INTRODUCTION TO THE PARAMETERIZATION OF PROTECTION RELAYS

ELECTRICAL PROTECTION IN POWER SYSTEMS

CT
A11
SEL-501

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TECHNICKÁ UNIVERZITA V KOŠICIACH

MONTÁŽE ČAKOVICE s.r.o.

SEL SCHWEITZER ENGINEERING LABORATORIES

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This textbook describes detailed procedures for parameterizing digital protection relays from SEL and a mechanical overcurrent relay, the theoretical basis for current transformer measurement, and the description and wiring of the individual components of electrical protection systems.

This textbook is intended for electrical engineering students in study programs focused on power engineering, for users of power engineering equipment, and for the professional public.

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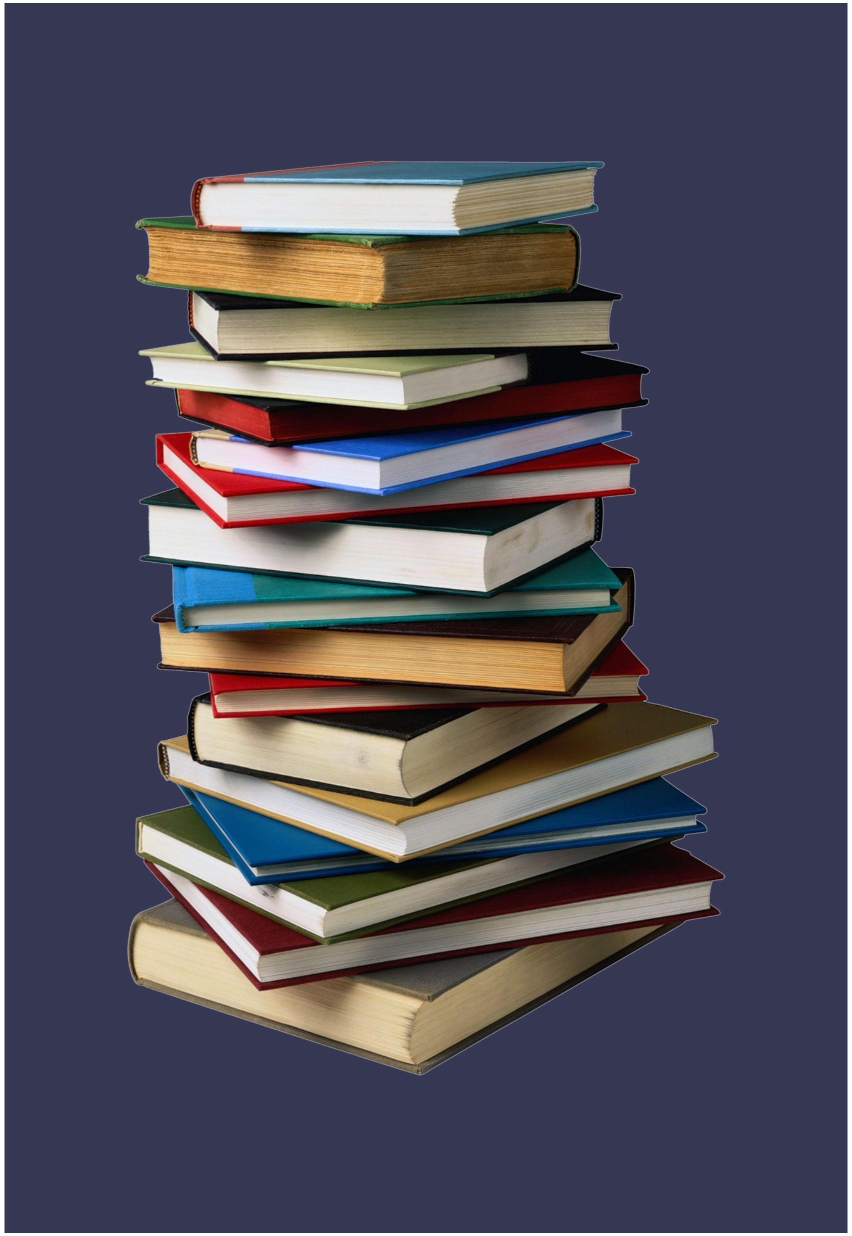
Thanks are also due to Schweitzer Engineering Laboratories, Inc. and Montáže Čakovice s.r.o. Praha for donating various digital protection relays.

Understanding and mastering them is essential for the follow-up course Protection Systems in Power Systems in the engineering study program.

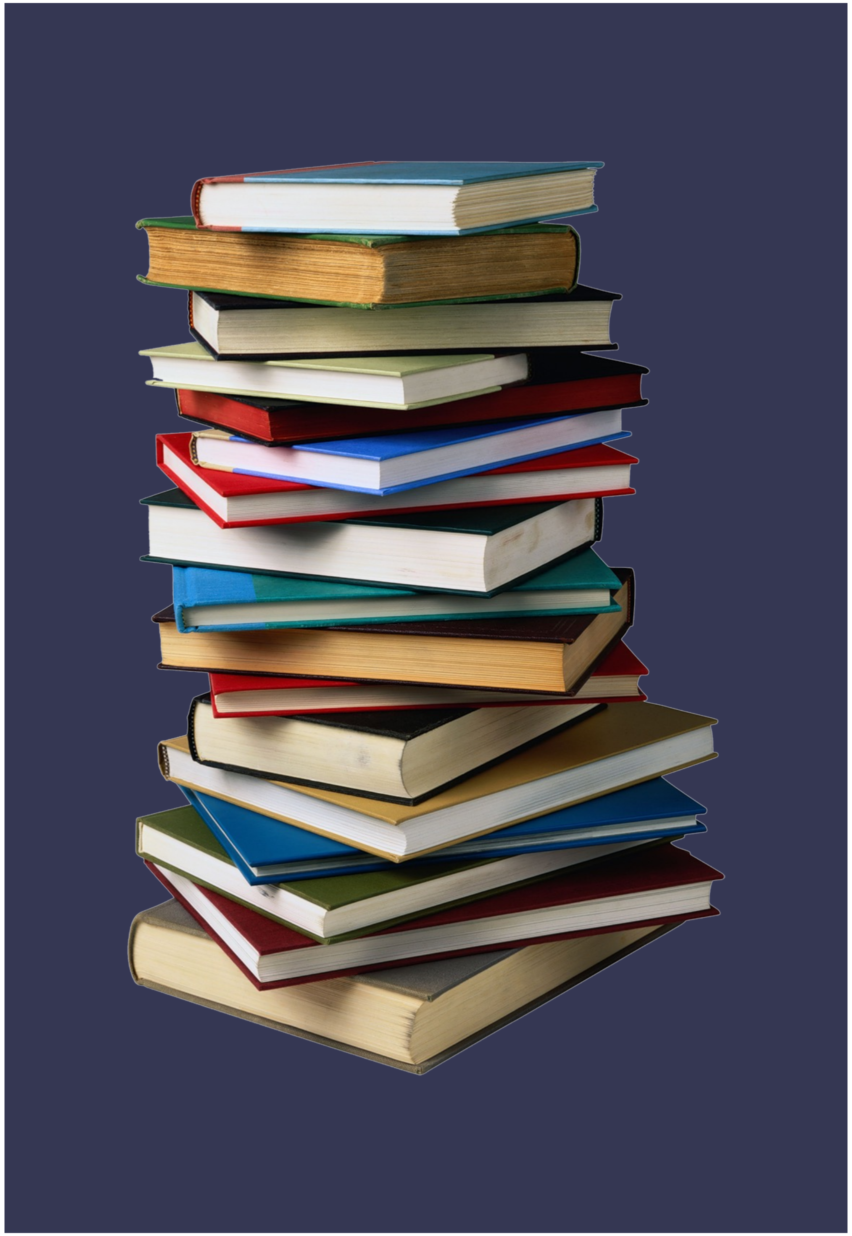


Protection Theory

The main task of protecting an electrical device is to ensure that the device or section is not exposed to adverse conditions, e.g. overloading of the device and the resulting reduction of its service life, or to random fault conditions caused by a short circuit.

