



Zbigniew Skibko

Low-voltage electrical installations

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Introduction

This script is dedicated primarily to students of an engineering degree, studying at the Faculty of Electrical Engineering of the Bialystok University of Technology, carrying out laboratory exercises under the Erasmus + program.

The thematic scope of the script includes exercises related to the construction and operation of power installations and equipment, as well as exercises associated with the testing of the effects of current flow by electrical power equipment.

Each of the exercises comprises a theoretical part, in which the information necessary to understand and solve the problem of the exercise, the description of the test stand, the research program and the needed information that should be included in the student report have been presented.

Many people contributed to the creation of the script, who work or worked in the Department of Electrical Power Engineering, Photonics and Lighting Technology at the Faculty of Electrical Engineering of the Bialystok University of Technology. The result of this joint work is this script. Therefore, I would like to thank all those people – employees and students who contributed to the making of this study, for their efforts in creating and continuous development of our laboratories.

Author

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Exercise no. 1

THE TEST OF WARMING OF WIRES UNDER THE INFLUENCE OF CURRENT FLOW

1. Introductory information

An electric wire is an electrical device designed to transmit electricity along a specified path. It is a product consisting of one or more conductors insulated without a coating or in a non-metallic coating, whereby a single conductor can be made of one or more strands twisted together (all strands of a given wire should have the same nominal diameter) [3].

Depending on the number of conductors, single and multi-conductor wires are distinguished. Single conductor wires are made of a single conductor covered with insulation. Multi-conductor wires consist of at least two insulated conductors placed in a sheathing (fig. 1.1).

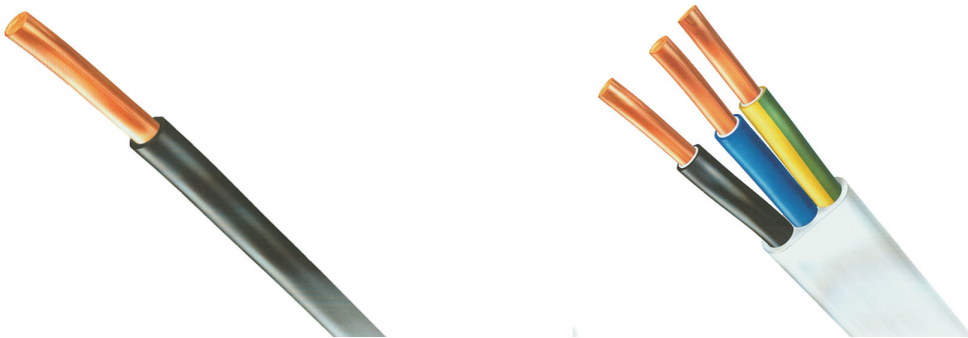


Fig. 1.1. The single-conductor and multi-conductor (three-conductor) wire

Conductor wires are made of copper or aluminum strands (aluminum can be used only for the construction of conductors with nominal cross-sections above 10 mm^2). A characteristic feature of each electric wire is the value of the cross-sectional area of a conductor expressed in mm^2 . The nominal cross-section values of the conductors are normalized and belong to the series:

0,15; 0,2; 0,35; 0,5; 0,75; 1; 1,5; 2,5; 4; 6; 10; 16; 25; 35; 50; 70; 95; 120; 150; 185; 240; 300; 400; 500; 625; 800; 1000 mm^2 .

The conductor insulation of the wire is the element used to separate the individual wire elements from each other and from the conductive parts available

and foreign. The insulation of the protective earthing conductor is green-yellow color, while the remaining conductors of the multi-conductor wire may have colors: blue (neutral conductor), black, brown and gray (phase conductors). The wire's outer sheath may adhere to the insulated conductors but may not be stuck on them. The color of the UV-resistant cover should be black, while the color of other external coatings can be optional (usually is white) [1].

As a result of the current flowing through the conductor of the wire (characterized by a specific value of resistance), it preheats. The heat thus created causes the temperature of the conductor to rise and next to the insulation (possibly the sheath) and it is partially released into the ambient.

The energy balance for a homogeneous wire, uninsulated and with the same cooling conditions on its entire surface, through which flows a current with a constant rms value (1) is expressed as [2, 4]:

$$k_d \cdot I^2 \cdot \frac{\rho \cdot l}{s} dt = s \cdot l \cdot c d\vartheta + \alpha \cdot S \cdot l \cdot (\vartheta - \vartheta_0) dt \quad (1.1)$$

where:

- ρ – resistivity of the wire material [$\Omega \cdot m$];
- l – length of the conductor [m];
- t – time [s];
- s – cross-section of the conductor [m^2];
- S – external surface of unit length [m^2/m];
- c – specific heat of the wire material [$J/m^3 \cdot deg$];
- ϑ, ϑ_0 – ambient and wire temperatures [$^{\circ}C$];
- α – factor of the heat rejection to the ambient [W/m^2];
- k_d – factor of additional losses ($1 < k_d < 1,15$).

The left side of the equation (1) allows us to calculate the amount of heat generated as a result of current flowing through the wire/cable conductor. The first part of the right side of the equation determines the amount of heat needed to warm the wire of the $d\vartheta$ magnitude, while the second part describes the amount of heat released to the ambient.

In the range not exceeding $120^{\circ}C$, changes in the parameters k_d, ρ, c, α are negligibly small, it can be assumed that they are invariable values. After entering the thermal time constant designation as T with the form:

$$\frac{c \cdot s}{\alpha \cdot S} = T \quad (1.2)$$

we can calculate the increase of the temperature of the wire above the ambient temperature:

$$\vartheta - \vartheta_o = \frac{k_d \cdot \rho}{\alpha \cdot S \cdot c} \cdot I^2 \cdot \left(1 - e^{-\frac{t}{T}}\right) + (\vartheta_o - \vartheta_o) \cdot e^{-\frac{t}{T}} \quad (1.3)$$

As $T > 0$, the expression $e^{-\frac{t}{T}}$, along with the passage of time, strives to zero. In turn, the temperature of the wire strives to a determined value ϑ_u expressed by the relationship:

$$\vartheta_u - \vartheta_o = \lim_{t \rightarrow \infty} (\vartheta - \vartheta_o) = \frac{k_d \cdot \rho}{\alpha \cdot S \cdot s} \cdot I^2 \quad (1.4)$$

After substituting the expression (4) to the formula (3), the equation of the heating curve is obtained:

$$\vartheta = \vartheta_u - (\vartheta_u - \vartheta_p) e^{-\frac{t}{T}} \quad (1.5)$$

Since the determined temperature ϑ_u depends on the ambient temperature ϑ_o , for each ϑ_o a different $\vartheta = f(t)$ curve is received with appropriately shifted (up or down) ordinates.

In order to remove the ambient temperature from dependence (5), the following increases of temperatures are introduced: $\tau = (\vartheta - \vartheta_o)$, $\tau_u = (\vartheta_u - \vartheta_o)$, $\tau_p = (\vartheta_p - \vartheta_o)$.

For any ambient temperature ϑ_o , the heating equation receives the form:

$$\tau_u - \tau = (\tau_u - \tau_p) e^{-\frac{t}{T}} \quad (1.6)$$

or

$$\tau = \tau_p + (\tau_u - \tau_p) \left(1 - e^{-\frac{t}{T}}\right) \quad (1.7)$$

in which the τ_p is the initial increase of the temperature of the wire above the ambient temperature [deg].

The value of the thermal time constant of heating can be determined by plotting at any point in the heating curve tangent to this curve until it intersects with the straight line $\tau_u = \text{const}$. The subtangent length measured on the straight line $\tau_u = \text{const}$ is equal to the time constant of heating in the taken timescale (fig. 1.2).

If the wire is loaded longer than four thermal time constants, it can be assumed that the wire is under long-term load. This means that a current of constant intensity flowing infinitely long will increase the temperature of the wire up to the permissible long-term of the limit value ϑ_z . From the relationship (4)

and the increase in the permissible long-term temperature of the $\tau_z=(\vartheta_z - \vartheta_0)$, we obtain:

$$I_z = \sqrt{\frac{s \cdot \alpha \cdot S}{k_d \cdot \rho}} \cdot (\vartheta_z - \vartheta_0) \quad (1.8)$$

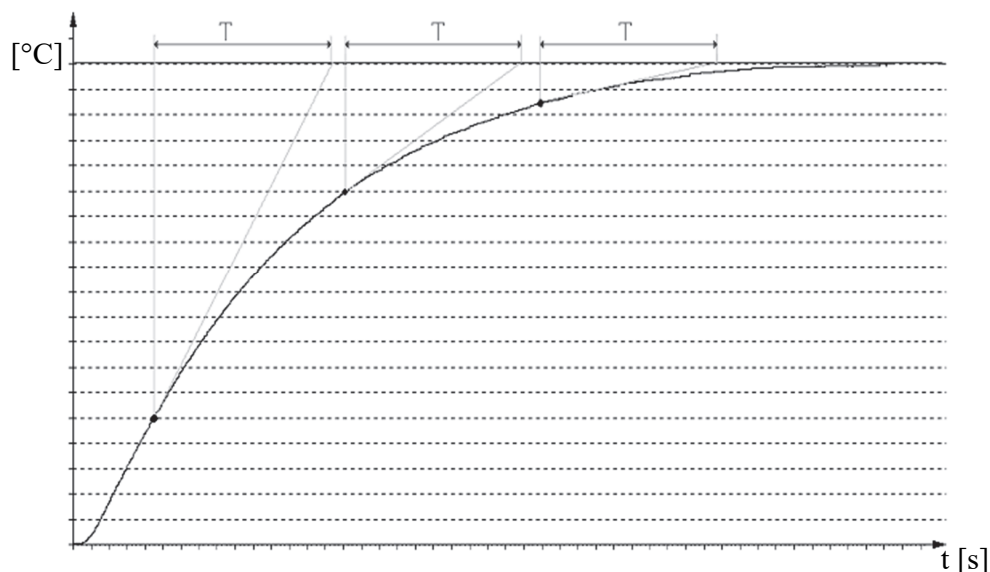


Fig. 1.2. Graphical delineation of the thermal time constant T based on the heating characteristics of the wire

Another type of wire load is the short-time overload. It is characterized by the fact that the current's flow time is insufficient to establish the temperature rise, after that followed by a break, during which the wire cools down to the ambient temperature. The largest value of the short-time current I_{dz} can be determined from the expression [4]:

$$I_{dz} = I_z \frac{1}{\sqrt{1 - e^{-\frac{t_p}{T}}}} \quad (1.9)$$

where:

t_p – duration of the wire's load.

The next type of load is an intermittent load. It is a load with cyclically repeated load periods (with an invariant current value) and the currentless break, whereby the wire does not heat up to a permissible long-time temperature and

does not cool down to ambient temperature. The maximum permissible value of intermittent load current is determined from the equation [4]:

$$I_{pZ} = I_Z \sqrt{\frac{1 - e^{-\frac{t_p}{\alpha' T}}}{1 - e^{-\frac{t_p}{T}}}} \quad (1.10)$$

where:

t_0 – duration of the break in the load,

α' – relative operating duration, expressed as:

$$\alpha' = \frac{t_p}{t_p + t_0} \quad (1.11)$$

2. Purpose and scope of exercise

The intent of the exercise is to get acquainted with thermal phenomena occurring during the current flow through electric wires depending on the method of electrical installation. The scope of the exercise includes recording heating curves of selected electrical circuits and determining on their basis the short-time and intermittent current carrying capacity of the tested systems.

3. Experiment process

3.1. Description of the test stand

The test stand consists of:

- the control section, on which the regulating system of the set load current is placed together with the displays of the temperature values in the tested system and the current flowing through the tested circuit,
- the test section, on which 10 electric circuits are located.

The schematic diagram of the test stand is shown in figure 3. The tested line is modified by screwing the back-end of the wire from the control station part to the terminal from L - 1 to L - 10 on the installation board (test part of the stand).

The back-end of the wire leaving the terminal Z - 0 should be screwed to terminal N - 0. The exception is the test of line L - 5 and L - 10 where the back-end of the wire should be connected to the terminal marked N - 1.

All connections in the circuit should be made with the switched off the stand.

The order of switching the stand:

- connect the power lines to the tested line,
- switch the main switch of the stand to „1” position,

During the heating of cables in lines L-5 and L-10, the symmetry of a load is assumed and only 3 conductors of the phase's wire are undergoing to load. Therefore, the total value of a currents' load is equal to 60 A.

4. Student report

The report on the exercise should contain:

- schemes of the tested circuits,
- list of measured quantity,
- graphs of dependencies $\vartheta=f(t)$,
- graphical determination of values of the thermal time constants of the tested circuits,
- calculations of the values of short-time and intermittent currents for three selected durations of a load and currentless interrupt,
- analysis of the received results,
- conclusions.

5. References

1. PN-EN 60445:2018-01 Fundamental principles and safety in human interaction with the machine, marking and identification - Identification of equipment terminals and wire terminals as well as the wires themselves [in Polish].
2. Seip G.G.: Electrical Installations Handbook. John Wiley and Sons. Third Edition, 2000.
3. Atkinson B., Lovegrove R., Gundry G.: Electrical Installations Designs. John Wiley and Sons. Fourth Edition, 2013.
4. Lejdy B.: Electrical installations in buildings, WNT, Warsaw 2015 [in Polish].

Exercise no. 2

TEST OF ASYMETRY OF THE CURRENTS AND VOLTAGES IN DISTRIBUTION SYSTEMS

1. Introductory information

1.1. Theoretical fundamentals of symmetrical components

By defining the phase quantities in the three-phase system respectively \underline{A}_A , \underline{A}_B , \underline{A}_C , equations are accomplished, which allow calculation of symmetrical components of a three-phase system [1]:

$$\underline{A}_0 = \frac{1}{3} \cdot (\underline{A}_A + \underline{A}_B + \underline{A}_C) \quad (2.1)$$

$$\underline{A}_1 = \frac{1}{3} \cdot (\underline{A}_A + a \cdot \underline{A}_B + a^2 \cdot \underline{A}_C)$$

$$\underline{A}_2 = \frac{1}{3} \cdot (\underline{A}_A + a^2 \cdot \underline{A}_B + a \cdot \underline{A}_C)$$

or in matrix form:

$$\begin{bmatrix} \underline{A}_0 \\ \underline{A}_1 \\ \underline{A}_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} \underline{A}_A \\ \underline{A}_B \\ \underline{A}_C \end{bmatrix} \quad (2.2)$$

where:

$\underline{A}_0, \underline{A}_1, \underline{A}_2$ - symmetrical components of the zero, positive and negative sequences,

$\underline{A}_A, \underline{A}_B, \underline{A}_C$ - phase quantity of currents or voltages,

a - symmetrical coefficient expressed as: $a = e^{j\frac{2\pi}{3}}$

Knowing $\underline{A}_0, \underline{A}_1$, and \underline{A}_2 , it is possible to determine $\underline{A}_A, \underline{A}_B$, and \underline{A}_C using the relationships [1]:

$$\underline{A}_A = (\underline{A}_0 + \underline{A}_1 + \underline{A}_2) \quad (2.3)$$

$$\underline{A}_B = (\underline{A}_0 + a^2 \cdot \underline{A}_1 + a \cdot \underline{A}_2)$$

$$\underline{A}_C = (\underline{A}_0 + a \cdot \underline{A}_1 + a^2 \cdot \underline{A}_2)$$

or in matrix form:

$$\begin{bmatrix} A_A \\ A_B \\ A_C \end{bmatrix} = \left(\frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \right)^{-1} \begin{bmatrix} A_0 \\ A_1 \\ A_2 \end{bmatrix} \quad (2.4)$$

and after transformation:

$$\begin{bmatrix} A_A \\ A_B \\ A_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} A_0 \\ A_1 \\ A_2 \end{bmatrix} \quad (2.5)$$

1.2. Determining the symmetrical components of currents based on measurements

In order to define the values describing the asymmetry of currents, on the basis of measurements of the rms values of currents and power factors of each phase, phase currents should be presented in a form of complex numbers. In addition, a symmetrical system of the phase voltages should be assumed [3].

