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кафедра
електричної інженерії

Fundamentals of Electrical Engineering

LABORATORY WORKS

Part 2

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«Fundamentals of Electrical Engineering. Laboratory works. Part 2»

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Схвалено й рекомендовано до публікації НМК факультету прикладних інформаційних технологій та електроінженерії Тернопільського національного технічного університету імені Івана Пулюя.
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Посібник складено відповідно до робочої програми курсу “Теоретичні основи електротехніки“.

Introduction

This manual is a guide for conducting laboratory works.

It describes 6 laboratory works that students perform according to the course "Fundamentals of Electrical Engineering" syllabus.

The laboratory works are designed taking into account the technical specifications of the measuring instruments used in the electrical engineering laboratory.

Before starting each laboratory work, in addition to reviewing the theoretical material, the student must complete a short homework task according to the variant specified by the instructor.

Each work provides brief theoretical information relevant to the lab work: basic analytical expressions, phasor diagrams, characteristic curves necessary for calculating and analyzing the operating modes of electrical circuits. Furthermore, it includes a list of measuring instruments, a circuit diagram and description of the circuit under investigation, explains the procedure for performing the laboratory work, as well as the order of processing experimental results and report formatting requirements. Students collect the electrical circuit diagrams independently under the guidance of the instructor. Control questions at the end of each work will help students navigate the studied material and prepare for the defense of their laboratory work.

The guide also provides definitions and units of measurement of physical quantities.

LABORATORY WORK 2.1
Investigation
of non-sinusoidal voltage spectrum

The purpose of the work. To define experimentally the harmonic constituents amplitudes of non-sinusoidal voltage.

Non-sinusoidal voltages or currents are the ones which are changed with the time according to periodical non-sinusoidal law. The cause of non-sine currents (voltages) is the source of non- sinusoidal voltage or the non-linear element of the circuit.

Such circuits may be represented by the Fourier series as the sum of sinusoidal functions in order to get calculated:

$$v = V_0 + V_{m1}\,sin(\,\omega t + \psi_{V1}) + V_{m2}\,sin(\,2\omega t + \psi_{V2}) + \ldots + V_{mk}\,sin(\,k\omega t + \psi_{Vk}) =$$

$$= V_0 + \sum_{k=1}^{\infty} V_{mk}\,sin(\,k\omega t + \psi_{Vk}),$$

where V_0 is the steady component; $v_1 = V_{m1}\,sin(\,\omega t + \psi_{V1})$ is the first (basic) harmonic component, (ω - the frequency of first harmonic), $v_k = V_{mk}\,sin(\,k\omega t + \psi_{Vk})$ - k harmonic component (called also as *harmonic*), V_{mk} - amplitude, ω - fundamental frequency, $k\omega$ - frequency of k harmonic, ψ_{Vk} - initial phase of k harmonic. The harmonics with the frequencies 2, 3,…k times larger than ω, are called higher harmonics.

We can represent the value $V_{mk}\,sin(\,k\omega t + \psi_{Vk}) \div A_{mk}\,sin(\,k\omega t + \phi_k)$ by the sum of two constituents (fig.1.1):

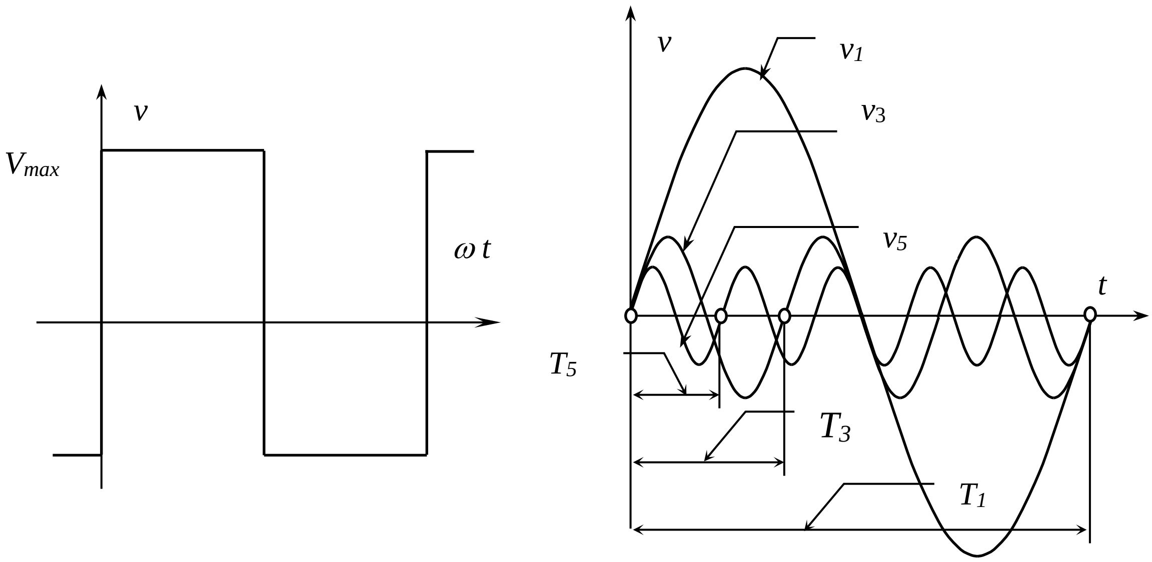


Fig.1.1

$$A_{mk}\,sin(\,k\omega t + \phi_k) = B_{mk}\,sin\,k\,\omega t + C_{mk}\,cos\,k\,\omega t,$$

where $B_{mk} = A_{mk}\,cos\,\phi_k$, $C_{mk} = A_{mk}\,sin\,\phi_k$, $A_{mk} = \sqrt{B_{mk}^2 + C_{mk}^2}$, $\phi_k = arctg(C_{mk}/B_{mk})$.

So, the Fourier series we can write down ($v \div f(\omega t)$):

$$f(\omega t) = A_0 + \sum_{k=1}^{\infty} B_{mk} \sin k\,\omega t + \sum_{k=1}^{\infty} C_{mk} \cos k\,\omega t.$$

The formulas for Fourier series coefficients:

$$A_0 = \frac{1}{2\pi}\int_0^{2\pi} f(\omega t)\cdot d(\omega t),\ B_{mk} = \frac{1}{\pi}\int_0^{2\pi} f(\omega t)\cdot \sin(\omega t)\cdot d(\omega t),$$

$$C_{mk} = \frac{1}{\pi}\int_0^{2\pi} f(\omega t)\cdot \cos(\omega t)\cdot d(\omega t).$$

Graphical method of determination the Fourier series harmonics is based on the definite integral replacement with the finite number of intervals. For that purpose the function $f(x)$ with period 2π is divided by n equal intervals $\Delta x = 2\pi/n$ and the sum of the function's values replaces the integral.

Thus, DC component is represented as:

$$A_0 = \frac{1}{2\pi}\sum_{p=1}^{n} f_p(x)\Delta x = \frac{1}{2\pi}\sum_{p=1}^{n} f_p(x) 2\pi/n \text{ or } A_0 = \frac{1}{n}\sum_{p=1}^{n} f_p(x),$$

where p is an incremental index from 1 to n,

$f_p(x)$ - is a function $f(x)$ value for $x = (p - 0.5)\Delta x$, in the middle of a p -interval.

Sine constituent amplitude of k harmonic is:

$$B_k = 2\frac{1}{2\pi}\sum_{p=1}^{n} f_p(x) 2\pi/(n)\cdot \sin_p k\,x \text{ or } A_k{}' = \frac{2}{n}\sum_{p=1}^{n} f_p(x) \sin_p k\,x.$$

Cosine constituent amplitude of k harmonic is:

$$C_k = \frac{2}{n}\sum_{p=1}^{n} f_p(x) \cos_p k\,x,$$

where $\sin_p k\,x$ and $\cos_p k\,x$ are the functions' $\sin k\,x$ and $\cos k\,x$ values for $x = (p - 0.5)\Delta x$, in the middle of a p -interval.

It is typical to divide the period into 24 or 18 intervals in calculations. Before calculations it is recommended to identify whether the function is relatively symmetrical across axises. The certain type of symmetry hints to the presence of particular harmonics.

If the function is symmetrical across the X axis $f(\omega t) = -f(\omega t \pm \pi)$ then Fourier series have only odd harmonics:

$$f(\omega t) = A_{m1}\sin(\omega t + \phi_1) + A_{m3}\sin(3\omega t + \phi_3) + A_{m5}\sin(5\omega t + \phi_5) + \ldots. =$$

$$= B_{m1}\sin\omega\,t + C_{m1}\cos\omega\,t + B_{m3}\sin 3\,\omega t + C_{m3}\cos 3\,\omega t + B_{m5}\sin 5\,\omega t + C_{m5}\cos 5\,\omega t + \ldots$$

If the function is symmetrical across the origin $f(\omega t) = -f(-\omega t)$ then Fourier series have only sin constituents:

$$f(\omega t) = B_{m1}\sin\omega\,t + B_{m2}\sin 2\,\omega t + B_{m3}\sin 3\,\omega t + \ldots$$

If the function is symmetrical across Y axis $f(\omega t) = f(-\omega t)$ then Fourier series have only steady component and cos constituents:

$$f(\omega t) = A_0 + C_{m1}\cos\omega\,t + C_{m2}\cos 2\,\omega t + C_{m3}\cos 3\,\omega t + \ldots$$

Fourier series has only steady component and cos constituents:

$$f(\omega t) = A_0 + C_{m1}\cos\omega\,t + C_{m2}\cos 2\,\omega t + C_{m3}\cos 3\,\omega t + \ldots$$

For example, the square shape of voltage (fig.4.1) can be represented in such a way (fig.4.2): $v = \frac{4V_{max}}{\pi \sin \omega \frac{1}{3} \sin 3 \frac{1}{5} \sin 5}$

Non-sinusoidal current $i = I_0 + \sum_{k=1}^{\infty} I_{mk} \, sin(k\omega t + \psi_{Ik})$ (i.e. the sum of the sinusoidal currents) is present in the circuit with non-sinusoidal voltage $v = V_0 + \sum_{k=1}^{\infty} V_{mk} \, sin(k\omega t + \psi_{Vk})$ (the sum of the sine voltages). The calculation of the circuit is based on the principle of superposition. The steady component of the current I_0 can be calculated by using the methods of DC circuits' calculation and harmonic of current i_k by using the methods of AC circuits' calculation.

As known reactance of the coil for k-harmonic is equal $X_{Lk} = k\omega L = kX_L$ and susceptance $B_{Lk} = 1/(k\omega L) = B_L/k$. Reactance of the coil for DC (as effect of the steady voltage component V_0) is $X_L(0) = 0 \cdot L = 0$. The susceptance of the capacitor for k-harmonic is $B_{Ck} = k\omega C = kB_C$ and reactance is $X_{Ck} = 1/(k\omega C) = X_C/k$. Reactance of the capacitor for DC (as effect of the steady voltage component V_0) is $X_C(0) = 1/(0 \cdot C) = \infty$, $I_0 = 0$. The resistance of the circuit doesn't actually depend on the frequency and is the same for every harmonic.

The non-sinusoidal circuit calculation order is:

– the source voltage is expressed by Fourier series as an infinite sum of harmonic (sinusoidal) components (functions);

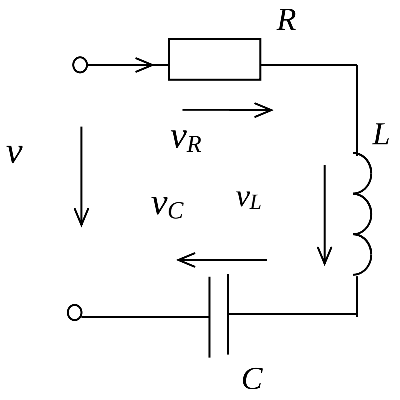


Fig.1.2

– the circuit for every harmonic component is calculated separately using DC and AC circuits' calculation methods. Also it should be taken into consideration that the reactances depend on the frequency;

– according to the superposition principle, the current instantaneous value is equal to the sum of currents instantaneous values of all harmonics, that's why the calculation results are considered at each particular moment. The effective values of voltage and current are equal correspondingly:

$$V = \sqrt{V_0^2 + V_1^2 + \ldots + V_k^2}, \; I = \sqrt{I_0^2 + I_1^2 + \ldots + I_k^2},$$

where V_k, I_k are harmonic voltages and currents effective values.

