Electrical Protections Theory

**Electrical protection** – device checking power system part operation (G, T, V) = *protected object*, to ensure normal operation

**Protected object** – physical device for el. energy transmission, function characterized by current values of measurable physical quantities = *state quantities* (U, I, P, Q, f, T, F,…)

**Protection operation** – it receives information about quantities (CT, VT, sensors), executes them and evaluates normal operation and inadmissible values limits.

The protected device is switched off from the supplies in case of protected object fault (failure) state → accident preventing or fault consequences reducing. Also sending signals about action for the operator.
Fault – object physical change (quantities), object state out of the normal state, dangerous

Fault quantity – causes the fault, \( u_2(t) \)

Output quantities \( y(t) \) – high values \( U, I \) → protections connected to the CT, VT secondary circuits with a treatable signals levels
**Electrical protections - definitions**

**Protection operation** – information evaluation about the object state \( x(t) \) and during the fault activity on the object by its output \( v(t) \), i.e. fault consequences reducing or preventing from them

**Protection input** \( y(t) \) – protected object measured outputs

**Protection output** \( v(t) \) – protection activity on the object

**Signal** – quantity announcing protection operation

**Protection algorithm** \( F \) – protection function description, relation between inputs and outputs

**Protection characteristic** – algorithm graphic interpretation

**Protection equation** – algorithm mathematical form

\[
v(t) = F[y(t), n]
\]

**Protection parameters** – constants for setting \( F \)
**Protection sensitivity** – the measured quantity smallest value (element \( y(t) \)) to activate the protection

**Protection adjustability** – the range of all possible protection sensitivities

**Protection resolution** – ability to distinguish two close object states (failure and non-failure), their minimal deviation

**Protection holding ratio** – input state quantities ratio during returning to the block position and during the run to the acting position

\[
\frac{x_i(t)_{\text{return}}}{x_i(t)_{\text{pitch}}} < 1
\]

**Protection activity time** \( t_p \) – time from the failure origin to a signal sending to the protection output

**Protection overload capacity** – protection input max. value not endangering the protection
**Protection consumption** – electric input necessary for the protection operation

**Primary protection** – it works without instrument transformers

**Secondary protection** – connected to CT, VT secondary circuits

**Protection item** – building element (relay, TRF, electromagnet, chip, processor, connector,…)

**Protection element** – set of items creating a function unit

**Basic protection** – basic object equipment

**Reserve protection** – delayed activity in comparison with the basic one, ev. other algorithm, for a higher safety
Fault states

Short-circuit
- phase-to-phase or phase-to-ground connection
- → possible electrical, heat, mechanical damaging, loss of synchronism

Overload
- too high current (power) through a device
- → heat, mechanical damaging

Overvoltage
- voltage over a permitted limit
- → insulation damaging and aging, additional losses, short-circuit danger
- atmospheric or switch influences, voltage control, capacitive load, no-load power line
**Undervoltage**
- voltage dip under a permitted limit
- current overloading, voltage control

**Frequency decrease**
- consumption surplus over production in ES
- $\rightarrow$ incorrect function, higher magnetizing currents and losses

**Frequency increase**
- production surplus over consumption in ES
- $\rightarrow$ incorrect function, mechanical stress

**Unbalanced load**
- single-phase load, el. traction
- $\rightarrow$ negative current component $\rightarrow$ additional losses in rotor, heating
Ground fault
- single-phase-to-ground connection in networks with insulated neutral point
- subsequent short-circuit probability

Power reverse flow
- turbine failure → steam input closing → motor operation

Loss of excitation
- excitation current drop under static stability limit → asynchronous operation
- → additional eddy current losses
Electrical protections sorting

a) according to protected object type
generator, motor, transformer, busbar, powerline, cable, switch, etc.

b) according to fault type
short-circuit, overload, undervoltage, overvoltage, under-, over-frequency, ground fault, reverse power flow, excitation loss, unbalance

c) according to functional principal
different characteristics

d) according to time activity
- immediate – activity time is limited only by information processing and protection reaction, i.e. it acts “immediately”
- dependent – activity time is proportional to the measured quantity
- time independent – constant activity time (adjustable)
e) according to construction
- electromechanical – relay elmag., inductive, heat, eldynamic,…
- transistor – semiconductor elements (diodes, transistors, integr. circuits)
- digital – discrete processing
Requirements for protections

a) Speed
   Given by the activity time = protection time + switch activity. Speed choice depends on the fault type (short-circuit x overload).

b) Selectivity
   Disconnecting as small as possible system part. Time, current, or place scaling.

c) Sensitivity and precision
   Measured quantity minimal value reacted by the protection and its relative error.

d) Reliability
   The ability to act during the fault and not to act if no fault. External conditions, protection mechanism, maintenance influence. Backup.

e) Easy maintenance and check-up
Generator protections

Protections against short-circuits and ground faults

Serious faults → to ensure machine switching off.

