TFEE-3 (Practical)

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

Dnipro University of Technology

Department of Electrical Engineering

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Guidelines to independent and practical works on discipline THEORETICAL FUNDAMENTALS OF ELECTRICAL ENGINEERING For full-time students' majoring in 141 "Electric Power, Electrical Engineering and Electromechanical"

Part 3
DC AND AC NONNLINEAR CIRCUITS, MAGNETIC CIRCUITS, TRANSIENTS INTO CIRCUITS WITH NONLINEAR ELEMENTS

Dnipro
2021

Рекомендовано до видання навчально-методичним відділом (протокол № від за поданням науково-методичної комісії зі спеціальності 141 – Електроенергетика, електротехніка та електромеханіка (протокол № 21/22-01 від 30.08.2021 р.)

Методичні вказівки до самостійних та практичних занять і контрольні завдання з дисципліни "Теоретичні основи електротехніки" (частина 3, розділи "Нелінійні електричні кола постійного і змінного струмів", "Магнітні кола", "Перехідні процеси в колах з нелінійними елементами") для студентів денної та заочної форм навчання за спеціальностями: 141 Електроенергетика, електротехніка та електромеханіка / В.С. Хілов – Дніпро: Національний технічний університет "Дніпровська політехніка" 2021. – 35 с.

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Методичні вказівки призначено для виконання самостійної роботи і контрольних завдань та проведення практичних занять з дисципліни "Теоретичні основи електротехніки" (частина 3, розділи "Нелінійні електричні кола постійного і змінного струмів", "Магнітні кола", "Перехідні процеси в колах з нелінійними елементами") студентами денної та заочної форм навчання за спеціальностями: 141 Електроенергетика, електротехніка та електромеханіка.

У кожному розділі подано короткі методичні вказівки, типові завдання з рішенням та необхідними поясненнями, а також вихідні дані для виконання самостійно студентами розрахунково-графічних завдань. Наводяться питання для самостійного контролю залишкових знань.

Друкується в редакції автора.

Part content 3

INTRODUCTION

The present methodological instructions (modulus 3, 4) for the calculation of the parameters of nonlinear electric circuits contain the calculation methods: Graphic; Equivalent generator; Replacement; Nodal potentials; According to instant significances of currents and voltages; Equivalent sinusoids.

The present methodological instructions are the direct continuation of methodological instructions for the calculation of DC circuits, of single phase sinusoidal currents and magnetically coupled circuits (moduluses 1, 2), as well as of three-phase schemes at harmonic voltage, of three-phase circuits at symmetrical polyharmonical voltages, of single-phase circuits at presence polyharmonics, of circuits in the unstationary work regimes (moduluses 3, 4).

Nonlinear electric elements find wide application in the practical appendices of electric engineering. This is ascribed to what in the presence of nonlinear elements in electric circuit it is possible the more broad class of phenomena which basically not attainable in linear electric circuits. Straightening of variables currents and voltages, multiplication and the transformation of the spectrum of frequencies, stabilization currents and voltages, the transformation of the levels of constants currents and voltages, the power amplification, the obtainment of modulated oscillations, the obtainment of relaxation oscillations, as well as of the oscillations of various form and frequencies and the row of other phenomena are possible only in nonlinear circuits.

Practically any electric circuit is nonlinear. Only at definite assumptions and on separate working districts we can insist that circuit is linear and to it applicable methods of the calculation of linear circuits.

Principled difference in the methods of the calculation of nonlinear circuits consists in the impossibility of applying of the superposition method and all the rest of the methods based on that method.

To the calculation of the concrete parameters of electric circuits precede brief methodological instructions which follows guided at the calculation of computative-graphic individual assignment.

In the every part end are presented typical questions at concrete tasks deciding. For the verification of the material learning degree for every student imperatively is recommended on one's own to decide indicated tasks.

Accuracy and the correctness of fulfiled computative-graphic tasks are verified by the teachers of cycle and after the obviation of errors are assumed to interlocution.

The interlocution according to the results of performed computative-graphic tasks presents there is dialog with teacher and answer toes set questions in the context of in question topic, or answers to test tasks. The results of interlocution are estimated as to five mark scale.

1. NONLINEAR ELECTRIC DC CIRCUITS CALCULATION METHODS

1.1. Methodological instructions as to the calculation of nonlinear DC circuits

1. Electric scheme comprising at least one nonlinear element on the whole is nonlinear. Nonlinear element is element, volt-ampere characteristic which is not direct line. There are assigned volt-ampere characteristics of nonlinear elements by methods of analytic, graphic or tabular.
2. Nonlinear elements on DC have static and dynamic resistances. Static resistance is always positive. Dynamic resistance for growing volt-ampere characteristics is positive, and for dropping volt-ampere characteristics is negative.
3. In linear elements static and dynamic resistances coincide in all points of volt-ampere characteristic.
4. The calculation methods of the nonlinear DC circuits are based on Kirchhoff's laws connecting between each other currents in nodes, electromotive forces and drops voltages in independent contours.
5. To the calculation of nonlinear circuits will not apply the principle of superposition, that is why all methods of circuits calculation based on the principle of superposition not applicable to nonlinear DC circuits.
6. If working district of nonlinear element it is possible approximate by direct line, then in this case the calculation of the circuit parameters it is possible linearized by means of the replacement of nonlinear element by equivalent dynamic resistance with power supply or static resistance. The calculation of linearized equivalent scheme in the suburb of working point be performed by analytical.
7. In presence in the circuits of two nodes the calculation rational to perform by the method of nodal potentials. With this end in view are built volt-ampere characteristics of every branch which will displacement relatively beginnings of coordinates on value included EMF in this branch. Then be built resulting volt-ampere characteristic of all circuit which lets to find voltage on parallel branches. Knowing voltage on parallel branches find the parameters of all branches.
8. If electric circuit comprises one nonlinear element, then calculation efficiently to perform by the method of equivalent generator. Circuit breaks on passive and active one-port schemes. Passive one-port scheme includes branch with nonlinear element, and active one-port scheme comprises all the rest of the circuit linear part. Active one-port scheme is replaced by equivalent generator. After determination of the linear equivalent generator parameters the task to add up to the search of parameters elementary single loop scheme with source EMF or two loops scheme with source current into nonlinear circuit. There is determining the working point

on nonlinear volt-ampere characteristic which lets linearize nonlinear volt-ampere characteristic by dynamic resistance with the supplementary source of energy or by static resistance. After linearize the calculation of all the rest of the parameters of circuit in initial scheme be performed as in linear one.

9. In case of two nonlinear elements the calculation to perform rational by using of theory of two-port scheme. Computative scheme is presented in the form of active two-port scheme to the clamps of these are connecting two nonlinear elements. Active two-port scheme is presented replacement T-shape scheme of passive two-port scheme with having two sources EMF open circuit. As a result of that the calculation to add up to the search of the parameters of circuit in two loops scheme with three linear and two nonlinear resistances and two sources EMF.

10. The properties of circuit with nonlinear elements substantially excellent from the properties of linear DC circuits. In circuits with nonlinear elements are possible the unstable regimes of work at negative dynamic resistances. In the linear circuits resistance always positive, that is why the work regimes of these circuits always stable.

1.2. The graphic calculation of parameters branched nonlinear circuit with single nonlinear element

Task.

Two linear (R_1=2 Ohm, R_2=40 Ohm) and one nonlinear elements are included as to scheme Fig.1.1, a. The volt-ampere characteristic of nonlinear resistance is set graphic, Fig.1.2 (curve $R_3(U_3(I_3))$). Scheme is included on voltage 50 V. Determine currents in all branches of and voltages on the scheme elements.

Task solution.

1. The most demonstrably calculation of the circuit parameters we can fulfil by graphic method.

As there resistances R_1=2 Ohm, R_2=40 Ohm are linear, their volt-ampere characteristics $U_1(I_1)$, $U_2(I_2)$ are direct lines which the most simply draw on two characteristic points belonging to VAC: the onset of coordinates and the voltage drop on linear resistances R_1 and R_2, for example, in current 1A will 2 V and 40 V, according. We connect these points with the onset of coordinates and obtain direct lines belonging to the volt-ampere characteristics of linear elements R_1 $(U_1(I_1))$, R_2 $(U_2(I_2))$, Fig.1.2.

2. As to VAC of nonlinear R_3 $(U_3(I_3))$and linear elements R_2 $(U_2(I_2))$ we draw of summarized VAC of parallel district R_{23} $(U_2(I_2+I_3)=U_3(I_2+I_3)=U_2(I_1)=U_3(I_1))$, thereby replacing parallel connection linear R_2 and nonlinear R_3 by one nonlinear R_{23} (Fig.1.1.b).

The curve construction performs with allowance at the parallel elements connection branches current are summarized at equal voltage on elements.

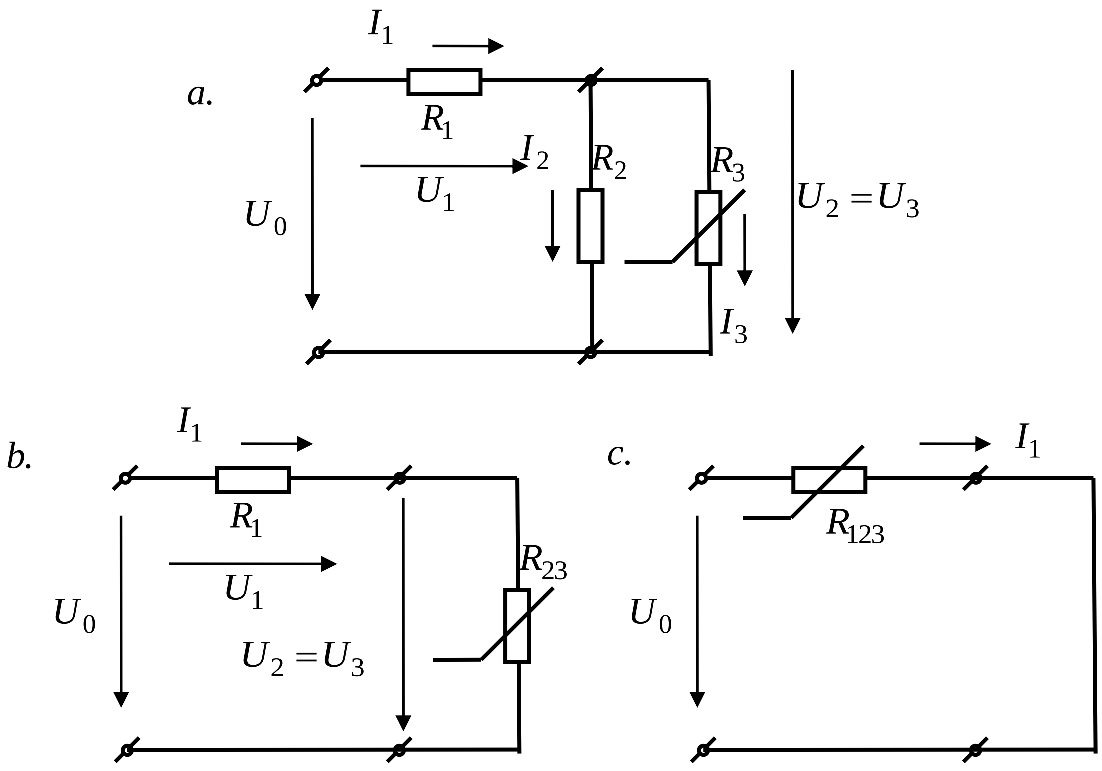


Рис. 1.1

3. As to VAC of linear R_1 $(U_1(I_1))$ and nonlinear R_{23} $(U_2(I_1) = U_3(I_1))$ elements we build the resulting VAC of all scheme R_{123} $(U(I_1))$, Fig.1.1.c, Fig.1.2. Resulting VAC is nonlinear characteristic. Namely presence at least of one nonlinear element in circuit makes all one nonlinear.

Building perform with allowance for, what in the series elements connection voltages on elements are summarized at identical in elements current.

4. As to known the supply voltage $U_0 = 50\,\text{V}$ and the resulting VAC of all scheme R_{123} $(U(I_1))$ we find current in unbranched part of circuit $I_1 = 3\text{A}$.

5. As to significance of input current $I_1 = 3\text{A}$ we find the voltage drop on падение on linear resistor R_1 as to it VAC $(U_1(I_1))$ $U_1 = 6\text{В}$ and voltage on parallel branches as to summarized characteristic of scheme parallel part R_{23} $(U_2(I_1) = U_3(I_1))$ $U_2 = U_3 = 44\,\text{V}$.

6. As to found voltages $U_2 = U_3 = 44\,\text{V}$ we find currents in parallel branches $I_2 = 1\text{A}$, $I_3 = 2\,\text{A}$, using characteristics of nonlinear R_3 $(U_3(I_3))$ and linear elements R_2 $(U_2(I_2))$, Fig.1.2.

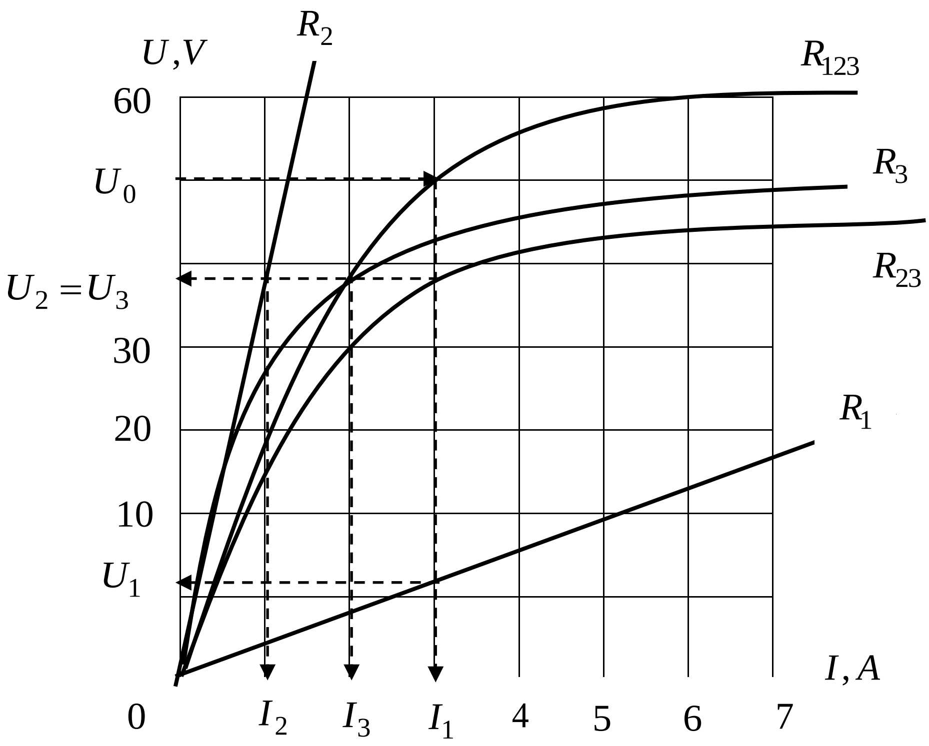


Рис. 1.4

7. The solution check we do according to Kirchhoff's laws:
– algebraic currents sum in node is equal to zero
$I_1 - I_2 - I_3 = 3 - 1 - 2 = 0$;
– algebraic voltages sum in close loop is equal to zero
$U_0 - U_1 - U_2 = 50 - 44 - 6 = 0$.

1.3. Parameters calculation of branched nonlinear circuit with one nonlinear element by the method of equivalent generator

Task.
In scheme of electric bridge рис.1.3. into one bridge branch include nonlinear element R_1. Volt-ampere characteristic of nonlinear element R_1 $U_1(I_1)$ is given on Fig.1.4.
Determine currents in all branches if the linear parameters of circuit are known: $R_2 = 4$ Ohm, $R_3 = 6$ Ohm, $R_4 = 12$ Ohm, $R_5 = 2$ Ohm. The voltage in bridge diagonal is $U_0 = 12$ V.

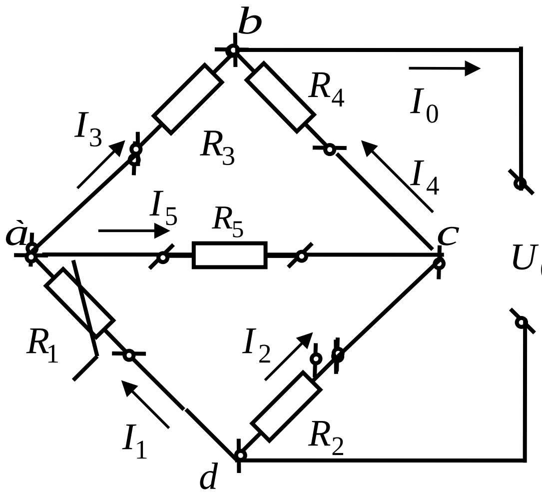


Fig.1.3

Task solution.

The current I_1 we shall determine taking advantage of the equivalent generator method.

We shall disconnect branch with element R_1 and shall find the open circuit voltageU_{oc}, i.e. voltage on terminals *ab*, having applicated second Kirchhoff law:

$U_{oc} = U_{ab} = R_3 I_{3oc} + R_5 I_{5oc} = 6 \cdot 1{,}2 + 2 \cdot 0{,}8 = 8{,}8, V,$

where under the Ohm's low $I_{3oc} = \dfrac{U_0}{R_3 + \dfrac{R_4(R_2 + R_5)}{R_4 + R_2 + R_5}} = 1{,}2, A;$

and according to the rule of division currents between two parallel branches $I_{5oc} = I_{3oc} \dfrac{R_4}{R_4 + R_2 + R_5} = 0{,}8, A.$

We shall determine the inner resistance R_{sc} of the equivalent generator relatively of terminals *ab* at the short circuit of clamps *ca*

$$R_{sc} = \frac{\left(R_5 + \dfrac{R_3 R_4}{R_3 + R_4}\right) R_2}{R_2 + R_5 + \dfrac{R_3 R_4}{R_3 + R_4}} = 2{,}4 \text{ Ohm}.$$

After transformation all linear circuit is replaced by equivalent generator with known open circuit EMF and by the short circuit inner resistance. The replacement equivalent scheme presents contour with series connected the equivalent generator and nonlinear resistance.

For finding the current I_1 we build load volt-amper characteristic of equivalent generator under on two characteristic points: open circuit $U_{oc} = 8{,}8, V$, $I_{oc} = 0, A$ and short circuit $U_{sc} = 0, V$ $I_{sc} = U_{oc} / R_{sc} = 3{,}7, A$, Fig.1.4.

The intersection point of the equivalent generator load characteristic with nlinear element VAC determines working regime of the replacement equivalent scheme.

The coordinates of the intersection point of VAC characteristics determine voltage of and current of nonlinear element R_1: $I_1 = 0{,}8, A$, $U_1 = 7{,}8, V$.

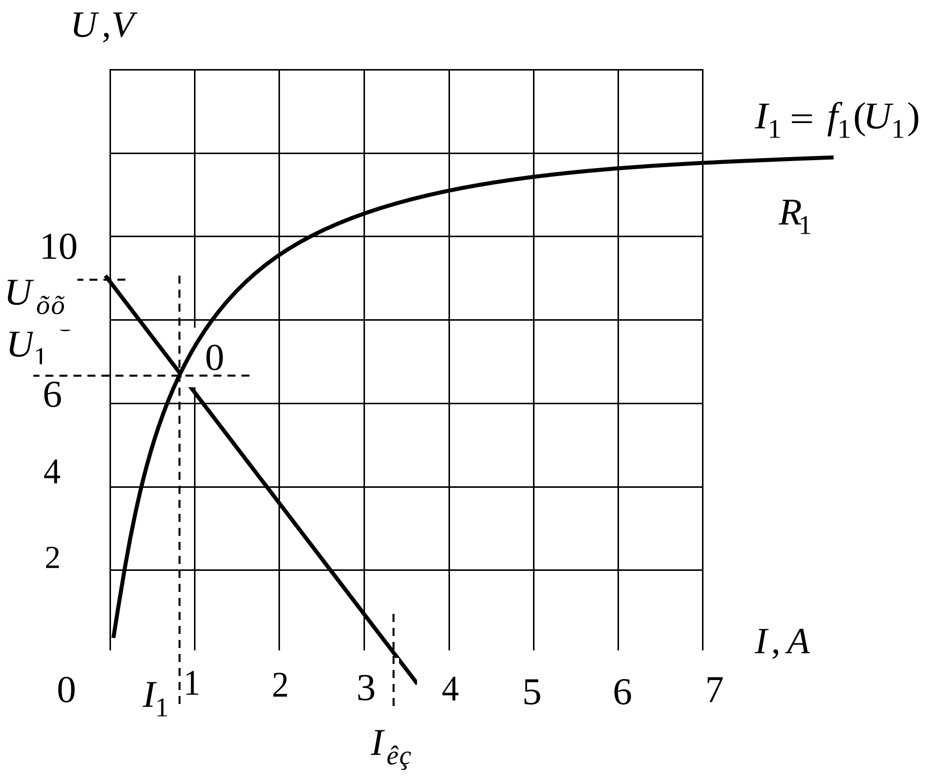


Fig. 1.4

Being returned to initial scheme, we may find branches current:

$$I_3 = \frac{U_0 - U_1}{R_3} = 0{,}7, A, \quad I_5 = I_1 - I_3 = 0{,}1, A, \quad I_4 = \frac{I_3 R_3 - I_5 R_5}{R_4} = 0{,}33, A,$$

$$I_2 = I_4 - I_5 = 0{,}23, A.$$

1.4. The calculation of parameters branched nonlinear circuit with two nonlinear elements by the replacement method

Task.

There is given bridge scheme having two nonlinear elements: in branch *ab* $R_1(I_1)$ and $R_2(I_2)$ in branch *bc* (Fig. 1.5.). Volt-ampere characteristics are presented on Fig. 1.6, resistances of the rest branches are equal $R_3 = 6$ Ohm, $R_4 = 12$ Ohm, $R_5 = 2$ Ohm. Voltage in the diagonal of feed source $U_0 = 12$ V.

It is necessary determine currents in all branches.

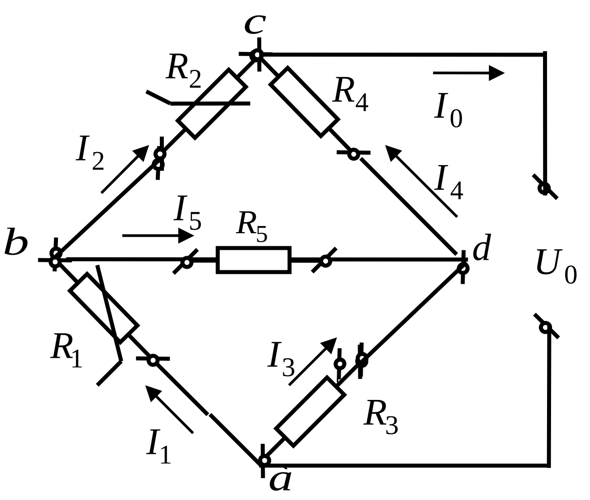


Fig.1.5

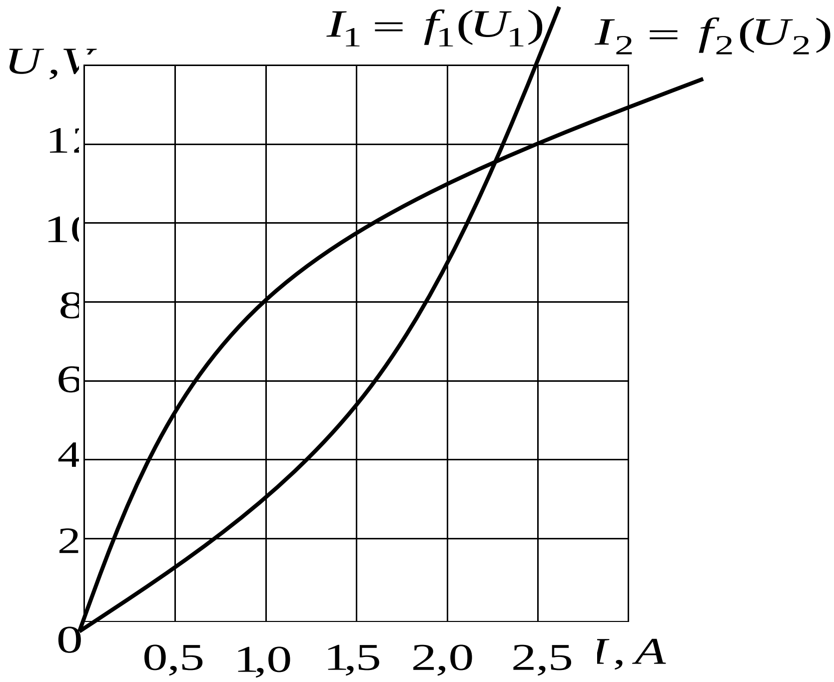


Fig.1.6

The task solution.

For calculation currents I_1 and I_2 in branches with nonlinear elements we use the compensation principle for that open these branches and find of open circuit voltages $U_{1oc} = U_{ab}$ и $U_{2oc} = U_{bc}$, Fig.1.7.a.

$$U_{1oc} = \frac{U_0 R_3}{R_3 + R_4} = 4, V$$

and $$U_{2oc} = \frac{U_0 R_4}{R_3 + R_4} = 8, V.$$

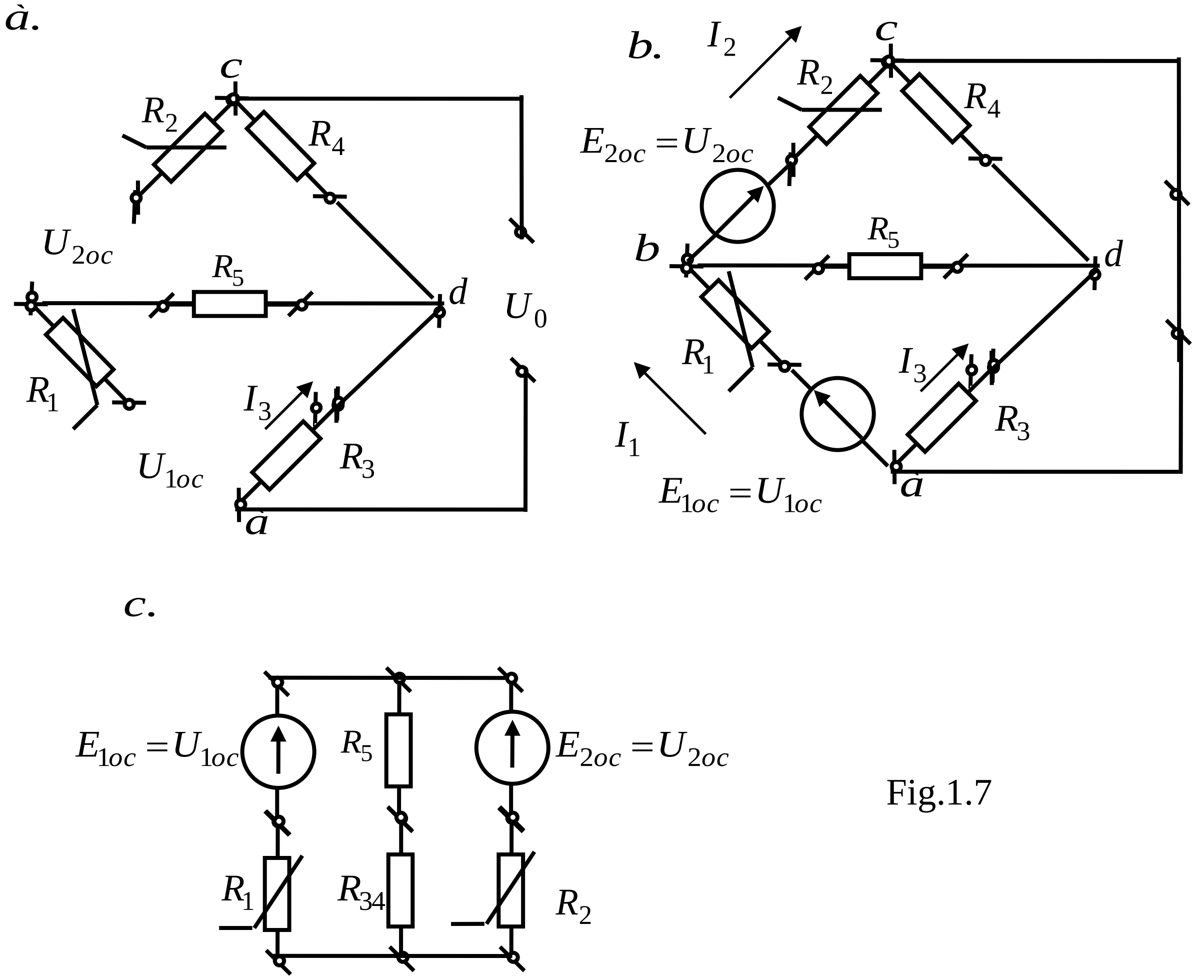


Fig.1.7

We shall include into branches with nonlinear elements EMFs $E_{1oc} = U_{1oc}$ and $E_{2oc} = U_{2oc}$ and close short clamps *ca*, to which is connected the external voltage source U_0, Fig.1.7.b.

Currents I_1 and I_2 in branches with the nonlinear elements in transformed scheme will be equal of real currents in initial scheme into corresponding scheme branches. After the replacement of two parallel branches with resisters R_3 and R_4 by one equivalent branch, we will receive scheme with two nodes (Fig.1.7.c), where

$R_2 = 2\,\text{Ohm}$ and $R_{34} = \dfrac{R_3 R_4}{R_3 + R_4} = 4\,\text{Ohm}$.

By using this scheme, it is possible currents I_1 and I_2 it is possible currents and determine by graphical method, as in task 1.2 having built characteristics, Fig. 1.6. As currents I_1 and I_2 are currents in initial scheme that current $I_5 = I_1 - I_2$ in equivalent scheme has also value, as in initial scheme. Currents I_3 and I_4 easily are determined on the grounds on Kirhhoff's laws in initial scheme. Current values are equal: $I_1 = 1{,}15$ A, $I_2 = 1{,}05$ A, $I_3 = 0{,}6$ A, $I_4 = 0{,}7$ A, and voltage on the clamps of nonlinear elements – $U_1 = 3{,}4\,\text{V}$, $U_2 = 8{,}6\,\text{V}$.

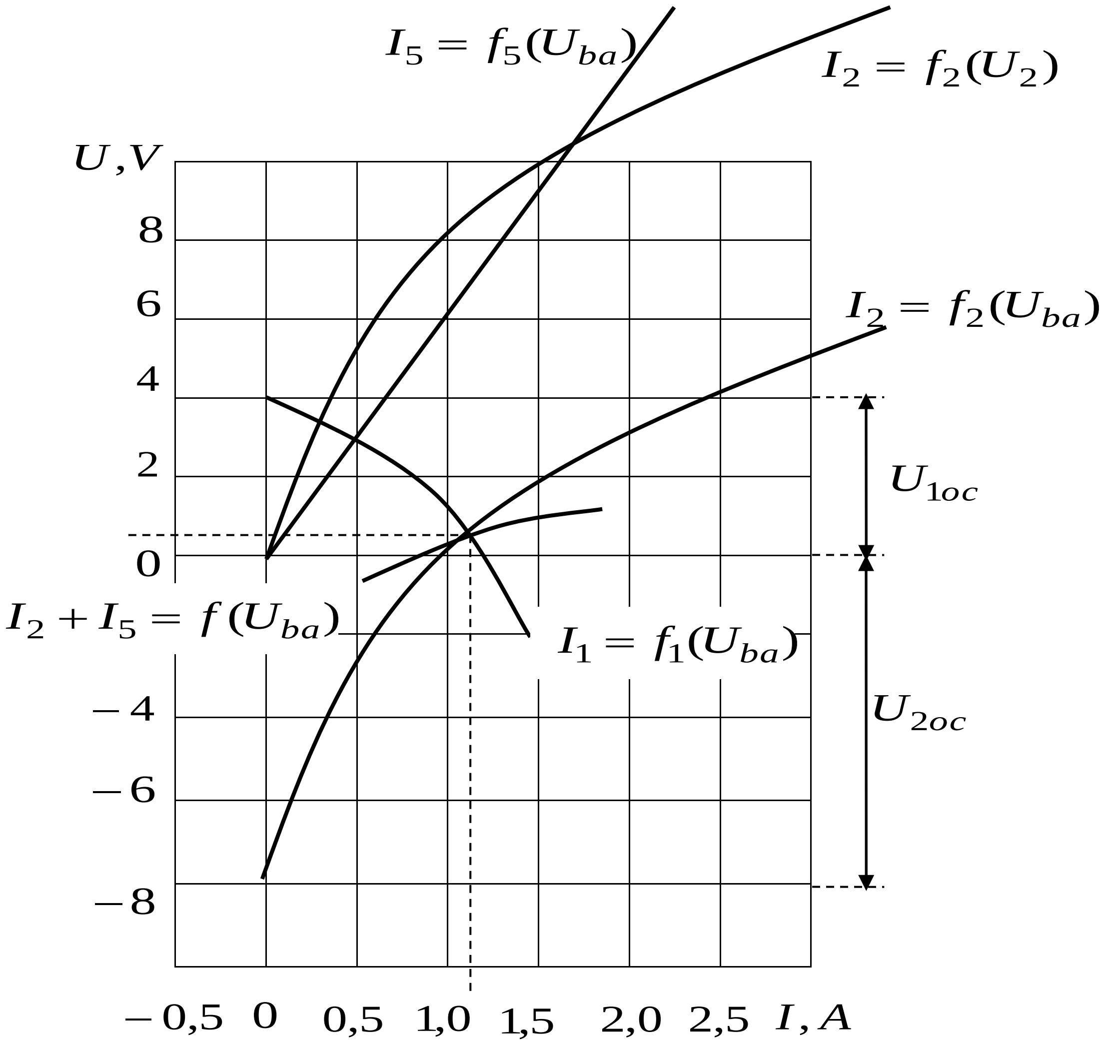


Fig.1.8

1.5. Parameters calculation of branched nonlinear circuit with three nonlinear elements by the nodal potentials method

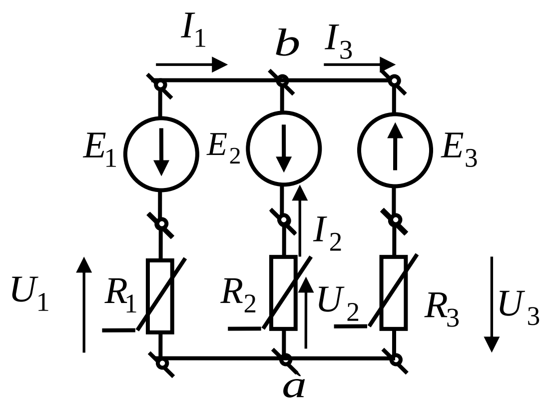


Fig.1.9

Task.
There is given the scheme of electric circuit with having three similar nonlinear elements, Fig.1.9. Electromotive forces of energy sources are equal
$E_3 = 100\,\text{V},\ E_1 = 10\,\text{V},\ E_2 = 30\,\text{V}.$
Determine currents into all branches, considerring sources EMF as ideal. Volt-ampere characteristics of nonlinear elements are given tabularly in the first quadrant and led in table 1.1.

Table 1.1.

U, В	0	4	8	25	110	115	118
I, мА	0	10	20	40	60	80	100

The task solution.