For these reasons, it is necessary to know the interaction between the device or section and its surrounding environment, which has a very significant influence on the device itself. We therefore need to know the mutual influence of the device on its surroundings and of the surroundings on the device. When setting and designing protection, we should have the most detailed information possible regarding these factors.

In the case of incomplete or unclear information, we should not even begin the calculation for protecting the device or section, or should assess the influence of the surroundings on the device more strictly.



CT Theory

CT Theory

Rated ratio p_I of a current transformer is the ratio of the rated primary current I_{1n} to the rated secondary current I_{2n}, thus:

$$p_I = \frac{I_{1n}}{I_{2n}} = \frac{N_2}{N_1} = \frac{U_{2N}}{U_{1N}} \qquad (1)$$

Let us denote ΔI as the projection of the phasor of current $\dot{I}2$ from the phasor of current $\dot{I}1$. This current ΔI represents the *absolute current error of the CT and is given by the relation:*

$$\Delta I = p_I * I_2 - I_1 \qquad (2)$$

Relative current error ε_I is given by the relation:

$$\varepsilon_I = \frac{\Delta I}{I_1} * 100 = \frac{p_I * I_2 - I_1}{I_1} * 100 \qquad (3)$$

CT Theory

<u>**Actual value of the external burden**</u> **Z_s, which is given by the sum of the impedances of the instruments and leads connected to the secondary terminals of the current transformer. The load therefore cannot exceed the nominal current I_{2s}.**

$$U_{2s} = Z_s * I_{2s} \rightarrow Z_s = \frac{U_{2s}}{I_{2s}} \qquad (4)$$

<u>**Rated burden**</u> **Z_n of the current transformer is the impedance that can be connected to the secondary terminals of the CT without exceeding the permissible current error within the measuring range.**

$$Z_n = \frac{S_n}{{I_{2n}}^2} \qquad (5)$$

<u>**Accuracy limit factor**</u> **n of a protection current transformer is defined as the n-multiple of the rated primary current I_{1n}, at which the total error of the current transformer reaches a specified value of 5% or 10% (CT accuracy class 5P or 10P).**

CT Theory – Accuracy Limit Factor

<u>Rated accuracy limit factor</u> n_n of a current transformer is the n_n-multiple of the rated primary current I_{1n} at which the relative error of the secondary current I_2 reaches the value ε_I = -10% of the total secondary current, when the CT is loaded with the rated burden Z_n, at the rated secondary power factor cos β_n = 0.8 inductive and at the rated frequency f_n.

$$n_n \cong n_s * \frac{Z_s}{Z_n} \rightarrow n \cong n_n * \frac{Z_n}{Z} \; or \; n_n * \frac{S_n}{S} \qquad (6)$$

<u>Value of the primary current</u> at which the secondary current error reaches –10%.

$$I_1' = n_s * I_{1n} \qquad (7)$$

CT Theory – Accuracy Limit Factor

<u>Actual value of the accuracy limit factor is determined</u> from the relation:

$$n_s = \frac{I_1'}{I_{1n}} \cong n_n * \frac{Z_n}{Z_s} \qquad (8)$$

<u>Total burden</u> Żc, which is given by the phasor sum of the external and internal burden of the current transformer:

$$\dot{Z}_c = \dot{Z} + \dot{Z}_i = \sqrt{(Z_n * \cos\beta + R_2)^2 + (Z_n * \sin\beta + R_2 * \tan\beta_i)^2} \qquad (9)$$

CT Theory – Accuracy Limit Factor

We construct a line with slope $U_0/I_0 = 9*Z_c$, which passes through the origin of the coordinate system. This line intersects the open-circuit (excitation) characteristic at point A. The horizontal coordinate of point A is the magnitude of the required current I_0', which is needed to determine the accuracy limit factor:

$$n = \frac{I_0'}{0{,}1 * I_{2n}} = 10 * \frac{I_0'}{I_{2n}} \qquad (10)$$

However, this method has its limitations, and therefore the accuracy limit factor is determined from point B, which is defined as the intersection of the characteristic and a line with slope $U_0/I_0 = 7*Z_c$. The vertical coordinate of point B is the required voltage U_{0n}. *Accuracy limit factor is determined from the relation:*

$$n = \frac{U_{0n}}{0{,}9 * I_{2n} * Z_c} \qquad (11)$$

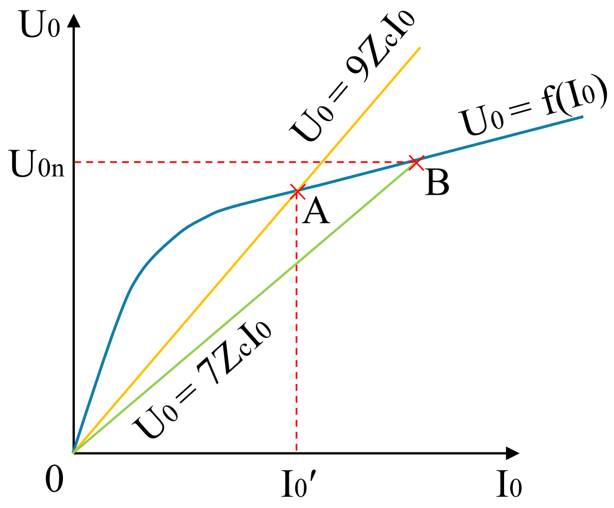


Fig. 1 Magnetization characteristic of the CT

CT Theory – Accuracy Limit Factor

Determining the values U_{lim}, I_{lim} from the definition based on the relative current error is difficult. The values U_{lim} and I_{lim} determine by how much the magnetic core of the current transformer must be oversized compared to a normal design, so that it does not saturate due to the DC component of the AC current:

$$U_{lim} > n_n * \left(\frac{S_n}{I_{2n}} + R_2 * I_{2n}\right) \qquad (12)$$

and the magnitude of the limiting current:

$$I_{lim} > n_n * I_{2n} * \delta \qquad (13)$$

Let us denote the current component ΔI_q, which is the projection of the phasor $\dot{I}_0$ perpendicular to the phasor of the primary current $\dot{I}_1$. This current component, in per-unit values, represents the phase (angular) error of the CT and is given by the relation:

$$\delta = \frac{\pi}{180} * \delta_{st} = \tan \delta_{st} = \frac{\Delta I_q}{I_1} \qquad (14)$$

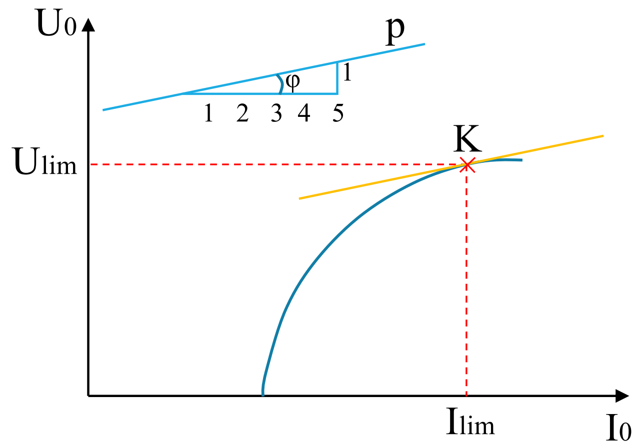


Fig. 2 Magnetization characteristic of the CT on a logarithmic scale

CT Theory – Example 1

A measuring current transformer with a ratio (p_I) of 400 A / 5 A is installed in the substation. Determine the actual value of the primary current I_1 flowing through the line if a secondary current I_2 of 3.6 A was measured on the secondary side of the CT:

$$I_1 = I_2 * pi = 3{,}6\ A * \frac{400\ A}{5\ A} = 288\ A \qquad (15)$$

Examples:

1. On the secondary side of a CT with a ratio of 1000 A / 1 A, a secondary current I_2 of 0.45 A was measured. Calculate the magnitude of the current flowing through the line, i.e. on the primary side of the CT. **Result:** I_1 is 450 A.
2. On the secondary side of a CT with a ratio of 750 A / 5 A, a secondary current I_2 of 2.3 A was measured. Calculate the magnitude of the current flowing through the line, i.e. on the primary side of the CT. **Result:** I_1 is 345 A.

