**Non-commercial Joint Stock Company**

**ALMATY UNIVERSITY OF POWER ENGINEERING & TELECOMMUNICATIONS**

Department of Theoretical Bases of Electrical Engineering

# THEORETICAL BASES OF ELECTRICAL ENGINEERING 2

## Three-phase linear electric circuit analysis & Transient process analysis in the second order linear electric circuits

Methodological guidelines and assignments for calculation graphical works № 1…3 for the baccalaureate 5B071800 – “Electrical Power Engineering” specialty

Almaty 2015

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Provides methodological guidelines and assignments for calculation graphical works of the "Theoretical Bases of Electrical Engineering 2" course for the next sections: "Three-phase linear electric circuits", "Transient process analysis in the second order linear electric circuits".

Calculation graphical assignments are intended for the baccalaureate 5B071800 – "Electrical Power Engineering" specialty students.

Illustration 14, tables 9, references 9 items.

Reviewer: Head of FL Department PhD V.S. Kozlov

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## Contents

## Introduction

Calculation Graphical Works (CGW) is an essential component in the study «Theoretical Bases of Electrical Engineering 2» (TBEE2) course. Performing CGW allows the student to apply theoretical principles in practical calculations, to gain the skills of independent circuit analysis that ultimately contribute to the successful mastering of the TBEE2 course.

This brochure contains assignments and methodological guidelines for three CGW on the main sections of the TBEE2, which should be studied in 4th semester.

CGW №1 is devoted to calculation of balanced and unbalanced three-phase linear electric circuits with static load by using basic methods of a circuit analysis.

CGW №2 is devoted to the calculation of an unbalanced three-phase linear electric circuit with dynamic load by using method of symmetrical components.

CGW №3 is devoted to transient process analysis in the second order linear electric circuit by using both classic method and applying the Laplace transform.

Variant of original data is determined by surname's first letter, last and penultimate digit of the credit book number and by the year of enrollment (even or odd).

### Requirements

1. CGW should be includes next sections: introduction, assignment, procedure of calculation, results graphic presentation, conclusion and list of references.
2. Choose the original assignment data according to your variant, assignments text should be rewritten to the explanatory note completely unabridged.
3. Each stage of a work should be named, all tasks are performed on only one side of a sheet (size A4, margins: left 25mm, right 18mm, top 20mm, bottom 25mm).
4. In an explanatory note are to be presented not only calculation formulas and final results, but also text with explanations, needed intermediate calculations, that allow to understand and verify your actions.
5. The number of credit book, academic group code, student's surname & initials should be written on the title page of CGW's explanatory note; template of the title page is represented on the next page.
6. It is necessary to write appropriate units for the parameters, having a particular of dimension; put a dot over complex parameters, that are a time function; complex parameters, that are not functions of time, such as impedance and conductance should be underlined.
7. Do not change of names of the nodes, parameters, resistors, inductances, capacitances and of the arbitrarily taken current and voltage positive directions.
8. The graphs of instantaneous values, phasor, topographic and circle diagrams should be done on the pasted sheets of graph or checkered paper, or by using computer applications.
9. It is necessary to sign coordinate axes and the names of variable on the graph, also choose a scale so that would be convenient to use a graph or diagram.

10. The circuit diagrams should be done in pencil using a ruler, or by PC applications.

Template of the title page:

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ALMATY UNIVERSITY OF POWER ENGINEERING &TELECOMMUNICATIONS

Department of Theoretical Bases of Electrical Engineering

Calculation Graphical Work № __
on the "Theoretical Bases of Electrical Engineering 2" course

_______________________________________
Title of the calculation graphical work

Done by student of the __________ group
academic group code

____________________________
Student's Surname & Initials
Credit book №_____________
"___" "___________" 201__yr

Checked by ___________________________
Teacher's Surname & Initials
"___" "___________" 201__yr

Almaty 201__ yr.

## 1 CGW №1. Modes analysis of balanced and unbalanced three-phase linear electric circuits with static load

Two balanced three-phase linear static loads, first assembled in a star (Y – wye connection) with phase impedances $\underline{Z}_1$, and second – in a triangle (Δ – delta connection), with phase impedances $\underline{Z}_2$, are feeding via a line by the three-phase balanced alternator. An impedance of each wire of a line is $\underline{Z}_{line}$. Each phase Electromotive Force (EMF) of an alternator is *E*. Circuit diagram is presented on the Figure 1.1.

Original data and assigned modes of a circuit is presented in the Tables 1.1…1.3 for a variety of variants. Choose the original data and assigned modes of a circuit according to your variant and enter it at the very beginning of the explanatory note.

### 1.1 Assignment

Calculate of the currents in the line's wires and currents in the phases of the each load, phase voltages by load’s side, active, reactive and apparent power of the each load and alternator, make up a voltage phasor diagram combined with current phasor diagram for the following circuit modes:

a) a balanced mode of the three-phase circuit;

b) an open one of the line wire;

c) an open one of the load’s phase wire.

