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NU “ZAPORIZHZHYA POLYTECHNIC”

METHODICAL INSTRUCTIONS
for independent work and implementation of
calculation-graphic work in theoretical electrical engineering
"The linear circuits of direct current"
for the students of specialty 141

2020

Methodical Instructions for for independent work and implementation of calculation-graphic work in theoretical electrical engineering "The linear circuits of direct current" for the students of specialty 141/Authors: Kozlov V.V., Nabokova O.V. – Zaporizhzhya: NU "ZAPORIZHZHIA POLYTECHNIC", 2020. – 22 p.

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1 COMMON INSTRUCTIONS

One must acquire knowledge of electric circuit analysis, in other words, a proficiency in carrying out a mathematical study of various types of interconnections of electric elements having paths for the flow of electric current. Electric circuit analysis not only aids us in pursuing further studies in electrical engineering but also broadens our scope and helps us to communicate with others involved in a common project (since a specialist invariably becomes a member of a team consisting of other engineers and managers). For a co-ordinate group effort it is important that various members of the group meaningfully communicate with each other.

The purpose of these methodical instructions is to teach the students to do the calculations of any electrical circuit by different methods.

These methods are represented here with the concrete examples of calculation.

The main task of the methodical instructions is to help to the students in using a correspondent method for solving problems of different complication.

The examples considered in data methodical instructions will help to the students to fulfil the necessary calculations and investigations when doing calculation-graphical works prescribed in TBE course.

These methodical instructions include the tasks to calculation-graphic work (C.G.W.) on calculation methods of d.c. linear circuit:

- method of Kirchhoff's laws;
- mesh current method;
- node voltage analysis;
- Thevenin's method or the method of equivalent generator;
- the construction of a potential diagram.
- the balance of powers on the base of Energy Relation in Electric Circuits.

1.1 The aim and the task of C.G.W.

The aim of this work is to assist students in independent study of suitable parts of theoretical electrical engineering. Students must get practical skills in using of the main methods of analysis and calculations of direct current linear electrical circuits.

1.2 Contents and the volume of the work

This design-graphic work consists of the explanatory report with the volume of about 7 - 10 pages including figures, graphs and tables.

The contents of the explanatory report:

a title-page;

content;

a task to C.G.W.;

the main part, i.e. the calculation of a network by different methods with figures and diagrams;

an abstract.

The essence of the explanatory report:

1) explanations to computations and independent calculations;

2) the checking up of rightness of the calculations;

3) conclusions;

4) the list of used original sources;

5) appendixes.

1.3 The organization and the leadership of C.G.W.

1.3.1 The lecturer is a manager of C.G.W. He conducts practical lesson on theoretical electrical engineering in the group.

1.3.2 All students' questions on using, checking up and designing of this C.G.W. must be decided at the weekly teacher's consultations according to teacher's time-table.

1.4 Designing and presenting of C.G.W.

When using this work one must carry out the following requirements:

a) the calculation of errors must be lower than 3%;

b) the explanatory report must be designed according to the requirements of the Ukrainian State Standard;

c) the main parts of the work done by a student must be checked up constantly by a lecturer.

2. THE TECHNICAL TASK TO C.G.W.

2.1 Every student has to do his own assignment. The number of his assignment equals the number of student's surname in a group register.

2.2 The values of passive elements and energy sources of voltage and current are given in Appendix A.

2.3 The figures of electrical circuits for calculations and a title-page are given in Appendix B.

3. THE INSTRUCTIONS ON USING THE WORK

3.1 The Method of Kirchhoff's laws

Kirchhoff's laws are used in circuit problems to find the branch currents. Since each branch carries a current of its own, there are as many unknown currents as there are branches. Before writing down the Kirchhoff's equations for solution, one should:

(a) draw the meshes, that is assume a positive direction for each current by placing an arrow along the respective branch;

(b) assume a positive direction for summation round each mesh (loop) so that the Kirchhoff's voltage law can be written by inspection of the meshes.

For uniformity the same direction of summation round all the meshes should be chosen, for example, clockwise.

Let there be m branches and n nodes in a network. Then for the equations to be linearly independent, as many of them should be written by the Kirchhoff's current law as there are nodes minus one, or (n - 1). By the Kirchhoff's voltage law one should write as many equations as there are branches minus the number of equations written by the Kirchhoff's current law, or $m-(n-1)$.

In writing equations by the Kirchhoff's voltage law it is important to choose the meshes successively so that each new mesh includes at least one branch not already included in a mesh. Such meshes are called *independent.*

It's the universal calculation method for any electrical circuit. According to this method one must work out as many independent equations as there are branches in the linear electrical circuit.