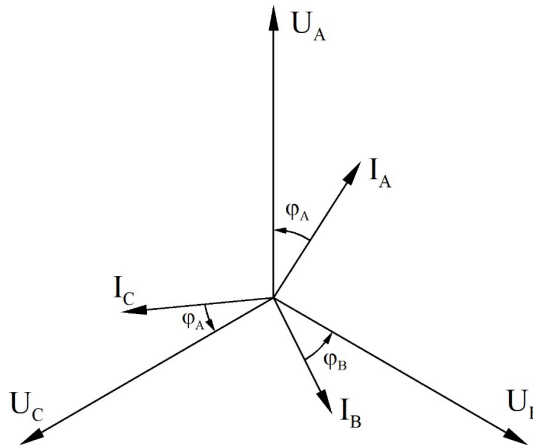


Fig. 2.1. Diagram of the phase-order of currents and voltages [3]

Phase currents I_A, I_B, I_C in a form of complex numbers can be written using the relationships [2]:

$$\underline{I}_A = I_A e^{j\phi_A} \quad (2.6)$$

$$\underline{I}_B = I_B e^{j\phi_B}$$

$$\underline{I}_C = I_C e^{j\phi_C}$$

The phase shift of individual currents I_A, I_B, I_C are calculated, on the basis of measurements of power factors in each phase, from the relationships [2]:

$$\phi_A = \arccos \phi_A \quad (2.7)$$

$$\phi_B = -120 - \arccos \phi_B$$

$$\phi_C = 120 - \arccos \phi_C$$

The angles phase shifts $\varphi_A, \varphi_B, \varphi_C$ between line currents and phase voltages can be described by the relationship:

$$\begin{bmatrix} \varphi_A \\ \varphi_B \\ \varphi_C \end{bmatrix} = \begin{bmatrix} \arg(U_A) \\ \arg(U_B) \\ \arg(U_C) \end{bmatrix} - \begin{bmatrix} \arg(I_A) \\ \arg(I_B) \\ \arg(I_C) \end{bmatrix} \quad (2.8)$$

After calculating the phase shifts of the currents, its symmetrical components are determined [2]:

$$\underline{I}_0 = \frac{1}{3} \cdot (\underline{I}_A + \underline{I}_B + \underline{I}_C) \quad (2.9)$$

$$\underline{I}_1 = \frac{1}{3} \cdot (\underline{I}_A + \underline{I}_B \cdot a + \underline{I}_C \cdot a^2)$$

$$\underline{I}_2 = \frac{1}{3} \cdot (\underline{I}_A + \underline{I}_B \cdot a^2 + \underline{I}_C \cdot a)$$

where:

$\underline{I}_A, \underline{I}_B, \underline{I}_C$ – complex values of phase currents;

$\underline{I}_0, \underline{I}_1, \underline{I}_2$ – complex values of currents' components,

a – symmetrical coefficient (rotation operator equals to 120 °).

1.3. Determining the symmetrical components of voltages based on measurements

Symmetrical components as well as asymmetry and voltage unbalanced factors can be calculated based on measurements of phase voltages U_A , U_B , U_C and two phase-to-phase voltages, e.g. U_{AB} and U_{AC} . These quantities are necessary to calculate the phase voltages shifts according to the relations resulting from the voltage vector system (fig. 2.2) [3].

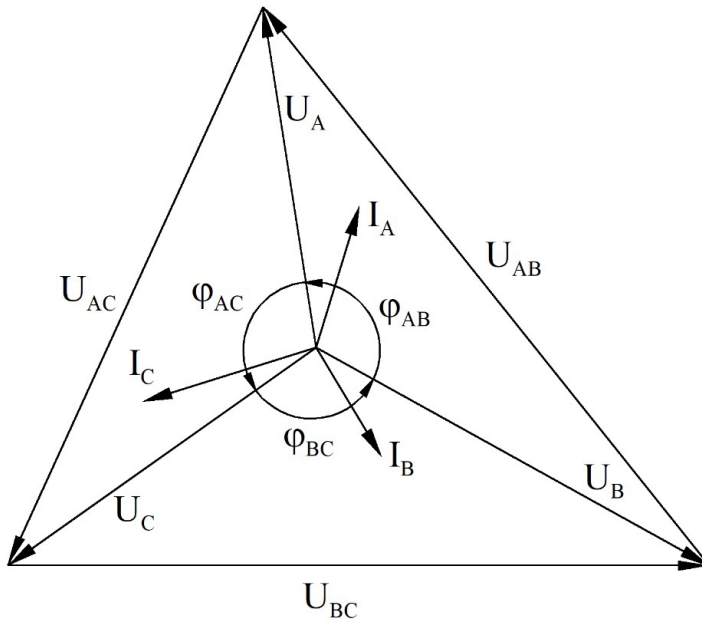


Fig. 2.2. Vector diagram of currents and voltages at the asymmetry condition [3]

Using the cosine theorem, shifts between phase voltages can be expressed as [2]:

$$U_{AC}^2 = U_A^2 + U_C^2 - 2 \cdot U_A \cdot U_C \cdot \cos \phi_{AC} \quad (2.10)$$

$$\cos \phi_{AC} = \frac{U_A^2 + U_C^2 - U_{AC}^2}{2 \cdot U_A \cdot U_C} \quad (2.11)$$

$$\phi_{AC} = \arccos \left(\frac{U_A^2 + U_C^2 - U_{AC}^2}{2 \cdot U_A \cdot U_C} \right) \quad (2.12)$$

$$\phi_{BC} = \arccos \left(\frac{U_B^2 + U_C^2 - U_{BC}^2}{2 \cdot U_B \cdot U_C} \right) \quad (2.13)$$

Assuming that the voltage phase U_A is equal to 0° , the complex values of the phase voltages will have the form [2]:

$$\underline{U}_A = U_A \cdot e^{j0^\circ} \quad (2.14)$$

$$\underline{U}_B = U_B \cdot e^{j(\phi_{AC} + \phi_{BC})}$$

$$\underline{U}_C = U_C \cdot e^{j\phi_{AC}}$$

If the voltages have only positive sequence components (they form a symmetrical voltage star) and the voltage phase A has a zero argument - the dependence is obtained:

$$\begin{bmatrix} U_A \\ U_B \\ U_C \end{bmatrix} = \begin{bmatrix} |U| e^{j0} \\ |U| e^{-j\frac{2}{3}\pi} \\ |U| e^{j\frac{2}{3}\pi} \end{bmatrix} \quad (2.15)$$

where – positive sequence component of the voltage (at the node under consideration).

In this case, phase asymmetry can only appear in currents. However, if the symmetrical star of supply voltages occurs only at a far supply node (in a radial configuration network), the phase asymmetry in the node we are considering can include both currents and voltages.

1.4. Indicators describing the asymmetry of currents and voltages

1.4.1. Currents asymmetry coefficients

Asymmetry of currents at individual phases of the power system is caused by an occurrence of the symmetrical components of the negative and/or zero sequences. Currents' asymmetry is described by the following coefficients [1]:

- coefficient of asymmetry of the negative sequence (currents' asymmetry)

$$\underline{\alpha}_{i2} = \frac{I_2}{I_1} = \alpha_{i2} e^{j\phi_{i2}} \quad (2.16)$$

$$\alpha_{i2} = |\underline{\alpha}_{i2}| = \frac{I_2}{I_1}$$

$$\alpha_{i2\%} = \alpha_{i2} \cdot 100\%$$

- coefficient of asymmetry of the zero sequence (currents' unbalanced)

$$\underline{\alpha}_{i0} = \frac{I_0}{I_1} = \alpha_{i0} e^{j\phi_{i0}} \quad (2.17)$$

$$\alpha_{i0} = |\underline{\alpha}_{i0}| = \frac{I_0}{I_1}$$

$$\alpha_{i0\%} = \alpha_{i0} \cdot 100\%$$

where:

I_0, I_1, I_2 – symmetrical components of currents;

$\underline{\alpha}_{i0}, \underline{\alpha}_{i2}$ – complex coefficients of phase currents asymmetry;

α_{i0}, α_{i2} – absolute values of coefficients of phase currents asymmetry;

$\alpha_{i0\%}, \alpha_{i2\%}$ – percentage values of coefficients of phase currents asymmetry.

1.4.2. Voltages asymmetry coefficients

The asymmetry of the voltage supply causes appearance of the symmetrical components of the negative and/or zero sequences. Therefore, the following indicators describing the asymmetry of phase voltages can be distinguished [1]:

- coefficient of asymmetry of the negative sequence (voltages' asymmetry)

$$\underline{\alpha}_{u2} = \frac{U_2}{U_1} = \alpha_{u2} e^{j\phi_{u2}} \quad (2.18)$$

$$\alpha_{u2} = |\underline{\alpha}_{u2}| = \frac{U_2}{U_1}$$

$$\alpha_{u2\%} = \alpha_{u2} \cdot 100\%$$

- coefficient of asymmetry of the zero sequence (voltages' unbalanced)

$$\underline{\alpha}_{u0} = \frac{U_0}{U_1} = \alpha_{u0} e^{j\phi_{u0}} \quad (2.19)$$

$$\alpha_{u0} = |\underline{\alpha}_{u0}| = \frac{U_0}{U_1}$$

$$\alpha_{u0\%} = \alpha_{u0} \cdot 100\%$$

where:

$\underline{U}_0, \underline{U}_1, \underline{U}_2$ – symmetrical components of voltages;

$\underline{\alpha}_{u0}, \underline{\alpha}_{u2}$ – complex coefficients of phase voltages asymmetry;

α_{u0}, α_{u2} – absolute values of coefficients of phase voltages asymmetry;

$\alpha_{u0\%}, \alpha_{u2\%}$ – percentage values of coefficients of phase voltages asymmetry.

1.5. Effect of asymmetry on power losses

One of the effects of the long-term operation of the LV line and MV/LV transformers at current asymmetry conditions is the escalate of load losses in these elements. In low voltage power lines, at symmetrical load, active power losses can be expressed as [3]:

$$\Delta P_s = 3 \cdot I_1^2 \cdot R_1 \quad (2.20)$$

where:

I_1 – rms value of the positive sequence component of current in power line,

R_1 – the resistance for the positive sequence component of the line section.

At the appearance of current asymmetry, active power losses can be expressed by equation [3] (assuming that the equivalent resistance of the earth-circuit has been (artificially) joined into R_0):

$$\Delta P_{ns} = 3 \cdot (I_1^2 \cdot R_1 + I_2^2 \cdot R_2 + I_0^2 \cdot R_0) \quad (2.21)$$

where:

I_{2p}, I_{1p}, I_{0i} – rms value of the negative, positive and zero sequence component of current in power line;

R_{2p}, R_{1p}, R_{0i} – the resistance of the line section for the negative, positive and zero sequence component.

Assuming that current asymmetry along the line is similar to the asymmetry measured at the beginning of the line, obtained relationship expressing the relative increase in active power losses at the line due to current asymmetry [3]:

$$\delta\Delta P_{ns} = \frac{\Delta P_{ns} - \Delta P_s}{\Delta P_s} = \alpha_{i2}^2 \cdot \frac{R'_2}{R_1} + \alpha_{i0}^2 \cdot \frac{R'_0}{R_1} \quad (2.22)$$

where:

R'_2, R'_1, R'_0 – unit resistance of line in [Ω/km] for the negative, positive and zero sequence component.

In lines where the conductor cross-sections of all wires are identical ($R'_f = R'_N$), the relative increase of active power losses in the line as a result of current asymmetry can be (approximately) described by equation [3]:

$$\delta\Delta P_{nsl} = \alpha_{i2}^2 + 4 \cdot \alpha_{i0}^2 \quad (2.23)$$

The increase of load losses in transformers due to current asymmetry can be defined in compliance with the relationship [3]:

$$\delta\Delta P_{ns} = \alpha_{i2}^2 + \alpha_{i0}^2 \cdot \frac{R'_0}{R_1} \quad (2.24)$$

For transformers with Yy, Yd and Dy configurations (with windings connected in a zigzag) the quantity of asymmetry depends on the construction of the core and the connections configuration of the windings and the details of the connection of neutral points with the ground. In the absence of detailed data, $R_\phi/R_1 = 0$ is assumed, then the expression (24) will take the form [3]:

$$\delta\Delta P_{nst} = \alpha_{i2}^2 + \alpha_{i0}^2 \quad (2.25)$$

2. Purpose and scope of exercise

The intent of the exercise is to assess the asymmetry of currents and voltages on the low voltage side of the transformer with unbalanced load.

The exercise includes testing the asymmetry of currents and voltages in low voltage distribution systems caused by unbalanced loads.

3. Experiment process

3.1. Description of the test stand

Figure 3 shows the view of the front panel with the schematic diagram of the network being a fragment of the ring network of the power supply system.