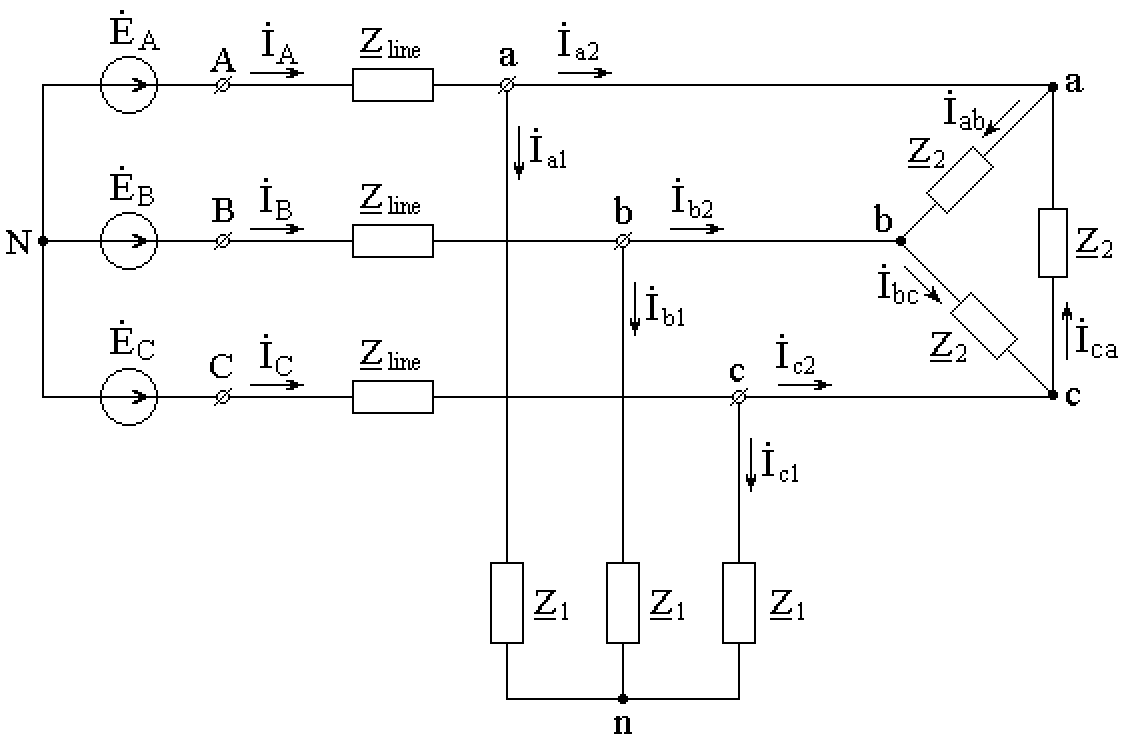



Figure 1.1 – Three-phase balanced linear electric circuit with static load

Table 1.1

| Enrollment year | First letter of the surname | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| even | АЯ | УЮФ | КХ | БЛЦ | ВМЧ | ТЭИ | ЖСЗ | ДОЩ | ЕПР | ГНШ |
| odd | ГНШ | АЯ | ЕПР | УЮФ | ДОЩ | КХ | БЛЦ | ЖСЗ | ТЭИ | ВМЧ |
| $E$, V | 220 | 110 | 127 | 120 | 130 | 150 | 140 | 100 | 200 | 170 |
| $\underline{Z}_{line}$, Ω | 2+j2 | 1+j2 | 0,5+j2 | 1+j1 | 1+j2,5 | 2+j2,5 | 2+j3 | 0,5+j1 | 0,4+j1 | 1+j1,5 |

Table 1.2

| Enrollment year | Last digit of the credit book number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| even | 9 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| odd | 0 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| $\underline{Z}_1$, Ω | 30+j15 | 35+j20 | 30+j20 | 40+j30 | 25+j15 | 20+j10 | 45+j20 | 15+j10 | 40+j15 | 25+j20 |
| Open line wire | A | B | C | A | B | C | A | C | B | A |

Table 1.3

| Enrollment year | Penultimate digit of the credit book number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| even | 9 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| odd | 0 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |

| $\underline{Z}_2$, Ω | 80–j95 | 90–j95 | 75–j90 | 40–j70 | 50–j65 | 50–j75 | 65–j80 | 55–j60 | 45–j75 | 70–j85 |
|---|---|---|---|---|---|---|---|---|---|---|
| Open phase wire | ab | $bn_1$ | bc | $cn_1$ | ca | $an_1$ | bc | $cn_1$ | ab | $bn_1$ |

**1.2 Methodological guidelines**

a) When calculating the balanced three-phase linear electric circuit mode (choice 1) it is appropriate the triangle of impedances $\underline{Z}_2$ to replace by equivalent star with $\underline{Z}_{2eqY}$. In the obtained circuit diagram all the neutral points $N$, $n_1$ and $n_2$ have the same potential since the electric circuit is balanced. Therefore, all of which $N$, $n_1$ and $n_2$ can be joined together. Their potential equal to zero.