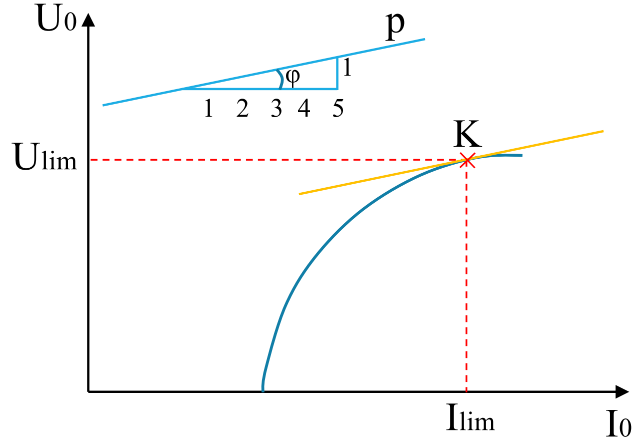


Fig. 2 Magnetization characteristic of the CT on a logarithmic scale

Theory of Electrical Protection – Overcurrent Protection

Theory of Electrical Protection – Overcurrent Protection

For the correct design of protection in power systems, it is necessary to become familiar with some basic concepts of protective relays. These quantities depend on the design of the relay, and are therefore different for each relay. *The rated values of the relay are given on the protection nameplate, separately for the main and auxiliary circuits.*

<u>Rated burden of a protective relay</u> S_n is the power consumed in the relay circuits, in VA for AC or in W for DC, at the rated value of current (voltage), steady-state relay temperature, and an ambient temperature of +20 °C. The relay burden is of great importance for correctly sizing the load of instrument current and voltage transformers. To pick up the relay, power equal to at least the minimum burden of the relay must be supplied. The relay burden during operation need not equal the rated burden Sn of the relay. *Calculation of the relay burden:*

$$S = U_r * I_r \qquad (16)$$

Theory of Electrical Protection – Overcurrent Protection

<u>Reset ratio of a protective relay</u> k_n is defined as the ratio of the dropout value to the pickup value. *The value of the reset ratio is always less than one and is given for unloaded relay contacts.* In that case the reset ratio value is at its maximum. If the contacts are loaded, then current flowing through the contacts generates a force that holds them together.

<u>The following applies for current relays:</u>

$$k_n = \frac{I_0}{I_r} \qquad (17)$$

<u>Where:</u>

I_0 is the dropout value of the relay current [A]

I_r is the pickup value of the relay current [A]

<u>The following applies for voltage relays:</u>

$$k_n = \frac{U_0}{U_r} \qquad (18)$$

<u>Where:</u>

U_0 is the dropout value of the relay voltage [V]

U_r is the pickup value of the relay voltage [V]

Theory of Electrical Protection – Overcurrent Protection

<u>Relay operating time</u> t_{dr} is the time that elapses from the instant of pickup to the instant the relay operates (e.g. until the relay contact closes). It is the inherent operating time of the electrical protection and depends on the complexity of the protection.

<u>Total relay operating time</u> $t_{c\text{-}dr}$ is the time that elapses from the instant of pickup to the operation of the electrical protection. This time consists of the times of several individual elements contained in the protection, e.g. the time of the starting (pickup) element, the time of the timing element, the time of the output element, etc.

<u>Relay scatter</u> $\pm\Delta X_{roz}$ is given by the difference between the mean value X determined from 10 measurements and the extreme maximum value X_{max} and minimum value X_{min}. It is important to know the scatter value, especially for time relays. *The relay scatter is calculated as follows:*

$$+\Delta X_{roz} = X_{str} - X_{min} \quad (19) \qquad -\Delta X_{roz} = X_{str} - X_{max} \quad (20)$$

Theory of Electrical Protection – Overcurrent Protection

<u>Relay error</u> ΔX is the difference between the actually determined (measured) pickup value of the relay X_r and the set value X_N on the protection or its part. ***It is calculated according to the relation:***

$$\Delta X = X_r - X_N \qquad (21)$$

<u>Relative relay error</u> ΔX_r is given as the ratio of the absolute relay error ΔX to the set relay value X_N and is expressed as a percentage. Both the absolute and relative relay error can be positive or negative. ***It is calculated as follows:***

$$\Delta X_r = \frac{\Delta X}{X_N} * 100 = \frac{X_r - X_N}{X_N} * 100 \qquad (22)$$

Theory of Electrical Protection – Overcurrent Protection

<u>Graded protection</u> – to ensure selective tripping, the operation must be provided with a time delay that is suitably graded, thereby ensuring mutual backup between protection devices. For this reason, they contain a pickup element and a timing element, which, possibly together with a measuring element and a directional element, determine the fault condition and, depending on the set times, will trip the protection. Graded protection includes overcurrent and distance protection.

<u>Overcurrent protection</u> operates on a simple principle and is used as backup protection, or on MV lines and less important LV lines as main protection. As the name implies, the protection responds to increased current values above the set pickup current I_r , in the event of line overloads or short circuits.

Theory of Electrical Protection – Overcurrent Protection

<u>Time-dependent (inverse time)</u> – has a decreasing dependence similar to fuses; the operating time is calculated according to equation (23) for $I/I_{nas} > 1$.

$$t = \frac{k * \alpha}{\left(\frac{I}{I_{nas}}\right)^{\beta} - 1} \qquad (23)$$

<u>Where:</u>

I is the measured current [A]

I_{nas} is the current set on the electrical protection [A]

k is the time multiplier [-]

α and β are coefficients for the specific type of tripping characteristic

If the value $I/I_N \leq 1$, then the operating time $t = \infty$.

Theory of Electrical Protection – Overcurrent Protection

<u>Semi-dependent</u> – has the same characteristic up to a magnitude of I_0. For larger currents $I/I_{nas} > I_0$, it already has a constant operating time and no longer depends on the change in current.

P_d - permitted region; P_z - forbidden region; h_0 - operating boundary

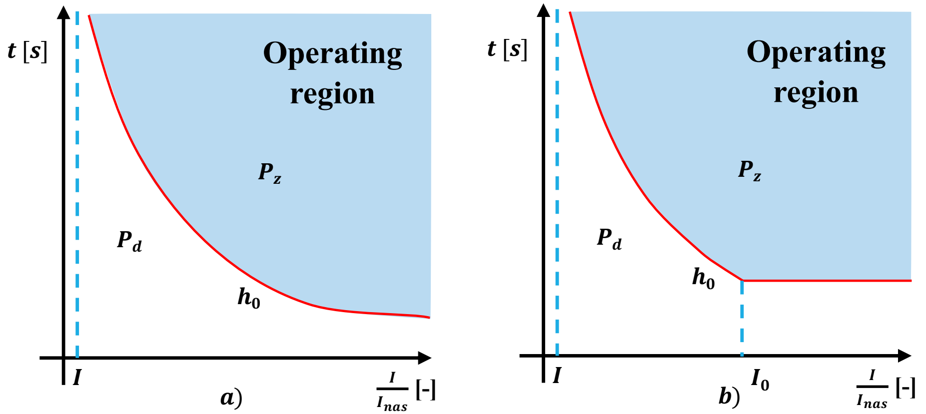


Fig. 3 Operating time characteristic a) time-dependent; b) semi-dependent

Theory of Electrical Protection – Overcurrent Protection

<u>Definite time (independent)</u> – operates according to the set time t> once the current kI> is reached. For larger currents I/Inas > kI> it already has a constant operating time and does not depend on the change in current.

<u>Instantaneous</u> – operates when the set current kI> is exceeded, almost without delay. The delay represents the reaction time of the protection itself, up to 30 ms.