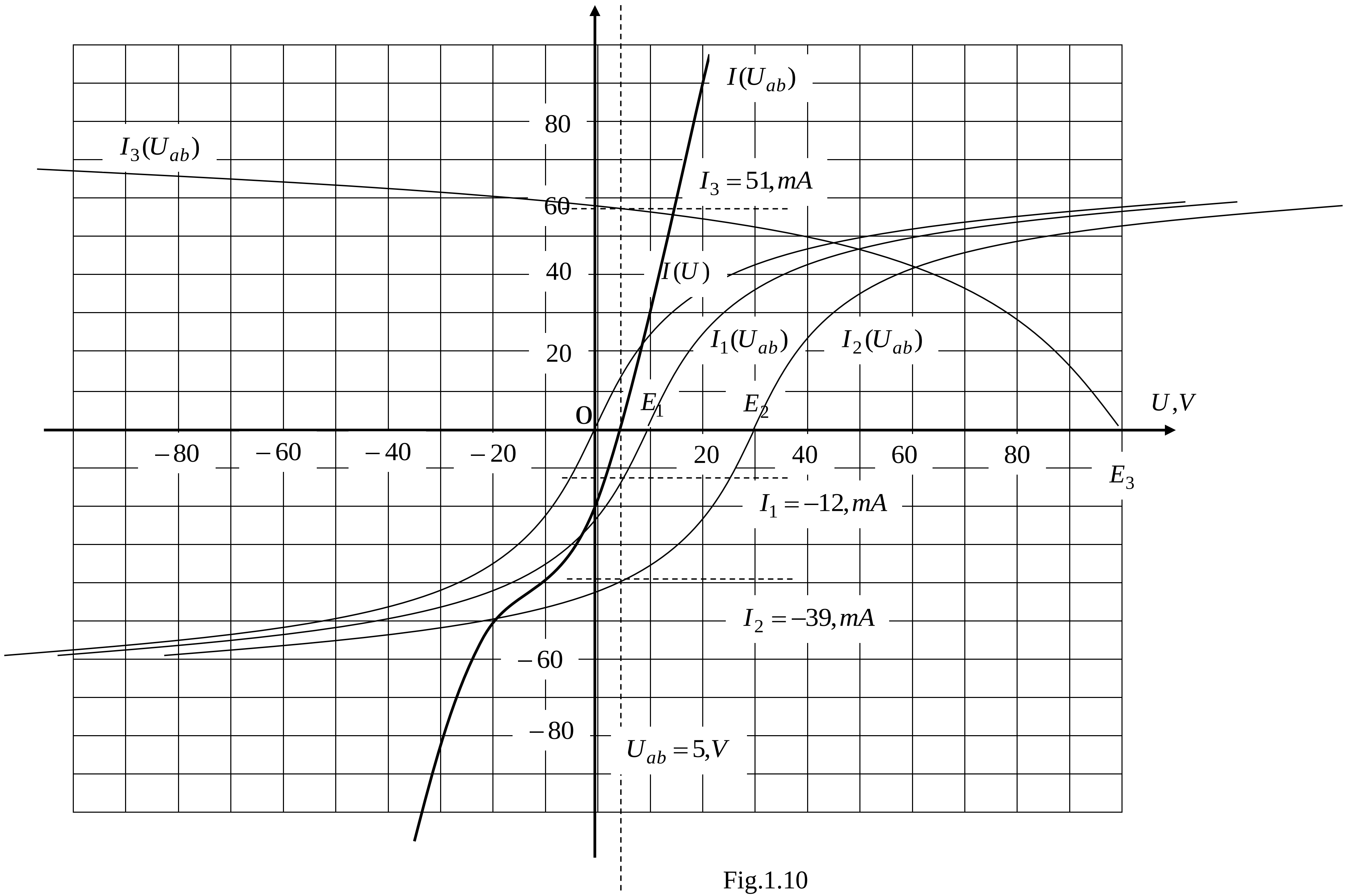
We assign the positive directions of branches current I_1, I_2, I_3 and build volt-ampere characteristics of branches (Fig.1.10) $I_1(U_{ab}) = I_1(E_1 + U_1)$, $I_2(U_{ab}) = I_2(E_2 + U_2)$, $I_3(U_{ab}) = I_3(-E_3 + U_3)$ based on potential equations on parallel branches

$U_{ab} = E_1 + U_1; U_{ab} = E_2 + U_2; U_{ab} = -E_3 + U_3$,

where U_1, U_2, U_3 – voltages on clamps nonlinear resistors, Fig.1.9.

On the grounds of curves $I_1(U_{ab}) = I_1(E_1 + U_1)$, $I_2(U_{ab}) = I_2(E_2 + U_2)$ we will build resulting curve $I(U_{ab})$ and find point intersections the resultant awry with axis of abscissas. At this point are fulfiled to both Kirhhoff's laws. By graphically method we find branches current value $I_1 = -12, mA$, $I_2 = -39, mA$, $I_3 = 51, mA$. Negative current values bear evidence about what of their true direction contrary beforehand chosen.

The voltage between the nodes of scheme likewise find by graphically method $U_{ab} = 5, V$.

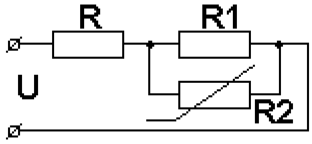


I(U_ab)
80
I_3(U_ab)
I_3 = 51, mA
60
40
I(U)
20
I_1(U_ab)
I_2(U_ab)
E_1
E_2
U, V
O
– 80
– 60
– 40
– 20
20
40
60
80
E_3
I_1 = –12, mA
I_2 = –39, mA
– 60
– 80
U_ab = 5, V

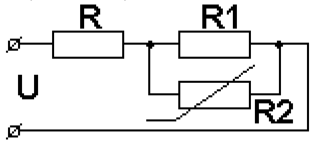
Fig.1.10

1.6. Questions for self-checking as to the calculation methods of nonlinear DC circuit

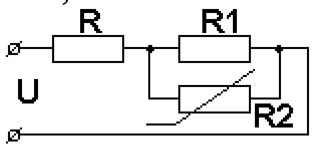
1. Find the applied voltage U, if resistor VAC R2 $U2=5\cdot(I2)^2$, R=R1=10 Ohm, resistor current R1 I1=4 A.



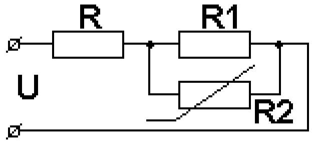
2. Find the value of static resistance R2 in working point, if resistor VAC R2 $U2=5\cdot(I2)^2$, R= R1=10, Ohm, resistor current R1 I1=4, A.



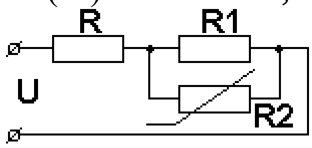
3. Find the value of dynamic resistance R2 in working point, if resistor VAC R2 $U2=5\cdot(I2)^2$ R= R1=10 Ohm, resistor current R1 I1=4, A.



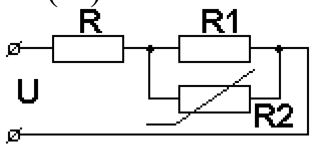
4. Find the value of nonlinear element current, if resistor VAC R2 $U2=5\cdot(I2)^2$ R= R1=10 Ohm, U=70 V.



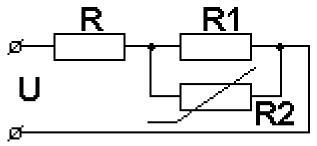
5. Find the value of nonlinear element dynamic resistance in working point, if resistor VAC R2 $U2=5\cdot(I2)^2$ R= R1=10, Ohm; U=70 V.



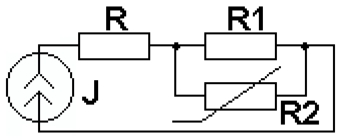
6. Find the value of nonlinear element static resistance in working point, if resistor VAC R2 $U2=5\cdot(I2)^2$ R= R1=10 Ohm; U=70 V.



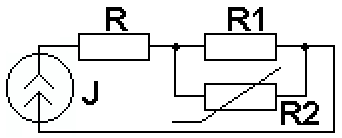
7. Find the power of the feed source, if resistor VAC R2 $U2=5\cdot(I2)^2$, R=R1=10 Ohm, resistor current R1 I1=4 A.



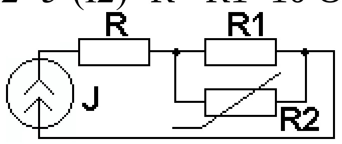
8. Find the drop voltage on resistor R, if VAC R_2 $U2=5\cdot(I2)^2$, R= R1=10 Ohm, resistor current R1 I1=2 A.



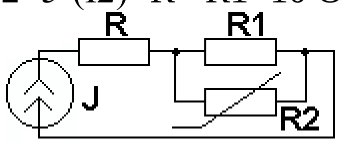
9. Find the power of the feed source, if resistor VAC R2 $U2=5\cdot(I2)^2$, R=R1=10 Ohm, resistor current R1 I1=2 A.



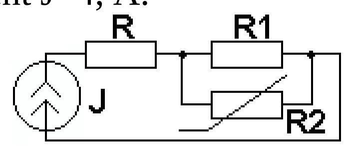
10. Find the value of nonlinear element static resistance in working point, if resistor VAC R2 $U2=5\cdot(I2)^2$ R= R1=10 Ohm; resistor current R1 I1=2 A.



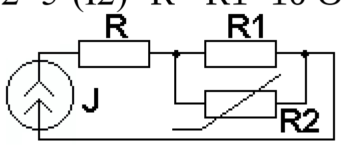
11. Find the value of nonlinear element dynamic resistance in working point, if resistor VAC R2 $U2=5\cdot(I2)^2$ R= R1=10 Ohm, resistor current R1 I1=2, A



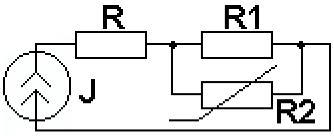
12. Find the nonlinear element current, if resistor VAC R2 $U2=5\cdot(I2)^2$ R= R1=10 Ohm, current J=4, A.



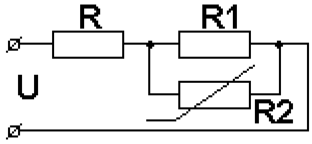
13. Find the value of nonlinear element static resistance in working point, if resistor VAC R2 $U2=5\cdot(I2)^2$ R= R1=10 Ohm; J=4 A.



14. Find the value of nonlinear element dynamic resistance in working point, if resistor VAC R2 $U2=5\cdot(I2)^2$ R= R1=10 Ohm; J=4 A.



15. Find the applied voltage U, if resistor VAC R2 $U2=5\cdot(I2)^2$, R=R1=10 Ohm, drop voltage on resistor R1 U1=40 V.



2. THE MAGNETIC CIRCUITS CALCULATION METHODS UNDER PERMANENT MAGNETIZING FORCES

2.1. Methodological instructions as to the calculation of magnetic circuits under DC

1. Magnetic circuit presents the aggregate of devices that comprising of ferromagnetic body and forming close loop, in which there is presence magnetezing force that generated magnetic flux.
2. Ampere's circuital law and the continuity principle of magnetic flood there are basic laws of magnetic circuits. On this principles establish relations between magnetomotive forces, magnetic fluxes and magnetic resistors.
3. Ohm's Llw for magnetic circuit: magnetic flux on the district of magnetic conductor circuit the directly proportional to the value of difference magnetic potentials that applied to ending points of magnetic conductor and the back proportional to the value of the district magnetic resistance.
4. The first Kirhhgoff's law for magnetic circuits (law of magnetic fluxes): the algebraic sum of magnetic fluxes in the magnetic circuit node is equal to zero.
5. The second Kirhhgoff's law for magnetic circuits (law of magnetic voltages): in any contour of close magnetic circuit the algebraic sum of magnetic voltages is equal to zero.
6. Magnetic circuit maybe presented by analog of electric scheme. The principled difference magnetic circuits from electric DC circuits is that magnetic resistance does not accept of infinite large value. That is why in the presence of magnetomotive force always exists magnetic flux which differ from zero. In electric DC circuits in presence EMF current in circuit can be absent.
7. Magnetic circuits comprise districts from ferromagnetic bodies, the magnetic resistance of which into many times less of air gap magnetic resistance. In such cases the major part of magnetic flux closed through districts without air gap.
8. The presence of air gap on district magnetic conductor give the possible to neglect the insignificant magnetic resistance of magnetic conductor versus the resistance of air gap.

9. As a rule presence of air gap brings to this circuit district become linear.
10. At calculations neglect the leakage fluxes. At the calculation of magnetic circuits we will suppose that magnetic flux closed into magnetic conductors and air gap without dispersion into surrounding medium.
11. Because the magnetic properties of ferromagnetic substances change depending on the value of the magnetic field intensity, that magnetic circuits with ferromagnetic materials are nonlinear. To the calculation of magnetic circuits with saturated magnetic conductors it is impossible to apply the principle of superposition and methods that based on this principle.
12. The calculation of magnetic circuit usually be bring to the search of magnetic fluxes as to given magnetomotive forces (inverse task) or to the search of magnetomotive forces as to given magnetic fluxes (direct task).

2.2. Calculation magnetizing current as to given magnetic flux of ferromagnetic core (direct task)

Task.
Steel core magnetic conductor is fulfiled from sheets electrical steel Э-31 with winding that has W=300 turns.
Find current I_1 in coil, if requested to create in core magnetic flux Φ = $1{,}3 \cdot 10^{-4}$ Wb. All sizes of magnetic conductor and air gap are given on Fig.3.1 in millimeters. Magnetizing curve B (H) of steel E-31 is given in table 2.1.

Table 2.1.

B, T	0	0,65	1,0	1,18	1,25	1,34	1,38
H, A/m	0	100	200	400	600	800	1000

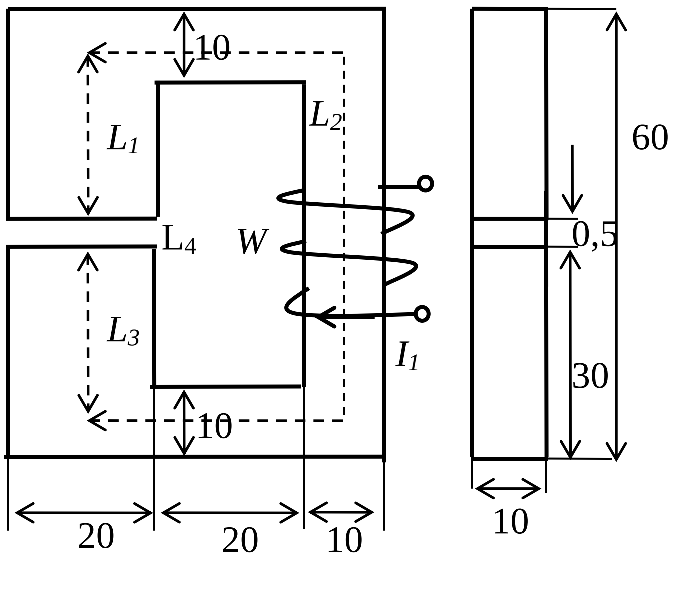


Fig. 2.1

The task solution.
The lengths of districts along middle magnetic lines of force $L_1 = 0{,}025$ m; $L_2 = 0{,}12$ m; $L_3 = 0{,}025$ m; $L_4 = 0{,}5 \cdot 10^{-3}$ m.
Cross-section of districts $S_1 = S_3 = S_4 = 2 \cdot 10^{-4}$ m^2; $S_2 = 1 \cdot 10^{-4}$ m^2.
The magnetic flux density values in cross-section of magnetic conductor
$B_1 = B_3 = B_4 = \hat{O} / S_1 = 0{,}65\,T;$
$B_2 = \hat{O} / S_2 = 1{,}3\ T.$

As to magnetizing curve find the magnetic field intensity on magnetic conductor districts

$H_1 = H_3 = 100$ *A/m*; $H_2 = 650$ *A/m*.

the magnetic field intensity in air gap

$H_4 = 0{,}8 \cdot 10^6 B_4 = 520 \cdot 10^3$ *A/m*.

Magnetomotive force of the winding

$F = I_1 W = H_1 L_1 + H_2 L_2 + H_3 L_3 + H_4 L_4 = 343 A$.

Winding magnetization current

$I_1 = F / W = 1{,}14\ A$.

2.3. The calculation of magnetic fluxes as to given magnetizing forces (inverse task)

Task.

The magnetic conductor from cast steel (Fig.2.2.) has two windings with currents $I_1 = 10$ A и $I_2 = 20$ A. The first winding W_1 has 200 turns, and second one W_2 has 218 turns. Currents positive directions in windigs are pointed on Fig.2.2 by arrows. The magnetic conductor sizes: $S_1 = S_2 = 30\ ñm^2$; $S_3 = S_0 = 36\ ñm^2$; $L_1 = L_2 = 46\ ñm$; $L_3 = 24{,}8\ ñì$; $l_0 = 0{,}2\ ñm$ $(L, l$ – there are lengths of middle magnetic lines and air gap). Find the distribution of magnetic fluxes in cores. By the leakage fluxes can be neglected.The magnetic conductor material is fulfiled from cold-rolled steel strip with thickness 1,75 mm.

The task solution.

The direction of magnetic fluxes we choose as arbitrary. On the grounds of the first and second Kirhhgoff's laws for magnetic circuits compose equations:

$$\left.\begin{aligned}
&\hat{O}_3 = \hat{O}_1 + \hat{O}_2;\\
&I_1 W_1 = H_1 L_1 + H_3 L_3 + H_0 l_0 = H_1 L_1 + U_{M3};\\
&I_2 W_2 = H_2 L_2 + H_3 L_3 + H_0 l_0 = H_2 L_2 + U_{M3};\\
&U_{M3} = H_3 L_3 + H_0 l_0.
\end{aligned}\right\}$$

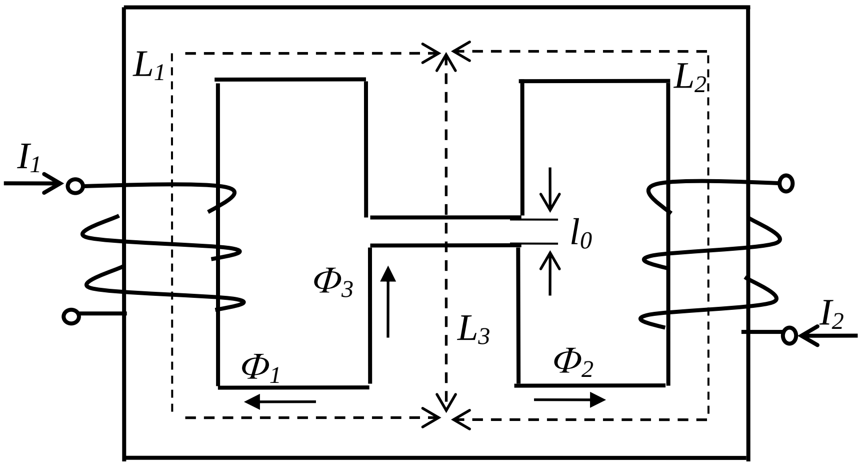


Fig. 2.2

Because dependence between magnetic flux *Φ* and the magnetic field strength *H* has no analytic expression that received equations set decide by graphic method. For equations set solution we draw dependences of magnetic fluxes in cores magnetic conductors from magnetic voltages U_{M3} (Fig.2.3). Values of magnetic fluxes assigning within from $150 \cdot 10^{-5}$ Wb till $510 \cdot 10^{-5}$ Wb, and find magnetic induction in cores, and then as to magnetization curve determine the magnetic field strength *H*.

Knowing the magnetic field strength *H*, we find the drops of magnetic potentials on districts for the various significances of magnetic fluxes. The results of calculations are tabulated into table 2.2.

Table 2.2.

$\Phi \cdot 10^{-5}$, *Wb*	$B_1 = B_2 \cdot 10^{-5}$, *Wb/ñm*^{2}	$H_1 = H_2$, *A/cm*	$H_1L_1 = H_2L_2$, *A*	$I_1W_1 - H_1L_1$, *A*	$I_2W_2 - H_2L_2$, *A*
150	5	2,3	106	1894	4254
210	7	4	184	1816	4176
240	8	5	230	1770	4130
300	10	7,5	345	1655	4015
360	12	12,5	575	1425	3785
390	13	16,7	770	1230	3560
450	15	35	1610	390	2750
510	17	73	3360	-1360	1000

According to data of tables 2.2 we draw curves $\hat{O}_1(I_1W_1 - H_1L_1)$; $\hat{O}_2(I_2W_2 - H_2L_2)$ (Fig.2.3) where $I_1W_1 - H_1L_1 = I_2W_2 - H_2L_2 = H_3L_3 + H_0l_0 = U_{M3}$, i.e. magnetic voltage on third district. Because the magnetic fluxes volue must content to equation $\hat{O}_3 = \hat{O}_1 + \hat{O}_2$, we draw another auxiliary curve $\hat{O}_1 + \hat{O}_2 = f(U_{M3})$.

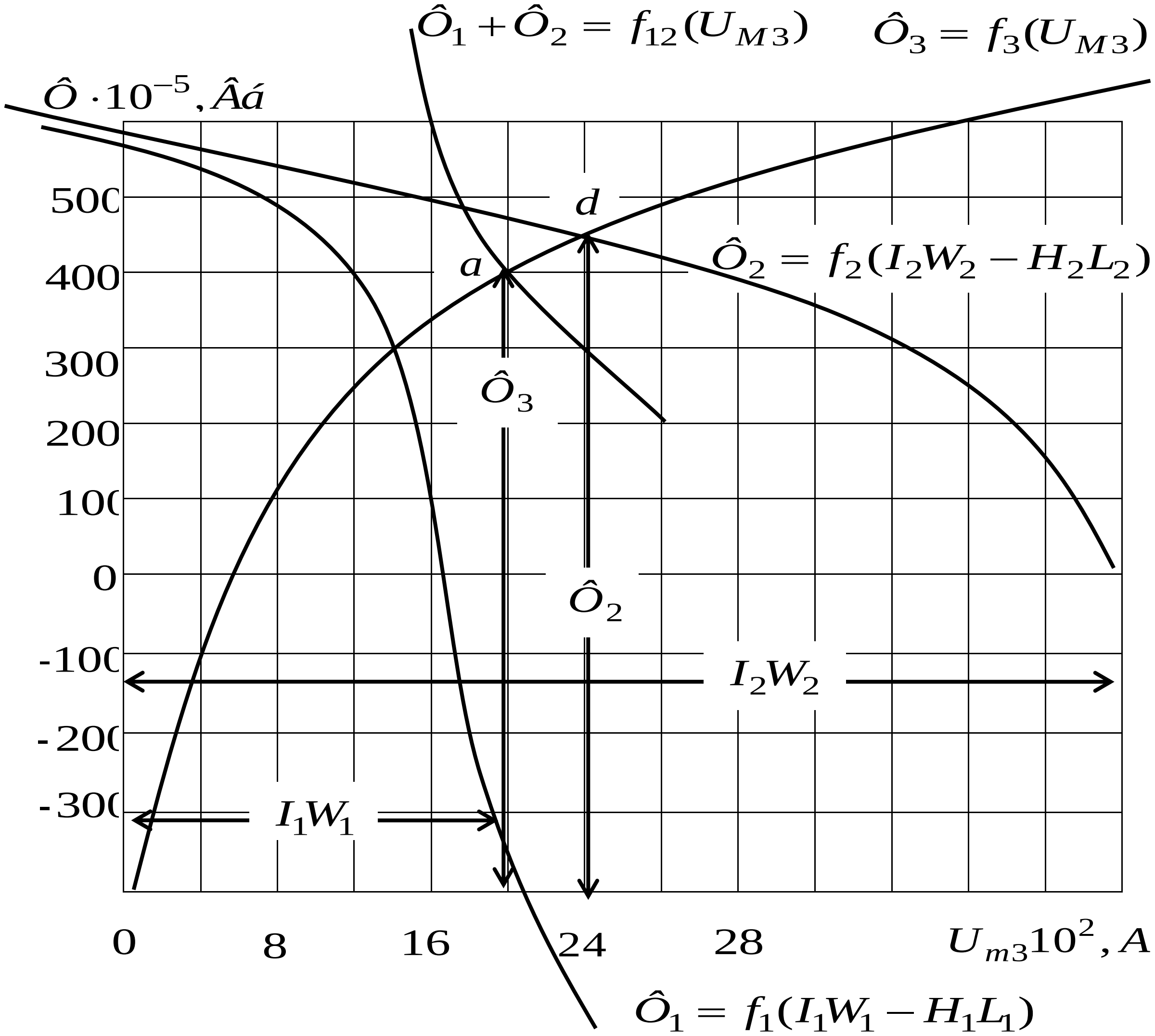


Fig.2.3

For drawing the auxiliary curve summarize ordinates of curves $\hat{O}_1 = f_1(U_{M3})$ and $\hat{O}_2 = f_2(U_{M3})$ for one and the same the significances of magnetic voltage U_{M3}. The intersection point ordinate of curve $\hat{O}_1 + \hat{O}_2 = f(U_{M3})$ with curve $\hat{O}_3 = f_3(U_{M3})$ determines the value of flux $\hat{O}_3$, because for this point fair all equations determining magnetic state of computative magnetic conductor, i.e. $\hat{O}_3 = \hat{O}_1 + \hat{O}_2$;

$I_1W_1 - H_1L_1 = I_2W_2 - H_2L_2 = H_3L_3 + H_0l_0$.

For the finding magnetic fluxes $\hat{O}_1$ and $\hat{O}_2$ we shall draw through point *a* direct line by parallel to axis of ordinates till intersection with curves $\hat{O}_1(I_1W_1 - H_1L_1)$

and $\hat{O}_2 = f_2(U_{M3})$. We shall receive intercepts which determining on scale fluxes $\hat{O}_1$=$\hat{O}_2$.

Shall notice that preliminarily chosen positive direction of flux $\hat{O}_1$ did not coincide with the real direction of flux in core magnetic conductor, and it value is received as negative.

2.4. The magnetic voltage drops calculation in cores magnetic conductor as to given magnetizing forces

Tasc.

The initial data of magnetic circuit are presented on Fig.2.4:

– the number turns of the first core spool W_1= 200 turns;

– second spool magnetization current I_2 =10A;

– the number turns of the second core spool W_2= 150 turns;

– the value of air gap in third core l_{02} =10 mm.

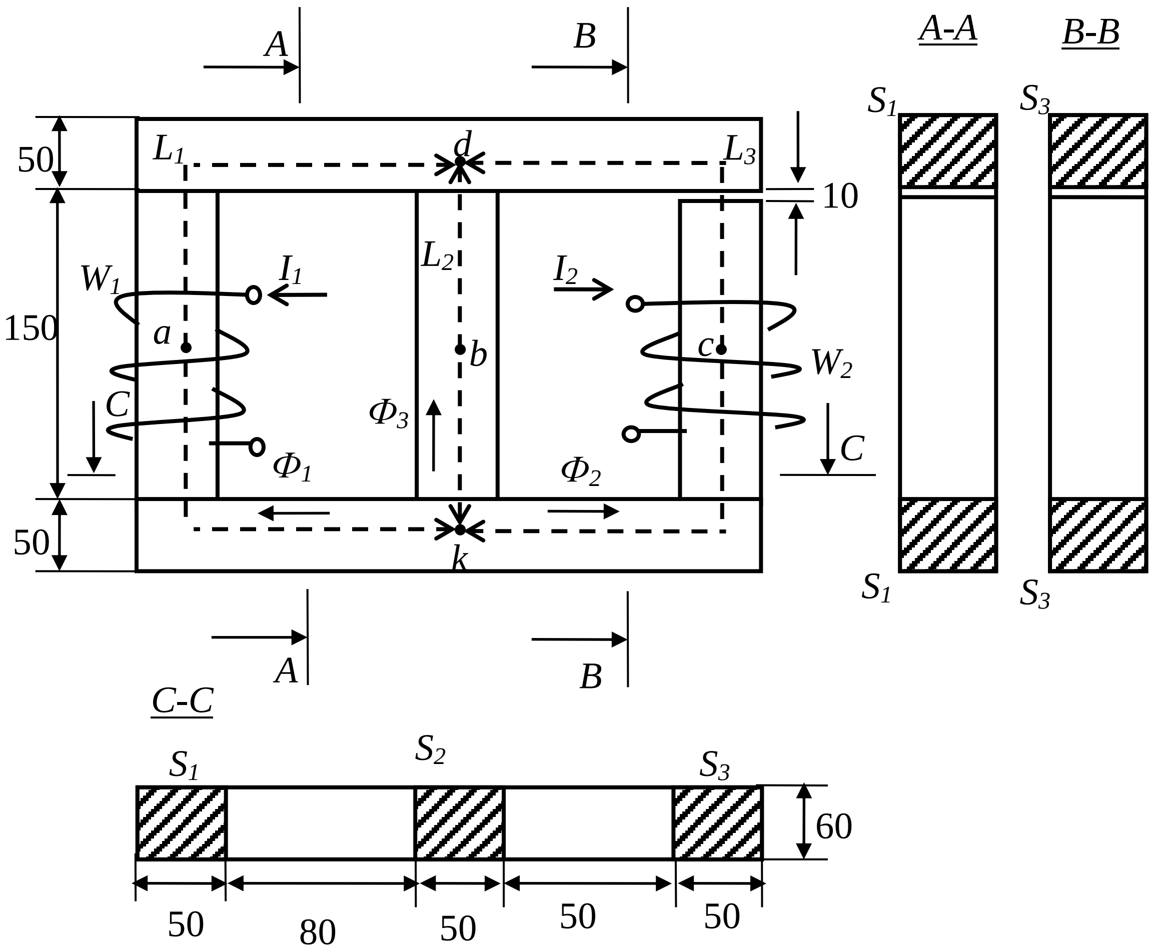


Fig. 2.4

Sizes of magnetic conductor on Fig.2.4 are indicated in millimetres. Auxiliary condition $\hat{O}_1 = \hat{O}_3$.

The magnetic conductor magnetization steel curve is set by tabular, Table 2.3.

Table 2.3.

B,T	0	0,4	0,8	1,2	1,6	2,0
H, A/m	0	200	400	950	3900	15000

For magnetic circuit (Fig. 2.4) calculate:
– the first spool magnatization current;
– branches magnetic fluxe;
– drop magnetic voltages between points *a* and *d* via of two ways having chosen the by-pass direction as to clockwise and against the one.
– to draw the replacement electric equivalent scheme and to point on the one directions of magnetic fluxes and magnetomotive forces;
– to compose the computative equations set as to Kirhhgoff's laws and determine the magnetic induction value in air gap.

The task solution.
For determining of magnetic fluxes the magnetic circuit split into homogeneous districts, each of which is fulfilled from homogeneous material and has similar cross-section along all district.
We determine lengths L_1, L_2, L_3 and cross-section S_1, S_2, S_3 of homogeneous magnetic conductor districts.
The length of the middle magnetic line of the first district
L_1=(25+80+25+25+150+25+25+80+25)* 10^{-3}=0,46 m.

The length of the middle magnetic line of the second district
$L_2 = L'_2 + L''_2$ = (25+50+25+25+150-10+25+25+50+25)* 10^{-3}=0,39 m.

The length of the air gap
l_{02} =10* 10^{-3} =0,01 m.

The length of the middle magnetic line of the third district
L_3=(25+150+25)*10^{-3}=0,2 m.

The first district cross-section $S_1 = 50*10^{-3}\,60*10^{-3} = 3*10^{-4}$ m²;

the second district cross-section $S_2 = 50*10^{-3}\,60*10^{-3} = 3*10^{-4}$ m²;

the third district cross-section $S_3 = 50*10^{-3}\,60*10^{-3} = 3*10^{-4}$ m².

According to right-hand screw rule (corkscrew rule) we find the direction of the action of magnetomotive forces in magnetic conductors cores. In the first core direction of magnetomotive force $I_1w_1 = F_1$ from node *d* to node *k* and in second core $I_2w_2 = F_2$ from node *k* to node *d*. The magnetic fluxes direction in cores of magnetic conductor we assign arbitrary: from node *k* to node *d*. We set the direction of magnetic fluxes from node *k* to node *d* relying that magnetic potential of the point *k* the above than magnetic potential of point *d*. In the reality for the carrying out of the first Kirhhgoff's law for magnetic fluxes which gathering in node, of one or two magnetic fluxes must have inverse value sign.

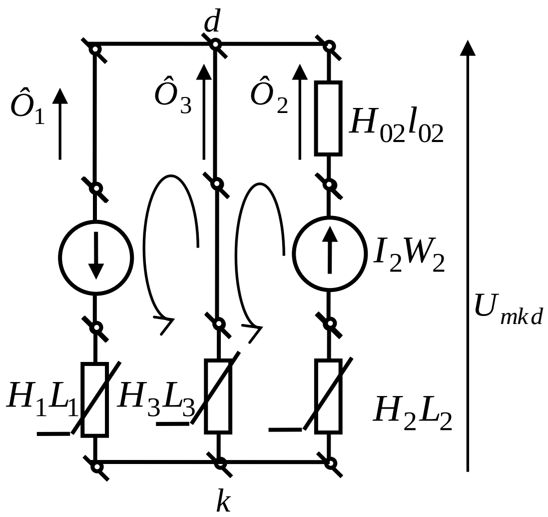


Fig.2.5

On Fig.2.5. is present the replacement electrical equivalent scheme of magnetic circuit. Magnetization forces are taken into account as energy sources, air gap as linear resistance, and ferromagnetic magneto conductors as nonlinear resistances. Magnetic fluxes are equivalent to electric currents, and magnetic voltage are equivalent to electric voltages. Scheme comprises three branches and two nodes, that is why rational to calculate magnetic fluxes by the method of two nodes.

For computative scheme compose one equation (in the scheme there are two nodes minus one node) as to the first Kirhhgoff's law and two as to second Kirhhgoff's law (in the scheme there are two independent contour)

$\Phi_1 + \Phi_2 + \Phi_3 = 0$ – for the node „*d*" – algebraic sum of currents in node is equal to zero;

$I_1W_1 = -H_1L_1 + H_3L_3$ – for left contour– the algebraic sum of magnetic drops voltage in contour is equal to zero;

$I_2W_2 = H_2L_2 + H_{02}l_{02} - H_3L_3$ – for right contour – the algebraic sum of magnetic drops voltage in contour is equal to zero.

The received equations set is nonlinear. In it change coefficients H_1, H_2, H_3 of equations due to the saturation of magneto conductor material. Is lost linear dependence between the magnetic field strength H and by magnetic induction In at the change of magnetization current in spool due to the phenomenon of saturation of magneto conductor.

Calculation we perform by graphic method with draw of weber-ampere characteristics of homogeneous branches of magneto conductor. For drawing weber-ampere characteristics compose potential equations for computative scheme

$U_{mkd} = H_1L_1 + I_1W_1$ – for the first core of magneto conductor;

$U_{mkd} = H_3L_3$ - for the third core of magneto conductor;

$U_{mkd} = -I_2W_2 + H_2L_2 + H_{02}L_{02}$ - for the second core of magneto conductor.

Because cores in magnetic circuit are included by parallel, that magnetic voltage on it should be equal.

Knowing cross-sections of magnetic conductors as to magnetization curve find the magnetic fluxes of cores $\hat{O}_1 = B \cdot S_1$, $\hat{O}_2 = B \cdot S_2$, $\hat{O}_3 = B \cdot S_3$. Magnetic inductions B choose in last equations from magnetization curve of steel magnetic conductor, table 2.3.

We shall lead the example of calculation the second (table 2.3) point of weber-ampere characteristics of magnetic conductor.

As to potential equations reckon the weber-ampere characteristics of branches magneto conductor.

For the first core magneto conductor do not known the magnetization current, that is why the displacement of weber-ampere characteristic relatively of onset of coordinates on this stage of calculation we cannot perform.

