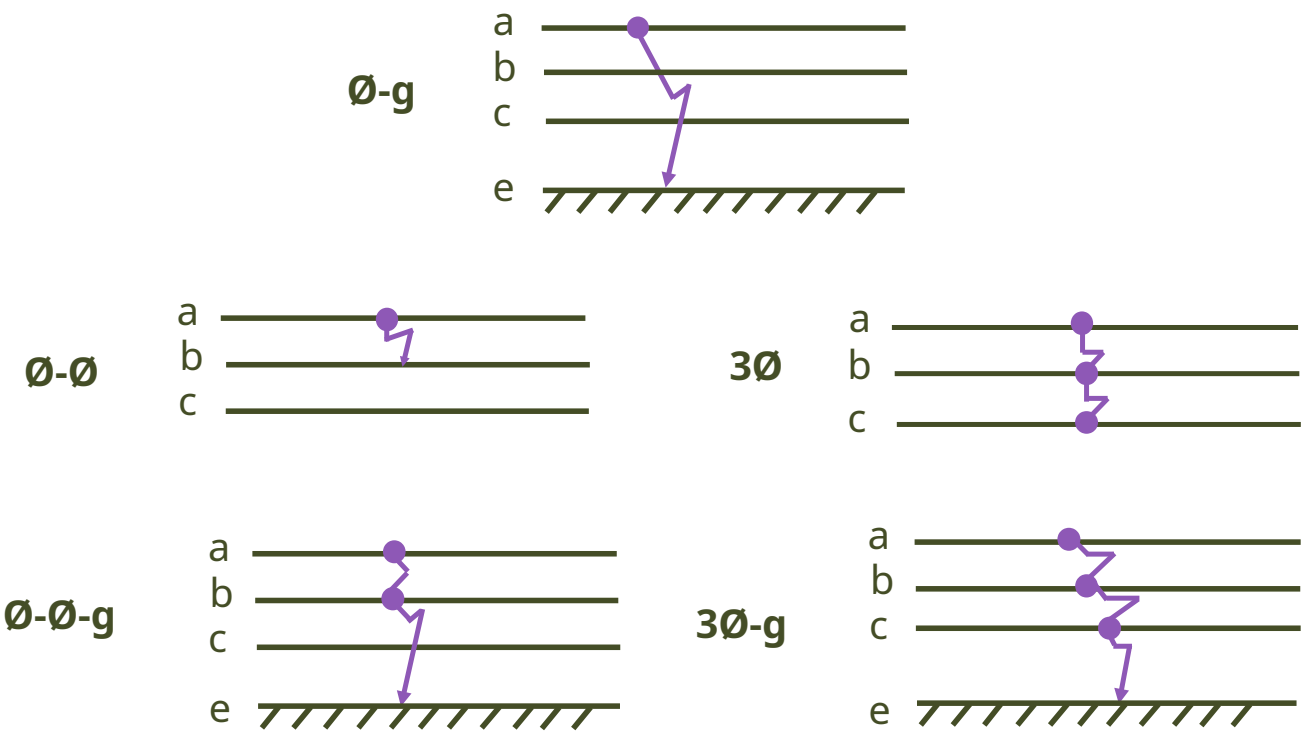
current



voltage



Types of Faults



Incidence of Faults

Equipment	% of faults
Overhead lines	~50
Underground cables	~10
Switchgear	~10
Transformers	~10
CTs and VTs	~1
Protection	~15
Control equipment	~2
Miscellaneous	~2

Purpose of Protection

A Protection Scheme must

- Detect faults and abnormal operating conditions
- Isolate the faulted equipment
- Reestablish/maintain normal operation for the safe region of the network

Generally, high current faults cleared instantaneously

- Lower current faults cleared after an appropriate delay
- Remote faults cleared after a delay sufficient to allow local protection to operate
- Balance between dependability, stability and speed

Protection Design Criteria

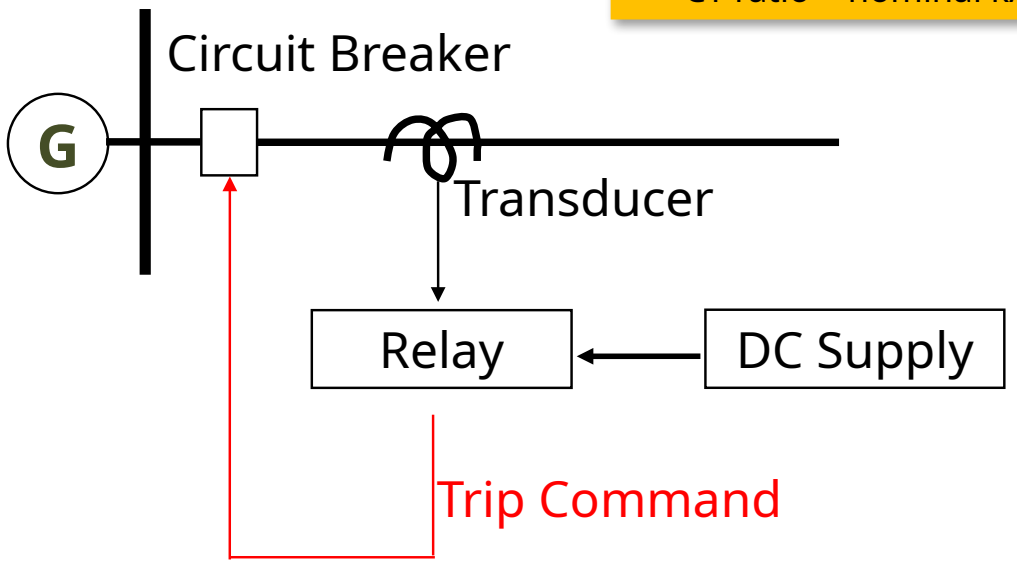
- Reliability
  - Assurance that the protection will perform correctly (even after months/years being idle)
- Selectivity
  - Avoid unnecessary false trips
- Speed of operation
  - Minimum fault duration and consequent equipment damage
- Simplicity
  - Minimum protective equipment and associated circuitry
- Economics
  - Maximum protection at minimum total costs (including cost due to fault)
- Compatibility
  - Ability of different devices to interact and communicate properly

Note: It's not possible to always satisfy these criteria. Compromises must be made.

Protection Components

1. Transducers
   - Current Transformer (CT)
   - Voltage Transformer (VT)
2. Relay
3. Battery (DC supply)
4. Circuit breaker (CB)

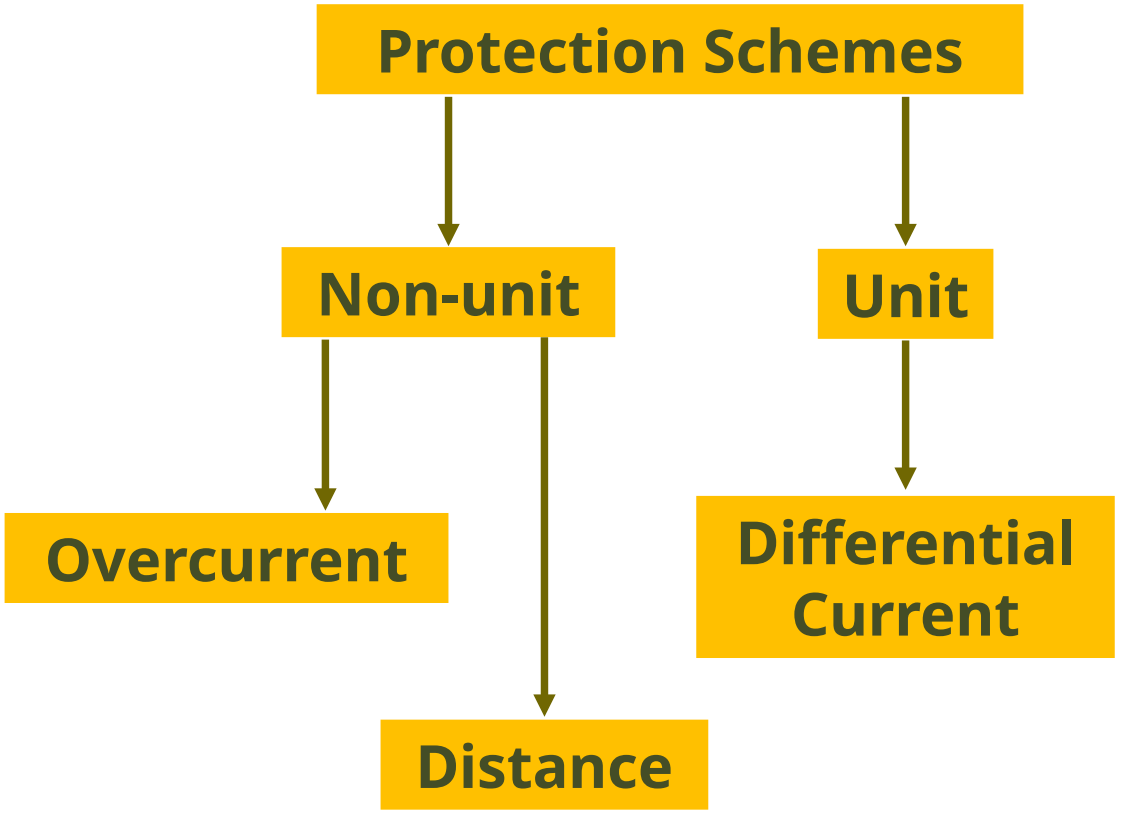
Typically:
- VT ratio = nominal kV / 110V
- CT ratio = nominal kA / 1A or 5A



Transducers

- Voltage transducer converts primary voltage (in kV) to secondary voltage (in V)
- Current transducer converts primary current (in kA) to secondary current (in A)