Homework

The circuit shown on fig.1.2 is connected to the source of non-sine voltage of $v(t) = (100 + 100\sqrt{2} \, sin \, \omega \, t + 76 \, sin \, 3 \, \omega t)V$, where $\omega = 314 \; rad/s$. The parameters of the circuit are given at the table. Define the voltage, the current's effective values.

Table 1.1

Var	1	2	3	4	5	6	7	8	9	10
R, Ω	5	10	15	20	25	30	35	40	45	50
L, H	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.095
C, μF	110	120	130	140	150	160	170	180	190	100

Elements of laboratory settings

The laboratory setting consists of a measuring generator of sine and rectangular sound frequencies, a resonant *LC* filter, which passes fluctuations with the frequency *f*, and a double-beam oscilloscope.

The work execution order

1.Collect the circuit according to the scheme in Fig. 1.3. Switch on the generator and oscilloscope.

2. By changing the generator frequency from *10* to *20 kHz*, find the frequency at which the amplitude of the signal at the output of the filter will be maximal. This frequency corresponds to the filter's frequency f_0. In this case, the ratio of the periods of the voltage at the generator output and at the filter output is 1:1.

3. Using the knobs for the generator's output voltage control or the sensitivity regulator for the *Y1* input of the oscilloscope, set them to such positions that the peak-to-peak amplitude of the first harmonic is exactly equal to 6 large divisions. Draw the waveform (oscillogram).

4.Reducing the generator frequency *k* times, where *k=2,3,4,...,10,11*, draw the corresponding waveforms. The exact value of the generator frequency *f/k* will be when the oscilloscope screen exhibits a stable, clear image of the generator signal and the signal at the output of the filter, and during one generator period there are exactly *k* periods of the signal at the output of the filter. Draw the waveform (oscillogram) for every *k*.

5.Using the oscillograms, draw the spectral diagram, dependence *A(k)* (amplitude(harmonic number)).

6. Make the conclusions, compare the experimental results and the mathematical representation of Fourier series.

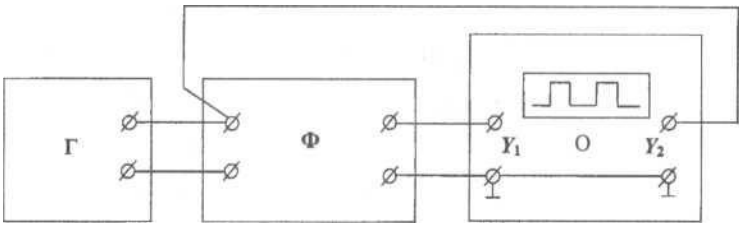


Fig.1.3

Report on the work

The title and the purpose of the work. Homework – the calculation of the circuit. The schematic diagram of the investigated circuit (fig 1.3). Oscillograms and spectral diagram. The conclusions.

Control questions

1. Give the definition of non-sine currents and voltages and the reasons for their appearance.
2. How can we represent a non-sinusoidal voltage (current) using Fourier series?
3. Explain the essence of the analytical method for Fourier series coefficients calculation.
4. Write down the expressions for Fourier series coefficients (analytical method).

5. Explain the essence of graphical method of Fourier series coefficients calculation.

6. Write down the expressions for Fourier series coefficients (grapfical method).

7. Calculation features of non-sine voltages with different types of symmetry (odd symmetry/across the origin, even symmetry/across the Y-axis, half-wave symmetry/across the X-axis).

8. Explain the calculation order for non-sinusoidal circuits.

9. Calculation features of reactances and susceptances for specific garmonics.

10. Write down the expressions for effective (RMS) values of non-sinusoidal voltages and currents.

LABORATORY WORK 2.2

Determination of parameters of non-sinusoidal voltages and currents by means of measuring devices of different systems

The purpose of the work. Investigate the influence of periodical voltage shape and frequency on the readings of measuring instruments of different systems.

Non-sinusoidal current $i = I_0 + \sum_{k=1}^{\infty} I_{mk}\, sin(\,k\omega t + \psi_{Ik})$ (i.e. the sum of the sinusoidal currents) is present in the circuit with non-sinusoidal voltage $v = V_0 + \sum_{k=1}^{\infty} V_{mk}\, sin(\,k\omega t + \psi_{Vk})$ (the sum of the sine voltages). The calculation of the circuit is based on the principle of superposition. The steady component of the current I_0 can be calculated by using the methods of DC circuits' calculation and harmonic of current i_k by using the methods of AC circuits' calculation.

As known reactance of the coil for k-harmonic is equal $X_{Lk} = k\omega L = kX_L$ and susceptance $B_{Lk} = 1/(k\omega L) = B_L/k$. Reactance of the coil for DC (as effect of the steady voltage component V_0) is $X_L(0) = 0 \cdot L = 0$. The susceptance of the capacitor for k-harmonic is $B_{Ck} = k\omega C = kB_C$ and reactance is $X_{Ck} = 1/(k\omega C) = X_C/k$. Reactance of the capacitor for DC (as effect of the steady voltage component V_0) is $X_C(0) = 1/(0 \cdot C) = \infty$, $I_0 = 0$. The resistance of the circuit doesn't actually depend on the frequency and is the same for every harmonic.

The non-sinusoidal circuit calculation order is:

– the source voltage is expressed by Fourier series as an infinite sum of harmonic (sinusoidal) components (functions);

– the circuit for every harmonic component is calculated separately using DC and AC circuits' calculation methods. Also it should be taken into consideration that the reactances depend on the frequency;

– according to the superposition principle, the current instantaneous value is equal to the sum of currents instantaneous values of all harmonics, that's why the calculation results are considered at each particular moment. The effective values of voltage and current are equal correspondingly:

$$V = \sqrt{V_0^2 + V_1^2 + \ldots + V_k^2},\ I = \sqrt{I_0^2 + I_1^2 + \ldots + I_k^2},$$

where V_k, I_k are harmonic voltages and currents effective values.
The *average value* of non-sinusoidal function $A_0(V_0, I_0)$ for the period:

$$A_0 = A_{AV} = \frac{1}{T}\int_0^T adt,$$

The *effective value* of non-sinusoidal function - *A (V, I)* is the mean-square value for the period T:

$$A = \sqrt{\frac{1}{T}\int_0^T a^2dt} = \sqrt{\sum_{k=o}^{n} A_k^2} = \sqrt{A_0^2 + \ldots + A_k^2}.$$

Shape factor is equal to the relation of function effective value to its average value: $K_{sh} = A/A_{AV}$. ($K_{sh} = 2/\pi = 1.11$ for sinusoidal curve).

Amplitude factor is equal to the relation of function amplitude value to its effective value: $K_a = \mathrm{A}_m/\mathrm{A}$. ($K_a = \sqrt{2} = 1.41$ for sinusoidal curve).

Distortion factor is equal the relation of first harmonic effective value to the function effective value:

$$K_d = A_1/A \text{ } (K_d = 1 \text{ for sinusoidal curve}).$$

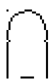
Harmonic factor is equal the relation of high harmonics effective values to the first harmonic effective value: $K_g = A_g/A_1$, where $A_g = \sqrt{A_2^2 + \ldots + A_k^2} = \sum_{k=2}^{\infty} A_k^2$ is the mean-square value of high harmonics effective values ($K_g = 0$ for sinusoidal curve).

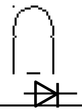
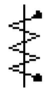
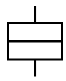
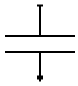
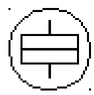
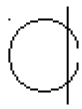
Active power of non- sinusoidal current is equal to the sum of harmonics active powers: $P = \sum_{k=o}^{n} V_k I_k = P_0 + P_1 + .. + P_k = P_0 + \Sigma P_k$, where $P_0 = V_0 I_0$ is the power of steady voltage component, $P_k = V_k I_k \cos\phi_k$ is the active power of k harmonic, $\phi_k = \psi_{Vk} - \psi_{Ik}$ - phase shift angle between k harmonic component of voltage and current. Reactive power of non- sinusoidal current is equal to the sum of harmonics reactive powers: $Q = \Sigma V_k I_k \sin\phi_k = \Sigma Q_k$.

Total power of non- sinusoidal current is: $S = \sqrt{P^2 + Q^2}$.

When measuring in non-sinusoidal current circuits, it is necessary to choose the system of the electric measuring device depending on what value of current or voltage needs to be measured. Electrical measuring devices are classified by the type of measuring quantity (ammeters, voltmeters, wattmeters, varmeters, ohmmeters, phase meters, frequency meters), by accuracy class (0.05, 0.1, 0.2, 0.5, 1, 1.5, 2.5, 4), by the type of current (voltage), and by the principle of operation (electromagnetic, electrodynamic, thermal, magnetoelectric, ferrodynamic, induction, electrostatic, amplitude electronics). Table 2.1 shows the main characteristics of devices of different systems.

Table 2.1

Device system	Marking	Measured value	Type of *I (V)*
Magnitoelectric		Steady component (average per period value)	DC or DV

Magnitoelectric with rectifier		Module average	AC or AV
Electromagnetic		Effective	AC,AV,DC, DV
Electrodynamic		Effective	AC,AV,DC, DV, power
Electrostatic		Effective	AC,AV,DC, DV
Thermal		Effective	AC,AV,DC, DV
Ferrodynamic		Effective	AC,AV, power
Induction			Energy meters
Amplitude electronics		Amplitude	AC or AV
Digital		Effective	AC,AV,DC, DV

Homework

Define the amplitude, shape factor, distortion factor, harmonic factor, effective (RMS) value, average value per period, and mean absolute value of the non-sinusoidal voltage, the instantaneous value of which is given in Table 2.2.

Table 2.2

Var	*Voltage instantaneous value, V*
1	$v(t) = 220 + 150\, sin\, \omega\, t + 50\, sin\, 2\, \omega t$
2	$v(t) = 100 + 141\, sin\, \omega\, t + 34.6\, sin\, 3\, \omega t$
3	$v(t) = 141 + 34.6\, sin\, 2\, \omega t + 54.6\, sin\, 4\, \omega t$
4	$v(t) = 100\, sin\, \omega\, t + 50\, sin\, 2\, \omega t + 35\, sin\, 3\, \omega t$
5	$v(t) = 141\, sin\, \omega\, t + 34.6\, sin\, 3\, \omega t + 54.6\, sin\, 5\, \omega t$
6	$v(t) = 220 + 100\, sin\, \omega\, t + 50\, sin\, 3\, \omega t$
7	$v(t) = 100 + 35\, sin\, 2\, \omega t + 18\, sin\, 4\, \omega t$
8	$v(t) = 150\, sin\, \omega\, t + 80\, sin\, 2\, \omega t + 40\, sin\, 3\, \omega t$
9	$v(t) = 110 + 50\, sin\, \omega\, t + 30\, sin\, 2\, \omega t$
10	$v(t) = 141\, sin\, \omega\, t + 34.6\, sin\, 3\, \omega t + 54.6\, sin\, 5\, \omega t$

Elements of laboratory settings

The laboratory setting consists of an investigation panel (transformer, diodes, and thyristor), voltmeters of electrodynamic, magnetoelectric,

magnetoelectric with rectifier, and digital systems, an oscilloscope, and a sound frequency generator.

The work execution order

1. Get acquainted with measuring devices of different systems from the investigation setup. Draw the legends (symbols) of different systems' measuring devices. What value does each voltmeter measure?
2. Connect voltmeters of different systems and the oscilloscope input (Fig. 2.1) to the sinusoidal voltage source of the research panel (terminals 3, 4) and record the voltage values and voltage waveforms. Write down the results of the measurements in Table 2.2.

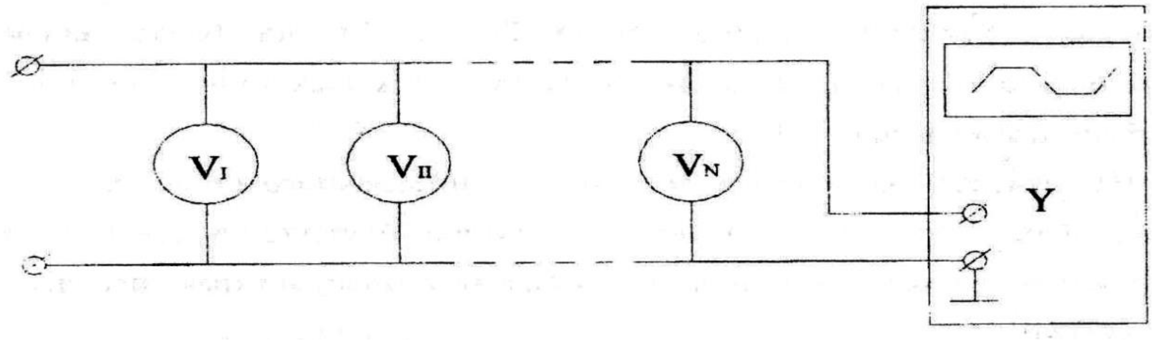


Fig. 2.1

3. Connect voltmeters of different systems and the oscilloscope input (Fig. 2.1) to other voltage waveform sources of the research panel (half-wave rectified voltage, full-wave rectified voltage, trapezoidal and rectangular voltages, full-wave rectified voltage for different cut-off angles). Record the voltage values and voltage waveforms. Write down the results of the measurements in Table 2.3.