Kirchhoff's current law, abbreviated ***KCL***, dictates that the sum of the current entering the node must equal to zero:

$$\sum I = 0$$

In other words, the sum of the currents entering the node is equal to the sum of the currents leaving it.

Kirchhoff's voltage law (***KVL***) provides relationship between the branch voltages of the circuit. It states that the algebraic sum of the branch voltages around a closed-circuit loop is identically zero. In other words, the sum of voltage drops at the resistors of the closed circuit equals to the sum of electro-motive forces in closed-circuit loop:

$$\sum RI = \sum E$$

The terms enter the respective sum with the "plus" sign if they are in the direction of summation round the circuit, and with the "minus" sign if the are in the opposite direction.

The quantity of equations according to the ***KVL*** is equal

$$m-(n-1),$$

where **m** is the quantity of branches in a network.

The example on this method one can see in Appendix C.

3.2 The Mesh-Current Analysis

The word network is used synonymously with the term circuit and refers to any arrangement of passive and active circuit elements which form closed paths.

A mesh is the most elementary form of a loop. It is a property of a planar network diagram and must be so identified that it cannot be further divided into other loops.

By definition, a mesh current is that current which flows around the perimeter of a mesh Equations are written for mesh currents. After they are solved, the branch currents are found in terms of mesh currents.

Thus, the mesh-current method is a form of network analysis on a current basis. The number of equations involved is the same as written by Kirchhoff's voltage law.

We shall consider here the mesh method of solving problems in circuitry because it offers some advantages over the methods discussed so far. To illustrate, let us describe the method and then apply it to an example.

The essence of *mesh-current method* consists that the true currents flowing in circuit branches, are exchanged by the algebraic sum of mesh currents. Thus for branches which enter only into one contour, the value of current is equal to the algebraic value of a corresponding mesh current (taken with the "+" sign if the directions of a branch current in and a mesh current coincide, or with the "-" sign if they do not coincide). For adjacent branches which are a part of several contours, the value of current is equal to an algebraic sum of corresponding mesh currents. The current signs are chosen analogously. The branches containing current sources can enter only into one independent contour.{n of the complex electric circuits with a considerable quantity of nodes. It allows to expel the equations which are made by the first Kirchhoff's law. The number of unknown values in this method is equal to the number of the equations which would be necessary to make for a circuit by the Kirchhoff's voltage law.

A mesh current is a fictitious current which is defined to circulate around only a mesh of the circuit.

In the mesh-current method (also known as the loop method), a circulating current is assigned to each independent mesh of the network being solved. Equations are written for mesh currents. After they are solved, the branch currents are found in terms of mesh currents.

Thus, the mesh-current method is a form of network analysis on a current basis. The number of equations involved is the same as written by Kirchhoff's voltage law.

Note, that each equation for a mesh has, on the left side of the equation, the sum of the resistance common to that mesh multiplying that mesh currents minus the product of the adjacent mesh current and the resistance common to both meshes – and on the right hand side the sum of any voltage sources encountered in traversing the mesh. If the voltage source tends to "push" in the direction of the mesh current, it appears in the sum on the right-hand side as a positive quantity, and as a negative quantity if it tends to oppose the mesh current. We'll find this to be a general rule.

In order to write mesh equations, all sources must be voltage sources. If some are current sources, they can be converted into voltage sources.

As the internal resistance of a current source is equal infinity, one can't compose the equation by the ***KVL*** for such a contour. So, we must choose contours without current sources in its branches.

The example is given in Appendix D.

3.3 Node-analysis Method

The current in any branch of a network can be found by Ohm's law for a branch containing an e.m.f. This calls for knowledge of the potential difference across the terminals of the branch or, which is the same, across the nodes bounding the branch in question. The analysis of network in which the unknown quantities are the voltages across the branches of the network is known as the node-analysis method.

When making the equations by node-analysis method one must choose a basis node to be earthed without affecting the distribution of currents around the network. In other words, we consider that its potential is equal to zero. As a result, the number of unknown potentials becomes equal to the number of the independent equations which are made by the first Kirchhoff's law. On solving the system concerning these potentials, it is possible to define currents through known potentials.

This method is expedient to use for calculation of the complicated electric circuits with a small amount of nodes. It allows to expel the equations which are made by the second Kirchhoff's law.

Node voltage analysis is a method for obtaining a set of equations to be solved for a set of circuit voltages – the node voltages. Once these node voltages are obtained, we can easily obtain all branch voltages and currents from them. Select one of the three nodes as a reference node. We consider it to be grounded.

