EEN442 - Power Systems II (Συστήματα Ισχύος II)

Part 6: Protection fundamentals

https://sps.cut.ac.cy/courses/een442/

Dr Petros Aristidou
Department of Electrical Engineering, Computer Engineering & Informatics
Last updated: November 14, 2022

This part's learning objectives

After this part of the lecture and additional reading, you should be able to . . .

1. . . . explain the basic principles of protections in electric power systems;
2. . . . understand the most common types of protections and their design process;
3. . . . use computational tools to perform protection design.

References:

1. ALSTOM, Network Protection & Automation Guide, 2002.
2. J. D. Glover, M. S. Sarma, and T. J. Overbye, Power System Analysis and Design, 2012.
3. A. Gómez-Expósito, A. J. Conejo, and C. A. Cañizares, Electric Energy Systems Analysis and Operation, 2018.

1 Outline

1 Protection requirements

- Power system equipment are very expensive – a capital investment of tens/hundreds/thousands of millions of euros.
- Power systems should operate continuously and reliably. Outages cost a huge amount of money.
- No matter how well designed, **faults will always occur**. These faults represent a risk to life and/or our equipment.
- A high-current fault can burn through copper conductors or weld together core laminations in a transformer or machine in tens or hundreds of milliseconds. Power plants can be damaged in a few seconds.

✍ 'the science, skill, and art of applying and setting relays and/or fuses to provide maximum sensitivity to faults and undesirable conditions, but to avoid their operation on all permissible or tolerable conditions' [a]

[a] J. L. Blackburn, Protective Relaying (New York: Dekker, 1997).

1 Protection requirements

The basic definitions needed in protection design are:

- **Protection System**: a complete arrangement of protection equipment and other devices required to achieve a specified function based on a protection principle (IEC 60255-20)
- **Protection Equipment**: a collection of protection devices (relays, fuses, etc.).
- **Protection Scheme**: a collection of protection equipment providing a defined function and including all equipment required to make the scheme work (i.e. relays, CTs, CBs, batteries, etc.)

1 Protection equipment

Protection systems have three basic components:

- **Instrument transformers**: Unlike power transformers, instrument transformers convert the voltage or current from from kV or kA to a few Volts or Amperes to be used as input signal to the relay. There are two basic types of instrument transformers: voltage transformers (VTs), formerly called potential transformers (PTs), and current transformers (CTs).
- **Protective relays**: It is a relay device (electrical switch) designed to trip a circuit breaker when a fault is detected. It usually receives input from the instrument transformers and/or communication signals.
- **Circuit breakers**: It is an automatically operated electrical switch. It receives input signal from a protective relay and interrupts the current flow.

1 Protection equipment

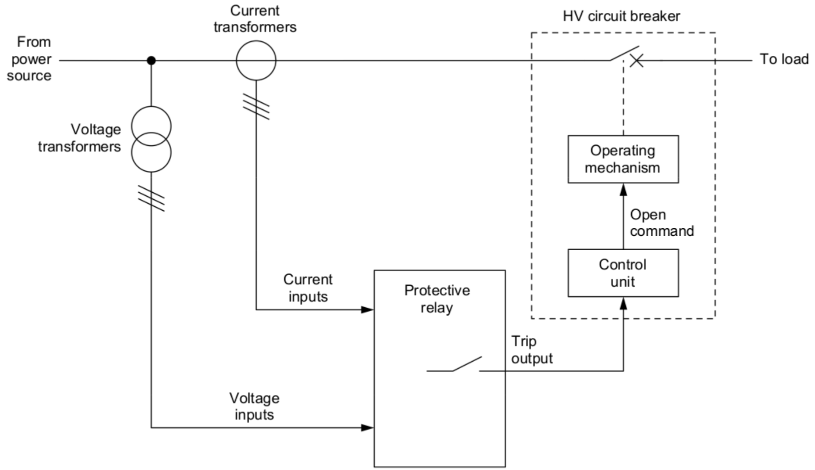
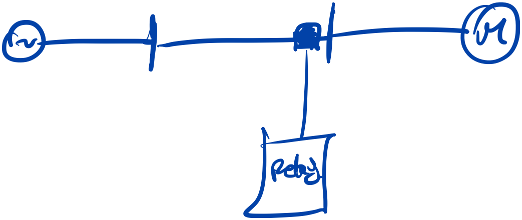


Figure: Connection of a protective relay and HV circuit breaker to a three-phase electric power circuit



max Sc → 1 kA

min Sc → 300 A

max normal operation → < min Sc (→ 270 A)

max Sc > min Sc > max normal oper. (10%)