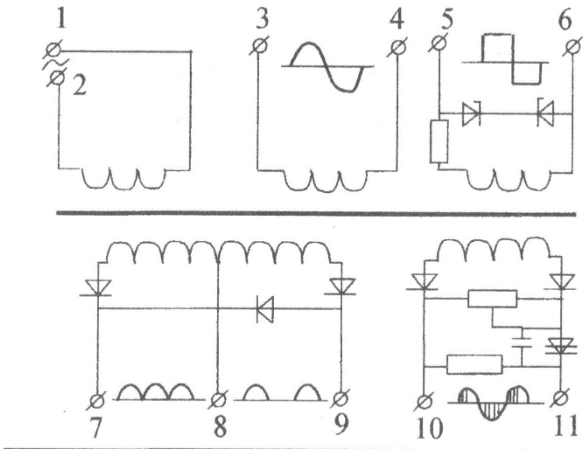


Fig. 2.2

4. Determine the amplitude, shape factor, distortion factor, and harmonic factors for all investigated voltage waveforms. Write down the results in Table 2.3.
5. Explain the differences in the readings of the different systems' measuring devices, depending on their principle of operation, calibration method, and the shapes of the voltage waveforms.

Table 2.3

№	Waveform	The voltage values				Factors			
		Amplitude	Effective	Av. for the half of period	Avg. for the	Amplitude	Shape	Distortion	Garmonics
1	2	3	4	5	6	7	8	9	10
1									
2									
3									
4									

5									
6									

6. Connect all voltmeters and the oscilloscope input to the output terminals of the sound frequency generator. Maintaining the voltage at the generator output equal to *10 V*, record the readings of all voltmeters in the frequency range from 25 Hz to 100 kHz. At each measurement, increase the generator frequency by a factor of two. Draw the graphs of the devices' readings versus frequency (on the abscissa axis, plot $log_2(f/f_1)$, where f is the generator frequency and $f_1=25\ Hz$).

7. Make conclusions.

Report on the work

The title and the purpose of the work. Homework. The schematic diagram of the investigated circuit (fig.2.2). The table 2.3. The graphs. The conclusions.

Control questions

1. Explain the calculation order for non-sinusoidal circuits.
2. Calculation features of reactances and susceptances for specific harmonics.
3. Write down the expressions for the effective (RMS) values of non-sinusoidal voltages and currents.
4. How to determine the effective (RMS) and average values of a non-sinusoidal voltage (current).
5. Explain the essence of the amplitude factor and the shape factor.
6. Explain the essence of the distortion factor and the harmonic factor.
7. What are the values of the amplitude factor and the shape factor for a sinusoidal waveform?
8. What are the values of the distortion factor and the harmonic factor for a sinusoidal waveform?
9. Write down the expressions to determine power in a non-sinusoidal circuit.

LABORATORY WORK 2.3

Investigation of transient processes in linear circuits

The purpose of the work. To investigate transient processes in first-order and second-order circuits with a DC source.

The transient processes occur when devices and circuits change their working regime. Transient processes may have negative effect in electrical engineering, but they can be useful in electronics.

The transient processes start at turning on/off the sources, changing the configuration of the scheme, circuit parameters, changing the current/voltage amplitude, phase, frequency or shape. Still the transient processes are typically caused by commutation (turning on/off the circuit).

The transient process is the process of transition from one energetic state of the circuit into another. This process cannot proceed stepwise, because the stock of energy can´t change abruptly. That's because the elements' values upon which the energy storage depends (*L*,*C*) don't allow to change current and voltage stepwise (i_L,v_C). Two main laws of transient processes come out from this point.

The first law states that the current through inductance just after the commutation $i_L(0+)$ is equal to the current through inductance just before the commutation $i_L(0-)$: $i_L(0+) = i_L(0-) = i_L(0)$.

The second law states that the voltage at capacity just after the commutation $v_C(0+)$ is equal to the voltage at capacity just before the commutation $v_C(0-)$: $v_C(0+) = v_C(0-) = v_C(0)$.

Initial conditions (voltage or current values at the commutation moment $t = 0$) are defined by these laws. The steady-state mode before the commutation is at $t < 0$. The steady-state mode after the commutation is after the transient process is over.

The transient process duration depends on the elements parameters. It is estimated as $t_{tr} = 5 \div 6\tau$, where τ is the time constant. It is time during which voltage or current changes *e*=2.7 times of its initial value.

The transient process can be described by linear differential equation, which is formed with the help of Kirchhoff's laws. Commutation laws should be used to solve this equation.

The partial solution of inhomogeneous differential equation is the steady-state component i_{SS} or v_{SS}. The general solution of homogeneous differential equation is the transient component i_T or v_T, which dies out with time. The solution of linear differential equation is current (voltage), which is equal to the sum of transient and steady-state components $i(t) = i_T + \mathrm{i}_{SS}$ ($v(t) = v_T + v_{SS}$). Therefore, to calculate transient process means to find the current or voltage changing rule.

Let's analyse the transient process when *RL* link is connected to DC source (fig.3.1). According the differential equation to the Voltage lawfor after commutation steady-state mode is: $Ldi/dt + Ri = V$. Its solution is $i(t) = i_T + \mathrm{i}_{SS}$. The partial solution i_{SS} of inhomogeneous differential equation $Ldi_{SS}/dt + Ri_{SS} =$

V is equal to the current value when transient process is over $i_{SS} = V/R$ (because $X_L = 0$ for DC).

i_T is the general solution of homogeneous differential equation $Ldi_T/dt + $

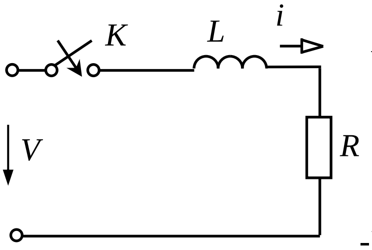


Fig.3.1

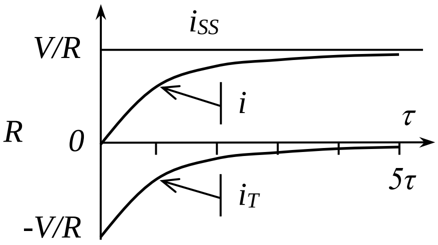


Fig.3.2

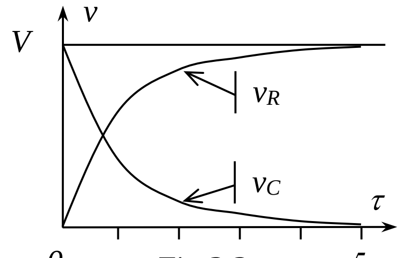


Fig.3.3

$Ri_T = 0$. The characteristic equation corresponding to this differential one is $pL + R = 0$ with its root $p = -R/L$. The time constant is $\tau = 1/p = L/R$. Since the characteristic equation has one real root, the transient component is $i_T = Ae^{pt}$. Constant of integration can be found from initial conditions: $i(0) = i_T(0) + i_{SS}(0) = A + V/R$. According to the first commutation law $i(0) = i(0-) = 0$, so $A = -V/R$, $i_T = -V/Re^{-(R/L)t}$.

The solution of differential equation is (fig.3.2):

$$i = i_T + i_{SS} = -V/Re^{-(R/L)t} + V/R = V/R(1 - e^{-(R/L)t}).$$

The voltage on resistive element is (fig.3.3):

$$v_R = Ri = R(V/R)(1 - e^{-(R/L)t}) = V(1 - e^{-(R/L)t}).$$

The voltage on inductive element is (fig.3.3):

$$v_L = L\frac{di}{dt} = L\frac{d}{dt}\left(\frac{V}{R}(1 - e^{-(R/L)t})\right) = L\frac{V}{R}(-\frac{R}{L}) \cdot (-e^{-(R/L)t}) = Ve^{-(R/L)t}.$$

Let's analyse the transient process when *RC* link is connected to DC source (fig.3.4). The differential equation according to the voltage law for after commutation steady-state mode is $Ri + v_C = V$, $i = C(dv_C/dt)$, then $RC(dv_C/$

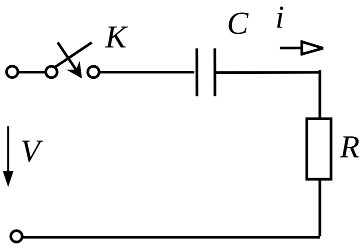


Fig.3.4

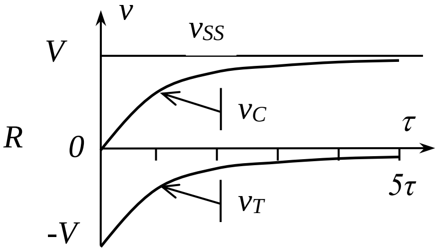


Fig.3.5

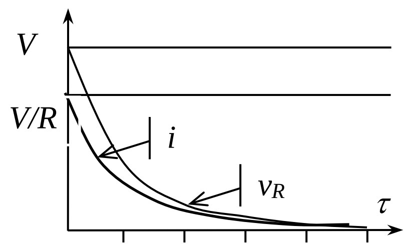


Fig.3.6

$dt) + v_C = V$. Its solution is $v_C = v_{CT} + u_{CSS}$. The partial solution v_{CSS} of inhomogeneous differential equation $RC(dv_C/dt) + v_C = V$ equals to the voltage value on *C* when the transient process is over. The circuit current equals zero in this case, because the input voltage is applied directly to capacitance $v_{CSS} = V$.

v_{CT} is the general solution of homogeneous differential equation $RC(dv_C/dt) + v_C = 0$. The characteristic equation corresponding to this differential one is $RCp + 1 = 0$ with its root $p = -1/(RC)$. The time constant is $\tau = 1/p = RC$. Since the characteristic equation has one real root, the transient component is $v_{CT} = Ae^{pt}$. Constant of integration can be found from initial conditions: $v_C(0) =$

$v_{CT}(0) + v_{CSS}(0) = A + V$. According to the first commutation law $v_C(0) = v_C(0-) = 0$, so $A = -V$, $v_{CT} = -Ve^{-t/RC}$.
The solution of differential equation is (fig.3.5):

$$v_C(t) = V - Ve^{-t/RC} = V(1 - e^{-t/RC}) = V(1 - e^{-t/\tau}).$$

The current is (fig.3.6):

$$i = C(dv_C/dt) = C\frac{d}{dt}\left(V - Ve^{-t/RC}\right) = -CV/(RC)(-e^{-t/RC}) = (V/R)e^{-t/RC}.$$

The voltage on resistive element is (fig.3.6):

$$v_R = Ri = R(V/R)(e^{-t/RC}) = Ve^{-t/RC}.$$

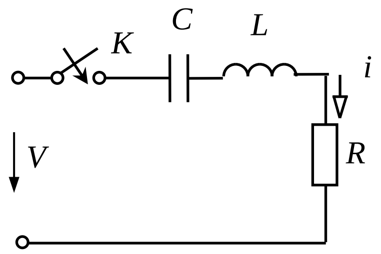


Fig.3.7

The transient process occurs in a *RLC* link that is switched on to a DC source (fig.3.7). According to the Kirchhoff's second law the differential equation for after commutation steady-state mode is: $v_L + v_C + v_R = V$. After the following substitution $v_L = L\frac{di}{dt}$, $v_R = Ri$, $v_C = \frac{1}{C}\int idt$ the final equation is $L\frac{di}{dt} + \frac{1}{C}\int idt + Ri = V$. After differentiation the second order equation is: $L\frac{d^2i}{dt^2} + R\frac{di}{dt} + \frac{1}{C}i = 0$, Since$dV/dt = 0$, the equation is a homogeneous one. It's solution is $i(t) = i_T + i_{SS}$, where partial solution i_{SS} is equal to the current value when transient process is over $i_{SS} = 0$ (because $X_C = \infty$ for DC). So $i(t) = i_T$. The characteristic equation corresponding to this differential one is $Lp^2 + Rp + 1/C = 0$. Its roots are $p_{1,2} = -\frac{R}{2L} \pm \sqrt{\frac{R^2}{(2L)^2} - \frac{1}{(LC)^2}}$. After substitutions $\delta = R/2L$ and $\omega_0 = 1/(LC)$, the equation makes $p_{1,2} = -\delta \pm \sqrt{\delta^2 - \omega_0^2}$. The character of transient process depends on circuit's parameters and the characteristic equation roots' characters. If they are real $\delta^2 - \omega_0^2 > 0$ and $p_1 \neq p_2$ the transient process is a capacitor aperiodic discharge. The capacitor is charging to the voltage V through the coil and resistor and then discharging to zero.