The mode of phase $A$ will not change if to exclude the phase $B$ and phase $C$ from the obtained circuit. As a result, will obtain a single-phase circuit diagram for the phase $A$ (Figure 1.2). Using this scheme it is possible to calculate a line current $\dot{I}_A$, a phase current $\dot{I}_{a1}$ of the first load with impedance $\underline{Z}_1$, a line current $\dot{I}_{a2}$ of the second load with impedance $\underline{Z}_2$ and load's phase potential $\dot{\varphi}_a$.

Currents and voltages in phases $B$ and $C$ will differ from similar in phase $A$ only on the initial phases of –120° and +120°, respectively.

Then you have return to the original circuit to calculate the phase voltages $\dot{U}_{ab}, \dot{U}_{bc}, \dot{U}_{ca}$ and phase currents $\dot{I}_{ab}, \dot{I}_{bc}, \dot{I}_{ca}$ second load with impedance $\underline{Z}_2$.

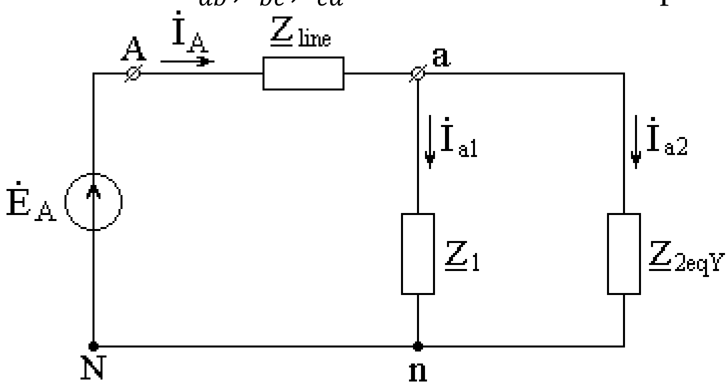



Figure 1.2 – Single-phase circuit diagram for the phase A

b) When calculating of the unbalanced three-phase circuit modes (choices 2 and 3) it is appropriate, vice versa, the star of impedances $\underline{Z}_1$ to replace by equivalent triangle with $\underline{Z}_{1eq\Delta}$. The parallel branches in the obtained circuit diagram should be replaced by a single equivalent. Using obtained circuit diagram it is possible to calculate line currents $\dot{I}_A, \dot{I}_B, \dot{I}_C$ and phase potentials $\dot{\varphi}_a, \dot{\varphi}_b$ and $\dot{\varphi}_c$.

Then you have to return to the original circuit to calculate of the voltages $\dot{U}_{ab}, \dot{U}_{bc}, \dot{U}_{ca}$ and sets of the phase currents $\dot{I}_{a1}, \dot{I}_{b1}, \dot{I}_{c1}$ and $\dot{I}_{ab}, \dot{I}_{bc}, \dot{I}_{ca}$, by the first and second load, respectively.

References: [R1] – §6.7…6.11; [R2] – §7.1…7.3; [R5] – lectures 1 and 2.

## 2 CGW №2. Modes analysis of unbalanced three-phase linear electric circuits with dynamic load

Balanced three-phase linear dynamic load is feeding via a line from the three-phase balanced alternator. An impedance of each wire of a line is $\underline{Z}_{line}$. Each phase Electromotive force (EMF) of an alternator is $E$. A circuit diagram with dynamic load, which phases are connected in triangle (Δ - connection), is presented on the Figure 2.1. A circuit with dynamic load, which phases are connected in a star with a grounded neutral (Y - connection), is presented on the Figure 2.2. One of the phases of the circuit in Figure 2.1 occurs short circuit to ground by load's side. In the circuit in Figure 2.2 occurs break in one of the line wire.

The original data and assigned modes are presented in the Tables 2.1…2.3 for a variety of variants, where are:

$E$ –Electromotive Force (EMF) of an alternator phase;

$\underline{Z}_{G1}$, $\underline{Z}_{G2}$ and $\underline{Z}_{G0}$ – the positive, negative and zero sequences impedances of the three phase alternator, respectively;

$\underline{Z}_{l1}$, $\underline{Z}_{l2}$ and $\underline{Z}_{l0}$ – the positive, negative and zero sequences impedances of the three phase line, respectively;

$\underline{Z}_{1}$, $\underline{Z}_{2}$ and $\underline{Z}_{0}$ – the positive, negative and zero sequences impedances of the three phase dynamic load, respectively;

$\underline{Z}_{N}$ – a grounded neutral impedance of the three phase alternator;

Choose the original data and assigned modes of a circuit according to your variant and enter it at the very beginning of the explanatory note.