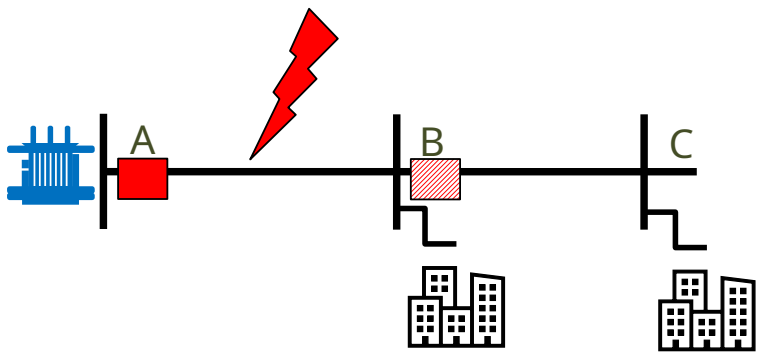
Protection Schemes



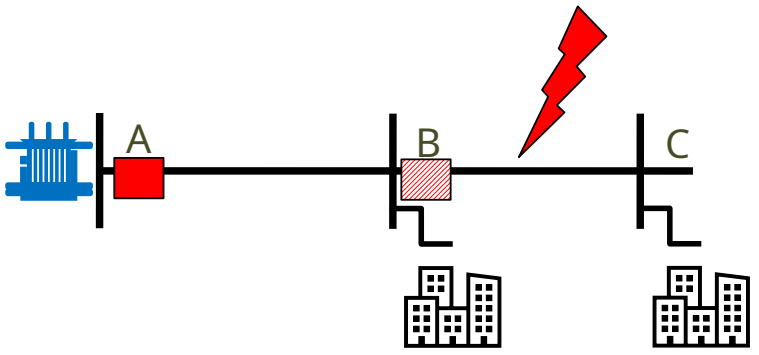
“Non-unit” Protection

“Non-unit” Protection measurements do not inherently specify a zone

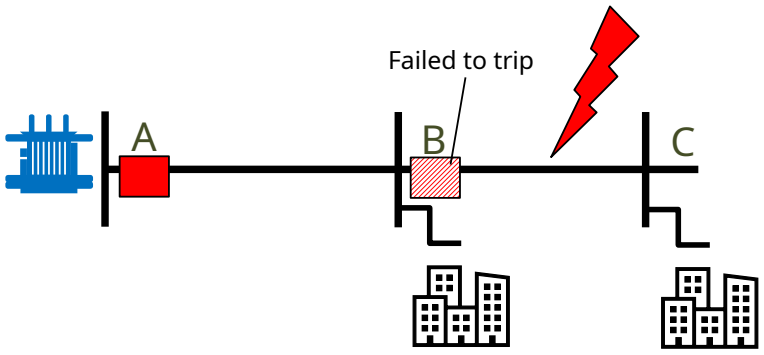
- Can provide backup protection, which is good
- Spatial coordination is needed
  - discrimination with downstream protection is usually done with time grading



Solid red box operates



Striped red box operates



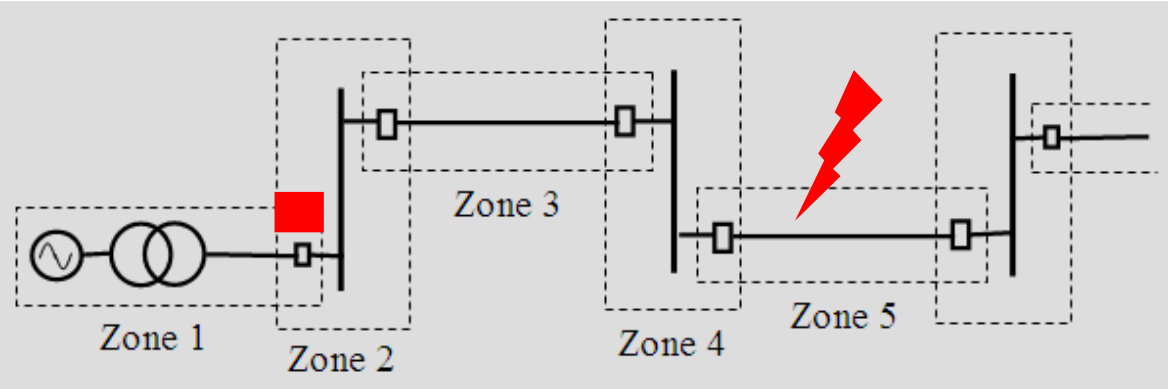
Solid red box operates (backup)

“Unit” Protection

Has an accurately defined zone of protection

- When protecting a power system, we divide it into overlapping zones or “units”
- Each zone is protected by a given protection scheme or part of it
- Any fault in that zone will cause all circuit breakers in that zone to trip

Protection schemes in other zones will not operate with “unit” protection (no back-up protection for downstream faults)



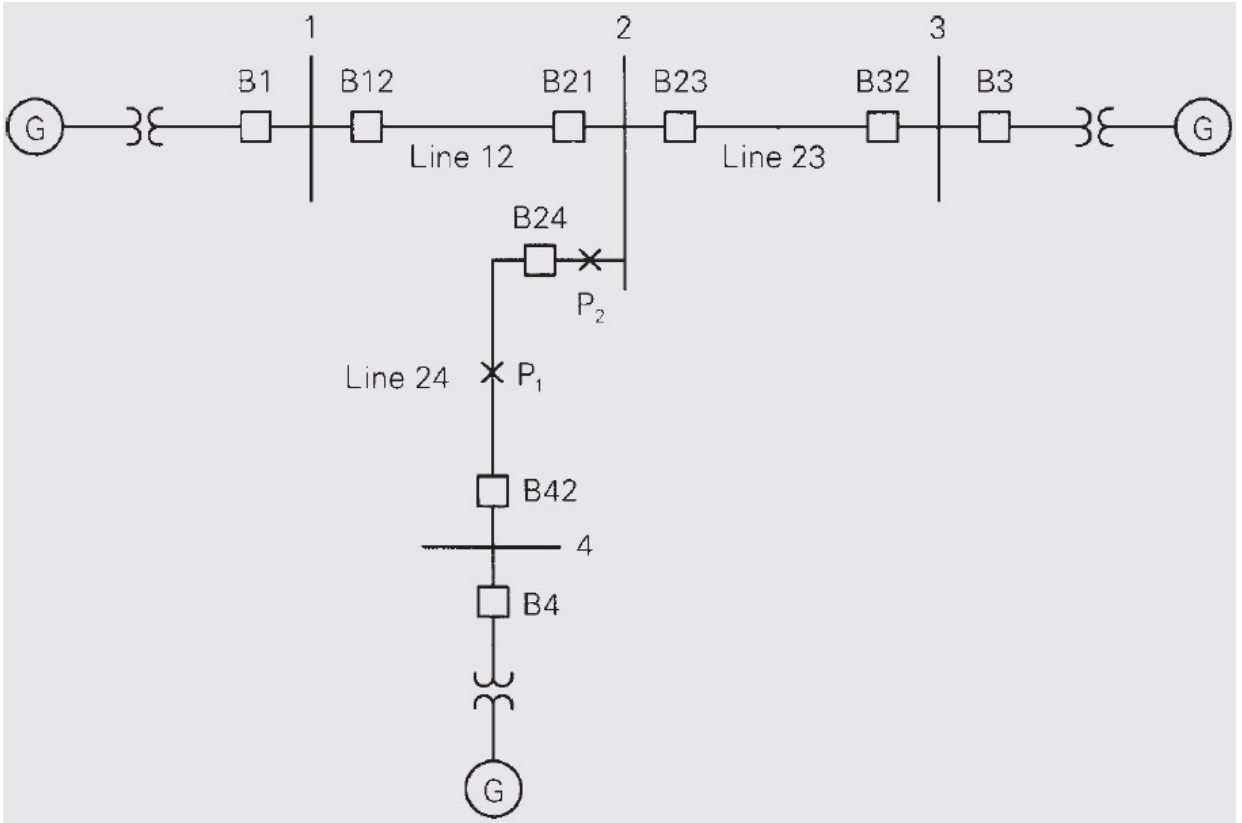
A fault in zone 5 will not trip the protection scheme (red square) in zone 1.

Exercise 1

Draw the protective zones for the power system shown in the figure.

Remember:

- Circuit breakers identify zone boundaries
- Circuit breakers exist to protect equipment

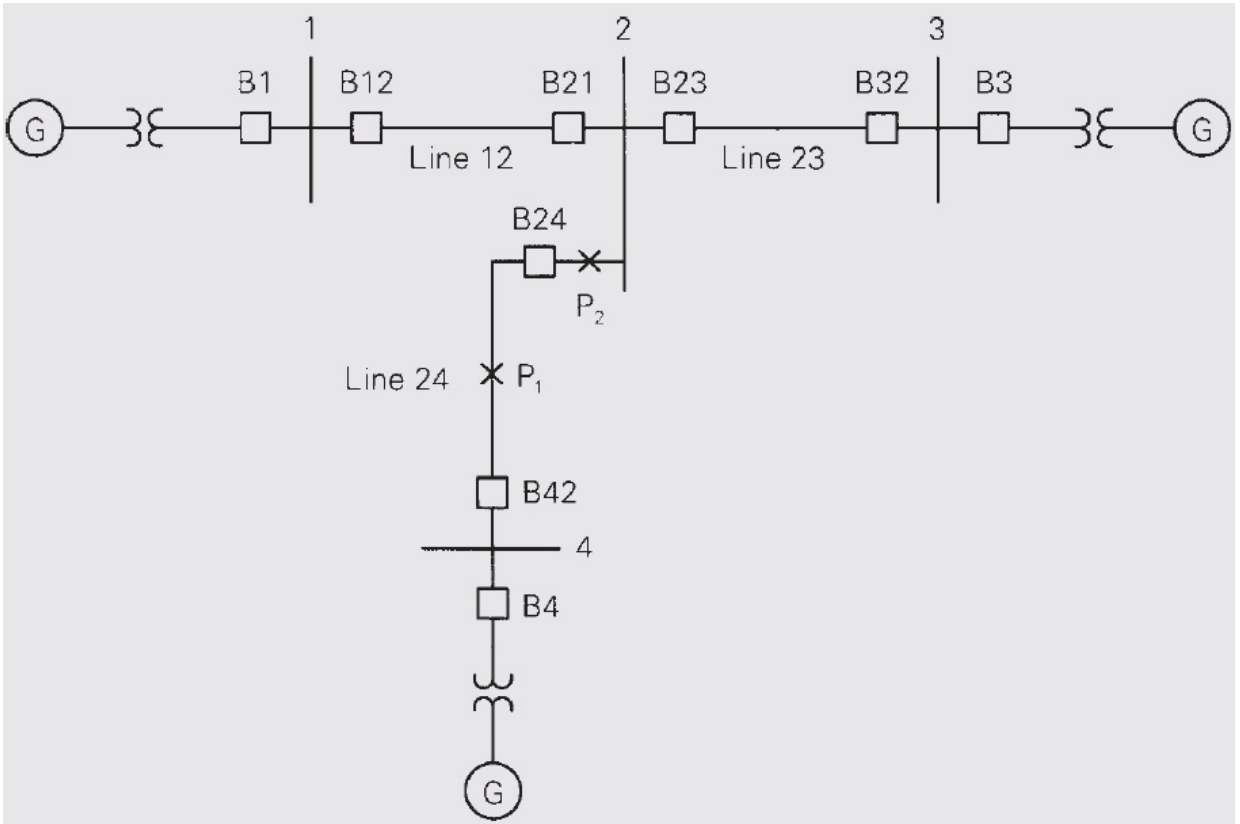


Exercise 2

Which circuit breakers should open for a fault at:

a) P_1

b) P_2



Relays: The “Brain” of the Protection Scheme

Discriminate between a fault within its protected zone and all other system conditions

Energize the trip coil of its circuit breaker for fault within its protected zone

They are the distributed decision-making hardware on the grid



Types of Relay:

- Magnitude relay (I>, V<, f<, etc.)
- Directional relay (Idir>)
- Ratio relay (Z<)
- Differential relay (DI>)

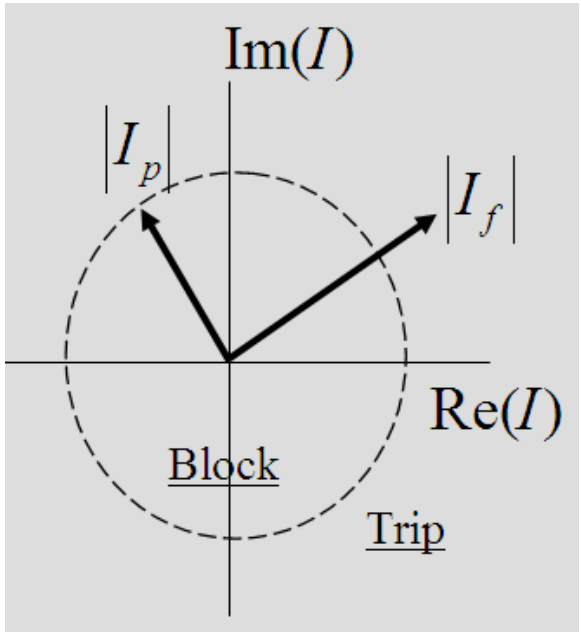
Based on the info from the transducers, a decision is made and *relayed* to the trip coil of the circuit breaker which will open the circuit – hence the name *relay*.