P_d - permitted region; P_z - forbidden region; h_0 - operating boundary; $t_>$ - time delay; $k_{I>}$ - current pickup threshold

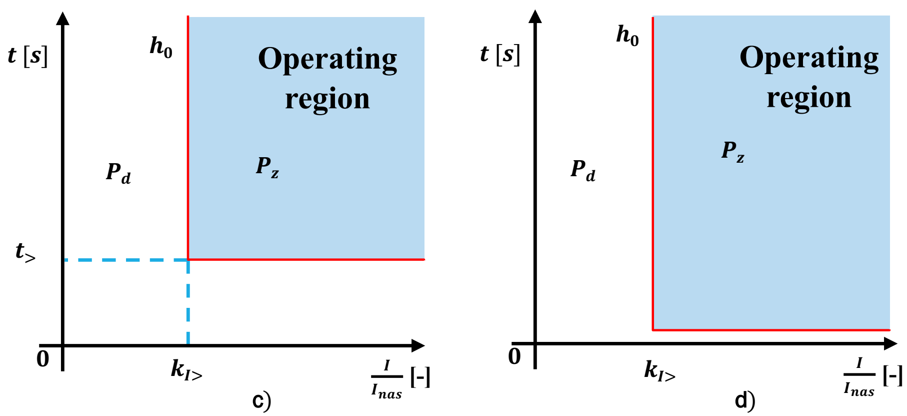


Fig. 4 Operating time characteristic c) definite time; d) instantaneous

Theory of Electrical Protection – Overcurrent Protection

When setting the individual times, the general assumption is that the most remote protection trips fastest, for which the equation $t_2 = t_1+\Delta t$ applies. The coordination time interval Δt depends on the design of the time relay and the circuit breaker, and is most often in the range of 0.2 to 0.5 s. At the same time, the current settings of the relays must not be overlooked, so that the protection devices provide mutual backup. To correctly set the pickup currents I_r it is necessary to know the current ratios of short-circuit currents, overloads, and rated currents. The magnitude of short-circuit currents can differ for different operating conditions. For these reasons, it is necessary to know the maximum and minimum short-circuit current.

When the network configuration changes, it is necessary to check whether the given protection settings are still adequate, and if necessary a different protection setting group can be used, since digital protection relays typically have 4 setting groups between which it is possible to switch.

Setting of Overcurrent Protection

<u>Determining the size of the coordination time interval Δt:</u>

- **the maximum errors of the time relay,**
- **the opening time of the power circuit breakers,**
- **and a backup safety margin, chosen at approximately 0.1 s.**

<u>Setting of the pickup current I_r:</u>

- **<u>the relay pickup current I_r must be greater than I_n :</u>**

$$I_r \geq I_n * \frac{k_b}{k_p * p_i} \qquad (24)$$

where I_n is the nominal current (standard fault-free condition)

k_b is the safety coefficient and is chosen from the range 1.1 to 1.35

k_p is the reset ratio of the relay, specified by the manufacturer within the range 0.94 to 0.98

p_i is the rated ratio of the current transformers.

I_{kmax} – maximum short-circuit current (3-phase); I_{kmin} – minimum short-circuit current; I_r – pickup current; I_0 – dropout current; I_{zmaxOZ} – maximum closing current for auto-reclosing; I_{zmaxM} – maximum motor starting current; I_n – nominal current; I_{pmax} – maximum operating current

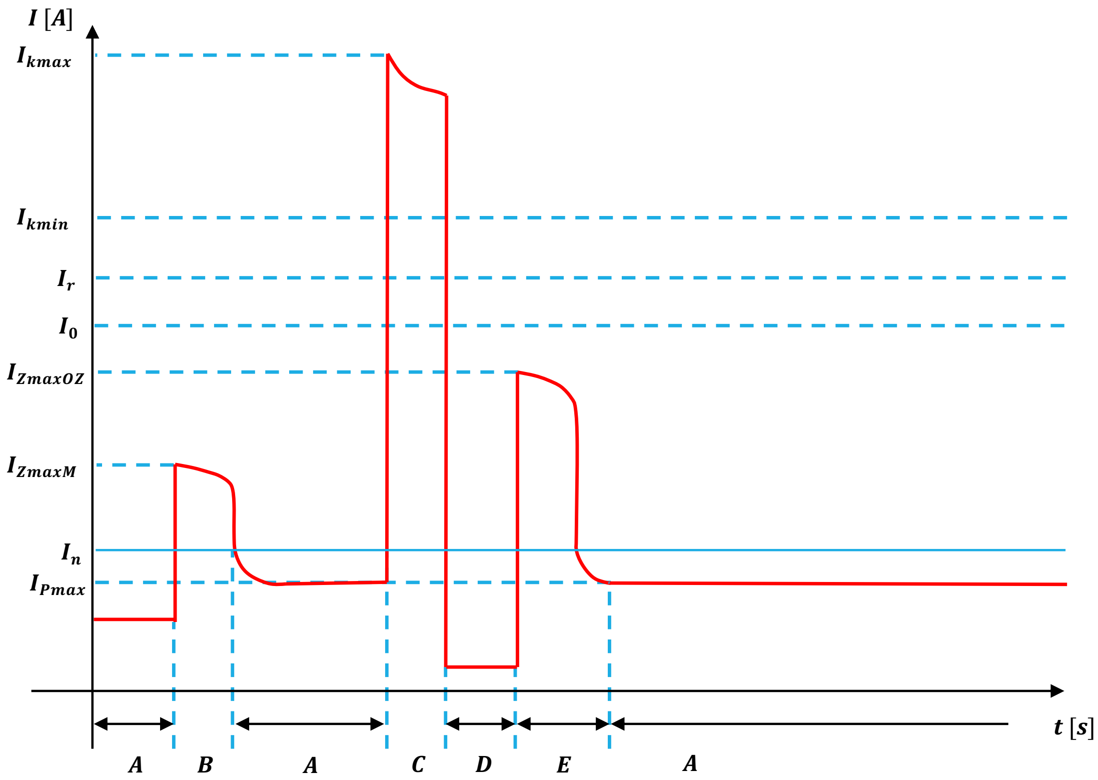


Fig. 5 Current ratios under various operating and fault conditions

Setting of Overcurrent Protection

Furthermore, the pickup current of the overcurrent relay must be smaller than the minimum calculated short-circuit current I_{k2fmin} at the end of the backup section.

$$I_r \leq I_{k2fmin} * \frac{1}{k_c * p_i} \qquad (25)$$

$$k_c = \frac{I_{k2fmin}}{I_r * p_i} \qquad (26)$$

where k_c is the sensitivity coefficient, at least 2 for instantaneous elements and 1.5 for the others.

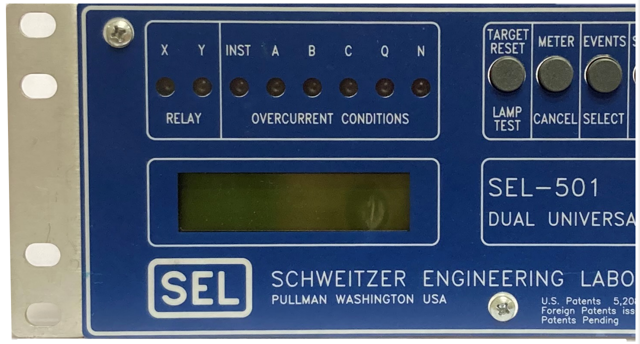
p_i is the rated ratio of the current transformers.

If the sensitivity coefficient k_c comes out smaller than 1.5 for definite-time overcurrent protection, the sensitivity of the protection is increased by reducing the value of the pickup current I_r . By readjusting the protection in this way, it will pick up at lower currents.

Setting of Overcurrent Protection

The three-phase short-circuit current is generally the largest. In the event of a short circuit near a transformer with an earthed neutral or an earthing transformer, the single-phase short-circuit current may be larger than the three-phase one. This applies mainly to transformers with Yz, Dy and Dz winding connections, for earthing of the y or z winding on the lower-voltage side of the transformer. For this reason, the two-phase short-circuit current is used when calculating the pickup fault currents.