### 2.1 Assignment

According to your variant of circuit and kind of damage should perform following:

1) Calculate of the currents and voltages in all sections of the circuit by applying a method of symmetrical components.

2) Calculate of the active, reactive and apparent power of the load, line and alternator. Check the active and reactive power balance equations.

3) Make up a voltage phasor diagram combined with the current phasor diagram.

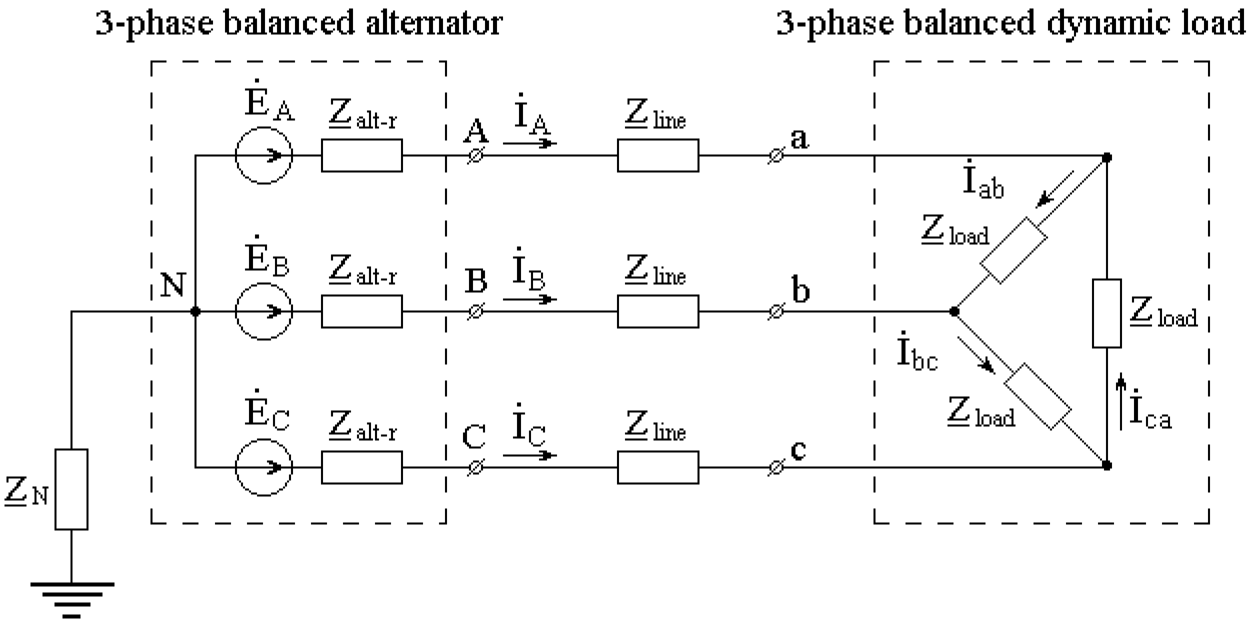



Figure 2.1 – Three phase balanced circuit with dynamic load - Δ connection

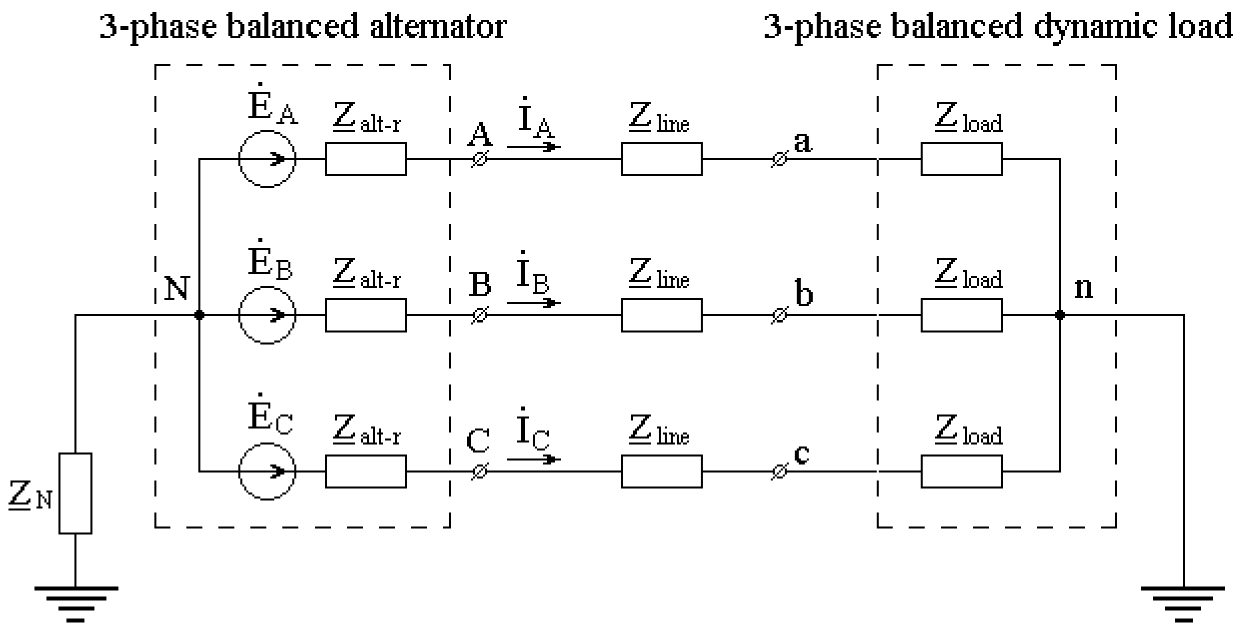



Figure 2.2 – Three phase balanced circuit with dynamic load - Y connection

Table 2.1

| Enrollment year | First letter of the surname | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| even | АЯ | ЕПР | УЮФ | БЛЦ | ВМЧ | ТЭИ | ЖСЗ | ДОЩ | КХ | ГНШ |
| odd | ГНШ | АЯ | ЕПР | УЮФ | ДОЩ | КХ | БЛЦ | ЖСЗ | ТЭИ | ВМЧ |
| № circuit | 2.1 | 2.2 | 2.1 | 2.2 | 2.1 | 2.2 | 2.1 | 2.2 | 2.1 | 2.2 |
| Short circuit in phase | A | – | B | – | C | – | A | – | C | – |
| Open line | – | C | – | A | – | B | – | C | – | B |

| in phase | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $E$, V | 420 | 380 | 190 | 220 | 127 | 110 | 510 | 300 | 330 | 470 |
| $\underline{Z}_0$, Ω | ∞ | j3,5 | ∞ | j5,5 | ∞ | j4,0 | ∞ | j4,5 | ∞ | j7,0 |

Table 2.2

| Enrollment year | Last digit of the credit book number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| even | 9 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| odd | 0 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| $\underline{Z}_1$, Ω | 30+j15 | 35+j20 | 30+j20 | 40+j30 | 25+j15 | 20+j10 | 45+j20 | 15+j10 | 40+j15 | 25+j20 |