1 Data requirements for protection design

The data required for a relay setting study are:

- The one-line diagram of the power system involved, showing the type and rating of the protection showing the type and rating of the protection devices and their associated current transformers
- the impedances in ohms, per cent or per unit, of all power transformers, rotating machine and feeder all power transformers, rotating machine and feeder circuits
- the maximum and minimum values of short circuit currents that are expected to flow through each protection device
- the maximum load current through protection devices
- the starting current requirements of motors and the starting and locked rotor/stalling times of induction motors
- the transformer inrush, thermal withstand and damage characteristics
- decrement curves showing the rate of decay of the fault current supplied by the generators
- performance curves of the current transformers

FIDVR

2 Outline

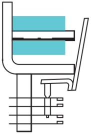
2 Protective relays

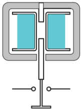
Relays may be classified according to the technology used:

- Electromechanical
- Static
- Digital
- Numerical

2 Electromechanical relay

- Earliest forms of relay used for the protection of power systems, and they date back around 100 years
- They work on the principle of a mechanical force operating a relay contact in response to a stimulus. The mechanical force is generated through current flow in one or more windings on a magnetic core or cores, hence the term electromechanical relay


(a) D.C. relay


(c) Solenoid relay


(b) Shading loop modification to pole of relay (a) for a.c. operation


(d) Reed relay

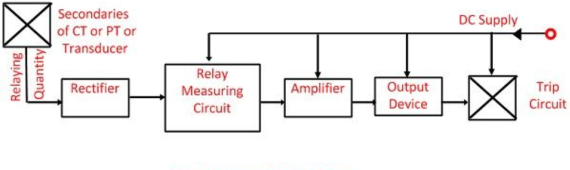
- The main advantage of such relays is that they provide galvanic isolation between the inputs and outputs in a simple, cheap and reliable form.
- These relays are still used for simple on/off switching functions where the output contacts carry substantial currents.

2 Electromechanical relay

- Typical attracted armature relay have an operating speed of between 100ms and 400ms. Operating power is typically 0.05-0.2 watts, but could be as large as 80 watts for a relay with several heavy-duty contacts and a high degree of resistance to mechanical shock.
- **Weaknesses:** They applied a high load (burden) on the current transformers and/or voltage transformers. They had a long operating time due to the inertia of the moving parts used in the relay. They also had a high maintenance cost.

2 Static relay

- In a protection relay, the term ***static*** refers to the absence of moving parts to create the relay characteristic.
- Introduced in the 1960s based on analogue electronic devices instead of coils and magnets to create the relay characteristic. It is considered as an analogue electronic replacement for electromechanical relays.
- User programming was restricted to the basic functions of adjustment of relay characteristic curves.
- **Weaknesses:** Their operation requires a highly reliable source of electric power and is sensitive to both interference and ambient temperature.



Block Diagram of Static Relay

Image: https://circuitglobe.com/static-relay.html

2 Digital relay

- Early examples were introduced around 1980 and are still current technology for many relay applications.
- Digital relays use analogue to digital conversion of all measured quantities and use a microprocessor to implement the protection algorithm.
- Digital relays have a wider range of settings, greater accuracy and a communications link to a remote computer.
- Limited computation power. Only for the specific protection functions.

Image: Siemens SIPROTEC 7SJ62 relay

2 Numerical relay

- Compared to digital relays, numerical relays use one or more digital signal processors (DSP) optimised for real time signal processing, running the mathematical algorithms for the protection functions.
- Highly programmable with extensive computational capabilities. Are able to implement multiple protective functions.
- A failure of a numerical relay may cause many more functions to be lost, compared to applications where different functions are implemented by separate hardware items. This might create reliability issues.

2 Numerical relay overview

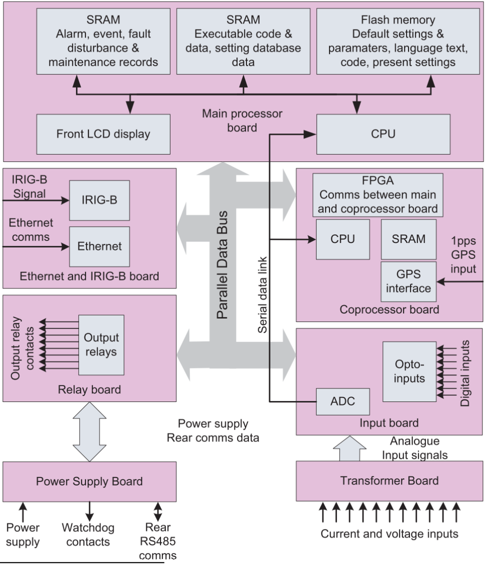


Image: ALSTOM, Network Protection & Automation Guide, 2002.