Then we write KCL at each node in terms of these node voltages. When we have all node voltages we can obtain the branch voltage across any R as the difference of; $\varphi_b - \varphi_c$ and so on. The branch currents are obtained by Ohm's law. $\varphi_a - \varphi_b$

The example is given in Appendix E.

3.4 Thevenin's Method or Equivalent Generator Method

Situations sometimes occur in electric engineering in which it is desirable to find a particular branch current in a network as the resistance of that branch is varied while all other resistances and sources remain constant. Then we remove this branch, and the remaining two-terminal network can be replaced by an equivalent voltage generator whose e.m.f. is equal to the one appearing across the two terminals when the branch is open circuited, that is there is no load on it, and whose internal resistance is equal to the driving-point resistance of the two-terminal network between the branch terminals.

This method is known as *Thevenin's Theorem* or *equivalent-generator method*. The remaining two-terminal network can be also replaced by an equivalent current source Sometimes we need find a current in one branch only.

Let a complex network contains some branch in which it is desired to find the current. We remove this branch and the remaining part of network may be replaced by an equivalent voltage source and an equivalent series resistance.

The voltage source is equal to the potential difference between two terminal points. The series resistance is the equivalent one looking into terminal points with all power sources inactive.

On finding these values we can calculate the current flowing through some load resistance R_L according to the formula: $I = U_{o.c.} / (R_{in} + R_L)$.

The value of this current must coincide with the same current calculated by another method.

The example is given in Appendix F.

3.5 The Construction of a Potential Diagram

This diagram gives us a possibility to check up the rightness of currents' calculations.

Earthing a function in a circuit will not affect the current distribution in this circuit. This is because no additional path if formed for a current to flow. The situation is different when two or more junctions are at different potentials are earthed (or grounded).

Then additional paths are formed through earth (or any conducting medium), so that the circuit arrangement or configuration changes, and the current distribution becomes different.

A potential diagram is a plot of potential distribution round a circuit, incomplete or complete, as a function of an independent variable, such as the circuit resistance. Resistances are then laid off as abscissa, and the potentials, as ordinate. For each point round a circuit there is a separate point in the potential diagram.

The sequence of construction of a potential diagram:

a) choose any closed mesh with one or two electro-motive forces;

b) assume a positive direction for summation round that mesh;

c) a node of circuit is grounded, i.e. its potential is equal to zero;

d) mark every point of the mesh after each element;

e) calculate the nodal potentials along the mesh in order.

If we have an e.m.f. between two points, and its direction coincides with the direction of summation, we take it with a plus sign. In opposite case its sign will be minus. If a current through resistor has the same direction as the direction for summation round the mesh, the voltage drop from this current will have a minus sign. If a current doesn't coincide with the direction of summation, we will take the voltage drop with a plus sign. We must remember that current always flows from the point with a higher potential to the point with a lower one.

The potential diagram is constructed in right-angled coordinate system. One must mark the calculation potentials of the respective points on the ordinate axis and the resistors of each part must be marked on the abscissa axis. If we have a resistor on some section of the circuit we get a sloping line on this part of the potential diagram. If we have a voltage source with a definite e.m.f. we get a perpendicular to X-axis on this part. It must be equal to the value of the voltage source.

The example is given in Appendix G.

3.6 Energy Relation in Electric Circuits

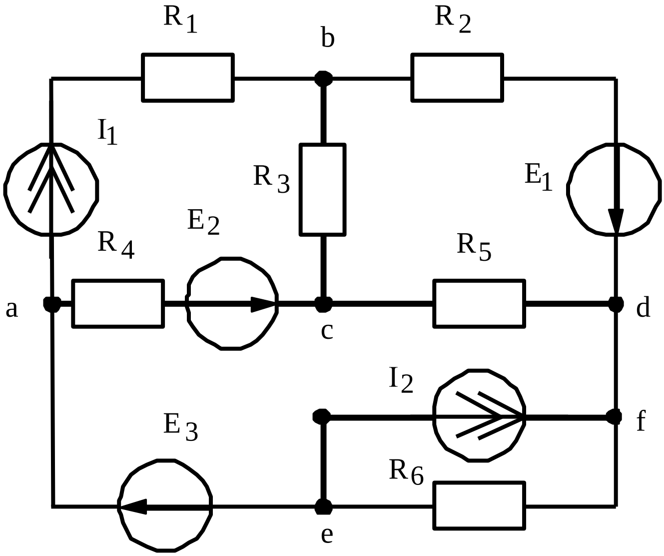
Current flow through resistance elements results in some energy is dissipation. On the basis of the law of conservation of energy, this dissipated energy to be made up for if a given circuit is to perform its function. In other words, the rate of energy input in d.c. circuit must be equal to the rate of energy dissipation by that circuit.