Magnitude/Overcurrent Relay

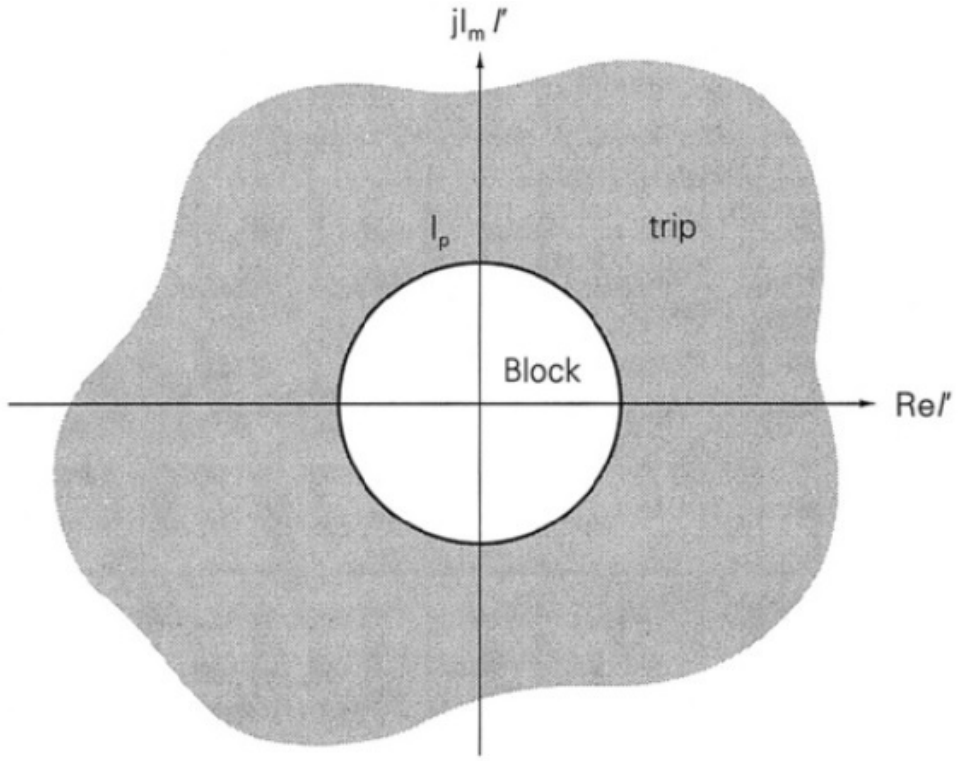
Simplest protection example

- Responds to magnitude of fault current, $|I_f|$
- Operates when current magnitude exceeds a threshold $|I_p|$
  - If $|I_f| > |I_p|$, then operate (“trip” circuit breaker)
  - If $|I_f| < |I_p|$, then do not operate (“block” circuit breaker)

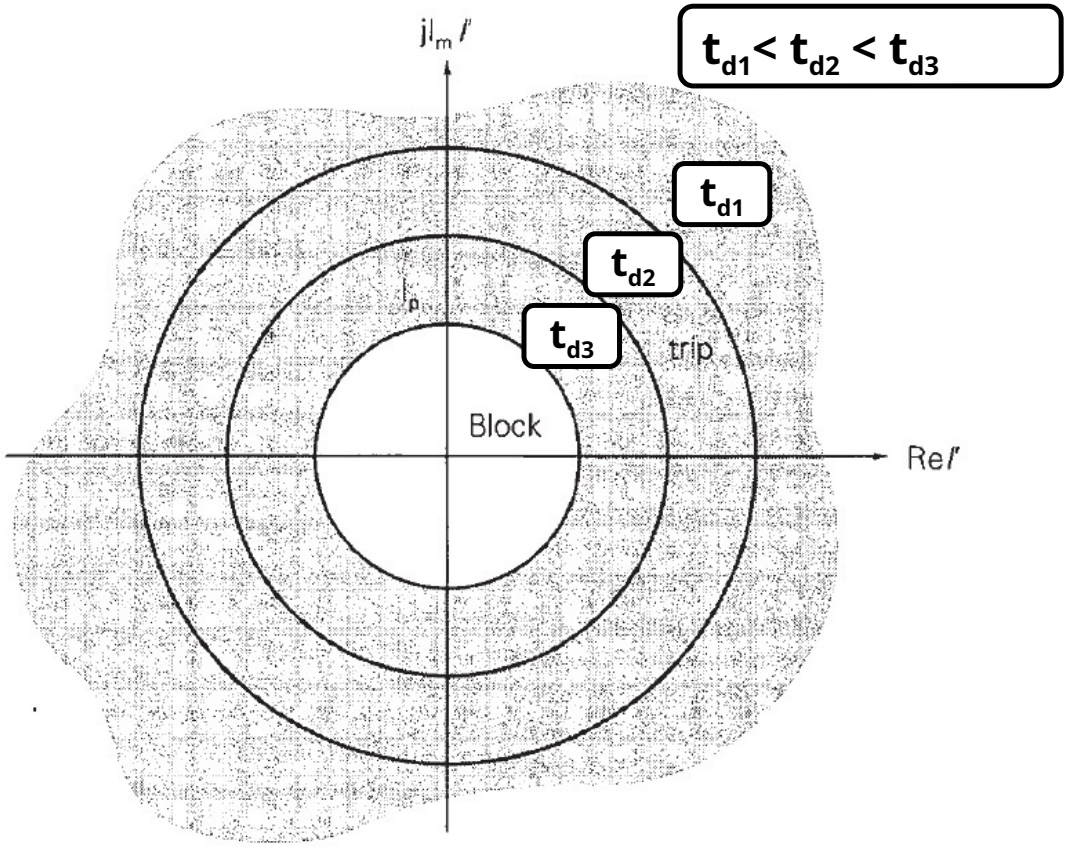
How to coordinate? → time-dependent tripping



Magnitude/Overcurrent Relay



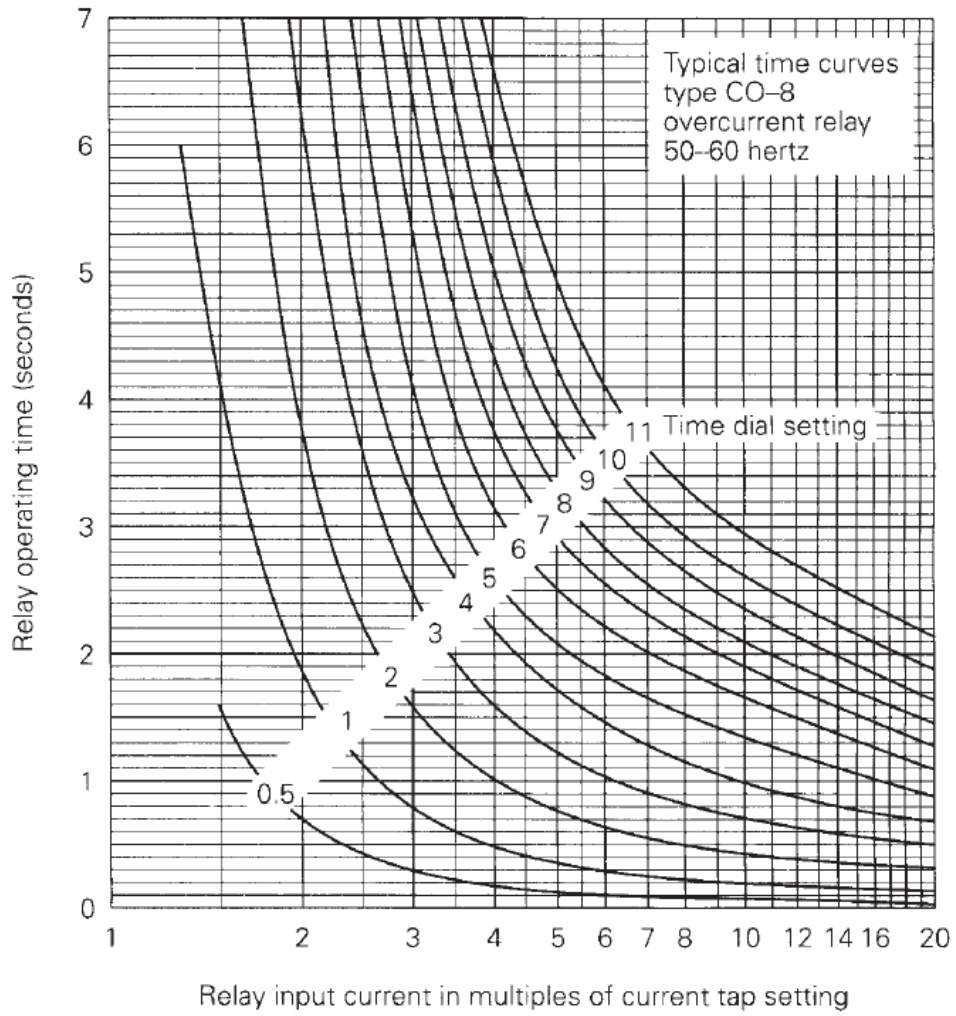
Instantaneous
Overcurrent Relay



Time-Delay
Overcurrent Relay

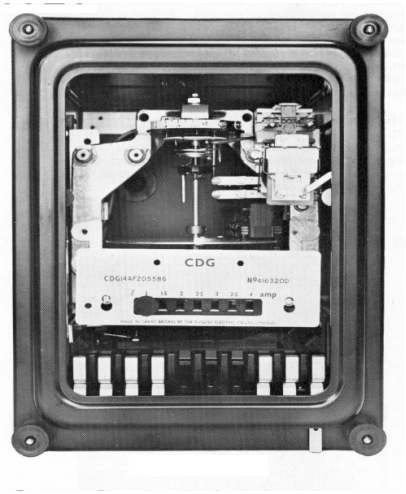
Magnitude/Overcurrent Relay

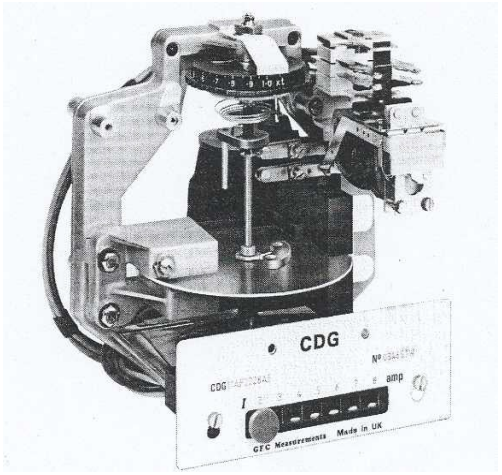
Characteristic curves of time-delay overcurrent relays