| $\underline{Z}_2$, Ω | 2+j1,5 | 2,5+j2 | 3+j1,5 | 5+j3,5 | 2,5+j2 | 0,5+j2 | 3+j2,0 | 1+j1,0 | 4+j3,0 | 1+j2,0 |
| $\underline{Z}_{l1} = \underline{Z}_{l2}$, Ω | j3,5 | j4,0 | j2,5 | j4,5 | j1,5 | j2,0 | j5,5 | j1,0 | j5,0 | j3,0 |
| $\underline{Z}_{l0}$, Ω | j9,0 | j12,0 | j7,0 | j13,5 | j4,5 | j5,5 | j15,0 | j3,0 | j14,0 | j10,0 |

Table 2.3

| Enrollment year | Penultimate digit of the credit book number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| even | 9 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| odd | 0 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| $\underline{Z}_{G1}$, Ω | 0,1+j0,7 | 0,1+j0,5 | 0,2+j1,0 | 0,2+j0,9 | 0,1+j0,6 | 0,2+j1,5 | 0,1+j0,8 | 0,3+j1,2 | 0,3+j1,5 | 0,3+j1,0 |
| $\underline{Z}_{G2}$, Ω | j0,09 | j0,05 | j0,12 | j0,10 | j0,05 | j0,20 | j0,08 | j0,15 | j0,2 | j0,07 |
| $\underline{Z}_{G0}$, Ω | j0,030 | j0,020 | j0,050 | j0,025 | j0,015 | j0,070 | j0,035 | j0,055 | j0,065 | j0,023 |
| $\underline{Z}_N$, Ω | j0,35 | j0,50 | j0,65 | j0,40 | j0,45 | j0,25 | j0,30 | j0,55 | j0,20 | j0,60 |

### 2.2 Methodological guidelines

To calculate of the unbalanced mode of a three-phase linear electric circuit with dynamic load it is appropriate using a compensation theorem and method of symmetrical components. The unbalanced circuit section (for example, short circuit to the earth one of the load’s phase or open one of the line wire) replacing by equivalent three phase unbalanced source of electromotive force $\dot{U}_A, \dot{U}_B, \dot{U}_C$. This source is represented as a sum of the three balanced three-phase sources of the positive, negative and zero sequences, respectively. Calculation of the positive, negative and zero sequences currents and voltages it is perform separately, i.e. applying a superposition theorem.

