Protection of power equipment

- **overload protection**
  - over heating causes hazard of fire or explosion
  - trip 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 due to Ik
  - other hazard: sag of conductors, broken conductor

- **earth fault protection**
  - single phase to earth fault causes hazard voltages
    - 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 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

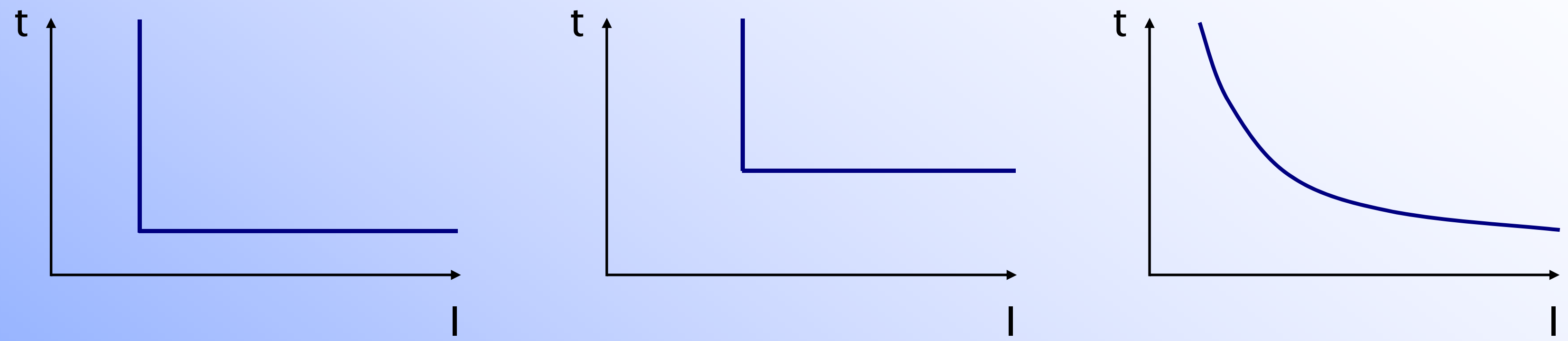
- works in case of primary protection fails
- important especially in transmission systems
- large machines and transformers

Main tasks of relay protection

- indicate faults
- limit affected area
- limit consequences

Types of relays

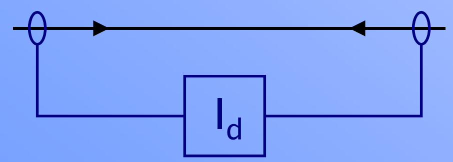
Over current relays :



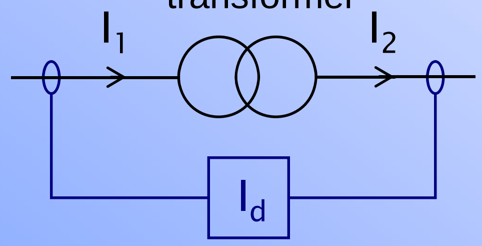
instantaneous — definite time — inverse time

Differential relays :

cable

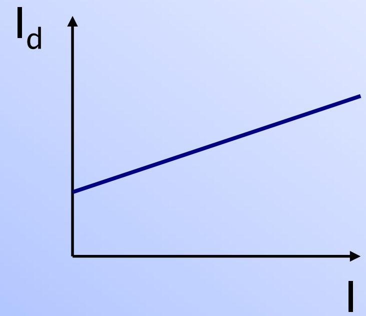


transformer



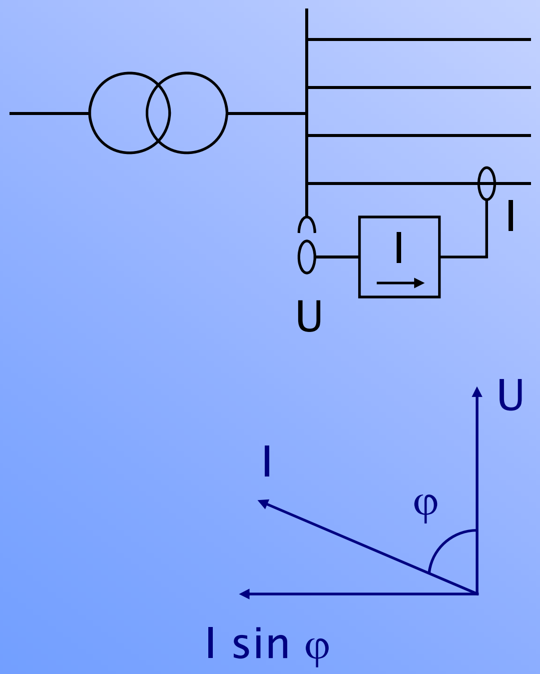
$I = (I_1 + I_2)/2$

$I_d = I_2 - I_1$

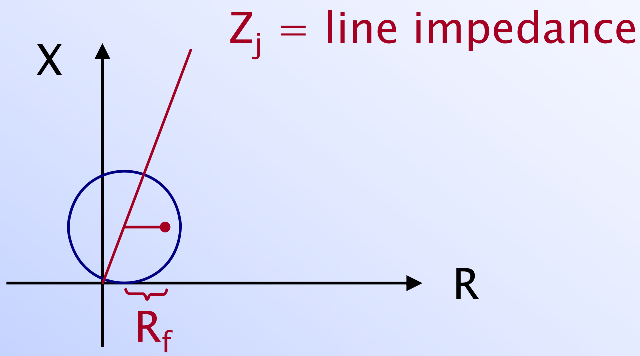


Relay types

Directional relays :