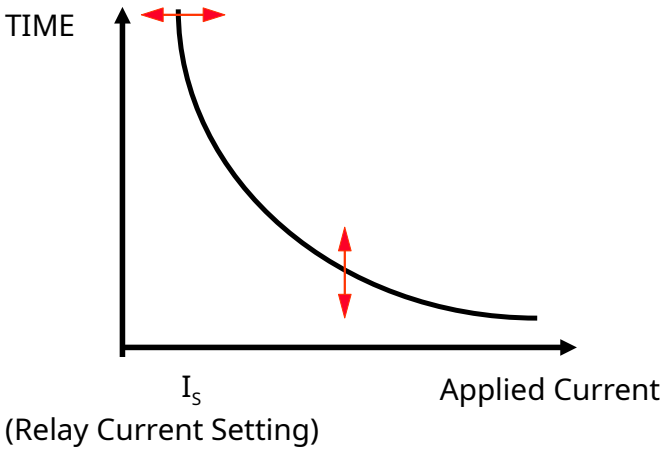


Different Generations of Relay Technology

Electro-mechanical overcurrent relays.

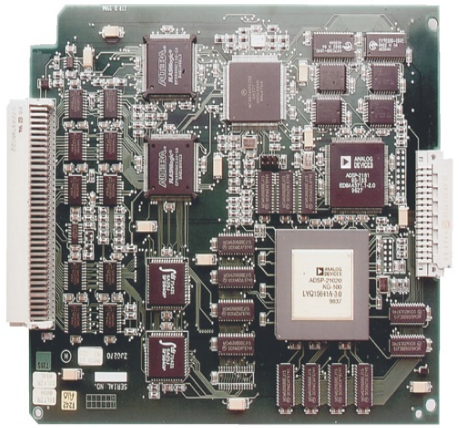


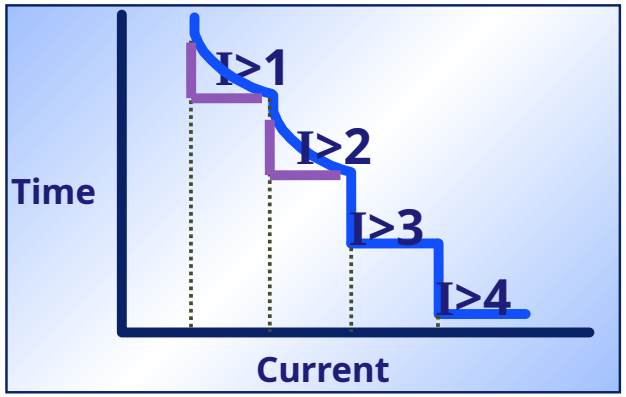




Different Generations of Relay Technology

Numerical or microprocessor relays





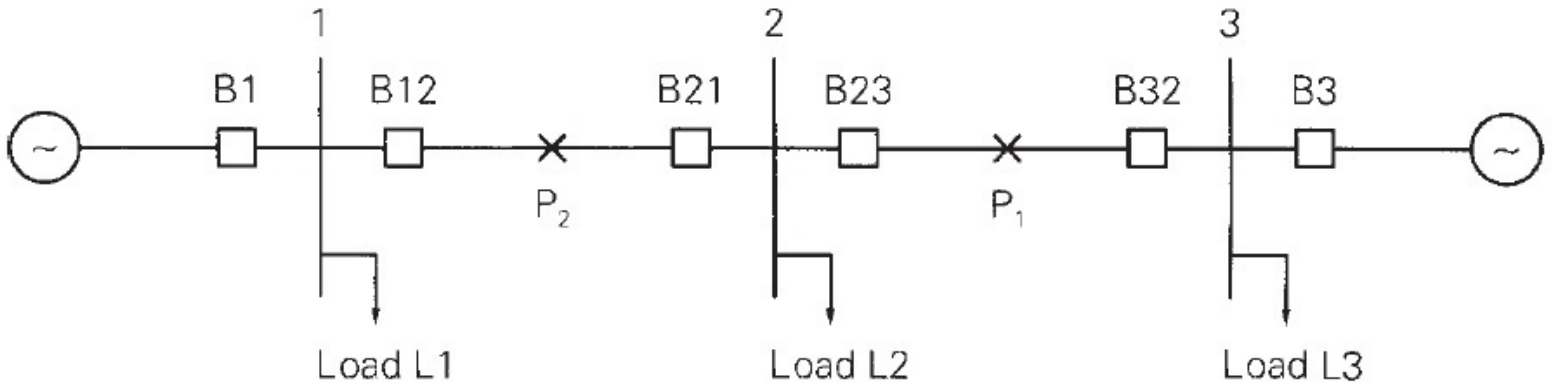
Exercise 3

Consider the power system shown below. All circuit breakers are equipped with overcurrent relays.

a) Assume a fault happens at P_2. Which circuit breakers should open?

b) Assume a fault happens at P_2. With no time coordination, which circuit breakers will open?

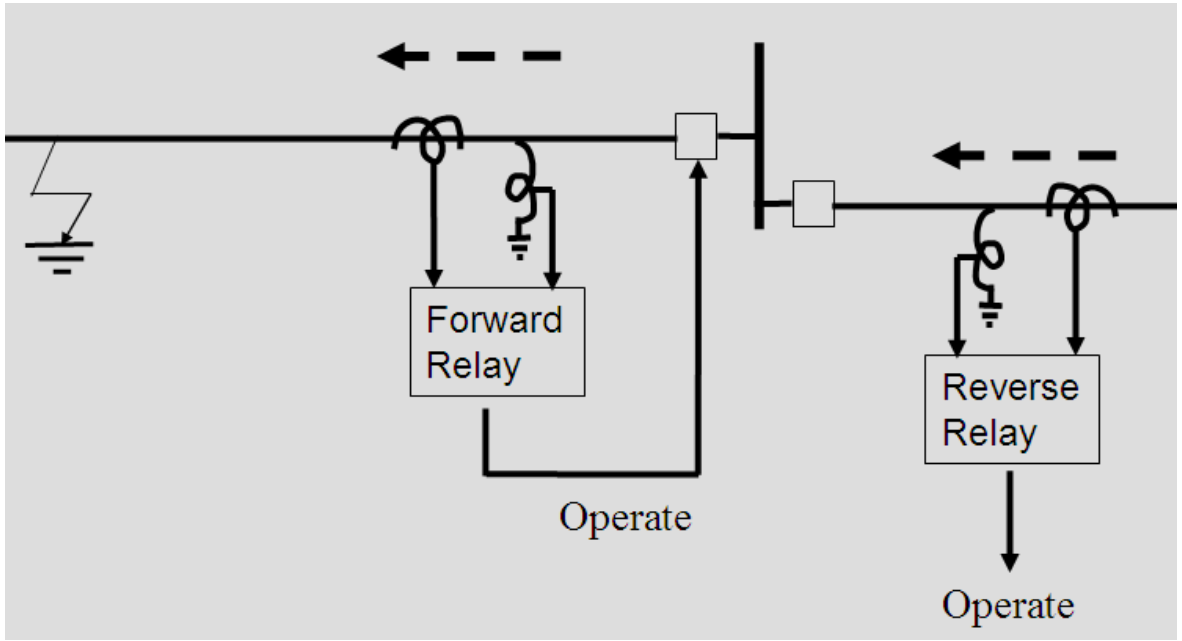
c) Assume B23 works faster than B21, and a fault happens at P_2. Which circuit breakers will open? Is it the most appropriate action?



Directional Relay

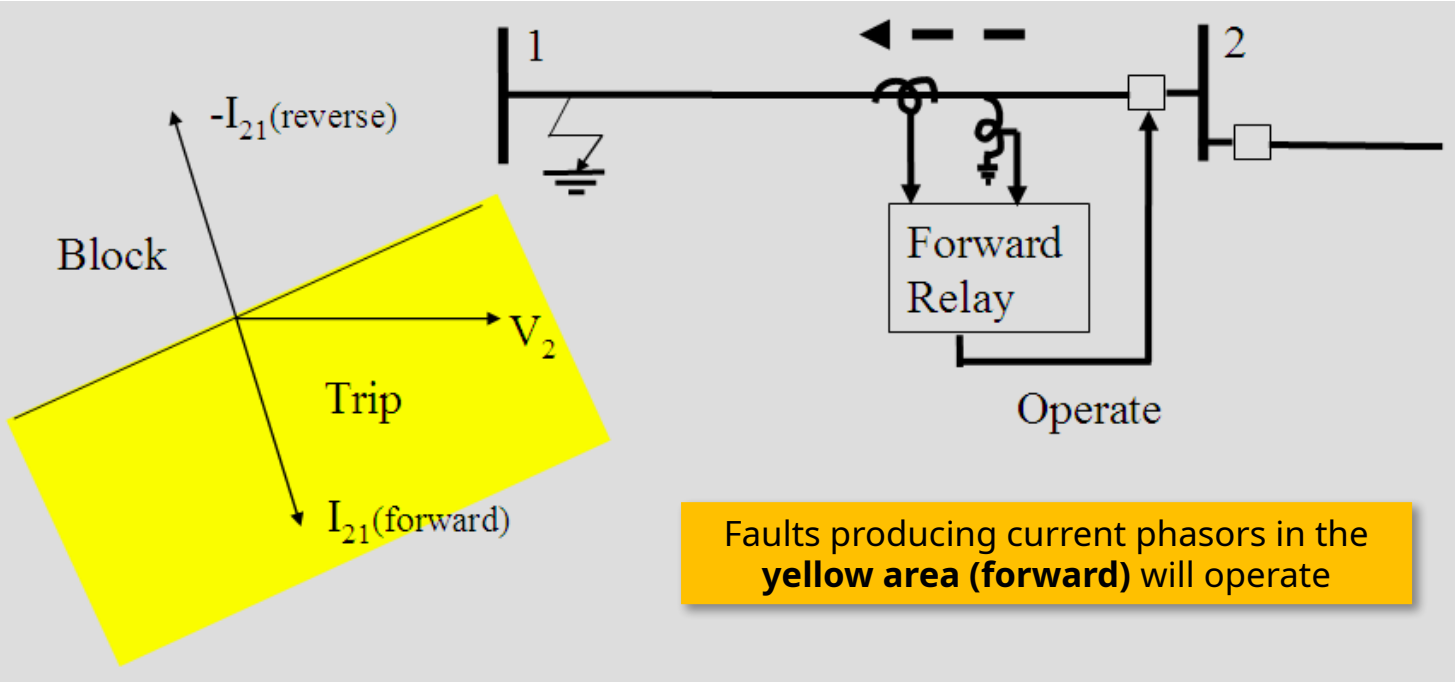
Forward directional relay operates if fault in “forward” direction

