Protection of power equipment

- **overload protection**
  - over heating causes hazard of fire or explosion
  - not used, if outage would be more dangerous; alarm needed anyway
  - overload protection can be integrated with short circuit protection

- **short circuit protection**
  - aim is to prevent excess heating of components
  - other hazard: sag of conductors, broken conductor

- **earth fault protection**
  - single phase to earth fault
    - into earthed equipment
    - into other system parts or objects
  - generally should be noticed up to $R_f = 500 \, \Omega$
  - automatic tripping versus alarm only

- **protection against hazard voltages**
  - public safety of people
  - risks of fire
  - risk of explosion
  - importance depends on circumstances
    - e.q. extremely hazardous or hazardous conditions
Protective relays

- measure continuously power system state
  - usually connected by measurement transformers
  - CT & VT (current & voltage transformer)

- detect abnormal situations
  - short circuit, earth fault, overload, over voltage, under voltage
  - relay operates when set values are exceeded

- objective is to prevent or limit large disturbances
  - alarm levels
  - try to limit the affected area (selectivity)

- operate after the set time delay
  - total fault time: relay delay + CB operation time (~ 100 ms)
Principles of relay protection

- Selectivity: minimum outage coverage
- Speed and sensitivity
  - in order to minimize the damages
  - in order to maintain transmission stability
- Redundancy
  - adjacent relays partly overlapping
  - always some back-up protection
  - no blind spots
- Reliable and simple
- Testing must be possible
  - on site
  - during operation
- Reasonable investment costs

Selectivity

- Relay detects the fault within protection zone
- Relay does not trip, if
  - there is no fault
  - fault is outside the protection zone
- Absolute selectivity
  - relay trips only for faults within protection zone
- Time grading
- Current grading
Protection zones

- formed by relays and circuit breakers
- lines, transformers, generators, motors

Back-up protection

- works in case of primary protection fails
- important especially in transmission systems
- large machines and transformers

Main tasks of relay protection

- indicate faults
- limit affected area
- limit consequences
Types of relays

Over current relays:

- **Instantaneous**

- **Definite time**

- **Inverse time**

Differential relays:

- Cable: $I_d = \frac{I_1 + I_2}{2}$
- Transformer: $I_d = I_2 - I_1$
Relay types

Directional relays:

Impedance relays:

\[ Z_j = \text{line impedance} \]
MV-line short circuit protection

Re-closing (RC):

$t_1$ 0,5 s  $t_2$  ~ 1-2 min $= \Delta t$  $t_3$

Equivalent fault duration:

$$t_{ekv} = (t_1 + t_2)e^{-\Delta t/\tau} + t_3$$

$\tau$ is the conductor cooling time constant

Maximum allowed fault duration is $t_{max}$

$$t_{max} = \frac{I_{1s}^2}{I_k^2}$$

$I_k$ = actual fault current (max)

$I_{1s}$ = 1s thermal rated current

*It must be* $t_{ekv} \leq t_{max}$

$t_1 + t_2 \leq t_{max}$
Overcurrent protection of a MV line

The relay settings include:
- $I_{\text{delayed}}$ delayed tripping current setting
- $t_{\text{delayed}}$ delayed tripping time setting
- $I_{\text{fast}}$ fast tripping current setting
- $t_{\text{fast}}$ fast tripping time setting
- $t_n$ re-closing time settings

Conditions for settings:
- $I_{\text{delayed}} > I_{\text{LOAD}}$
- $I_{\text{fast}} < I_{k,\text{min}}$ (2-phase short circuit)
- $t_{\text{fast}}: t_{\text{ekv}} < t_{\text{max}}$ (thermal limiting current)

The time setting $t_{\text{fast}}$ must be clearly higher than the time delay of the relay downstream, but clearly lower than the setting of the back-up protection upstream.

Fast tripping takes care of strong faults close to the substation. Often re-closings are blocked in this case.