**Differential protection (DP)**
Longitudinal DP – compares object input and output (more often)
Cross DP – compares two objects inputs, i.e. protects two identical objects operating in parallel

Longitudinal DP – activity in case of $i_R > i_{set} = 10x \% I_n$, complete immediate switching-off
CT inaccuracy compensation

\[ i_R = i_1 + i_2 \]

\[ i_R = i_1 - i_2 \]
3ph DP at generator
Longitudinal DP ($R_B$) for block in „3-point connection“ – as the $R_G$ backup
Cross DP – in case of fault $I_1 \neq I_2$ and the protection acts

e.g. as the generator turn protection (stator winding of 2 parallel branches)
**Overcurrent short-circuit protection**

- for identifying outside short-circuits, also as the DP backup for inside short-circuits
- distance (impedance) protection principle
- short-circuit distance distinguishing
- activity doesn’t depend on the short-circuit current size (in time)
**Stator ground protection**
Stator winding ground fault → neutral point moving → its voltage to the ground non-zero (higher U if ground fault closer to machine terminals). Risks of unbalance, fault current, 2^{nd} ground fault.

**Voltage protection**
- GF identifying up to 95% winding (also more – active injection)
- neutral point or zero component voltage (artificial neutral point and open triangle)
- frequency filter for 1^{st} harmonic

**Current protection**
- resistance in the neutral point reduces ground current (plates burning-up)
- high R reduces protection range
Rotor ground protection
Current circuit interconnection in case of GF $\rightarrow$ switching-off. In case of 2$^{\text{nd}}$ GF mag. field deformation and radial mechanical forces.

$AC$ superposition
DC superposition
Protections against abnormal operating states

Protection against current overloading
- protects against heating (ageing, insulation break-out)
- often independent with a longer time 10x s (machine can endure short-time overload)

Protection against overvoltage
- protects against relieving, controller malfunction

Protection against reverse power flow
- to prevent motor operation in case of turbine failure, watt

Protection against unbalanced load
- unbalance → reverse magnetic field in the stator → eddy currents in the rotor and damper → dangerous heating, vibrations
- for the certain negative component value $i_2$ there is a permitted operation time according to the machine heating curve
- limit according to coefficient $K_{\text{max}}$ by the producer

$$K(T) = \int_0^T i_2^2(t) \, dt$$
- multilevel protections, they measure $i_2$ from three phases
- also as a backup for unbalanced short-circuits
Transformers protections

Protections according to fault type

A. Transit faults (outside influence) – overcurrent and short-circuit protection
   1) Overload
   2) Outside short-circuit

B. Inside faults
   a) Sudden – differential, gas relay, vessel (cage) protection
      1) Short-circuits on the terminals, winding
      2) Ground faults
   b) Gradual – gas relay
      1) Wrong plates insulation → arcs in the vessel
      2) Cooling failures → bubbles in the oil

Differential protection

Basic protection against inside faults.
Principle as at the generators but difficulties:
a) unequal CT ratios – rated TRF currents but CT ratios normalized →
incorrect activity during outside short-circuit
b) unequal CT construction – different overcurrent numbers

c) unequal primary and secondary winding connection → difference currents because of phasors turning → to connect CT windings as the opposite TRF winding (Y, D)
d) magnetizing current impact during TRF switching-on with open circuit → 2\textsuperscript{nd} harmonic filter
e) voltage control at tap-changing TRF → higher DP start-up current
**Gas (Bucholz) relay**  
At TRF with oil cooling, between cover and conserver.  
2 levels:  
1) Signalization (float P1)  
2) Switching-off (float P2 + clack K)  
   Quick gas generation during short-circuit, oil leakage.
Power line protections

Against short-circuits, overload, overvoltage, ground fault.

Against short-circuits:
- overcurrent – simple powerlines (alt. with the directional element)
- comparative – meshed networks
- distance – meshed networks

Distance protections
- measures power line impedance ($u/i$) from the protection to the short-circuit place
- switching-off time proportional to the impedance
- good selectivity
- collaboration with AR (auto-reclosing) system
Switching-off characteristics

1st level: $0,8 z_a$
$0,01 - 0,02$ s (immediate)

2nd level $0,8(z_a + 0,8 z_b)$
$0,6$ s

3rd level $0,8[z_a + 0,8(z_b + 0,8 z_c)]$
$1,1 - 1,2$ s
Comparative protections

- compares el. values at the beginning and at the end (direction of I, P, Q, phase of I)
- identifies only values inequality
- disconnects immediately and only one powerline section → “sectional protection”
- auxiliary connection (communication) of both stations for the comparison purpose
- collaboration with AR (auto-reclosing) system
Motors protection