Reverse directional relay operates if fault in “reverse” direction



Directional Relay

Directional relays determine direction by measuring the local current and voltage phasors



Fault to left of relay: current flows from 2 to 1 and (mostly) lags voltage

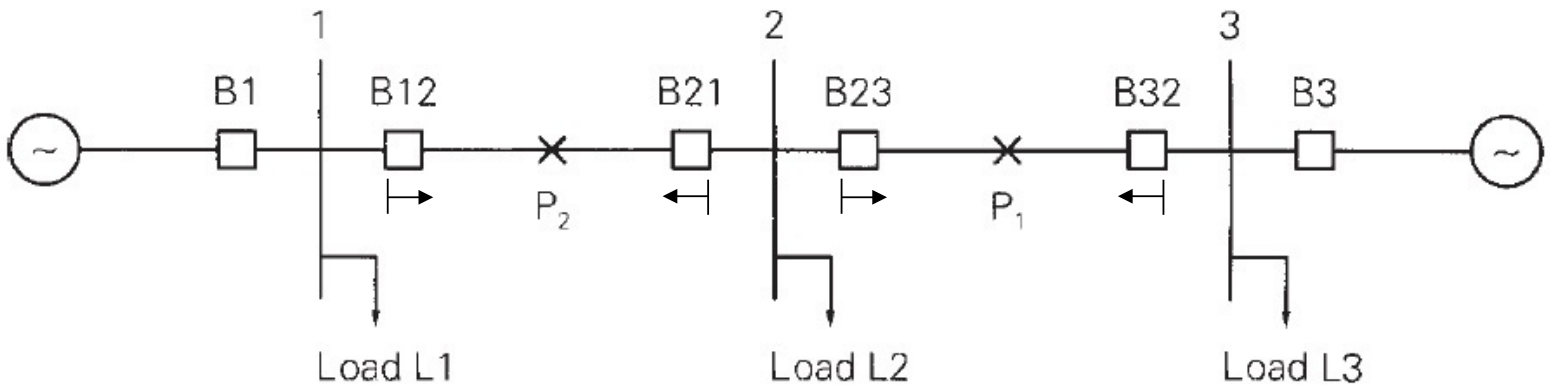
Fault to right of relay: current flows from 1 to 2 and (mostly) leads voltage

Exercise 4

Consider the power system shown below. All circuit breakers are equipped with overcurrent relays and some of them also are directional (forward).

a) Assume a fault happens at P_2. Which circuit breakers should open?

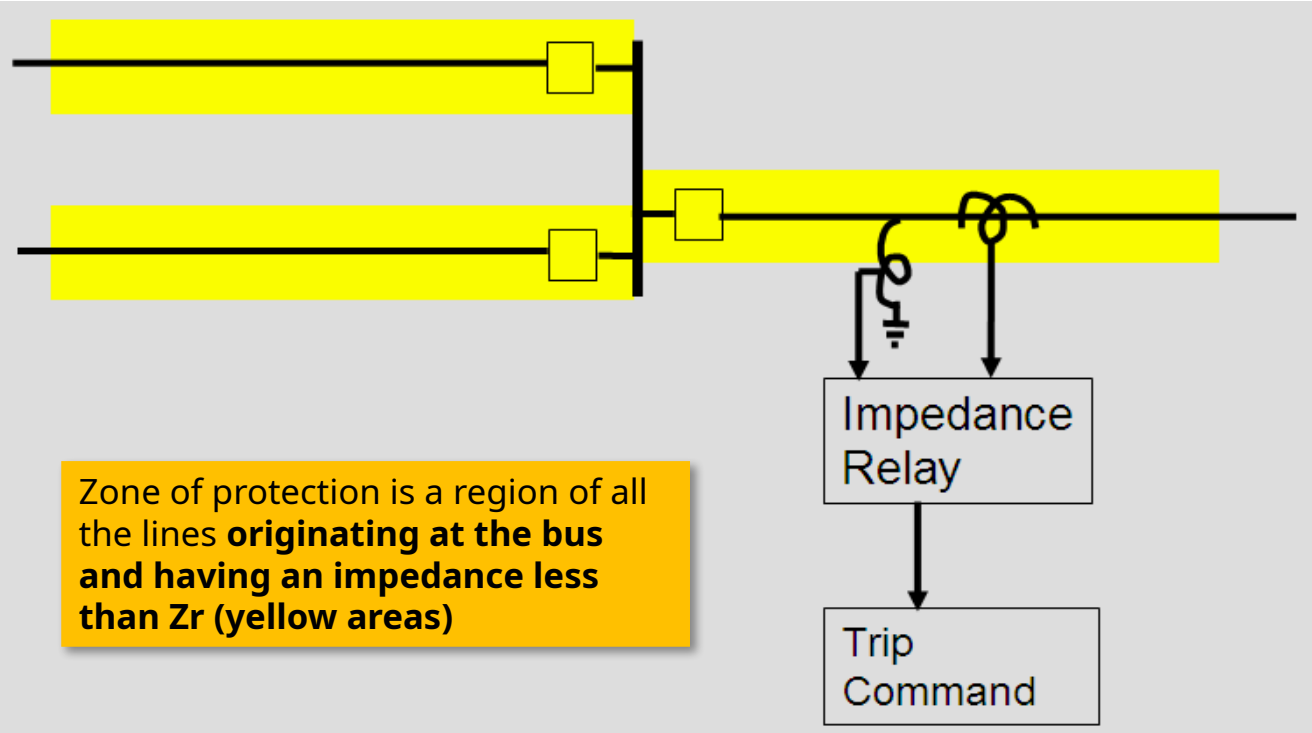
b) Assume B23 works faster than B21, and a fault happens at P_2. Which circuit breakers will open?



⟼: Relay Direction

Ratio/Impedance Relay

Relay operates for all faults located a certain **distance** of its location on **any line** originating at associated bus.

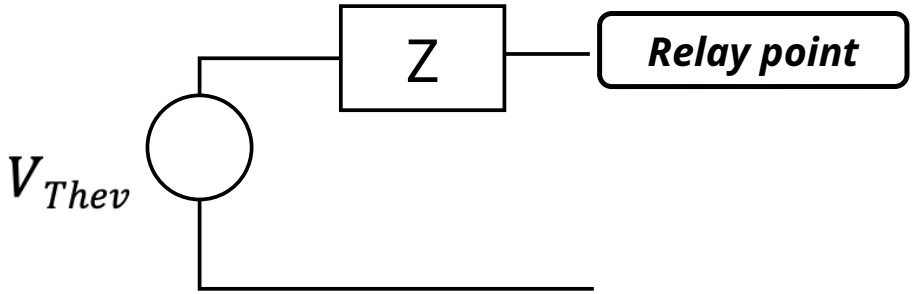


Ratio/Distance/Impedance Relay

Measured Impedance

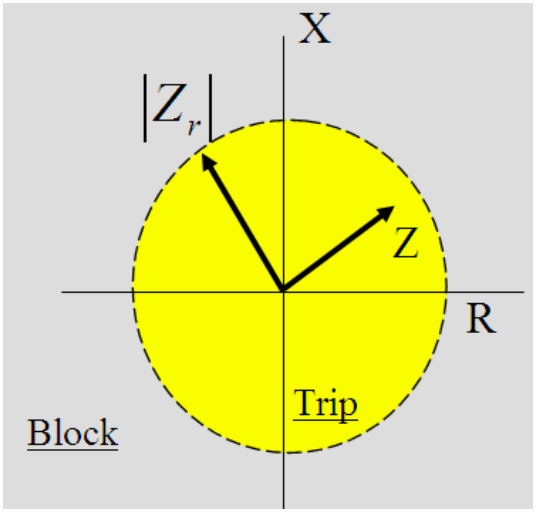
- If $|Z| < |Z_r|$, then relay trips
- Smaller $|Z|$ → closer to the fault