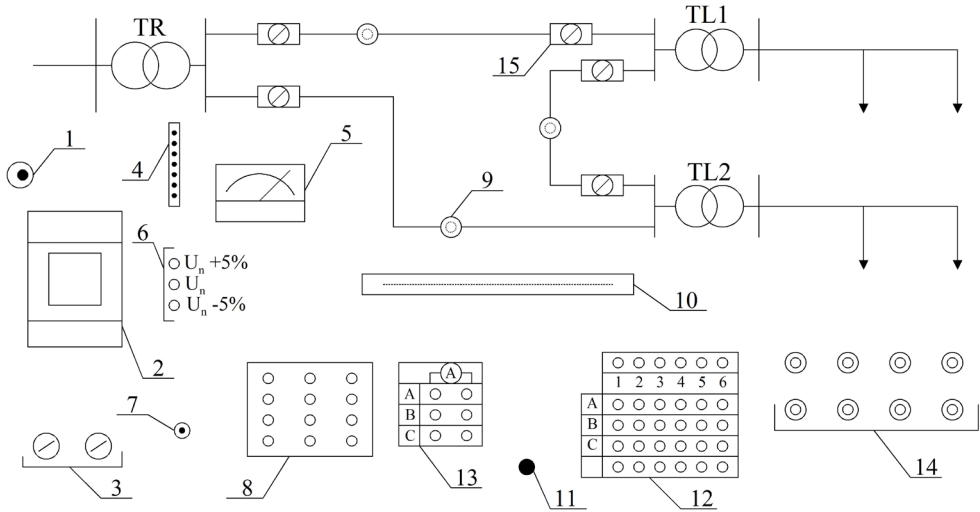


Fig. 2.3. Front plate of the station with a schematic diagram of the network and distribution of measuring, signaling and control elements: 1 – circuit breaker of station, 2 – voltage regulator, 3 – switch of work type of the regulator, 4 – light indicators of the position of the tap changer, 5 – voltage level indicator, 6 – buttons for changing the voltage level of the transformer, 7 – emergency switch of the station, 8 – terminals and measuring points of the regulator, 9 – measuring socket of the line currents, 10 – control buttons for line breakers, 11 – measurement probe for current measurements, 12 – voltage measurement terminals, 13 – line current measurement terminals, 14 – control buttons for receivers, 15 – position indicators of line circuit breakers.

Switching on the station (supplying voltage to point 1) is carried out by using the panel switch. The voltage to point 2 is supplied by activating one of the buttons number 6 in fig. 2.3. The choice of the configuration of the system is made by WL line circuit breakers. The station has an emergency switch, which turns off the voltage of the entire system.

3.2. Testing the asymmetry of voltages and currents

The exercise should be carried out for the following load variants:

- without load,
- single-phase load (one resistance heater connected to the receiver number 1),
- two-phase load (two resistance heaters connected to the receiver number 1),
- unbalanced single-phase load (one resistance heater connected to the receiver number 1 and symmetrical heater system connected to the receiver number 2),
- unbalanced two-phase load (two resistance heaters connected to the receiver number 1 and symmetrical heater system connected to the receiver number 2).

All measurements should be performed for three network configurations:

- radial system – fig. 2.4,
- series system – fig. 2.5,
- meshed system – fig. 2.6.

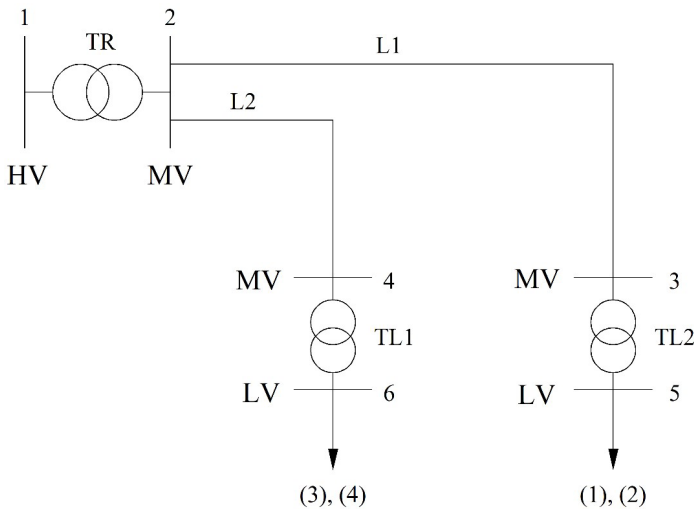


Fig. 2.4. Diagram of the radial distribution system

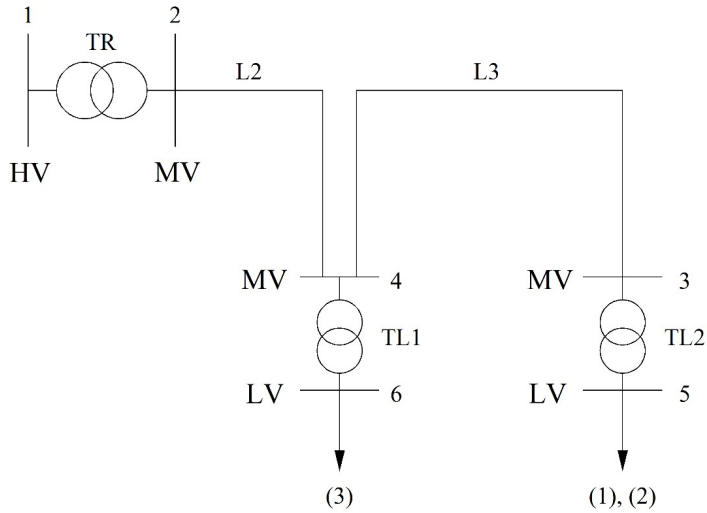


Fig. 2.5. Diagram of the series distribution system

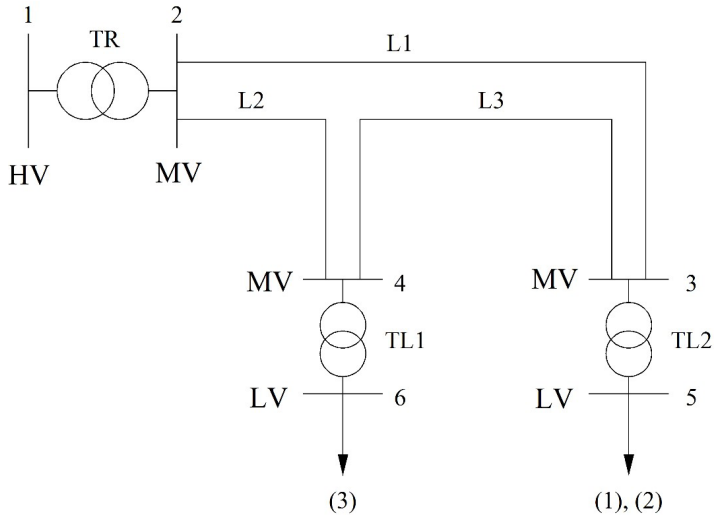


Fig. 2.6. Diagram of the meshed distribution system

The tests at the station should be performed in the following order:

1. Connect the receivers' system according to the indicated load configuration.
2. Set the voltage regulator in position R.
3. Switch on the voltage supplying the station.
4. Configure the selected network using WL circuit breakers (fig. 2.4, 2.5 or 2.6).

5. Using the PS button, turn on the supply voltage to the distribution system.
6. Switch on the receivers.
7. For each load configuration and connection arrangement, perform voltage measurements on the busbars of all distribution substation i.e.: HV (point 1), MV (points 2, 3, 4) and LV (points 5, 6).
8. Perform currents measurement on L1, L2, and L3 lines (depending on a form of configuration of the system) and receivers' currents for all load options.
9. For each load configuration and network connection system, juxtapose the measurement results in tables 2.1 and 2.2.

Table 2.1. List of voltages measurement results

Measuring point number	Phase-to-phase voltage			Phase voltage		
	U_{AB}	U_{BC}	U_{AC}	U_A	U_B	U_C
	[V]	[V]	[V]	[V]	[V]	[V]
1						
2						
3						
4						
5						
6						

Table 2.2. List of currents measurement results

Line	I_A	I_B	I_C	I_0
	[A]	[A]	[A]	[A]
L1				-
L2				-
L3				-
Receiver				

1. Calculate symmetrical components as well as currents and voltages asymmetry coefficients for individual load configurations and juxtapose the results of computations in tables 3 and 4.
2. Compute the values of power loss increase in the lines and transformer for individual load configurations and calculated results juxtapose in table 5.

Table 2.3. List of results of symmetrical components calculations and voltages asymmetry coefficients

Measuring point number	Symmetrical components			Asymmetry coefficients	
	U_0	U_1	U_2	$\alpha_{u0\%}$	$\alpha_{u2\%}$
	[V]	[V]	[V]	%	%
1					
2					
3					
4					
5					
6					

Table 2.4. List of results of symmetrical components calculations and currents asymmetry coefficients

Line	Symmetrical components			Asymmetry coefficients	
	I_0	I_1	I_2	$\alpha_{i0\%}$	$\alpha_{i2\%}$
	[A]	[A]	[A]	%	%
L1					
L2					
L3					
Receiver					

Table 2.5. List of results of calculations of power loss increase in a lines and transformer

Line	Coefficient of power loss increase	
	$\delta\Delta P_{ns}$	
	[%]	
L1		
L2		
L3		
Receiver		
Transformer		

4. Student report

The report on the exercise should contain:

- scheme of the tested system,
- a list of measured and calculated quantities,
- comparison of the obtained results of measurements and calculations depending on the impact of load asymmetry on the work condition of the power system (power losses and voltage asymmetry),
- conclusions.

5. References

1. Baggini A.: Handbook of Power Quality. John Wiley and Sons, 2008.
2. Hanzelka Z.: Quality of electricity supply: disturbances of the rms voltage value. AGH publishing house, Cracow, 2013 [in Polish].
3. Schlabbach J., Blume D., Stephanblome T.: Voltage Quality in Electrical Power Systems. The Institution of Engineering and Technology, London, 2001.

Exercise no. 3

LIGHT CONTROL SYSTEMS

1. Introductory information

1.1. General information

Electrical installation is called a compilation of electrical devices with coordinated technical parameters, at nominal voltage up to 1 kV alternating current (AC) and 1.5 kV direct current (DC) (these values could be different in different countries), used to supply electricity from the distribution system (from the supply-terminals) to load. The installation includes electric wires and cables, devices with installation accessories, protective devices, protective systems, instrumentation, and control equipment, metering equipment and enclosures with supporting structures along with emergency power systems [3].

Due to the way of supplying the receivers, the electrical installation can be distinct, respectively [1, 2]:

- a lighting installation, consisting of light sources and portable, low-powered electric devices,
- power installation, supplying devices with high power consumption (usually above 2 kW).

The design of the electrical installation and its structure should guarantee an invariant supply of electricity and protection against electric shock, fire, switching overvoltages and other dangers resulting from the operation of electrical equipment.

1.2. Electric power wires and cables

Electric power cables and wires are called the elements of the power system, which are used to transmit electricity in power lines and electrical installations.

Cable is an industrial product consisting of one or more insulated conductors, in a coating, possibly an oversheath and armor, immunity to damaging environmental effects, such as: ultraviolet radiation, ground influence.

A wire is an industrial product consisting of one or several twisted strands with or without insulation.

The main part of the wire/cable is a conductor. It is usually made of copper or aluminum. Due to the construction of the conductor, the wires/cables are distinguished as:

- single-conductor (-core) – the conductor is made of a single strand,
- multi-conductor (-core) – stranded wire – the conductor is made by twisting a specific number of strands.

To determine the parameters of the cable or wire, letter symbols were introduced to inform about the material composition and structure. Popular single-core cables have DY and LY denotations. DY wires type is made of one copper conductor in polyvinyl chloride (PVC) insulation. In LY wires type, the conductor is made as multi-core and sheathed with polyvinyl chloride (PVC) insulation. The nominal cross-sections of the conductors have been normalized and are produced in cross-sections from 0.5 to 10 mm² for single-conductors, and from 0.5 to 240 mm² for multi-conductors.

The most popular multi-core wires are YDY wires type. The conductors of the wires are sheathed with PVC insulation and additionally, they are covered by an additional PVC coating. Depending on the type of multi-conductor wire (YDY (t, p) žo), these wires take different shapes (fig. 3.1). Depending on how the conductor is made, wires with conductors are distinguished in the form of stranded copper wires (YLY) and with conductors in the form of single-strand (YDY). The mark “žo” in the wire symbol indicates the presence of a protective conductor in it (yellow-green color).



Fig. 3.1. Three-core wire: a) flat type YDYpžo, b) round type YDYžo

To characterize the phase wires should be used brown, black or gray color and the neutral wire should be marked in blue. For protective reasons, eliminating the risk due to mistaken wires, a single yellow and single green color should not be used together with the green-yellow one. The PEN wire should be marked with a yellow-green color along its entire length and at an end of wire with a blue color (or oppositely).

1.3. Installation switches

Installation switches are the simplest electrical switching devices designed for switching on and off low voltage operational currents. The change process of switch condition should take place with a high speed, regardless of how the button is manipulated. By quickly disconnecting the contacts – suppressing the appearing arc between its surfaces prevents fast wear of the contacts [3].

Due to the construction and assembly, the switches are divided into sunk and surface.

Due to switching functions in circuits, installation switches can be divided into:

- single-pole switches for switching on and off one circuit,
- quick make-and-break switches, used to turn on one circuit by giving a pulse to the control system,
- multi-break switches, used for independent switching on and off of two or more circuits,
- landing switches, used to switch on and off the circuit from two different places,
- four-way switches used to switch on and off the circuit from three or more places - supplementing landing switches.

1.4. Plug-in sockets

Plug-in sockets in connection with plugs are used for connecting mobile and portable receivers to installations. They are produced in single- and three-phase variants. Single-phase plug-in sockets are made as sunk and surface, for 250V as well as 10 and 16A nominal current. The sockets should have a protective contact (usually made in the form of a pin). After inserting the plug into the socket, the active contacts of the plug in the form of pins are in abut with the socket contacts (plates profiled in the shape of the sleeve) and allowing the current's flow. This type of connection should have low resistance and no sparking during operation.

The construction of plug-in sockets should provide protection against direct contact of parts being live.

1.5. Sequential bistable relays

The sequential bistable relay is used to control lighting or other electrical devices from several different points using parallel connected control buttons.

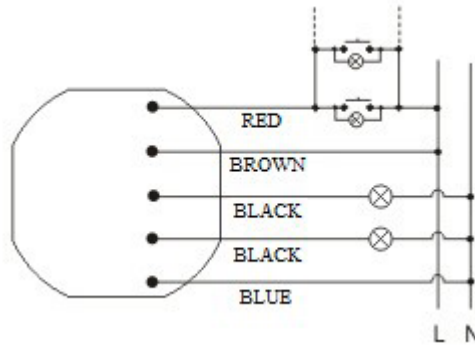


Fig. 3.2. Diagram of connections of bistable relays [5]

Impulse	Operating condition
1	Switch on only R1 section
2	Switch on only R2 section
3	Switch on R1 and R2 sections
4	Switch off R1 and R2 sections

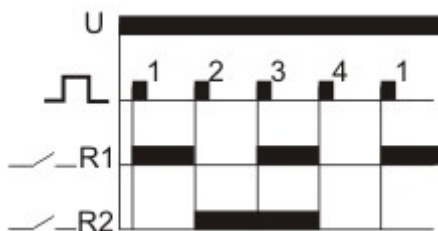


Fig. 3.3. The process of operating conditions of the sequential bistable relay [5]

The first receiver is switched on after the first current pulse has been applied using a quick make-and-break installation switch. At the entering time of the second pulse, the first receiver switches off and the second receiver switches on. Entering the third pulse switches on both receivers. The last fourth pulse switches off all sections.