The general solution of homogeneous second order differential equation is $i_T = A_1e^{p_1t} + A_2e^{p_2t}$ (fig.3.8). The constant of integration is defined from initial conditions. The initial condition for the current (according to the first commutation law) is: $i(0) = i(0_-) = 0$. Thus $i(0) = i_T(0) = A_1 + A_2 = 0$ and $A_1 = -A_2$. The second initial condition is defined for the derivative $\left.\frac{di}{dt}\right|_{t=0} = \frac{di(0)}{dt}$ from differential equation $L\frac{di}{dt} + v_C + Ri = V$. For the time moment $t = 0$: $L\frac{di(0)}{dt} + v_C(0) + Ri(0) = V$. Taking into account that $v_C(0) = 0$ and $i(0) = 0$, the following is true $L\frac{di(0)}{dt} = V$, $\frac{di(0)}{dt} = V/L$.

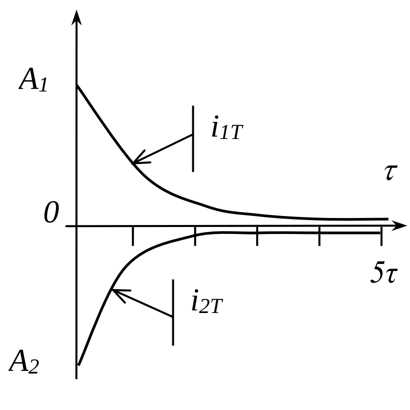


Fig.3.8

The following equation is to be resolved to define the constant of integration:

$\frac{di}{dt} = \frac{di_T}{dt} = \frac{d}{dt}(A_1 e^{p_1 t} + A_2 e^{p_2 t}) = A_1 p_1 e^{p_1 t} + A_2 p_2 e^{p_2 t}$ At the moment $t = 0$ $\frac{di(0)}{dt} = \frac{di_T(0)}{dt} = A_1 p_1 + A_2 p_2 = \frac{V}{L}$.
Taking into account that $A_1 = -A_2$ the following is true $A_1 = -A_2 = V/L(p_2 - p_1), = V/(2L\sqrt{\delta^2 - \omega_0^2})$. Thus, the current is: $i = i_T = \frac{V}{2L\sqrt{\delta^2 - \omega_0^2}}(e^{p_1 t} - e^{p_2 t})$.

The transient current consists of two exponential constituents $i = i_T = A_1 e^{p_1 t} + A_2 e^{p_2 t} = i_{1в} + i_{2в}$.

If the characteristic equation roots are real $\delta^2 - \omega_0^2 = 0$ and equal $p_1 = p_2$, the transient process is the capacitor aperiodic boundary discharge $p_1 = p_2 = p = -\delta$.

The general solution of homogeneous second order differential equation is $i_T = (A_1 + A_2 t)e^{pt}$. From initial conditions $i(0) = 0$ and $\frac{di(0)}{dt} = V/L$ the constant of integration is defined as $i(0) = i_T(0) = A_1 = 0$. Taking into account that $\frac{di_T}{dt} = A_2 e^{pt} + A_2 pte^{pt}$, the following is true $\frac{di_T(o)}{dt} = A_2 + A_2 p = \frac{V}{L}$, $A_2 = \frac{V}{L(1+p)}$. Thus, $i = i_T = \frac{V}{L(1-\delta)} te^{-\delta t}$.

If the characteristic equation roots are complex-conjugates $\delta^2 - \omega_0^2 < 0$, the transient process is a damped oscillatory process and the capacitor periodically discharges to the coil. The characteristic equation roots are

$$p_{1,2} = -\delta \pm j\sqrt{\omega_0^2 - \delta^2},$$

After the substitution $\sqrt{\omega_0^2 - \delta^2} = \omega_T$, the roots are $p_{1,2} = -\delta \pm j\omega_T$

The general solution of homogeneous second order differential equation for complex-conjugates roots is $i = i_T = Ae^{-\delta t} \sin(\omega_T t + \varphi)$. From initial conditions $i(0) = 0$ and $\frac{di(0)}{dt} = V/L$ the constant of integration A and angle φ are defined. $i(0) = i_T(0) = A \sin\varphi = 0$, so, $\sin\varphi = 0$, $\varphi = 0°$.

$$\frac{di}{dt} = \frac{di_T}{dt} = -A\delta e^{-\delta t} \sin(\omega_T t + \varphi) + A\omega_T e^{-\delta t} \cos(\omega_T t + \varphi),$$

$$\frac{di(0)}{dt} = \frac{di_T(0)}{dt} = -A\delta \sin\varphi + A\omega_T \cos\varphi = A\omega_T = V/L.$$

Therefore, $A = V/(L\omega_T)$, $i = i_T = \frac{V}{L\sqrt{\omega_0^2 - \delta^2}} e^{-\delta t} \sin(\sqrt{\omega_0^2 - \delta^2}\, t)$.

Homework

Define the capacitor transient voltage expression for the circuit at fig.3.7 when the key switch on. Tasks variants are listed in the table 3.1.

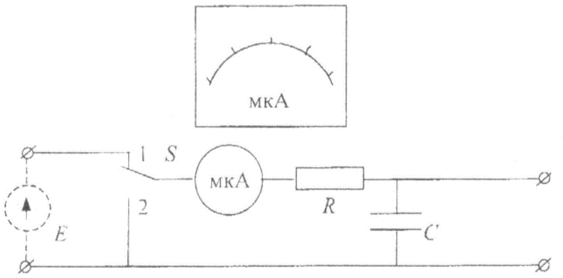
Table 3.1

Var	1	2	3	4	5	6	7	8	9	10
E,V	10	8	6	12	14	16	18	20	5	4
R, Ω	300	200	100	400	500	600	700	800	80	60
C, μF	300	200	100	400	500	600	700	800	200	100
L, H	0.05	0.04	0.03	0.06	0.07	0.08	0.09	0.1	0.02	0.01

Elements of laboratory settings

The laboratory setting consists of two investigation panels: one for investigating first-order circuits and another for second-order circuits.

The work execution order



Research the first order circuit (with one reactive element).

1. Write down the characteristic equation for the circuit shown in Fig. 3.4. Define its root and the constant of integration, taking into consideration the measured values of *R* and *V* for charging and discharging the capacitor.

2. Fill in Table 3.2 with the current values for charging and discharging the capacitor. The time interval should be *10 s*, ranging from *0* to *100 s*.

Table 3.2

t, s	*I*	*I*
0		
10		
20		
30		
40		
50		
60		
70		
80		
90		
100		

3. Draw the graphs of the capacitor's charging and discharging processes. Define the transient process time constant graphically and then determine the capacitance value using the formula $\tau=RC$. Compare the calculated and the nominal (real) capacitor values.

4. Make conclusions about the characteristics of the transient process.

Research the second order circuit (with two reactive elements).

1. Write down the characteristic equation for the circuit shown in Fig. 3.7. Define its roots and analyze them for real or complex values.

2. Assemble the circuit (Fig. 3.9). The parameters of the circuit are provided by the instructor.

3. Record the transient process waveform of the circuit. Define the angular frequency of free oscillations $\omega_0=2\pi/T$ and the damping coefficient δ using the relation $\delta=1/t$.

4. Compare the experimentally obtained and calculated values of ω_0 and δ.

5.Increase the active resistance value of the loop to *200 Ω* and repeat steps 3 and 4. Determine experimentally the critical resistance value at which the oscillating free process transitions to an exponentially decaying one. Compare this experimental result with the calculated result (for *D=0*).

6. Determine the capacitor voltage steady-state value v_{CSS} using the transient process waveform. Compare it with the measured DC voltage value *V*.

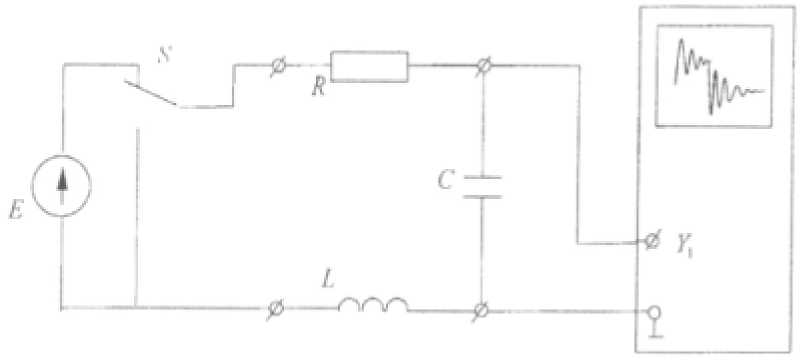


Fig.3.9

7. Make conclusions about the characteristics of the transient process.

Report on the work

The title and the purpose of the work. Homework – the calculation of the circuit. The schematic diagrams of the investigated circuits (fig 3.4 and 3.7). The table 3.2. The results of calculations. The graphs. The conclusions.

Control questions

1.Give the definition of transient processes. Explain the reasons for transient processes.

2. Explain the commutation laws.

3. What methods are used to calculate transient processes?

4. Explain the essence of the classical method for calculating transient processes.

5. Explain the essence of the transient and steady-state components of a transient process.

6. How can we write down the characteristic equation of a circuit? Give examples.

7. Characterize the transient process based on the values of the roots of the characteristic equation for first-order and second-order circuits.

8. Explain how to define the integration constant in the classical method.

9. How can we define the transient process time constant analytically and experimentally for first-order and second-order circuits?

LABORATORY WORK 2.4

Investigation of the inductive coil with ferromagnetic core at DC and AC circuits

The purpose of the work. To investigate the inductive coil with ferromagnetic core at DC and AC circuits, define the coil parameters and investigate its current-voltage characteristics.

The electromagnetic device consists of electric and magnetic circuits. The electric circuit consists of winding with a current that excites the magnetic field with the tension H. The magnetic circuit in electrical devices is the way in which magnetic field lines are closed. The magnetic circuit has a desired configuration and is characterized by induction of the magnetic field *B*. Magnetic circuit is a combination of magnetic and non-magnetic areas, which close the magnetic flux.

The magnetic field in devices with constant magneto-motive force (m.m.f.) is created by a permanent magnet or a DC powered electromagnet.

Magnetic circuits don't have air gaps in electrical converters like transformers, magnetic amplifiers, etc. However, air gap is required for electromechanical power converters like relays, contactors, solenoids, starter,

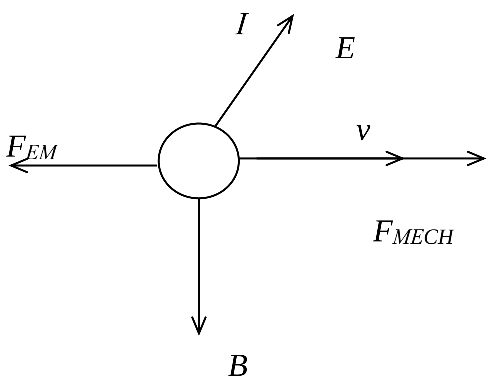


Fig. 4.1

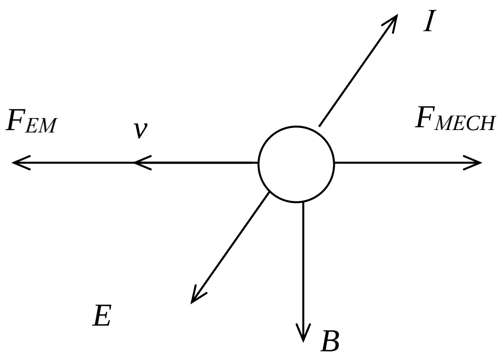


Fig. 4.2

electric cars, some measuring devices, etc.

The magnetic field is represented by magnetic field lines, which look like concentric circles. The direction of the lines is determined by the rule of the right screw.

According to the law of electromagnetic induction, a moving in a magnetic field conductor induces electromotive force $E = Bl\upsilon$, where l is the length of the conductor; v - speed of its movement and B - the magnetic field induction. The direction of the electromotive force is determined by the right hand rule (fig.4.1).