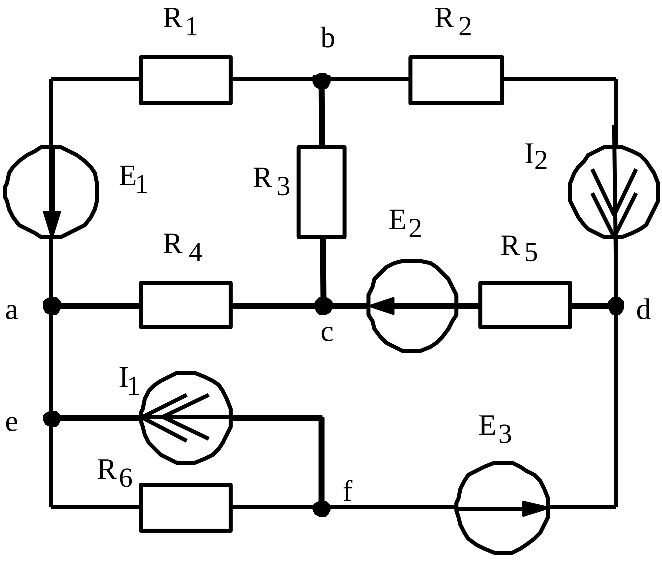
The way such a circuit operates depends on whether the current $\boldsymbol{I}$ through the source E is in the same or the opposite direction with the value of e.m.f. When I is in the same direction as E, the source delivers energy to the circuit, and the power ($E \cdot I$ watts), enters the energy balance equation with a "+" sign. When I flows against E, the source absorbs energy from the circuit and the product $E \cdot I$ enters the equation with a "-" sign. The energy balance equation has the form $\sum I^2 \cdot R = \sum E \cdot I$.

APPENDIX A
Data for calculation of electrical circuits

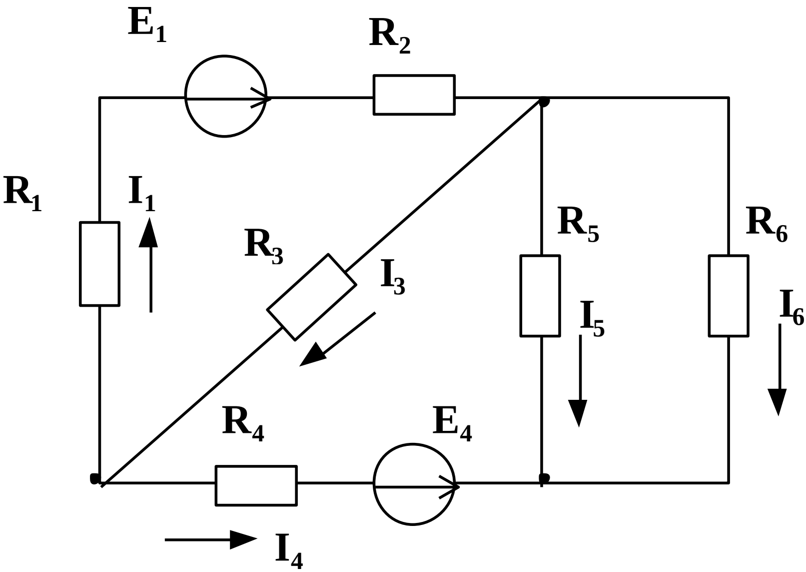
V	D	R_1	R_2	R_3	R_4	R_5	R_6	E_1	E_2	E_3	I_1	I_2
		Ω	Ω	Ω	Ω	Ω	Ω	V	V	V	A	A
1	1	12	4	8	6	10	10	0	0	70	5	4
2	2	5	8	5	4	20	10	25	0	80	2	4
3	2	10	20	30	40	15	5	60	0	0	8	2
4	1	4	8	6	12	10	6	0	60	0	2	6
5	1	8	12	10	18	20	15	60	0	0	3	5
6	2	20	10	30	40	60	10	0	0	90	4	5
7	1	2	7	5	3	11	15	0	0	90	3	4
8	2	9	8	14	22	16	20	0	40	0	5	2
9	1	30	15	20	10	12	12	30	0	0	3	4
10	2	2	8	16	24	12	10	0	60	0	8	5
11	2	10	15	25	14	16	8	60	0	0	6	4
12	1	20	16	10	30	14	10	0	0	80	3	4
13	1	6	8	10	14	20	20	0	0	90	6	2
14	2	10	20	40	15	25	12	0	40	0	5	10
15	1	10	20	12	24	12	30	50	0	0	4	2
16	2	12	6	9	15	18	10	0	0	90	4	4
17	1	25	15	10	12	16	16	0	60	0	5	5
18	2	8	16	24	12	18	10	60	0	0	8	6
19	1	16	40	24	42	30	20	0	0	80	2	2
20	2	4	8	20	12	16	15	0	30	0	4	6
21	1	12	10	16	18	24	12	0	40	0	4	5
22	2	10	20	24	18	16	10	80	0	0	4	8
23	2	4	10	8	16	10	6	0	30	0	10	5
24	1	24	16	18	20	8	10	0	0	90	8	4
25	1	12	24	36	10	15	5	0	0	80	4	6
26	2	30	25	15	40	36	10	0	0	80	4	5
27	1	10	25	60	30	35	15	0	40	0	2	2
28	2	24	15	10	25	30	10	0	0	90	5	5