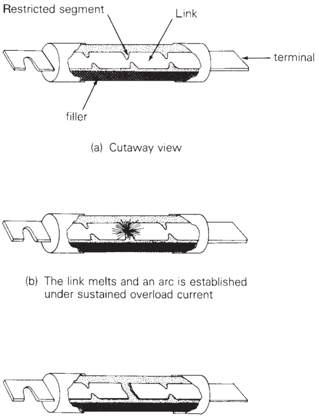
3 Outline

3.1 Overcurrent protection

- Protection against excess current was naturally the earliest protection system to evolve.
- Not be confused with 'overload' protection, which normally makes use of relays that operate in a time related in some degree to the thermal capability of the plant to be protected
- Overcurrent protection is directed entirely to the clearance of faults.

3.1 Fuses

- Consists of a metal ”fusible” link (e.g., silver), packed in filler material (e.g., sand), and connected to contact terminals.
- Inexpensive, fast operating, easily co-ordinated, and reliable. Do not require protective relays or instrument transformers.
- Disadvantage: fuse or the fuse link must be manually replaced after it melts (one-shot devices).



(a) Cutaway view

(b) The link melts and an arc is established under sustained overload current

(c) The “open” link after clearing the overload current.

Image: J. D. Glover, M. S. Sarma, and T. J. Overbye, Power System Analysis and Design, 2012.

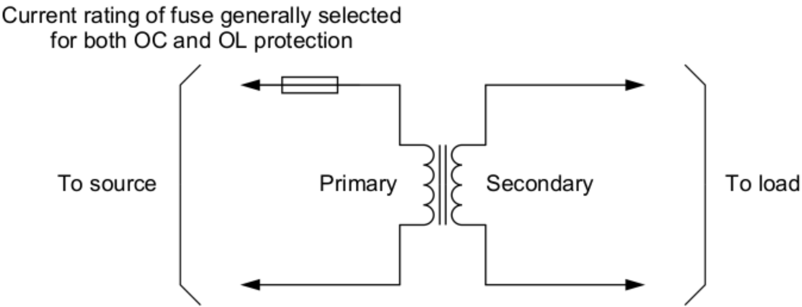


Figure: Overcurrent and overload protection of a single-phase power transformer using a single fuse (at the primary winding)

Figure: Pole-mounted secondary distribution transformer with its OC fuse (shown with a white arrow)

3.1 Fuses

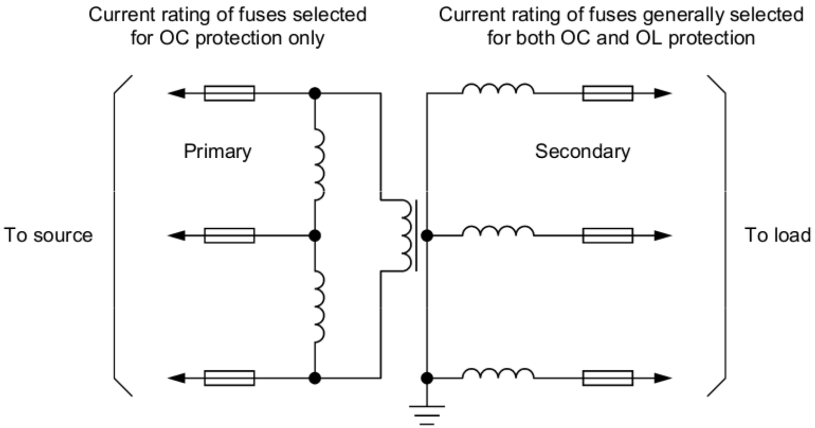


Figure: Overcurrent and overload protection of a three-phase power transformer using fuses at the primary and secondary windings

3.1 Miniature Circuit Breaker (MCB) and Molded Case Circuit Breaker (MCCB)

- Used for LV systems.
- Does not need to be replaced with a new unit once open.
- Easy to operate, test, and maintain.
- MCCB has higher rating (up to 1600 A instead of 125 A for MCB)

Figure: Contrary to the fuse, the circuit breaker does not need to be replaced with a new unit once open. The contacts may be reclosed using a reset lever