1.6. Configurations of switches

- *Single-pole single throw switch* – switching on and off the electric circuit at one point.

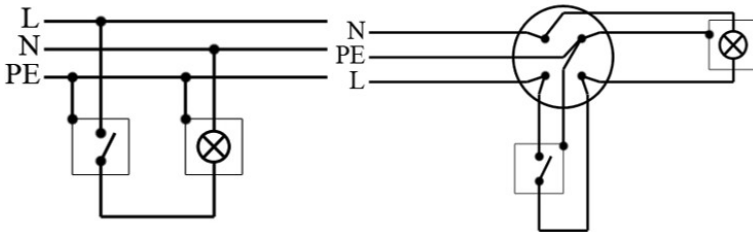


Fig. 3.4. Configurations (simplified and assembled) of a single-pole single throw switch [3]

- *Double-pole single throw switch* – switching on and off two circuits at one point.

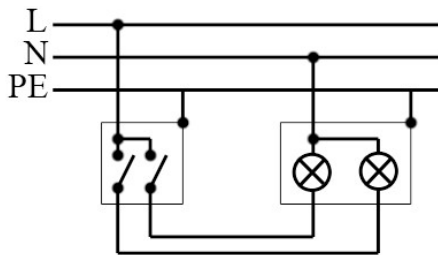


Fig. 3.5. Configurations (simplified) of a double-pole single throw switch [3]

- *Two-way light switch* – switching on and off the circuit from two points.

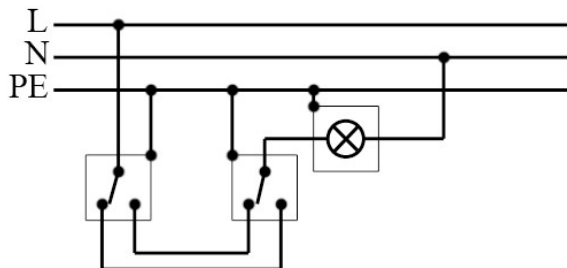


Fig. 3.6. Simplified configuration of two-way light switch

- *Four-way switch* – switching on and off the circuit at three or more points.

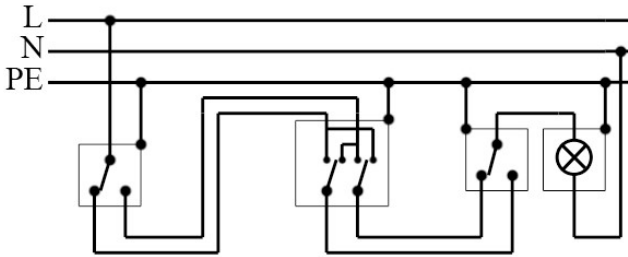


Fig. 3.7. Simplified configuration of four-way switch [3]

- *Push button switch* – switching on and off the circuit from any number of points using a bistable relay.

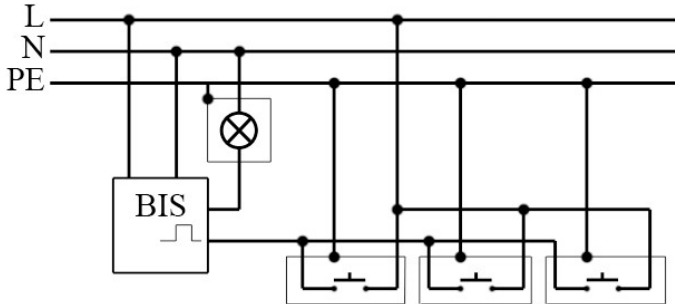


Fig. 3.8. Simplified configuration of push button switch [3]

- *Fluorescent lamp* (traditional construction - without frequency conversion)
The switching system of the fluorescent lamps includes: tube of fluorescent lamp (R_s), starter (Z) and magnetic stabilizer (D).

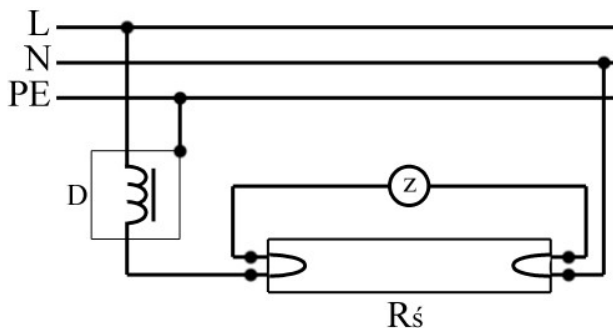


Fig.3.9. Scheme of fluorescent lamp configuration [4]

- Tungsten halogen lamp

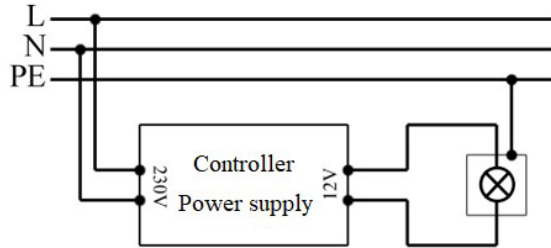


Fig. 3.10. Scheme of tungsten halogen lamp configuration [3]

- *Automatic staircase light switch* – device used to switch off the power after a specified (set) time.

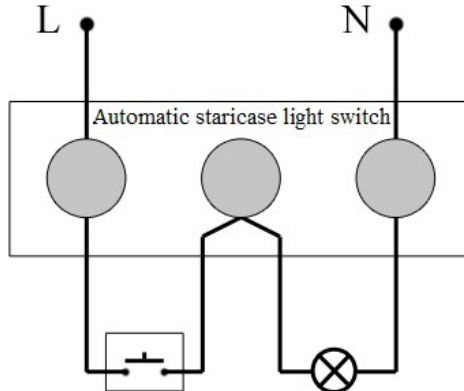


Fig. 3.11. Scheme of automatic staircase light switch configuration [3]

2. Purpose and scope of exercise

The intent of the exercise is to acquaint students with different types of electrical installations, their structure and the basic rules for connecting lighting installations.

The scope of the exercise includes the assembly of selected lighting control systems together with the observation of the principles of operation of respective circuits.

3. Experiment process

3.1. Description of the test stand

Figures 3.12 and 3.13 show the view of the front and switching plates of the station.

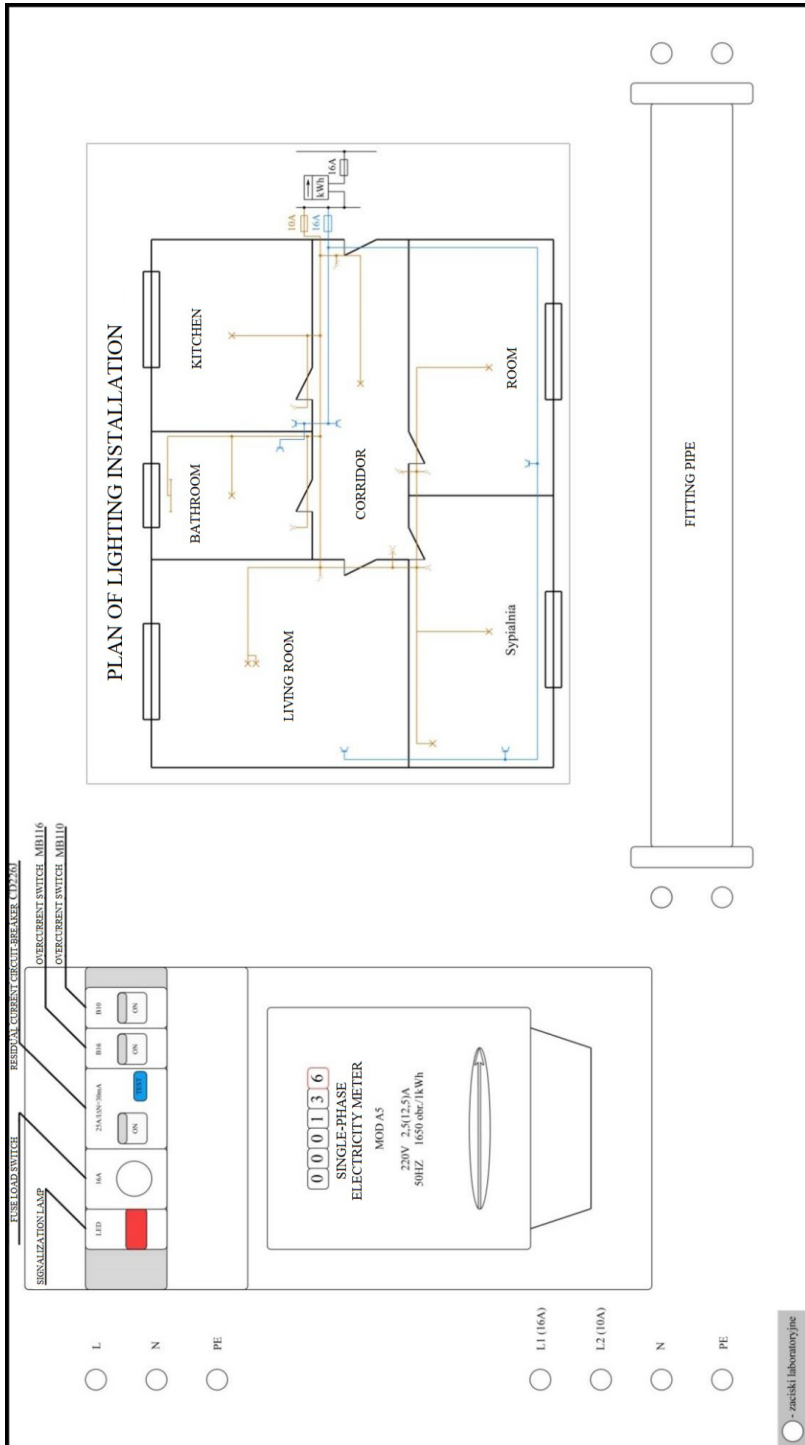


Fig. 3.12. Scheme of the front plate of the laboratory station

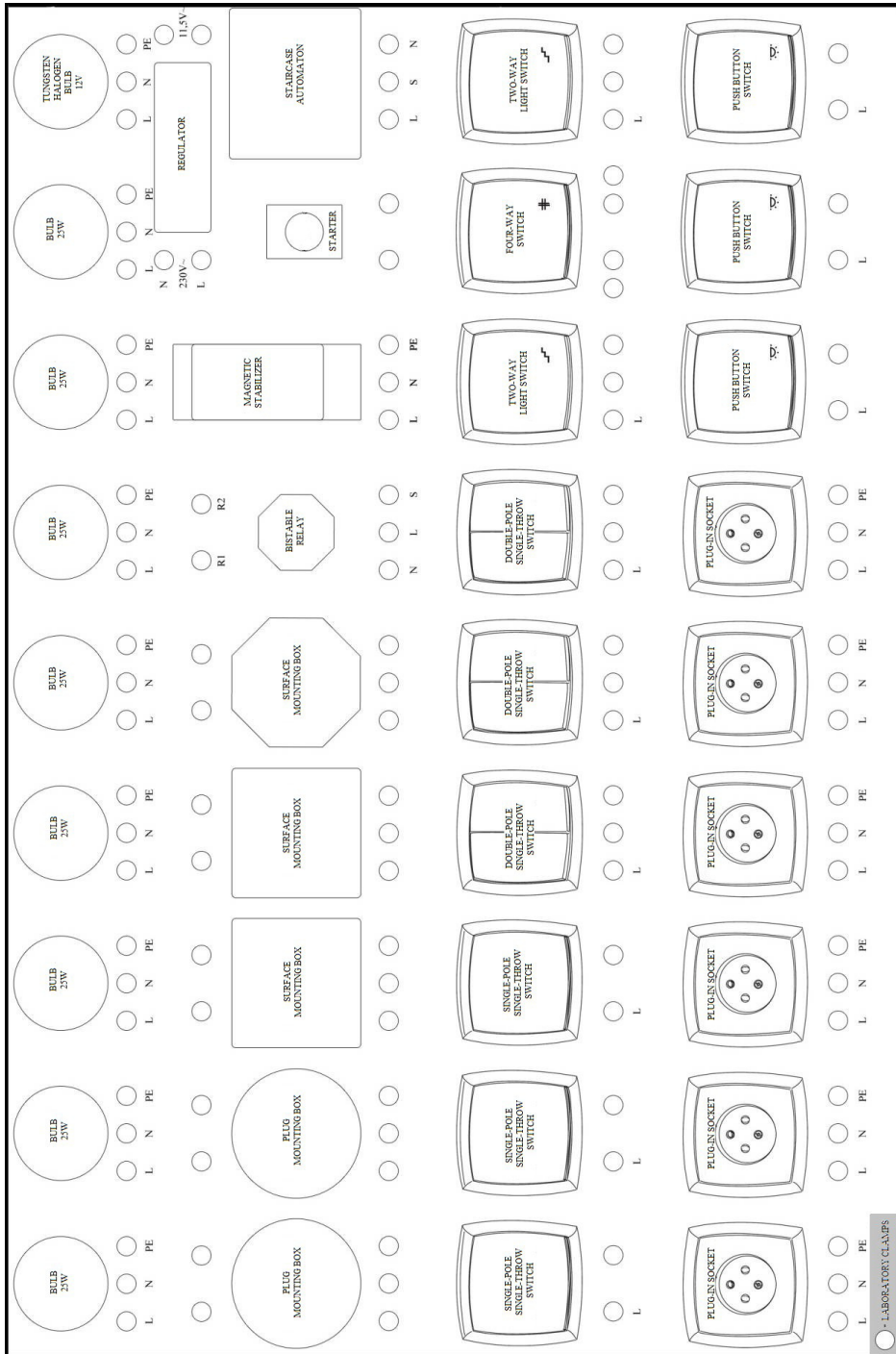


Fig. 3.13. Scheme of switching plate of laboratory station

The realization of the exercise consists in drawing the assembly diagram and connection (using the junction boxes) controls system, indicated by the instructor, of the selected light sources.

4. Student report

The report on the exercise should contain:

- connection diagrams (assembly and assembly simplified) of the systems performed during the exercise,
- description of the intended of the assembled systems, with an allocation of where they are extensively used,
- description of the principle of operation of the starter that is part of the fluorescent lamp system,
- description of the functions of the respective elements included in the fluorescent lamp and the principles of operation of this system,
- description of the principle of operation of the automatic staircase light system,
- analysis of systems performed in the exercise,
- conclusions.