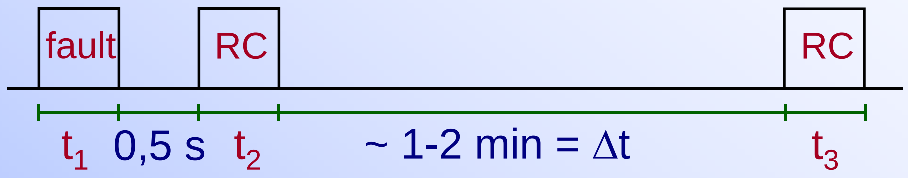


Impedance relays :



MV-line short circuit protection

Re-closing (RC) :



Equivalent fault duration:

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

τ is the conductor cooling time constant

Maximum allowed fault duration is t_{max}

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

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 :

- **$I_>$ delayed tripping current setting**
- **$t_>$ delayed tripping time setting**
- **$I_{>>}$ fast tripping current setting**
- **$t_{>>}$ fast tripping time setting**
- **t_n re-closing time settings**

Conditions for settings :

- **$I_> >> I_{LOAD}$**
- **$I_> << I_{k,min}$ (2-phase short circuit)**
- **$t_>$: $t_{ekv} < t_{max}$ (thermal limiting current)**

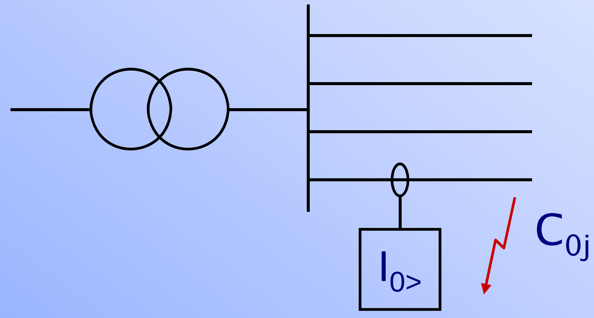
The time setting $t_>$ must be clearly higher than the time delay of the relay downstream, but clearly lower than the setting of the back-up protection upstream.

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

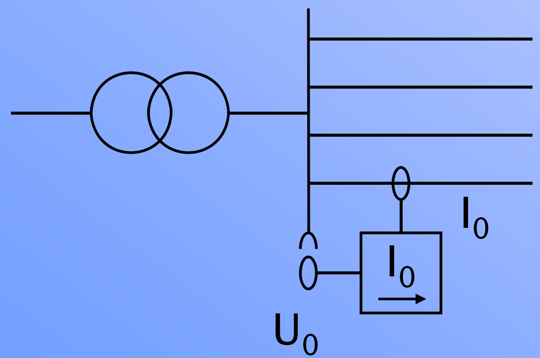


$I_f = 3\omega C_{0\varepsilon} \cdot E$

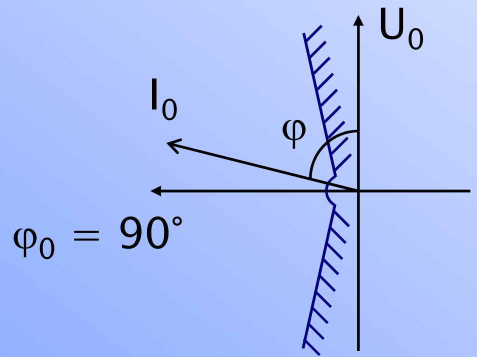
- works in unearthed systems
- the fault current must be clearly higher than the capacitive charge current in the sound line case.

$$\sum_{\substack{i \\ i \neq j}} C_{0i} >> C_{0j}$$

2) Zero sequence directional relay in reactive current connection



- works in unearthed systems

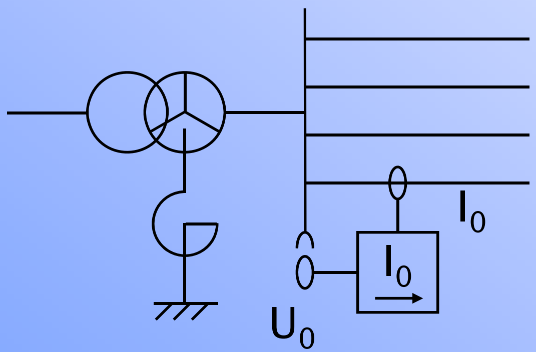


condition :

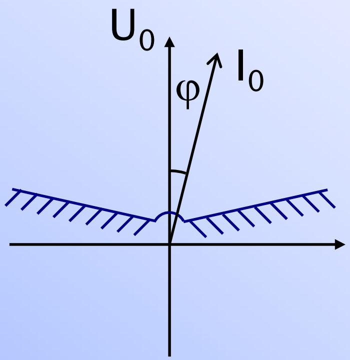
$I_0 \sin \varphi > I_{as}$

Earth fault protection in compensated neutral systems

3) Zero sequence directional relay in active current connection



- works properly in coil earthed systems



condition:

$I_0 \cos \varphi > I_{as}$

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

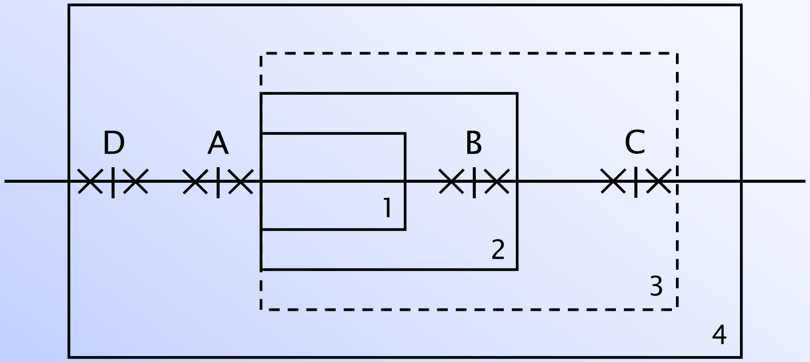
- only short lines (cables)

Distance relays

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

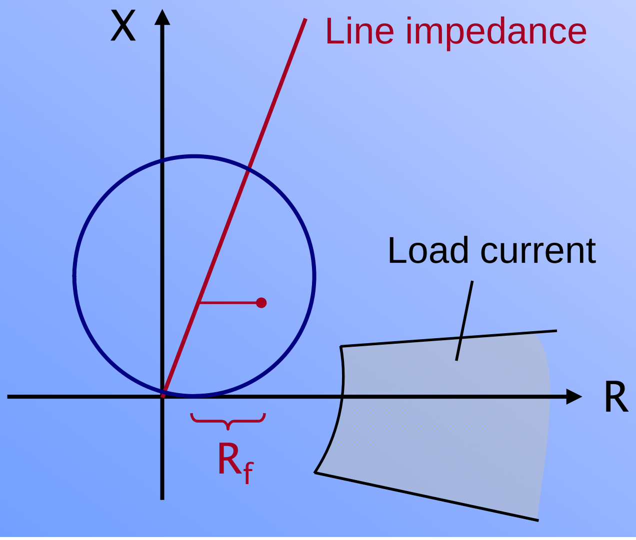
- Switching
  - pick-up unit
  - measurement unit
  - short circuit / earth fault connection
  - works in 30…70 ms

Protection zones of a distance relay

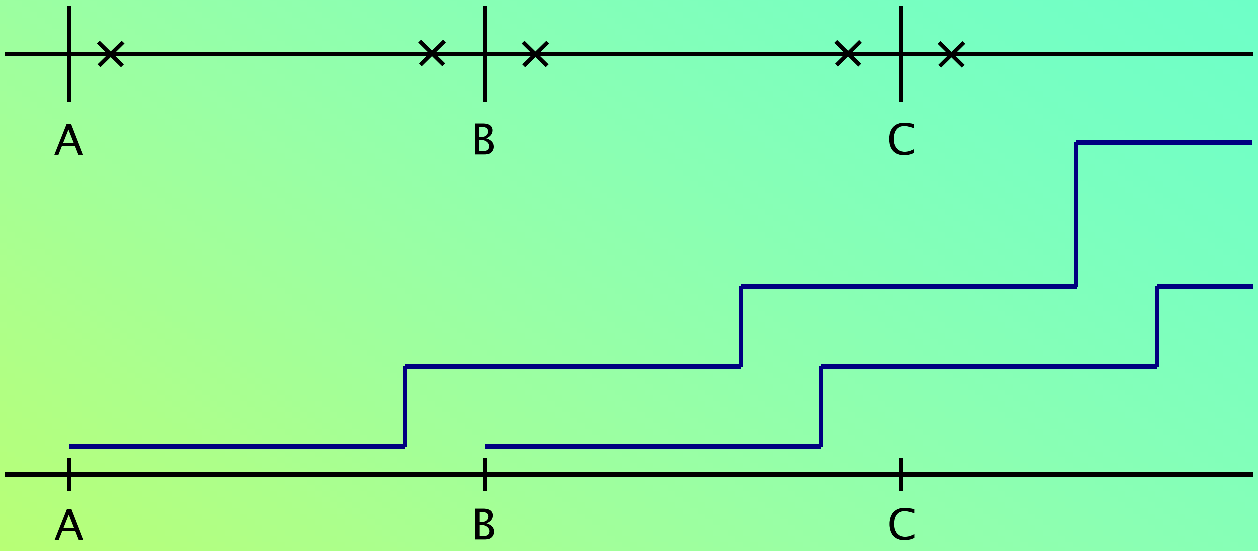


Example:

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: reach120 % of line A-C, time delay 1 s
Zone 4: reach forward A-C, time delay 4 s