Since electrical equipment is sized for the highest short-circuit current, which in most cases is precisely the three-phase short-circuit current. Unlike overhead lines, cable lines almost always experience three-phase short circuits, since the arc damages the insulation of all three phases. Two-phase short circuits on lines can cause increased stress for single-phase transformers connected to three-phase busbars.



Overcurrent Protection Characteristic

$t_{>}$ - time delay for overload; $t_{>>}$ - time delay for short circuits; $I_{>}$ - current pickup setting for overload; $I_{>>}$ - current pickup setting for short circuits

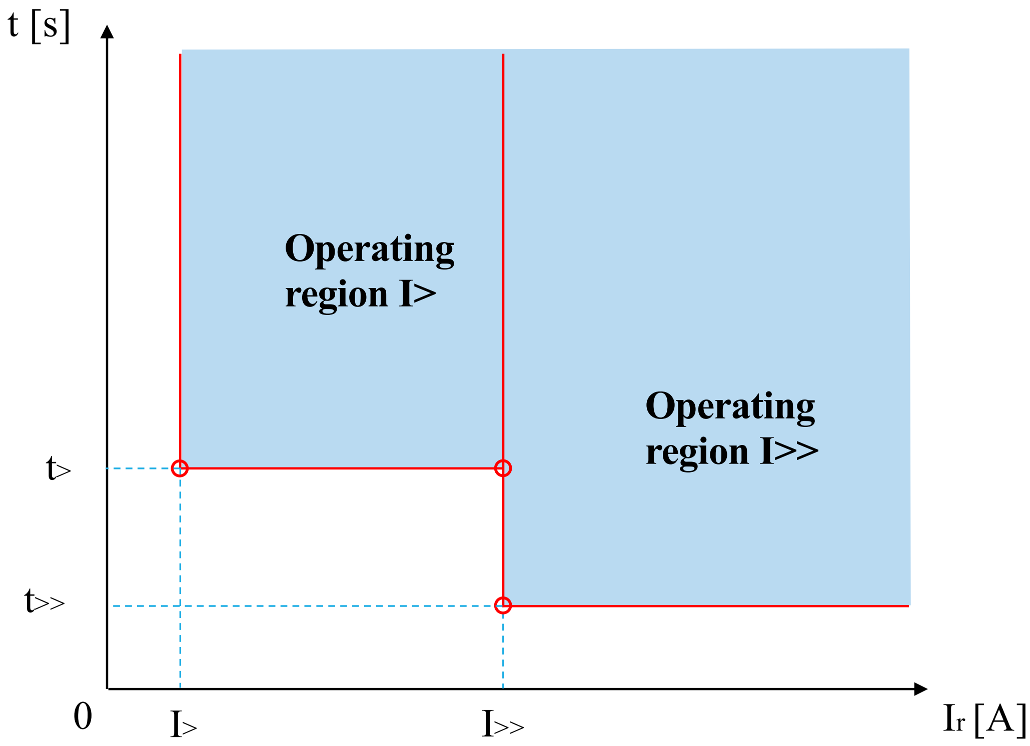


Fig. 6 Overcurrent Protection Characteristic

Theory of Electrical Protection – Example 1

An overcurrent relay with a rated current I_n = 5 A has a set pickup current value I_r equal to 1.8 times I_n. The overcurrent relay closes its contacts at a current value of I_r = 9 A. It opens its contacts at a dropout current value of I_o = 7.5 A. The setting range of the overcurrent relay is (0.8-2) * I_n. Calculate the reset ratio and the relay error scatter:

$$k_n = \frac{I_o}{I_r} = \frac{7{,}5\ A}{9\ A} = 0{,}8\overline{3} < 1;\ k_n = 83{,}3\overline{3}\ \% \qquad (27)$$

The largest permitted current error at the set value I_r is given by the accuracy class:

$$\Delta X_r = \frac{I_{rmax} - I_{rmin}}{I_{nas}} = \frac{9{,}45 - 8{,}55}{9} = 0{,}1 = 10\ \% \qquad (28)$$

Description of Electrical Protection

Overcurrent Relay A11

1 Scale with rotary switch 4-10A

2 Status indication reset button

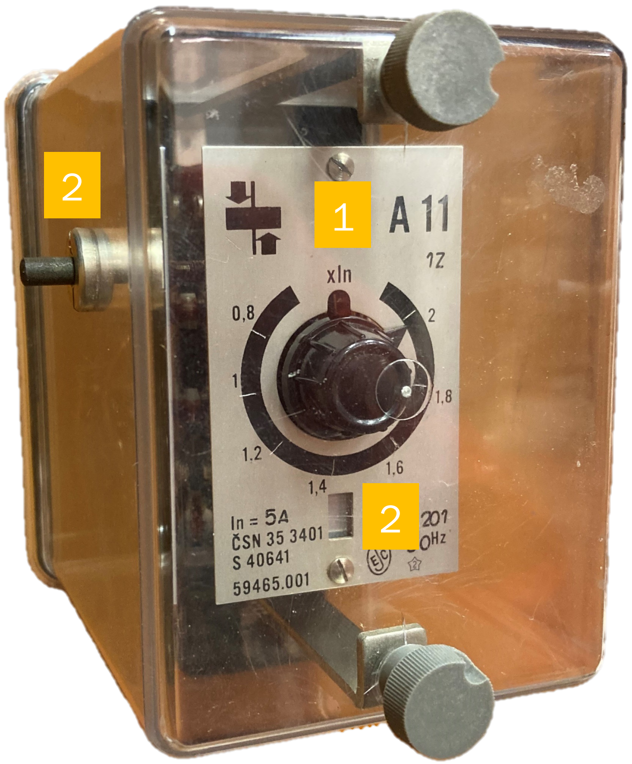


Fig. 7 Overcurrent relay A11 – front view

Overcurrent Relay A11

1 Power supply inputs (1; 2) 2 Relay outputs (3; 4)

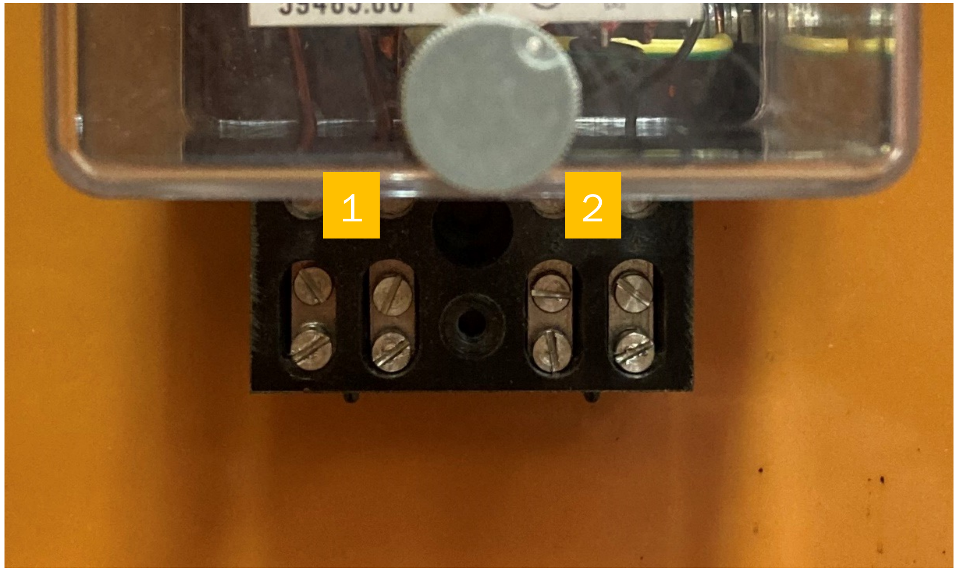


Fig. 8 Overcurrent relay A11 - terminal block view

Sample Calculation – Overcurrent Protection

Overcurrent Protection

%Source network impedance

Z1siet = Un/(sqrt(3)*Ik3siet) = 22e3/(sqrt(3)*3.2328e3) = 3.929Ω

% Nominal branch current

IN = Sn/(sqrt(3)*Un1) = 1000e3/(sqrt(3)*22e3) = 26.2432 A

%Cable line impedance

Xl = 0.14Ω/km

Z1vedenia = l*Xl = 1*0.14 = 0.14Ω

%Transformer impedance

ur = dPk/Sn = 9500/1000000 = 0.0095

Rt = (ur*Un2^2)/Sn = (0.0095*400^2)/1000000 = 0.0015Ω

ux = sqrt(uk^2-ur^2)= sqrt(0.04^2 – 0.0095^2) = 0.0389

Xt = (ux*Un2^2)/Sn = (0.0389 *400^2)/1000000 = 0.0062Ω

Kt2 = 0.95/(1+0.6*(Xt/(Un2^2/Sn))) = 0.95/(1+0.6*(0.0062 /(400^2/1000000)))