By the electromagnetic force law (Ampere's law), the force acting on the current-carrying conductor, which moves in a magnetic field, makes $F = BlI$, where l is the conductor length. The direction of the electromagnetic force is determined by the left-hand rule (fig.4.2). Induced in the conductor electromotive force *E* is directed to suppress the current I.

Magnetic induction *B (T)* describes the intensity of the magnetic field and the magnetic flux *Φ (Wb)* is an integral characteristic of the magnetic field. The magnetic field is considered to be uniform if the magnetic induction at all points of the field is the same ($B = const$). Magnetic flux of uniform magnetic field passing through the surface *S*, placed perpendicular to the lines of magnetic induction is $\Phi = BS$.

Total current law in integral form is: $\oint \overline{H}\, d\,\overline{l} = \int H \cos\alpha\, d\,l = \sum I$, which means that the circulation of magnetic field tension vector *H* along the closed path *l* is equal to the algebraic sum of currents encircled with this path. The magnetic circuit is homogeneous if the magnetic induction is the same along the magnetic circuit. Total current law for homogeneous and heterogeneous (with air gap) magnetic circuits is: $H\,l = wI$, $\quad H\,l + H_\delta \delta = wI$, where H is the magnetic field tension in the magnetic circuit with length *l*; H_δ - the magnetic field tension in the air gap δ; w - the number of winding turns and $wI = F$ - a magneto-motive force. The coil linkage is $\Psi = LI = w\Phi$.

Magnetic permeability μ describes the properties of the conducting medium,

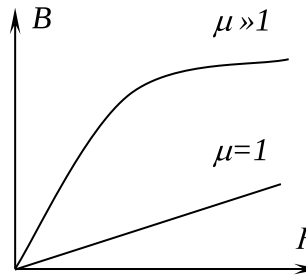


Fig. 4.3

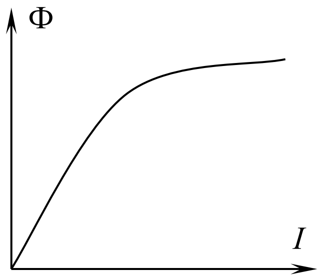


Fig. 4.4

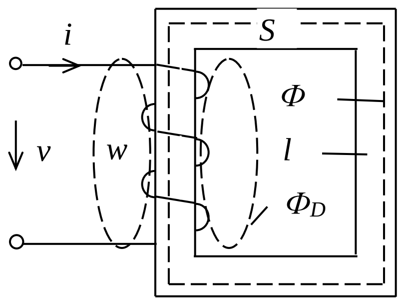


Fig. 4.5

which shows how many times the medium increases the magnetic field of the coil. Diamagnetics and paramagnetics belong to nonmagnetic materials, where $\mu_r = 1$ and ferromagnetics belong to magnetic materials, where $\mu_r >> 1$. Magnetic induction *B* is connected with magnetic field tension *H* by the following equation: $B = \mu_0 \mu_r H$, where relative magnetic permeability μ_r, vacuum magnetic permeability $\mu_0 = 4\pi \cdot 10^{-7}$. So, the magnetic resistance is $R_m = l/(\mu_0 \mu_r S)$.

Magnetic flux will be much larger in a coil with the ferromagnetic core than in a coil without it, as the flux is created not only by the current but also by the ferromagnetic substance of magnetic circuit.

The magnetic characteristics $B(H)$ for magnetic ($\mu >> 1$) and nonmagnetic ($\mu = 1$) materials are shown in fig. 4.3. Given that the magnetic flux is proportional to the magnetic induction $\Phi \equiv B$, and the current proportional to the magnetic field tension $I \equiv H$, a dependence $\Phi(I)$- or so called weber-ampere characteristic can be obtained (fig. 4.4). As can be seen from it, an additional core of magnetic (ferromagnetic) material is required to reduce the current needed to generate a given magnetic flux of the coil.

The coil electromagnetic circuit is shown in fig.4.5. Applied to the coil voltage v initiates current i, which results in a magnetic flux. Magnetic flux Φ is the vector sum of the main magnetic flux Φ_o, which is closed through the core, and the magnetic flux of dissipation Φ_D, which closes in the air around the coils $\underline{\Phi} = \underline{\Phi}_o + \underline{\Phi}_D$. Dissipation magnetic flux is not involved in energy transmission (in transformers). The core permeability ($\mu >> 1$) is much higher than air permeability ($\mu = 1$), that means $\Phi_o >> \Phi_D$, but the magnetic fluxes can shift the phase.

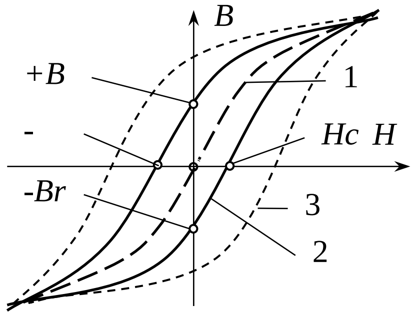


Fig.4.6

The basic magnetization curve (curve 1 in big dashed line on fig.4.6) passes through the center of coordinate grid. When the coil is powered by alternating voltage the magnetic flux changes in time and core is cyclically re-magnetized. After several AC periods a closed symmetrical across the origin hysteresis loop is set (curve 2 in solid lines fig.4.6), which is called the static hysteresis loop. A residual induction in the core B_r is stored at $H = 0$. $H = H_C$ at $B = 0$ and it is called a coercive (holding) force.

The magnetic losses in the core ΔP_{M} consist of magnetic hysteresis losses ΔP_H and eddy current losses ΔP_E: $\Delta P_{\mathrm{M}} = \Delta P_H + \Delta P_E$. Hysteresis losses are the losses due to the cyclical magnetization of the core and they are proportional to the area embraced by static hysteresis loop. These are determined by the formula: $\Delta P_H = \gamma_H \sigma f B_m^2$,
where $\gamma_H$are specific power losses for hysteresis; σ - magnetic circuit mass; f - current frequency; B_m - magnetic induction amplitude. To reduce the magnetic hysteresis losses the magnetic circuits are made of soft magnetic (ferromagnetic) materials, which have a narrow hysteresis loop.

Eddy currents occur in solid metal parts as a result of the magnetic field.

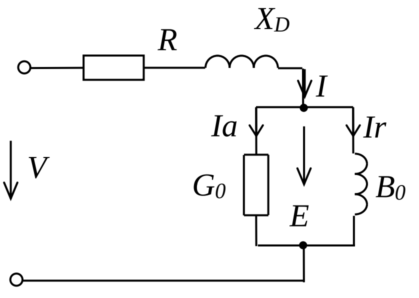


Fig. 4.7

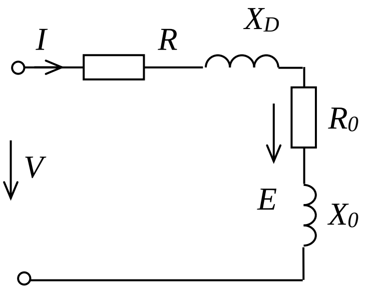


Fig. 4.8

Eddy currents losses occur when the coil is fed with AC, which demagnetize the magnetic circuit. Eddy currents losses are proportional to the difference between the areas of dynamic (curve 3 in small dash line) and static (curve 2 in solid line) hysteresis loops. They are determined by the formula:

$$\Delta \rightleftarrows P_E = \gamma_E \sigma f^2 B_m^2,$$

where $\gamma_E$are specific power losses for eddy currents; σ - magnetic circuit mass; f - current frequency; B_m - magnetic induction amplitude. To reduce eddy currents losses the magnetic cores are collected from thin electrical steel plates (or tape) with a thickness of 0.2 - 0.5 mm, which are isolated from each other by dielectric layers.

Fig. 4.7 shows a series-parallel equivalent circuit of the coil with core, where $\Delta P_E = R\,I^2$ are electrical losses in the coil winding; $X_D = \omega L_D$- coil reactance caused by dissipation; L_D - inductance, equivalent to the dissipation magnetic flux Φ_D; G_0- the conductance, equivalent to core magnetic losses $\Delta P_M = G_0\,E^2$; B_0 - susceptance, equivalent to the main magnetic flux Φ_0.

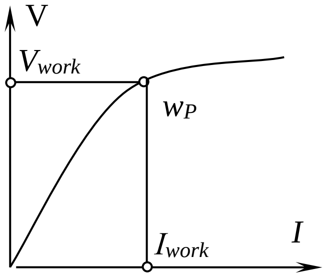


Fig. 4.9

Fig. 4.8 shows a serial equivalent circuit of the coil, where $\underline{V} = -\underline{E} + R_0\underline{I} + jX_0\underline{I}$.Vwo

Electromotive forces induced by the main magnetic flux are:

$$e = -w\,d\Phi / dt, \qquad E = \omega w\,\Phi_m / \sqrt{2} = 4.44 fw\,\Phi_m \;.$$

Electromotive forces induced by the dissipation magnetic flux are: $e_D = -L_D di/dt$, . $\underline{E}_D = -j\omega L_D I = -X_D\underline{I}$.

The equation of electric state of the coil is written by the second Kirchhoff 's law in complex form: $\underline{V} = -\underline{E} + R\underline{I} + jX_D\underline{I}$.

Current-voltage characteristic *V(I)* (fig. 4.9) of the coil is derived from weber-voltage characteristic $\Phi(I)$. By zooming magnetic flux $\Phi \equiv E \approx U$ curve *V(I)* is obtained, which coincides with the curve $\Phi(I)$.

Working point (*wp*) for the coil is chosen at the bent-point of current-voltage characteristic. When chosen below that point the magnetic circuit is irrationally used – it is increased in size. When chosen above that point, the electrical losses are increased due to the increased current.

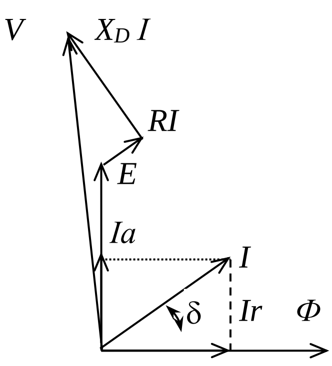


Fig.4.10

Neglecting the relatively small resistances R, X_D (fig. 4.7), the following can be taken approximately $\underline{V} \approx \underline{E}$ and if $E \equiv \Phi$, so $U \approx E \equiv \Phi$. When the voltage is sinusoidal, electromotive force and magnetic flux are also sinusoidal. It follows from weber-current non-linear characteristic $\Phi(I)$ that the coil current is non-sinusoidal at sinusoidal magnetic flux. When analyzing non-sinusoidal current the first and third harmonics are taken into consideration: $i = I_{1m}\sin\omega_1 t + I_{3m}\sin\omega_3 t$.

To simplify the analysis of the coil with non-sinusoidal current it is substituted by the equivalent sinusoidal current $i = I_m\, sin(\omega t + \delta)$ with amplitude $I_m = \sqrt{I_{1m}^2 + I_{3m}^2}$ and frequency $\omega = \omega_1$. Magnetic flux lags behind the phase of current at an angle δ (angle of the magnetic delay or magnetic losses) due to hysteresis effects.

The vector diagram of the coil (fig.4.10) corresponds to the electrical state equation $\underline{V} = \underline{E} + R\underline{I} + jX_D\underline{I}$. The current at vector diagram is represented by active I_a and reactive I_r components according to the equivalent scheme (fig.4.7).

If the magnetic circuit has the air gap (magnetic circuit is non-homogenous) the magnetic resistance increases significantly. Therefore, it leads to a reduction of magnetic flux according to the full current law. However, this does not happen, because the magnetic flux is constant at constant voltage. The amplitude of the magnetic flux in electromagnetic devices does not depend on the size of the air gap, but the current effective value in the coil depends on it. Thus, the coil starting current for the core with an air gap is much greater than nominal current.

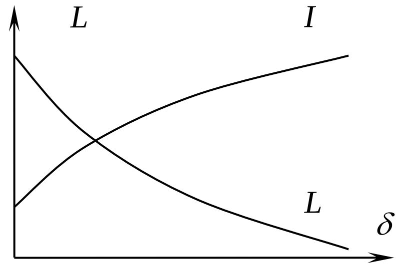


Fig. 4.11

The dependence of coil inductance and current from size of air gap is shown at fig. 4.11. Air gap δ can change its value by changing resistances at AC circuits. The air gap is unavoidable in brake solenoids, relays, contactors, etc.