5. References

1. Electrical installation guide. According to IEC international standards. Schneider Electric S.A. 2013.
2. Seip G.G.: Electrical Installations Handbook. John Wiley and Sons. Third Edition, 2000.
3. Electrical Engineer's Guidebook, collective work, WNT publishing house, Warsaw 1997 and later editions [in Polish].
4. Patterson E.G.: Lighting Systems. Thomson Learning, London, 2001.
5. DiLouie C.: Advanced Lighting Controls: Energy Savings, Productivity, Technology and Applications. The Fairmont Press, Inc., Lilburn, 2006.

Exercise no. 4

CONTROL OF INDUCTION MOTOR WITH CONTACTORS

1. Introductory information

1.1. Construction and operation principle of the contactor switches

The main technical parameters on the basis of which electrical contactors are selected are [2]:

- power of receiver and its characteristics - the higher power of receiver, the larger overall dimension of contactor. The characteristic of the contactor switch depends on the currents being switched on. The most common types are AC-1 (load with low inductance), AC-2 (slip-ring induction motors) and AC-3/4 (cage induction motors),
- nominal voltage of the contactor - the voltage on which the main contacts of the contactor were built for long-term operation,
- voltage of the control system - the voltage to which the contactor coil was built (DC or AC). Most often the contactor coils are built for voltages: 24, 48, 110, 230 and 400 V,
- admissible switching frequency - number of cycles prearranged for one hour of work.

The contactor switch consists of several basic elements (fig. 4.1) [1]:

- electromagnet with movable jumper,
- contacts of main circuit,
- contacts of control circuit – make (NO interlock) and break (NC interlock),
- quench chamber,
- insulating basis.

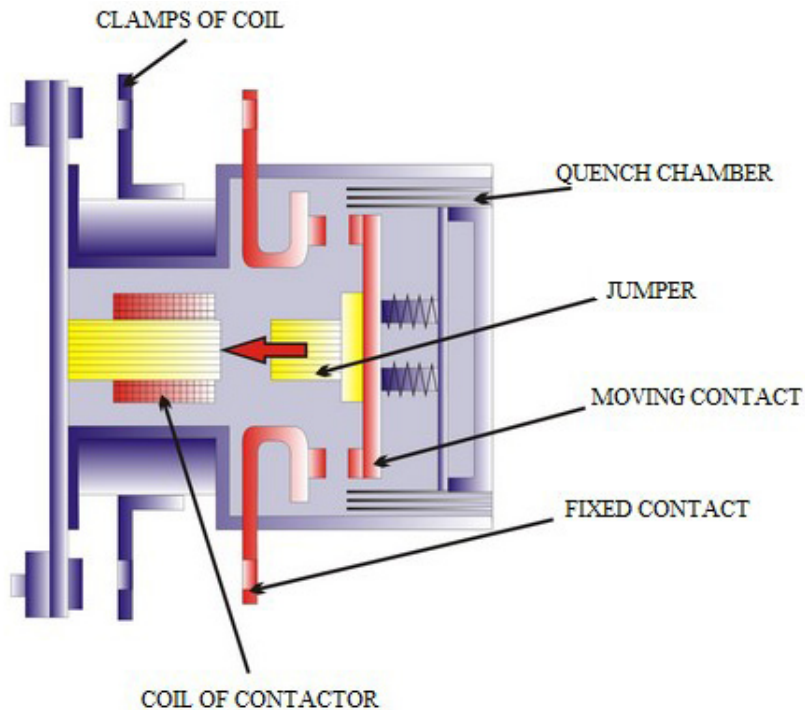


Fig. 4.1. Construction of an electromagnetic contactor [5]

The operational principle of the contactor is based on supplying the nominal voltage of the contactor coil of the electromagnet, which causes - for the time of supplying the coil - the change of the position of the movable contacts of the main circuit (closing of the main contacts of the contactor). When there is a power failure of the coil, the return of the movable contacts to the initial position occurs due to the turning springs. Contactor switches are used to switch on and off operational and no-load currents. Due to the lack of capability of switching off short-circuit currents, the contactor should be protected by overcurrent protection [3].

Quench chambers in the contactor are used to interrupt the arc, which can occur when the main contacts under load are disconnected. The construction of the quench chambers depends primarily on the intensity of the current flowing through the main contacts. With negligible load currents, the quench chamber acts as an insulating cover, protecting the system against ground and phase-to-phase faults. At high switching currents, the quench chambers are equipped with transverse shutters (steel or copper).




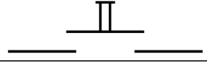




The main advantage of contactor switches is the ability to remotely control them from many places located both at the machine and at some distance from




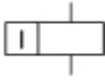
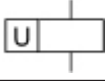


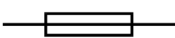





it. In addition, contactors have the capability to prevent autoreclosing of the circuit (e.g. after the supply voltage returns), which may be inadvisable for safety or technological reasons.

The contactors are used primarily in control systems, which can be divided into available (manual) and self-acting (automatic). Manual control is based on direct or indirect (remote) human intervention on the devices controlling the operation of the receiver. Self-acting control depends on the operation of control devices depending on changes in the value of specific physical quantities (e.g. time, temperature, voltage).

Control systems of electric motors can be shown in the form of varied schemes and plans, among which the most popular are functional diagrams, presented in a compact and expanded form. Electrical diagrams in compact form are used in low-complexity circuits. Whereas diagrams in the expanded form should be used in more complex systems. In practice, the main circuits are usually represented in compact form, and control circuits - in the expanded form. This helps in understanding the operation of the system and the correct reading used in a given connection system. All connections in the diagrams are drawn with single lines, and the names of the respective electrical apparatus are replaced by electric symbols. Examples of graphic symbols used in control systems are presented in table 4.1.

Table 4.1. Examples of graphic symbols used in electrical diagrams [3,4,5]

O.n.	Name	Symbol
Switches' contact:		
1.	a) make (normal open)	
	b) break (normal closed)	
	c) change-over	
	d) handy driven make contact	
	e) handy driven break contact	
	f) handy driven make contact button with self-acting back	
	g) handy driven break contact button with self-acting back	
2.	Break contact of the thermal electric relay	

O.n.	Name	Symbol
3.	Three-pole switch	
4.	Contactor coil:	
	a) general symbol	
	b) AC current's coil	
	c) current's coil	
	d) voltage's coil	
	f) time's coil	
5.	Driven system of the thermal electric relay	
6.	Switch-fuse	
7.	Bell button	
8.	Indicating lamp (general symbol)	
9.	Motor:	
	a) general symbol	
	b) three-phase asynchronous motor with shaded rotor	
c) three-phase asynchronous motor with slip-ring rotor		

2. Selected control systems of electric motors by contactors

2.1. Control of a single induction motor

Starting or stopping the induction motor in the system presented in fig. 4.2 is carried out by pressing the button Pz (switching on) or Pw (switching off), but after releasing the pressure on these buttons, they return to the earlier positions.

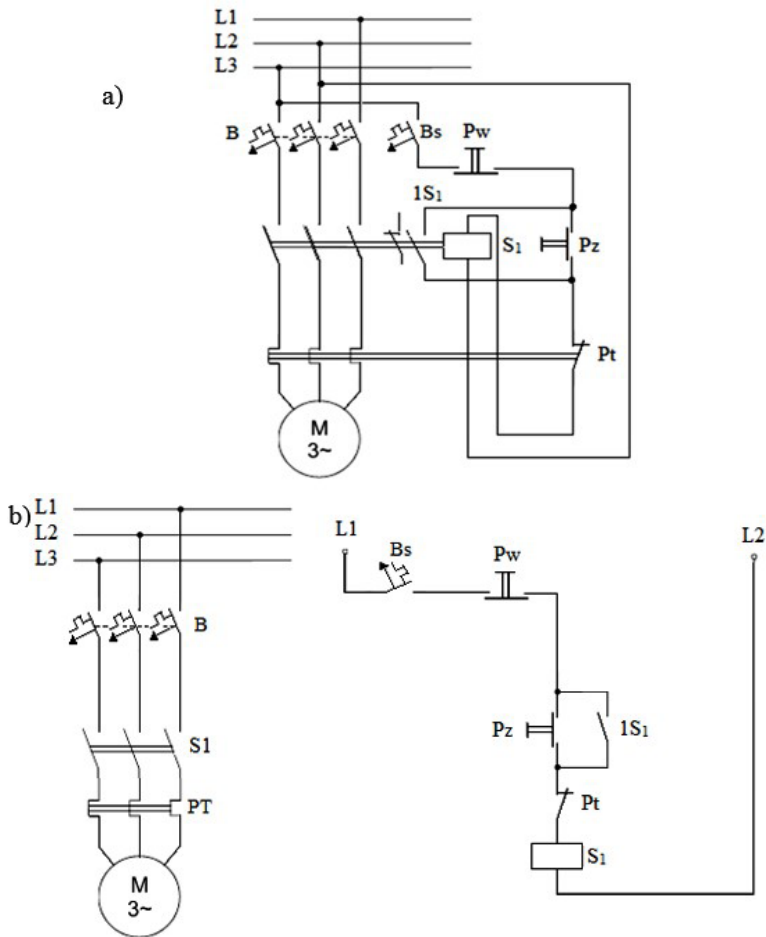


Fig. 4.2. The control diagram of the induction motor by a contactor switch is presented in the form: (a) compact, (b) expanded. Bs – overcurrent switch, Pw – switch off button, Pz – switch on button 1S1 – make auxiliary contact, Pt – auxiliary contact of thermal relay

2.2. Control of the induction motor by a contactor switch of a sense of rotation

After pressing the switch on the Pz_1 button, the contactor $S1$ is activated, which causes the rotor of the induction motor to rotate to the left (fig. 4.3). Starting the motor in the opposite direction of rotation is possible only after the $S1$ contactor has been switched off by pressing the Pw button and switching off the Pz_2 button. Then the motor's rotor should rotate in the opposite direction from the previous one (rotate to the right).

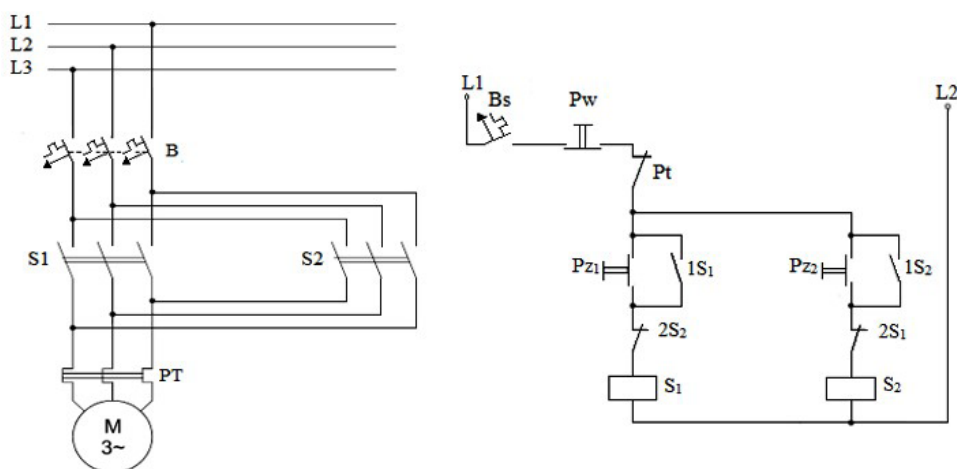


Fig. 4.3. Control diagram of the motor by a contactor switch of a sense of rotation: Bs – overcurrent switch, Pw – switch off button, Pt – auxiliary contact of thermal electric relay, Pz_1 – switch on button of contactor no. 1, Pz_2 – switch on button of contactor no. 2, $1S_1$, $2S_1$ – auxiliary contact of contactor no. 1, $1S_2$, $2S_2$ – auxiliary contact of contactor no. 2, S_1 , S_2 – coils of contactors

2.3. Control of the induction motor by a contactor switch in a delta-star configuration

By pressing the turn on Pz button, the contactor $S3$ is activated, at the same time closes the auxiliary contact $1S_3$ and opens the auxiliary contact $2S_3$ (the stator winding of the motor is connected in a star). The consequence is the operation of the PC time relay, which begins to measure the previously set delay time. At the same time, contactor $S1$ is activated, which joins the contacts at the main circuit and starts the electric motor. A short circuit in the system is protected

by a break contact $2S_3$, which prevents the contactor S2 from being switched on at the same time. After setting elapsed time in the PC relay the contact 1 opens, which interrupts the contactor circuit S3. The result is the return of the $2S_3$ contact to the make position, and because the S1 contact is also powered, contactor S2 is switched on. The stator winding of the electric motor is switched from star to delta. The motor works with the nominal power. To turn off the motor, press the Pw button.

The star/delta switch can be used to limit the starting current of the motor.

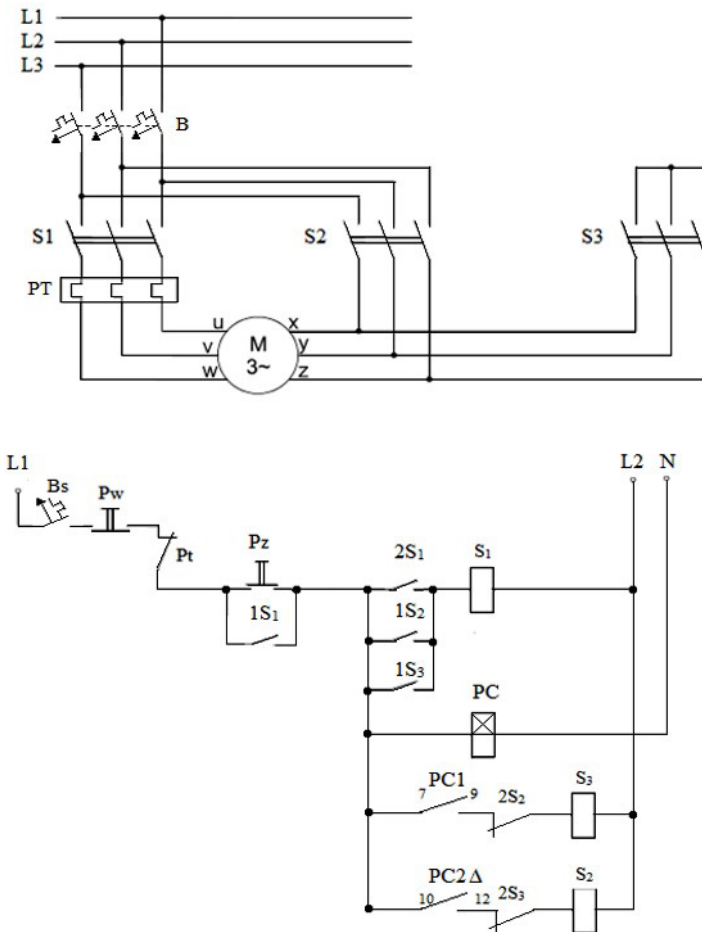


Fig. 4.4. Control diagram of the induction motor by a contactor switch in a delta-star configuration: Bs – overcurrent switch, Pw – switch off button, Pt – auxiliary contact of the thermal relay, Pz – switch on button, $1S_1$, $2S_1$ – auxiliary contacts of contactor no. 1, $1S_2$, $2S_2$ – auxiliary contacts of contactor no. 2, $1S_3$, $2S_3$ – auxiliary contacts of contactor no. 3, PC1 contact of time relay switching on star configuration, PC2 – contact of time relay switching on delta configuration, PC – coil of time relay, S_1 , S_2 , S_3 – coils of contactors

2.4. Control of the induction motor in a cascaded system

The first motor is turned on by pressing the Pz_1 button, by closing the electrical circuit and connecting the main contacts and the auxiliary contact $1S_1$ (ensuring the flow of electric current through the electrical circuit despite opening the contact of the Pz_1 button). The second motor turns on in the same way as the first one. In order to turn off the electric motors, the circuit should be interrupted by the switch off Pw_1 button, which will open the contacts of the main contactors $S1$ and $S2$ (fig. 4.5).