= 0.9284

Z1T1 = Kt2*(Rt+1j*Xt) = 0.9284*(0.0015 +1j* 0.0062) = 0.0014+j0.0058Ω

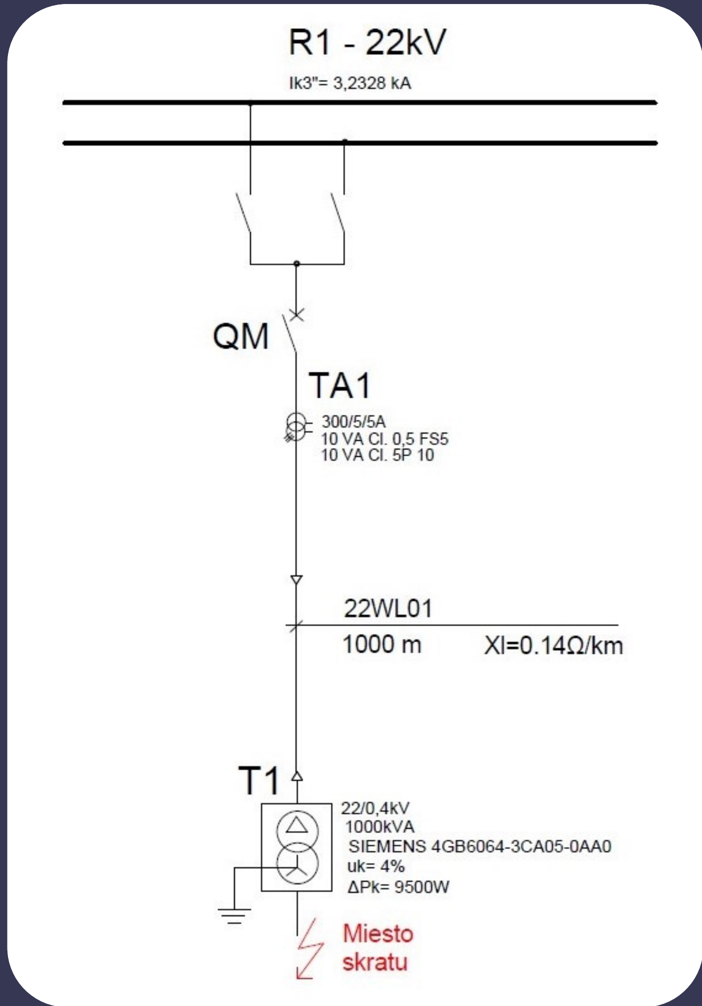


Fig. 9 Sample problem statement

Overcurrent Protection

%Short-circuit current calculation

Z1skrat = Z1siet+Z1vedenia+abs(Z1T1) =

= 3.929*(0.4/22)^2 + 0.14*(0.4/22)^2 + 0.006 = 0.0073Ω

Ik3R1= Un/(sqrt(3)*abs(Zk1))= 400/(sqrt(3)*abs(Z1skrat)) = 31.635kA

Ik2R1 = sqrt(3)/2*Ik3R1 = sqrt(3)/2*31.635 = 27.397kA

%Conversion of short-circuit current to the 22kV side of the transformer

Ik2R122 = Ik2R1*(0.4/22) = 498.1273A

% Calculation of the protection pickup current for overload

I> = (kb*IN)/(kp*pp) = (1.1* 26.2432) / (0.95*300/5) = 0.5064A

% Calculation of the protection pickup current for short circuits

I>> = (0.8*Ik2R122)/(kc*pp) = (0.8*498.1273) / (1.5*300/5) = 4.428A

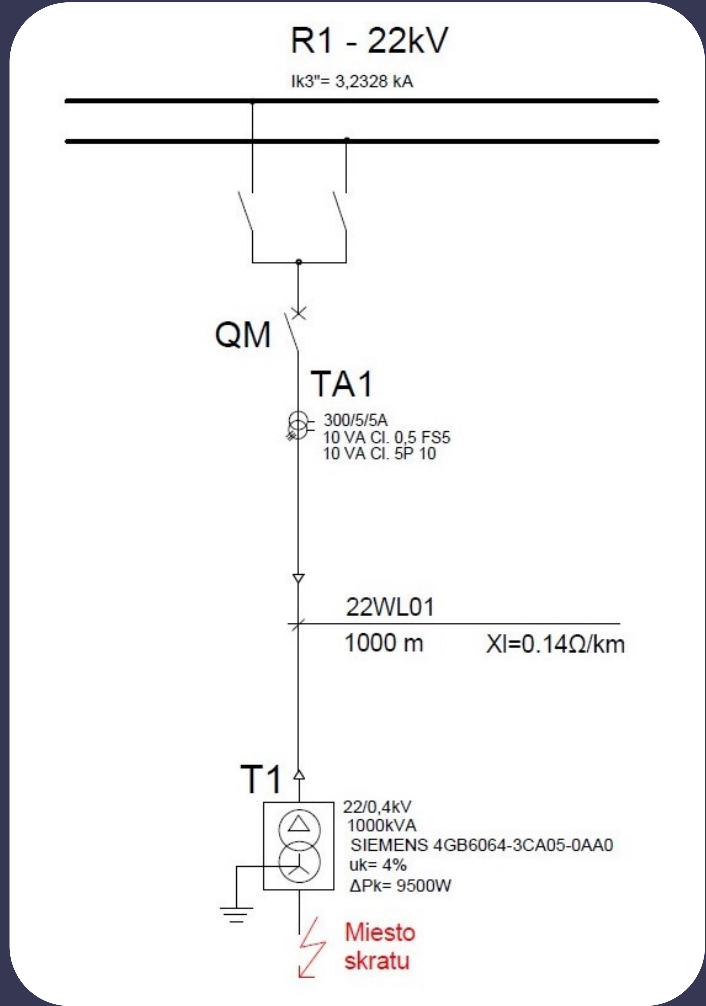


Fig. 9 Sample problem statement

Overcurrent Protection

%Pickup current value of the protection for overload

$$I_{>} \leq I_{R>}$$

$$0.5064A \leq I_{R>}$$

$$I_{R>} = 1A$$

%Pickup current value of the protection for short circuits

$$I_{\gg} \geq I_{R\gg} > I_{R>}$$

$$4.428A \geq I_{R\gg} > 1A$$

$$I_{R\gg} = 3.5A$$

We choose the time delay for overload as t> 0.25s and for short circuits as t>> 0s, considering that further downstream sections are protected only by fuses and circuit breakers.