APPENDIX B
The diagrams of electric circuits





APPENDIX C
The example of working out the equations by Kirchhoff's laws



The network has three nodes. So, two equations can be written by Kirchhoff's current law:

node ***a***: $I_3 - I_1 - I_4 = 0$

node ***b***: $I_1 - I_3 - I_5 - I_6 = 0$

According to the second Kirchhoff's law we have three independent closed-circuit loops. So for the first contour (we move round the contour in the direction of clockwise):

$$(R_1 + R_2) \cdot I_1 + R_3 I_3 = E_1$$

For the second contour (we move it anticlockwise):

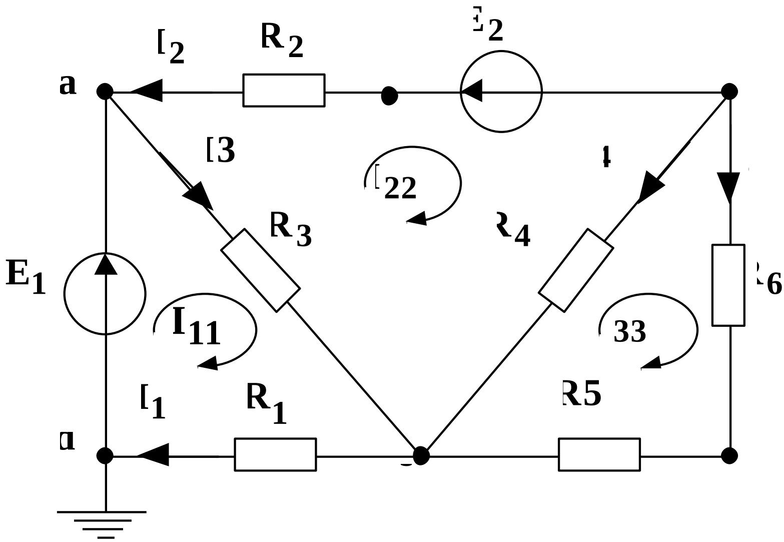
$$R_3 I_3 + R_4 I_4 - R_5 I_5 = E_4$$

For the third one (in the direction of clockwise):

$$-R_5 I_5 + R_6 I_6 = 0$$

To the right-hand side of this equation we have zero because there is no voltage source in this contour.

APPENDIX D
The example of working out the equations by Mesh-current analysis



All mesh currents are represented as circulating clockwise. The system of equations for the circuit:

$$(R_1 + R_3) \cdot I_{11} - R_3 I_{22} = E_1$$

$$-R_3 I_{11} + (R_2 + R_3 + R_4) \cdot I_{22} - R_4 I_{33} = -E_2$$

$$-R_4 I_{22} + (R_4 + R_5 + R_6) \cdot I_{33} = 0$$

The currents in the outside branches are equal to the correspondent mesh currents. The real currents in adjacent branches are determined as the algebraic sum of two meshes currents flowing through this branch.