The magnetic flux of second branch find as to magnatization curve, table 2.3, and cross-section of magnetic conductor, for example for second point in the first quadrant $\Phi_2 = B_2 * S_2 = 0,4*3*10^{-4} = 1,2*10^{-4}$ *Wb.*

Magnetic voltage in this point of weber-ampere characteristic

$U_{mdk} = -I_2 W_2 + H_2 L_2 + H_{02} l_{02} = -10*150+200*0,39+32*10^4*10*10^{-3} = 1778$A

where H_0 – the magnetic-field strength in air gap, define from correlation

$$H_{02} = \frac{B}{\mu\mu_0} = \frac{0,4}{1*12,56*10^{-7}} = 32*10^4 \ A/m;$$

$\mu_0 = 4\pi*10^{-7}$ *Гн/м* – absolute magnetic vacuum permeability;

$\mu = 1$ – relative magnetic air permeability.

Magnetic voltage on third core

$U_{mdk} = H_3 L_3 = 200*0,2 = 40$A.

Magnetic flux in the second point of third core

$\Phi_3 = 0,4*3*10^{-4} = 1,2*10^{-4}$ *Вб.*

The results of calculations tabulated into Table 2.4.

The magnetic voltage drop between the nodes of magnetic circuit

$$U_{mdk} = -I_2 W_2 + H_2 L_2 + H_{02} L_{02} = -1500 + H_2*0,39 + \frac{B}{1*12,56*10^{-7}} 0,01 =$$

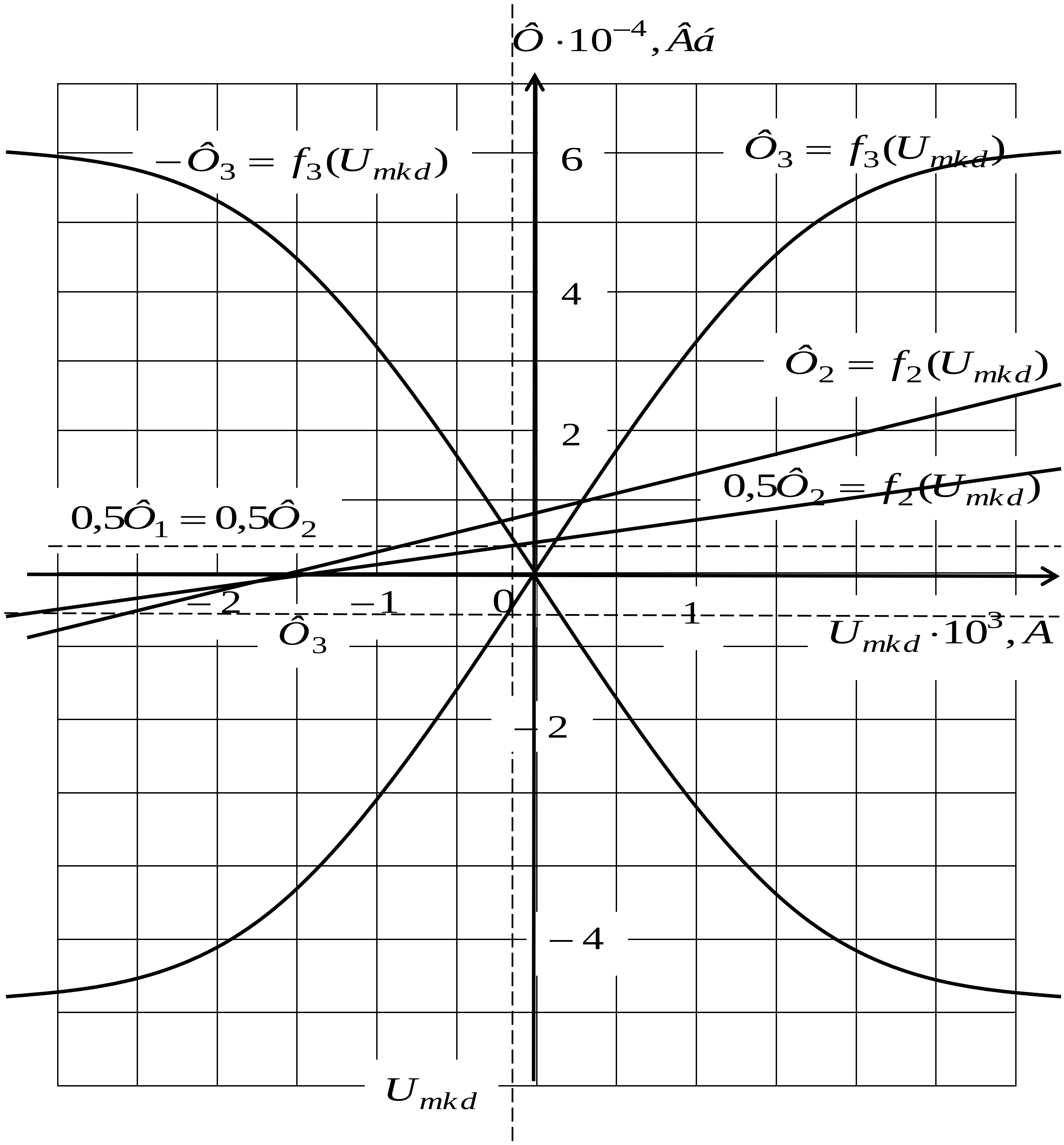


Fig.2.6

On Fig.2.6. are built the weber-ampere characteristics of branches magnetic conductors. In the beginning are built characteristics of second and third core according to the data of Table 2.4. Then is used auxiliary condition $\hat{O}_1 = \hat{O}_3$, then as to the first Kirhhgoff's law for magnetic circuits we have $\Phi_1 + \Phi_2 + \Phi_3 = 0$, i.e. $\Phi_2 + 2\,\Phi_3 = 0$ or $\Phi_2 = -2\,\Phi_3$ and finally $0{,}5\Phi_2 = -\Phi_3$.

Are built graphs $0{,}5\hat{O}_2 = f_2(U_{mkd})$ and $-\hat{O}_3 = f_3(U_{mkd})$. The intersection point of last graphs determines working point of magnetic cores. From graphs determine: $\Phi_3 = -0{,}4 * 10^{-4}$ *Вб*; $\Phi_2 = 0{,}8 * 10^{-4}$ *Wb*, i. e. $\Phi_1 = \Phi_3 = -0{,}4 * 10^{-4}$ *Wb*. Magnetic voltage on parallel branches $U_{mdk} = -150\ A$.

Table 2.4

B,T	$H,Am\text{м}$	Second core		Third core	
		U_{mdk} = $-I_2W_2 + H_2L_2 + H_{02}L_{02}$, A	$\hat{O}_2 = B \cdot S_2$ $*10^{-4}$, Wb	$U_{mdk} = H_3L_3$, A	$\hat{O}_3 = B \cdot S_3$ $*10^{-4}$, Wb
-2,0	-15000	-23274	-6,0	-3000	-6,0
-1,6	-3900	-15760	-4,8	-780	-4,8
-1,2	-950	-11425	-3,6	-190	-3,6
-0,8	-400	-8025	-2,4	-80	-2,4
-0,4	-200	-4762	-1,2	-40	-1,2
0	0	-1500	0	0	0
0,4	200	1762	1,2	40	1,2
0,8	400	5025	2,4	80	2,4
1,2	950	8425	3,6	190	3,6
1,6	3900	12760	4,8	780	4,8
2,0	15000	20274	6,0	3000	6,0

The negative sign of magnetic fluxes bears evidence about the contrary direction of fluxes in third and the first cores.

Knowing the magnetic flux in the first core find magnetic induction in the first core

$B_1 = \hat{O}_1 / S_1 = -0{,}4 \cdot 10^{-4} / 3 \cdot 10^{-4} = -0{,}13$, T.

We perform straight-line interpolation by direct line which passing through two the points of initial magnetization curve and reckon the magnetic field strength in the first core

$$\frac{B_1 - 0}{0{,}4 - 0} = \frac{H_1 - 0}{200 - 0};\ H_1 = -65\text{A/m.}$$

For the first magnito conductor core $U_{mkd} = H_1L_1 + I_1W_1$, from where we find the magnetization current of the first spool

$$I_1 = \frac{U_{mkd} - H_1L_1}{W_1} = -0{,}6\text{, A.}$$

The current direction should be contrarily pointed to Fig.2.4. Magnetic induction in third core

$B_3 = \hat{O}_3 / S_3 = -0{,}4 \cdot 10^{-4} / 3 \cdot 10^{-4} = -0{,}13$, T.

The magnetic field strength in third core coincides with the magnetic field strength in the first core

$H_3 = -65$ A/m.

The drop of magnetic voltage on district *a-d*

$$U_{mad} = -\frac{1}{2}\left(H_1L_1 + I_1W_1\right) = -74{,}95\text{, A.}$$

The drop of magnetic voltage on district *a-k-b-d*

$$U_{makbd} = \frac{H_1 L_1}{2} + H_3 L_3 = -27{,}95, \text{ A.}$$

2.5. The personal computative-graphic task “ The calculation parameters of magnetic circuits under permanent magnetizing forces”

As to the initial data of magnetic circuit, Table 2.5, fulfil following calculations:
1. Calculate magnetic circuit that presented on Fig.2.7, by the method of two nodes, to determine of specified quantity which stated in Table 2.5.

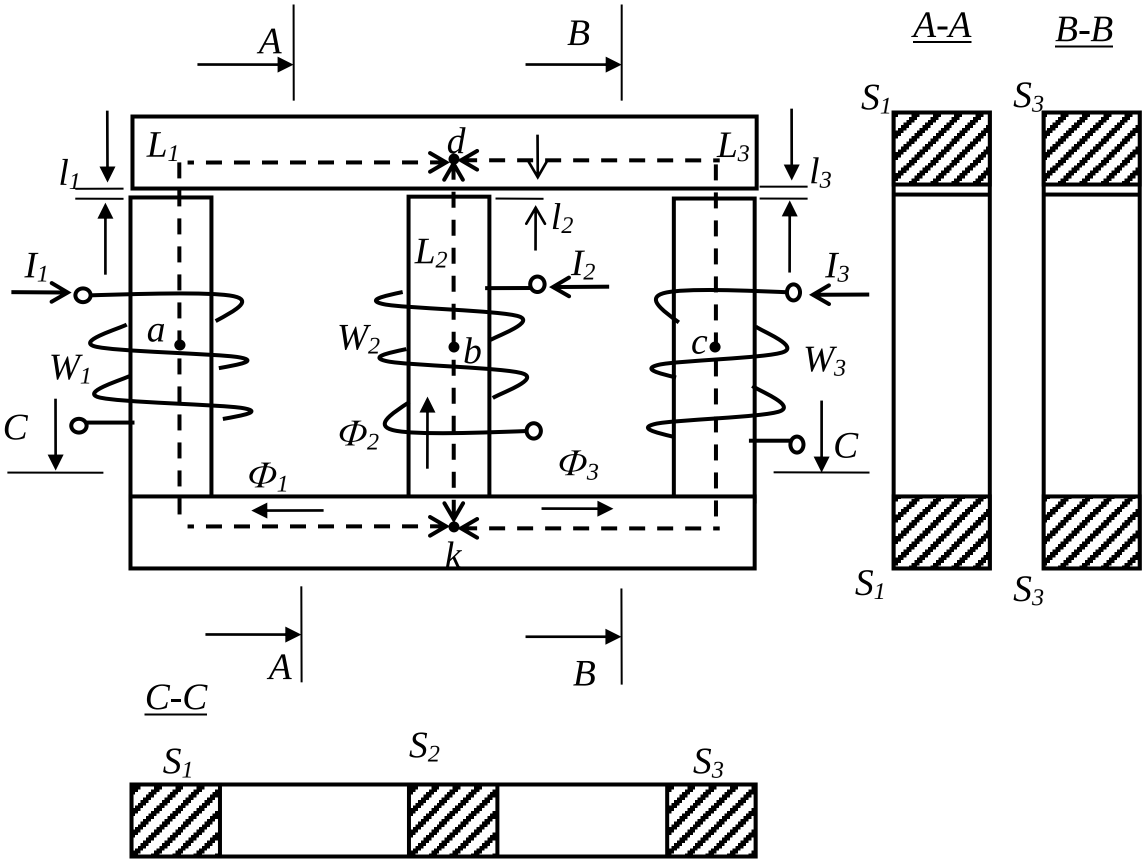


Fig. 2.2

As to results received in calculation point 1, to find magnetic voltage between two points of magnetic circuit having calculated it one time as to

Table 2.5.

Variant	The first core of magnetic conductor					The second core of magnetic conductor					The third core of magnetic conductor					Auxiliary condition $\Phi*10^{-4}$ Wb	Define
	L_1, cm	S_1, cm²	W_1, turns	I_1, A	l_{01}, mm	L_2, тм	S_2, cm²	W_2, turns	I_2, A	l_{02}, mm	L_3, cm	S_3, cm²	W_3, turns	I_3, A	l_{03}, mm		
00	25,0	8,5	250	0,07	0,0	14,0	8,2	–	0,2	0,0	23,0	14,9	98	1,2	0,0	Φ_2-Φ_1 =30,0	W_2, Φ_2
01	20,0	4,0	413	1,1	0,5	12,0	6,06	0	0,0	0,0	38,0	4,05	250	1,0	0,0	–	Φ_1, Φ_2
02	80,0	5,7	300	0,6	0,0	25,0	3,9	200	–	0,0	80,0	9,5	0	0,0	0,0	Φ_1 = Φ_2	I_2, Φ_1
03	20,0	4,0	100	0,3	0,0	10,0	8,0	300	–	0,0	30,0	5,6	250	0,21	0,0	Φ_2 =0,0	I_2, Φ_3
04	33,5	7,6	500	0,21	0,0	12,0	12,0	600	0,05	0,0	45,0	11,3	975	–	0,0	Φ_3-Φ_1 =20,0	I_3, Φ_1
05	45,0	15,4	300	1,0	0,0	22,0	10,4	0	0,0	0,0	40,0	15,0	400	0,5	1,0	–	Φ_1, Φ_2
06	45,0	44,0	300	0,5	0,0	15,0	14,2	–	0,3	0,0	35,0	13,7	0	0,0	0,0	Φ_3 = Φ_2	W_2, Φ_1
07	20,0	3,9	215	1,0	0,0	10,0	4,8	–	0,1	0,0	26,0	4,6	500	0,2	0,0	Φ_2 =0,0	W_2, Φ_3
08	17,0	7,9	615	0,1	0,0	5,0	4,8	420	0,05	0,0	26,0	4,4	150	–	0,0	Φ_2-Φ_3 =20	I_3, Φ_2
09	60,0	60,0	400	0,65	0,0	20,0	84,0	0	0,0	1,25	60,0	60,0	400	0,575	0,0	–	Φ_1, Φ_2
10	50,0	25,0	500	0,7	0,0	28,0	51,0	0	0,0	0,0	50,0	50,0	300	–	0,0	Φ_1 = Φ_3	I_3, Φ_1
11	12,0	2,0	100	–	0,0	4,0	1,0	500	0,04	0,0	12,0	12,0	196	0,1	0,0	Φ_1 = 25,0	I_1, Φ_3
12	40,0	3,0	300	0,2	0,0	12,0	5,0	390	–	0,0	40,0	8,0	0	0,0	0,0	Φ_2-Φ_1 =20,0	I_2, Φ_2
13	20,0	8,0	0	0	0,1	7,0	2,0	500	0,2	0,0	20,0	1,78	500	0,3	0,0	–	Φ_2, Φ_3
14	25,0	5,3	100	0,5	0,0	10,0	5,0	–	0,2	0,0	32,0	10,2	0	0,0	0,0	Φ_1 = Φ_2	W_2, Φ_1
15	30,0	8,0	1450	0,1	0,0	12,0	14,0	204	0,25	0,0	35,0	7,0	2000	–	0,0	Φ_3 = 98,0	I_3, Φ_2
16	25,0	3,8	76	0,25	0,0	12,0	7,6	275	–	0,0	32,0	10,1	160	0,5	0,0	Φ_2-Φ_1 =20,0	I_2, Φ_1
17	15,0	7,2	135	0,47	0,0	8,0	4,8	–	0,1	0,0	20,0	2,9	70	0,2	0,0	Φ_2 =70,0	W_2, Φ_1
18	85,0	100,0	3000	0,1	0,0	33,0	200,0	500	0,7	0,52	85,0	100,0	0	0,0	0,0	–	Φ_1, Φ_2
19	45,0	12,,00	0	0,0	0,0	15,0	12,0	550	0,4	0,0	45,0	9,0,0	520	–	0,0	Φ_3 = Φ_2	I_3, Φ_3
20	30,0	9	350	0,05	0,0	10,0	7,8	–	0,2	0,0	25,0	15	1175	0,1	0,0	Φ_2-Φ_1 =30,0	W_2, Φ_1

Continuation of Table 2.5.

Variant	The first core of magnetic conductor					The second core of magnetic conductor					The third core of magnetic conductor					Auxiliary condition $Ф*10^{-4}$ Wb	Define
	L_1, *cm*	S_1, cm^2	W_1, *turns*	I_1, *A*	l_{01}, *mm*	L_2, *тм*	S_2, cm^2	W_2, *turns*	I_2, *A*	l_{02}, *mm*	L_3, *cm*	S_3, cm^2	W_3, *turns*	I_3, *A*	l_{03}, *mm*		
21	30,0	4,0	300	1,52	0,5	10,0	6,0	0	0,0	0,0	30,0	4,0	100	2,5	0,0	–	$Ф_1$, $Ф_2$
22	100,0	6,15	600	0,3	0,0	33,0	4,2	200	–	0,0	100,0	10,0	0	0,0	0,0	$Ф_1 = Ф_2$	I_2, $Ф_1$
23	30,0	4,3	300	0,1	0,0	12,0	6,0	300	–	0,0	20,0	4,8	125,0	0,42	0,0	$Ф_2 =0,0$	I_2, $Ф_3$
24	30,0	7,3	105	1,0	0,0	11,5	12,3	100	0,3	0,0	22,5	10,0	975	–	0,0	$Ф_3-Ф_1 =20,0$	I_3, $Ф_1$
25	32,0	14,4	400	0,75	0,0	25,0	10,5	0	0,0	0,0	40,0	15,0	200	1,0	1,0	–	$Ф_3$, $Ф_2$
26	40,0	42,0	375	0,4	0,0	13,0	14,0	–	0,3	0,0	40,0	15,0	0	0,0	0,0	$Ф_3 = Ф_2$	W_2, $Ф_1$
27	30,0	4,2	430	0,5	0,0	10,0	4,8	–	0,1	0,0	32,0	4,9	200	0,5	0,0	$Ф_2 =0,0$	W_2, $Ф_3$
28	19,0	8,1	400	0,154	0,0	6,5	5,1	210	0,1	0,0	15,0	3,2	150	–	0,0	$Ф_2-Ф_3 =20,0$	I_3, $Ф_2$
29	55,0	55,0	260	1,0	0,0	18,0	84,0	0	0,0	1,25	57,0	57,0	230	1,0	0,0	–	$Ф_3$, $Ф_2$
30	55,0	25,3	700	0,5	0,0	25,0	50,0	0	0,0	0,0	47,0	45,5	300	–	0,0	$Ф_1 = Ф_3$	I_3, $Ф_3$
31	12,0	2,0	100	–	0,0	4,0	1,0	500	0,04	0,0	12,0	12,0	196	0,1	0,0	$Ф_1 = 25,0$	I_1, $Ф_3$
32	35,0	2,9	240	0,25	0,0	10,0	4,75	390	–	0,0	45,0	8,33	0	0,0	0,0	$Ф_2-Ф_1 =20,0$	I_2, $Ф_2$
33	13,5	7,5	0	0	0,1	4,32	1,9	100	1,0	0,0	19,8	1,75	300	0,5	0,0	–	$Ф_1$, $Ф_3$
34	30,0	5,6	250	0,2	0,0	10,0	5,0	200	–	0,0	18,0	8,9	0	0,0	0,0	$Ф_1 = Ф_2$	I_2, $Ф_3$
35	28,0	7,95	290	0,5	0,0	11,5	13,8	51	1	0,0	37,0	7,1	2000	–	0,0	$Ф_3 = 98,0$	I_3, $Ф_2$
36	28,0	3,9	38	0,5	0,0	8,0	6,8	275	–	0,0	28,0	9,9	320	0,25	0,0	$Ф_2-Ф_1 =20,0$	I_2, $Ф_2$
37	25,0	8,0	635	0,1	0,0	10,0	5,0	–	0,1	0,0	25,0	3,0	7	2,0	0,0	$Ф_2 =70,0$	W_2, $Ф_3$
38	70,0	97,0	750	0,4	0,0	35,0	220,0	250	1,4	0,57	70,0	92	0	0,0	0,0	–	$Ф_3$, $Ф_2$
39	43,0	11,9	0	0	0,0	14,0	11,5	200	1,1	0,0	48,0	9,1	520	–	0,0	$Ф_3 = Ф_2$	I_3, $Ф_1$
40	32,0	9,3	270	0,065	0,0	9,0	7,7	–	0,2	0,0	30,0	15,5	168	0,7	0,0	$Ф_2-Ф_1 =30,0$	W_2, $Ф_2$

Continuation of Table 2.5.

Variant	The first core of magnetic conductor					The second core of magnetic conductor					The third core of magnetic conductor					Auxiliary condition $Ф*10^{-4}$ Wb	Define
	L_1, *cm*	S_1, *cm²*	W_1, *turns*	I_1, *A*	l_{01}, *mm*	L_2, *тм*	S_2, *cm²*	W_2, *turns*	I_2, *A*	l_{02}, *mm*	L_3, *cm*	S_3, *cm²*	W_3, *turns*	I_3, *A*	l_{03}, *mm*		
41	25,0	4,0	505	0,9	0,5	14,0	6,15	0	0,0	0,0	25,0	3,9	625	0,4	0,0	–	$Ф_3$, $Ф_2$
42	90,0	6,0	360	0,5	0,0	30,0	4,0	200	–	0,0	90,0	9,7	0	0,0	0,0	$Ф_1 = Ф_2$	I_2, $Ф_3$
43	25,0	4,15	150	0,2	0,0	8,0	4,0	300	–	0,0	35,0	5,95	100	0,525	0,0	$Ф_2 = 0,0$	I_2, $Ф_1$
44	40,0	8,0	210	0,5	0,0	22,5	14,0	300	0,1	0,0	30,0	10	975	–	0,0	$Ф_3 - Ф_1 = 20,0$	I_3, $Ф_3$
45	40,0	15,0	600	0,5	0,0	20,0	10,3	0	0,0	0,0	40,0	15	800	0,25	1,0	–	$Ф_1$, $Ф_3$
46	35,0	10,0	150	1,0	0,0	10,0	13,7	–	0,3	0,0	30,0	14,2	0	0,0	0,0	$Ф_3 = Ф_2$	W_2, $Ф_2$
47	35,0	4,3	215	1,0	0,0	10,0	4,8	–	0,1	0,0	20,0	4,4	1000	0,1	0,0	$Ф_2 = 0,0$	W_2, $Ф_1$
48	16,0	7,8	205	0,3	0,0	5,5	4,9	300	0,07	0,0	23,0	4,2	150	–	0,0	$Ф_2 - Ф_3 = 20,0$	I_3, $Ф_3$
49	65,0	71,0	520	0,5	0,0	22,0	84,0	0	0,0	1,25	62,0	62,0	460	0,5	0,0	–	$Ф_1$, $Ф_2$
50	48,0	24,9	350	1,0	0,0	30,0	51,5	0	0,0	0,0	52,0	51,5	300	–	0,0	$Ф_1 = Ф_3$	I_3, $Ф_2$
51	13,0	2,05	100	–	0,0	3,0	0,94	1000	0,02	0,0	11,0	1,18	132	0,15	0,0	$Ф_1 = 25,0$	I_1, $Ф_3$
52	45,0	3,1	200	0,3	0,0	14,0	5,3	390	–	0,0	35,0	7,8	0	0,0	0,0	$Ф_2 - Ф_1 = 10,0$	I_2, $Ф_2$
53	19,5	7,7	0	0,0	0,1	10,0	2,1	200	0,5	0,0	24,2	1,8	750	0,2	0,0	–	$Ф_2$, $Ф_1$
54	18,0	4,9	200	0,25	0,0	10,0	5,0	–	0,2	0,0	25,0	9,5	0	0,0	0,0	$Ф_1 = Ф_2$	W_2, $Ф_1$
55	26,0	7,9	145	1,0	0,0	11,0	13,6	102	0,5	0,0	39,0	7,2	2000	–	0,0	$Ф_3 = 98,0$	I_3, $Ф_2$
56	35,0	4,1	19	1,0	0,0	6,0	6,3	275	–	0,0	25,0	9,6	400	0,2	0,0	$Ф_2 - Ф_1 = 20,0$	I_2, $Ф_3$
57	20,0	7,7	107	0,59	0,0	9,0	4,9	–	0,1	0,0	15,0	2,6	20	0,7	0,0	$Ф_2 = 70,0$	W_2, $Ф_3$
58	100,0	104,0	125	2,4	0,0	28,0	182,0	125	2,8	0,48	95,0	200,0	0	0,0	0,0	–	$Ф_1$, $Ф_3$
59	40,0	11,8	0	0,0	0,0	13,0	11,0	100	2,2	0,0	50,0	9,3	520	–	0,0	$Ф_3 = Ф_2$	I_3, $Ф_2$
60	34,0	9,5	175	0,1	0,0	12	8,0	–	0,2	0,0	28,0	15,6	47	2,5	0,0	$Ф_2 - Ф_1 = 30,0$	W_2, $Ф_3$

Continuation of Table 2.5.

Variant	The first core of magnetic conductor					The second core of magnetic conductor					The third core of magnetic conductor					Auxiliary condition $\Phi*10^{-4}$ Wb	Define
	L_1, cm	S_1, cm²	W_1, turns	I_1, A	l_{01}, mm	L_2, тм	S_2, cm²	W_2, turns	I_2, A	l_{02}, mm	L_3, cm	S_3, cm²	W_3, turns	I_3, A	l_{03}, mm		
61	35,0	4,1	350	1,3	0,5	8,0	5,8	0	0,0	0,0	20,0	3,8	500	0,5	0,0	–	Φ_1, Φ_2
62	90,0	6,0	100	1,8	0,0	30,0	4,0	–	1,1	0,0	85,0	9,7	0	0,0	0,0	$\Phi_1 = \Phi_2$	W_2, Φ_2
63	15,0	3,8	60	0,5	0,0	6,0	2,0	300	–	0,0	20,0	4,8	350	0,15	0,0	$\Phi_2 = 0,0$	I_2, Φ_1
64	37,5	7,8	200	0,525	0,0	13,0	12,8	150	0,2	0,0	37,5	10,5	975	–	0,0	$\Phi_3 - \Phi_1 = 20,0$	I_3, Φ_2
65	35,0	14,6	900	0,3	0,0	18,0	10,2	0	0,0	0,0	40,0	15,0	1000	0,2	1,0	–	Φ_1, Φ_3
66	30,0	38,0	600	0,25	0,0	17,0	14,7	–	0,3	0,0	45,0	15,3	0	0,0	0,0	$\Phi_3 = \Phi_2$	W_2, Φ_3
67	25,0	4,0	1075	0,2	0,0	10,0	4,8	–	0,1	0,0	29,0	4,8	2000	0,05	0,0	$\Phi_2 = 0,0$	W_2, Φ_3
68	20,0	8,2	615	0,1	0,0	7,0	5,2	105	0,2	0,0	17,0	3,6	150	–	0,0	$\Phi_2 - \Phi_3 = 20,0$	I_3, Φ_1
69	58,0	58,0	200	1,3	0,0	9,0	84,0	0	0,0	1,25	55,0	55,0	575	0,4	0,0	–	Φ_1, Φ_2
70	45,0	24,7	700	0,5	0,0	27,0	50,4	0	0,0	0,0	48,0	47,5	300	–	0,0	$\Phi_1 = \Phi_3$	I_3, Φ_1
71	10,0	1,92	100	–	0,0	4,5	10,15	200	0,1	0,0	14,0	1,26	9,8	0,2	0,0	$\Phi_1 = 25,0$	I_1, Φ_2
72	38,0	2,97	400	0,15	0,0	11,0	4,9	390	–	0,0	43,0	8,25	0	0,0	0,0	$\Phi_2 - \Phi_1 = 20,0$	I_2, Φ_3
73	29,8	8,2	0	0,0	0,1	13,0	2,2	1000	0,1	0,0	25,0	1,82	200	0,75	0,0	–	Φ_2, Φ_3
74	32,0	6,0	125	0,4	0,0	10,0	5	200	–	0,0	20,0	9,0	0	0,0	0,0	$\Phi_1 = \Phi_2$	I_2, Φ_2
75	32,0	8,1	725	0,2	0,0	12,5	14,1	170	0,3	0,0	33,0	6,9	2000	–	0,0	$\Phi_3 = 98,0$	I_3, Φ_1
76	30,0	4,0	38	0,5	0,0	10,0	7,0	275	–	0,0	30,0	10,0	400	6,2	0,0	$\Phi_2 - \Phi_1 = 20,0$	I_2, Φ_2
77	30,0	8,4	89	0,73	0,0	12,0	5,2	–	0,1	0,0	26,0	3,0	35	0,4	0,0	$\Phi_2 = 70,0$	W_2, Φ_1
78	110,0	105,0	600	0,5	0,0	27,0	17,7	175	2,0	0,46	100,0	240	0	0,0	0,0	–	Φ_1, Φ_2
79	48,0	12,1	0	0,0	0,0	16,0	12,9	220	1,0	0,0	43,0	8,8	520	–	0,0	$\Phi_3 = \Phi_2$	I_3, Φ_1
80	26,0	8,6	125	0,14	0,0	13,0	8,1	–	0,2	0,0	22,0	14,7	25	4,7	0,0	$\Phi_2 - \Phi_1 = 30,0$	W_2, Φ_1

Continuation of Table 2.5.

Variant	The first core of magnetic conductor					The second core of magnetic conductor					The third core of magnetic conductor					Auxiliary condition $\Phi*10^{-4}$ Wb	Define
	L_1, cm	S_1, cm²	W_1, turns	I_1, A	l_{01}, mm	L_2, тм	S_2, cm²	W_2, turns	I_2, A	l_{02}, mm	L_3, cm	S_3, cm²	W_3, turns	I_3, A	l_{03}, mm		
81	40,0	4,1	455	1,0	0,5	10,0	6,0	0	0,0	0,0	40,0	4,15	125	2,0	0,0	–	Φ_1, Φ_3
82	85,0	5,9	200	0,9	0,0	25,0	3,9	–	1,1	0,0	95,0	9,9	0	0,0	0,0	$\Phi_1 = \Phi_2$	W_2, Φ_3
83	30,0	4,3	200	0,15	0,0	10,0	8,0	300	–	0,0	20,0	4,8	150	0,35	0,0	$\Phi_2 = 0,0$	I_2, Φ_1
84	40,0	8,0	420	0,25	0,0	15,0	13,0	150	0,2	0,0	30,0	10,0	975	–	0,0	$\Phi_3 - \Phi_1 = 20,0$	I_3, Φ_1
85	48,0	15,6	1500	0,2	0,0	20,0	10,3	0	0	0,0	40,0	15,0	800	0,25	1,0	–	Φ_3, Φ_2
86	38,0	41,0	500	0,3	0,0	12,0	13,8	–	0,3	0,0	50,0	15,8	0	0,0	0,0	$\Phi_3 = \Phi_2$	W_2, Φ_1
87	18,0	3,8	860	0,25	0,0	10,0	4,8	–	0,1	0,0	23,0	4,5	100	1,0	0,0	$\Phi_2 = 0,0$	W_2, Φ_3
88	18,0	8,0	205	0,3	0,0	6,0	5,0	210	0,1	0,0	20,0	4,0	150	–	0,0	$\Phi_2 - \Phi_3 = 20,0$	I_3, Φ_2
89	63,0	66,5	650	0,4	0,0	21,0	84,0	0	0,0	1,25	65,0	65,0	200	1,15	0,0	–	Φ_3, Φ_2
90	52,0	25,2	1000	0,35	0,0	29,0	51,0	0	0,0	0,0	55,0	55,3	300	–	0,0	$\Phi_1 = \Phi_3$	I_3, Φ_2
91	14,0	2,7	100	–	0,0	5,0	1,03	100	0,2	0,0	10,0	11,4	392	0,05	0,0	$\Phi_1 = 25,0$	I_1, Φ_2
92	42,0	3,07	600	0,2	0,0	13,0	5,14	390	–	0,0	37,0	7,9	0	0,0	0,0	$\Phi_2 - \Phi_3 = 20,0$	I_2, Φ_3
93	42,5	9,0	0	0,0	0,1	20,0	2,4	50	2,0	0,0	40,5	2,0	150	1,0	0,0	–	Φ_1, Φ_3
94	20,0	5,0	400	0,125	0,0	10,0	5,0	–	0,2	0,0	30,0	10,0	0	0,0	0,0	$\Phi_1 = \Phi_2$	W_2, Φ_1
95	34,0	8,3	290	0,5	0,0	13,0	14,2	255	0,2	0,0	31,0	6,8	2000	–	0,0	$\Phi_3 = 98,0$	I_3, Φ_2
96	32,0	4,06	76	0,25	0,0	14,0	8,3	275	–	0,0	35,0	10,4	800	0,1	0,0	$\Phi_2 - \Phi_1 = 20,0$	I_2, Φ_3
97	22,0	7,8	635	0,1	0,0	15,0	5,5	–	0,1	0,0	28,0	3,1	28	0,5	0,0	$\Phi_2 = 70,0$	W_2, Φ_2
98	90,0	100,0	150	2,0	0,0	30,0	180,0	700	0,5	0,5	90,0	100	0	0,0	0,0	–	Φ_1, Φ_2
99	50,0	12,1	0	0,0	0,0	17,0	14,0	440	0,5	0,0	40,0	8,6	520	–	0,0	$\Phi_3 = \Phi_2$	I_3, Φ_2

short way and another time as to any another way chosen at the own discretion.

2. For accepted in calculation point 1 the positive directions of magnetic fluxes and the given direction of magnetizing forces to compose the equations set under Kirhhgoff's laws.

Note: Points *a, b, c, d, k* reside in the middle of every magnetic conductor district.

3. THE NONLINEAR AC ELECTRIC CIRCUITS CALCULATION METHODS IN STEADY-STATE REGIMES

3.1. Methodological instructions to the calculation of nonlinear electric circuts in steady-state regimes

1. AC nonlinear elements as to its properties subdivide into symmetrical, non-symmetrical, inertial, noninertial, resistive, reactive, with positive and negative dynamic resistances.
2. The properties of symmetrical nonlinear elements are not dependent on direction flowing in it current or applied voltage.
3. The inertial properties of nonlinear elements are conditioned by the presence of heat inertia which brings to linear dependence between current and voltage instantaneous values and to nonlinear dependence between current and voltage effective values.
3. Differentiate nonlinear electric circuits with homogeneous energy sources, when in circuits act the sources of equal frequency, and circuits with nonhomogeneous energy sources comprising the sources of different frequencies.
4. In circuits comprising nonlinear elements with negative dynamic resistance possibly self-oscillating processes appearance, when at using of the DC source nonlinear chain generates steady-state current oscillations.
5. The research of circuits with electric valve (diode) elements is performed in assumption which diode owns ideal volt-ampere characteristic: in conducting direction (conducting state) its resistance tend to zero, and in contrary (lock state) direction its resistance tend to infinity.
6. Diod is in conducting state when the anode potential above of the cathode potential.
7. The calculation of complex AC electric circuits is performed on the grounds of Kirhhgoff's laws applying. This operation is fulfiled whether by analytically at the analytic expressions of volt-ampere characteristics presence, whether by graphically at the assignment of characteristics in the form of the graphs or tables.
8. For calculation nonlinear electric and magnetic circuits which assuming the piecewise-linear approximation of characteristics, is efficient method of successive approximations that allowing to calculate the parameters of any arbitrary complex circuits.