The variable inductance coil (by change of the air gap) is used to adjust the AC at welding machines and electric ovens. Electromagnetic system of variable inductance coil includes a rod (stationary part) on which a coil is placed (inductor), armature (moving part) and a yoke for connection the rod and the armature in a closed magnetic system. Electromagnets are used in cranes, drive brakes, clutches, electrical switching equipment, measuring devices, machines, relays, etc. The air gap is undesirable in some cases (like transformers, AC engines), since it leads to the current increase, the winding dimensions, reactive power consumption and electromagnetic devices $cos\varphi$ reduction.

Homework

To calculate magneto-motive force *F*, magnetic field tension *H*, magnetic flux *Φ*, magnetic resistance R_m, coil induction *L* for the coil with toroidal ferromagnetic core at given medial line magnetic circuit length *l*, cross-section area *S*, coil current *I*, number of winding turns *w*, steel relative magnetic permeability μ_r, vacuum magnetic permeability μ_0=4π·10^{-7} . Tasks variants are listed in the table 4.1.

Table 4.1.

Var.№	1	2	3	4	5	6	7	8	9	10
I ,A	0.5	0.7	1	1.2	1.4	1.6	1.8	2.	2.2	2.4
w	30	40	50	60	70	80	90	100	120	110
l, sm	20	19	18	17	16	15	14	12	11	10
S, sm^2	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4
μ_r	950	850	900	800	700	600	200	300	400	500
$P_{П}$*,Bm*	6.75	10.15	2.52	9.8	20.25	8	2	6.25	14.4	3.2
$I_{П}$*,A*	1.5	1.3	0.6	1.4	1.5	2	0.5	1.25	1.2	0.8
V,B	50	60	70	80	100	90	65	75	90	110
I_3*,A*	0.7	1	1.1	1.2	1.5	1.6	0.8	0.9	1.3	1.4
P_3*,Bm*	20	35	40	45	60	25	35	30	50	55

Elements of laboratory settings

The laboratory setup consists of the investigated coil with a demountable core; an autotransformer 0 ... 36 V; an autotransformer 0 ... 230 V; a multimeter to measure voltage; an ammeter with a measuring limit of 2 A; and a wattmeter.

The work execution order

1 Measure the active resistance of the coil using a multimeter or the ammeter-voltmeter method.

2. Assemble the circuit (Fig. 4.12). Changing the current from 0 to 1.75 A in steps of 0.25 A,

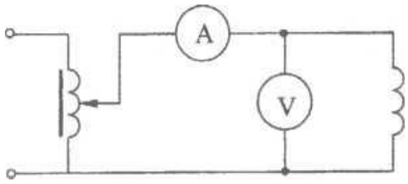


Fig.4.12

Table 4.2

		Measuring						
	I, A	0.25	0.5	0.75	1	1.25	1.5	1.75
1	*V, V*							
2	*V, V*							
3	*V, V*							
4	*V, V*							
5	*V, V*							
6	*V, V*							
7	*V, V*							

record the volt-ampere characteristics of the coil: without the core (line 1); with direct cores (line 2); with the U-shaped core (line 3); with a closed U-shaped core and two non-magnetic gaps (line 4); and with a closed U-shaped core without non-magnetic gaps (line 5). Fill in Table 4.2 with the results.

3.Repeat the previous experiment with the yoke rotated 90º relative to the longitudinal axis (line 6).

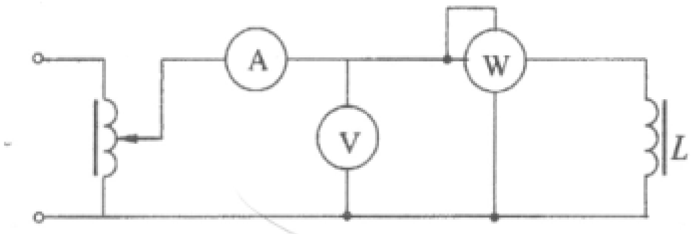


Fig.4.13

4. Repeat the same experiment with the yoke of cast steel (line 7).

5. Draw family of volt-ampere characteristics (VAC) of the coil.

Table 4.3

		1	2	3
Meas.	*V, V*			
Meas.	*P, W*			

6. Assemble the circuit (Fig. 4.13) and conduct the same experiments as in item 2 for a current of 1.75 A for the coil with the core without any gap. Fill in Table

4.3 with the results (with straight cores (column 1), with the U-shaped core (column 2), and with a closed U-shaped core without non-magnetic gaps (column 3)). Determine the parameters of the coil's equivalent circuit. Compare the losses for all experiments.

7. Draw the coil's equivalent circuit for the closed U-shaped core without non-magnetic gaps for a current of 1.75 A.

8. Analyze the results and make conclusions.

Report on work

The title and purpose of the work. The schematic diagram of the investigated circuit (fig.4.13). The tables 4.2, 4.3. The graphs. Calculations. Coil substitutional scheme. Conclusions.

Control questions

1. Explain the principle of electromagnetic devices and the roles of their components.
2. State the law of electromagnetic induction. What affects the value and direction of the electromotive force?
3. State the law of electromagnetic force. What affects the value and direction of the electromagnetic force?
4. Write down full current law expression for the inhomogeneous magnetic circuit and explain the difference between the intensity and induction of magnetic field.
5. Draw a diagram of the electromagnetic induction coil with a core. What are the losses in the coil and the core?
6. What are the losses in ferromagnetic core and how they can be reduced?
7. Draw a coil series-parallel substitutional scheme and explain the physical meaning of its elements.
8. Write down the e.m.f. instantaneous and effective values expressions, induced by coil main and dissipation magnetic fluxes.
9. Write down coil electrical state equation and draw a vector diagram.

LABORATORY WORK 2.5

Investigation the characteristics and properties of non-linear resistive elements at DC circuits.

The purpose of the work: to investigate the current-voltage characteristics of linear and nonlinear electrical circuits elements, to draw the resulting characteristics of their scheme combinations, investigate the possibilities of non-linear elements practical using at DC circuits.

Non-linear circuits consist of one or more non-linear elements. We call an element non-linear when its resistance is not constant and depends on voltage, current, temperature, light, etc. The current-voltage characteristic (*IV* curve) $V(I)$ is the main characteristic of non-linear element and it's non-linear (fig.5.1).

There are non-controlled and controlled non-linear elements. Non-controlled elements have two clamps (lamps, diodes), controlled elements have three or more clamps (transistors, thyristors). *IV* curve of non-linear elements may be symmetrical or non-symmetrical. If the resistance of the element doesn't depend on the direction of the current and the polarity of voltage then the characteristic is symmetrical ($V(I)=-V(-I)$). We can present *IV* curve by graphs, tables or formulas $V(I)$.

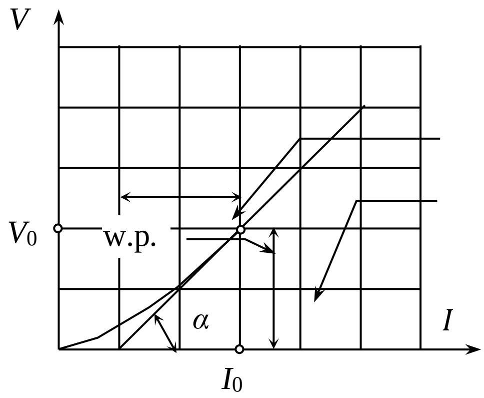


Fig.5.1.

Non-linear circuits can be calculated by analytical or graph methods. If we use graph method we define the voltage and current of the circuit using IV CURVEs of the elements. We can use Ohm's and Kirchhoff's laws as well. Analytical methods (two nodes method and equivalent generator method, replacing several parallel-connected branches with one equivalent) can be used when the *IV* curve is presented by a formula.

Non-linear element is characterized by static and dynamic resistance. We can calculate them for every point of *IV* curve (at fig. 5.1 for work point – w.p.):

$$R_S = V_0/I_0, R_\partial = \Delta V/\Delta I = dV/dI = tg\alpha,$$

α– the angle between axe X and tangent to working point (w.p.). $R_S > 0$, $R_д > 0$ when *IV* curve rise and $R_\partial < 0$ when *IV* curve drops.

Volt-ampere characteristics (*IV* curve) of different types of resistors are shown in Fig. 5.2.

Characteristics like those in Fig. 5.2a are typical for incandescent lamps with a metallic filament. When the current through the filament increases, it heats up more, and its resistance also increases. This characteristic is symmetrical.

Characteristics like those in Fig. 5.2б are typical for some types of thermistors and incandescent lamps with a carbon filament. When the current through the filament increases, its resistance decreases. This characteristic is also symmetrical.

Characteristics like those in Fig. 5.2в are typical for a barretter, which is used to stabilize the current of the filament of electronic lamps when the supply voltage fluctuates. This characteristic is also symmetrical.

Characteristics like those in Fig. 5.2г are typical for semiconductor diodes (silicon, germanium). They pass current in only one direction. This characteristic is non-symmetrical.

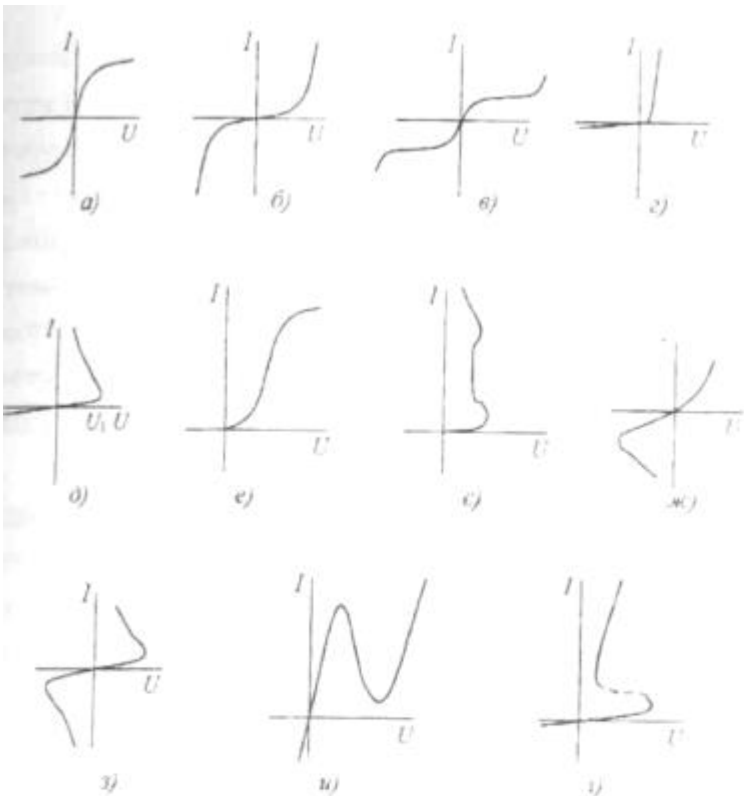


Fig.5.2.

Characteristics like those in Fig. 5.2d are typical for an electric arc with different electrodes and some types of thermistors. When the voltage increases from zero, the current increases very slowly and remains very small. After reaching a certain voltage U_1, the current increases sharply, and the element voltage decreases (for this part of the characteristic, the dynamic resistance is negative).

Characteristics like those in Fig. 5.2e are typical for a two-electrode rectifier tube – a kenotron. Those in Fig. 5.2f are typical for lamps with a glow discharge (gas stabilizers and neon lamps). Those in Fig. 5.2g are typical for some types of point-contact germanium and silicon diodes. An electric arc between symmetric electrodes made from the same material and under the same conditions has a *IV* curve like the one in Fig. 5.2h. The *IV* curve of a tunnel diode is shown in Fig. 5.2i, and in Fig. 5.2j is the *IV* curve of a four-layer germanium (silicon) thyristor-dinistor.

Electrical circuits with non-linear elements can be analyzed using the graphical method (for simple circuits) and the analytical method (for complex circuits). For the graphical method, the currents and voltages of a non-linear circuit are determined using the *q* curve of the elements in that circuit (Fig.5.3).