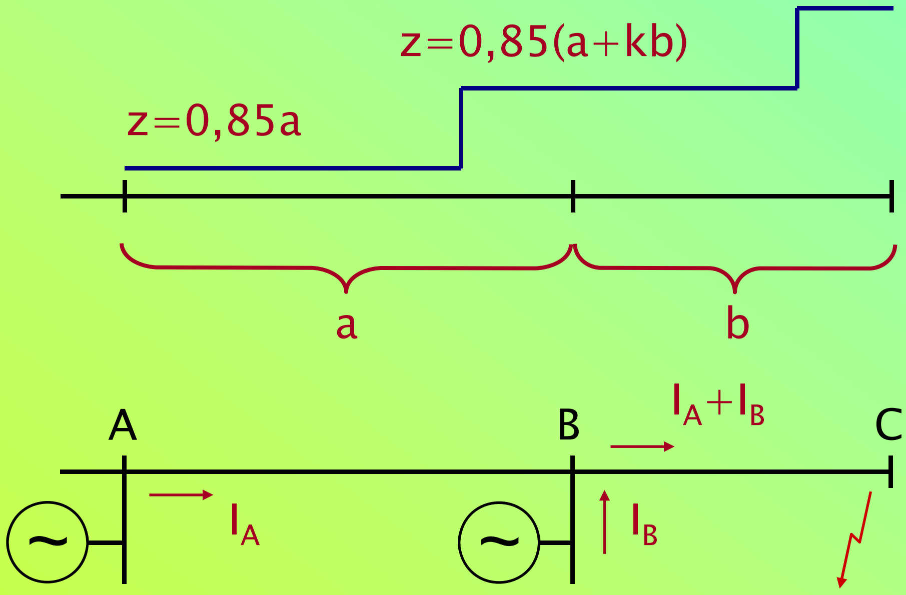


Zones of protection



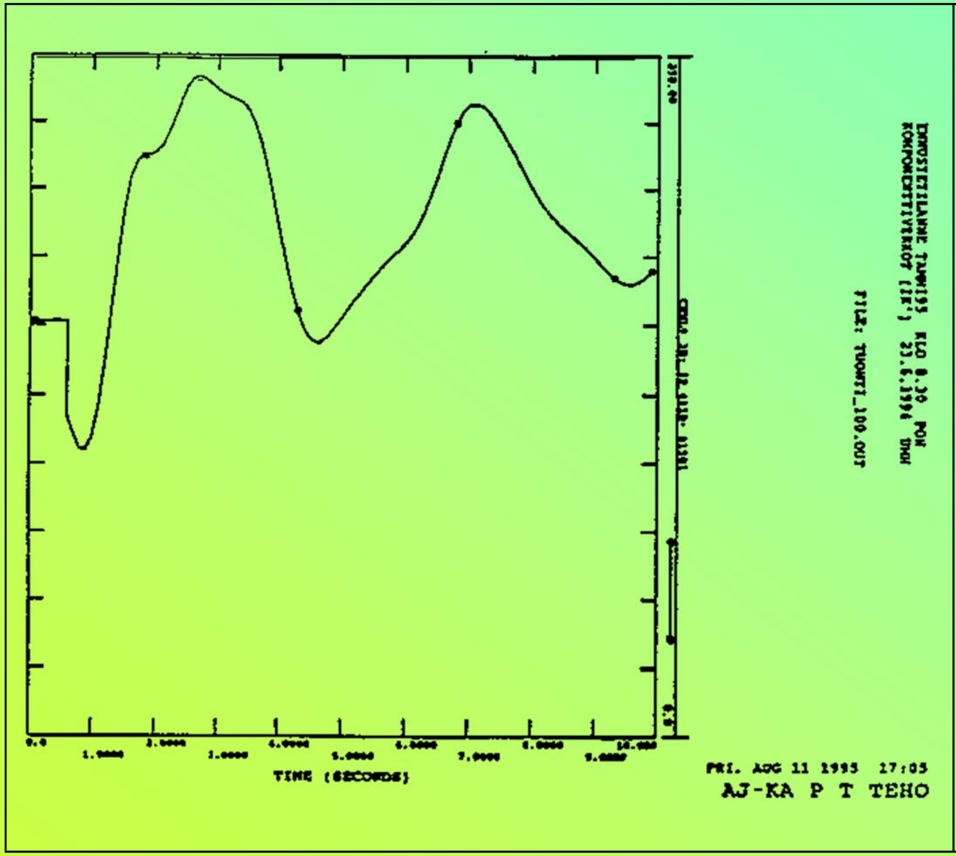
The effect of side-feeds:

$$k = \frac{I_A + I_B}{I_A}$$

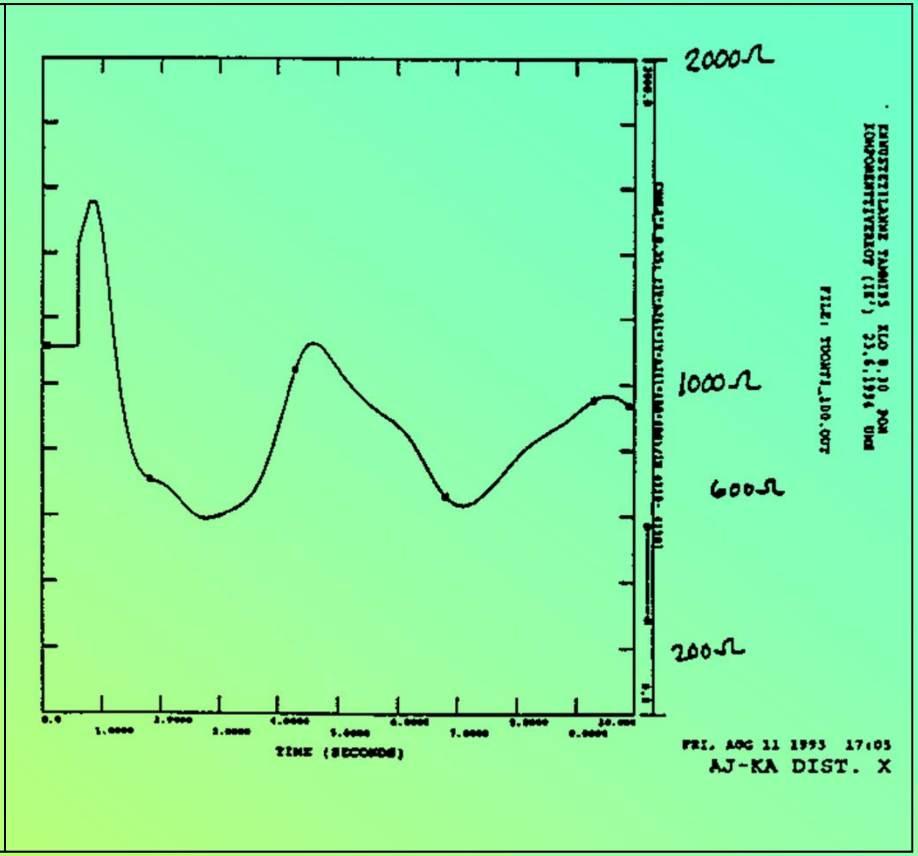


The power swing must not trip the relay

Example: switching state change

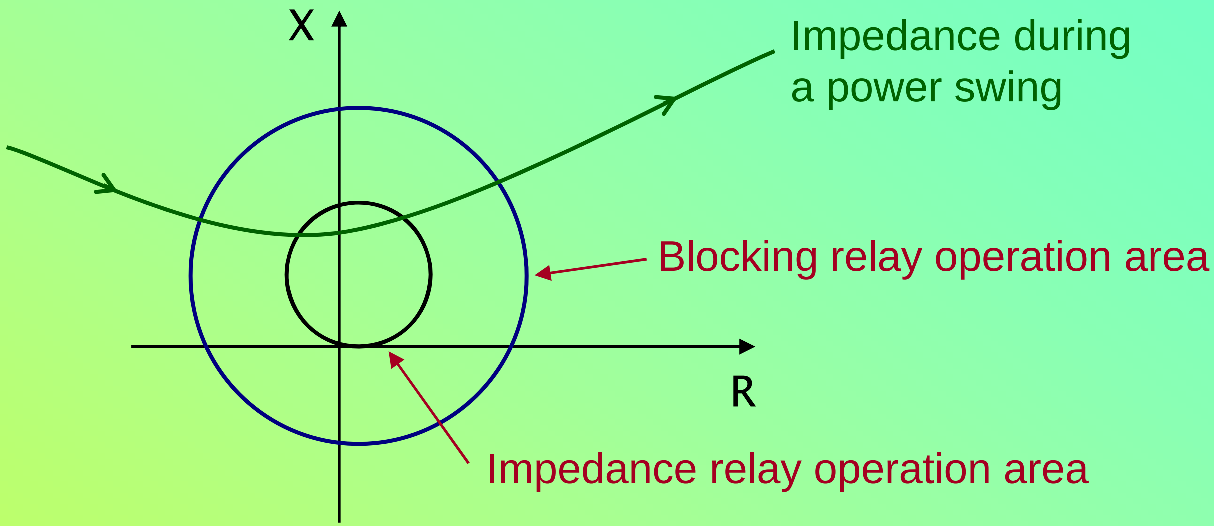


Power



Impedance

Power swing blocking relay



- If power swing relay picks-up, it will block the distance relay after time delay Δ**t**