3.1 Overview of OC relay and circuit breaker

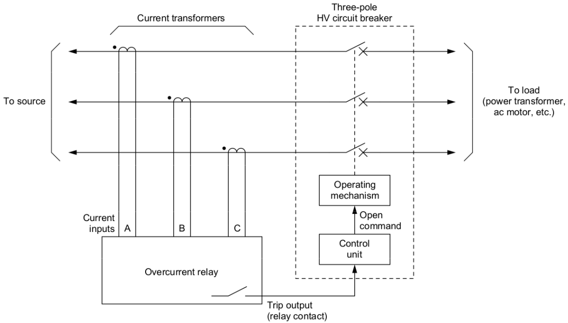


Figure: Protection of a three-phase power circuit using an overcurrent relay and an HV circuit breaker

3.1 Fuse specifications

- **Voltage rating**: Ability of a fuse to suppress the internal arc that occurs after the fuse link melts. A blown fuse should be able to withstand its voltage rating (LV 250-600 V, MV 2.4-34.5 kV).
- **Continuous current rating**: Fuse should carry this rms current indefinitely, without melting and clearing.
- **Interrupting current rating**: TThe largest rms asymmetrical current that the fuse can safely interrupt (LV 200 kA, MV 65, 80, and 100 kA).
- **Time response**: The melting and clearing time of a fuse. Usually specified by an inverse "time–current" curve. The highest the current the faster it melts.

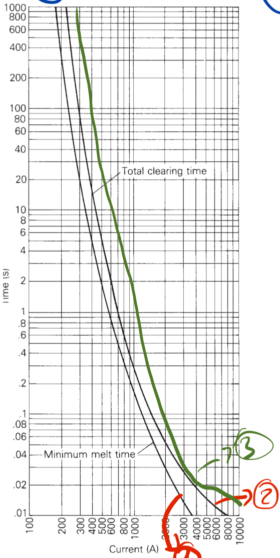
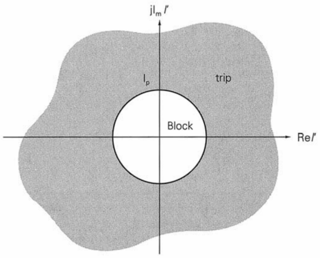


Image: J. D. Glover, M. S. Sarma, and T. J. Overbye, Power System Analysis and Design, 2012.

3.1 Instantaneous overcurrent relays

- If the current magnitude $|I|$ exceeds a specified adjustable current magnitude I_p, called the ***pickup current***, then the relay contacts close ”instantaneously” to energize the circuit breaker trip coil

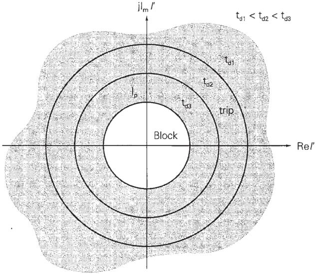
- If $|I|$ is less than the pickup current I_p, then the relay contacts remain open, blocking the trip coil.



- Able to reset (manually or automatically) after energizing.

3.1 Time-delay overcurrent relays

- Respond to the magnitude of their input current, but with an intentional ***time delay***.
- The time delay depends on the magnitude of the relay input current.
- If $|I|$ is a large multiple of the pickup current I_p, then the relay operates (or trips) after a small time delay.



- For smaller multiples of pickup, the relay trips after a longer time delay.
- If $|I| < I_p$, the relay remains in the blocking position.
- Allows to coordinate protections based on current and time discrimination.

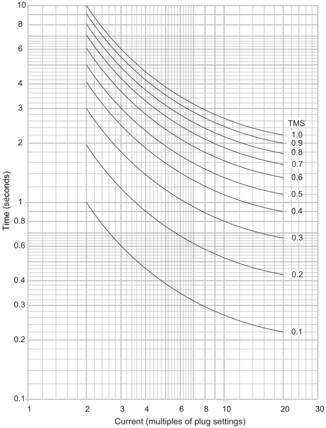
3.1 Overcurrent protection coordination

The basic rules for correct relay co-ordination can generally be stated as follows:

- whenever possible, use relays with the same operating characteristic in series with each other
- make sure that the relay farthest from the source has current settings equal to or less than the relays behind it, that is, that the primary current required to operate the relay in front is always equal to or less than the primary current required to operate the relay behind it

- The characteristic curves are usually shown with operating time in seconds versus relay input current as a multiple of the pickup current. $I_r = \frac{|I|}{I_p}$
- The inverse time characteristic can be shifted up or down by adjustment of the Time Multiplier Setting (TMS).