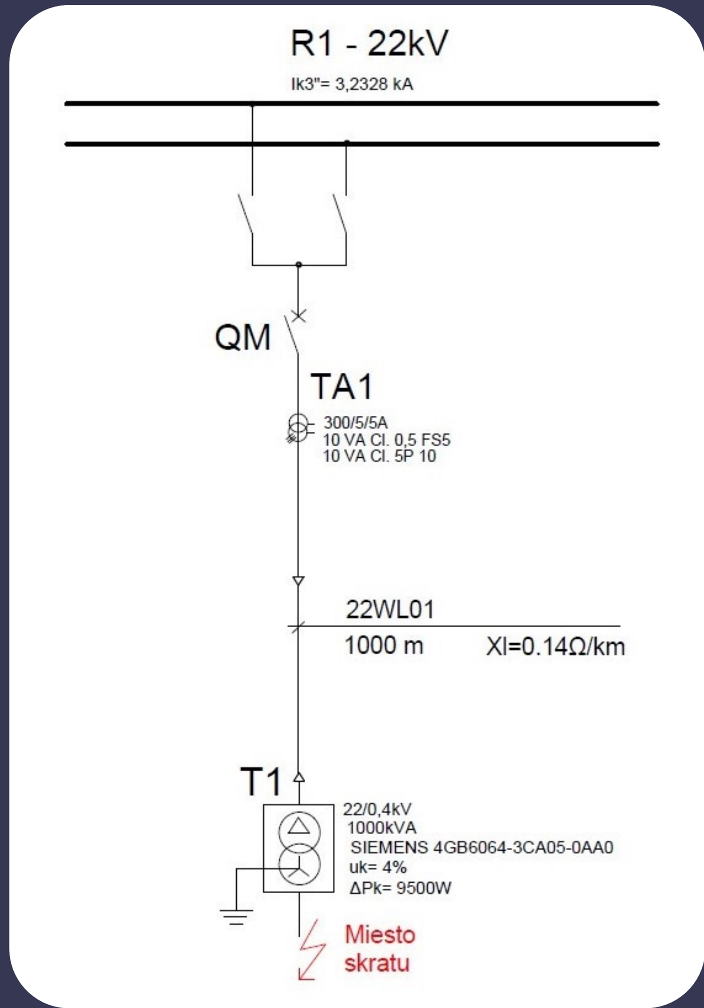


Fig. 9 Sample problem statement

Sample Wiring of Protection Settings and Testing

Dual Overcurrent Protection SEL-501

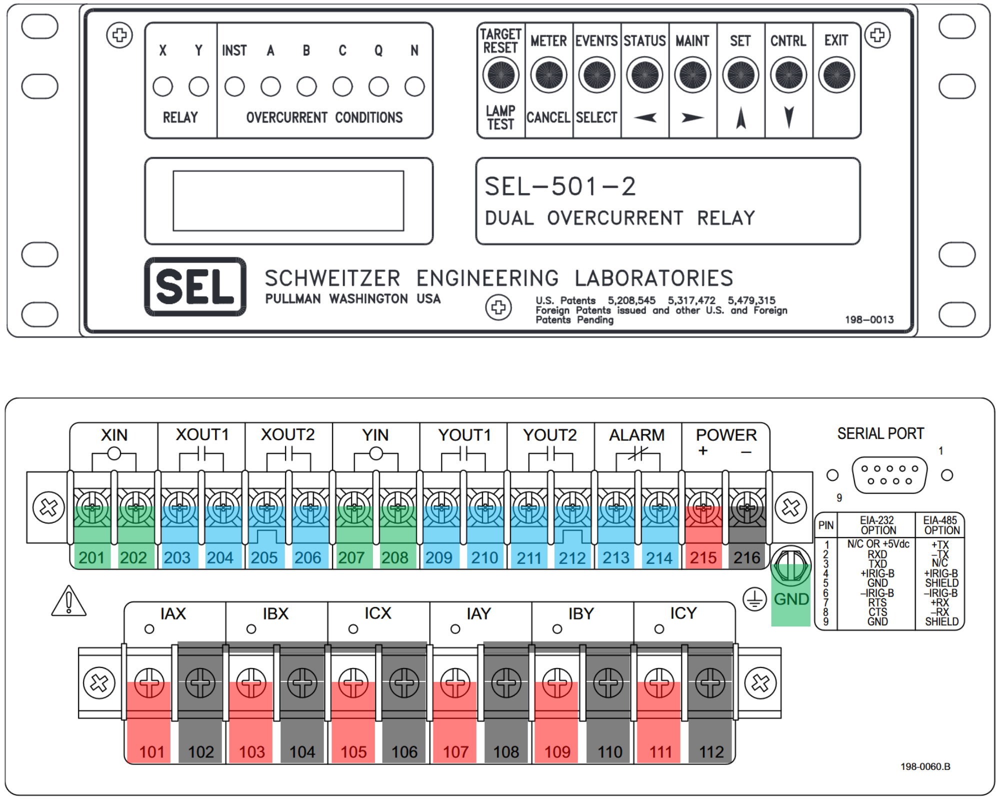


Fig. 10 Overcurrent Relay SEL-501

Dual Overcurrent Protection SEL-501

Wiring diagram of the SEL-501 digital protection relay

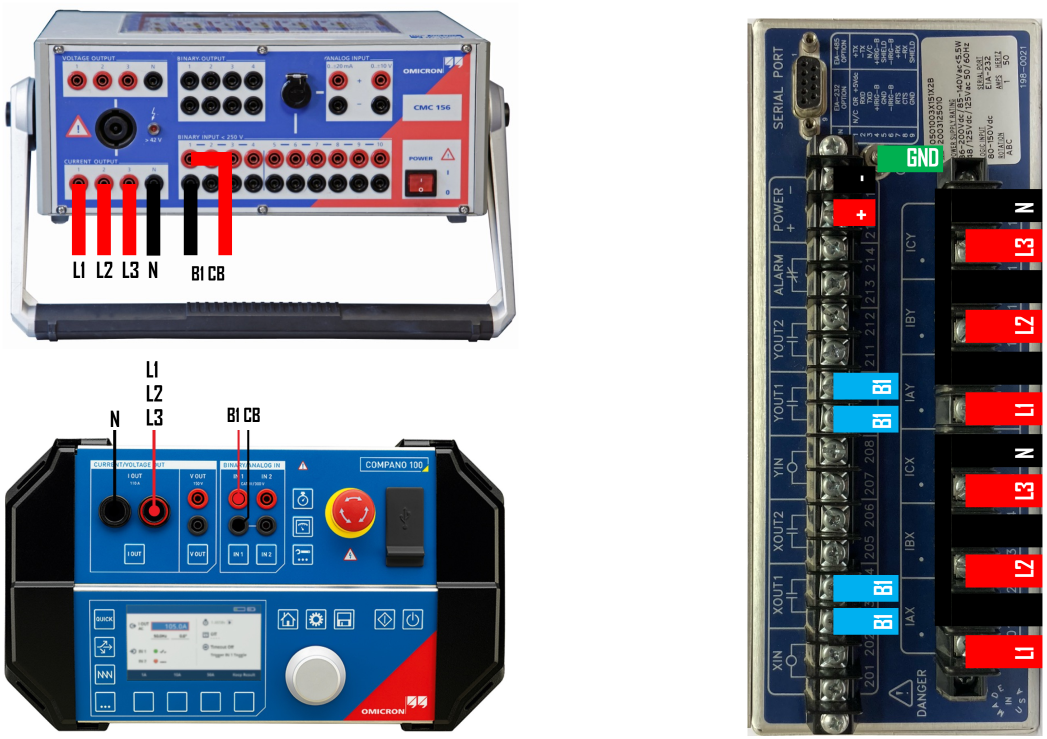


Fig. 11 Overcurrent Relay SEL-501 - testing

Overcurrent Relay A11

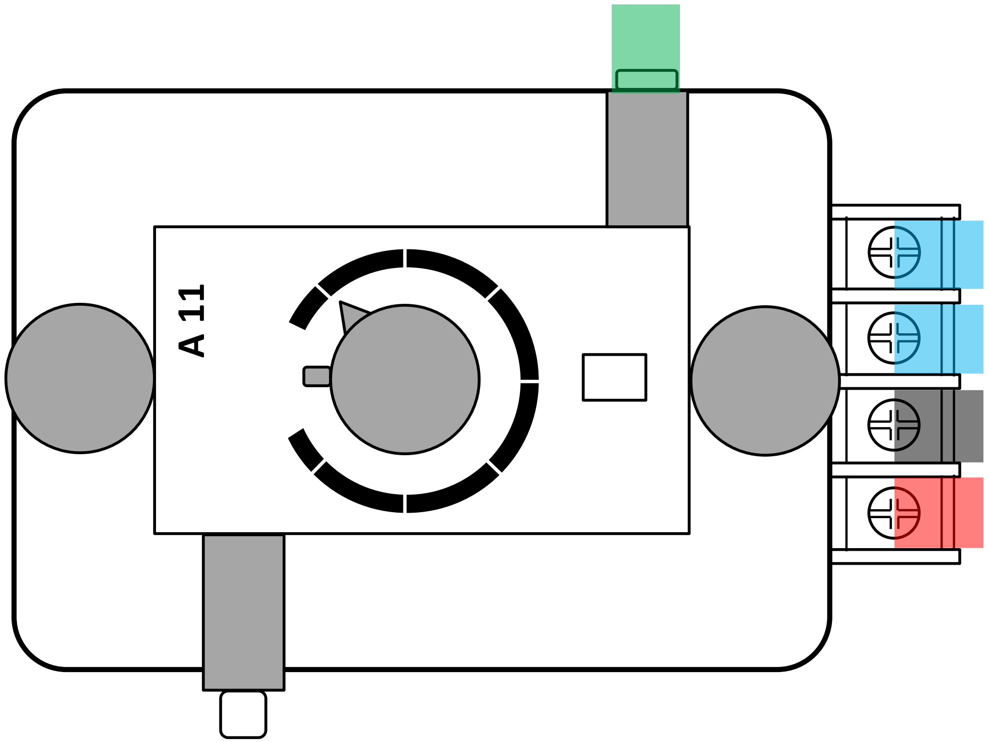


Fig. 12 Overcurrent Relay A11 – schematic diagram