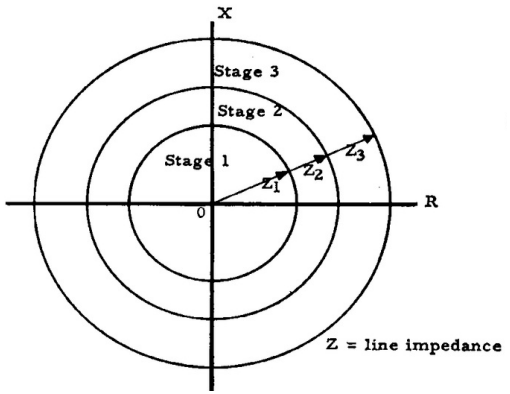
$$Z = \frac{V_{local}}{I_{local}}$$



In the complex Z plane

- relay has operating locus of constant $|Z_r|$
- i.e., circle of radius $|Z_r|$



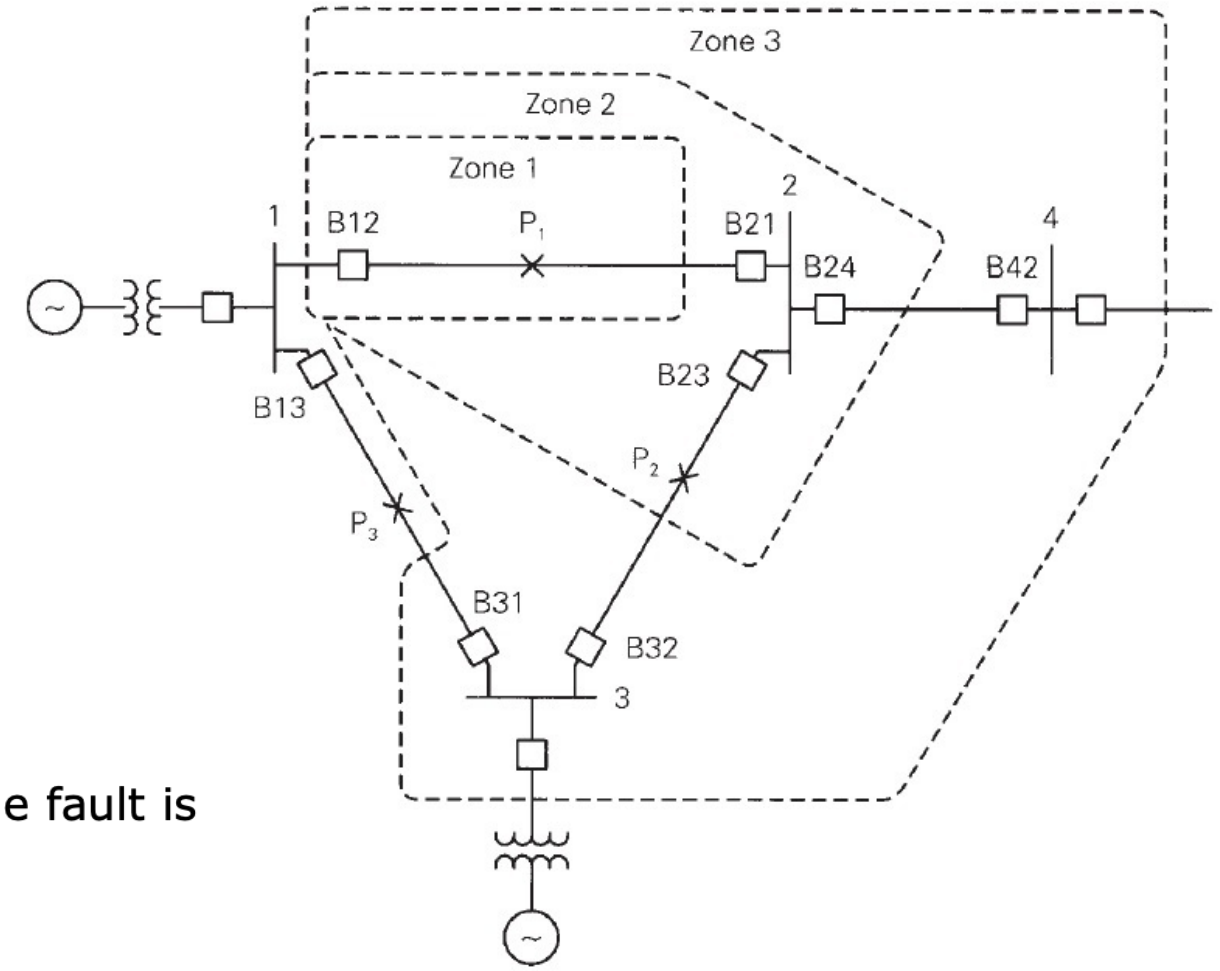


We can create ‘stages’ based on the impedances.

Ratio Relay (Example of Directional Ratio Relay)

Using directional ratio relays (forward)

- Fault at P_1
  → $|Z_{B21}| < |Z_{B32}|$
  B21 should operate faster than B32
- Fault at P_2
  → $|Z_{B32}| < |Z_{B13}|$
  B32 should be faster than B13
- Fault at P_3
  → $|Z_{B13}| < |Z_{B21}|$
  B13 should be faster than B21

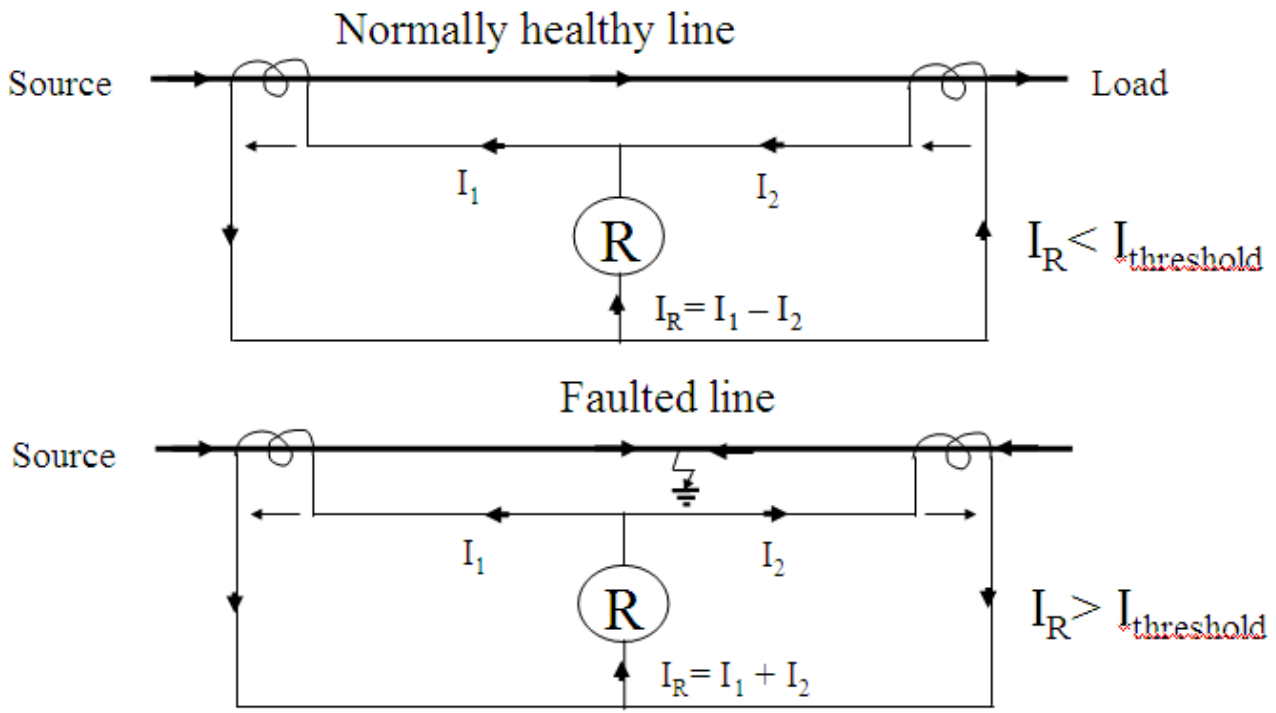


A distance relay uses Z to infer how far away the fault is

Differential Relay

Compares the current (or voltage) measurements at each end of a protected zone

- Operation depends on that difference (magnitude, phase)



Applications mainly for feeders, busbars, transformers, generators.

Other Types of Protection

- Miscellaneous
  - Under and Over Voltage
  - Under and Over Frequency
  - Rate-of-Change-of-Frequency (RoCoF)

- Special Relays for Generators, Transformers, Motors, etc.

Impacts of DERs on Distribution Network Protection

Protection schemes designed for one direction power flow (downstream)

High penetration of DERs (e.g., PVs), can create reverse power flows (upstream)

Integration of DERs into distribution networks may create some challenges with respect to protection systems

Protection Scheme Designed for:

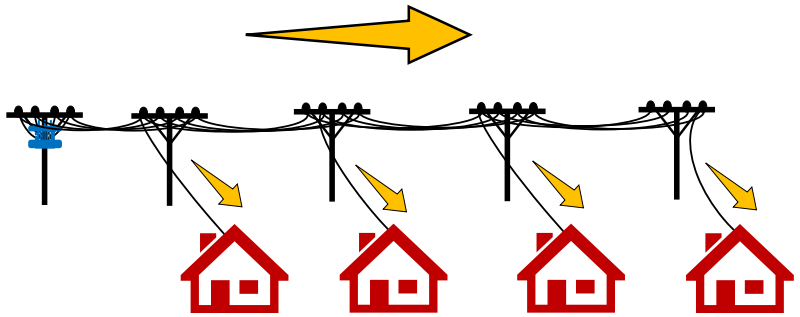


Figure: Prof. Nando Ochoa

DERs are causing:

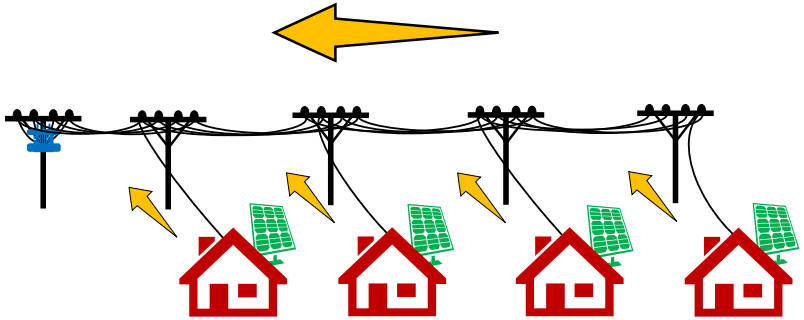


Figure: Prof. Nando Ochoa

Integration of DERs presents protection challenges

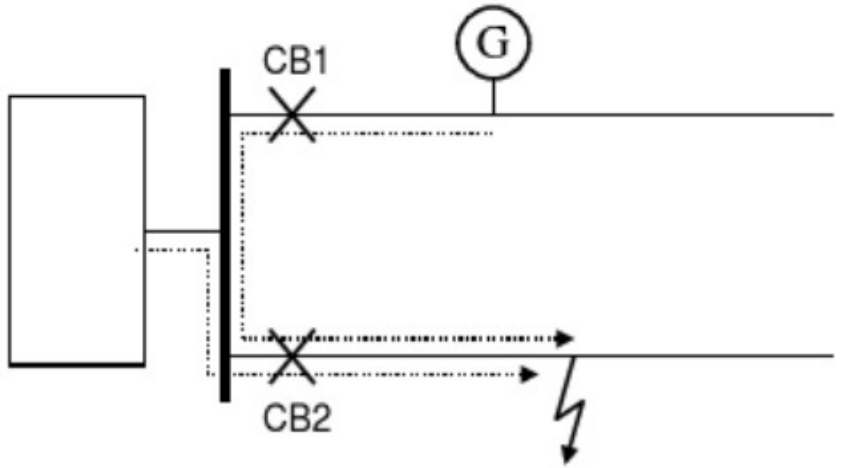
Impacts of DERs on Protection: “Sympathetic Tripping”

Appropriate protection scheme:

- Circuit breaker “CB2” should open and “CB1” should not
- The DER “G” should not trip

However, the contribution of the DER “G” to the fault may be mistaken by the protection associated with circuit breaker “CB1”

- Most distribution networks → Overcurrent protection without directional capability



The circuit breaker “CB1” will trip incorrectly.