Relay Characteristic	Equation (IEC 60255)
Standard Inverse (SI)	$t = TMS \times \frac{0.14}{I_r^{0.02} - 1}$
Very Inverse (VI)	$t = TMS \times \frac{13.5}{I_r - 1}$
Extremely Inverse (EI)	$t = TMS \times \frac{80}{I_r^2 - 1}$
Long time standby earth fault	$t = TMS \times \frac{120}{I_r - 1}$



- Different characteristics allow for more steep response
- The IEC 60255 Standard Inverse is shown in the figure right for different TMS values

Current setting:

- An overcurrent relay has a minimum operating current, known as the ***current setting*** of the relay.
- The current setting must be chosen so that the relay does not operate for the **maximum load current** in the circuit being protected, but does operate for a current equal or greater to the **minimum expected fault current**.
- A relay minimum current setting of at least 1.05 times the short-time rated current of the circuit is usually chosen.

Grading margin or coordination time interval:

- The time interval that must be allowed between the operation of two adjacent relays to achieve correct discrimination between them.
- If a grading margin is not provided, or is insufficient, more than one relay will operate for a fault, leading to difficulties in determining the location of the fault and unnecessary loss of supply to some consumers.
- Precise determination of relay operating times is complicated by several factors, including CT error, dc offset component of fault current, and relay over-travel.
- Typical coordination time intervals **from 0.2 to 0.5 s**

Cyprus University of Technology

3.2 Directional protection

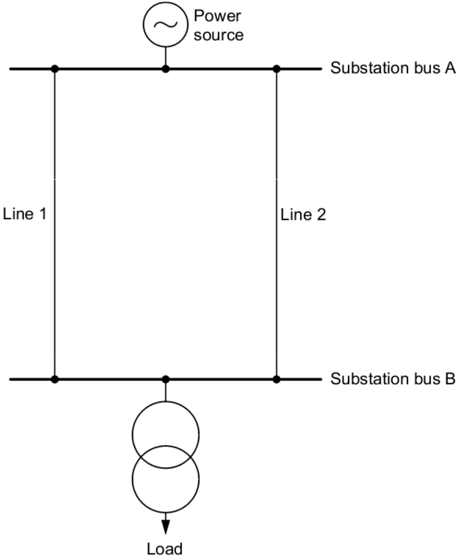


Figure: Two lines connected in parallel to convey power to a substation

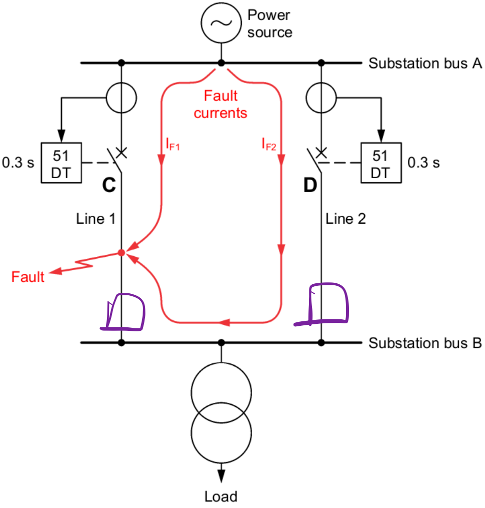


Figure: Protection of two parallel lines using overcurrent relays

3.2 Directional protection

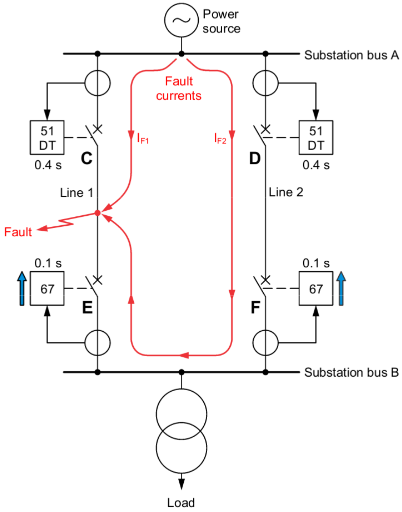


Figure: Directional overcurrent protection of two power lines connected in parallel

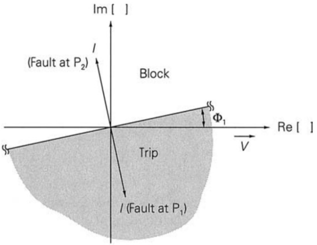
Cyprus University of Technology

- Directional relays are designed to operate for fault currents in only one direction.