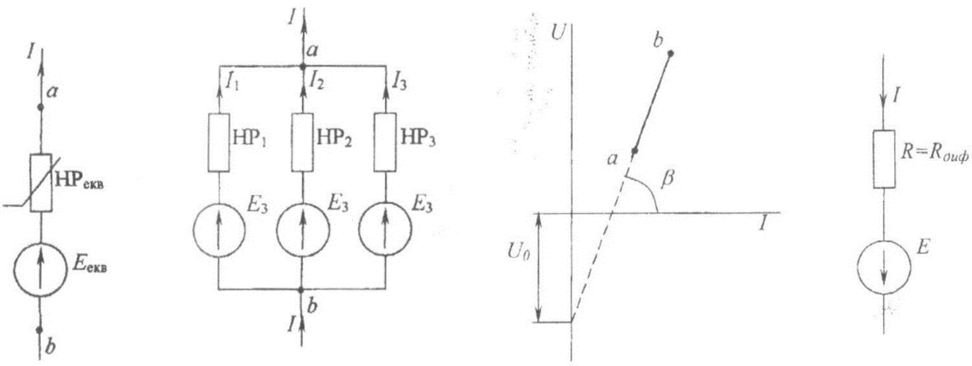


Fig.5.3

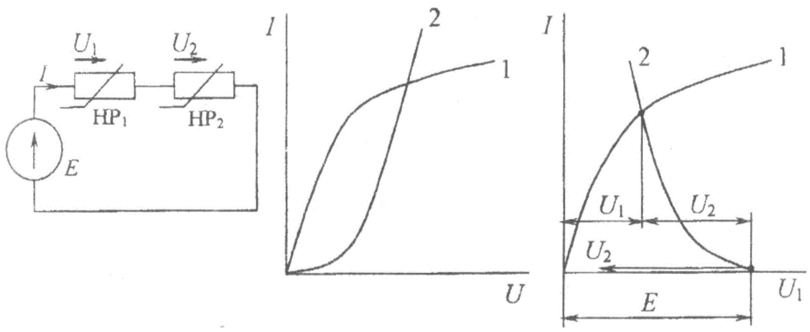


Fig.5.4

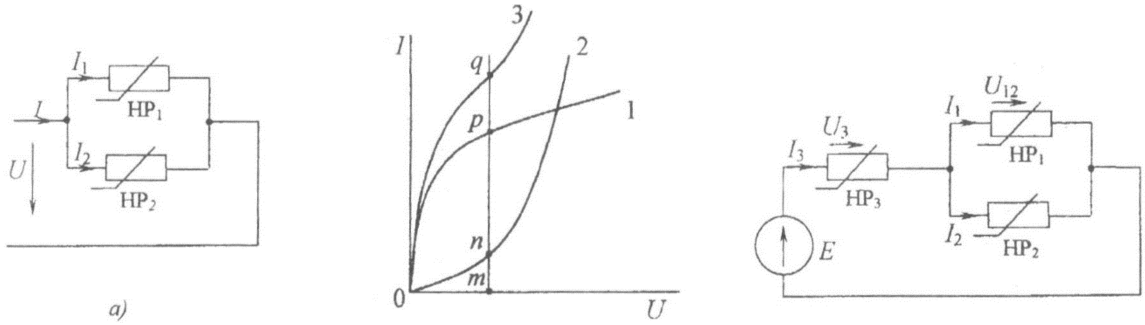


Fig.5.5

With a series connection of non-linear elements (fig.5.4) $R_1(I)$ and $R_2(I)$ we add the voltages V_1 and V_2 on the current-voltage characteristic (*IV* curve) at each current value *I*, and thus obtain the resulting *IV* curve for the series connection (fig.5.4) $V(I)=V_1(I)+ V_2(I)$.

With a parallel connection of non-linear elements (fig.5.5) $R_1(I_1)$ and $R_2(I_2)$ we add the currents I_1 and I_2 on the current-voltage characteristic (*IV* curve) at each voltage value *V*, and thus obtain the resulting *IV* curve for the parallel connection (fig.5.5) $I(V)=I_1(V)+ I_2(V)$.

With a mixed connection of non-linear elements (fig.5.5) $R_1(I_1)$, $R_2(I_2)$ and $R_3(I_3)$ we first add the currents I_2 and I_3 on the *IV* curve at each voltage value *V*, and thus obtain the resulting *IV* curve for the parallel connection $I_{12}(V_{12})=I_1(V_1)+ I_2(V_2)$. Then for series connection of $R_3(I_3)$ and $R_{12}(I_{12})$ add the voltages V_{12} and V_3) at each current value I_{12} , and thus obtain the resulting *IV* curve for the mixed connection $V(I)=V_{12}(I_{12})+ V_3(I_3)$.

When the linear element *R* is connected in serial with non-linear R_{HP} (fig.5.4), the working point define according voltage law. $E=V_{HP}+RI$, or $V_{HP}(I)= E - RI$ –non-linear element voltage.

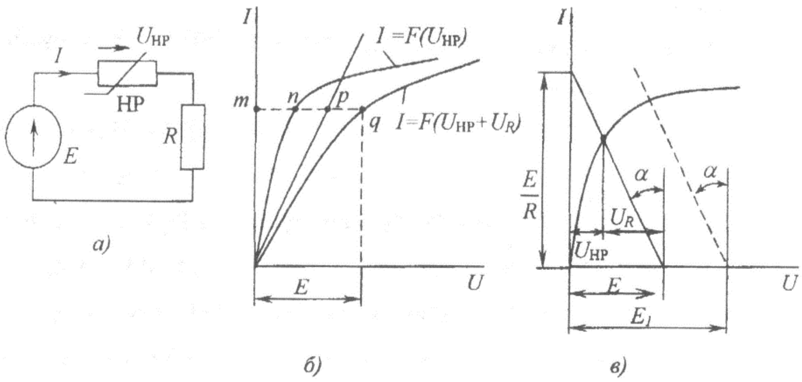


Fig.5.4

Homework

Define graphically the current of the non-linear element in the circuit (Fig. 5.5). The *IV* curve of the element is shown in Fig. 6.6. Task variations are listed in the table 6.1.

Table 5.1

Var	1	2	3	4	5	6	7	8	9	10
R, Ω	2.5	10	15	10	30	70	14	42	100	5
E, *V*	2	4	10	3	5	7	9	11	12	1

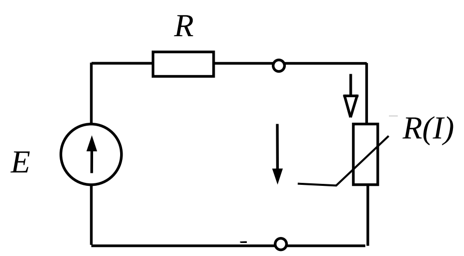


Fig.5.5.

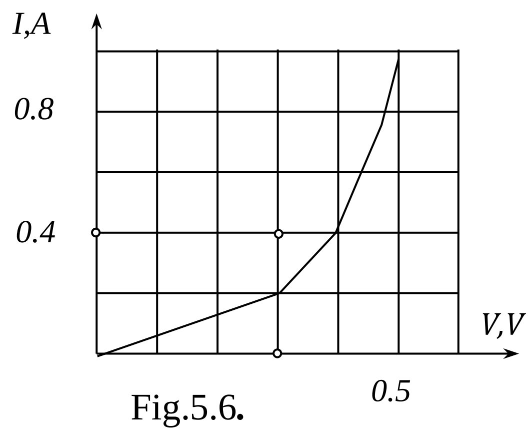


Fig.5.6.

Elements of laboratory settings

Laboratory setup consists of a set of non-linear elements with different *IV* curves, an adjustable power supply, ammeters, voltmeters, and a potentiometer for DC voltage adjustment.

The work execution order

1.To obtain the characteristics for both forward and reverse polarity of their connection. The investigated circuit is shown in Fig. 5.7. Record the results in Table 5.2.

Table 5.2

Element	*V,V*									
Resistor	*I,A*									
Diod	*I,A*									
LED	*I,A*									
Thyristor	*I,A*									

Draw *IV* curve of investigated elements.

2. Experimentally obtain the characteristics of series and parallel connections of the elements. Plot the characteristics of the series and parallel connections of the elements using the characteristics obtained in item 1. Compare the results.

3. Investigate the possibility of using the non-linear element (diode) to stabilize the DC voltage using the circuit shown in Fig. 5.8.

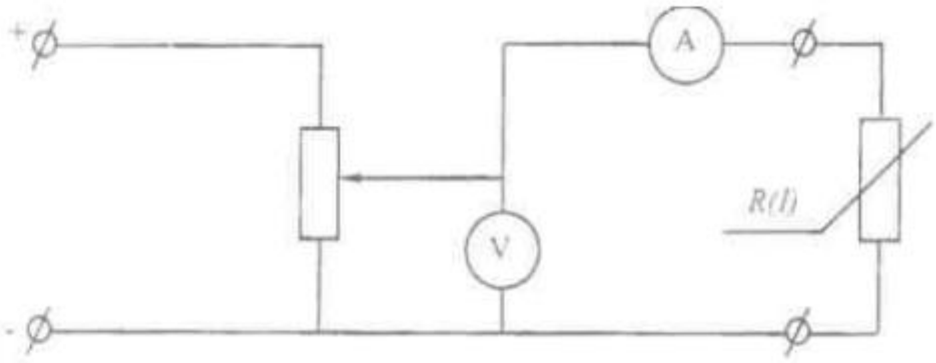


Fig.5.7.

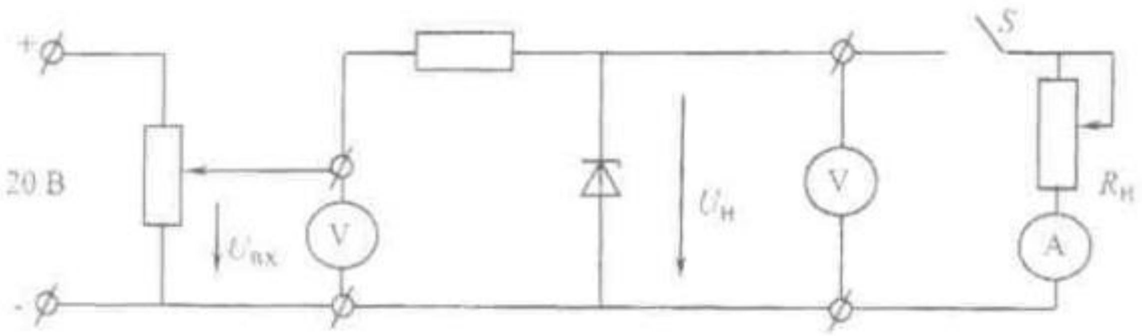


Fig.5.8

For the nominal input voltage define the range of load currents from *0* to I_{max} for which the load voltage will be stable $V_{load}=V_{st}$ (the diode stabilization voltage) . $\Delta V_{load}=0.05V_{st}$. Change the current by varying the load resistance.

For a constant load current $I_{load}= I_{max}/2$ find the range of input current for which $V_{load}=V_{st}$ $(\Delta V_{load}=0.05V_{st})$.

Make the conclusions.

Report on work

The title and purpose of the work. The schematic diagrams of the investigated circuits (fig.5.7 and 5.8). Table 5.2. The *IV* curves of the elements and the *IV* curves of their connections. The current range for voltage stabilization. Conclusions.

Control questions

1. What elements are non-linear?
2. Explain the classification of non-linear elements.
3. What characteristics are symmetrical and non-symmetrical? Give examples.
4. Give examples of several non-linear elements and their *IV* curves.
5. Explain the essence of static and dynamic resistance on the graph and write down the expressions.
6. Explain when dynamic resistance is positive and negative. Give examples.
7. What are the main methods of calculating circuits with non-linear elements?
8. Explain the essence of the graph-analytical method using an example of a series (parallel or mixed) connection of non-linear elements.

9. How can we use a non-linear element for voltage and current stabilization?

LABORATORY WORK 2.6
Investigation
of linear passive four-pole

The purpose of the work. To study the properties of a four-pole, experimentally determine its parameters, characteristic impedance, phase constant, and attenuation constant.

A two-port network or four-pole (Fig. 6.1) represents any part of a circuit considered with respect to two pairs of terminals (1-1' and 2-2'). It can be active (containing sources) or passive (without sources). Two-port networks are considered equivalent if they can be interchanged within an electrical circuit without altering the currents and voltages in the external part of the circuit. A four-pole is called symmetrical if interchanging its output terminals with its input terminals leaves the currents and voltages in the rest of the circuit unchanged. Otherwise, the four-pole is non-symmetrical. A *reversible* four-pole is one for which the reciprocity theorem holds, meaning that the transfer impedance (ratio of input voltage to output current) is the same regardless of which pair of terminals is designated as the input and which as the output. Otherwise, the four-pole is irreversible. Passive, linear, and symmetrical two-port networks are reversible. Asymmetrical active (autonomous and non-autonomous) two-port networks are irreversible.