Asynchronous motors

Protections according to faults:
1) bearing failure – bearing temperature measuring
2) inside short-circuits – differential, current pr.
3) ground fault – ground protection
4) overload – current dependent, start-up, thermal picture
5) unbalance – negative component measuring
6) undervoltage – contactor, undervoltage protection
7) one phase disconnecting
Synchronous motors
AM + others:
8) start-up protection – asynchronous start-up
9) protection against excitation loss – loss of synchronism danger (mechanical surges) → power angle monitoring
10) protection against reverse power flow

DC motors
1) short-circuit protection – immediate, depends on commutation
2) protection against overload – current dependent pr.
3) loss of excitation – speed and stator current increase, undercurrent protection
4) ground protection
5) bearing protection
Protections in LV distribution

Fuses

- the oldest protective principle against overcurrents
- artificially made the weakest place in the circuit where the current flow is broken
- a calibrated wire (belt) is remelted
- remelting in the extinguishing environment (soft sand)
- (+) simplicity, reliability
- (-) necessary exchange after activity, possibility of remelting only in one phase (at 3ph consumers)
- they mustn’t be repaired unprofessionally
- usage in LV, MV x not in HV
- normal (quick) and slow (delay for start-up current)
- time-current characteristic construction from heating curves for different overloads
- time-current char. is dependent
Fuses dividing according to the construction

- *screw-in* – lower currents
- *leg* – higher currents, quick $\rightarrow$ „power“
- *with contact flags* – very quick (x ms), limiting ability, for semiconductor elements
- *apparatuses* – weak glass tubes, fusible wire in the air
- *car* – ceramic cylinder
- *others* – belts, coils,…

Circuit-breakers

- self-acting overcurrent breakers
- overcurrent (bimetal, overload) and short-circuit (electromagnet, short-circuits) trigger
- they switch off in the current zero, don’t have limiting ability
- sometimes to add fuse for short-circuits if insufficient breaking capacity
• (+) repeatable function, multi-pole construction for 3ph consumers
• (-) complication, costs

Table of symbols:
P....spring
K....contacts
B....bimetal belt
E....electromagnet

\[ t(s) \]
\[ kI_n \]
\[ t(s) \]
\[ kI_n \]
Circuit-breakers dividing

- $I_n$ size – small (to 25A, 500V AC, 250V DC), higher (over 25A, to 1000V AC, 1200V DC)
- purpose – for power line, motor (delay for start-up), protective (with voltage trigger)
- poles number – 1 (1ph), 2 (DC), 3 (3ph), 4 (special)
- contacts placing – air, oil (only 3-pole, also for motors switching)
VYPÍNACÍ CHARAKTERISTIKY

Podle ČSN EN 60 898
při teplotě okolí +30°C

<table>
<thead>
<tr>
<th>Vypínací charakteristika</th>
<th>tepelný spoušť</th>
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<tr>
<td></td>
<td>zkušební proud</td>
<td>vyhnaní doba</td>
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<tr>
<td>B</td>
<td>lₜₐ</td>
<td>tₚ</td>
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<td></td>
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<td>&lt;tₚ</td>
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<td>C</td>
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<tr>
<td>D</td>
<td>1,4ₜₐ</td>
<td>&lt;tₚ</td>
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</tbody>
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Pro lₜ = 2,5ₜₐ platí: pro lₜ ≤ 32ₜₐ
                           1ₚₘ ≤ 0,1ₚₘ
                           1ₚₘ ≤ 0,1ₚₘ
Protective overcurrent relays

- protection against overload, 2-phase operation
- not against short-circuits (small breaking capacity)
- often collaboration with contactor (disconnects power circuit or only contactor coil)
- adjustable current trigger (±20 % $I_n$)
- dependent time-current char.
**Protectors**
- self-acting fault disconnecting in a very short time
- in places with a higher accident danger (recommendation or prescription)
- additional protection against danger contact

**Current protector**
- currents sum of all operating conductors
- during the fault \( \sum i \neq 0 \) (summation transformer)
- residual current trips a relay, all operating conductors are disconnected
- disconnecting caused by tripping residual current (e.g. 50 % \( I_{\Delta n} \))
- \( I_{\Delta n} = 15, 30, 100, \ldots \) mA
- testing button
- sometimes with implemented circuit-breaker against overload
\[ I_\Delta = I_F + I_a \]

- \( I_\Delta \) ……residual current
- \( I_F \) ……fault current
- \( I_a \) ……conductive current – usually neglected
One phase protector connection
V......Switch
SM....Switching mechanism
DR....Differential relay
ST.....Summation transformer
Voltage protector

- grounded switching-off coil to the case
- it disconnects at adjusted voltage (permitted touch voltage)
- it disconnects all operating conductors (also neutral conductor) → 2-pole, 4-pole