- Take as input $V\underline{/0}$ and $I\underline{/\phi}$ and only trip if:

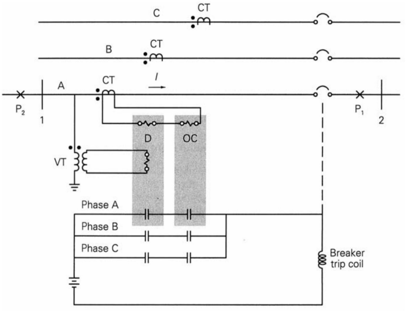
$$-180^\circ < (\phi - \phi_1) < 0^\circ$$

where ϕ_1 is the boundary between trip and block regions.



3.2 Directional protection

- For a fault at P_1 to the right of the CT, the fault current moves from bus 1 to bus 2.
- Since lines are inductive, the current lags the voltage. Thus the fault current is detected.
- For a fault at P_2 to the left of the CT, the fault current moves from bus 2 to bus 1.
- Since lines are inductive, the current leads the voltage. Thus the fault current is blocked.



Cyprus University of Technology

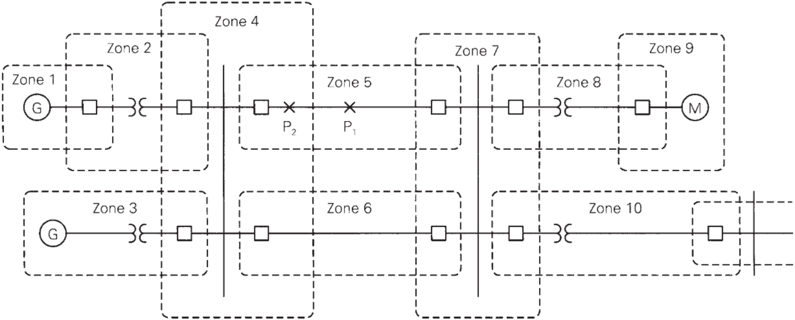
1. **Protection fundamentals**

2. **Protective relays**

3. **Protection design**
   - Overcurrent protection
   - Directional protection
   - Zones
   - Distance protection
   - Differential protection
   - Tele-protection

3.3 Protection zones

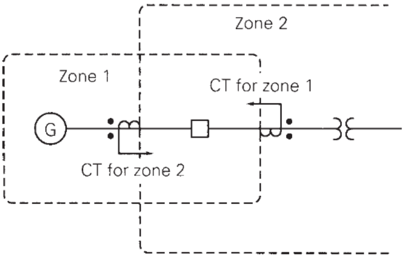
To limit the extent of the power system that is disconnected when a fault occurs, protection is arranged in zones. If a fault occurs anywhere within a zone, action will be taken to isolate that zone from the rest of the system.



3.3 Protection zones

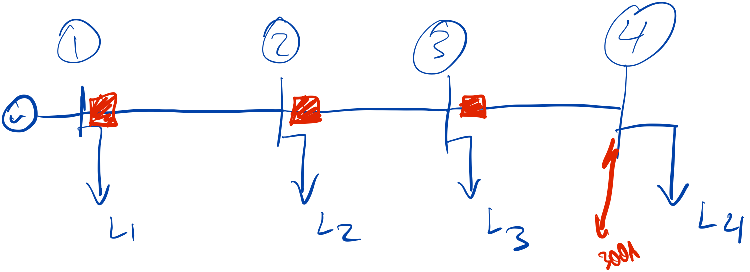
Cyprus University of Technology

- Zones are defined for generators, transformers, buses, transmission and distribution lines, and motors.
- Zones should overlap. Overlap is accomplished by having two sets of instrument transformers and relays for each circuit breaker.
- Circuit breakers are located in the overlap regions.
- For a fault anywhere in a zone, all circuit breakers in that zone open to isolate the fault.



3.4 Distance protection

- Coordinating time-delay overcurrent relays can also be difficult. With too many radial lines and buses, the time delay for he breaker closest to the source becomes excessive.
- Instead of using the current measurment we can use the impedance ”seen” by the relay, based on the voltage-to-current ratio Z.
- During a three-phase fault, current increases while bus voltages close to the fault decrease.
- The impedance of a transmission line is proportional to its length. It is appropriate to use a relay capable of measuring the impedance of a line up to a predetermined point (the reach point).
- If the measured impedance is less than the reach point impedance, it is assumed that a fault exists on the line between the relay and the reach point.


1
2
3
4
L1
L2
L3
L4
300A

- Relay trips for $|Z| < Z_r$, where Z_r the relay setting.
- During normal operation, the ratio $|Z|$ is large (small currents compared to voltages).
- During a fault, $|Z|$ moves withing Z_r and the relay trips.