Distinguishing feature of this method is a balanced mode in the three-phase circuit for each sequences.

Procedure of calculation:

1) Replace the unbalanced circuit section by equivalent three phase unbalanced source of electromotive force: $\dot{U}_A, \dot{U}_B, \dot{U}_C$. Represent it as a series connected three balanced three-phase sources of the positive $\dot{U}_{A1}, \dot{U}_{B1}, \dot{U}_{C1}$, negative $\dot{U}_{A2}, \dot{U}_{B2}, \dot{U}_{C2}$ and zero $\dot{U}_{A0}, \dot{U}_{B0}, \dot{U}_{C0}$ sequences, respectively.

2) Make the first three equations to describe damage (short circuit or open line).

3) Make an equivalent replacement circuit and a corresponding equation for positive sequence currents, voltages and electromotive forces. Due to a balanced mode in this circuit it is possible to make a single phase circuit for calculation. As a rule, phase "A" taken as a base phase.

4) By analogy, make the single phase "A" circuits and the corresponding equations for negative and zero sequences currents, voltages and electromotive forces.

5) As a result is obtained six simultaneously equations relatively unknown values: $\dot{I}_1, \dot{I}_2, \dot{I}_0, \dot{U}_1, \dot{U}_2, \dot{U}_0$. Ordinarily, at first the currents are found and then voltages.

6) Further, it is necessary to find the symmetrical components of the currents and voltages in all section of the three-phase circuit by using corresponding single-phase circuits of the positive, negative and zero sequences.

7) The values of actual currents and voltages in all sections of the original three-phase circuit is determined as the sum of the corresponding symmetrical components. For example:

$$\dot{I}_{a\,shc} = \dot{I}_1 + \dot{I}_2 + \dot{I}_0, \quad \dot{I}_{b\,shc} = a^2\dot{I}_1 + a\dot{I}_1 + \dot{I}_0, \quad \dot{I}_{c\,shc} = a\dot{I}_1 + a^2\dot{I}_1 + \dot{I}_0,$$

$$\dot{U}_{an} = \dot{U}_1 + \dot{U}_2 + \dot{U}_0, \quad \dot{U}_{bn} = a^2\dot{U}_1 + a\dot{U}_2 + \dot{U}_0, \quad \dot{U}_{cn} = a\dot{U}_1 + a^2\dot{U}_2 + \dot{U}_0,$$

where are: $a = e^{j120°}$, $a^2 = e^{j240°} = e^{-j120°}$, $1 + a + a^2 = 0$.

8) At last, it is possible to calculate of the active, reactive and apparent power of the load, line and alternator and make up voltage and current phasors diagram.

References: [R1] – §6.20…6.21; [R2] – §7.4…7.5; [R5] – lectures 5…7.

## 3 CGW №3. Transient process analysis in the second order linear electric circuits

In the electric circuits (Figures 3.1…3.10) a transient process occur as a result of the switch commutation.

Parameters of elements and the number of the analyzed scheme are presented in Tables 3.1 ... 3.3 for different variants. Choose the original data and circuit diagram according to your variant and enter it at the very beginning of the explanatory note.

### 3.1 Assignment

For a given variant of the circuit diagram needs to be done the following:

1) Find the time function of the transient current in one of the branches or transient voltage across one of the element of the circuit after the switching (Table 3.1). The calculation should be performed by two methods: classical and by applying Laplace transform (operator calculation method). Compare the calculation methods and make conclusion.

2) Draw a timing diagram of the found transient function based on the obtained analytical expression.

Table 3.1

| Enrollment year | Last digit of the credit book number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| even | 9 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| odd | 0 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| № circuit | 3.1 | 3.2 | 3.3 | 3.4 | 3.5 | 3.6 | 3.7 | 3.8 | 3.9 | 3.10 |
| Find | $i_C(t)$ | $u_L(t)$ | $u_{R1}(t)$ | $i_C(t)$ | $i_{R2}(t)$ | $u_L(t)$ | $i_C(t)$ | $u_L(t)$ | $i_{R2}(t)0$ | $u_{R3}(t)$ |

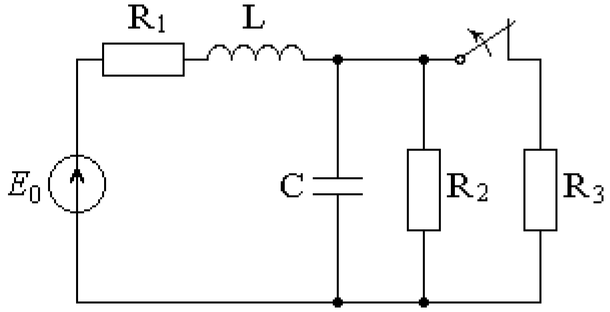
Table 3.2

| Enrollment year | Penultimate digit of the credit book number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| even | 9 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| odd | 0 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| $E_0$, Ω | 50 | 15 | 12 | 24 | 36 | 20 | 10 | 35 | 40 | 30 |
| $R_1$, Ω | 56 | 300 | 120 | 160 | 290 | 150 | 270 | 75 | 90 | 190 |
| $R_2$, Ω | 120 | 170 | 220 | 150 | 110 | 210 | 330 | 50 | 100 | 120 |
| $L$, mH | 30 | 45 | 20 | 50 | 70 | 25 | 60 | 40 | 10 | 35 |