- Δ**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

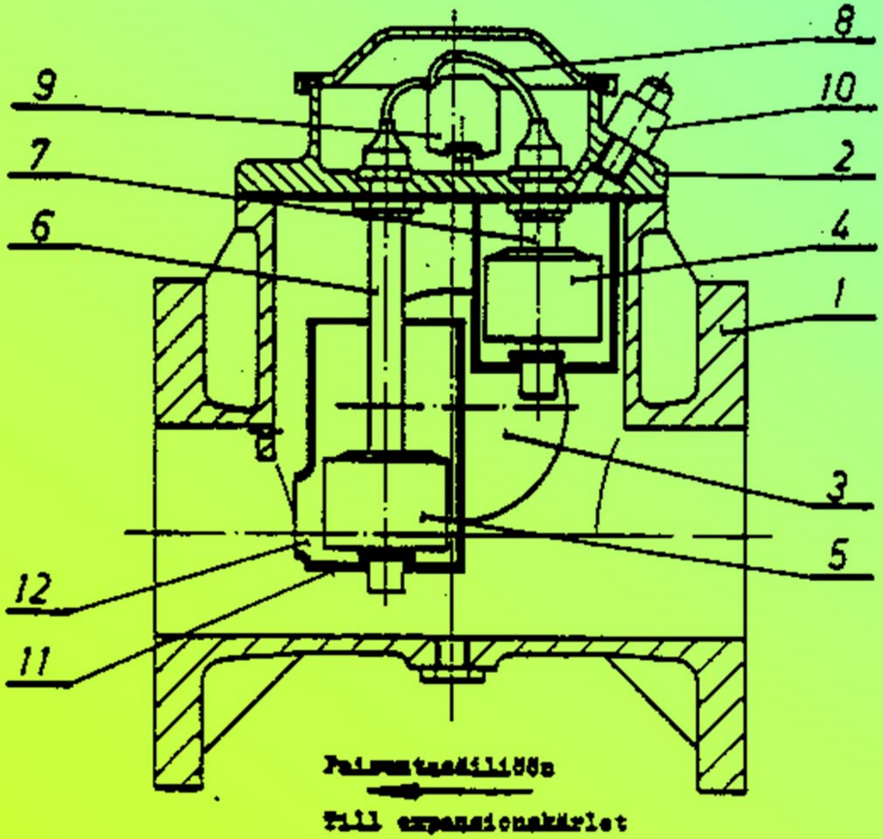
- Buchholz-relay or gas relay

  - 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:

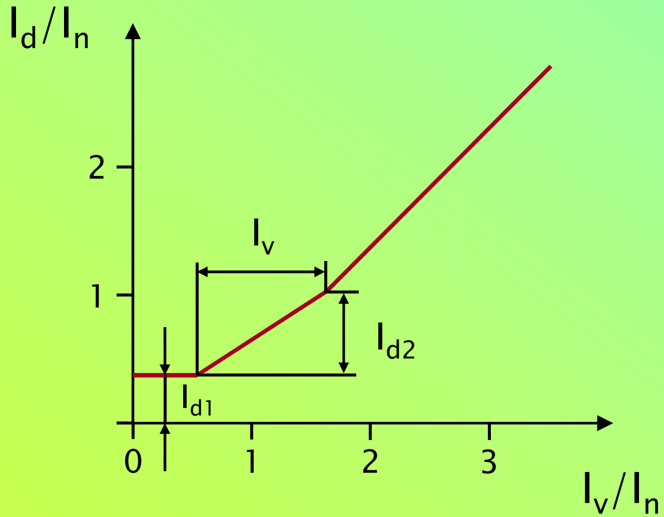
- importance of the transformer
- type of neutral earthing
- type of network
  - radial, or looped

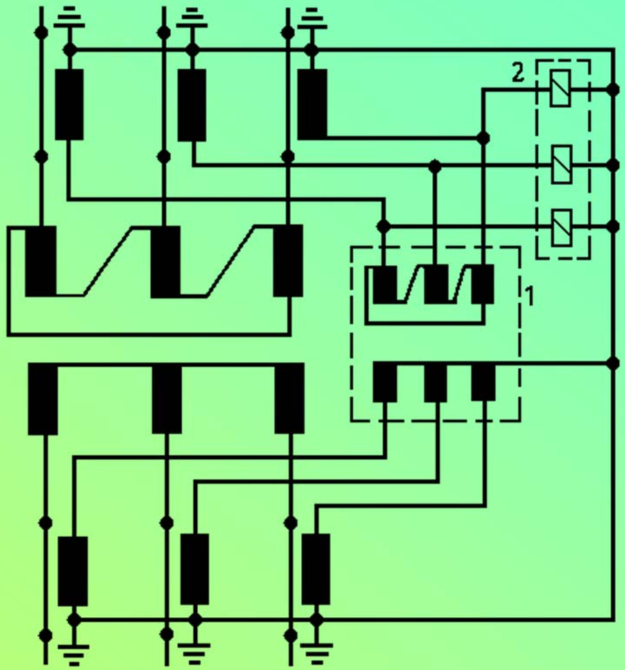
Differential relay in transformer protection

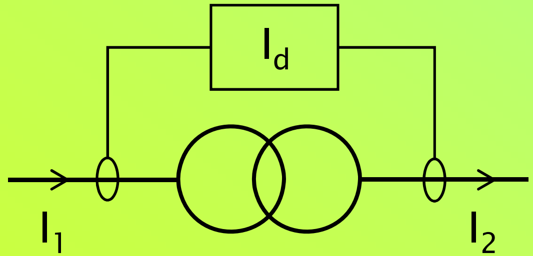
$$I_v = (I_1 + I_2) / 2 \quad \& \quad I_d = I_1 - I_2$$