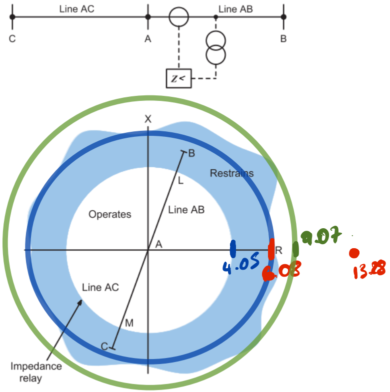
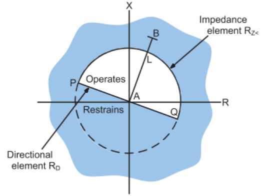
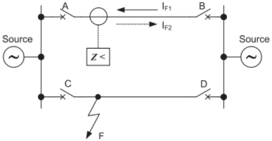


Image: ALSTOM, Network Protection & Automation Guide, 2002.

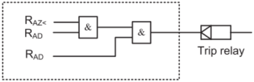
- By restricting to the upper or lower semi-circle, we can discriminate based on directionality.
- The ***reach*** of an impedance relay denotes how far down the line the relay detects faults.
- An 80% reach means that the relay will detect any (solid three-phase) fault between the relay and 80% of the line length.
- This can be used for designing backup protection in zones.



(a) Characteristic of combined directional/ impedance relay



(b) Illustration of use of directional/impedance relay: circui diagram



Combined directional/impedance relay

$R_{AZ<}$: distance element at A

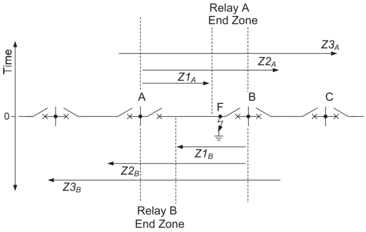
R_{AD} : directional element at A

(c) Logic for directional and impedance elements at A

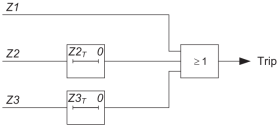
Image: ALSTOM, Network Protection & Automation Guide, 2002.

3.4 Three-zone distance protection: Zone 1

- Usually have a reach setting of up to 80% of the protected line impedance
- The resulting 15-20% safety margin ensures that there is no risk of the Zone 1 protection over-reaching the protected line due to errors in the current and voltage transformers, inaccuracies in line impedance data provided for setting purposes and errors of relay setting and measurement.
- Zone 2 of the distance protection must cover the remaining 15-20% of the line.



(a) Stepped time/distance characteristics



(b) Trip logic

Image: ALSTOM, Network Protection & Automation Guide, 2002.

3.4 Three-zone distance protection: Zone 2

- The reach setting of the Zone 2 protection should be at least 120% of the protected line impedance.
- Zone 2 tripping must be time-delayed to ensure grading with the primary relaying applied to adjacent circuits that fall within the Zone 2 reach. Typically 0.25 to 0.4 seconds.

- Remote back-up protection for all faults on adjacent lines can be provided by a third zone of protection that is time delayed to discriminate with Zone 2 protection plus circuit breaker trip time for the adjacent line.
- Zone 3 reach should be set to at least 120% the impedance presented to the relay for a fault at the remote end of the second line section. This should be added to the 100% of the protected line.

3.5 Differential protection

- Principle is to sense the difference in currents between the incoming and outgoing terminals of the unit being protected.
- Current is measured at the two ends of the protection zone. If the currents are the same, there is no fault. If the currents are different, there is a fault.
- Differential relays are commonly used to protect generators, buses, and transformers. Application in LV residential systems with residual-current device (RCDs) with 10-30 mA setting.

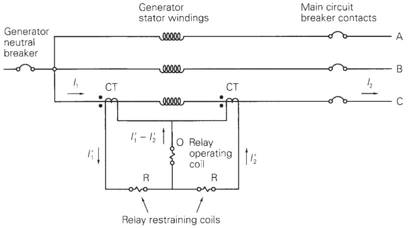


Image: J. D. Glover, M. S. Sarma, and T. J. Overbye, Power System Analysis and Design, 2012.

3.5 Differential protection

- As k increases, the block region becomes larger and the relay less sensitive.
- Differential relaying provides primary zone protection without backup
- No need to calculate system fault currents

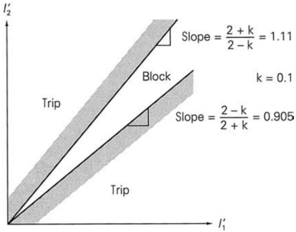


Image: J. D. Glover, M. S. Sarma, and T. J. Overbye, Power System Analysis and Design, 2012.