Table 3.3

| Enrollment year | First letter of the surname | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| even | АЯ | УЮФ | КХ | БЛЦ | ВМЧ | ТЭИ | ЖСЗ | ДОЩ | ЕПР | ГНШ |
| odd | ГНШ | АЯ | ЕПР | УЮФ | ДОЩ | КХ | БЛЦ | ЖСЗ | ТЭИ | ВМЧ |
| $R_3$, Ω | 51 | 33 | 70 | 110 | 100 | 150 | 120 | 47 | 60 | 75 |
| $C$, μF | 6,0 | 12,0 | 2,5 | 9,0 | 4,5 | 1,5 | 3,0 | 7,5 | 5,0 | 10,0 |

Circuit diagram variants:



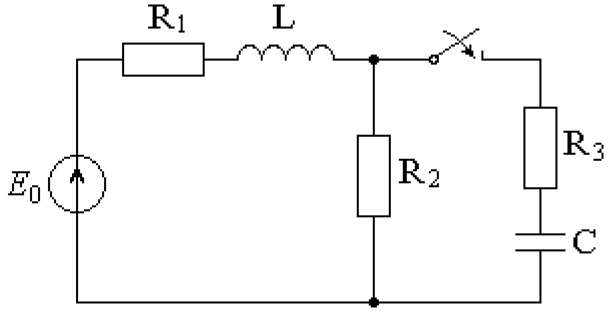
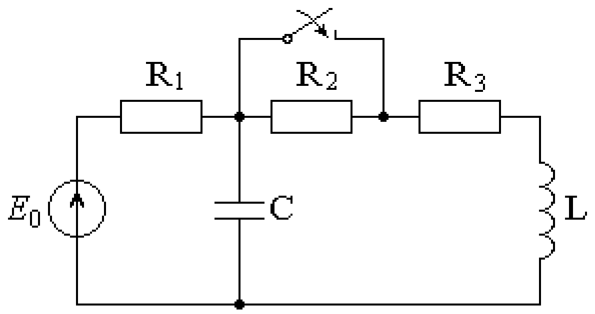