This is bad

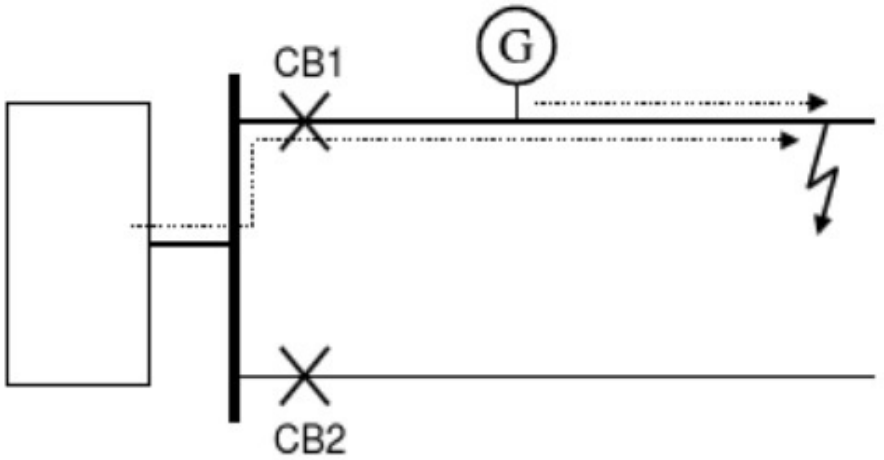
Impacts of DERs on Protection: “Protection Blinding”

Appropriate protection scheme:

- Circuit breaker “CB1” should open

However, the contribution of the DER “G” may reduce the fault current at “CB1”

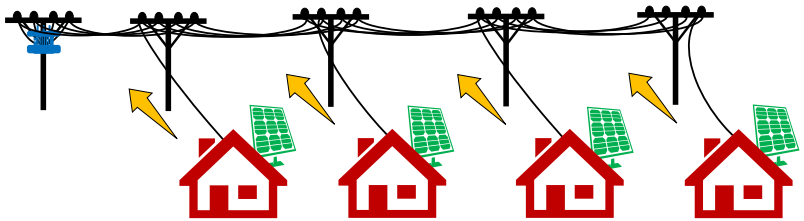
The overcurrent protection may no longer detect the fault



The circuit breaker “CB1” will not trip.

This is bad

Impacts of DERs on Distribution Protection: Potential Solutions



Change of protection settings

- Low cost since there is no investment in new equipment

Additional time in protection coordination

- May create new problems due to withstanding fault currents

Additional circuit breakers

- For example, dividing a feeder into two protection zones
- Requires new equipment (circuit breakers, relays, CT, CV, etc) → expensive

Different protection methods

- For example, directional relays or communication between relays
- Requires new equipment → expensive

How will the transition from rotating machines → IBRs affect protection?

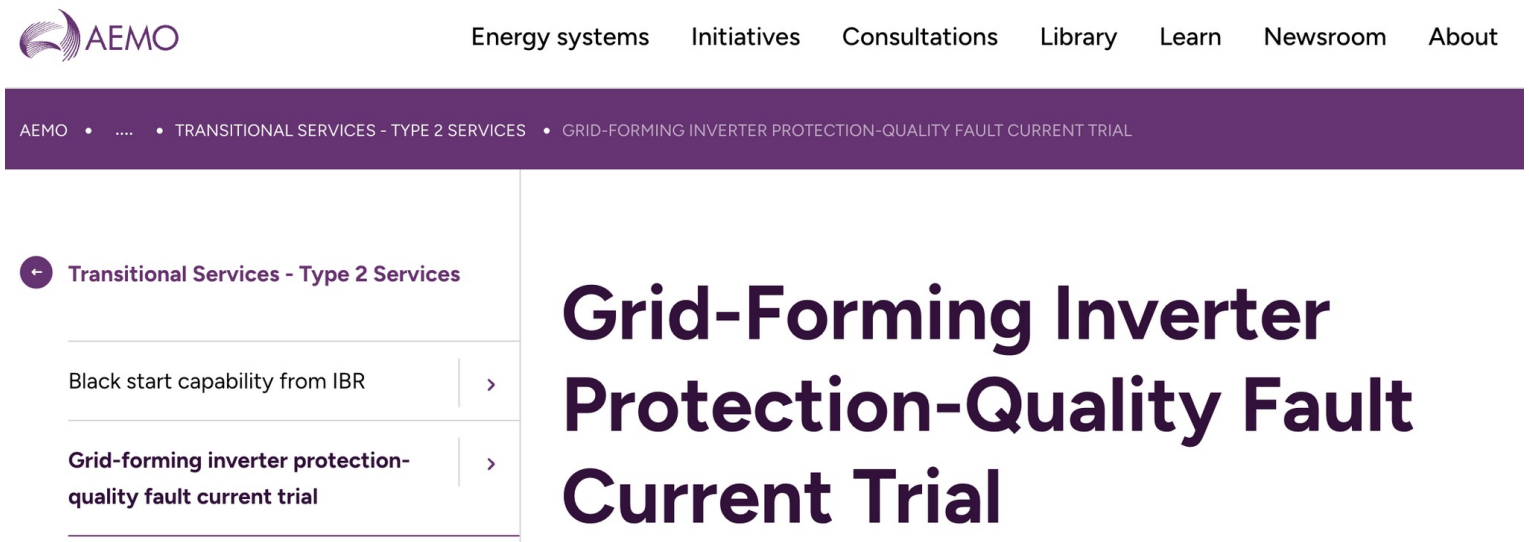
This is a major concern

Some concerns are real. Others are red herrings (not major concerns)

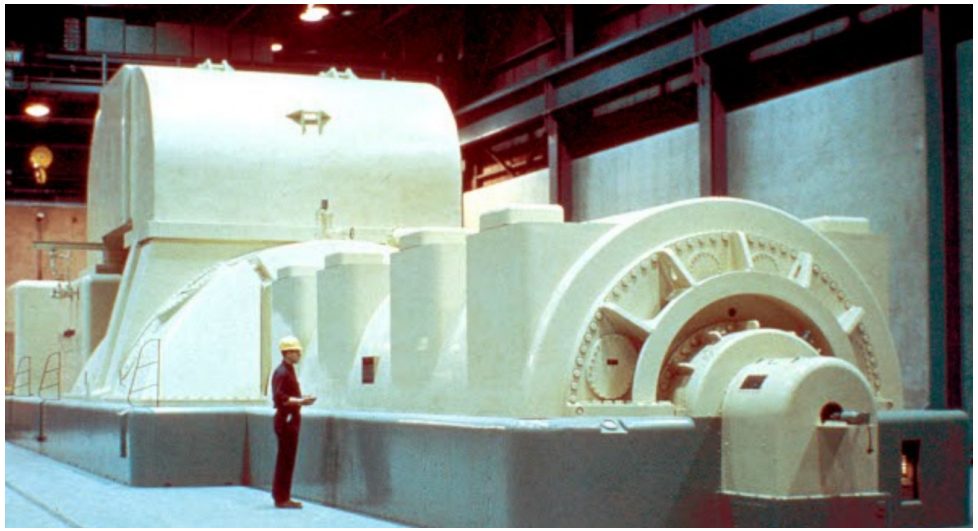
Important point: distribution faults and transmission network faults are different

When someone says “IBRs can’t provide protection currents”
A good response *might* be, “No, they can. We just need to do our job as engineers”

This is not just an academic exercise



Rotating Machines



- Coiled wires in the stator
- Mechanical inertia
- Current limit determined by machine Z
  - Max current ~5–6 pu

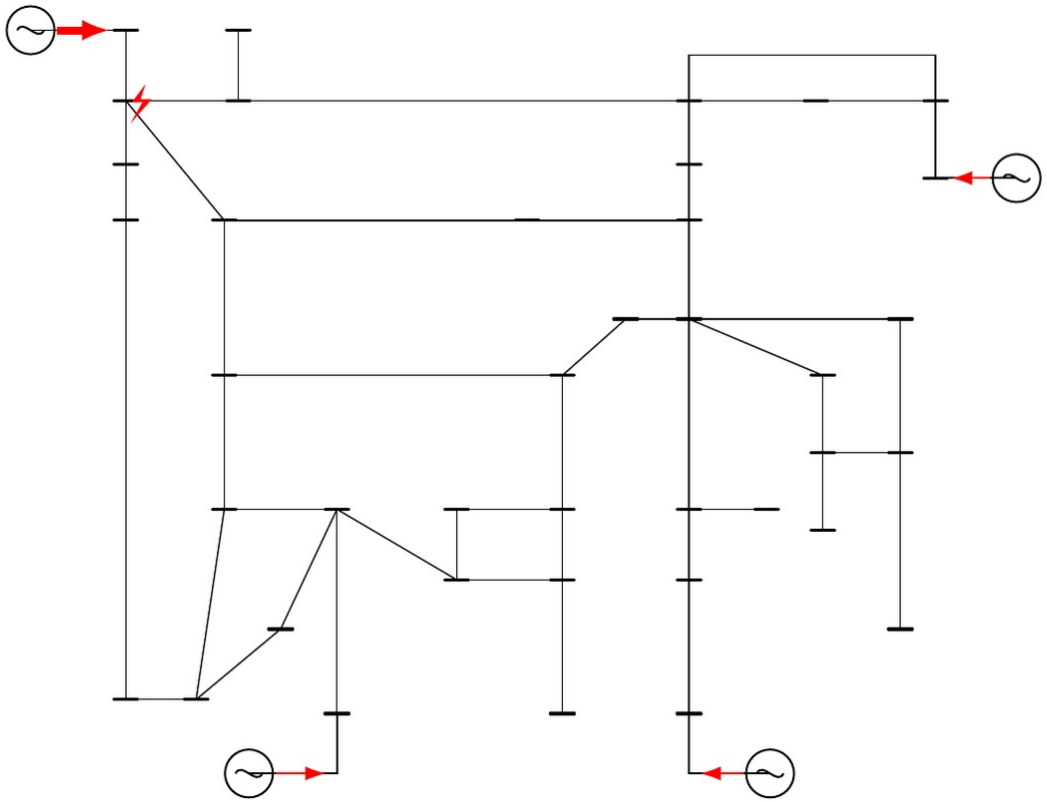
Inverters



- Transistor switches
- Control laws
- **Strict current limits**
  - Max current ~1.2 pu