9. If it is known that nonlinear element working on the district of volt-ampere characteristic which approximately can be assume as linear, this task maybe linearization by means of the substitutions of volt-ampere characteristic working district by direct line and the definitions of the replacement scheme equivalent parameters.
10. At the research of spools with ferromagnetic cores the efficient method of circuit parameters calculation is the equivalent sinusoids method, at which real unsinusoidal values are replaced by equivalent sinusoidal one. The conditions of equivalence are: similar effective values and losses in circuits from initial unsinusoidal curve and the replaced sinusoidal one.

3.2. Parameters calculation in nonhomogeneous resistance-diode circuit as to instantaneous values

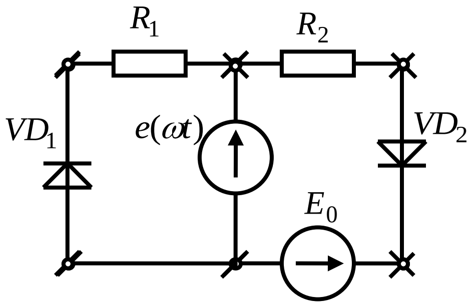


Fig. 3.1

Task.
Calculate branches current in nonhomogeneous resistance-diode circuit, Fig.3.1 which comprising nonlinear ideal semiconductor diodes VD_1, VD_2 and linear elements: $R_1 = 20$ Ohm, $R_2 = 10$ Ohm, $E_0 = 5$ B, $e(\omega t) = 20 \sin \omega t$ V, *f=50* Hz.

The task solution.
The electric circuit comprises three branches and three contour with two nonlinear elements. In circuts are absent storage energies, that is why currents and drop voltages instantaneous coincide as to phase on the circuit elements. The inner resistance of harmonic ideal source EMF is equal to zero, that is why scheme has two independent contour: left contour in which there are series included doide VD_1, resistor R_1 and harmonic power supply $e(\omega t)$ and right contour where there are series connected harmonic power supply, resistor R_2, diode VD_2 and the source of DC EMF E_0.
The vibration period of harmonic power supply
$T = 1/f = 0{,}02$ s.
The left independent contour. In the first half-period of the positive output voltage of harmonic power supply for time $t = 0 \ldots 0{,}01$ s the potential of the diode cathode VD_1 above potential of anode and diode there is in lock state. At this the time period left contour current is equal to zero $i_1(\omega t) = 0$. The drop voltage on the first resistive element is equal
$u_{R1}(\omega t) = R_1 i_1(\omega t) = 0$.
The voltage of power supply is applied to closed diode VD_1
$u_{VD1}(\omega t) = 20 \sin \omega t$ B.

Into second half-period the negative harmonic power supply output voltage for time $t = t_0 \ldots T$ s the potential of diode cathode VD_1 to become below the potential of anode and the diode at the moment of time $t_0 = 0{,}01$ s by bounce turns into open state. The left contour current confines by resistor R_1, is determined under the Ohm's law

$i_1(\omega t) = e(\omega t)/R_1 = 1 \cdot \sin \omega t$ A.

The voltage drop on open diode is equal to zero $u_{VD1}(\omega t) = 0$, the power supply voltage is appended to resistor $u_{R1}(\omega t) = 20 \sin \omega t$ V.

The right independent contour. Presence in the right contour of the constant EMF source E_0 brings to the increase of the anode potential on value E_0, that is why time of transition second diode VD_2 into open state will displace aside delay from the points of transition through the zero of the instantaneous value of the power supply voltage on value t_1

$$E_0 = 20 \sin \omega t_1 = 5; t_1 = \frac{\arcsin 0{,}25}{2\pi f} = 0{,}25\, ðàä = 8 \cdot 10^{-4} \text{ s.}$$

On the time districts $0 \ldots t_1$ s, $t_0 - t_1 \ldots t_0$ s and $t_0 \ldots T$ s the diode VD_2 is locked and contour current is equal to zero $i_2(\omega t) = 0$. The of power supply voltage is applied to closed diode VD_2 $u_{VD1}(\omega t) = 20 \sin \omega t$ V.

On the time district $t_1 \ldots t_0 - t_1$ the cathode potential of diode VD_2 to become below the potential of anode and diode at the moment of time $t_1 = 0{,}01$ s by bounce turns into open state. The right contour current confines by resistor R_2, is determined under the Ohm's law

$i_2(\omega t) = (e(\omega t) - E_0)/R_2 = 1{,}5 \cdot \sin \omega t$ A.

The power supply current $i_0(\omega t)$ is determined as sum of left $i_1(\omega t)$ and right $i_2(\omega t)$ contours current:

– the time district $0 \ldots t_1$ s $i_0(\omega t) = 0$;

– the time district $t_1 \ldots t_0 - t_1$ c $i_0(\omega t) = i_2(\omega t) = 1{,}5 \cdot \sin \omega t$ A;

– the time district $t_0 - t_1 \ldots t_0$ c $i_0(\omega t) = 0$;

– the time district $t_0 \ldots T$ c $i_0(\omega t) = 1{,}5 \cdot \sin \omega t$ A.

Graphics of computative branches current and voltage values, are presented on Fig. 3.2.

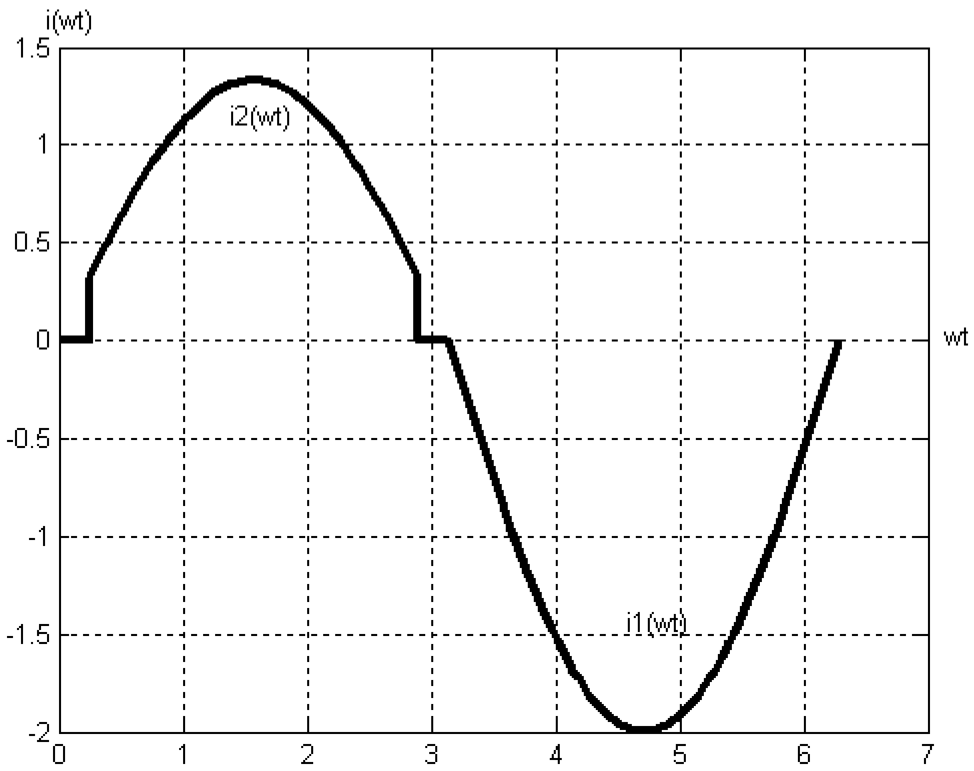


Fig.3.2

3.3. Parameters calculation in homogeneous resistive-diode circuit by instantaneous values

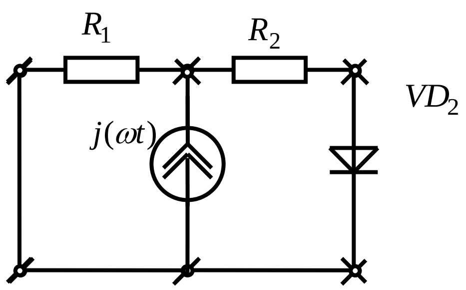


Fig. 3.3

Task.

Calculate branches current in homogeneous resistive-diode circuit, Fig.3.3 comprising nonlinear ideal semiconductor diode VD_2 and linear elements: $R_1 = 20$ Ohm, $R_2 = 10$ Ohm, $j(\omega t) = 2\sin\omega t$ A, *f=50* Hz.

The task solution.

Electric circuit comprises three branches and three contours with one nonlinear element. In circuit are absent energies storage, that is why instantaneous values of currents and drops voltages coincide as to phase on the circuit elements. The inner resistance of harmonic ideal current source is equal to infinity. We single out in the scheme two contours: left contour, in which are included resistor R_1 and harmonic power supply $j(\omega t)$ and right contour, where are connected harmonic power supply, resistor R_2, diode VD_2.

The oscillation period of harmonic power supply

$T = 1/f = 0{,}02$ s.

The first half-cycle output current. In the first half-cycle of positive output current the harmonic power supply in period of time $t = 0 \ldots t_0$ s the potential of diode's cathode VD_2 below the potential of anode, diode to reside in open state. At this time period left branch current is determined according to the rule of current divider $i_1(\omega t) = j(\omega t)\dfrac{R_2}{R_1 + R_2} = 0{,}67\sin\omega t$ A. The voltage drop on the first resistive element is equal $u_{R1}(\omega t) = R_1 i_1(\omega t) = 13{,}3\sin\omega t$ V.

The right branch current is $i_2(\omega t) = j(\omega t)\dfrac{R_1}{R_1 + R_2} = 1{,}33\sin\omega t$ A.

The second half-cycle output current. In the second half-cycle of negative output current the harmonic power supply in period of time $t = t_0 \ldots T$ s the potential of diode's cathode VD_2 become above of anode potential and diode at the moment of time $t_0 = 0{,}01$ s by step turns into closed state. The left branch current is equal to current of current source $i_1(\omega t) = j(\omega t) = 2\sin\omega t$ A. The right branch current is equal to zero.

The voltage drop on closed diode is equal to the voltage drop on resistor R_1 $u_{VD2}(\omega t) = 40\sin\omega t$ V, the power supply voltage is applied to resistor R_1 $u_{R1}(\omega t) = 20\sin\omega t$ V.

3.4. The scheme parameters calculation in homogeneous nonlinear resistive-capacitive circuit as to instantaneous values

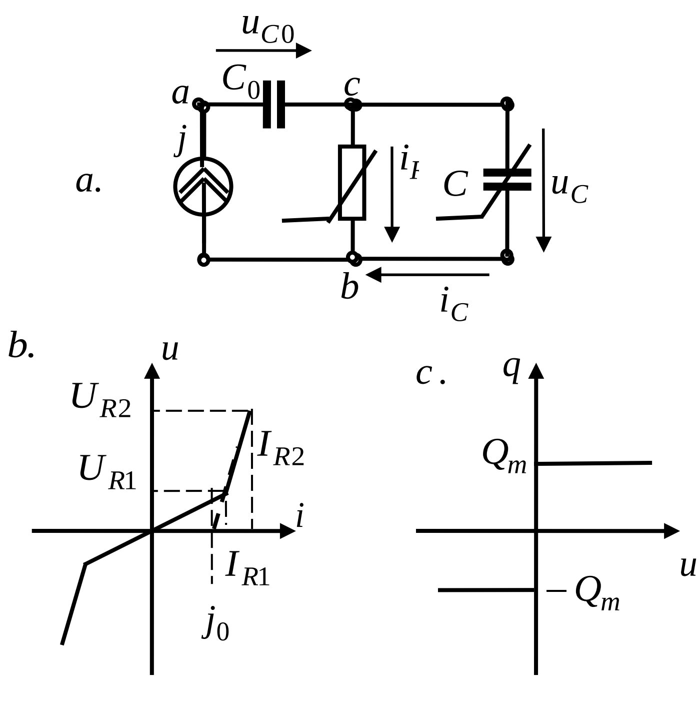


Fig.3.4

Task.

To ideal current source $j = 0{,}15\sin\omega t$ A, $(\omega = 10000\, ðàä/ñ)$ Fig.3.4.a, are connected linear capacitor $C_0 = 10$ μF, nonlinear capacitor C, coulomb-volt characteristic is given on Fig.3,4.c ($Q_m = 1{,}5 \cdot 10^{-5}$ C) and nonlinear resistor which volt-ampere characteristic, that given on Fig.3.4.b (U_{R1}=1 V, U_{R2}=3 V, I_{R1}=0,1 A, I_{R2}= 0,2 A). It is necessary to build the graphs of voltages change on the scheme elements.

The task solution.

Coulomb-voltage characteristic of nonlinear capacitor C has two characteristic district: horizontal and vertical one. Electric capacitance define as the quotient of the increments of charge to voltage, that is why on horizontal district cubic nonlinear capacitor capacitance is equal to zero, and on vertical one tend to infinity. Capacitive reactance of nonlinear capacitor reciprocal to capacity that is why on the horizontal district of the nonlinear capacitor coulomb-volt characteristic C its resistance is equal to infinity (there is break in branch), and on vertical district is equal to zero (shunting the branch with nonlinear ohmic resistance).

The transition moment from horizontal district on vertical ones of nonlinear capacitor coulomb-volt characteristic C is determined by the achievement of the maximal charge value on capacitor Q_m.

Knowing the current of ideal current source $j = 0{,}15\sin 10000t$ A we shall find charge, which power supply generated

$$q = \int j dt = -\frac{0{,}15}{10000}\cos\omega \cdot t = -1{,}5 \cdot 10^{-5}\cos 10000t \text{ C.}$$

We find the time moment of the of the achievement the maximal charge Q_m on capacitor

$$Q_m = -1{,}0 \cdot 10^{-5} = -1{,}5 \cdot 10^{-5}\cos\omega \cdot t_C, C;$$

$$\omega \cdot t_C = \arccos\frac{-1{,}0 \cdot 10^{-5}}{-1{,}5 \cdot 10^{-5}} = 0{,}84, rad.$$

The sinusoidal current power supply vibration period

$\omega \cdot T = 2\pi = 6{,}28$, ðàä.

Nonlinear ohmic resistance has two district with various dynamic resistances. Dynamic resistance on the first district

$R_{d1} = \Delta U_1 / \Delta I_1 = U_{R1} / I_{R1} = 1/0{,}1 = 10$, Ohms.

The dynamic resistance of nonlinear resistor on the second district of volt-ampere characteristic

$R_{d2} = \Delta U_2 / \Delta I_2 = (U_{R2} - U_{R1})/(I_{R2} - I_{R1}) = 2/0{,}1 = 20$, Ohms.

The displacement of the nonlinear resistor volt-ampere characteristic second district, relatively of coordinates beginnings we will find by means of linear interpolation by direct line which passing through two points (U_{R1}=1 V, U_{R2}=3 V, I_{R1}=0,1 A, I_{R2}= 0,2 A) initial direct line of second district

$$\frac{j_0 - I_{R2}}{I_{R2} - I_{R1}} = \frac{0 - U_{R2}}{U_{R2} - U_{R1}}; \; j_0 = 0{,}05\text{A.}$$

Found displacement is taken into account in the replacement scheme by means of the parallel connection of current supply source $j_0 = 0{,}05$ A to dynamic resistance R_{d2} on the second approximation district.

The drop voltage on the first district of nonlinear resistor volt-ampere characteristic

$u_{R1} = jR_{d1} = 0{,}15 \cdot 10\sin\omega t = 1{,}5\sin\omega t$ V.

The voltage drop on the second district of nonlinear resistor volt-ampere characteristic

$u_{R2} = (j + j_0)R_{d2} = (0{,}05 + 0{,}15\sin\omega t)\cdot 20 = 1{,}0 + 3{,}0\sin\omega t$ V.

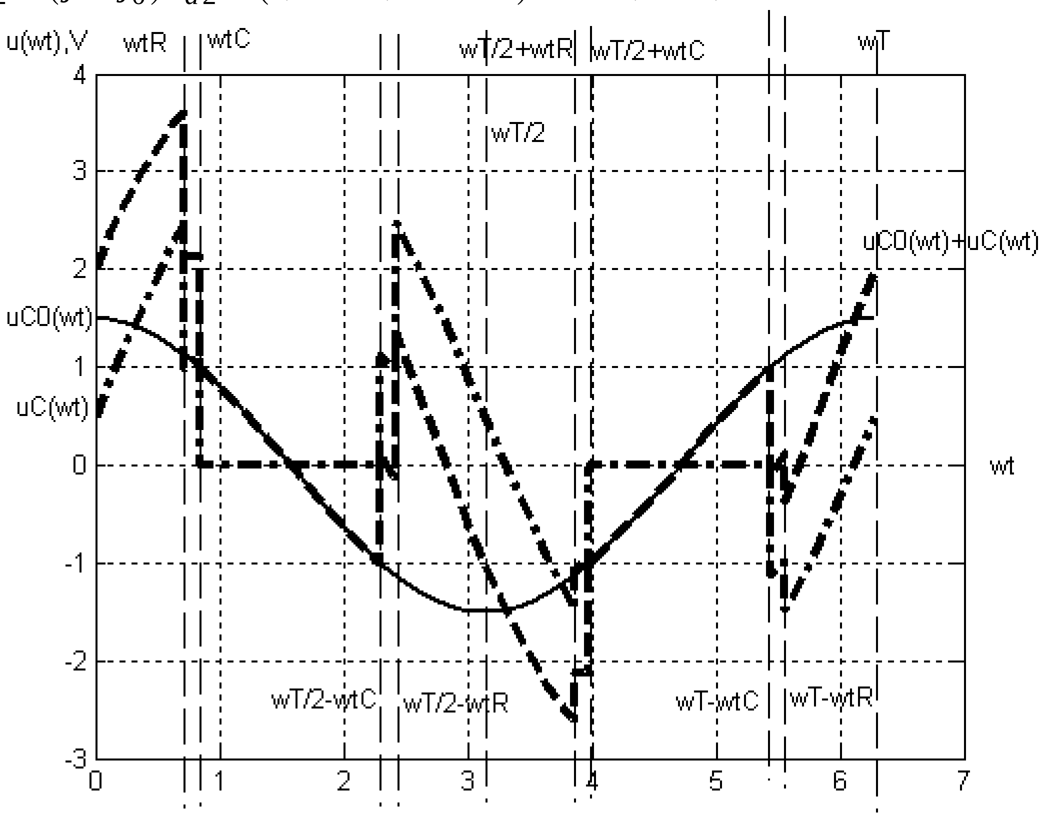


Fig.3.5

The transition time from the first district to the second one of nonlinear resistor volt-ampere characteristic

$I_{R1} = 0{,}1 = j(t_R) = 0{,}15\sin\omega t_R, A;$

$$\omega\cdot t_R = \arcsin\frac{0{,}1}{0{,}15} = 0{,}72, rad.$$

The voltage drop on the linear capacitor

$$u_c = \frac{j}{\omega\cdot C}\sin\left(\omega t - \frac{\pi}{2}\right) = 1{,}5\sin\omega t\left(\omega t - \frac{\pi}{2}\right) \text{ B.}$$

The graphs of voltage drops, are given on Fig.3.5.

3.5. Parameters calculation in homogeneous nonlinear resistance-inductance circuit as per instantaneous values

Task.

To the ideal voltage source $e = 4{,}0\sin\omega t$ V, ($\omega = 1000 rad/s$) Fig.3.6.a, are connected linear inductance $L_1 = 10$ mH, nonlinear inductance L_2, weber-ampere characteristic given on Fig.3,4.c ($\psi_m = 2{,}0\cdot 10^{-3}$ Vs), linear resistor $R_2 = 10$ Ohm and nonlinear resistor which volt-ampere characteristic, that given on Fig.3.4.b

(U_{R1}=1 V, I_{R1}=0,1 A). It is necessary to build the graphs of currents change in the scheme branches.

The task solution.

The nonlinear inductance weber-ampere characteristic L_2 has two characteristic districts: horizontal and vertical. Inductance of coil L_2 is determined by the quotient of aggrandizements the flux linkage to current, that is why on the horizontal district of nonlinear coil inductance is equal to zero, and on vertical one tend to infinity. The inductive reactance of nonlinear coil directly proportionally to inductance, that is why on the horizontal district of the weber-ampere characteristic of nonlinear coil L_2 its resistance equal to zero (closed the branch district), and on vertical one equal to infinity (the branch open district with linear ohmic resistance R_2).

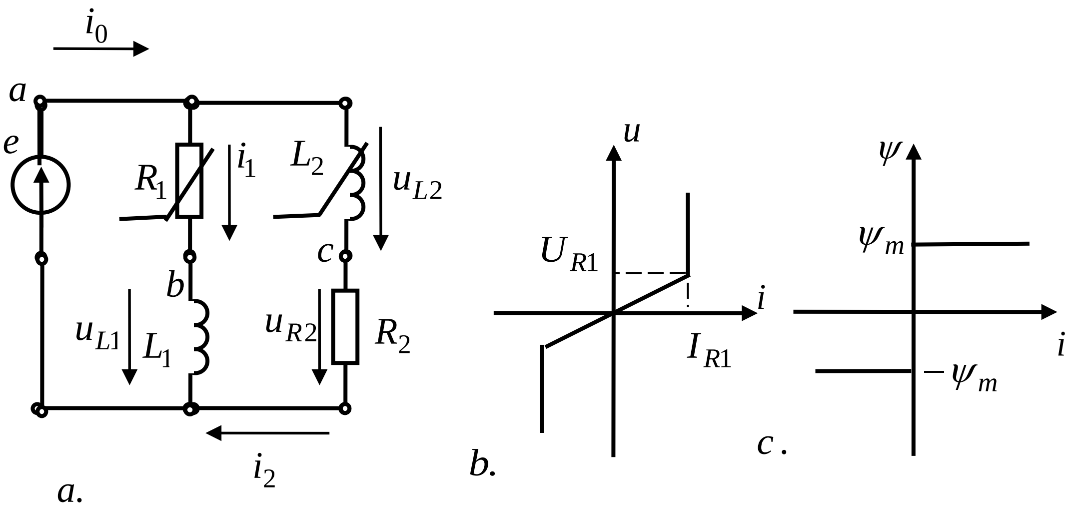


Fig.3.6

The transition moment from horizontal district on vertical one of nonlinear inductance weber-ampere characteristic L_2 is determined by the achievement of value maximal потокосцепления on coil ψ_m.

Knowing the voltage of ideal power supply $e = 4{,}0\sin 1000t$ V we shall find flux linkage in nonlinear inductance L_2

$$\psi = \int e dt = -\frac{4{,}0}{1000}\cos\omega\cdot t = -4{,}0\cdot 10^{-3}\cos 10000t \text{ Vs.}$$

We find the time moment of the achievement flux linkage maximum value ψ_m in inductance

$$\psi_m = -2{,}0\cdot 10^{-3} = -4{,}0\cdot 10^{-3}\cos\omega\cdot t_L, Vs;$$

$$\omega\cdot t_L = \arccos\frac{-2{,}0\cdot 10^{-3}}{-4{,}0\cdot 10^{-3}} = 1{,}04, rad.$$

The vibration period of the power supply sinusoidal voltage

$\omega\cdot T = 2\pi = 6{,}28, rad.$

Nonlinear ohmic resistor has two district with various dynamic resistances. Dynamic resistance on the first district

$R_{d1} = \Delta U_1 / \Delta I_1 = U_{R1} / I_{R1} = 1/0{,}1 = 10$, Ohm.

Nonlinear resistor dynamic resistance on the volt-ampere characteristic second district $R_{d2} = \infty$, Ohm.

The voltage drop on the first district of nonlinear resistor volt-ampere characteristic at endlessly large nonlinear inductance reactive resistance L_2

$$u_{R1} = R_{d1} \cdot \frac{e}{\sqrt{R_{d1}^2 + (\omega L_1)^2}} \sin\left(\omega t - arctg\frac{\omega L_1}{R_{d1}} + \frac{\pi}{2}\right) = 0{,}63\sin\left(\omega t + \frac{\pi}{4}\right) \text{ V.}$$

The voltage drop on the second district of nonlinear resistor volt-ampere characteristic at endlessly large nonlinear inductance reactive resistance L_2

$u_{R2} = 4{,}0 \sin \omega t$ B.

The transition time from the first to the second district of nonlinear element volt-ampere characteristic

$$I_{R1} = 0{,}1 = \frac{e}{R_{d1}} \sin \omega \cdot t_R = 0{,}4 \sin \omega \cdot t_R, A;$$

$$\omega \cdot t_R = \arcsin \frac{0{,}1}{0{,}4} = 0{,}25, rad.$$

The time interval $0 \ldots \omega \cdot t_R$. The circuit parameters value $R_1 = R_{d1} = 10$ Ohm, $L_2 = \infty$:

$$i_1 = \frac{e}{\sqrt{R_{d1}^2 + (\omega L_1)^2}} \sin\left(\omega t - arctg\frac{\omega L_1}{R_{d1}}\right) = 0{,}63\sin\left(\omega t - \frac{\pi}{4}\right) \text{ A;}$$

$$u_{R1} = R_{d1} \cdot \frac{e}{\sqrt{R_{d1}^2 + (\omega L_1)^2}} \sin\left(\omega t - arctg\frac{\omega L_1}{R_{d1}}\right) = 0{,}63\sin\left(\omega t - \frac{\pi}{4}\right) \text{ V;}$$

$$u_{L1} = \omega L_1 \cdot \frac{e}{\sqrt{R_{d1}^2 + (\omega L_1)^2}} \sin\left(\omega t - arctg\frac{\omega L_1}{R_{d1}} + \frac{\pi}{2}\right) = 0{,}63\sin\left(\omega t + \frac{\pi}{4}\right) \text{ V;}$$

$i_2 = 0$ A.

The time interval $\omega \cdot t_R \ldots \omega \cdot t_L$. The circuit parameters value $R_1 = R_{d2} = \infty$ Ohm, $L_2 = \infty$:

$i_1 = I_{R1} = 0{,}1$ A, – resistor works in the regime of current stabilization;

$u_{R1} = 4{,}0 \cdot \sin \omega \cdot t$ V;

$u_{L1} = 0$ V;

$i_2 = 0$ A.

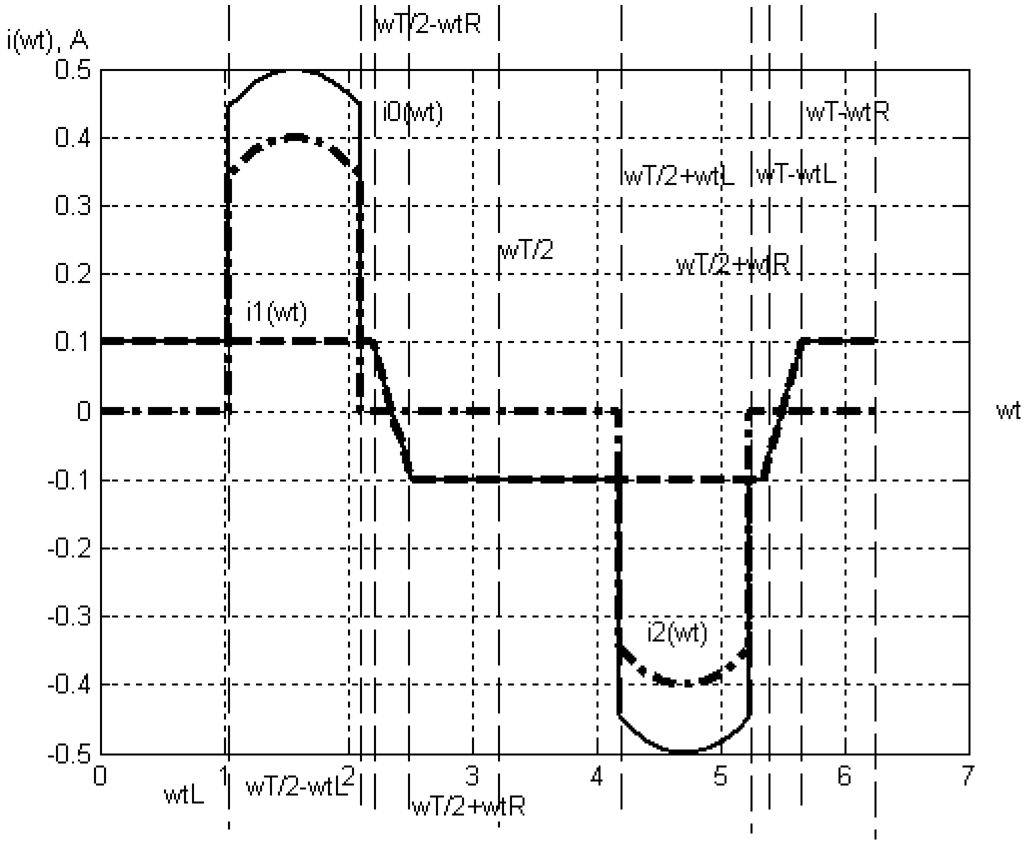


Fig.3.7.

The time interval $\omega \cdot t_L \ldots \pi / 4$. The circuit parameters value $R_1 = R_{d2} = \infty$ Ohm, $L_2 = 0$:

$i_1 = I_{R1} = 0{,}1$ A, – resistor works in the regime of current stabilization;

$u_{R1} = 4{,}0 \cdot \sin \omega \cdot t$ V;

$u_{L1} = 0$ V;

$u_{L2} = 0$ V;

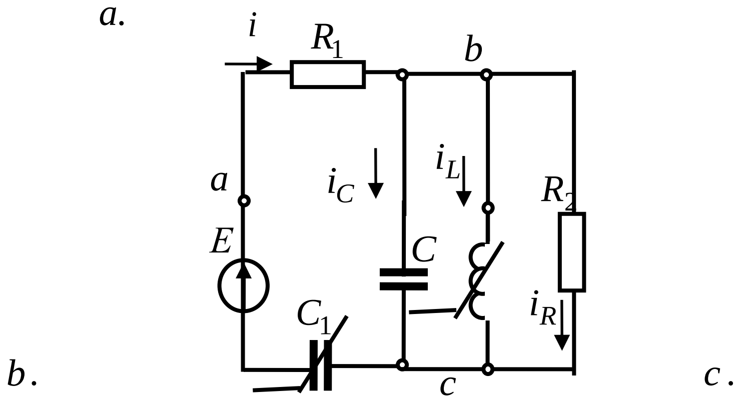
$i_2 = e / R_2 = 0{,}4 \sin \omega \cdot t$ A.

In further process is repeated. Graphs of current branches are given on Fig.3.7.

3.6. Parameters calculation in homogeneous nonlinear resistance-inductance-capacitance circuit as to equivalent sinusoids effective values

Task.

There is given nonlinear electric scheme, Fig.3.8.a, on the input of which acts harmonic source. Considering in the first approximation that in scheme act the equivalent sinusoidal currents and voltage which coinciding with the first harmonics, to determine currents and voltages phasor value in the scheme branches and to build phasor digram.. Nonlinear capacitance and inductance are given by вольт volt-ampere characteristics, Fig.3.8.b, c. The parameters of the scheme linear elements: $x_C = R_1 = R_2 = 100$ Ohm.



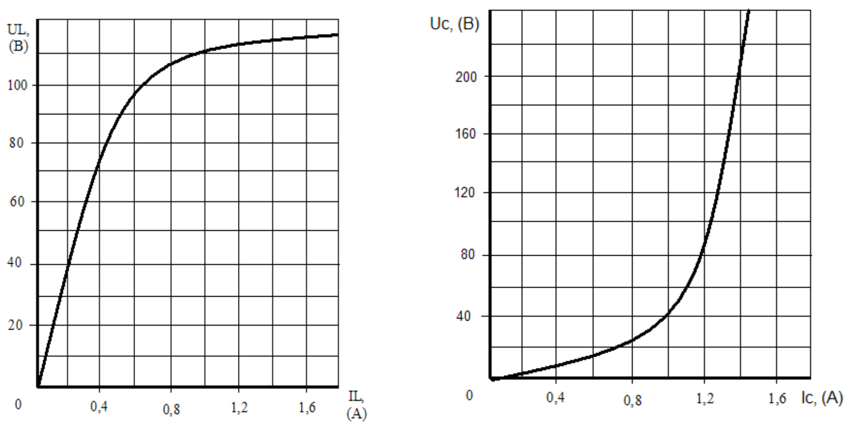


Fig.3.8

The task solution.

We arbitrarily assign current's magnitude and the phase of nonlinear inductive element $\underline{I}_L = 0{,}4e^{j0^0}$ A, according to volt-ampere characteristic Fig.3.8.b the inductance voltage phasor value $\underline{U}_L = 70e^{j90^0}$ V.

The voltage on ohmic resistance R_2 is equal to voltage on inductive element

$\underline{U}_{R2} = \underline{U}_L = 70e^{j90^0}$ V.

The resistor current R_2 $\underline{I}_R = \underline{U}_{R2} / R_2 = 0{,}7e^{j90^0}$ A.

The voltage on capacitive element C is equal to voltage on inductive element $\underline{U}_C = \underline{U}_L = 70e^{j90^0}$ V. The capacitive current C $\underline{I}_C = \underline{U}_{R2} / (-jx_C) = 0{,}7e^{j180^0}$ A.

Input current find as to the first Kirhhgoff's law

$$\underline{I} = \underline{I}_L + \underline{I}_C + \underline{I}_R = 0{,}4e^{j0^0} + $$
$$+ 0{,}7e^{j180^0} + 0{,}7e^{j90^0} = 0.76e^{j113^0}$$ A.

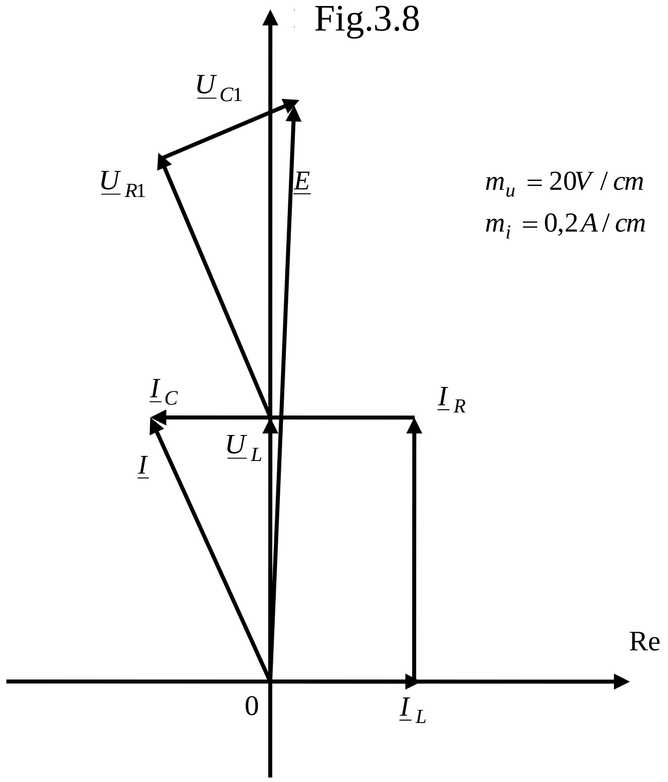


Fig.3.9

Knowing the input current magnitude 0.76 A as to the volt-ampere characteristic of nonlinear capacitor, Fig.3.8.c, we find voltage on the first capacitor

$\underline{U}_{C1} = 20e^{j(113^0 - 90^0)} = 20e^{j23^0}$.