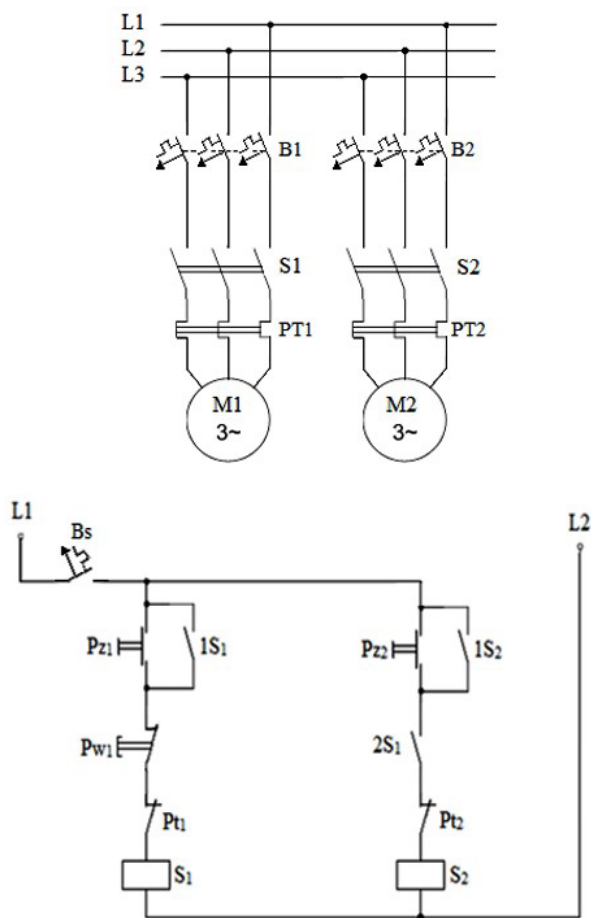


Fig. 4.5. Control diagram of the induction motor in a cascaded system: Bs – overcurrent switch, Pw_1 – switch off button, Pz_1 – switch on button of contactor no. 1, Pz_2 – switch on button of contactor no. 2, $1S_1$, $2S_1$ – auxiliary make contacts of contactor no. 1, $1S_2$ – auxiliary make contact of contactor no. 2, Pt_1 , Pt_2 – auxiliary contacts of thermal relay no. 1 and no. 2, S_1 , S_2 – coils of contactors

3. Purpose and scope of exercise

The intent of the exercise is to familiarize with the construction and operation of contactors and with the simple control systems of induction motors by contactors. The exercise includes designing and constructing control systems set by the instructor.

4. Experiment process

4.1. Construction of laboratory stand

The laboratory stand is used to test cage induction motors by powers and currents of not higher than 4 kW and 10 A.



Fig. 4.6. Front panel of the laboratory stand

4.2. Accomplishment of exercise

During the exercise, design, connect and start the control systems indicated by the instructor.

5. Student report

The report on the exercise should contain:

- purpose and scope of exercise,
- description of the test stand and used electric motors,
- diagrams of designed and constructed electrical systems,
- analysis of the principle of operation of respective systems,
- analysis of the advantages and disadvantages of respective systems with an indication of possible ways to eliminate these defects,
- conclusions.

6. References

1. VandenBurg R., Flokstra R.: Electricity and Electrical Devices, Ontario Alliance of Christian Schools, 2009.
2. Bayliss C., Hardy B.: Transmission and Distribution Electrical Engineering, Third edition, Elsevier, Oxford 2007.
3. Bhattacharya S. K.: Control Of Electrical Machines, New Age International, Delhi 2003.
4. Stephen L. Herman: The Complete Lab Manual for Electricity. Third edition, Delmar, 2009.
5. Industry websites.

Exercise no. 5

STUDY OF CURRENTS AND POWER LOAD FLOW IN ELECTRICAL POWER SYSTEMS

1. Introductory information

1.1. Types of electric power systems

The power system is a combination of fundamental network components, such as power stations and power lines. They should be combined in such a way that the created system provides the consumers with an appropriate level of reliability of electricity supply of an appropriate quality. There are four basic types of network systems: radial, series, loop-in and meshed [1].

The radial system (fig. 5.1) is characterized by the fact that each receiver is supplied from a separate branch of the electricity system. In this case, single- and multistage radial systems are distinguished. The main advantage of radial systems is clearness and simplicity. However, the disadvantages include, above all, low reliability, which means that they are used in systems that are not require – inter alia – high power stability.

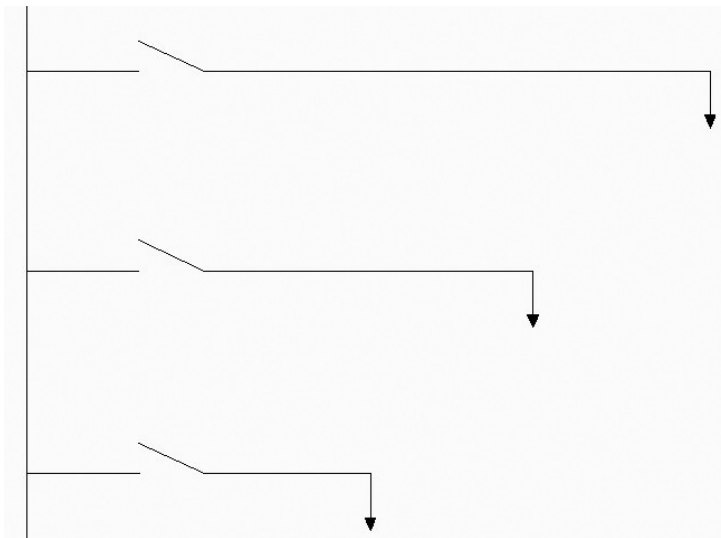


Fig. 5.1. Diagram (single-line) of a radial system [1]

The simplest series system consists of a single line, to which several loads are connected (fig. 5.2). These systems are characterized by a low price compared to radial systems and very low reliability.

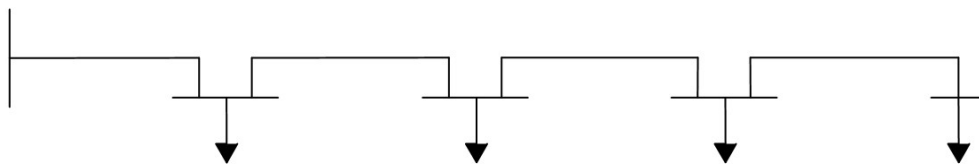


Fig. 5.2. Diagram of a series system [1]

The loop-in system is characterized by supplying consumers from both sides. It is created the so-called a loop in which electricity is supplied from one point (fig. 5.3a) or from two different power stations (fig. 5.3b). Most often, the system works as a separated at the natural point of a split of the system. If radio-controlled disconnectors are installed in the system, it is possible to remotely select (depending on needs) the system partition point - this is mainly used to guarantee customer power supply in cases of system segment failure or in instances of planned repairs. During the occurrence of the disturbance, the split is made in a place allowing to eliminate the damaged section, while maintaining supply in the „healthy” parts of the system. The ring system is characterized by high reliability.

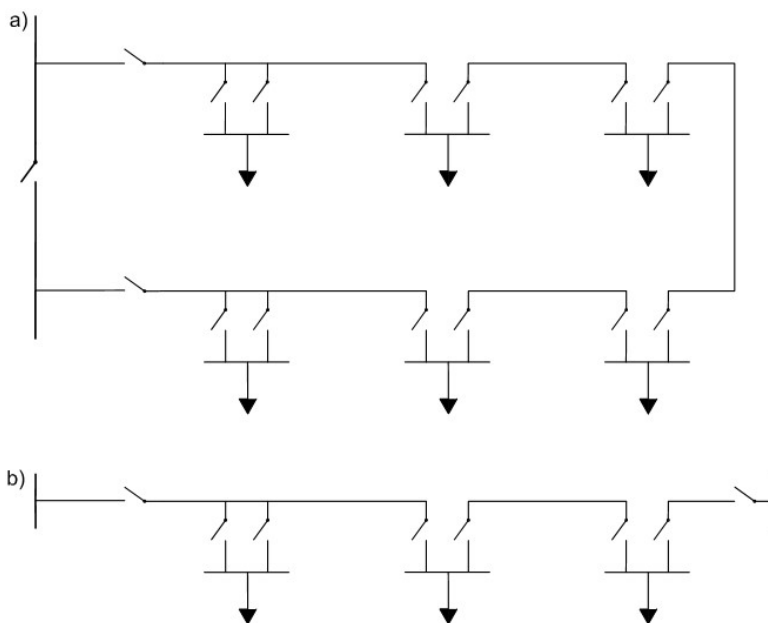


Fig. 5.3. Diagram of a loop-in system supplying from: a) one station, b) two stations [2, 3]

Meshed systems are distinguished by the supply of electricity from two sides of a section of the installation. An example of such a solution is the ring system (fig. 5.4).

Distinguishing features of the meshed system:

- very high reliability factor,
- low voltage drops (in standard situations),
- low level of power losses,
- risk of spreading the disturbance,
- the need for more advanced protection,
- usually more accurate damping capabilities of electromechanical fluctuation (improvement of stability) and preservation of wider ranges (reserve) of voltage stability.

Meshed systems, due to high installation costs, are used in systems where electrical reliability is the most important.

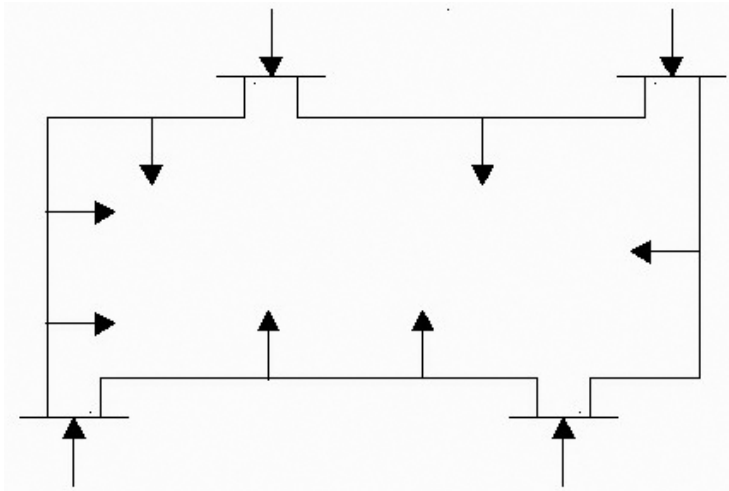


Fig. 5.4. Diagram of a meshed system [3]

1.2. Currents and power load flow in electrical power systems

Understanding of the load flow of currents and power in electrical power systems allows not only to maintain the stability of the system but also to determine the value of voltage drops and power losses in respective elements of the system, as well as allows to analyze the costs of losses.

To calculate the flow of currents in power lines, we should know the currents at the consumption points. Most often the consumptions are determined by the power value, and the calculations should be based on the voltage actually present at respective consumption points (due to the accuracy of the calculations). Because in practice the voltage is usually not known, (due to voltage drops along energy transmission paths), the nominal voltage of system is usually used for calculations, and the results obtained in this way are sufficiently accurate for practical purposes. In high voltage networks, apart from the difference in node voltage modules, there are anomalies in arguments of the complex voltage of a node..

The load flow of currents in a radial system loaded at multiple points is determined by the first law of Kirchoff, regarding the balance of currents in the circuit node. The principle of determining the load flow in a line powered from a single-sided, loaded at many points, is presented in fig. 5.5.

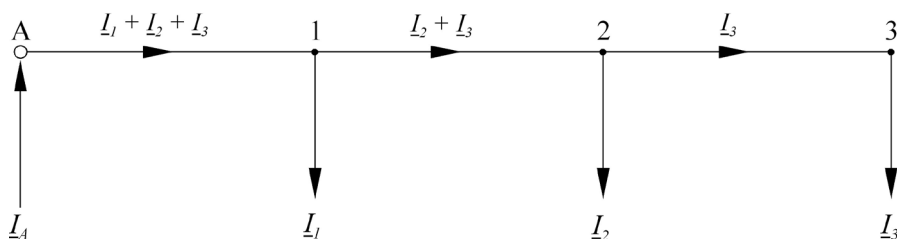


Fig. 5.5. Load flow of currents in a radial circuit loaded at many points [3]

$$I_A = I_{A1} = I_1 + I_2 + I_3 \quad (5.1)$$

$$I_{12} = I_2 + I_3 \quad (5.2)$$

$$I_{23} = I_3 \quad (5.3)$$

In the same way, the power load flow is determined in such a system (fig. 5.6).

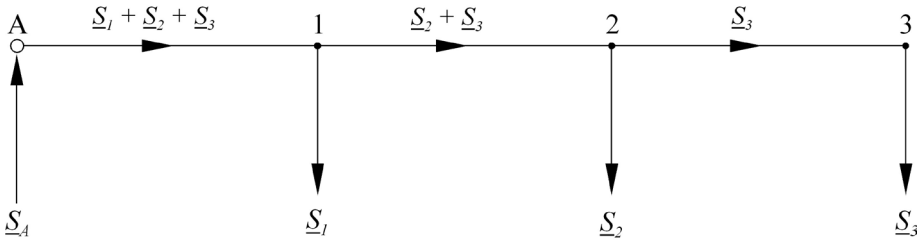


Fig. 5.6. Power load flow in radial circuit loaded at many points [3]

$$\underline{S}_A = \underline{S}_{A1} = \underline{S}_1 + \underline{S}_2 + \underline{S}_3 \quad (5.4)$$

$$\underline{S}_{12} = \underline{S}_2 + \underline{S}_3 \quad (5.5)$$

$$\underline{S}_{23} = \underline{S}_3 \quad (5.6)$$

1.3. Drop and loss of voltage in the electric power system

Voltage drop is the algebraic difference of voltage absolute values at the beginning and end of the considered electric power system. In the instance of a difference in phase voltages, this is a decrease in the phase voltage (ΔU_p), and in the case of a difference in line (phase-to-phase) values it is a line voltage drop (phase-to-phase) (ΔU), described by the following expressions:

$$\Delta U_f = U_{fp} - U_{fk} \quad (5.7)$$

$$\Delta U = U_p - U_k \quad (5.8)$$

where:

U_{fk} , U_k – absolute values of the phase and line voltage at the end of the electric power system,

U_{fp} , U_p – absolute values of the phase and line voltage at the beginning of the electric power system.