Minimum time grading: mechanical relays 0.5 s; static relays 0.3 s; numeric relays 0.15 s
Earth fault protection of a MV-line

1) Zero sequence over current relay
   - works in unearthed systems
   - the fault current must be clearly higher than the capacitive charge current in the sound line case.
   \[ I_f = 3\omega C_{0j}E \]

2) Zero sequence directional relay in reactive current connection
   - works in unearthed systems
   \[ \sum_{i \neq j} C_{0i} >> C_{0j} \]
   condition: \[ I_0 \sin \varphi > I_{as} \]
   \[ \varphi_0 = 90^\circ \]
Earth fault protection in compensated neutral systems

3) Zero sequence directional relay in active current connection

- works properly in coil earthed systems

condition: \( I_0 \cos \phi > I_{as} \)
Relay protection in transmission systems

400 kV line protection

Distance relay
- both short circuit and earth fault protection
- back-up protection for other network parts
- pilot wire systems

Differential relay
- only short lines (cables)
Distance relays

· Not-switching
  - very fast
  - 6 measurement units
    - phase-phase
    - phase-earth
  - works in 20 ms

· Switching
  - pick-up unit
  - measurement unit
  - short circuit / earth fault connection
  - works in 30…70 ms
Protection zones of a distance relay

Example:

Zone 1: reach 85 % of line A-B, operation time < 100 ms
Zone 2: reach 120 % of line A-B, time delay 400 ms
Zone 3: reach 120 % of line A-C, time delay 1 s
Zone 4: reach forward A-C, time delay 4 s
Zones of protection

The effect of side-feeds:

\[ z = 0.85(a + kb) \]

\[ k = \frac{I_A + I_B}{I_A} \]
The power swing must not trip the relay

Example: switching state change
- If power swing relay picks-up, it will block the distance relay after time delay $\Delta t$.

- $\Delta t$ is taken big enough that blocking has not time to operate during faults, but short enough that it works during power swings before the relay trips.
Transformer protection

- protection for short circuits inside and downstream
- primary partly protected by the feeding line relay
- short circuit protection by over current relay
  - small primary transformers
  - fast tripping for primary faults
  - delayed tripping for downstream faults
- the use of differential relays
  - compensation of the transforming ratio
  - blocking for inrush currents
    - 100 Hz component
  - the effect of on-load tap-changer must be considered
- Buchholz-relay or gas relay
  - between tank and expansion chamber
  - overload and arc produces gas
  - first alarm, then trip
  - strong faults: fast trip
Transformer protection

Buchholz-relay
- detection of insulation faults
- operation time 100...300 ms
- steps for alarm and trip
- gas analysis ⇒ fault type!

Parts of a gas relay
1. body
2. cover
3. window for inspection
4. alarm float
5. trip float
6. tube for alarm contact
7. tube for trip contact
8. connection wires
9. connection screws
10. valve for gas sample
Transformer overload protection:
- temperature measurement of top-oil
- modeling circuit for winding

Earth fault protection:
- zero sequence over current relay

In the case of large transformers:
- earth fault protection
- oil level indication
- flow relay for on-load tap-changer

Factors affecting the protection solutions:
- importance of the transformer
- type of neutral earthing
- type of network
  - radial, or looped
Differential relay in transformer protection

\[ I_v = \frac{(I_1 + I_2)}{2} \quad \& \quad I_d = I_1 - I_2 \]

\[ p = \text{basic setting} = \frac{I_{d1}}{I_n} \]

\[ s = \text{pick-up ratio} = \frac{I_{d2}}{I_v} \]
Factors affecting the setting of a differential relay

- saturation of current transformers
- transformer magnetizing inrush current
- errors of current transformers (< 13%)
- steps of on-load tap-changer (< 15%)

An example of the inrush current
Example of the transformer protection

(110 / 20 kV primary transformer)
Generator protection

- investment costs
- operation costs
  - faults
  - maintenance
  - preventive maintenance
  - outage costs
    - these all depend on the protection

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Generator protection

- Basic protection relays
  - over current
  - stator earth fault protection
  - disconnection and synchronizing relays
- protection of the turbine
- magnetizing control and stopping logic
- winding cooling system
- fire protection (CO$_2$)
- bearing lubrication and cooling
An example

- Voltage rise
- Inter-turn faults
- Rotor earth fault
- Reverse power
- Over load
- Load unsymmetry
- Over current
- Stator earth fault