The voltage drop on linear resistor R_1 $\underline{U}_{R1} = \underline{I} \cdot R_1 = 76e^{j113^0}$ V.

The voltage phasor value of power supply E

$\underline{E} = \underline{U}_{R1} + \underline{U}_C + \underline{U}_{C1} = 76e^{j113^0} + 70e^{j90^0} + 20e^{j23^0} = 148e^{j94^0}$ V.

The mixed phasor digram of currents and voltages is presented on Fig.3.9.

3.7. The coil with steel core parameters calculation by the equivalent sinusoids method

Task.

At connection coil with steel core (choke) to the sinusoidal voltage source as to scheme Fig.3.10, are fixed the indications of apparatus: ammeter 0.2 A, voltmeter 120 V, wattmeter 1.2 W. The ohmic resistance of winding coil (the resistance of the coil copper) is measured and equal R_M =9 Ohm.

Calculate the scheme parameters of the replacement of coil with steel and build phasor digram.

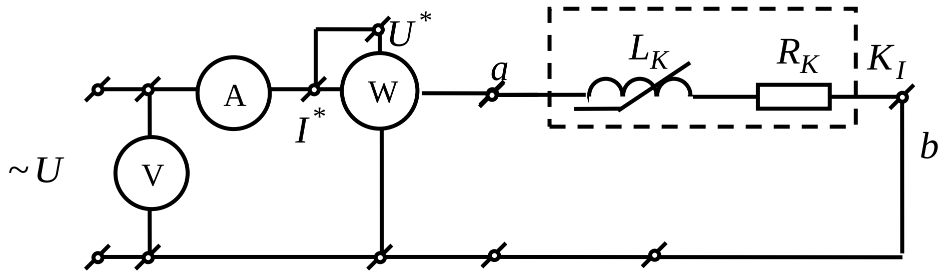


Fig.3.10

The task solution.

As magnetic flux is proportional to applied voltage, that is why at voltage increasing the coil magnetic conductor is saturated, that brings to the decrease of inductance contour to and the decrease of inductive resistance. Voltage increasing brings to saturation magnetic conductor and current in coil begins to change not as to sinusoid.

For the calculation of AC electric circuits with nonlinear inductive element (coil with steel core), its are replaced by the series or parallel replacement scheme (Fig. 3.11, 3.12).

In schemes the resistance R_M is ohmic resistance of the winding coil wires (the resistance of the coil copper). In the simplified replacement schemes the magnetic leakage fluxes we neglect. That is why leakage inductance and contour leakage inductive resistance are equal to zero. The ohmic resistance R_{CT} and fitting conduction G_{CT} take into consideration the active losses occurrence in core (resistance became spool takes into account the presence of active losses on cyclic magnetization reversal magnetic conductor). Reactive resistance x_μ and conduction b_μ take into account the presence of main magnetic flux which enclose into magnetic conductor.

The series replacement scheme parameters calculation at leakage inductance counting not.

For parameters calculation of the replacement scheme is made assumption which in circuit flow equivalent sinusoidal current, value of which is determined by ammeter *I*=0,2 A.

We neglect leakage inductance (approximate calculation) $x_S = 0$.

Reactive power which is release in inductance, that provided by main magnetic flux, is determined by correlation

$$Q = \sqrt{S^2 - P^2} = \sqrt{(UI)^2 - P^2} = \sqrt{(120 \cdot 0{,}2)^2 - 1{,}2^2} = 23{,}96, \text{ var},$$

where *S=UI*, VA – apparent consumed power;

U, I, P – the measured values of voltage, V, equivalent current, A, active power, W.

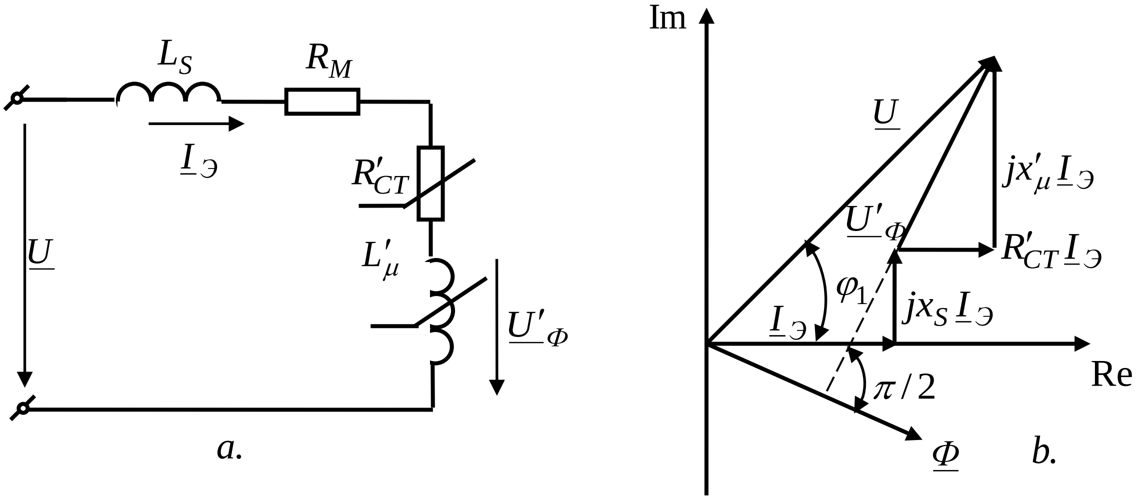


Fig.3.11

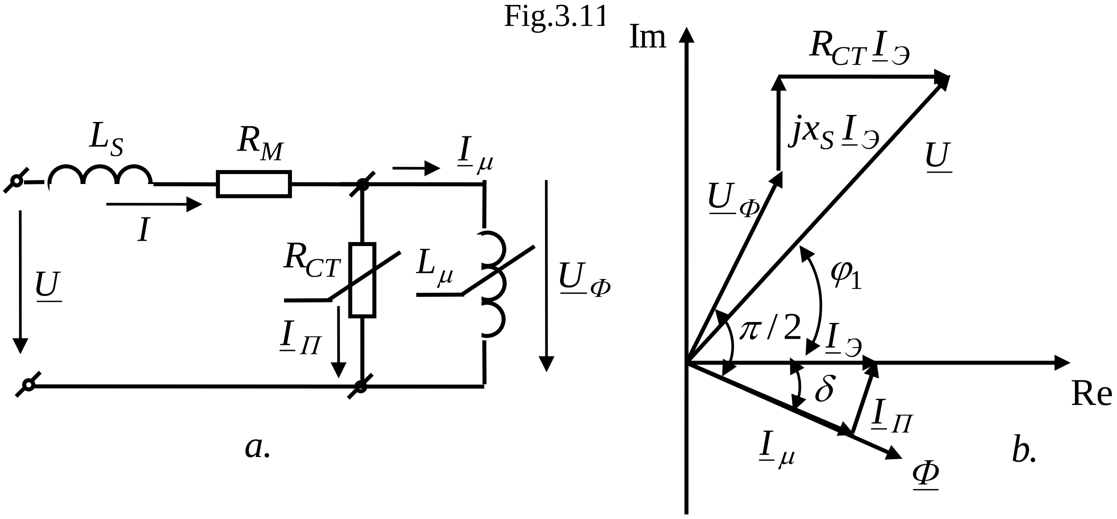


Fig.3.12

The approximate value of the coil reactive resistance

$$x_{\mu}^{'} = \omega L_{\mu}^{'} = \frac{Q}{I^2} = \frac{23{,}96}{0{,}2^2} = 599{,}24, \text{ Ohm.}$$

The approximate value of the coil inductance

$$L_{\mu}^{'} = \frac{x_{\mu}^{'}}{\omega} = \frac{599{,}24}{314} = 1{,}9, \text{ H}$$

where $\omega = 2\pi f$ – the cyclic frequency of applying voltage, f=50 Hz – angular frequency.

The parallel replacement scheme parameters calculation with allowance the leakage inductance.

We do calculation with allowance for presence inductance from the leakage fluxes. We accept the value of the leakage flux equal to 10% from main magnetic flux that enclose in magnetic conductor. At such assumption the leakage flux is determined as

$$L_S = 0{,}1 L_{\mu}^{'} = 0{,}19 \text{ H.}$$

Reactive resistance from the leakage flux

$$x_S = \omega L_S = 314 \cdot 0{,}19 = 59{,}66, \text{ Ohm.}$$

From the power triangle we find the lag angle φ of input equivalent current from supply voltage

$$\varphi = \arccos \frac{P}{S} = \arccos \frac{1{,}2}{120 \cdot 0{,}2} = 87^0.$$

We determine the phasor values of supply voltage $\underline{U}$ and equivalent input current $\underline{I}$

$$\underline{U} = U e^{j\psi_U} = 120 e^{j87^0} V; \underline{I} = I e^{j\psi_I} = 0{,}2 e^{j0^\circ} A.$$

where U, I – indications of apparatus;

ψ_u, ψ_i – phases of voltage and current that connected between each other by correlation

$$\psi_u - \psi_i = \varphi.$$

One of phases (ψ_u ore ψ_i) is accepted as initial (for example, is accepted equal to zero equivalent current phase).

We reckon voltage on magnetization contour

$$\underline{U}_{\hat{o}} = \underline{U} - \underline{I}(R_M + jx_S) = 120 e^{j87^0} - 0{,}2 e^{j0^0}(9 + j59{,}66) = 107{,}9 e^{j87^0} V = U_{\hat{o}} e^{\psi_U} \text{ V.}$$

Active losses in winding coil (in the resistance of the coil copper)

$$P_M = R_M I^2 = 0{,}36 \text{ W.}$$

Active losses on reversal magnetization of steel reversal magnetization (in the conductions of steel magnetic conductor)

$$P_C = P - P_M = 1{,}2 - 0{,}36 = 0{,}84 \text{ W.}$$

The conductions of steel magnetic conductor

$$G_{CT} = \frac{P_C}{U_{\hat{o}}} = \frac{0{,}84}{107{,}9} = 7{,}78 \cdot 10^{-3} \text{ S.}$$

Current in the losses contour that conditioning losses in steel

$$I_{Ï} = U_{ô} \cdot G_{CT} = 107{,}9 \cdot 7{,}78 \cdot 10^{-3} = 0{,}84 \text{ A.}$$

Losses current coincides as to phase with voltage on magnetization contour that is why its phasor value

$$\underline{I}_{Ï} = I_{Ï}\, e^{j\psi_U} = 0{,}84 e^{j87^0} \text{ A.}$$

The contour current phasor value of main flux magnetic conductor magnetization

$$\underline{I}_{\mu} = \underline{I} - \underline{I}_{Ï} = 0{,}2e^{j0^0} - 0{,}84e^{j87^0} = 0{,}85e^{-j79^0} = I_{\mu} e^{j\psi_{\mu}}, \text{ A.}$$

The accurate value of inductive the conduction of magnetization contour

$$L_{\mu} = \frac{1}{\omega \cdot b_{\mu}} = \frac{U_{Ô}}{\omega \cdot I_{\mu}} = \frac{107{,}9}{314 \cdot 0{,}85} = 0{,}4 \text{ H.}$$

The reactive losses in magnetization contour

$$Q_{\mu} = \frac{I_{\mu}^2}{b_{\mu}}, \text{ var.}$$

The reactive losses in inductance of leakage flux

$$Q_S = x_S I^2, \text{ var.}$$

The magnetic flux magnitude

$$\hat{O} = \frac{U_{ô}}{4{,}44 \cdot fW}, \text{ Wb,}$$

where W=100 – the turns quantity of winding coil.

Magnetic flux lags behind from voltage on magnetization contour on angle $\frac{\pi}{2}$, that is why its phasor value

$$\underline{\Phi} = \Phi \cdot e^{j(\psi_U - \frac{\pi}{2})}, \text{ Wb.}$$

Similar calculations with allowance the leakage inductance we can do and for the series replacement scheme, Fig.3.11.

At drawing the voltage phasor diagram that combined with currents vector diagram and magnetic flux, as initial vector may be chosen one of parameters: vector of input current, or vector of input voltage or vector o magnetic flux, Fig.3.12. All the rest vectors are draw in scales according to found phasor values. The initial data for drawing phasor diagram are taking according to performed calculations.

3.8. The personal computative-graphic task “The steady-flow process calculation in nonlinear electric AC circuits”

This job consists of two tasks. The first task envisages the calculation of periodical processes in nonlinear electric circuit as to instantaneous values, second task there is calculation of periodical processes in nonlinear electric circuit as to effective values of equivalent sinusoids.

Task 1. In electric circuits Fig.3.33, 3.34 act the sources of constant EMF E_0, harmonic EMFs $e(\omega \cdot t)$ and currents $j(\omega \cdot t)$. The circuit parameters are given in tables 3.1.-3.8. The nonlinear characteristic of capacitance is set by coulomb-volt characteristic and for inductance by weber-ampere characteristic, and for resistor by volt-ampere characteristic, Fig.3.35. It is needed to determine in the time functions $\omega \cdot t$ the law of variation given in tables 3.1.-3.8. functions. On the grounds of received analytic expression for functions to build the graph of the change of found values on the repetition period.

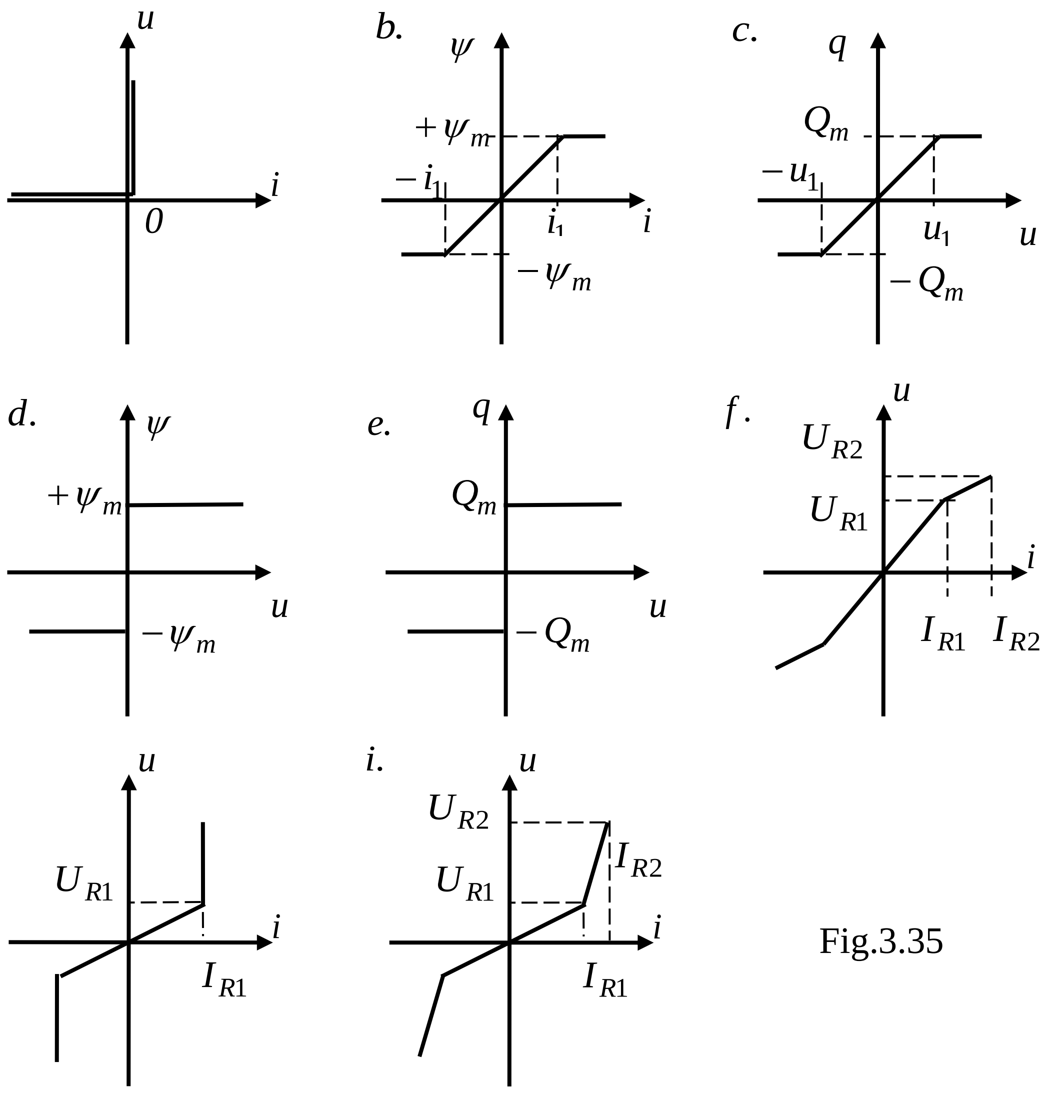


Fig.3.35

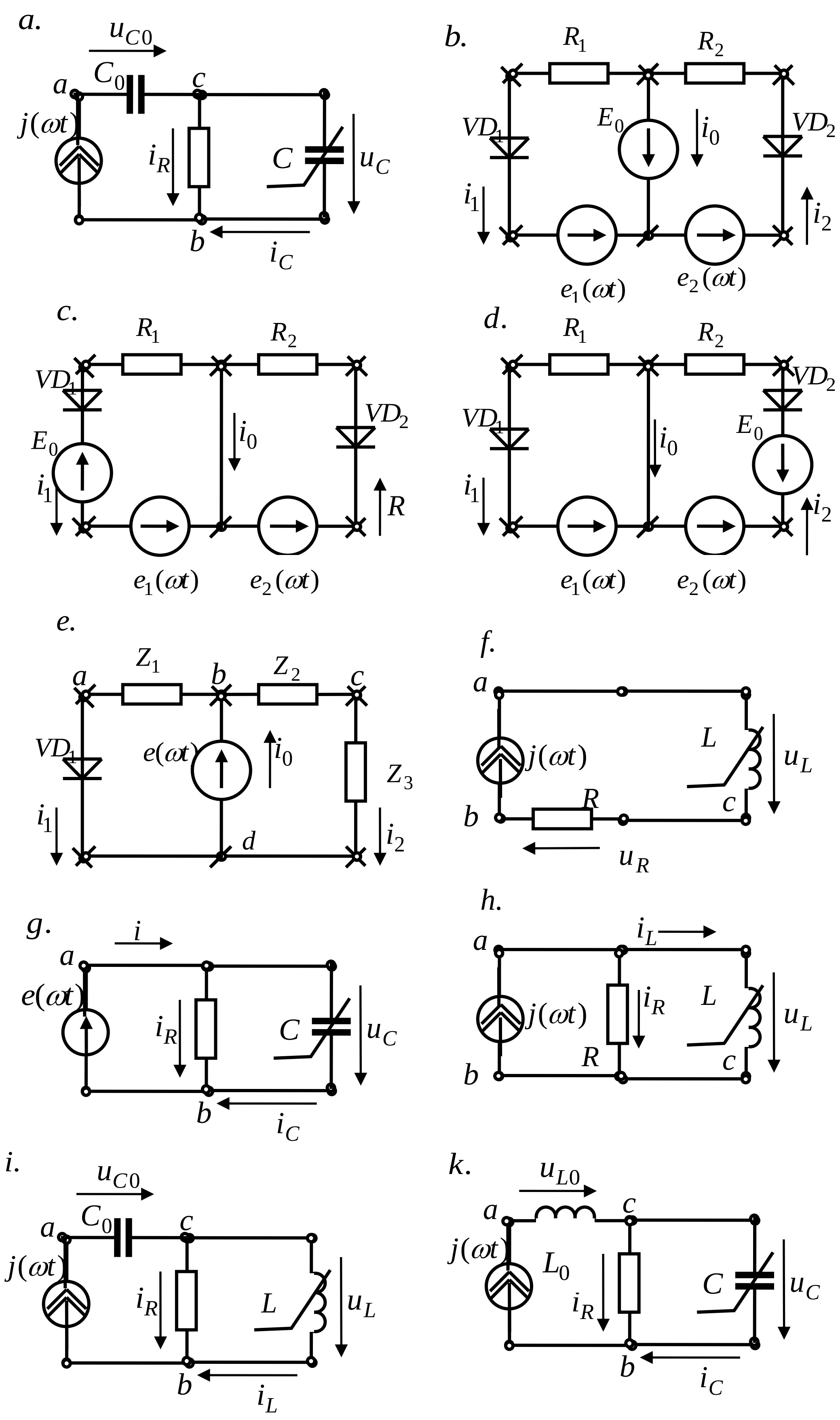

a.
uC0
C0
a
c
j(ωt)
iR
C
uC
b
iC
b.
R1
R2
VD1
E0
i0
VD2
i1
i2
e1(ωt)
e2(ωt)
c.
R1
R2
VD1
E0
i0
VD2
i1
R
e1(ωt)
e2(ωt)
d.
R1
R2
VD1
VD2
i0
E0
i1
i2
e1(ωt)
e2(ωt)
e.
Z1
Z2
a
b
c
VD1
e(ωt)
i0
Z3
i1
i2
d
f.
a
j(ωt)
L
uL
R
c
b
uR
g.
i
a
e(ωt)
iR
C
uC
b
iC
h.
iL
a
j(ωt)
iR
L
uL
R
c
b
i.
uC0
C0
a
c
j(ωt)
iR
L
uL
b
iL
k.
uL0
a
c
j(ωt)
L0
iR
C
uC
b
iC

Fig.3.33

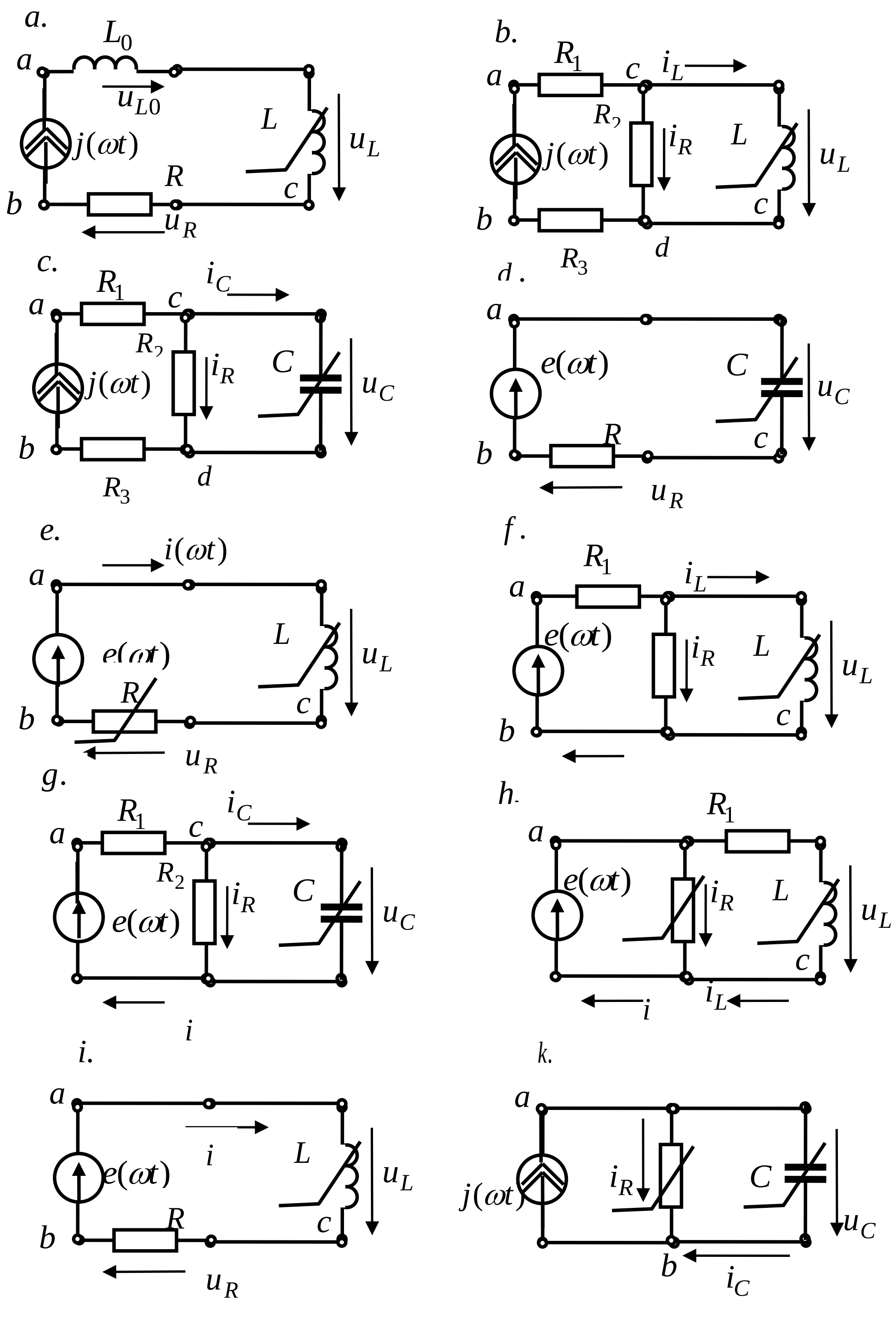
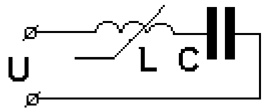

a.
b.
c.
d.
e.
f.
g.
h.
i.
k.
L_0
u_{L0}
$j(\omega t)$
$e(\omega t)$
$i(\omega t)$
R_1
R_2
R_3
i_L
i_R
i_C
u_L
u_C
u_R

Fig.3.34

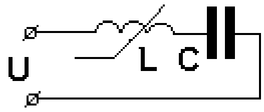
Task 2. There are given nonlinear electric schemes, Fig.3.36-3.38. On the scheme input acts voltages that changed in time as to harmonic law with constant frequency. By seting four current values for nonlinear element, there is needed to calculate periodical processes by means of volt-ampere characteristics Fig.3.39 as to the first harmonic for acting values of equivalent currents and voltages. To build phasor diagrams.
The initial data for the calculation of the circuit parameters and the number of scheme are set as to the variant number in table 3.9 and are chosen as to two last numbers the numbers of course for credit book.

3.9. Questions for self-testing as to the calculation methods of nonlinear AC circuits

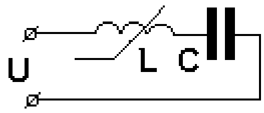
1. Calculate the boundary values of district volt-ampere characteristic which has negative dynamic resistance, if $U^2_L = 4\cdot(I)$; $U_C = 2\cdot I$



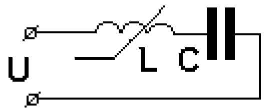
2. Dynamic resistance calculate value on unstable district volt-ampere characteristic if we know $U^2_L = 4\cdot(I)$; $U_C = 2\cdot I$



3. Find the capacity value C, at which in point I=2 A, appears phenomenon voltage ferroresonance, if $U^2_L = 4\cdot(I)$; f=50 Hz.



4. Find the capacity value C, at which in point I=1 A appears phenomenon voltage ferroresonance, if $U^2_L = 4\cdot(I)$; f=50 Hz.



5. Find the drop voltage on scheme elements and current in circuit at voltage ferroresonance, if $U^2_L = 4\cdot(I)$; $x_C = 10$ Ohm; R=5 Ohm.

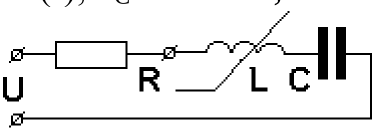


Table 3.1.

Variant	The scheme numbers and the nonlinear element characteristics		The scheme linear elements parameters								Determine in functions of ωt
	scheme	*element*	E_0, V	$e_1(\omega t)$, V	$e_2(\omega t)$, V	R_1,Ohm	R_2,Ohm	Z_1,Ohm	Z_2,Ohm	Z_3,Ohm	
01	3.33.b	3.35.a	5	$10\sin(\omega t)$	$15\sin(\omega t)$	50	100	0	0	0	i_3, u_{VD1}
02	3.33.b	3.35.a	10	$20\sin(\omega t)$	$30\sin(\omega t)$	100	200	0	0	0	i_3, u_{VD2}
03	3.33.b	3.35.a	15	$30\sin(\omega t)$	$40\sin(\omega t)$	150	300	0	0	0	i_2, u_{VD1}
04	3.33.b	3.35.a	5	$10\sin(\omega t)$	$14\sin(\omega t)$	50	100	0	0	0	i_1, u_{VD2}
05	3.33.b	3.35.a	10	$20\sin(\omega t)$	$25\sin(\omega t)$	100	200	0	0	0	i_1, i_2
06	3.33.c	3.35.a	5	$10\sin(\omega t)$	$15\sin(\omega t)$	50	100	0	0	0	i_3, u_{VD1}
07	3.33.c	3.35.a	10	$20\sin(\omega t)$	$30\sin(\omega t)$	100	200	0	0	0	i_3, u_{VD2}
08	3.33.c	3.35.a	15	$30\sin(\omega t)$	$40\sin(\omega t)$	150	300	0	0	0	i_2, u_{VD1}
09	3.33.c	3.35.a	5	$10\sin(\omega t)$	$14\sin(\omega t)$	50	100	0	0	0	i_1, u_{VD2}
10	3.33.c	3.35.a	10	$20\sin(\omega t)$	$25\sin(\omega t)$	100	200	0	0	0	i_1, i_2
11	3.33.d	3.35.a	5	$10\sin(\omega t)$	$15\sin(\omega t)$	50	100	0	0	0	i_3, u_{VD1}
12	3.33.d	3.35.a	10	$20\sin(\omega t)$	$30\sin(\omega t)$	100	200	0	0	0	i_3, u_{VD2}
13	3.33.d	3.35.a	15	$30\sin(\omega t)$	$40\sin(\omega t)$	150	300	0	0	0	i_2, u_{VD1}
14	3.33.d	3.35.a	5	$10\sin(\omega t)$	$14\sin(\omega t)$	50	100	0	0	0	i_1, u_{VD2}
15	3.33.d	3.35.a	10	$20\sin(\omega t)$	$25\sin(\omega t)$	100	200	0	0	0	i_1, i_2
16	3.33.e	3.35.a	5	$10\sin(\omega t)$	$15\sin(\omega t)$	0	0	5	3j	4	u_{ab}, U_{ab}
17	3.33.e	3.35.a	10	$20\sin(\omega t)$	$30\sin(\omega t)$	0	0	7	3	4j	u_{ab}, U_{ab}
18	3.33.e	3.35.a	15	$30\sin(\omega t)$	$40\sin(\omega t)$	0	0	9	-3j	4	u_{ab}, U_{ab}
19	3.33.e	3.35.a	5	$10\sin(\omega t)$	$14\sin(\omega t)$	0	0	10	4	-3j	u_{ab}, U_{ab}
20	3.33.e	3.35.a	10	$20\sin(\omega t)$	$25\sin(\omega t)$	0	0	12	-6j	8	u_{ab}, U_{ab}

Variant	The scheme numbers and the nonlinear element characteristics		The scheme linear elements parameters							Determine in functions of ωt
	scheme	*element*	$j(\omega t)$, *A*	R_1,*Ohm*	R_2,*Ohm*	R_3,*Ohm*	C_0, μF	*R*,*Ohm*	L_0, *mH*	
21	3.33.a	3.35.e, $Q_m = 10^{-5}$,C	$0.04\sin(10^3 t)$	-	-	-	4	250	-	i_R, u_{ab}, i_C, q
22	3.33.a	3.35.e, $Q_m = 10^{-5}$, C	$0.01\sin(250t)$	-	-	-	16	1000	-	i_R, u_{ab}, u_{ac}, u_{cb}
23	3.33.a	3.35.e, $Q_m = 10^{-5}$, C	$0.02\sin(500t)$	-	-	-	8	500	-	i_C, q, u_{ac}, u_{cb}
24	3.33.a	3.35.e, $Q_m = 10^{-5}$, C	$0.08\sin(2 \cdot 10^3 t)$	-	-	-	2	125	-	i_R, q, u_{ac}, u_{cb}
25	3.33.a	3.35.e, $Q_m = 10^{-5}$, C	$0.06\sin(1.5 \cdot 10^3 t)$	-	-	-	6	167	-	i_R, u_{ab}, i_C, u_{cb}
26	3.33.k	3.35.e, $Q_m = 10^{-5}$, C	$0.04\sin(10^3 t)$	-	-	-	-	250	250	q, i_R, i_C, u_{ac}
27	3.33.k	3.35.e, $Q_m = 10^{-5}$,C	$0.01\sin(250t)$	-	-	-	-	1000	4000	q, i_R, i_C, u_{cb}
28	3.33.k	3.35.e, $Q_m = 10^{-5}$,C	$0.02\sin(500t)$	-	-	-	-	500	1000	i_R, i_C, u_{ac}, u_{cb}
29	3.33.k	3.35.e, $Q_m = 10^{-5}$, C	$0.08\sin(2 \cdot 10^3 t)$	-	-	-	-	125	62,5	q, i_C, u_{ac}, u_{cb}
30	3.33.k	3.35.e, $Q_m = 10^{-5}$,C	$0.06\sin(1.5 \cdot 10^3 t)$	-	-	-	-	167	110	q, i_R, u_{ac}, u_{cb}

Table 3.2.

Table 3.3.