3.5 Differential bus protection

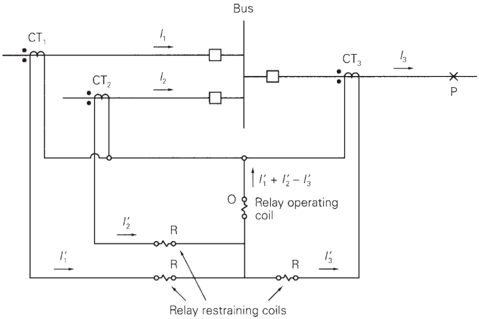
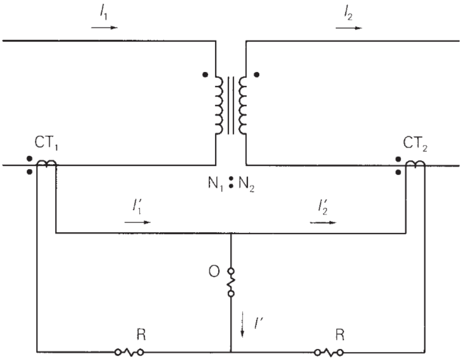


Image: J. D. Glover, M. S. Sarma, and T. J. Overbye, Power System Analysis and Design, 2012.

3.5 Differential transformer protection



Note: CTs might need a phase shift to compensate for the transformer phase shift.

Image: J. D. Glover, M. S. Sarma, and T. J. Overbye, Power System Analysis and Design, 2012.

3.6 Outline

1. **Protection fundamentals**
2. **Protective relays**
3. **Protection design**
   - Overcurrent protection
   - Directional protection
   - Zones
   - Distance protection
   - Differential protection
   - Tele-protection

3.6 Tele-protection overview

- Several relays located remotely from each other communicate between each location to achieve a unit protection function.
- Communications facilities are needed when remote circuit breakers need to be operated due to a local event. This communication is known as ***intertripping***.
- Comparison of local and remote signals provides the basis for both fault detection and discrimination of the schemes.

3.6 Technology overview

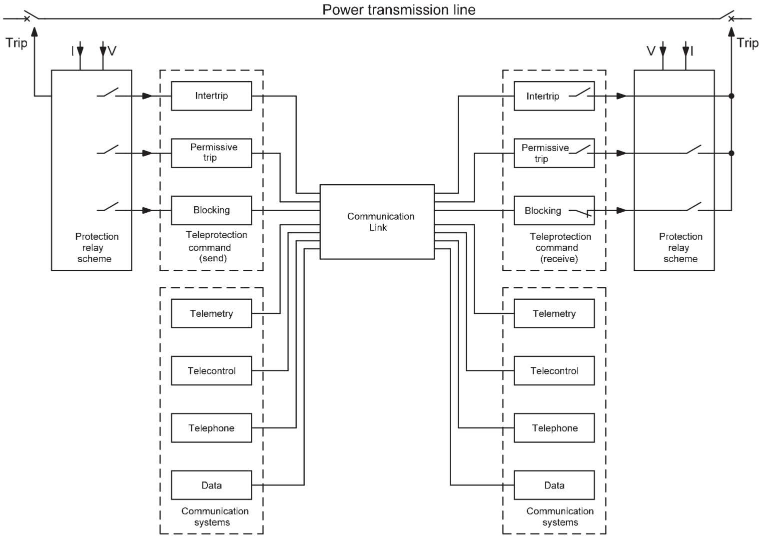


Image: ALSTOM, Network Protection & Automation Guide, 2002.

3.6 Differential protection example

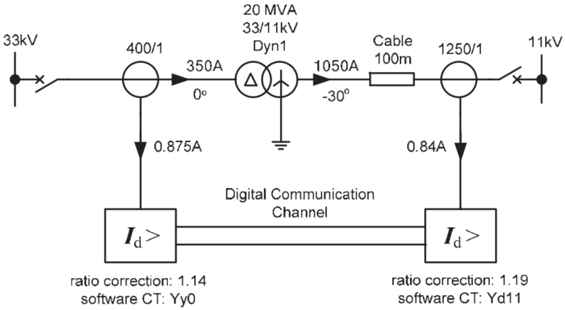


Image: ALSTOM, Network Protection & Automation Guide, 2002.