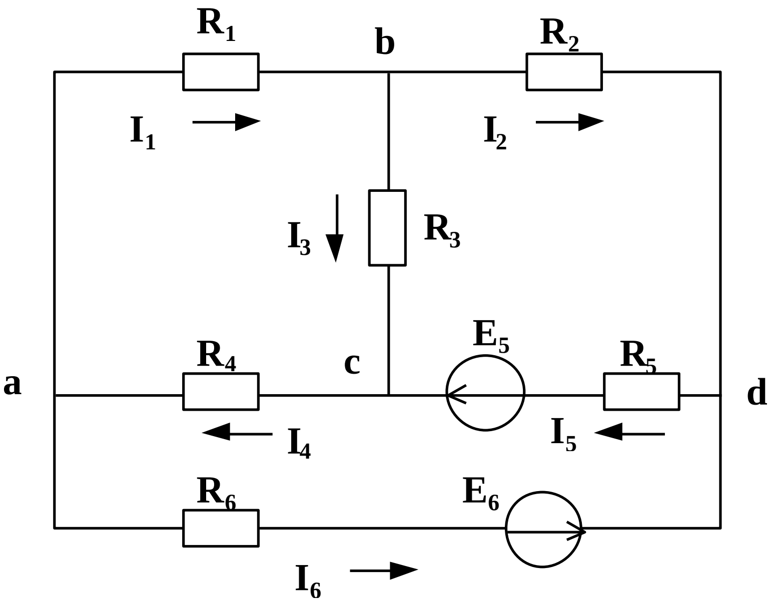
$$I_1 = I_{11} \qquad I_3 = I_{11} - I_{22}$$

$$I_2 = -I_{22} \qquad I_4 = I_{22} - I_{33}$$

$$I_5 = I_{33}$$

If some currents are negative it means that their real (actual) directions must be opposite.

APPENDIX E
The example of using Node voltage analysis



Suppose, that $\varphi_c = 0$. The equation for node "***a***":

$$\varphi_a\left(1/R_1 + 1/R_4 + 1/R_6\right) - \varphi_b \cdot 1/R_1 - \varphi_d \cdot 1/R_6 = -E_6 \cdot 1/R_6 .$$

The equation for node "***b***":

$$-\varphi_a \cdot 1/R_1 + \varphi_b\left(1/R_1 + 1/R_2 + 1/R_3\right) - \varphi_d \cdot 1/R_2 = 0 .$$

The equation for node "***d***":

$$-\varphi_a \cdot 1/R_6 - \varphi_b \cdot 1/R_2 + \varphi_d\left(1/R_2 + 1/R_5 + 1/R_6\right) =$$

$$= E_6 \cdot 1/R_6 - E_5 \cdot 1/R_5$$

Then currents in the branches may be obtained according Ohm's Law^

$$I_1 = \frac{(\varphi_a - \varphi_b)}{R_1} \qquad I_3 = \frac{(\varphi_b - \varphi_c)}{R_3} \qquad I_5 = \frac{(\varphi_d - \varphi_c + E_5)}{R_5}$$

$$I_2 = \frac{(\varphi_b - \varphi_d)}{R_2} \qquad I_4 = \frac{(\varphi_c - \varphi_a)}{R_4} \qquad I_6 = \frac{(\varphi_a - \varphi_d + E_6)}{R_6}$$

APPENDIX F
The example of calculation with the help of Thevenin's Theorem

Consider this method using the figure from the mesh-current method.

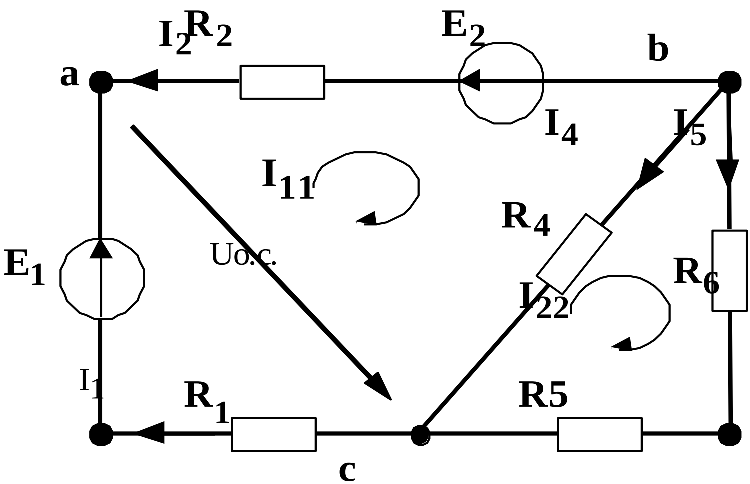
Let this complex network contains some branch "ac" in which it is desired to find the current. We remove this branch and the remaining part of network may be replaced by an equivalent voltage source and an equivalent series resistance.

For example, we need the current in the third branch "ac", i.e. I_3.