Variant	The scheme numbers and the nonlinear element characteristics		The scheme linear elements parameters						Determine in functions of ωt
	scheme	*element*	$j(\omega t)$, *A*	R_1, *Ohm*	R_2, *Ohm*	R_3, *Ohm*	*R*, *Ohm*	L_0, *mH*	
31	3.34.c	3.35.e, $Q_m = 10^{-5}$, C	$0{,}05\sin(10^3 t)$	40	100	60	-	-	i_R, i_C, u_{ab}, u_{cd}
32	3.34.c	3.35.e, $Q_m = 10^{-5}$, C	$0{,}045\sin(900t)$	60	100	40	-	-	i_R, i_C, u_{ab}, u_{cd}
33	3.34.c	3.35.e, $Q_m = 10^{-5}$, C	$0{,}055\sin(1100t)$	30	90	70	-	-	i_R, i_C, u_{ab}, u_{cd}
34	3.34.c	3.35.e, $Q_m = 10^{-5}$, C	$0{,}052\sin(1050t)$	70	90	30	-	-	i_R, i_C, u_{ab}, u_{cd}
35	3.34.c	3.35.e, $Q_m = 10^{-5}$, C	$0{,}047\sin(950t)$	45	100	55	-	-	i_R, i_C, u_{ab}, u_{cd}
36	3.34.k	3.35.e, $Q_m = 10^{-5}$, C; 3.35.i, $U_{R1} = 1$, V; $U_{R2} = 3$, V; $I_{R1} = 0{,}1$, A; $I_{R2} = 0{,}2$, A	$0.15\sin(1.0 \cdot 10^4 t)$	-	-	-	250	250	i_R, i_C, u_{ab}
37	3.34.k	3.35.e, $Q_m = 10^{-5}$, C; 3.35.i, $U_{R1} = 1$, V; $U_{R2} = 3$, V; $I_{R1} = 0{,}1$, A; $I_{R2} = 0{,}2$, A	$0.16\sin(1.1 \cdot 10^4 t)$	-	-	-	1000	4000	i_R, i_C, u_{ab}
38	3.34.k	3.35.e, $Q_m = 10^{-5}$, C; 3.35.i, $U_{R1} = 1$, V; $U_{R2} = 3$, V; $I_{R1} = 0{,}1$, A; $I_{R2} = 0{,}2$, A	$0.17\sin(1.2 \cdot 10^4 t)$	-	-	-	500	1000	i_R, i_C, u_{ab}
39	3.34.k	3.35.e, $Q_m = 10^{-5}$, C; 3.35.i, $U_{R1} = 1$, V; $U_{R2} = 3$, V; $I_{R1} = 0{,}1$, A; $I_{R2} = 0{,}2$, A	$0.18\sin(1.3 \cdot 10^4 t)$	-	-	-	125	62,5	i_R, i_C, u_{ab}
40	3.34.k	3.35.e, $Q_m = 10^{-5}$, C; 3.35.i, $U_{R1} = 1$, V; $U_{R2} = 3$, C; $I_{R1} = 0{,}1$, A; $I_{R2} = 0{,}2$, A	$0.19\sin(1.4 \cdot 10^4 t)$	-	-	-	167	110	i_R, i_C, u_{ab}

Variant	The scheme numbers and the nonlinear element characteristics		The scheme linear elements parameters						Determine in functions of ωt
	scheme	*element*	$e(\omega t)$, *V*	R_1, *Ohm*	R_2, *Ohm*	R_3, *Ohm*	*R* *Ohm*$_M$	L_0, *mH*	
41	3.33.g	3.35.c $Q_m = 10^{-4}$, C, u_1=7,1 V	$10\sin(10^3 t)$	-	-	-	71	-	i, i_C, i_R, q
42	3.33.g	3.35.c $Q_m = 10^{-4}$, C, u_1=14,2 V	$20\sin(2\cdot 10^3 t)$	-	-	-	71	-	i, i_C, i_R, q
43	3.33.g	3.35.c $Q_m = 10^{-4}$, C, u_1=10,6 V	$15\sin(1.5\cdot 10^3 t)$	-	-	-	71	-	i, i_C, i_R, q
44	3.33.g	3.35.c $Q_m = 10^{-4}$, C, u_1=17,7 V	$25\sin(2.5\cdot 10^3 t)$	-	-	-	71	-	i, i_C, i_R, q
45	3.33.g	3.35.c $Q_m = 10^{-4}$, C, u_1=21,3 V	$30\sin(3\cdot 10^3 t)$	-	-	-	71	-	i, i_C, i_R, q
46	3.34.d	3.35.e, $Q_m = 10^{-5}$ C	$30.0\sin(10^3 t)$	-	-	-	1000	250	i, u_C, q
47	3.34.d	3.35.e, $Q_m = 10^{-5}$ C	$60.0\sin(2.0\cdot 10^3 t)$	-	-	-	1000	4000	i, u_C, q
48	3.34.d	3.35.e, $Q_m = 10^{-5}$ C	$90.0\sin(3.0\cdot 10^3 t)$	-	-	-	1000	1000	i, u_C, q
49	3.34.d	3.35.e, $Q_m = 10^{-5}$ C	$120.0\sin(4.0\cdot 10^3 t)$	-	-	-	1000	62,5	i, u_C, q
50	3.34.d	3.35.e, $Q_m = 10^{-5}$ C	$150.0\sin(5.0\cdot 10^3 t)$	-	-	-	1000	110	i, u_C, q
51	3.34.g	3.35.e, $Q_m = 10^{-5}$ C	$30.0\sin(10^3 t)$	1000	1000	-	-	-	i_C, i_R, u_{ac}, q
52	3.34.g	3.35.e, $Q_m = 10^{-5}$ C	$60.0\sin(2.0\cdot 10^3 t)$	1000	1000	-	-	-	i_C, i_R, u_{ac}, q
53	3.34.g	3.35.e, $Q_m = 10^{-5}$ C	$90.0\sin(3.0\cdot 10^3 t)$	1000	1000	-	-	-	i_C, i_R, u_{ac}, q
54	3.34.g	3.35.e, $Q_m = 10^{-5}$ C	$120.0\sin(4.0\cdot 10^3 t)$	1000	1000	-	-	-	i_C, i_R, u_{ac}, q
55	3.34.g	3.35.e, $Q_m = 10^{-5}$ C	$150.0\sin(5.0\cdot 10^3 t)$	1000	1000	-	-	-	i_C, i_R, u_{ac}, q

Table 3.4.

Variant	The scheme numbers and the nonlinear element characteristics		The scheme linear elements parameters							Determine in functions of ωt
	scheme	*element*	$j(\omega t)$, *A*	*R₁, Ohm*	*R₂, Ohm*	*R₃, Ohm*	*C₀, μF*	*R, Ohm*	*L₀, mH*	
56	3.33.f	3.35.b; $\psi_m = 10^{-2}$, Vs, i_1=0,5 A	$1.0\sin(10^3 t)$	-	-	-	-	20	-	ψ, u_{ab}, u_L, u_R
57	3.33.f	3.35.b; $\psi_m = 10^{-2}$, Vs, i_1=0,5 A	$2.0\sin(2\cdot10^3 t)$	-	-	-	-	20	-	ψ, u_{ab}, u_L, u_R
58	3.33.f	3.35.b; $\psi_m = 10^{-2}$, Vs, i_1=0,5 A	$4.0\sin(4\cdot10^3 t)$	-	-	-	-	20	-	ψ, u_{ab}, u_L, u_R
59	3.33.f	3.35.b; $\psi_m = 10^{-2}$, Vs, i_1=0,5 A	$1.5\sin(1.5\cdot10^3 t)$	-	-	-	-	20	-	ψ, u_{ab}, u_L, u_R
60	3.33.f	3.35.b; $\psi_m = 10^{-2}$, Vs, i_1=0,5 A	$3.0\sin(3\cdot10^3 t)$	-	-	-	-	20	-	ψ, u_{ab}, u_L, u_R
61	3.33.h	3.35.d, $\psi_m = 10^{-2}$, Vs	$0.5\sin(2\cdot10^3 t)$	-	-	-	-	200	-	ψ, u_{ab}, i_2, i_3
62	3.33.h	3.35.d, $\psi_m = 10^{-2}$, Vs	$0.8\sin(2\cdot10^3 t)$	-	-	-	-	125	-	ψ, u_{ab}, i_2, i_3
63	3.33.h	3.35.d, $\psi_m = 10^{-2}$, Vs	$1.0\sin(2\cdot10^3 t)$	-	-	-	-	100	-	ψ, u_{ab}, i_2, i_3
64	3.33.h	3.35.d, $\psi_m = 10^{-2}$, Vs	$0.4\sin(2\cdot10^3 t)$	-	-	-	-	250	-	ψ, u_{ab}, i_2, i_3
65	3.33.h	3.35.d, $\psi_m = 10^{-2}$, Vs	$1.25\sin(2\cdot10^3 t)$	-	-	-	-	200	-	ψ, u_{ab}, i_2, i_3
66	3.33.i	3.35.d; $\psi_m = 1.25\cdot10^{-2}$, Vs	$1.25\sin(2\cdot10^3 t)$	-	-	-	6,25	80	-	ψ, u_{ab}, i_R, i_L
67	3.33.i	3.35.d; $\psi_m = 1.25\cdot10^{-2}$, Vs	$0.4\sin(2\cdot10^3 t)$	-	-	-	2	250	-	ψ, u_{ab}, i_R, u_{cb}
68	3.33.i	3.35.d; $\psi_m = 1.25\cdot10^{-2}$, Vs	$0.5\sin(2\cdot10^3 t)$	-	-	-	2,5	200	-	ψ, u_{ab}, u_{ac}, u_{cb}
69	3.33.i	3.35.d; $\psi_m = 1.25\cdot10^{-2}$, Vs	$0.8\sin(2\cdot10^3 t)$	-	-	-	4	125	-	ψ, i_L, u_{ac}, u_{cb}
70	3.33.i	3.35.d; $\psi_m = 1.25\cdot10^{-2}$, Vs	$1.0\sin(2\cdot10^3 t)$	-	-	-	5	100	-	i_R, i_L, u_{ac}, u_{cb}

Table 3.5.

Table 3.6.

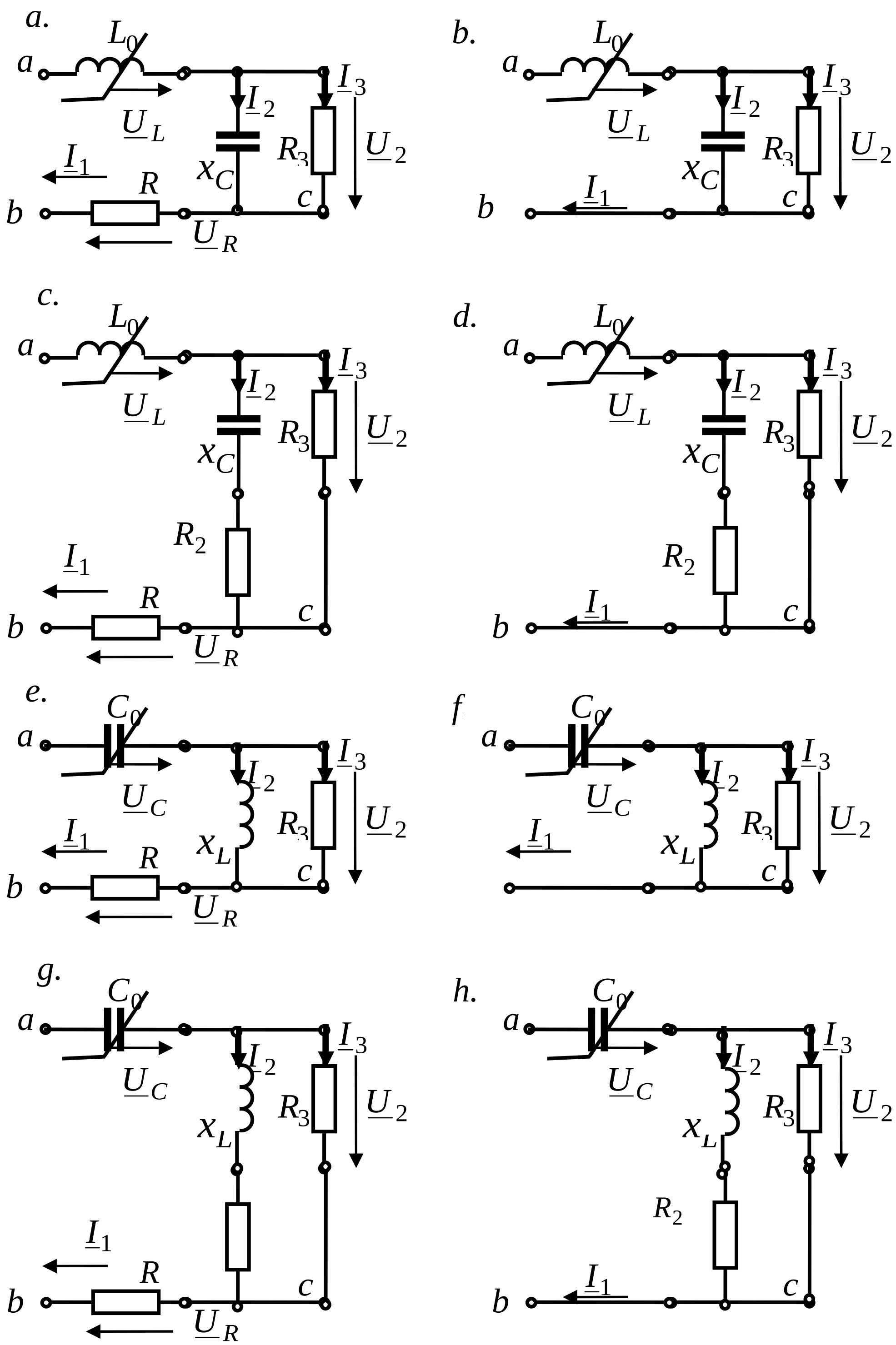
Variant	The scheme numbers and the nonlinear element characteristics		The scheme linear elements parameters							Determine in functions of ωt
	scheme	*element*	$j(\omega t)$, *A*	R_1, *Ohm*	R_2, *Ohm*	R_3, *Ohm*	C_0, *μF*	*R*, *Ohm*	L_0, *mH*	
71	3.34.a	3.35.b; $\psi_m = 10^{-2}$, Vs, i_1=0,5 A	$1.0\sin(500\cdot t)$	-	-	-	-	20	0,02	ψ, u_{ab}, u_L
72	3.34.a	3.35.b; $\psi_m = 10^{-2}$, Vs, i_1=1,0 A	$2.0\sin(1\cdot 10^3 t)$	-	-	-	-	20	0,01	ψ, u_{ab}, u_L
73	3.34.a	3.35.b; $\psi_m = 10^{-2}$, Vs, i_1=2,0 A	$4.0\sin(2\cdot 10^3 t)$	-	-	-	-	20	0,005	ψ, u_{ab}, u_L
74	3.34.a	3.35.b; $\psi_m = 10^{-2}$, Vs, i_1=0,75 A	$1.5\sin(750\cdot t)$	-	-	-	-	20	0,013	ψ, u_{ab}, u_L
75	3.34.a	3.35.b; $\psi_m = 10^{-2}$, Vs, i_1=1,5 A	$3.0\sin(1{,}5\cdot 10^3 t)$	-	-	-	-	20	0.0067	ψ, u_{ab}, u_L
76	3.34.b	3.35.d; $\psi_m = 1.0\cdot 10^{-2}$, Vs	$0.5\sin(1.0\cdot 10^3\cdot t)$	20	100	30	-	-	-	i_2, i_L, u_{cd}
77	3.34.b	3.35.d; $\psi_m = 1.0\cdot 10^{-2}$, Vs	$0.49\sin(1\cdot 10^3 t)$	30	102	20	-	-	-	i_2, i_L, u_{cd}
78	3.34.b	3.35.d; $\psi_m = 1.0\cdot 10^{-2}$, Vs	$0.51\sin(1.0\cdot 10^3 t)$	25	98	25	-	-	-	i_2, i_L, u_{cd}
79	3.34.b	3.35.d; $\psi_m = 1.0\cdot 10^{-2}$, Vs	$0.495\sin(1.0\cdot 10^3\cdot t)$	20	101	30	-	-	-	i_2, i_L, u_{cd}
80	3.34.b	3.35.d; $\psi_m = 1.0\cdot 10^{-2}$, Vs	$0.505\sin(1{,}0\cdot 10^3 t)$	30	100	20	-	-	-	i_2, i_L, u_{cd}

Variant	The scheme numbers and the nonlinear element characteristics		The scheme linear elements parameters				Determine in functions of ωt
	scheme	*element*	$e(\omega t)$, *V*	R_1, *Ohm*	R_2, *Ohm*	R_3, *Ohm*	
81	3.34.e	3.35.f, $U_{R1}=3$, V; $U_{R2}=4$, V; $I_{R1}=0{,}2$, A; $I_{R2}=1$, A; 3.35.d, $\psi_m=2.0\cdot10^{-3}$, Vs	$3.5\sin(10^3 t)$	-	-	-	i, u_R, u_L, ψ
82	3.34.e	3.35.f, $U_{R1}=3$, V; $U_{R2}=4$, V; $I_{R1}=0{,}2$, A; $I_{R2}=1$, A; 3.35.d, $\psi_m=2.0\cdot10^{-3}$, Vs	$3.6\sin(10^3 t)$	-	-	-	i, u_R, u_L, ψ
83	3.34.e	3.35.f, $U_{R1}=3$, V; $U_{R2}=4$, V; $I_{R1}=0{,}2$, A; $I_{R2}=1$, A; 3.35.d, $\psi_m=2.0\cdot10^{-3}$, Vs	$3.7\sin(10^3 t)$	-	-	-	i, u_R, u_L, ψ
84	3.34.e	3.35.f, $U_{R1}=3$, V; $U_{R2}=4$, V; $I_{R1}=0{,}2$, A; $I_{R2}=1$, A; 3.35.d, $\psi_m=2.0\cdot10^{-3}$, Vs	$3.8\sin(10^3 t)$	-	-	-	i, u_R, u_L, ψ
85	3.34.e	3.35.f, $U_{R1}=3$, V; $U_{R2}=4$, V; $I_{R1}=0{,}2$, A; $I_{R2}=1$, A; 3.35.d, $\psi_m=2.0\cdot10^{-3}$, Vs	$3.9\sin(10^3 t)$	-	-	-	i, u_R, u_L, ψ
86	3.34.h	3.35.g, $U_{R1}=1.0$, V; $I_{R1}=0{,}2$, A; 3.35.d, $\psi_m=2.0\cdot10^{-3}$, Vs	$3.5\sin(10^3 t)$	14	-	-	i, i_R, i_L, ψ
87	3.34.h	3.35.g, $U_{R1}=1.0$, V; $I_{R1}=0{,}2$, A; 3.35.d, $\psi_m=2.0\cdot10^{-3}$, Vs	$3.6\sin(10^3 t)$	14	-	-	i, i_R, i_L, ψ
88	3.34.h	3.35.g, $U_{R1}=1.0$, V; $I_{R1}=0{,}2$, A; 3.35.d, $\psi_m=2.0\cdot10^{-3}$, Vs	$3.7\sin(10^3 t)$	15	-	-	i, i_R, i_L, ψ
89	3.34.h	3.35.g, $U_{R1}=1.0$, V; $I_{R1}=0{,}2$, A; 3.35.d, $\psi_m=2.0\cdot10^{-3}$, Vs	$3.8\sin(10^3 t)$	15	-	-	i, i_R, i_L, ψ
90	3.34.h	3.35.g, $U_{R1}=1.0$, B; $I_{R1}=0{,}2$, A; 3.35.d, $\psi_m=2.0\cdot10^{-3}$, Bc	$3.9\sin(10^3 t)$	16	-	-	i, i_R, i_L, ψ

Table 3.7.

Table 3.8.

Variant	The scheme numbers and the nonlinear element characteristics		The scheme linear elements parameters							Determine in functions of ωt
	scheme	*element*	$e(\omega t)$, *V*	R_1,*Ohm*	R_2,*Ohm*	R_3,*Ohm*	C_0, μF	*R*,*Ohm*	L_0, *mH*	
91	3.34.f	3.35.d, $\psi_m = 1.0 \cdot 10^{-2}$, Vs	$230\sin(5.0 \cdot 10^3 \cdot t)$	100	100	-	-	-	-	i, i_R, i_L, ψ
92	3.34.f	3.35.d, $\psi_m = 1.0 \cdot 10^{-2}$, Vs	$240\sin(5.2 \cdot 10^3 t)$	100	100	-	-	-	-	i, i_R, i_L, ψ
93	3.34.f	3.35.d, $\psi_m = 1.0 \cdot 10^{-2}$, Vs	$235\sin(5.1 \cdot 10^3 t)$	100	100	-	-	-	-	i, i_R, i_L, ψ
94	3.34.f	3.35.d, $\psi_m = 1.0 \cdot 10^{-2}$, Vs	$225\sin(4.9 \cdot 10^3 \cdot t)$	100	100	-	-	-	-	i, i_R, i_L, ψ
95	3.34.f	3.35.d, $\psi_m = 1.0 \cdot 10^{-2}$, Vs	$245\sin(5{,}3 \cdot 10^3 t)$	100	100	-	-	-	-	i, i_R, i_L, ψ
96	3.34.i	3.35.d; $\psi_m = 1.0 \cdot 10^{-2}$, Vs	$10\sin(450t)$		-	-	-	100	-	i, u_R, u_L, ψ
97	3.34.i	3.35.d; $\psi_m = 1.0 \cdot 10^{-2}$, Vs	$10\sin(475t)$		-	-	-	120	-	i, u_R, u_L, ψ
98	3.34.i	3.35.d; $\psi_m = 1.0 \cdot 10^{-2}$, Vs	$10\sin(500t)$		-	-	-	110	-	i, u_R, u_L, ψ
99	3.34.i	3.35.d; $\psi_m = 1.0 \cdot 10^{-2}$, Vs	$10\sin(525t)$		-	-	-	115	-	i, u_R, u_L, ψ
00	3.34.i	3.35.d; $\psi_m = 1.0 \cdot 10^{-2}$, Vs	$10\sin(550t)$		-	-	-	90	-	i, u_R, u_L, ψ



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L0
a
UL
I2
I3
R3
U2
xC
I1
R
c
b
UR
b.
L0
a
UL
I2
I3
R3
U2
xC
I1
b
c
c.
L0
a
UL
I2
I3
R3
U2
xC
R2
I1
R
c
b
UR
d.
L0
a
UL
I2
I3
R3
U2
xC
R2
I1
b
c
e.
C0
a
UC
I2
I3
R3
U2
xL
I1
R
c
b
UR
f
C0
a
UC
I2
I3
R3
U2
xL
I1
c
g.
C0
a
UC
I2
I3
R3
U2
xL
I1
R
c
b
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h.
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UC
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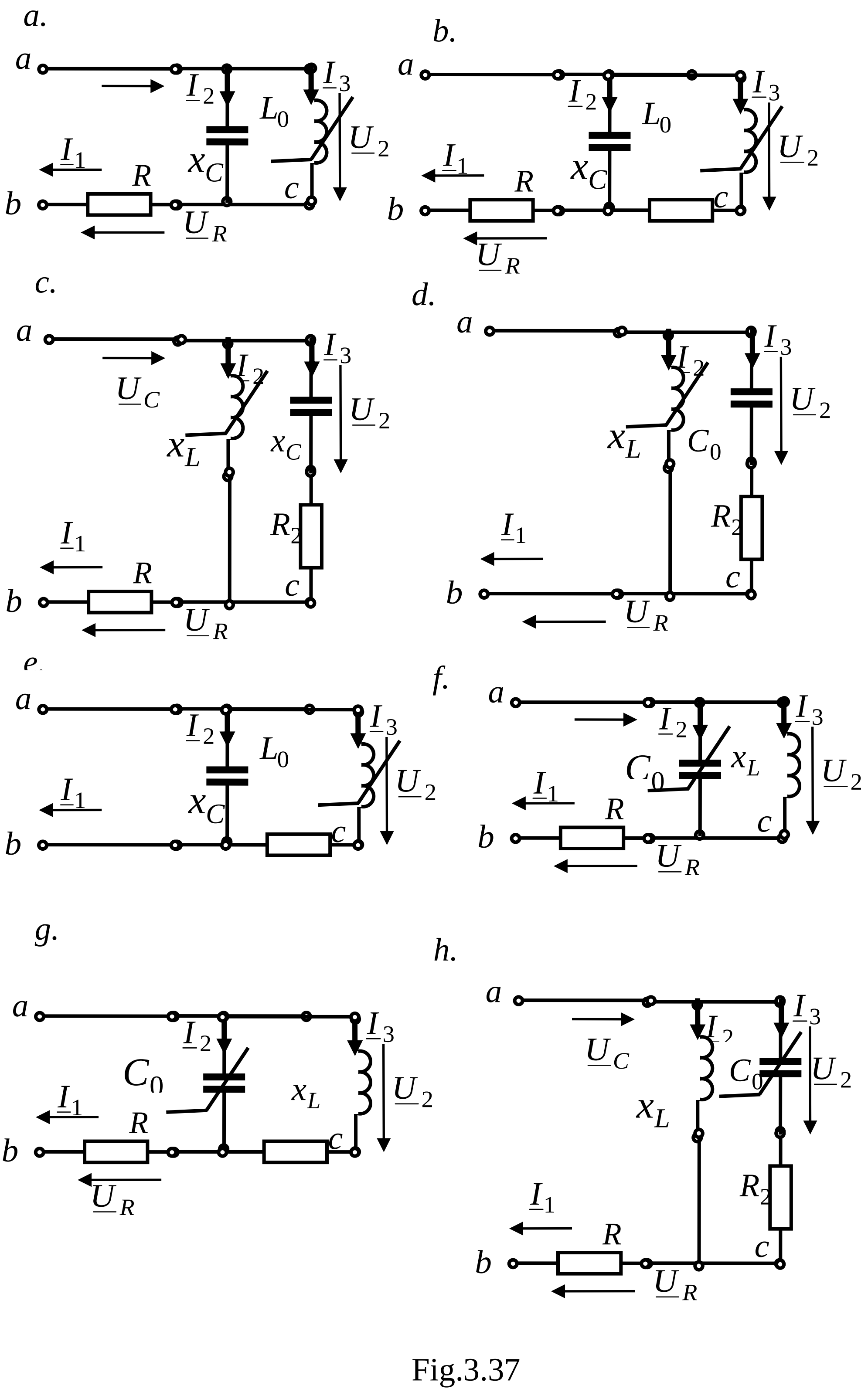
I3
R3
U2
xL
R2
I1
b
c

Fig.3.36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a
b
c
R
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$\underline{I}_2$
$\underline{I}_3$
L_0
x_C
$\underline{U}_2$
$\underline{U}_R$
b.
a
b
c
R
$\underline{I}_1$
$\underline{I}_2$
$\underline{I}_3$
L_0
x_C
$\underline{U}_2$
$\underline{U}_R$
c.
a
b
c
R
R_2
$\underline{I}_1$
$\underline{I}_2$
$\underline{I}_3$
$\underline{U}_C$
x_L
x_C
$\underline{U}_2$
$\underline{U}_R$
d.
a
b
c
R_2
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C_0
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a
b
c
$\underline{I}_1$
$\underline{I}_2$
$\underline{I}_3$
L_0
x_C
$\underline{U}_2$
f.
a
b
c
R
$\underline{I}_1$
$\underline{I}_2$
$\underline{I}_3$
x_L
$\underline{U}_2$
$\underline{U}_R$
g.
a
b
c
R
$\underline{I}_1$
$\underline{I}_2$
$\underline{I}_3$
x_L
$\underline{U}_2$
$\underline{U}_R$
h.
a
b
c
R
R_2
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x_L
$\underline{U}_2$
$\underline{U}_R$

Fig.3.37

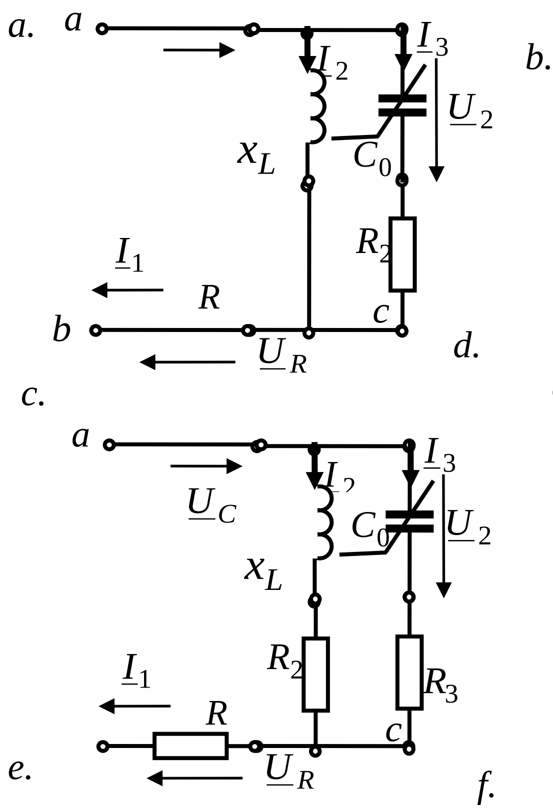


Fig.3.38

a. *b.*

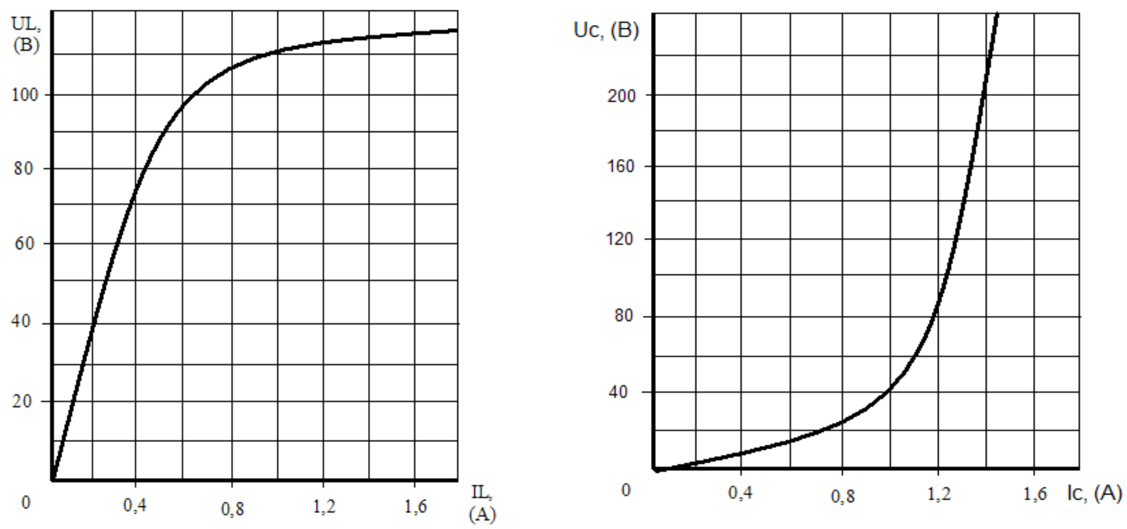


Fig.3.39

Table 3.9

Variant	Scheme	VAC	x_C, Ohm	x_L, Ohm	R_1, Ohm	R_2, Ohm	R_3. Ohm	R, Ohm	Define
01	3.36.a	3.39.a	100	-	0	0	500	200	$U_{ab}(I_1)$
02	3.36.a	3.39.a	200	-	0	0	200	100	$U_{ab}(I_2)$
03	3.36.a	3.39.a	100	-	0	0	300	300	$U_R(I_3)$
04	3.36.a	3.39.a	200	-	0	0	200	200	$U_2(I_1)$
05	3.36.a	3.39.a	100	-	0	0	100	100	$U_{ab}(I_3)$
06	3.36.b	3.39.a	100	-	0	0	500	0	$U_{ab}(I_1)$
07	3.36.b	3.39.a	200	-	0	0	200	0	$U_{ab}(I_2)$
08	3.36.b	3.39.a	100	-	0	0	300	0	$U_{R2}(I_3)$
09	3.36.b	3.39.a	200	-	0	0	200	0	$U_2(I_1)$
10	3.36.b	3.39.a	100	-	0	0	100	0	$U_{ab}(I_3)$
11	3.36.c	3.39.a	200	-	0	400	160	200	$U_{ab}(I_1)$
12	3.36.c	3.39.a	100	-	0	200	100	300	$U_{ab}(I_2)$
13	3.36.c	3.39.a	300	-	0	300	150	200	$U_R(I_3)$
14	3.36.c	3.39.a	200	-	0	200	100	100	$U_2(I_1)$
15	3.36.c	3.39.a	100	-	0	100	200	300	$U_{ab}(I_3)$
16	3.36.d	3.39.a	200	-	0	400	160	0	$U_{ab}(I_1)$
17	3.36.d	3.39.a	100	-	0	200	100	0	$U_{ab}(I_2)$
18	3.36.d	3.39.a	300	-	0	300	150	0	$U_L(I_3)$
19	3.36.d	3.39.a	200	-	0	200	100	0	$U_2(I_1)$
20	3.36.d	3.39.a	100	-	0	100	200	0	$U_{ab}(I_3)$
21	3.36.e	3.39.b	-	100	0	0	500	200	$U_{ab}(I_3)$
22	3.36.e	3.39.b	-	200	0	0	200	100	$U_{ab}(I_1)$
23	3.36.e	3.39.b	-	150	0	0	300	300	$U_{ab}(I_2)$
24	3.36.e	3.39.b	-	250	0	0	200	200	$U_L(I_3)$
25	3.36.e	3.39.b	-	50	0	0	100	100	$U_2(I_1)$
26	3.36.f	3.39.b	-	100	0	0	500	0	$U_{ab}(I_3)$
27	3.36.f	3.39.b	-	200	0	0	200	0	$U_{ab}(I_1)$
28	3.36.f	3.39.b	-	150	0	0	300	0	$U_{ab}(I_2)$
29	3.36.f	3.39.b	-	250	0	0	200	0	$U_L(I_3)$
30	3.36.f	3.39.b	-	50	0	0	100	0	$U_2(I_1)$
31	3.36.g	3.39.b	-	200	0	400	160	200	$U_{ab}(I_1)$
32	3.36.g	3.39.b	-	100	0	200	100	300	$U_{ab}(I_2)$

Continue of Table 3.9

Variant	Scheme	VAC	x_C, Ohm	x_L, Ohm	R_1, Ohm	R_2, Ohm	R_3. Ohm	R, Ohm	Define
33	3.36.g	3.39.b	-	300	0	300	150	200	$U_R(I_3)$
34	3.36.g	3.39.b	-	200	0	200	100	100	$U_2(I_1)$
35	3.36.g	3.39.b	-	100	0	100	200	300	$U_{ab}(I_3)$
36	3.36.h	3.39.b	-	200	0	400	160	0	$U_{ab}(I_1)$
37	3.36.h	3.39.b	-	100	0	200	100	0	$U_{ab}(I_2)$
38	3.36.h	3.39.b	-	300	0	300	150	0	$U_R(I_3)$
39	3.36.h	3.39.b	-	200	0	200	100	0	$U_2(I_1)$
40	3.36.h	3.39.b	-	100	0	100	200	0	$U_{ab}(I_3)$
41	3.37.a	3.39.a	100	-	-	-	-	200	$U_{ab}(I_1)$
42	3.37.a	3.39.a	200	-	-	-	-	100	$U_{ab}(I_2)$
43	3.37.a	3.39.a	100	-	-	-	-	300	$U_R(I_3)$
44	3.37.a	3.39.a	200	-	-	-	-	200	$U_2(I_1)$
45	3.37.a	3.39.a	100	-	-	-	-	100	$U_{ab}(I_3)$
46	3.37.b	3.39.a	100	-	0	400	0	200	$U_{ab}(I_1)$
47	3.37.b	3.39.a	200	-	0	200	0	100	$U_{ab}(I_2)$
48	3.37.b	3.39.a	100	-	0	300	0	300	$U_R(I_3)$
49	3.37.b	3.39.a	200	-	0	200	0	200	$U_2(I_1)$
50	3.37.b	3.39.a	100	-	0	100	0	100	$U_{ab}(I_3)$
51	3.37.c	3.39.a	100	-	0	400	0	200	$U_{ab}(I_1)$
52	3.37.c	3.39.a	100	-	0	200	0	100	$U_{ab}(I_2)$
53	3.37.c	3.39.a	200	-	0	300	0	300	$U_R(I_3)$
54	3.37.c	3.39.a	100	-	0	200	0	200	$U_2(I_1)$
55	3.37.c	3.39.a	200	-	0	100	0	0	$U_{ab}(I_3)$
56	3.37.d	3.39.a	100	-	0	400	0	0	$U_{ab}(I_1)$
57	3.37.d	3.39.a	200	-	0	200	0	0	$U_{ab}(I_2)$
58	3.37.d	3.39.a	100	-	0	300	0	0	$U_R(I_3)$
59	3.37.d	3.39.a	300	-	0	200	0	0	$U_2(I_1)$
60	3.37.d	3.39.a	200	-	0	100	0	0	$U_{ab}(I_3)$
61	3.37.e	3.39.a	100	-	0	400	0	0	$U_{ab}(I_1)$
62	3.37.e	3.39.a	200	-	0	200	0	0	$U_{ab}(I_2)$
63	3.37.e	3.39.a	100	-	0	300	0	0	$U_R(I_3)$
64	3.37.e	3.39.a	300	-	0	200	0	0	$U_2(I_1)$

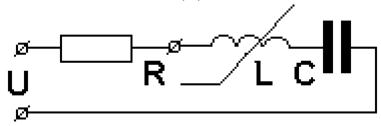
Continue of Table 3.9

Variant	Scheme	VAC	x_C, Ohm	x_L, Ohm	R_1, Ohm	R_2, Ohm	R_3. Ohm	R, Ohm	Define
65	3.37.e	3.39.a	200	-	0	200	0	0	$U_{ab}(I_3)$
66	3.37.f	3.39.b	-	100	0	0	0	200	$U_R(I_3)$
67	3.37.f	3.39.b	-	200	0	0	0	100	$U_2(I_1)$
68	3.37.f	3.39.b	-	100	0	0	0	300	$U_{ab}(I_3)$
69	3.37.f	3.39.b	-	200	0	0	0	200	$U_{ab}(I_1)$
70	3.37.f	3.39.b	-	100	0	0	0	100	$U_{ab}(I_2)$
71	3.37.g	3.39.b	-	100	0	400	0	200	$U_{ab}(I_1)$
72	3.37.g	3.39.b	-	200	0	200	0	100	$U_{ab}(I_2)$
73	3.37.g	3.39.b	-	100	0	300	0	300	$U_R(I_3)$
74	3.37.g	3.39.b	-	200	0	200	0	200	$U_2(I_1)$
75	3.37.g	3.39.b	-	100	0	100	0	100	$U_{ab}(I_3)$
76	3.37.h	3.39.b	-	100	0	400	0	200	$U_{ab}(I_1)$
77	3.37.h	3.39.b	-	200	0	200	0	100	$U_{ab}(I_2)$
78	3.37.h	3.39.b	-	100	0	300	0	300	$U_R(I_3)$
79	3.37.h	3.39.b	-	200	0	200	0	200	$U_2(I_1)$
80	3.37.h	3.39.b	-	100	0	100	0	100	$U_{ab}(I_3)$
81	3.38.a	3.39.b	-	100	0	400	0	200	$U_{ab}(I_1)$
82	3.38.a	3.39.b	-	200	0	200	0	100	$U_{ab}(I_2)$
83	3.38.a	3.39.b	-	100	0	300	0	300	$U_R(I_3)$
84	3.38.a	3.39.b	-	200	0	200	0	200	$U_2(I_1)$
85	3.38.a	3.39.b	-	100	0	100	0	100	$U_{ab}(I_3)$
86	3.38.b	3.39.b	-	100	0	0	0	200	$U_{ab}(I_1)$
87	3.38.b	3.39.b	-	200	0	0	0	100	$U_{ab}(I_2)$
88	3.38.b	3.39.b	-	100	0	0	0	300	$U_R(I_3)$
89	3.38.b	3.39.b	-	200	0	0	0	200	$U_2(I_1)$
90	3.38.b	3.39.b	-	100	0	0	0	100	$U_{ab}(I_3)$
91	3.38.c	3.39.b	-	100	0	400	160	200	$U_{ab}(I_1)$
92	3.38.c	3.39.b	-	200	0	200	100	300	$U_{ab}(I_2)$
93	3.38.c	3.39.b	-	100	0	300	150	200	$U_R(I_3)$
94	3.38.c	3.39.b	-	200	0	200	100	100	$U_2(I_1)$
95	3.38.c	3.39.b	-	100	0	100	200	300	$U_{ab}(I_3)$
96	3.38.d	3.39.b	-	1670	0	400	160	200	$U_{ab}(I_1)$

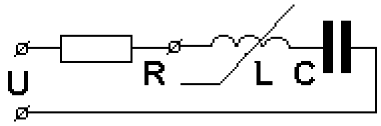
Continue of Table 3.9

Variant	Scheme	VAC	x_C, Ohm	x_L, Ohm	R_1, Ohm	R_2, Ohm	R_3. Ohm	R, Ohm	Define
97	3.38.d	3.39.b	-	200	0	200	100	300	$U_{ab}(I_2)$
98	3.38.d	3.39.b	-	100	0	300	150	200	$U_R(I_3)$
99	3.38.d	3.39.b	-	200	0	200	100	100	$U_2(I_1)$
00	3.38.d	3.39.b	-	100	0	100	200	300	$U_{ab}(I_3)$

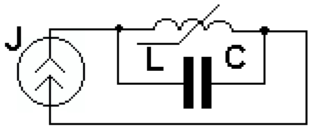
6. Find the capacity value C, at which in point I=2 A appears phenomenon voltage ferroresonance, if $U^2_L=4\cdot(I)$; R=5 Ом; f=50 Hz.