In the instance of branch systems (in low voltage networks, when longitudinal impedances can be treated as pure resistive, and branch reactive powers as negligible small.) loaded at many points, the voltage drop is determined by the relationships [3, 4]:

- for single-phase systems:
 - segment method:

$$\Delta U_f = 2 \cdot \sum_{p=1}^n I_{(p-1),p} \cdot R_{(p-1),p} \quad (5.9)$$

$$\Delta U_f = \frac{2}{\gamma \cdot S} \cdot \sum_{p=1}^n I_{(p-1),p} \cdot l_{(p-1),p} \quad (5.10)$$

$$\Delta U_{f\%} = \frac{200}{\gamma \cdot S \cdot U_f} \cdot \sum_{p=1}^n I_{(p-1),p} \cdot l_{(p-1),p} \quad (5.11)$$

- moments method:

$$\Delta U_f = 2 \cdot \sum_{p=1}^n I_p \cdot R_{A,p} \quad (5.12)$$

$$\Delta U_f = \frac{2}{\gamma \cdot S} \cdot \sum_{p=1}^n I_p \cdot l_{A,p} \quad (5.13)$$

$$\Delta U_{f\%} = \frac{200}{\gamma \cdot S \cdot U_f} \cdot \sum_{p=1}^n I_p \cdot l_{A,p} \quad (5.14)$$

- for three-phase systems (phase symmetry of a voltage and conformity of currents in-phase):
 - segment method:

$$\Delta U_f = \sum_{p=1}^n I_{(p-1),p} \cdot R_{(p-1),p} \quad (5.15)$$

$$\Delta U_f = \frac{1}{\gamma \cdot S} \cdot \sum_{p=1}^n I_{(p-1),p} \cdot l_{(p-1),p} \quad (5.16)$$

$$\Delta U_{f\%} = \frac{100}{\gamma \cdot S \cdot U_f} \cdot \sum_{p=1}^n I_{(p-1),p} \cdot l_{(p-1),p} \quad (5.17)$$

- moments method:

$$\Delta U_f = \sum_{p=1}^n I_p \cdot R_{A,p} \quad (5.18)$$

$$\Delta U_f = \frac{1}{\gamma \cdot S} \cdot \sum_{p=1}^n I_p \cdot l_{A,p} \quad (5.19)$$

$$\Delta U_{f\%} = \frac{100}{\gamma \cdot S \cdot U_f} \cdot \sum_{p=1}^n I_p \cdot l_{A,p} \quad (5.20)$$

Voltage loss is the geometrical difference of voltages vectors at the beginning and end of the considered electrical power system. In the instance of difference in phase voltages vectors, this is a phase loss (ΔU_p), in the instance of a differential at line voltages (phase-to-phase) it is a line (phase-to-phase) loss (ΔU):

$$\Delta \underline{U}_f = \underline{U}_{fp} - \underline{U}_{fk} \quad (5.21)$$

$$\Delta \underline{U} = \underline{U}_p - \underline{U}_k \quad (5.22)$$

where:

\underline{U}_{fk} , \underline{U}_k – phase and line voltage at the end of the electric power system,

\underline{U}_{fp} , \underline{U}_p – phase and line voltage at the beginning of the electric power system.

In the instance of branch systems loaded at many points, the voltage loss is determined by the relationships [3, 4]:

- for single-phase systems:
 - segment method:

$$\Delta \underline{U}_f = 2 \cdot \sum_{p=1}^n I_{(p-1),p} \cdot R_{(p-1),p} \quad (5.23)$$

$$\Delta \underline{U}_f = \frac{2}{\gamma \cdot s} \cdot \sum_{p=1}^n I_{(p-1),p} \cdot l_{(p-1),p} \quad (5.24)$$

$$\Delta \underline{U}_{f\%} = \frac{200}{\gamma \cdot s \cdot U_f} \cdot \sum_{p=1}^n I_{(p-1),p} \cdot l_{(p-1),p} \quad (5.25)$$

- moments method:

$$\Delta \underline{U}_f = 2 \cdot \sum_{p=1}^n I_p \cdot R_{A,p} \quad (5.26)$$

$$\Delta \underline{U}_f = \frac{2}{\gamma \cdot s} \cdot \sum_{p=1}^n I_p \cdot l_{A,p} \quad (5.27)$$

$$\Delta \underline{U}_{f\%} = \frac{200}{\gamma \cdot s \cdot U_f} \cdot \sum_{p=1}^n I_p \cdot l_{A,p} \quad (5.28)$$

- for three-phase systems (phase symmetry of a voltage and conformity of currents in-phase):
 - segment method:

$$\Delta \underline{U}_f = \sum_{p=1}^n \underline{I}_{(p-1),p} \cdot R_{(p-1),p} \quad (5.29)$$

$$\Delta \underline{U}_f = \frac{1}{\gamma \cdot S} \cdot \sum_{p=1}^n \underline{I}_{(p-1),p} \cdot l_{(p-1),p} \quad (5.30)$$

$$\Delta \underline{U}_{f\%} = \frac{100}{\gamma \cdot S \cdot U_f} \cdot \sum_{p=1}^n \underline{I}_{(p-1),p} \cdot l_{(p-1),p} \quad (5.31)$$

- moments method:

$$\Delta \underline{U}_f = \sum_{p=1}^n \underline{I}_p \cdot R_{A,p} \quad (5.32)$$

$$\Delta \underline{U}_f = \frac{1}{\gamma \cdot S} \cdot \sum_{p=1}^n \underline{I}_p \cdot l_{A,p} \quad (5.33)$$

$$\Delta \underline{U}_{f\%} = \frac{100}{\gamma \cdot S \cdot U_f} \cdot \sum_{p=1}^n \underline{I}_p \cdot l_{A,p} \quad (5.34)$$

1.4. Power loss in an electric power systems

Power losses are a negative phenomenon in electrical power systems because they cause additional loads on respective components of the system and the need to create additional energy in power plants. It causes the need to install additional devices in systems and power plants, increase the cross-sections of wires and cables in power lines and nominal power of transformers, turbines, and generators and force the use of more fuel in power plants, which entails increased costs of electricity generation and transmission. In the AC systems, there is flow and losses of active and reactive power.

The active power losses occur in the resistive elements of the system, and the reactive power losses in the reactance elements (inductive or capacitive). Energy losses occur only in resistive elements (however, the existence of reactive power raises line's current modules, so it increases (to some extent) energy losses).

The active power losses (ΔP) in a branch system loaded at multiple points are determined from the relationships:

- for single-phase systems:

$$\Delta P = 2 \cdot \sum_{p=1}^n I_{(p-1),p}^2 \cdot R_{(p-1),p} \quad (5.35)$$

$$\Delta P = \frac{2}{\gamma \cdot S} \cdot \sum_{p=1}^n I_{(p-1),p}^2 \cdot l_{(p-1),p} \quad (5.36)$$

- for three-phase systems:

$$\Delta P = 3 \cdot \sum_{p=1}^n I_{(p-1),p}^2 \cdot R_{(p-1),p} \quad (5.37)$$

$$\Delta P = \frac{3}{\gamma \cdot S} \cdot \sum_{p=1}^n I_{(p-1),p}^2 \cdot l_{(p-1),p} \quad (5.38)$$

The percentage power loss is described by the expression:

$$\Delta P_{\%} = \frac{\Delta P}{P} \cdot 100 \quad (5.39)$$

2. Purpose and scope of exercise

The intent of the exercise is to familiarize with the issues of currents and power load flow in opened line, branched, loaded at many points. The scope of the exercise includes determining the values of currents, power, power and voltage losses in respective branches of selected electric power systems.

3. Experiment process

3.1. Description of the test stand

The subject of the test is a model of a branching low voltage power system loaded at many points. The laboratory stand for testing the currents and power load flows in power systems consists of a panel and a front panel. On the front panel (fig. 5.7), models of sections of single-phase low voltage lines and capacitive loads were installed. Whereas, models of resistive and inductive loads were set on the panel (fig. 5.8).

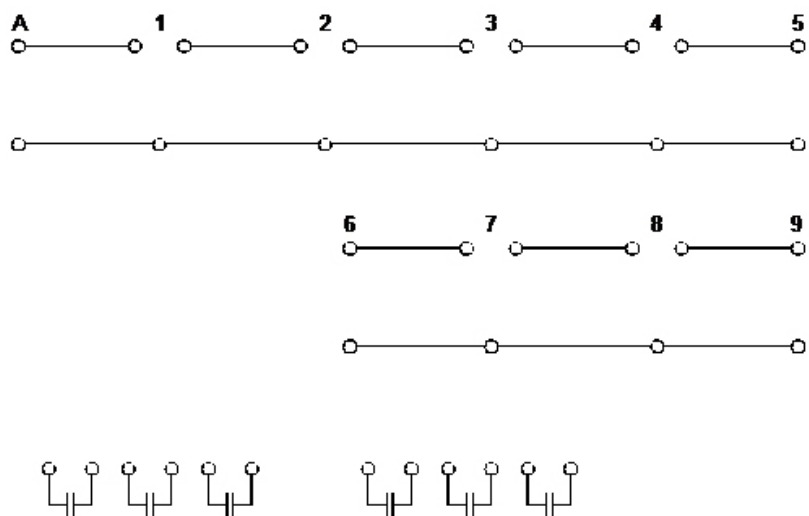


Fig. 5.7. Scheme of a front panel of the test stand

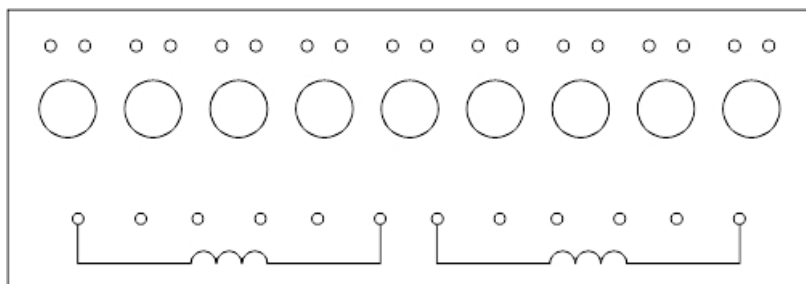


Fig. 5.8. Scheme of a panel of the test stand

The construction of the stand enables selection of any configuration of the line segment connections and their load.

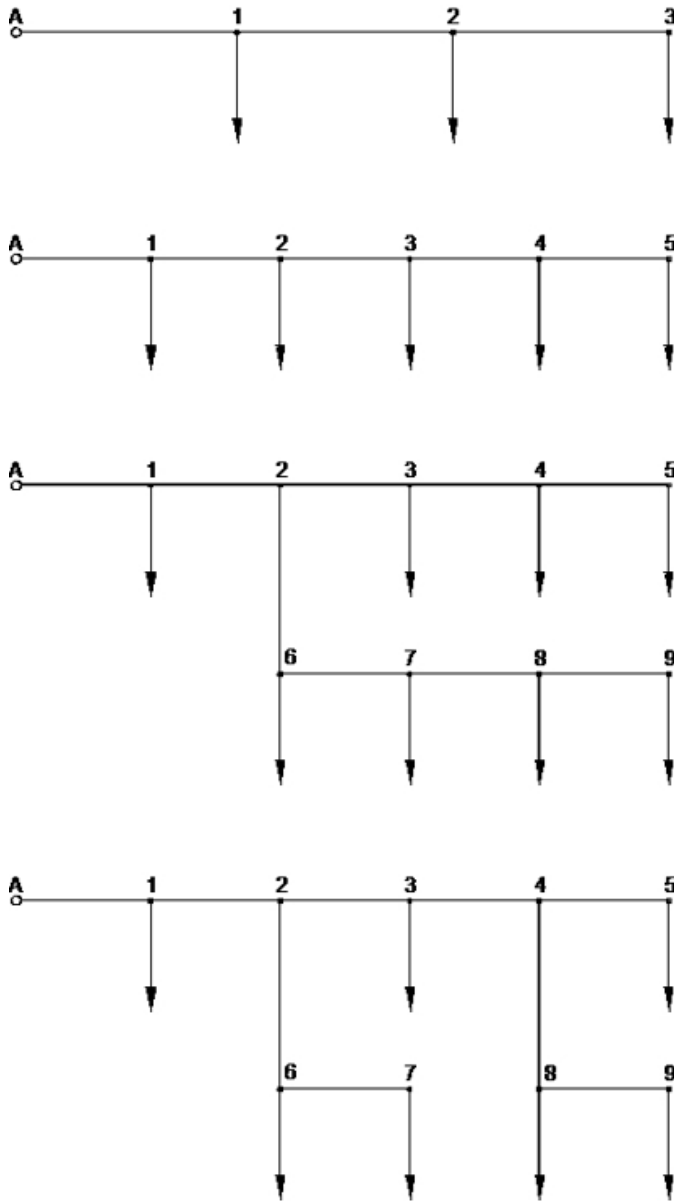


Fig. 5.9. Examples of configurations of lines section connections and their loads

3.2. Accomplishment of exercise

During the exercise:

- connect the scheme of the tested line in the configuration indicated by the instructor;
- measure the values of the fundamental electrical quantities of respective receivers, which constitute loads of the analyzed system. The results set in table 5.1.

Table 5.1. List of measured values on loads

Load no.	Load current	Active power	Reactive power	Apparent power	Power factor
	I_{load}	P_{load}	Q_{load}	S_{load}	$\cos \varphi_{load}$
	A	W	var	VA	-
1					
2					
...					

- measure the values of fundamental electrical quantities in respective segments of the analyzed line. The results set in table 5.2.

Table 5.2. List of measured values on line segments

Segment no.	Segment current	Active power	Reactive power	Apparent power	Power factor
	I_{seg}	P_{seg}	Q_{seg}	S_{seg}	$\cos \varphi_{seg}$
	A	W	var	VA	-
A-1					
1-2					
...					

- measure the values of fundamental electrical quantities in respective nodes of the analyzed line. The results set in table 5.3.

Table 5.3. List of measured values of the voltage in nodes

Node no.	Voltage
	U
	V
A	
1	
...	

- determine drops of voltages and resistance of respective line segments and set in table 5.4.

Table 5.4. List of measured values of voltages' drops at line segments

Segment no.	Voltage drop
	ΔU_{seg}
	V
A-1	
1-2	
...	