Overcurrent Relay A11

Wiring diagram of the mechanical overcurrent protection

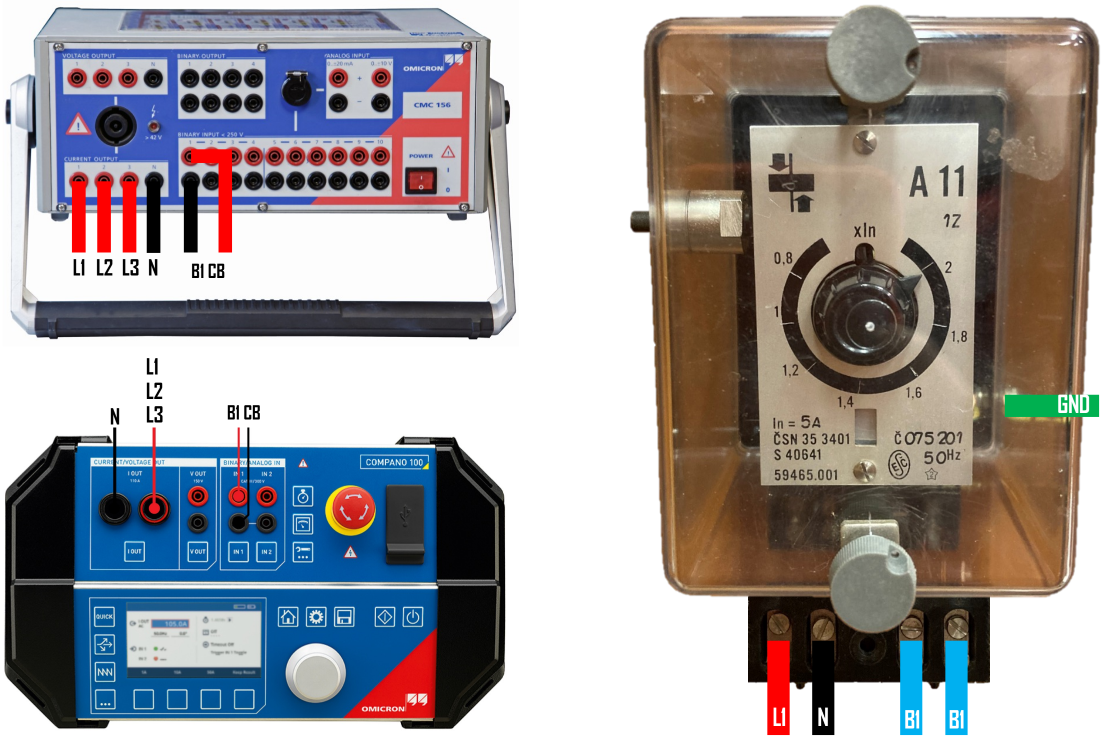


Fig. 13 Overcurrent Relay A11 - testing

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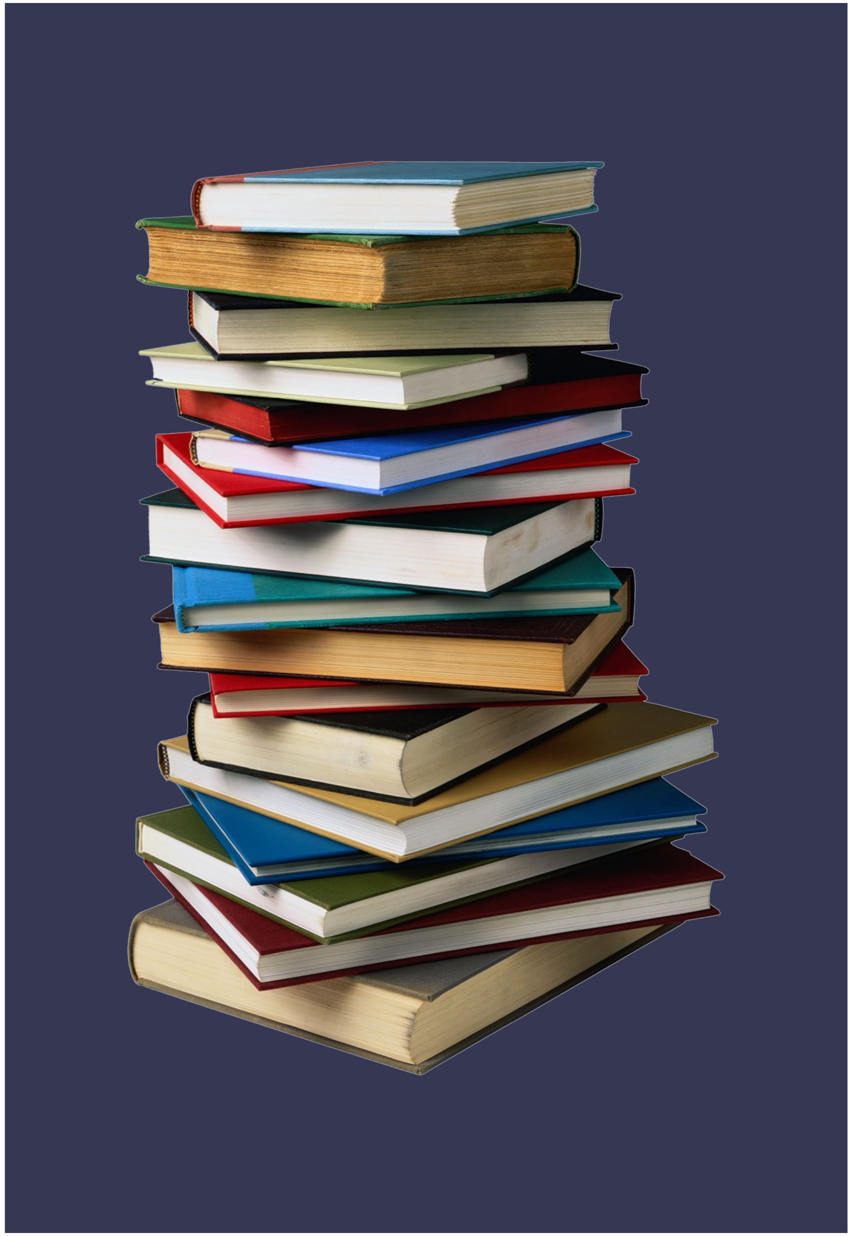

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This textbook is intended for students of electrical engineering faculties in study programs focused on power engineering, for users of power engineering equipment, and for the professional public.