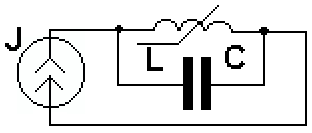
7. Relying, that in circuit acts equivalent sinusoidal current calculate drop voltages on scheme elements at current I=2.5 A and draw phasor diagram, if $U^2_L=4\cdot(I)$; $U_C=2\cdot I$; $R=5\cdot I$.



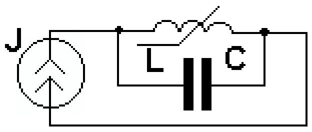
8. Calculate the boundary values of district volt-ampere characteristic which has negative dynamic resistance, if $I_L=0.02\cdot(U)^2$; $I_C=0.2\cdot U$



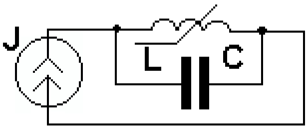
9. Dynamic resistance calculate value on unstable district volt-ampere characteristic if we know $I_L=0.02\cdot(U)^2$; $I_C=0.2\cdot U$



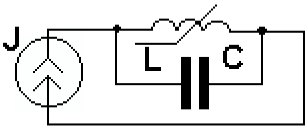
10. Find the capacity value C, at which in point U=10 B, appears phenomenon current ferroresonance, if $I_L=0.02\cdot(U)^2$; f=50 Hz.



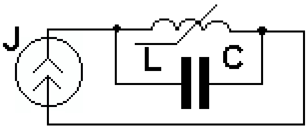
11. Find the capacity value C, at which in point U=20 V, appears phenomenon current ferroresonance, if $I_L=0.02\cdot(U)^2$; f=50 Гц.



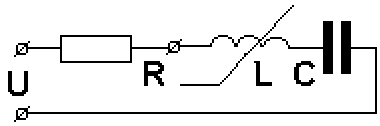
12. Relying, that in circuit acts equivalent sinusoidal voltage calculate currents in scheme elements at voltage U=4 V and draw phasor diagram, if $I_L=0.02U^2$; $I_C=0.2U^2$.



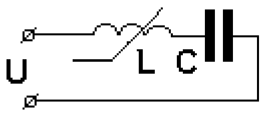
13. Relying, that in circuit acts equivalent sinusoidal voltage calculate currents in scheme elements at voltage U=12 V and draw phasor diagram, if $I_L=0.02U^2$; $I_C=0.2U^2$.



14. Relying, that in circuit acts equivalent sinusoidal current calculate drop voltages on scheme elements at current I=0.2 A and draw phasor diagram, if $U^2{}_L=4\cdot(I)$; $U_C=2\cdot I$; $R=5\cdot I$.



15. Calculate the boundary values of district volt-ampere characteristic which has negative dynamic resistance, if $U^2{}_L=4\cdot(I)$; $U_C=3\cdot I$



4. THE TRANSIENT CALCULATION METHODS IN CIRCUITS WITH NONLINEAR ELEMENTS

4.1. Methodological instructions as to the calculation of transient in nonlinear electric circuits

1. The transient calculation in nonlinear circuits basically differs from calculation one in linear circuits. On the transient character influence scheme elements parameters and the connections elements in scheme. In the linear circuits the characteristic equation roots value over the time of all process do not change. In nonlinear circuits the roots of characteristic equation change its value over the time of process, that is why processes in such circuits are accompanied by qualitative new phenomena which not attainable in linear circuits.
2. The calculation of transients in circuits with nonlinear elements can be performed only by deciding of nonlinear differential equations.
3. Methods that based on the superposition principle using the application (overlay enforced and natural components, operational method, the method that based on Duamel integral), to nonlinear circuits not applicable.
4. Nonlinear differential equations describing transienrs in nonlinear circuits, will be not integrated in known functions and are decided by approximated approaches. The most widespread are methods:
– conditional linearization method – nonlinear characteristic approximate by direct line, define deciding for transient function, and then solution is specified with using of initial nonlinear dependence;
– the method of the analytic expression of nonlinear characteristic with direct integrating – is choose the analytical approximation of initial nonlinear dependence, be performed the analytical integrating of the differential equations of circuit with nonlinear coefficients;
– the method of piecewise-linear approximation – linear approximation _ the initial characteristic of nonlinear element divide into the row of conventional-linear districts, for which find differential equations with constant coefficients. Linear differential equations are integrated, solutions are connected by means of the choice of appropriate of integrating constants in found equations;
– step-by-step method – is estimated the awaited duration of transient which divide on the small intervals of the increment of time. According to it differential values which enter equations are replaced by finite increments which will enable the differential equations to replace by algebraic ones. Per the step of integrating are specified the significances of initial curve of nonlinear element;
– метод графического интегрирования – define auxiliary graph that include the properties of nonlinear element in which square corresponds the current time of transient;
– the equivalent generator method – very efficient in the case of presence of single nonlinear element in circuit;

– the phase-plane method – the transient is built on plane with axes: moving coordinate _ derivative from moving coordinate. To the transient corresponds the phase portrait which is drawed on phase plane by portraying point in the form of the phase trajectory.
5. In linear electric circuits the real parts of characteristical equation roots always had negative value which brought to subside transients. In nonlinear circuits this is not always fulfiled, what brings to unsubside or divergent transients. For the work regimes research in nonlinear circuits are applied the methods of phase plane. In subside transients the phase trajectory is ending on the onset of coordinates.

4.2. The transient calculation in nonlinear electric circuits by conditional linearization method

The transient processes calculation methods in nonlinear electric circuits we consider on the example of the coil with steel core switching on the DC source, whereat neglect hysteresis loop square, by eddy currents and the leakage fluxes.
The coil with ferromagnetic core is switching with the help of of key S on DC source *U=100 V*, Fig.4.1.a. Turns number in coil *W=150*, coil windings ohmic resistance R_M*=12,5 Ohm*, normal magnetization curve is given by graphically, Fig. 4.1.b. Find by the conditional linearization method the graphics of current and flux linkage transient functions.
The coil with steel core replacement scheme is presented on Fig. 4.2.a. We neglect the losses in steel magnetic conductor and by the leakage fluxes ($R_{CT} = 0$, $L_S = 0$), then computative scheme is simplified and to reduce to scheme that shown on Fig.4.4.b.
Value of enforced current at termination transient process

$$i_{ïð} = I_0 = U_0 / R_M = 50/12{,}5 = 0{,}8, A.$$

As to normal magnetization curve find value enforced flux linkage for enforced regime $\psi_f = \Psi_0 = 0{,}8, Wb$.
Static inductance of coil with ferromagnetic core in enforced regime

$$L_{st} = \Psi_0 / I_0 = 0{,}8/0{,}8 = 1{,}0, H.$$

After switched the key S, Fig.4.2.b, process in circuit are described under the second Kirchhoff's law

$$U_0 = R_M i + \frac{d\psi}{dt}.$$

We linearize equation by means of replacement the initial normal magnetization curve by direct line that passing through the onset of coordinates and the point of enforced regime

$$U_0 = R_M i + \frac{d\psi}{dt} = \frac{R_M}{L_{st}}\psi + \frac{d\psi}{dt} = \frac{\psi}{\tau} + \frac{d\psi}{dt},$$

where the time constant of transient process in enforced regime

$$\tau = \frac{L_{st}}{R_M} = 0{,}08\,\text{s}.$$

Solution of received the linearize differential equation obtain by classical approach in the form

$$\psi = \Psi_0 - \Psi_0 e^{-t/\tau} = 0{,}8(1 - e^{-t/0{,}08}),\ \text{Wb}.$$

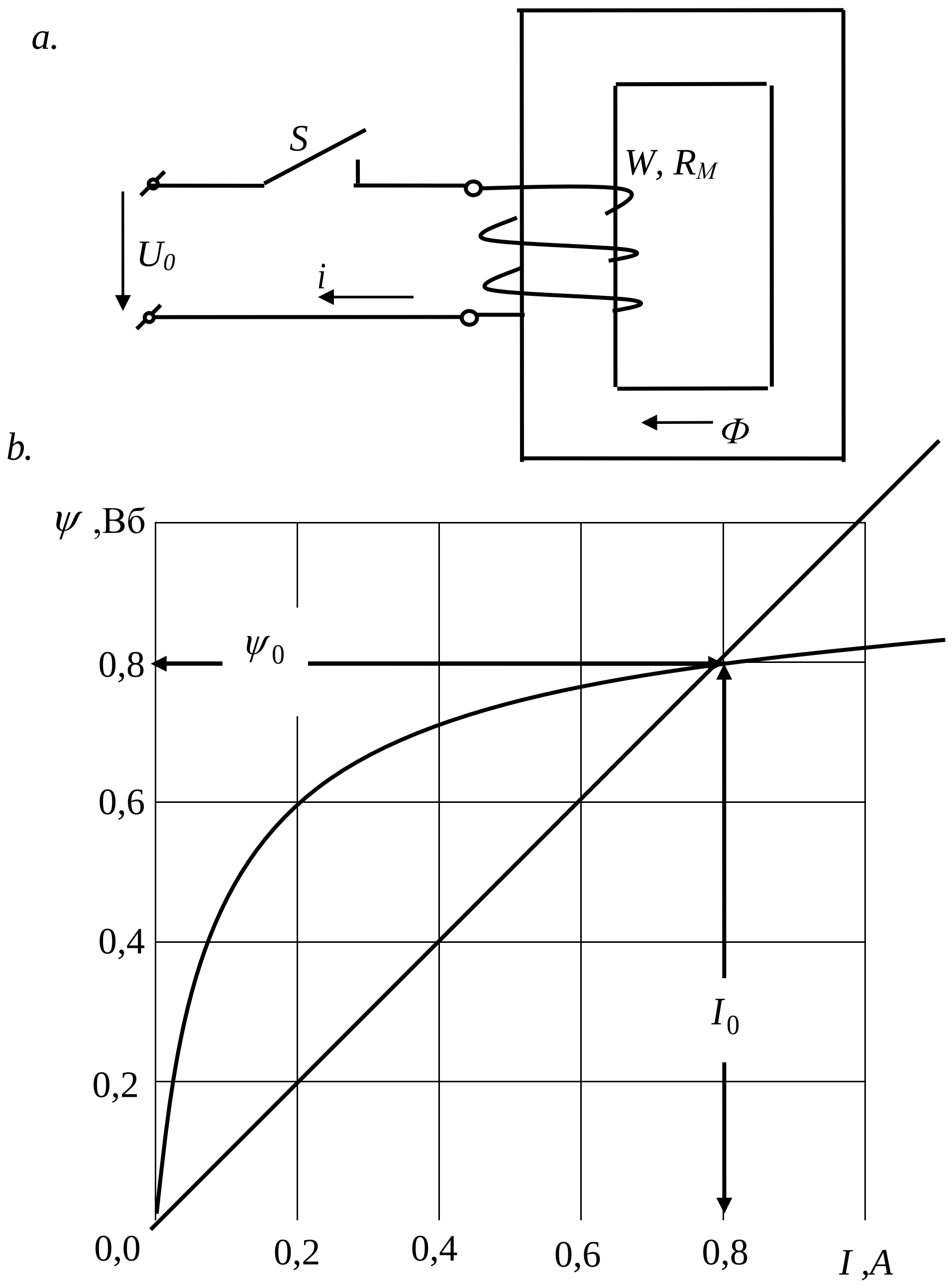


Fig. 4.1

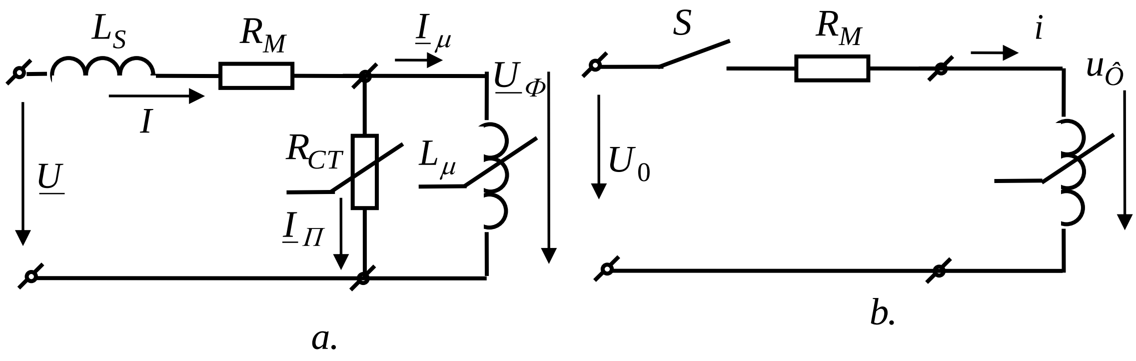


Fig. 4.2

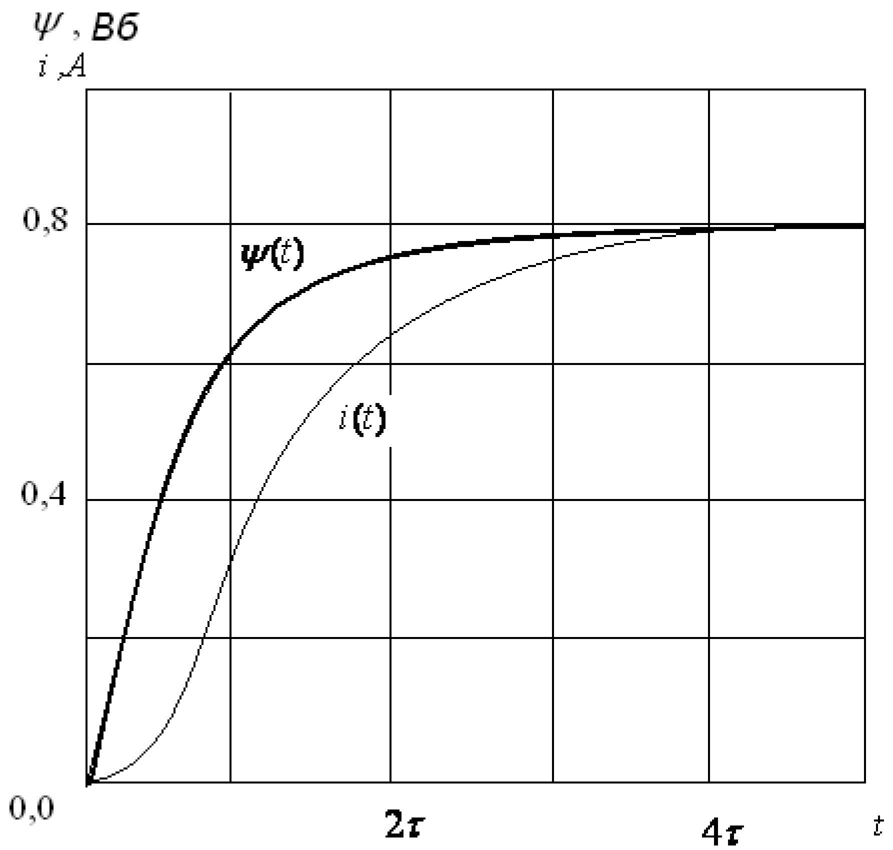


Fig.4.3.

The dependence of current transient function $i(t)$ find as to transient function flux linkage $\psi(t)$ and normal curve magnetization $\Psi(I)$ by assigning the time values and setting correspondence flux linkage and current, Fig.4.3.

Current curve $i(t)$ essentially differs from exponential function. This is ascribed to that at small magnetization currents the differential inductance more than static inductance, and in larger currents – less than static one, of that is why the current at the beginning of transient process accrues slowly, than flux linkage exponential function, and then faster than exponential function.

In this calculation method dependence flux linkage $\psi(t)$ is received as a result of the approximate task solution, however obtained solution of current curve $i(t)$ whereat has same disposition, as in solutions achieved by more exact methods.
The graphical integrating method lets to specify solution for curve flux linkage.

4.3. The transient process calculation in nonlinear electric circuits by the graphic integrating method

We decide previous task by the method of graphic integrating. In initial differential equation

$$U_0 = R_M i + d\psi / dt$$

separate variables

$$dt = d\psi / (U_0 - R_M i)$$

and after integrating obtain

$$t = \int_0^{\psi_0} d\psi / (U_0 - R_M i).$$

For the arriving at a solution we build dependence $\psi\left(\frac{1}{U_0 - R_M i}\right)$ by using normal magnetization curve $\Psi(I)$ and setting flux linkage values in limit from zero till enforced value, Fig.4.4. Square between auxiliary curve $\psi\left(\frac{1}{U_0 - R_M i}\right)$ and axis of ordinates Ψ on scale of the time determines the running time of transient process.

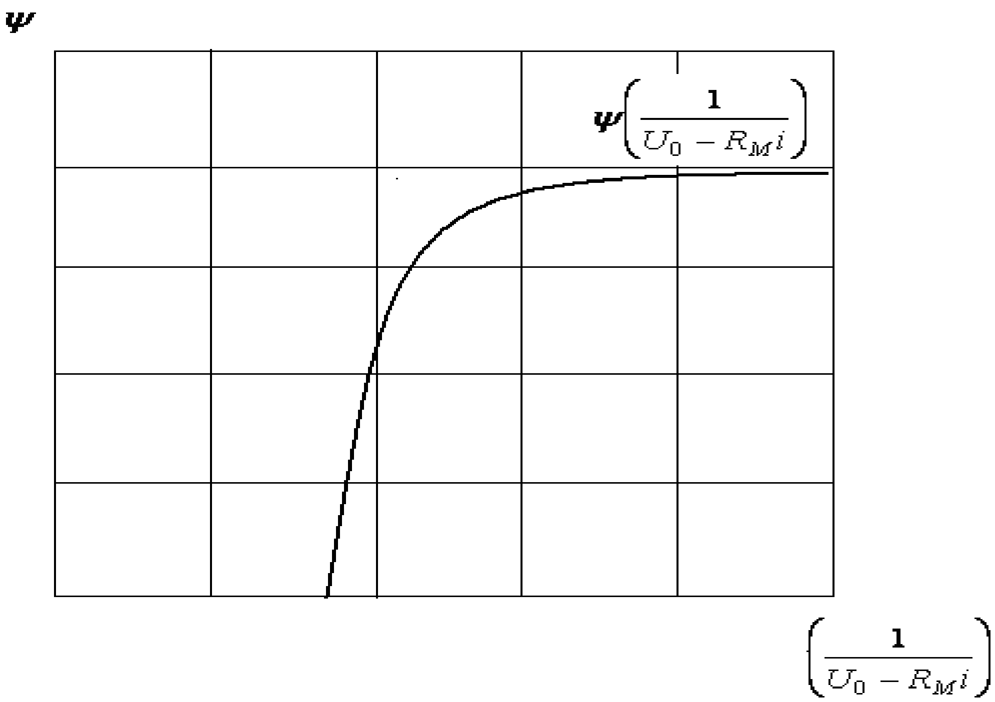


Fig.4.4

Calculation convenient to conduct in table form Table.4.1. The results of calculations are shown on Fig.4.5.

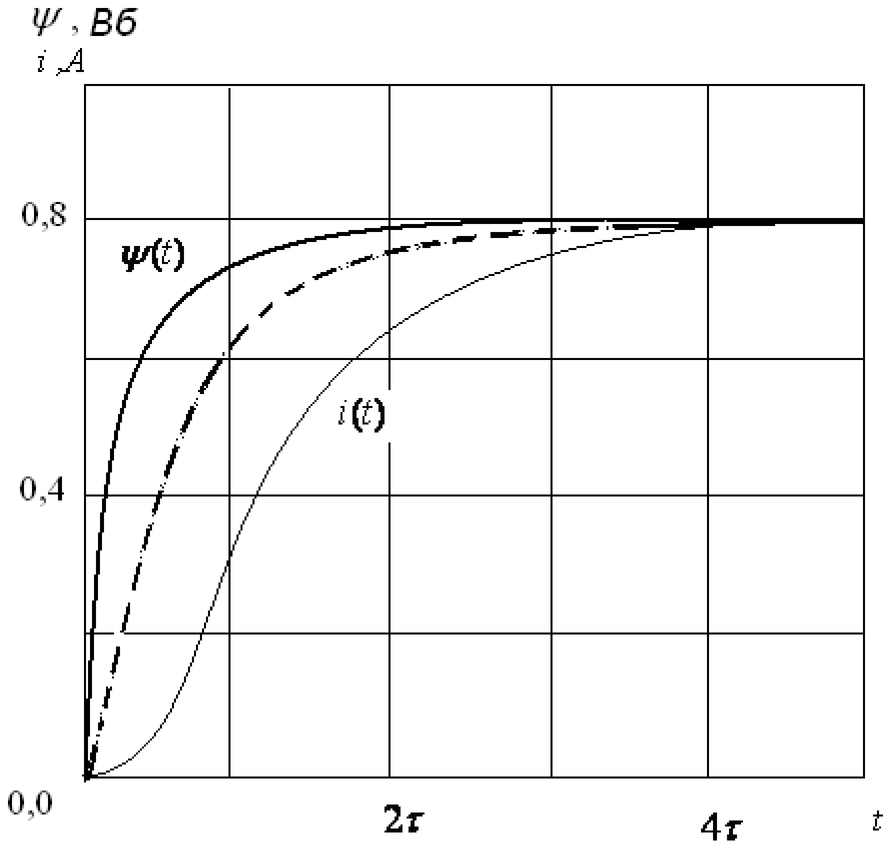


Fig.4.5.

Table 4.1.

ψ , Wb	i, A	$R_M i$, V	$U_0 - R_M i$	$\frac{1}{U_0 - R_M i}$	t, s
0	0	0	100	0,01	0
0,2	0,02	0,25	99,75	0,01002	0,0005
0,4	0,06	0,75	99,25	0,01007	0,04
0,6	0,2	2,5	97,5	0,01025	0,08
0,8	0,8	10,0	90	0,01111	0,24

The graphic integrating method lets to specify changes in the time of curve flux linkage e which differs from exponential function (Fig.4.5 exponential function is shown by the dotted line). Graphic integrating method differs from conditional linearization method by considering normal magnetization curve in awry of flux linkage. As opposed to analytical approach such method of calculation does not detect total ties between the parameters of electric scheme.

Connection between the parameters of electric circuit and transient functions lets to establish analytic approximations method of normal magnetization curve.

4.4. The transient process calculation in nonlinear electric circuits by the nonlinear characteristic analytical approximation method

Nonlinear characteristic approximately replace (approximate) by analytical function that allowing to receive of differential equation solution in analytical form.

The most simply task is decided, if approximate initial normal magnetization curve (Fig.4.6 solid line) by square-law parabola $i = b\psi^2$.

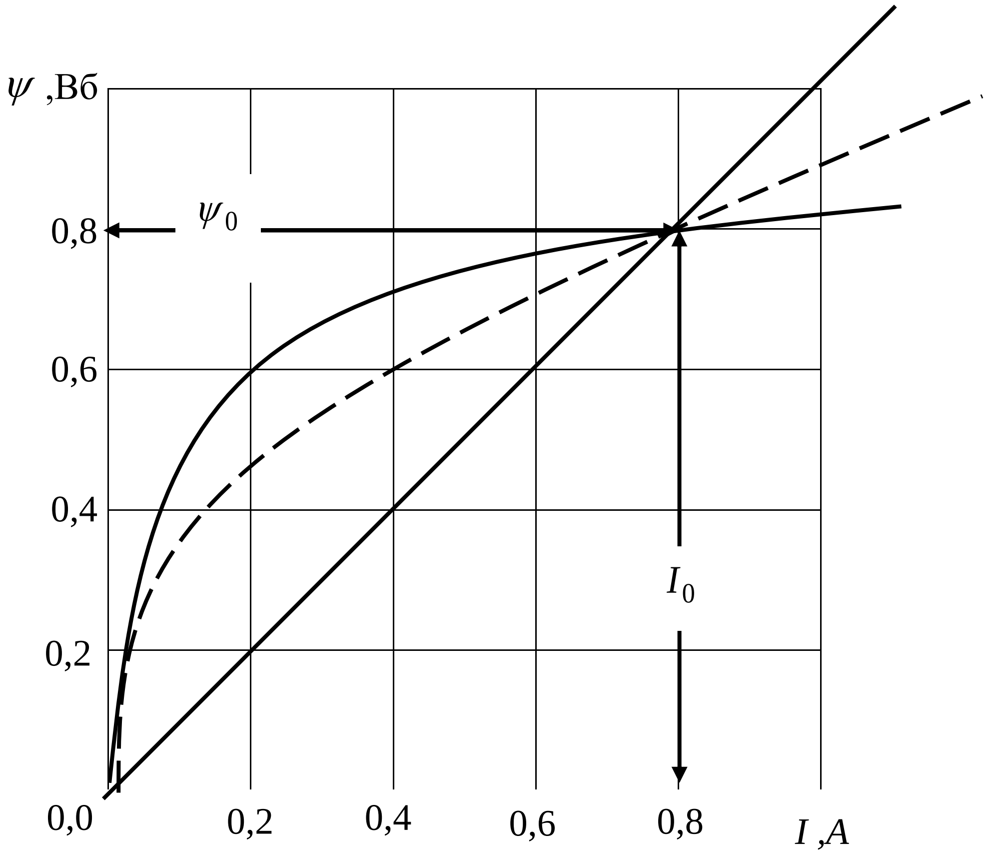


Fig. 4.6

We suppose that desired analytic expression corresponds to the given normal magnetization curve $\Psi(I)$ in the point of enforced regime Ψ_0, I_0. For the point of enforced regime find the coefficient of proportionality b

$I_0 = b\psi_0;\ b = I_0/\psi_0^2 = 0{,}8/0{,}8^2 = 1{,}25.$

Found analytical approximation $i = 1{,}25 \cdot \psi^2$ coincides with initial normal magnetization curve $\Psi(I)$ in two points: the onset of coordinates and enforced regime. Initial differential equation we shall receive on basis of the second Kirchhgoff's law

$$U_0 = R_M i + \frac{d\psi}{dt}$$

In which deliver from transient current and obtain the differential equation relatively only single variable flux linkage

$$U_0 = 1{,}25 \cdot R_M \cdot \psi^2 + \frac{d\psi}{dt}.$$

After separate variables

$$dt = \frac{d\psi}{U_0 - 1{,}25 \cdot R_M \cdot \psi^2}$$

and integrating equation

$$t = \int_0^t dt = \int_0^{\psi_0} \frac{d\psi}{U_0 - 1{,}25 \cdot R_M \cdot \psi^2} = \int_0^{\psi_0} \frac{d\psi}{U_0 - I_0/\psi_0^2 \cdot R_M \cdot \psi^2} =$$

$$= \frac{\psi_0}{I_0 R_M} arth \frac{I_0 R_M \psi}{\psi_0 U_0} = \frac{L_{ñò}}{R_M} arth \frac{R_M \psi}{L_{ñò} U_0}.$$

From last equation separate out flux linkage and express it’s in explicit form

$$\psi = \frac{L_{st} U_0}{R_M} th \frac{t}{\tau} = 8 \cdot th 12{,}5 \cdot t, \text{ Wb},$$

where $L_{ñò} = \psi_0 / I_0$ – static inductance in enforced regime; $\tau = L_{st} / R_M$ – transient process constant time in enforced regime.

The current transient function

$$i = b\psi^2 = 1{,}25 \cdot (8 \cdot th 12{,}5 \cdot t)^2 = 80 \cdot (th 12{,}5 \cdot t)^2, \text{ A}.$$

Current and flux linkage transient function graphs are shown on Fig.4.5 (solid line).

Received of correlation for current and flux linkage approximately describes the transient process of the coil with steel core switch on DC source. The merit of analytical approach is that received correlations give possibility to analyze the influence to the transient processes of the circuit parameters.

The accuracy of solution so much higher, than closer analytic expression corresponds to nonlinear characteristic. Applying of the approximation of type $i = a\psi + b\psi^2$ lets to receive the more exact analytic expression of nonlinear characteristic, but deciding of task whereat considerably is complicated.

4.5. The transient process calculation in nonlinear electric circuits by the piecewise-linear approximation method

The normal magnetization curve $\Psi(I)$, Fig.4.7, we replace by jogged line 0-1-2-3 using tangent lines (may be used secant lines).