p = basic setting = I_{d1}/I_n

s = pick-up ratio = I_{d2}/I_v

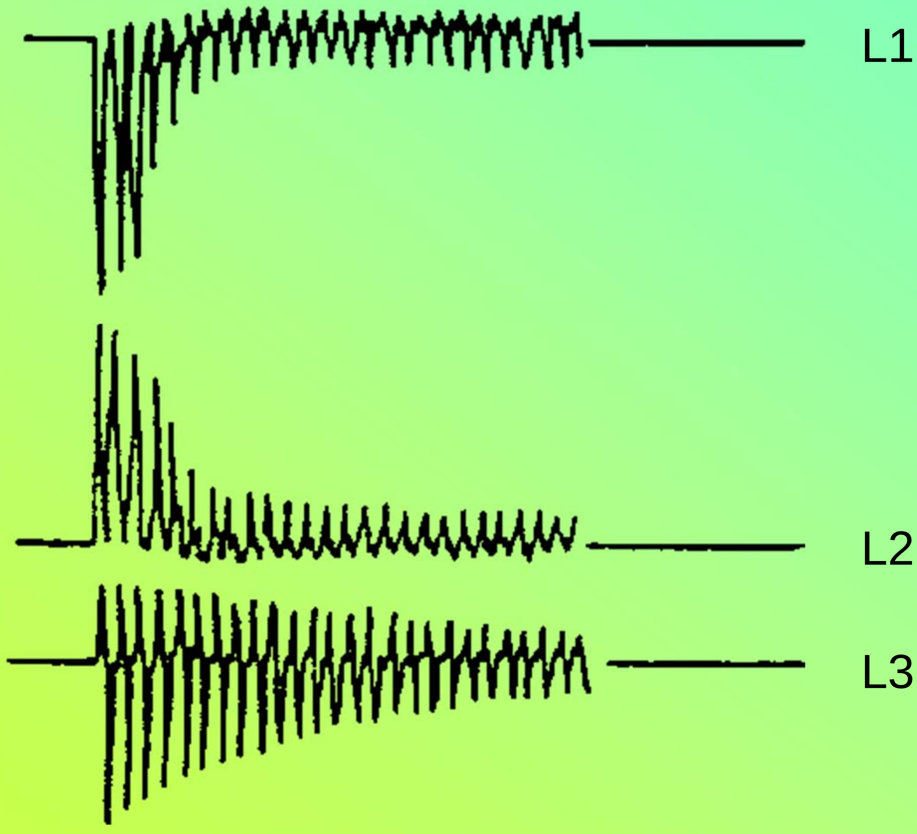






Factors affecting the setting of a differential relay

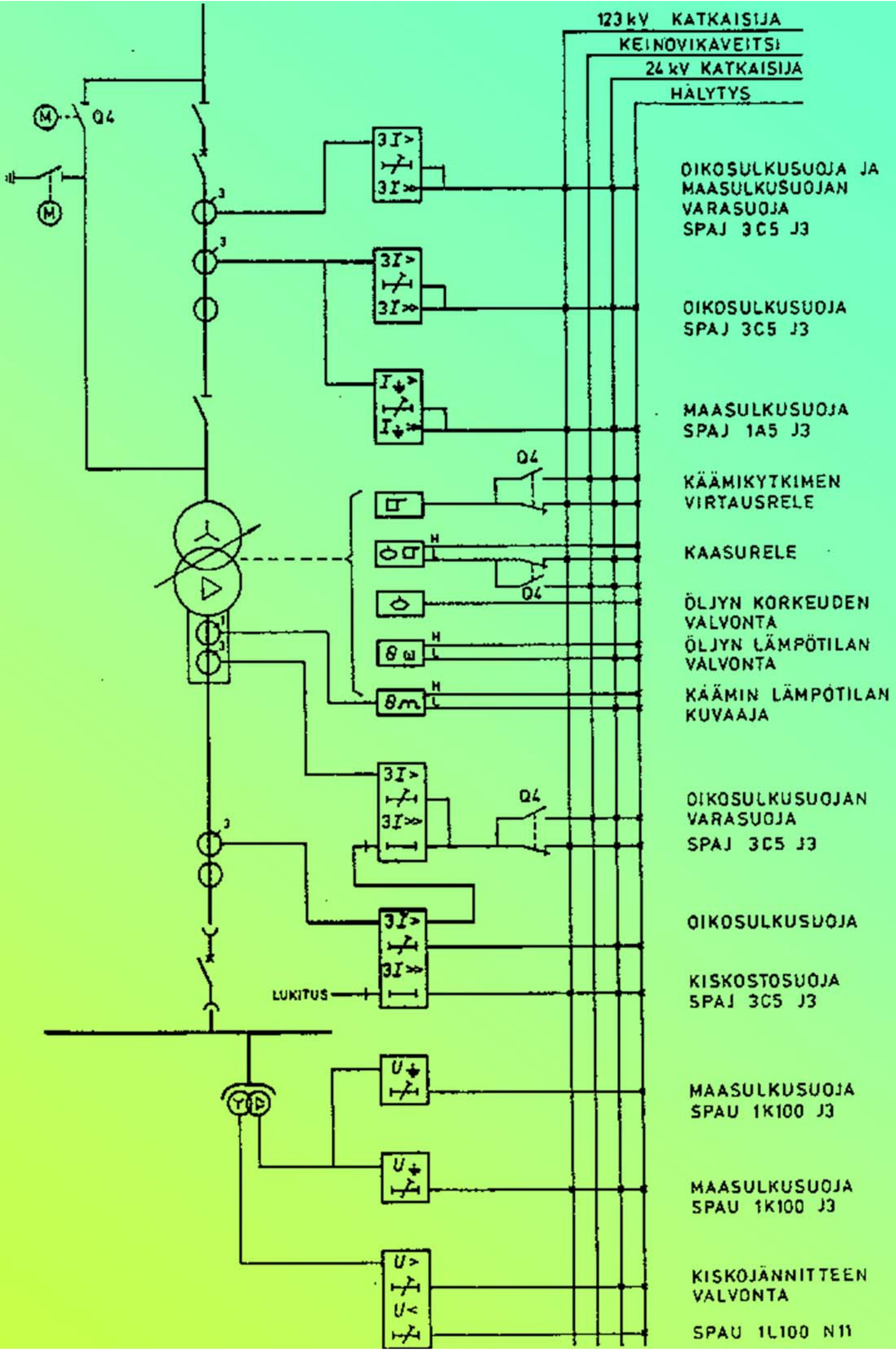
- saturation of current transformers
- transformer magnetizing inrush current
- errors of current transformers (< 13%)
- steps of on-load tap-changer (< 15%)