We can calculate the current flowing through this load resistance R_3 according to the formula:

$$I_3 = \frac{Uo.c.}{Rin + R_3}$$

The open-circuit voltage is equal to the potential difference between two terminal points "a" and "c". The series resistance is the equivalent one looking into terminal points with all power sources inactive.



Imagine the terminals "***ac***" open-circuited and find the open-circuit voltage across them: $Uo.c.(ac) = \varphi_a - \varphi_c = E_1 - R_1 I_1$.

The unknown current we can calculate using mesh-current method for this circuit. We have two independent contours here, so one can compose the following system of equations:

$$I_{11}(R_1 + R_2 + R_4) - I_{22} \cdot R_4 = E_1 - E_2$$
$$-I_{11} \cdot R_4 + I_{22}(R_4 + R_5 + R_6) = 0$$

On calculating mesh currents I_{11} and I_{22} we can find actual currents: $I_1 = I_{11}$,

The input resistance is the equivalent one looking into terminal points "ac" with all power sources inactive. We begin the calculation with resistances R_5 and R_6 which are connected in series. So, their common resistance is equal to the sum: $R_{56} = R_5 + R_6$.

The resistance R_4 is in parallel to R_{56}. So, we can define their common resistance $R_{456} = \dfrac{R_{56} \cdot R_4}{R_{56} + R_4}$.

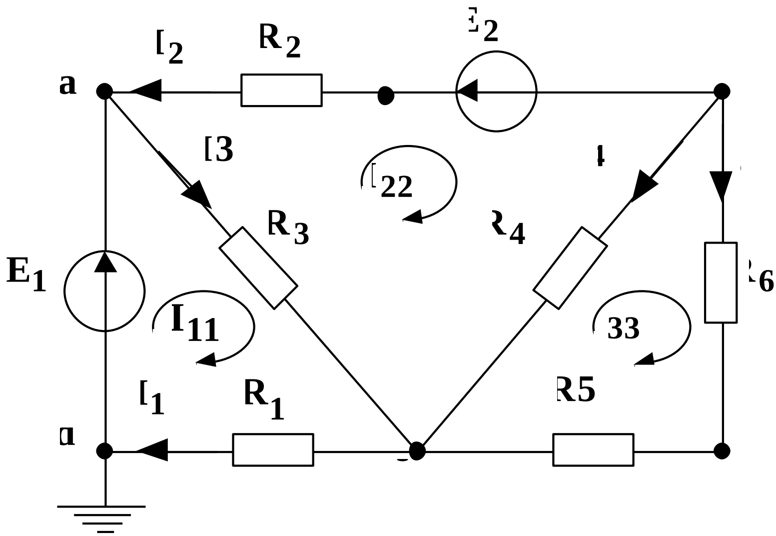
Then $R_{2456} = R_2 + R_{456}$, as they are connected in series. Now we can calculate the input resistance seeing that two last branches are connected in parallel according the terminals "ac".

Input resistance $R_{in} = \dfrac{R_1 \cdot R_{2456}}{R_1 + R_{2456}}$.

On knowing open-circuit voltage and input resistance we can substitute them into formula (F.1) and find the current I_3.

APPENDIX G
The construction of the potential diagram

Construct the potential diagram for the mesh "*dafbecd*" for the following figure:



We choose scales for the x- and y-axis, and set the potential at, say, junction "***d***" at zero. So, $\varphi_d = 0$ is considered to be earthed. In the potential diagram this will be the origin of coordinates. Now we can calculate the potentials of nodes along the outside mesh. We must start from junction "**d**" and end at the same point.

The potential at "***a***" will be

$$\varphi_a = \varphi_d + E_1$$

because the e.m.f. increases the potential of the next node.

The potential at "***f***":

$$\varphi_f = \varphi_a + R_2 \cdot I_2$$

because the current flows from the node with the higher potential to the node with the lower one.

The potential at "***b***": $\varphi_b = \varphi_f - E_2$.

The next point along the mesh is "**e**":

$$\varphi_e = \varphi_b - R_6 \cdot I_5$$

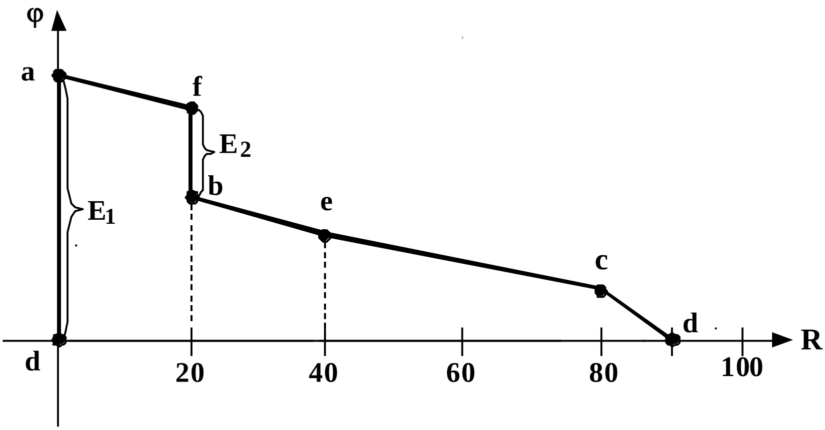
The potential at "***c***":