Figure 3.1

Figure 3.2



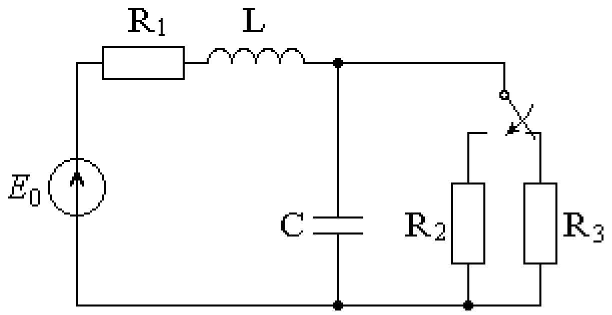




Figure 3.3

Figure 3.4

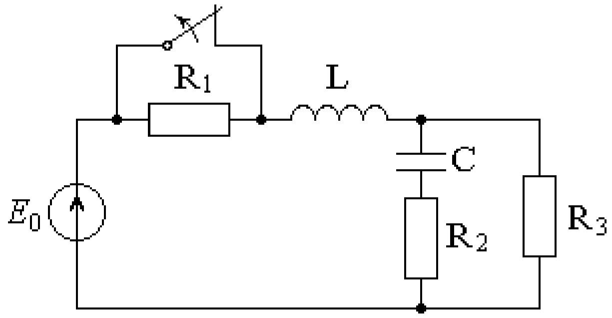



Figure 3.5

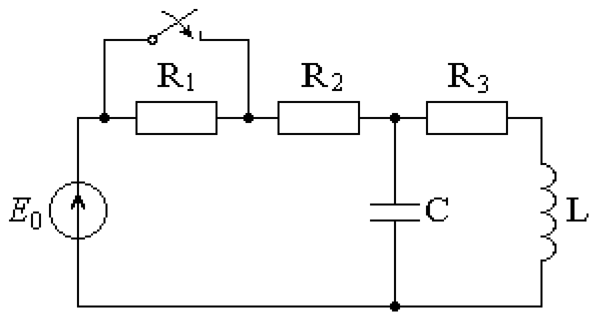



Figure 3.6

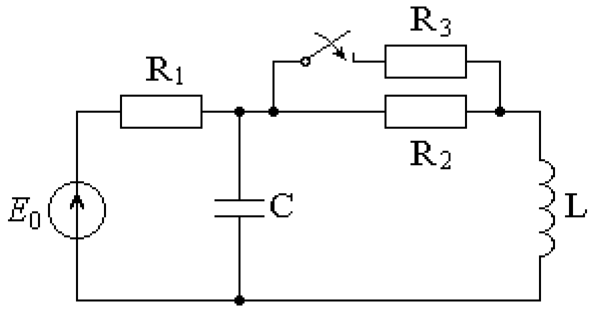



Figure 3.7

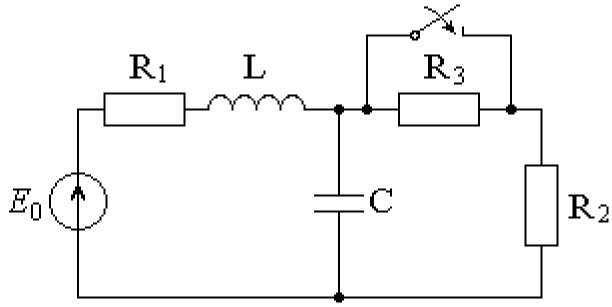



Figure 3.8

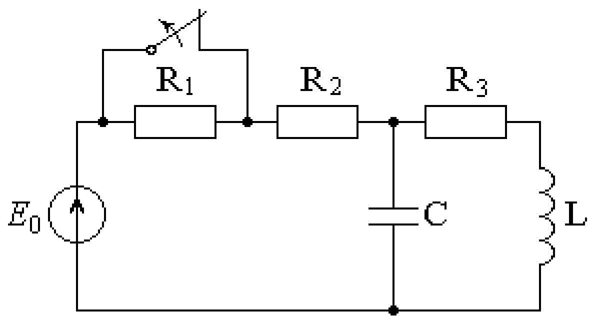



Figure 3.1

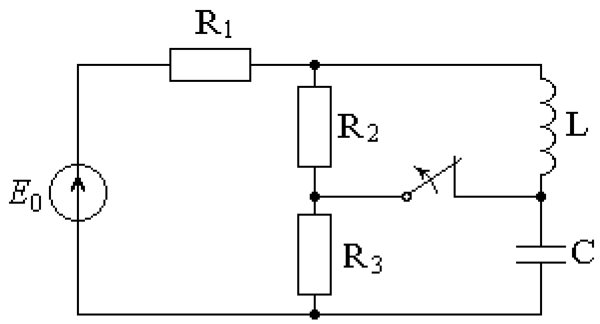



Figure 3.2

**3.2 Methodological guidelines**

Transient process analysis by applying classic calculation method.

Recommended procedure:

1) Calculate the independent initial conditions.

The current in an inductor $i_L(0+)$ and potential difference across capacitor $u_C(0+)$ at first moment after commutation are the independent initial conditions (IIC). The IIC keep their values the same as before commutation. According the commutation law: $i_L(0+) = i_L(0–)$ и $u_C(0+) = u_C(0–)$.

That is why the IIC calculation is carried out using the circuit before commutation by applying steady state analysis methods.

2) Calculate a steady state component of the unknown time function. The calculation is carried out using the circuit diagram after commutation by applying steady state analysis methods.

3) Make a characteristic circuit equation and find its roots.

A characteristic circuit equation composing as input impedance of the circuit after commutation. A circuit's source is replaced by its internal resistance.

Write an expression for the free component of the unknown time function according to kind of the characteristic circuit equation roots. An expression for the free component is a common solution of the homogeneous differential equation. This expression consist of two constants of integration.

4) Calculate the constants of integration.

To calculate two constants of integration it is necessary to find numeric values of the function itself and its first derivative (i.e. function changing velocity) at first moment after commutation $t$ = 0+. In order to do that it is necessary make a system of equation based on Kirchhoff's law for a circuit after commutation. Substitute known IC and find numeric values of the function itself and its first derivative.

Transient analysis by applying Laplace transform.

Recommended procedure:

1) Calculate the independent initial conditions $i_L(0+)$ and $u_C(0+)$.

This point of procedure is the same on a classic method. Therefore, you can use the results of IIC obtained in classic method.

2) Make up the equivalent replacement circuit for the currents and voltages images.

Calculate of an image of the unknown transient function $F$(p). For this purpose, it is possible to apply known steady state mode calculation of methods like the mesh analysis or nodal analysis.

3) Calculate an original of the unknown transient function $f$(t). Apply an expansion theorem to find an original of the transient time function $f$(t) by using its image $F$(p) found before.

References: [R1] – section 8; [R3] – sections 9 and 10; [R6] – §10…11.

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