An example of the inrush current

Example of the transformer protection

(110 / 20 kV primary transformer)



123kV CB
Art fault
24kV CB
Alarm

Short circuit &
Earth fault Back-up

Short circuit

Earth fault

Tap changer
Flow relay

Gas relay

Oil level
Oil temperature

Winding temp model

Short circuit
Back-up

Short circuit

Busbar protection

Earth fault

Earth fault

Busbar voltage
monitoring

Generator protection

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

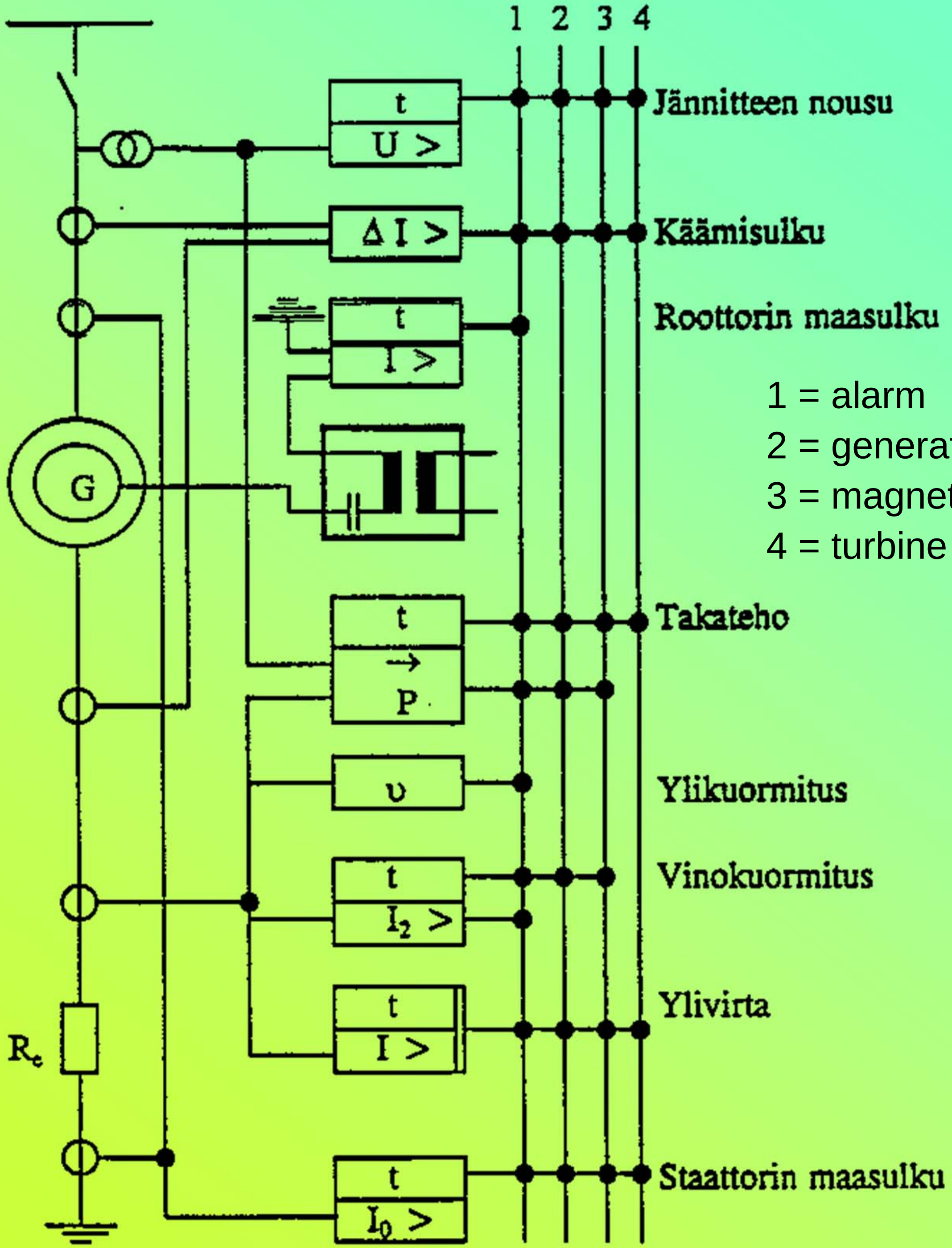
Faults of generators in Finland in the years 1970-1983

year	-70	-71	-72	-73	-74	-75	-76	-77	-78	-79	-80	-81	-82	-83
generators pcs	89	95	102	104	106	109	111	118	118	118	118	119	120	120
faults pcs	1	6	4	2	0	5	3	5	6	4	4	9	9	5
fault costs Mmk / case	3,8	0,9	0,6	7,9	0	1,7	8,0	3,5	4,8	5,2	7,5	2,5	3,4	2,1
average outage time (days)	60	57	65	225	0	77	140	43	60	52	25	110	70	60

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



1 = alarm
2 = generator CB
3 = magnetizing CB
4 = turbine trip

voltage rise

inter-turn faults

rotor earth fault

reverse power

over load

load unsymmetry

over current

stator earth fault