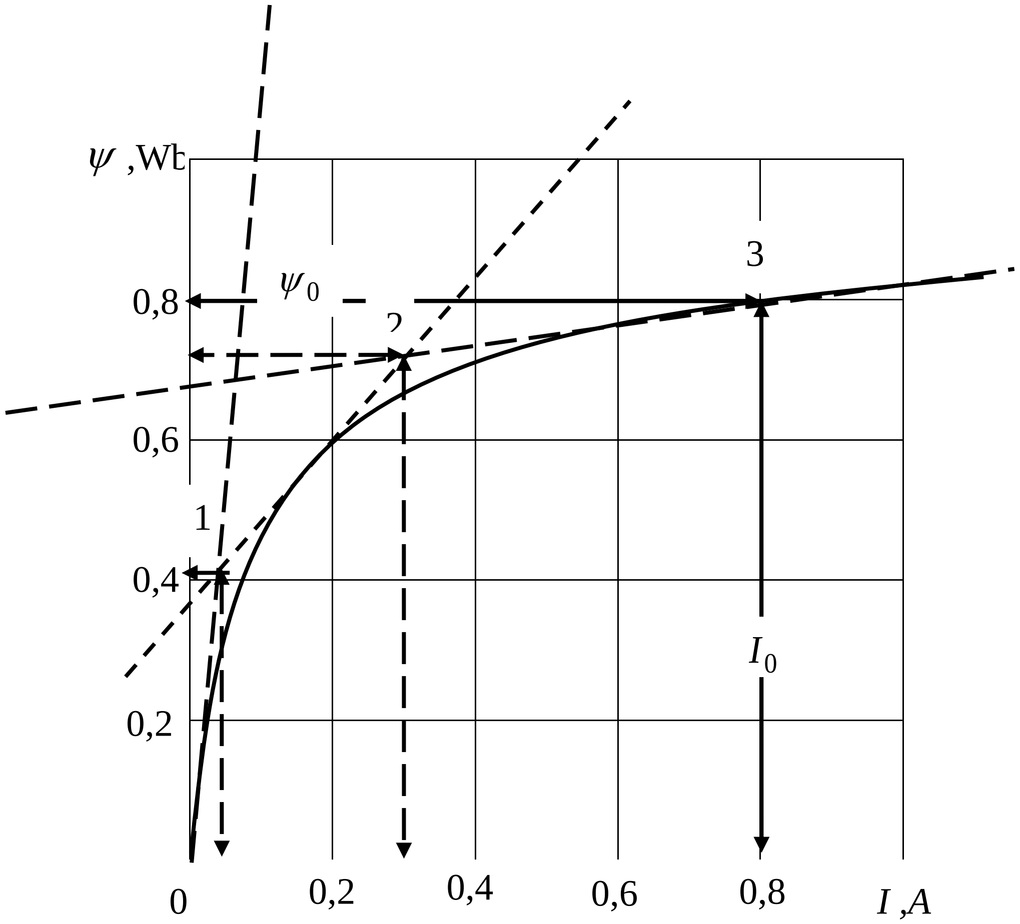


Fig.4.7

Every partition district characterized by its dynamic inductance and time constant

– district 0-1

$$L_{dyn1} = \Delta\psi_1 / \Delta I_1 = 0{,}41/0{,}05 = 8{,}2, H;$$

$$\tau_1 = L_{dyn1} / R_M = 8{,}2/12{,}5 = 0{,}656, s;$$

– district 1-2

$$L_{dyn2} = \Delta\psi_2 / \Delta I_2 = (0{,}71 - 0{,}41)/(0{,}3 - 0{,}05) = 1{,}2, H;$$

$$\tau_2 = L_{dyn2} / R_M = 1{,}2/12{,}5 = 0{,}096, s;$$

– district 2-3

$$L_{dyn3} = \Delta\psi_3 / \Delta I_3 = (0{,}8 - 0{,}71)/(0{,}8 - 0{,}3) = 0{,}018, H;$$

$$\tau_3 = L_{dyn3} / R_M = 0{,}018/12{,}5 = 0{,}00144, s.$$

The piecewise-linear approximation lets analytical to write down normal magnetization curve in the form

– district 0-1

$\psi = L_{dyní1} \cdot i, Wb$

$0 < i < I_1 = 0{,}05, A;$

– district 1-2

$\psi = \psi_1 + L_{äèí\ 2} \cdot i, Wb$

$I_1 = 0{,}05, A < i < I_2 = 0{,}3, A;$

– district 2-3

$\psi = \psi_2 + L_{äèí\ 3} \cdot i, Wb$

$I_2 = 0{,}3, A < i < I_0 = 0{,}8, A.$

According to the quantity of the chosen approximation districts the whole time of the transient process we split into three districts. For every district obtain own differential equation

– district 0-1

$$U_0 = L_{dyn1} \frac{di}{dt} + iR_M, V$$

$0 < i < I_1 = 0{,}05, A;$

$0 < t < t_1;$

– district 1-2

$$U_0 = L_{dyn2} \frac{di}{dt} + iR_M, V$$

$I_1 = 0{,}05, A < i < I_2 = 0{,}3, A;$

$t_1 < t < t_2;$

– district 2-3

$$U_0 = L_{dyn3} \frac{di}{dt} + iR_M, V$$

$I_2 = 0{,}3, A < i < I_0 = 0{,}8, A;$

$t_2 < t < \infty.$

Equations solution we obtain in the following type

– district 0-1

$i = I_0 + A_1 e^{-t/\tau 1}, A$

$0 < i < I_1 = 0{,}05, A;$

$0 < t < t_1;$

– district 1-2

$i = I_0 + A_2 e^{-(t1-t)/\tau 2}, A$

$I_1 = 0{,}05, A < i < I_2 = 0{,}3, A;$

$t_1 < t < t_2;$

– district 2-3

$i = I_0 + A_3 e^{-(t2-t)/\tau 3}, A$

$I_2 = 0{,}3, A < i < I_0 = 0{,}8, A;$

$t_2 < t < \infty.$

From the condition of the impossibility of change current by stepwise at transition through the points of fracture 0, 1, 2 find of integrating constant

$A_1 = -I_0 = -0{,}8, A;$

$A_2 = I_1 - I_0 = 0{,}05 - 0{,}8 = -0{,}75, A;$

$A_3 = I_2 - I_0 = 0{,}3 - 0{,}8 = -0{,}5, A.$

The transition times from the first to second t_1 and from second to third district t_2 are determined from following conditions

$i(t_1) = I_1 = I_0(1 - e^{-t1/\tau 1});$

$i(t_2) = I_2 = I_0 + (I_1 - I_0)e^{-(t2+t1)/\tau 1}.$

From where we have

$$t_1 = \tau_1 \ln \frac{I_0}{I_0 - I_1} = 0{,}656 \ln \frac{0{,}8}{0{,}8 - 0{,}05} = 0{,}041, s;$$

$$t_2 = t_1 + \tau_2 \ln \frac{I_0 - I_1}{I_0 - I_2} = 0{,}041 + 0{,}096 \ln \frac{0{,}8 - 0{,}05}{0{,}8 - 0{,}3} = 0{,}079, s.$$

Transient process graph is shown on Fig.4.8.

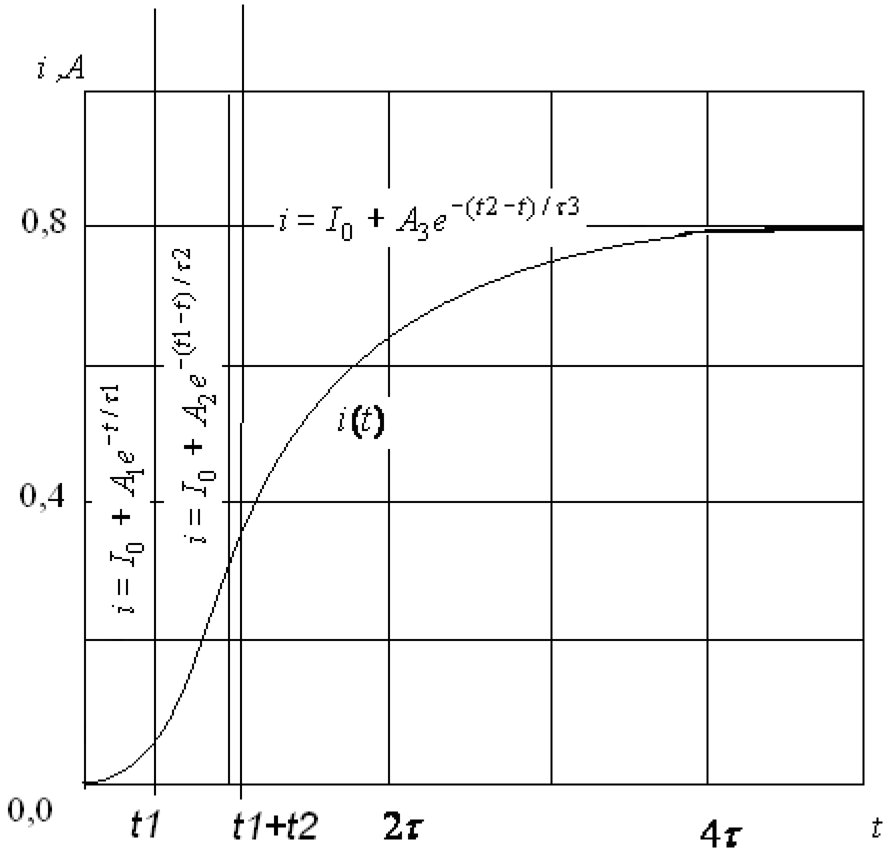


Fig.4.8.

4.6. The transient process calculation in nonlinear electric chains by step-by-step method

Deciding by the step-by-step method consists in chosen as to static inductance the transient process duration and shall divide the transient process time on row of the equal and fairly small the time increment intervals Δt**,** following which we do the digital integrating of differential equations, preliminarily having presented their through increments on current and previous interval.

We calculate transient process in scheme Fig.4.1 at accepted assumptions.

The duration of transient process estimate as to static inductance in enforced regime $t_c = 5\dfrac{L_{st}}{R_M} = 5\cdot\tau = 5\cdot 0{,}08 = 0{,}4, s.$ The time of transient process split into of hundred equal intervals, that is why $\Delta t = 0{,}1\cdot t_c = 0{,}004, s$.

Initial differential equation shall receive on basis of the balance circuit voltages (of second Kirhhgoff's law)

$$U_0 = R_M i + \frac{d\psi}{dt}.$$

We do variables separation

$$d\psi = (U_0 - R_M i)\cdot dt.$$

From differential pass on to increments

$$\Delta\psi_k = \psi_k - \psi_{k-1} = (U_0 - R_M i_{k-1})\cdot\Delta t$$

where *κ* – the running integrating interval; *κ-1* – the previous integrating interval.

The first time increment from 0 till Δt: initial values $\psi_0 = 0; i_0 = 0$.

We find flux linkage increment on the first calculation interval

$$\Delta\psi_1 = \psi_1 - \psi_0 = (U_0 - R_M i_0)\cdot\Delta t = U_0\Delta t = 100\cdot 0{,}004 = 0{,}4, Wb.$$

As to normal magnetization curve $\Psi(I)$**,** Fig.4.1, find current value in the end of the first time increment $i_1 = 0{,}07$, A.

The flux linkage in the end of the first increment interval

$$\psi_1 = \psi_0 + \Delta\psi_1 = 0{,}4, Wb.$$

The second integrating interval: initial values

$$\psi_1 = 0{,}4, Wb; i_0 = 0{,}07, \grave{A}.$$

We find flux linkage increment on the second calculation interval

$$\Delta\psi_2 = \psi_2 - \psi_1 = (U_0 - R_M i_1)\cdot\Delta t = (100 - 12{,}5\cdot 0{,}07)\cdot 0{,}004 = 0{,}39, Wb.$$

The flux linkage in the end of the second integration interval

$$\psi_2 = \psi_1 + \Delta\psi_2 = 0{,}79, Wb.$$

As to normal magnetization curve $\Psi(I)$**,** Fig.4.1, find current value in the end of the second time increment $i_2 = 0{,}57$, A.

Repeating similarly calculation as to mention algorithm for the rest of the 98 times period, shall receive the digital values of flux linkage transient functions and current as time behavior.

Task.

There is given nonlinear electric scheme, in which acting EMF of DC sources, Fig.4.9.a. The parameters of circuit are known $E=4$ V, $R_1=1$ Ohm, $R_2=1$ Ohm, $J=1$ A, $u_C(q)=10^5 q+10^{12} q^2$ V. Determine the capacitor's charge transient function after switching key S.

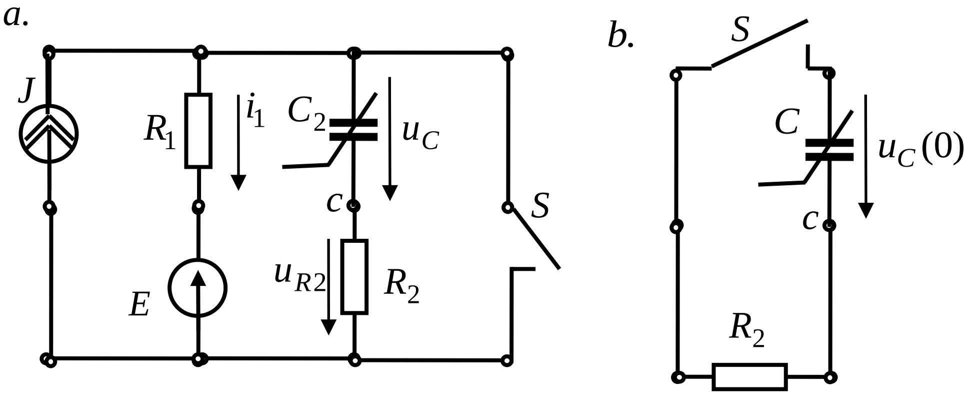


Fig.4.9

The task solution.

Initial condition on capacitive element

$$u_C(0)=E_0=E-J\cdot R_1=4-1\cdot1=2, \text{ V};$$

$$u_C(0)=10^5 q(0)+10^{12} q^2(0);$$

$$q(0)=\frac{-10^5\pm\sqrt{10^{10}+4\cdot2\cdot10^{12}}}{2\cdot10^{12}}=1{,}37\cdot10^{-6} \text{ Wb.}$$

Enforced voltage components and the capacitor's charge

$$u_{Cf}=0 \text{ V},\quad q_f=0 \text{ C.}$$

The nonlinear capacity value at initial conditions

$$C_0=q(0)/u_C(0)=1{,}36\cdot10^{-6}/2=0{,}68\cdot10^{-6} \text{ F.}$$

Transient process time constant at initial conditions

$$\tau=C_0R_2=0{,}68\cdot10^{-6}\cdot1=0{,}68\cdot10^{-6} \text{ s.}$$

Transient process duration

$$t_c=5\tau=3{,}4\cdot10^{-6} \text{ s.}$$

We choose ten steps of integrating, then the increment time on each integrating step $\Delta t=0{,}1t_c=3{,}4\cdot10^{-7}$ s.

Initial differential equation we shall receive on basis of the voltages balance in the circuit (second Kirhhgoff's law)

$$0=R_2 i+u_C=R_2\frac{dq}{dt}+u_C.$$

We do variables separation

$$dq = -\frac{u_C}{R_2} \cdot dt.$$

From differential pass on to increments

$$\Delta q_k = q_k - q_{k-1} = (-u_{C\,k-1}) \cdot \Delta t,$$

where *к* – the running integrating interval; *к-1* – the previous integrating interval.

The first time increment from 0 till Δt: initial values $q(0) = 1{,}37 \cdot 10^{-6}; u_C(0) = 2$.

We find charge increment on the first calculation interval

$$\Delta q_1 = q_1 - q(0) = (-u_{Ck-1}) \cdot \Delta t = -2 \cdot 3{,}4 \cdot 10^{-7} = -6{,}8 \cdot 10^{-7}, C.$$

As initial given curve $u_C(q) = 10^5 q + 10^{12} q^2$, find voltage value on capacitor in the end of the first time increment $u_{C1} = 0{,}53$, V.

The charge on capacitor in the end of the first time increment

$$q_1 = q(0) + \Delta q_1 = 0{,}69 \cdot 10^{-6}, C.$$

The second integrating interval: initial values

$$q_1 = 0{,}69 \cdot 10^{-6}, C; u_{C1} = 0{,}53, V.$$

We find charge increment on capacitor on the second calculation interval

$$\Delta q_2 = q_2 - q_1 = (-u_{C1}) \cdot \Delta t = (-0{,}53) \cdot 3{,}4 \cdot 10^{-7} = -1{,}8 \cdot 10^{-7}, C.$$

The charge on capacitor in the end of the second integration interval

$$q_2 = q_1 + \Delta q_2 = 0{,}51 \cdot 10^{-7}, C.$$

On the bases of initial given curve $u_C(q) = 10^5 q + 10^{12} q^2$, we find on capacitor voltage in the end of the second increment time $u_{C2} = 0{,}37$, V.

Repeating similarly calculation as to mention algorithm for the rest of the 8 times period, shall receive the digital values of charge transient functions and voltage as time behavior.

4.7. The transient process calculation in nonlinear electric circuits by phase-plane method

Initial differential equation for the scheme Fig.4.2.b we shall receive on basis of the voltages balance in the circuit (second Kirhhgoff's law)

$$U_0 = R_M i + L_{cò}(i)\frac{di}{dt}.$$

We input phase coordinates $i = x$, $\frac{di}{dt} = y$

$U_0 = R_M x + L_{ñò}(i) y$ or $I_0 = x + \tau(i) y$.

At constant static inductance phase trajectory draw on phase plane direct line (Fig.4.10 is marked by dotted line). In nonlinear circuit the phase trajectory differs from direct line (on Fig.4.10 is marked by solid line).

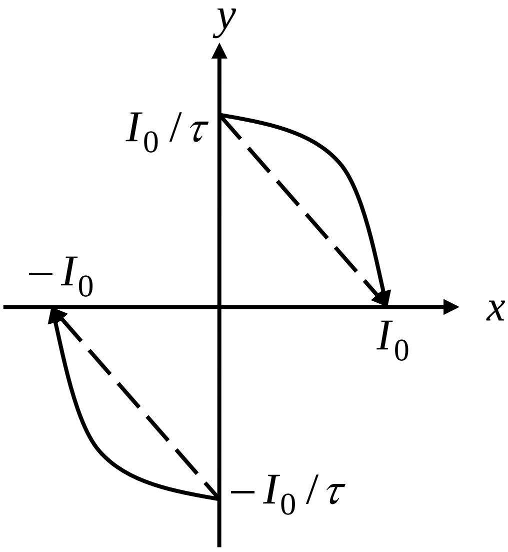


Fig.4.10.

4.8. The transient process calculation in nonlinear electric circuits by the equivalent generator method

Task.

There is given nonlinear electric scheme, in which acting EMF of DC sources, Fig.4.11.a. The parameters of circuit are known E =2 V, R_1=1 Ohm, R_2=1 Ohm, J =1 A, $i_L(\psi) = 10^2\psi + 10^3\psi^2$ A. Determine the flux linkage transient function after switching key S.

The task solution.

In circuit there is single nonlinear element, that is why solution rational to perform by the method of equivalent generator.

Initial condition on coil inductance

$i_L(0) = J_0 = 0$, $\psi(0) = 0$.

The current and flux linkage enforsed components of coil inductance

$$i_{Lïð} = \frac{J}{2} + \frac{E}{R_1 + R_2} = 1{,}5 \text{ A}, \quad i_{Lïð}(\psi) = 10^2\psi_{ïð} + 10^3\psi_{ïð}^{\ 2}.$$

$$\psi_{ïð} = \frac{-10^2 \pm \sqrt{10^4 + 4\cdot 1{,}5\cdot 10^3}}{2\cdot 10^3} = 1{,}3\cdot 10^{-2} \text{ Wb.}$$

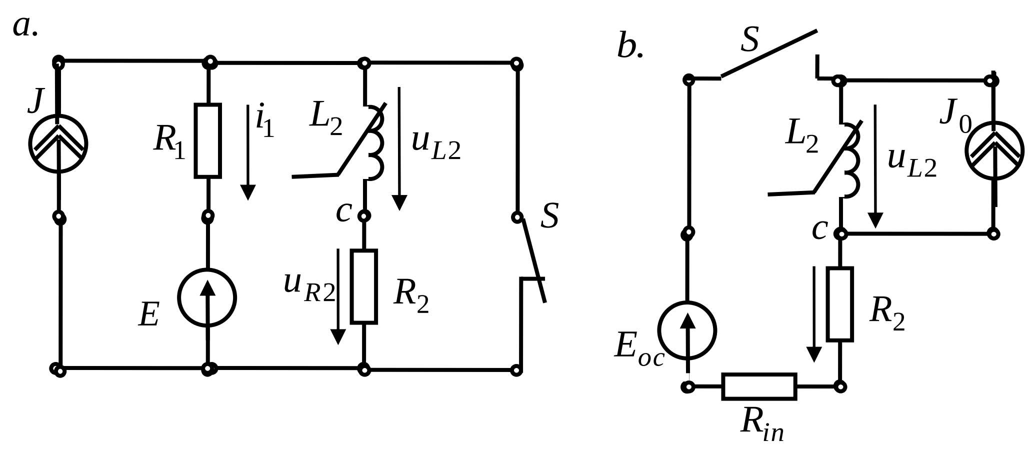


Fig.4.11

Equivalent generator's electromotive force

$$E_{oc} = E - \frac{J}{2}R_1 = 2 - 0{,}5 = 1{,}5, \text{ V.}$$

Equivalent generator's inner resistance

$R_{in} = R_1$=1 Ohm.

The the replacement scheme of computative scheme is shown on Fig.4.11.b. For the scheme of replacement fair

$$E_{oc} = (R_2 + R_{in})i + \frac{d\psi}{dt}.$$

In further we do calculation by the step-by-step method.

We do variables separation

$$d\psi = (E_{oc} - (R_{in} + R_2)\cdot i)\cdot dt.$$

From differential pass on to increments

$$\Delta\psi_k = \psi_k - \psi_{k-1} = (E_{oc} - (R_{in} + R_2)\cdot i_{k-1})\cdot\Delta t$$

where *κ* – the running integrating interval; *κ-1* – the previous integrating interval.

Static inductance in enforced regime

$$L_{cò} = \psi_{ïð} / i_{Lïð} = 1{,}3\cdot 10^{-2}/1{,}5 = 8{,}7\cdot 10^{-3} \text{ H.}$$

Constant time in enforced regime

$$\tau = L_{cò}/(R_{in} + R_2) = 8{,}7\cdot 10^{-3}/2 = 4{,}35\cdot 10^{-3} \text{ s.}$$

Transient process duration

$$t_c = 5\tau = 21{,}75\cdot 10^{-3} \text{ s.}$$

We choose ten steps of integrating, then the increment time on each integrating step $\Delta t = 0{,}1 t_c = 2{,}175\cdot 10^{-3}$ s.

The results of calculations we tabulate into table 4.2.

Table.4.2.

t, s	ψ , Wb	i, A	$(R_2+R_{in})i$, V	$E_{oc}-(R_2+R_{in})i$, V	$\Delta\psi$, Wb
0	0	0	0	1,5	$3{,}262\cdot10^{-3}$
$2{,}175\cdot10^{-3}$	$3{,}262\cdot10^{-3}$	0,33	0,66	0,84	$1{,}827\cdot10^{-3}$
$4{,}35\cdot10^{-3}$	$5{,}089\cdot10^{-3}$	0,51	1,02	0,48	$1{,}044\cdot10^{-3}$
$6{,}525\cdot10^{-3}$	$6{,}133\cdot10^{-3}$	0,62	1,24	0,26	$0{,}565\cdot10^{-3}$
$8{,}7\cdot10^{-3}$	$6{,}698\cdot10^{-3}$	0,67	1,34	0,29	$0{,}631\cdot10^{-3}$
$1{,}087\cdot10^{-2}$	$7{,}329\cdot10^{-3}$	0,74	1,38	0,21	$0{,}744\cdot10^{-3}$
$1{,}305\cdot10^{-2}$	$8{,}073\cdot10^{-3}$	1,181	1,39	0,18	$0{,}834\cdot10^{-3}$
$1{,}522\cdot10^{-2}$	$8{,}908\cdot10^{-3}$	1,292	1,42	0,08	$0{,}835\cdot10^{-3}$
$1{,}74\cdot10^{-2}$	$9{,}548\cdot10^{-3}$	1,397	1,46	0,06	$0{,}640\cdot10^{-3}$
$1{,}95\cdot10^{-2}$	$11{,}092\cdot10^{-3}$	1,481	1,48	0,05	$0{,}594\cdot10^{-3}$
$2{,}175\cdot10^{-2}$	$12{,}922\cdot10^{-3}$	1,498	1,49	0,03	$0{,}049\cdot10^{-3}$

4.9. The personal computative-graphic task “The transient process calculation in nonlinear DC electric scheme”

On Fig.4.12, 4.13 there are given nonlinear electric schemes with single nonlinear element: inductance or capacitance. The nonlinear inductance given by weber-ampere characteristic $i_L(\psi)=10^2\psi+10^3\psi^2$ (current dimension in amperes and flux linkage dimension in webers), the unlunear capacitance given by coulomb-volt characteristic $u_C(q)=10^5q+10^{12}q^2$ (voltage dimension in volts, and charge in coulombs). In circuits acting sources of DC electromotion forces and currents. The circuit parameters according to the number of variant are indicated in table 4.3. To determine flux linkage or charge curve changes in time after commutation.

Table 4.3

Variant	Schehe	R_1, Ohm	R_2, Ohm	J , A	E , V	Define
01	4.12.a	1	1	2	0	$\psi(t)$
02	4.12.b	1	1	0	2	$q(t)$
03	4.12.c	1	1	0	2	$\psi(t)$
04	4.12.d	50	50	0,04	0	$q(t)$

05	4.12.e	1	1	2	0	$\psi(t)$
06	4.12.f	1	1	0	2	$q(t)$
07	4.13.a	10	10	1	10	$\psi(t)$
08	4.13.b	1	1	1	1	$q(t)$
09	4.13.c	1	1	0	2	$\psi(t)$
10	4.13.d	1	1	2	0	$q(t)$
11	4.12.a	1	2	3	0	$\psi(t)$
12	4.12.b	2	1	0	3	$q(t)$
13	4.12.c	2	2	0	4	$\psi(t)$
14	4.12.d	40	10	0,05	0	$q(t)$
15	4.12.e	2	2	2	0	$\psi(t)$
16	4.12.f	2	2	0	2	$q(t)$
17	4.13.a	20	20	1	20	$\psi(t)$
18	4.13.b	2	2	0,5	1	$q(t)$
19	4.13.c	2	2	0	4	$\psi(t)$
20	4.13.d	2	2	1	0	$q(t)$
21	4.12.a	1	3	4	0	$\psi(t)$
22	4.12.b	3	1	0	4	$q(t)$

Continue of Table 4.3

Variant	Schehe	R_1, Ohm	R_2, Ohm	J, A	E, V	Define
23	4.12.c	3	1	0	6	$\psi(t)$
24	4.12.d	20	20	0,1	0	$q(t)$
25	4.12.e	3	3	2	0	$\psi(t)$
26	4.12.f	3	3	0	2	$q(t)$
27	4.13.a	30	30	1	30	$\psi(t)$
28	4.13.b	4	4	0,25	1	$q(t)$
29	4.13.c	3	1	0	6	$\psi(t)$
30	4.13.d	4	4	0,5	0	$q(t)$
31	4.12.a	1	4	5	0	$\psi(t)$
32	4.12.b	4	1	0	5	$q(t)$
33	4.12.c	4	1	0	8	$\psi(t)$
34	4.12.d	10	20	0,2	0	$q(t)$
35	4.12.e	4	4	2	0	$\psi(t)$
36	4.12.f	4	4	0	2	$q(t)$
37	4.13.a	40	40	1	40	$\psi(t)$

38	4.13.b	8	8	0,125	1	$q(t)$
39	4.13.c	4	1	0	8	$\psi(t)$
40	4.13.d	5	5	0,4	0	$q(t)$
41	4.12.a	1	5	6	0	$\psi(t)$
42	4.12.b	5	1	0	6	$q(t)$
43	4.12.c	5	5	0	10	$\psi(t)$
44	4.12.d	8	12	0,25	0	$q(t)$
45	4.12.e	5	5	2	0	$\psi(t)$
46	4.12.f	5	5	0	2	$q(t)$
47	4.13.a	50	50	1	50	$\psi(t)$
48	4.13.b	10	10	0,1	1	$q(t)$
49	4.13.c	5	5	0	10	$\psi(t)$
50	4.13.d	8	8	0,25	0	$q(t)$
51	4.12.a	1	6	7	0	$\psi(t)$
52	4.12.b	6	1	0	7	$q(t)$
53	4.12.c	6	2	0	12	$\psi(t)$
54	4.12.d	5	5	0,4	0	$q(t)$
55	4.12.e	6	6	2	0	$\psi(t)$
56	4.12.f	6	6	0	2	$q(t)$
57	4.13.a	60	60	1	60	$\psi(t)$

Continue of Table 4.3

Variant	Schehe	R_1, Ohm	R_2, Ohm	J, A	E, V	Define
58	4.13.b	20	20	0,05	1	$q(t)$
59	4.13.c	6	2	0	12	$\psi(t)$
60	4.13.d	10	10	0,2	0	$q(t)$
61	4.12.a	1	7	8	0	$\psi(t)$
62	4.12.b	7	1	0	8	$q(t)$
63	4.12.c	7	3	0	14	$\psi(t)$
64	4.12.d	4	6	0,5	0	$q(t)$
65	4.12.e	7	7	2	0	$\psi(t)$
66	4.12.f	7	7	0	2	$q(t)$
67	4.13.a	70	70	1	70	$\psi(t)$
68	4.13.b	25	25	0,4	1	$q(t)$
69	4.13.c	7	3	0	14	$\psi(t)$
70	4.13.d	12,5	12,5	0,16	0	$q(t)$
71	4.12.a	1	8	9	0	$\psi(t)$

72	4.12.b	8	1	0	9	$q(t)$
73	4.12.c	8	2	0	16	$\psi(t)$
74	4.12.d	2,5	7,5	0,8	0	$q(t)$
75	4.12.e	8	8	2	0	$\psi(t)$
76	4.12.f	8	8	0	2	$q(t)$
77	4.13.a	80	80	1	80	$\psi(t)$
78	4.13.b	40	40	0,25	1	$q(t)$
79	4.13.c	8	2	0	16	$\psi(t)$
80	4.13.d	20	20	0,1	0	$q(t)$
81	4.12.a	1	9	10	0	$\psi(t)$
82	4.12.b	9	1	0	10	$q(t)$
83	4.12.c	9	1	0	18	$\psi(t)$
84	4.12.d	2	3	1	0	$q(t)$
85	4.12.e	9	9	2	0	$\psi(t)$
86	4.12.f	9	9	0	2	$q(t)$
87	4.13.a	90	90	1	90	$\psi(t)$
88	4.13.b	50	50	0,02	1	$q(t)$
89	4.13.c	9	1	0	18	$\psi(t)$
90	4.13.d	25	25	0,08	0	$q(t)$
91	4.12.a	1	10	11	0	$\psi(t)$
92	4.12.b	10	1	0	11	$q(t)$

Continue of Table 4.3

Variant	Schehe	R_1, Ohm	R_2, Ohm	J, A	E, V	Define
93	4.12.c	10	10	0	20	$\psi(t)$
94	4.12.d	1	4	2	0	$q(t)$
95	4.12.e	10	10	2	0	$\psi(t)$
96	4.12.f	10	10	0	2	$q(t)$
97	4.13.a	100	100	1	100	$\psi(t)$
98	4.13.b	100	100	0,01	1	$q(t)$
99	4.13.c	10	10	0	20	$\psi(t)$
00	4.13.d	40	40	0,5	0	$q(t)$

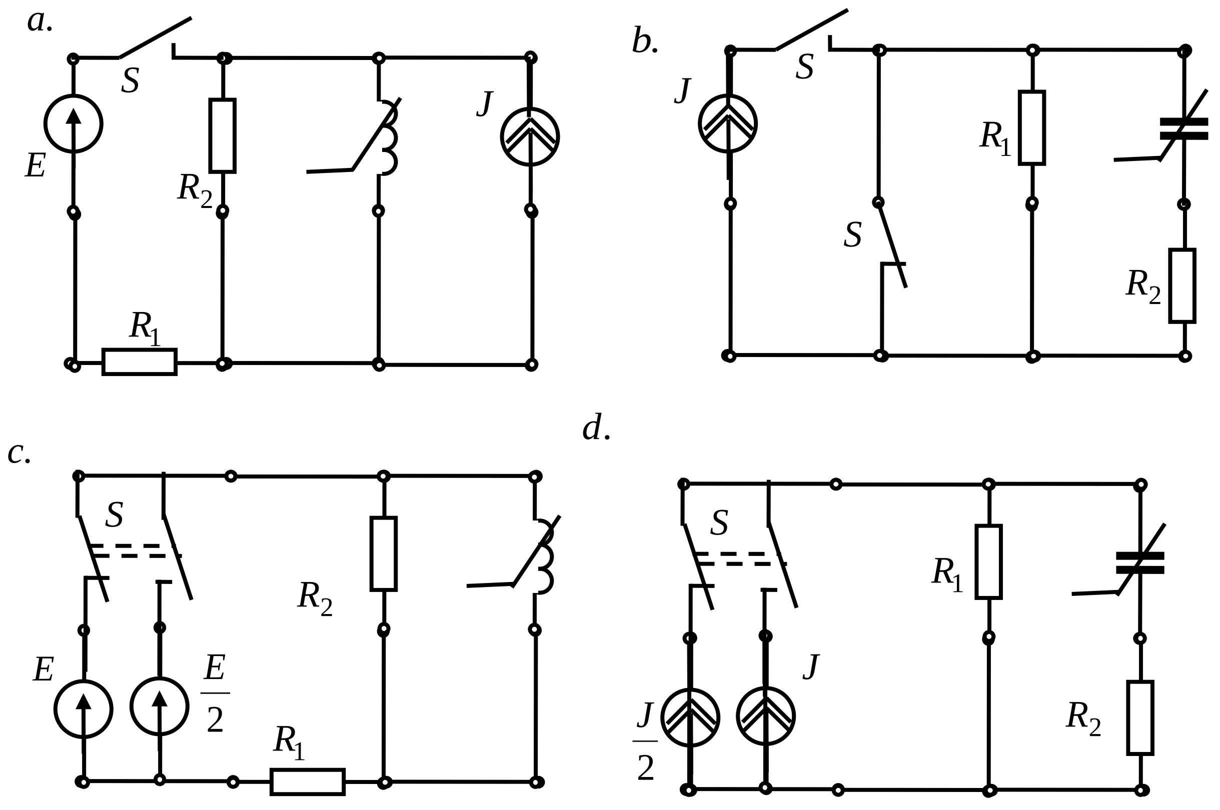


Fig.4.13

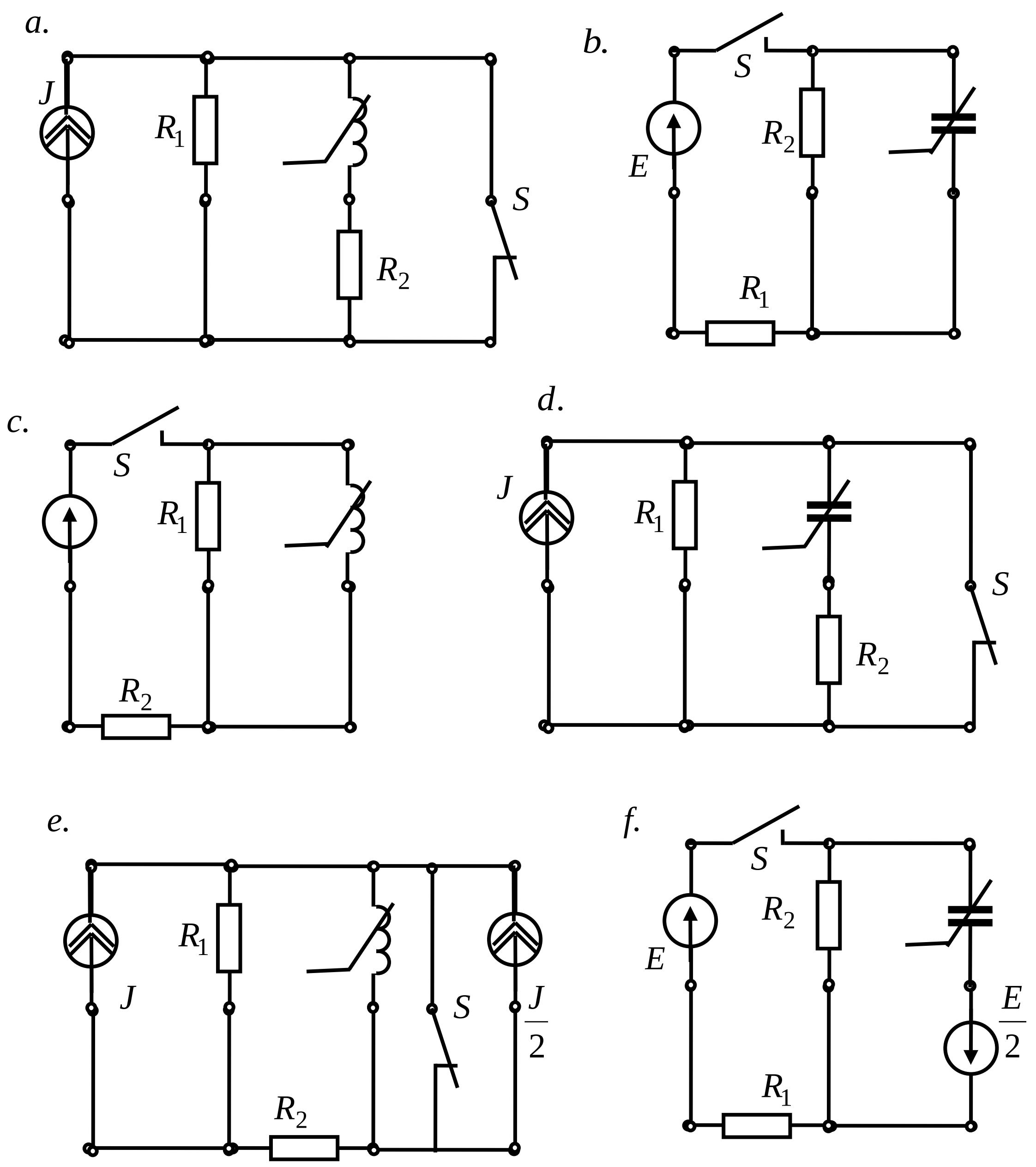


Fig.4.12

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