$$\varphi_c = \varphi_e - R_5 \cdot I_5$$

Now we must return to junction "***d***";

$$\varphi_d = \varphi_c - R_1 \cdot I_1$$

The schematic potential diagram

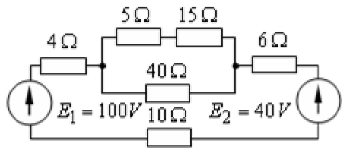


We have got a sloping line where there is a resistor in this part of the mesh. These are segments "***a***" – "***f***", "***b***" – "***e***", "***e***" – "***c***" and "***c***" – "***d***". If we have the e.m.f. in the part of the mesh there will be a perpendicular to y-axis on the diagram. There are two such segments here: "***d***" – "***a***" which is numerically equal to the value of E_1, and "***f***" – "***b***" which is numerically equal to the value of E_2.

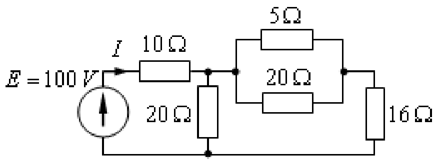
For any contour in the network the potential diagram shows us the change of the potentials when we go round the mesh.

The tasks for protection of this topic

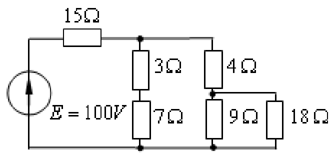
1. In the following circuit determine the voltage drop across each circuit element as well as the power dissipated. All resistances are in ohms.



2. Find current *I* for this circuit. All resistance values are in ohms.

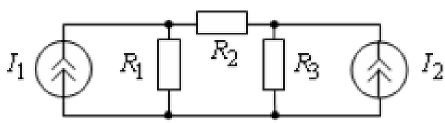


3. Determine the equivalent resistance appearing at the battery terminals in the circuit.

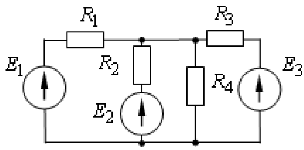


4. Determine: a) the voltage across *ab* when the voltage across the 15-Ω resistor is 45 V; b) the equivalent resistance between terminals *ab*.

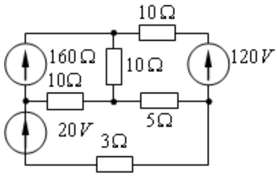
5. $I_1 = 10A,\ I_2 = 4A$, $R_1 = 1\Omega,\ R_2 = 2.5\Omega,\ R_3 = 0.5\Omega$. Find all mesh currents. Determine the voltages across resistances R_1 and R_3.



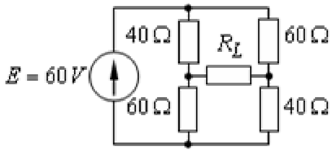
6. Find current through R_4 which is equal to 4.5 if circuit parameters $E_1 = 60V;\ E_2 = 70V; E_3 = 40V$, $R_1 = 10\,\Omega;\ R_2 = 20\,\Omega;\ R_3 = 5\,\Omega$.



7. Use Thevenin's theorem to find the across the 5-Ω resistor when this branch is open circuited.



8. Use Thevenin's theorem to find current in R_L which is 50 Ohms.



RECOMMENDED LITERATURE

1. The schoolbook "Theoretical Electrical Engineering" / Nabokova O.V. - Zaporozhye: ZNTU, 2014. - 530 p.
2. Козлов В.В., Набокова О.В. Теоретичні основи електротехніки. Усталені режими у лінійних електричних колах. -Запоріжжя: ЗНТУ, 2016. – 428 с.
3. Мілих В.І. Електротехніка та електромеханіка. К.: Каравела, 2010. – 376 с.
4. Paul C.R., Nazzsar S.A. Introduction to electrical engineering. - New York: Electrical Engineering University of Kentucky, 1999. - 800 p.