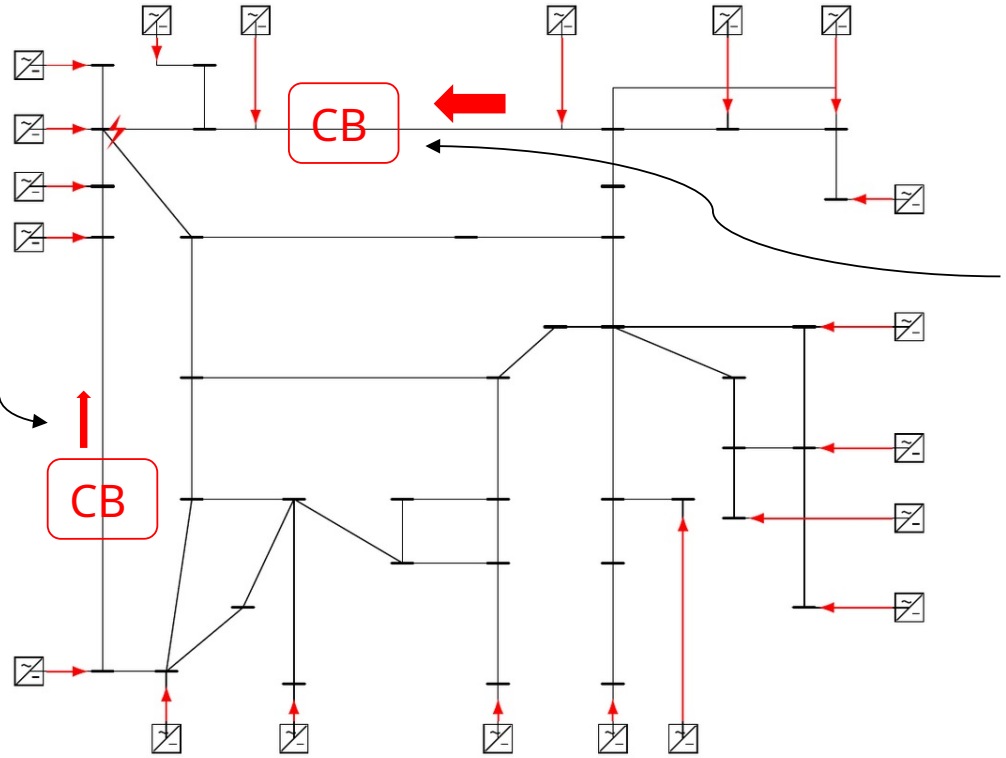
So you need ~25 inverters to provide the same fault current magnitude overhead

Synchronous machine-powered grid, fault on the **transmission network**



- One or a few synchronous machines supply large currents
- The fault current travels a short, easily predictable distance
- The voltage drop is steep and is close to the fault

IBR-powered grid, fault on the **transmission network**



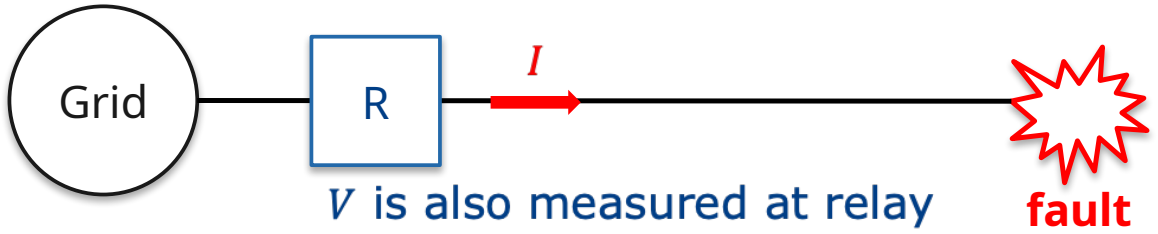
In some “weak” regions, fault current may be insufficient for over-current protection.

In these regions, distance protection may solve the problem.

In many cases, the fault current will be sufficient to trip over-current protection.

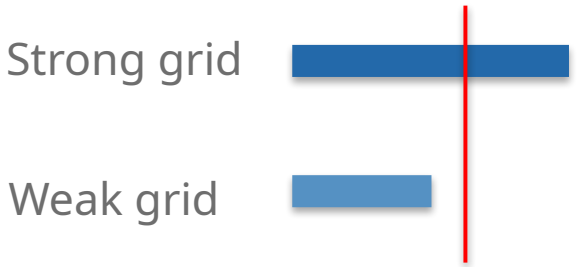
But, careful engineering and new protection studies are required.

- Many IBRs supply small currents
- The fault current travels from further, and is harder to predict
- The voltage drop is diffuse, reaching throughout the network



Overcurrent protection

$I > I_{pickup}$



Distance / impedance protection

$Z_{app} = \frac{V}{I} \approx$ line impedance to the fault

If I is small, V is also small. Why?

→ Fault voltage is 0, $V = IZ$

Thus, distance protection can detect faults, even when current is limited.

Big open question: how should inverters feed unbalanced faults?

The inverters “current budget” must be divided between positive, negative and zero sequence.

This is one of the many important, open questions in IBR-based fault response.

How will the transition from rotating machines → IBRs affect protection?

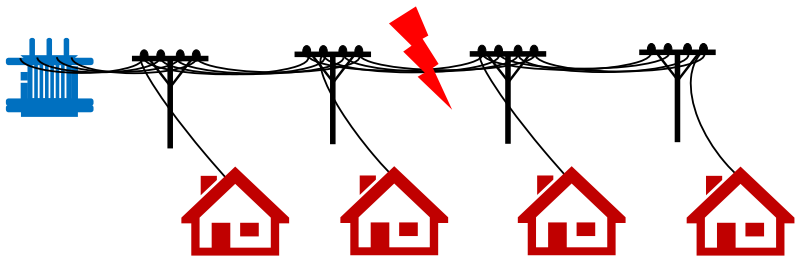
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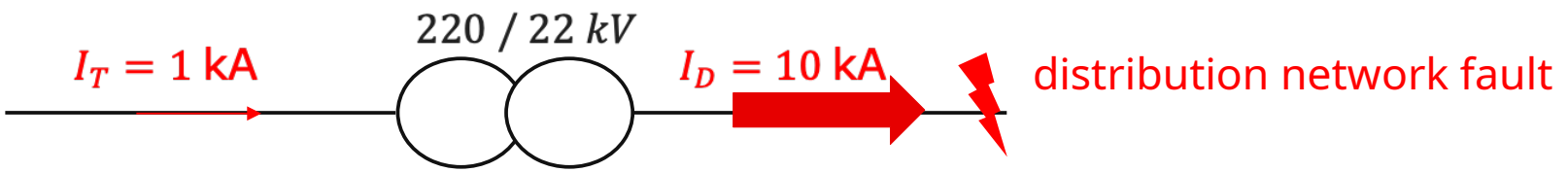
Important point: distribution faults and transmission network faults are different.

When someone says “IBRs can’t provide protection currents”
Respond with “No, they can. We just need to do our job as engineers.”

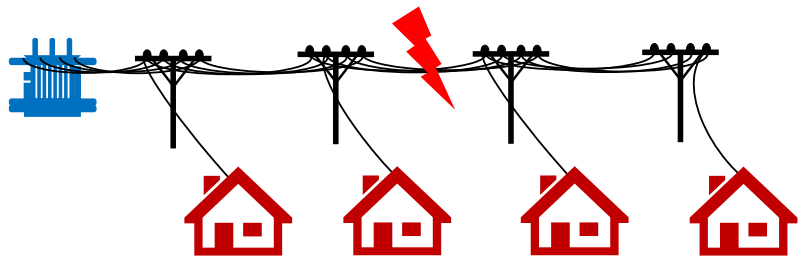
Synchronous machine-powered grid, fault on the **distribution network**

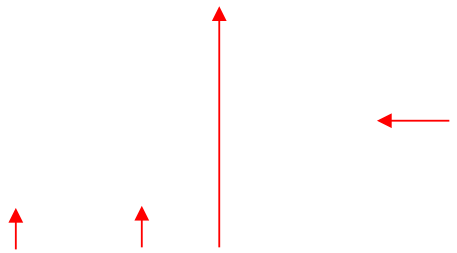


Because of the transformer, the fault current seen on the transmission network is much smaller

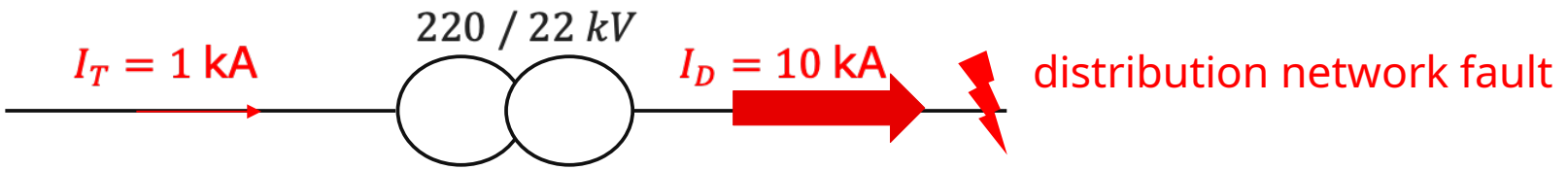


IBR-powered grid, fault on the **distribution network**

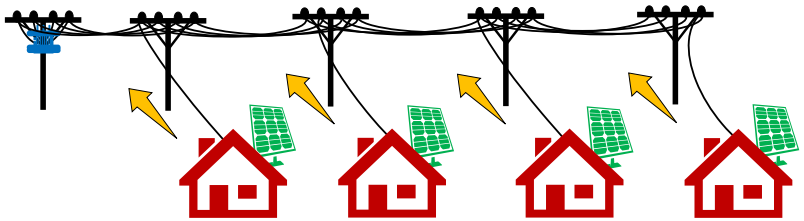




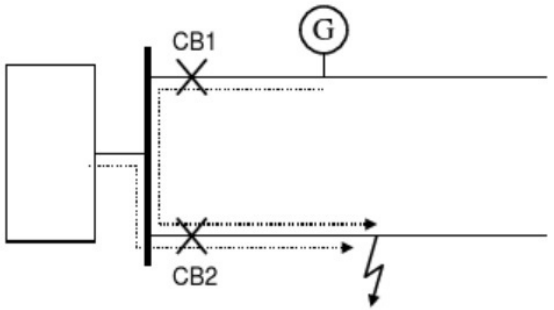
The same applies to IBR-powered grids → Transmission generation mix is not a concern for dist. faults



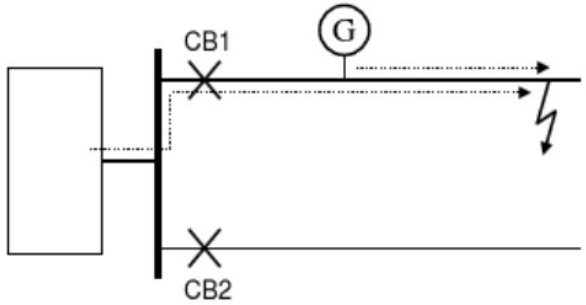
Still, other distribution network challenges persist:



Sympathetic Tripping



Protection Blinding



Still, approximately 1/3 of Australian homes have PV panels and the dist. grids are safe.

→ this is impressive and world-leading

Intro to Power System Protection

ELEN90060

Keith Moffat