On the grounds of the results of the measurements, determine the voltage drop and power loss values for the tested line and calculate the same values theoretically based on the measured load currents and the determined resistance of respective line segments.

4. Student report

The report on the exercise should contain:

- purpose and scope of the exercise,
- diagrams of measuring systems,
- list of test results,
- calculations,
- conclusions.

In conclusions, we should pay attention to elaborate the obtained measurement results and to explain the reasons for the difference between the measurements and the results of theoretical calculations, as well as to determine the parameters on which the voltage drop and power loss values depend.

5. References

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2. Parashar M.: Continuum modeling of power networks, Cornell University, 2003.
3. Acha E., Fuerte-Esquivel C. R., Ambriz-Pérez H., Angeles-Camacho C.: Modeling and Simulation in Power Networks, John Wiley and Sons. 2004.
4. Electrical Engineer's Guidebook, collective work, WNT publishing house, Warsaw 1997 and later editions [in Polish].

Exercise no. 6

STUDY OF DROPS OF VOLTAGES IN ELECTRICAL INSTALLATIONS

1. Introductory information

In each electrical installation, it is pursued at providing that electric energy receivers work, at their activation, at a voltage as close as possible to the nominal voltage, whereby the deviation of the voltage supplied from the distribution system may not exceed $\pm 10\%$ (95% of the time per week) . In transmission lines supplying the energy receivers, the losses of the resistance of the conductors of the wire occurring. The resistance value R_L of the wire can be determined on the basis of equation [1, 2, 4]:

$$R_L = \frac{l}{\gamma \cdot s} \quad (6.1)$$

where:

l – length of wire [m];

γ – specific conductivity of wire material [$\frac{m}{\Omega \cdot mm^2}$];

s – cross-section area of the wire [mm²]

The specific conductivity of copper is (depending on the purity of the material from which the conductor is made) about $55 \frac{m}{\Omega \cdot mm^2}$, while for aluminum it is about $35 \frac{m}{\Omega \cdot mm^2}$.

The voltage drop in a single-phase line, loaded with current I of constant intensity, is determined by the expression [2, 4] (it was assumed that in addition to the longitudinal substitute resistance in the line (branch) there is also inductive longitudinal reactance, and the power charged by the load is active and reactive):

$$\Delta U = 2 \cdot I \cdot (R_L \cos \phi \pm X_L \sin \phi) \quad (6.2)$$

because:

$$\Delta U \approx 2 \operatorname{Re}[(R_L + jX_L) \cdot \frac{|S| (\cos \varphi_L + j \sin \varphi_L)^*}{U_f^*}] \quad (6.3)$$

and for the three-phase systems:

$$\Delta U = \sqrt{3} \cdot I \cdot (R_L \cos \phi \pm X_L \sin \phi) \quad (6.4)$$

because:

$$\Delta U \approx \sqrt{3} \operatorname{Re}[(R_L + jX_L) \cdot \frac{|S^{\sim}| (\cos \varphi_l + j \sin \varphi_l)^*}{3U^{(1)*}}] \quad (6.5)$$

Percentage drop of the line voltage:

$$\Delta U_{(\%)} = \frac{\Delta U}{U_n} 100\% = \frac{P R}{U_n^2} = \frac{P l}{U_n^2 s \gamma} 100\% = \frac{\sqrt{3} U_n I l \cos \varphi}{U_n^2 s \gamma} 100\% = \frac{\sqrt{3} I R \cos \varphi}{U_n} 100\% \quad (6.6)$$

Percentage drop of the phase voltage:

$$\Delta U_{f(\%)} = \frac{\Delta U_f}{U_f} 100\% = \frac{P l}{U_n^2 s \gamma} 100\% = \frac{\sqrt{3} U_n I l \cos \varphi}{U_n^2 s \gamma} 100\% = \frac{\sqrt{3} I R \cos \varphi}{U_n} 100\% \quad (6.7)$$

where:

$\Delta U_{(\%)}, \Delta U_{f(\%)}$ – percentage drop of the line/phase voltage [%],

$\Delta U, \Delta U_f$ – drop of the line/phase voltage [V],

I – current in transmission line [A],

P – load power of the line [W],

U_n – nominal voltage [V],

R – resistance of the line [Ω],

γ – specific electrical conductivity of the wire material [$\frac{m}{\Omega \cdot mm^2}$],

s – cross-section of the wire [mm^2],

l – length of the line [m],

$\cos \varphi$ – factor of the load power,

φ_1 – the complex current's argument at the value of the complex voltage of the load located on the real number axis.

In equations (2) and (3), the plus sign refers to inductive loads (e.g. induction motors), and the minus sign refers to capacitive loads (e.g. capacitors) (the current is delayed relative to the voltage or overrun to the voltage) [3].

In circuits with wires with a conductor cross-section up to 16 mm^2 , reactance can be omitted, because the resistance value of wires is more than five times higher than their reactance [4]. This simplification has no significant effect on the accuracy of the calculation results. Regarding this simplification, the voltage drop in a single-phase line is described by the following relationship:

$$\Delta U = 2 \cdot I \cdot R_L \cdot \cos \phi \quad (6.8)$$

It should be remembered that for resistive receivers (e.g. bulbs) $\cos\phi$ is approximately 1.

The too low voltage which supplying receivers may cause incorrect operation of electrical devices, which in extreme cases may contribute to their damage. In addition, voltage drops cause increased power losses, which often contributes to excessive heating of wires and electric cables.

The value of the voltage drop in the low voltage electric system depends on:

- values of current flowing through the system (power values of installed loads),
- cross-section area of a conductor (conductors) of a wire or cable,
- the material which the wire or cable conductor is made,
- total length of wires in the analyzed circuit,
- the resistance of contacts on the connections of electrical devices, and the resistance of other devices installed in the system.

The current regulations [5] require that the percentage of voltage drop in the electrical installation on the section from the supply-terminals to the load does not exceed 4% of the nominal voltage. In the literature [1, 2], there are also requirements for acceptable values of voltage drops, depending on the construction and purpose of the electrical installation (table 6.1).

Table 6.1. Acceptable percentage drops of the voltage in electrical power installations with the voltage higher than 24 V

Supply source	Acceptable voltage drop, at %, in installations supplying the loads:		
	lighting	lighting, line-to-line and (or) heating	line-to-line and (or) heating
internal power transmission line	2	2	3
system with $U_n \leq 1$ kV	4	4	6
main switchgear of plant or another source	5	7	9

The values of acceptable voltage drops may be higher than 4% for the transmission lines supplying the motors during their start-up or other receivers with a high starting current, but they should not exceed [4]:

- for the soft start-up 35%,
- for the hard and infrequent start-up (less than 15 times per hour) 15%,
- for the hard and frequent start-up (more than 15 times per hour) 10%.

The too high voltage drop values can be caused by:

- selection, at the design stage, of the wire supplying the receivers with too small cross-section area,
- connection to the system the receiver with a power greater than that for which it was designed and made,

- bad contacts of devices, a loose connection of wires, increasing the resistance of the circuit.

2. Purpose and scope of exercise

The intent of the exercise is to study the phenomenon of voltage drop in the electrical installation and its impact on the work of electricity receivers. The exercise includes determining the value of voltage drops in the electrical system depending on the voltage supplying the tested circuit and the characteristic of the load-resistive, resistive-inductive, resistive-capacitive.

3. Experiment process

3.1. Description of the laboratory stand

The subject of the study is a single-phase (two-wires) model of electrical installation working on two levels of nominal voltage: 24 V and 230 V.

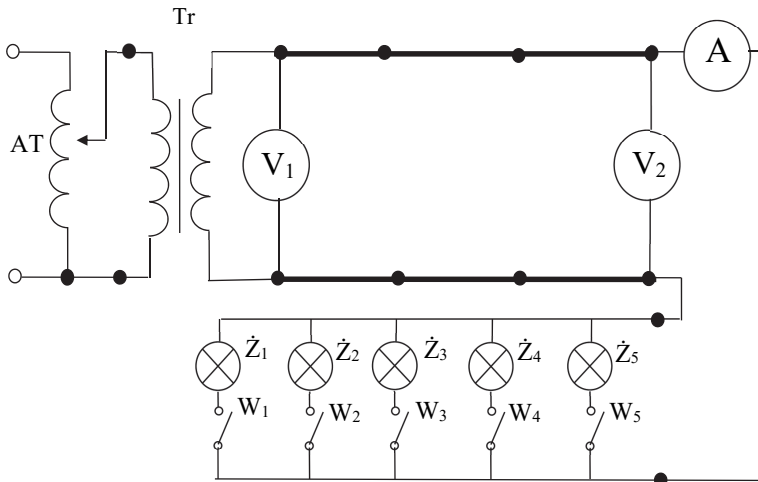


Fig. 6.1. Diagram of the measurement system for determining voltage drops in a single-phase line with a nominal voltage of 24 V.

Measurements of values of the voltage drops in the tested line with a nominal voltage of 24 V should be performed in a system whose scheme is presented in fig. 1. In this system, the model of the line (marked with a thick line) is supplied from an AT autotransformer with a voltage regulation range 0÷250 V,

through transformer lowering voltage Tr with 220/24 V ratio. The system is loaded with $\dot{Z}_1 \div \dot{Z}_5$ bulbs with a nominal voltage equal to 24 V, switched using $W_1 \div W_5$ connectors.

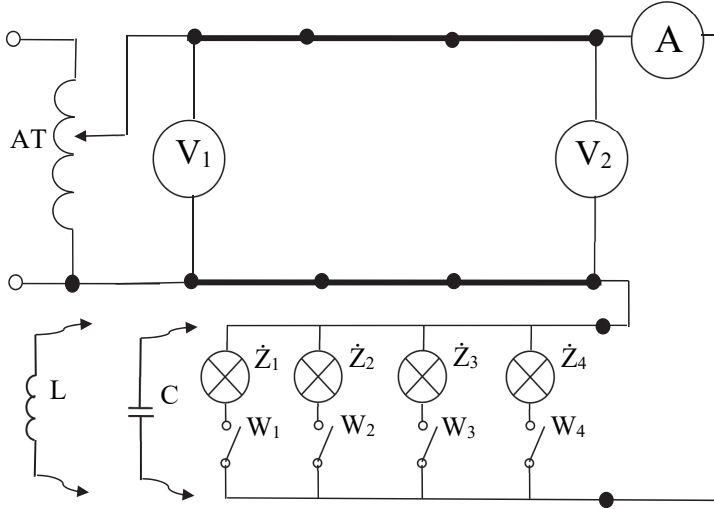


Fig. 6.2. Diagram of the measurement system for determining voltage drops in a single-phase line with a nominal voltage of 230 V.

In the case when the nominal voltage of the line is 230 V, measurements should be made in the configuration, the diagram of which is presented in fig. 6.2, as loads using:

- bulbs with a nominal voltage of 230 V,
- bulbs with a nominal voltage of 230 V with an inductive element connected in parallel (inductor),
- bulbs with a nominal voltage of 230 V with a capacitive element connected in parallel (capacitor).

When performing tests with a 230 V supply voltage, remember to include a wattmeter (with the appropriate measuring range) in the measurement system that will allow you to determine the $\cos \varphi$ occurring in the tested system.

3.2. Accomplishment of exercise

3.2.1. Testing of the line with nominal voltage of 24 V

Connect the measurement system according to the diagram shown in fig. 6.1, paying attention to the ranges of measuring instruments.

Using the autotransformer, set the voltage U_1 to the nominal value (24 V) and keep this value for the entire duration of the measurements.

Changing the load of the line - by switching on or off respective loads $\dot{Z}_1 \div \dot{Z}_5$ (using all possible (different) combinations of the total power of light bulbs) - measure the voltages at respective points of the line's measurement and the current intensity I flowing in loaded wires.

The results set in table 2.

Table 6.2. List of measured values for $U = 24 \text{ V}$

No.	Measured values							Calculated values				
	P_n	U_1	U_2	U_3	U_4	U_5	I	R_{L1-5}	ΔU_{1-5}	ΔP_{1-5}	$\Delta U_{\%}$	$\Delta P_{\%}$
	W	V	V	V	V	V	A	Ω	V	W	%	%

Assuming the average value of the resistance R_L of the wire and assuming that the wire with the cross-section $s = 2.5 \text{ mm}^2$ is made of copper, calculate the actual length of the line l .

Based on the table, prepare and discuss graphs: $\Delta U = f(I)$, $\Delta U_{\%} = f(I)$, $\Delta P = f(I)$, $\Delta P_{\%} = f(I)$.

3.2.2. Testing of the line with nominal voltage of 230 V

Connect the measurement system according to the diagram presented in fig. 6.2, paying attention to the ranges of measuring instruments.

Using the autotransformer, set the voltage U_1 to the nominal value (230 V) and keep this value for the entire duration of the measurements.

Changing the load of the line - by switching on or off respective loads $\dot{Z}_1 \div \dot{Z}_4$ (using all possible (different) combinations of the total power of light bulbs)

- measure the voltages at respective points of the line's measurement, the current intensity I flowing in loaded wires and the active power P .

Then repeat the measurements with the inductive and capacitive load connected in parallel to the system (next circuits).

The results set in table 6.3.

Table 6.3. List of measured values for $U = 230\text{ V}$

No.	Measured values							Calculated values				
	P_n	U_1	U_2	U_3	U_4	U_5	I	R_{L1-5}	ΔU_{1-5}	ΔP_{1-5}	$\Delta U_{\%}$	$\Delta P_{\%}$
	W	V	V	V	V	V	A	Ω	V	W	%	%

Assuming the average value of the resistance R_L of the wire and assuming that the wire with the cross-section $s = 2.5\text{ mm}^2$ is made of copper, calculate the actual length of the line l .

Based on the table, prepare and discuss graphs: $\Delta U = f(I)$, $\Delta U_{\%} = f(I)$, $\Delta P = f(I)$, $\Delta P_{\%} = f(I)$.

4. Student report

The report on the exercise should contain:

- purpose and scope of exercise,
- diagrams of measuring systems,
- list of experiments' results,
- calculations and diagrams,
- conclusions.

The conclusions should notice to the discussion of the diagrams obtained diagrams based on accomplished measurements, as well as to circumscribe the parameters on which the voltage drop value depends.

5. References

1. Lejdy B.: Electrical installations in buildings, WNT publishing house, Warsaw 2015 [in Polish].
2. Seip G.G.: Electrical Installations Handbook. John Wiley and Sons. Third Edition, 2000.

3. Atkinson B., Lovegrove R., Gundry G.: Electrical Installations Designs. John Wiley and Sons. Fourth Edition, 2013.
4. Electrical Engineer's Guidebook, collective work, WNT publishing house, Warsaw 1997 and later editions [in Polish].
5. IEC 60364-5-52:2011 Low-voltage electrical installations - Part 5-52: Selection and erection of electrical equipment - Wiring systems