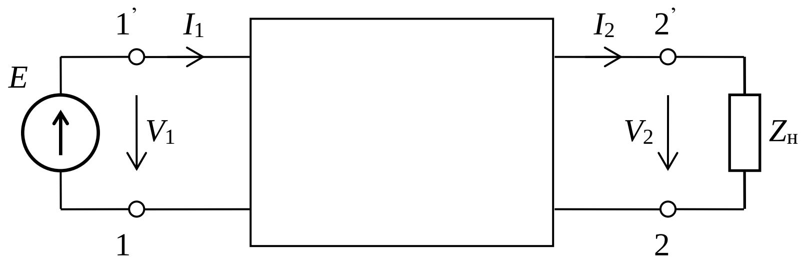


Fig.6.1

The properties of any four-pole, regardless of its internal structure, are completely determined by two equations that relate the input (at terminals 1-1') and output (at terminals 2-2') voltages and currents V_1, V_2, I_1, I_2. Generally, we can write six types of such equations. We will consider one of them, the A-parameters (transmission parameters).

$$\underline{V_1} = \underline{A}\underline{V_2} + \underline{B}\underline{I_2}$$
$$\underline{I_1} = \underline{C}\underline{V_2} + \underline{D}\underline{I_2}$$

The *A*-parameters are the primary parameters of the two-port network.
The significance of these parameters is as follows:
$\underline{A} = \underline{V_1}/V_2$ - voltage transfer function for output open circuit $I_2 = 0$;
$\underline{B} = \underline{V_1}/\underline{I_2}$ - transfer impedance for output short circuit $V_2 = 0$;
$\underline{C} = \underline{I_1}/\underline{V_2}$ - transfer admittance for output open circuit $I_2 = 0$;
$\underline{D} = \underline{I_1}/\underline{I_2}$ - current transfer function for output short circuit $V_2 = 0$.

The A-parameter (transmission parameter) equations are convenient to use when the four-pole acts as a transfer link between the source and the load.

A four-pole is reversible if $\underline{AD} - \underline{BC} = 1$. For a symmetrical four-pole $\underline{A}_{11} = \underline{A}_{22}$.

Any real passive reversible four-pole can be represented by one of two equivalent circuit models: a T-network or a Π-network (fig.7.2). The number of elements of the equivalent circuit model corresponds to the number of independent parameters of the four-pole. Expressions relating the parameters of the four-pole to the elements of the equivalent circuit models:

$$\underline{A} = 1 + \frac{\underline{Z}_1}{\underline{Z}_3};\ \underline{B} = \underline{Z}_1 + \underline{Z}_2 + \frac{\underline{Z}_1\underline{Z}_2}{\underline{Z}_3};\ \underline{C} = \frac{1}{\underline{Z}_3};\ \underline{D} = 1 + \frac{\underline{Z}_2}{\underline{Z}_3}$$

$$\underline{Z}_3 = 1/\underline{C};\ \underline{Z}_1 = (\underline{A} - 1)/\underline{C};\ \underline{Z}_2 = (\underline{D} - 1)/\underline{C}.$$

$$\underline{A} = 1 + \frac{\underline{Z}_4}{\underline{Z}_6};\ \underline{B} = \underline{Z}_4;\ \underline{C} = \frac{\underline{Z}_4 + \underline{Z}_5 + \underline{Z}_6}{\underline{Z}_5\underline{Z}_6};\ \underline{D} = 1 + \frac{\underline{Z}_4}{\underline{Z}_5}.$$

$$\underline{Z}_4 = B;\ \underline{Z}_5 = \underline{B}/(\underline{D} - 1);\ \underline{Z}_6 = \underline{B}/(\underline{A} - 1).$$

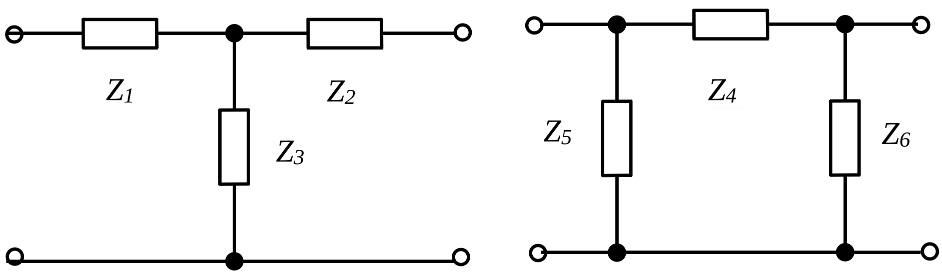


Fig.7.2

For a symmetrical four-pole, where A=D the elements of the T-network are: $\underline{Z}_1 = \underline{Z}_2$, and the elements of the Π-network are: $\underline{Z}_5 = \underline{Z}_6$.

Often of the four-pole are used: the characteristic impedances and the transfer constant.

Characteristic impedance it is the ratio of input voltage to input current (if terminals 1-1` are input):

$$\underline{Z}_{c1} = \frac{\underline{V}_1}{\underline{I}_1} = \frac{\underline{AV}_2 + \underline{BI}_2}{\underline{CV}_2 + \underline{DI}_2}.$$

Characteristic impedance it is the ratio of input voltage to input current (if terminals 2-2` are input):

$$\underline{Z}_{c2} = \frac{\underline{DV}_2 + \underline{BI}_2}{\underline{CV}_2 + \underline{AI}_2}.$$

The characteristic impedances Z_{c1}, Z_{c2} depend on the termination. Because $\underline{V}_2 = \underline{I}_2\underline{Z}_{\text{H}}$, characteristic impedances depend on the load Z_{H}. If the symmetric four-pole (A=D) has balanced load $\underline{Z}_{\text{H}} = \underline{Z}_{c1}$, then $\underline{Z}_{c1} = \sqrt{\underline{B}/\underline{C}}$. So

$$\underline{U}_1 = \underline{U}_2(\underline{A} + \sqrt{\underline{BC}}),\ \underline{I}_1 = \underline{I}_2(\underline{A} + \sqrt{\underline{BC}}).$$

Complex number $\underline{A} + \sqrt{\underline{BC}}$ take equal e^g, where g – transfer function,

$$\underline{g} = ln(\underline{A} + \sqrt{\underline{BC}}) = a + jb,$$

Where a is attenuation constant, b is phase constant.

From $\underline{V}_1 = \underline{V}_2 e^a e^{jb}$, $\underline{I}_1 = \underline{I}_2 e^a e^{jb}$ follows, that magnitude $\underline{V}_1$ is e^a times larger than magnitude $\underline{V}_2$; magnitude $\underline{I}_1$ is e^a times larger magnitude $\underline{I}_2$. $\underline{V}_1$ leads the phase $\underline{V}_2$ by the angle b; current $\underline{I}_1$ leads the phase $\underline{I}_2$ also by angle b.

The complex amplitude ration $\underline{V_1}/\underline{V_2}$ can be represent at exponential form:

$$\frac{\underline{V_1}}{\underline{V_2}} = \frac{V_1}{V_2} e^{j\phi_K},$$

where ϕ_K- phase shift angle between $\underline{U_1}, \underline{U_2}$. So, it follows that

$$ln\frac{\underline{V_1}}{\underline{V_2}} = ln\frac{V_1}{V_2} + j\phi_K.$$

Compare this expression with the expression for transfer constant g, we can write down:

$$a = ln\frac{V_1}{V_2};\ \ b = \phi_K.$$

The attenuation constant *a* represents the intrinsic (wave) attenuation of the two-port network. It quantifies the decrease in voltage and current amplitudes as they propagate from the input to the output of the two-port network.

The phase constant *b* indicates the change in phase of the voltage and current as they propagate through the two-port network.

To determine the parameters of a four-pole experimentally, two independent measurements are necessary, typically an open-circuit (o.c.) test and a short-circuit (s.c.) test.

Homework

The symmetric four-pole parameters for the frequency *100 Hz* are given at the table 6.1. To define the parameters of *T*- network and *П*- network equivalent circuit models.

Table 6.1

Var.№	*A*	*B*	*C*
1	1+j0.314	200+j31.4	$j3.14*10^{-3}$
2	1+j0.35	150+j30	$j3*10^{-3}$
3	2+j0.3	100+j30	$j5*10^{-3}$
4	2+j0.5	100+j25	$j5*10^{-3}$
5	1.5+j0.5	75+j50	$j3*10^{-3}$
6	1-j0.7	70-j50	$j2*10^{-3}$
7	1-j0.5	100-j50	$j3*10^{-3}$
8	1.5+j0.7	120+j40	$j3*10^{-3}$
9	1.8+j0.7	100+j40	$j3*10^{-3}$
10	1+j0.4	15+j30	$j3*10^{-3}$

Elements of laboratory settings

The laboratory setup includes the investigated two-port network, an adjustable power supply, a phasemeter, ammeters, a multimeter, and a selection of resistors, inductors, and capacitors.

The work execution order

1.Collect the circuit (fig.6.3) and provide o.c. experiment (open terminals *2-2'*) $\underline{I_2}=0$, measure voltages V_1 and V_2 , phase shift angle between them. Define four-pole parameter $\underline{A}$.

2. For the same circuit o.c. experiment (open terminals *2-2'*) $\underline{I}_2=0$, measure voltage V_2 and current I_1, phase shift angle between them. Define four-pole parameter $\underline{C}$.

3. Collect the circuit (fig.6.3) and provide s.c. experiment (shorten terminals *2-2'*) $\underline{V}_2=0$, measure voltage V_1 and current I_2, and phase shift angle between them. Define four-pole parameter $\underline{B}$.

4. For the same circuit s.c. experiment (shorten terminals *2-2'*) $\underline{V}_2=0$, measure currents I_1 and I_2, phase shift angle between them. Define four-pole parameter $\underline{D}$.

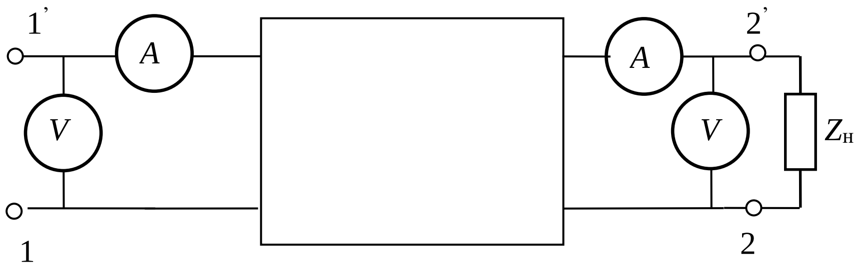


Fig.6.3

5. Verify if the expression $\underline{AD} - \underline{BC} = 1$ holds for a reversible two-port network.

6. Determine the parameters of the T-network and П-network equivalent circuit models.

7. Investigate the operating mode of the two-port network. Calculate the input impedance of the four-pole at terminals *1-1'* for three different loads: a resistor, an inductor (coil), and a capacitor.

8. Determine the transfer constant, attenuation constant, and phase constant of the four-pole for a balanced load $\underline{Z}_н = \underline{Z}_{c1}$.

Report on work

The title and purpose of the work. The schematic diagram of the investigated circuit (fig.6.3). Calculations. Four-poul equivalent circuit models. Conclusions.

Control questions

1. What is a two-port network?
2. What types of two-port networks do you know?
3. Write down the *A*-parameter equations for a two-port network.
4. How can we determine the parameters of a four-pole experimentally? Explain.
5. How can we determine complex impedances experimentally? Explain.
6. What defines a symmetrical two-port network?
7. Draw the equivalent circuit models (T-network and П-network) for a two-port network.
8. Write down the expressions relating the parameters of a four-pole to the elements of its equivalent circuit models.
9. What are the primary and secondary parameters of a two-port network, and what is their physical significance?

10. What operating mode of a four-pole is called balanced?
11. What are the characteristic impedances of a two-port network? Write down their expressions.
12. What is the transfer constant of a two-port network? Write down its expression.
13. How can we determine the attenuation constant and phase constant of a two-port network?

References

1. Hambley, Allan R. Electrical Engineering: Principles and Applications. 7th ed., Pearson Education, 2017.
2. Kothari, D.P., and I.J. Nagrath. Basic Electrical Engineering. 4th ed., McGraw Hill Education (India), 2019.
3. Mehta, V.K., and Rohit Mehta. Basic Electrical Engineering. Revised 2nd ed., S. Chand Publishing, 2023.
4. Theraja, B.L., and A.K. Theraja. Electrical Technology. Vol. 1, 24th ed., S. Chand Publishing, 2016.
5. Theraja, B.L., and A.K. Theraja. Electrical Technology. Vol. 2, 24th ed., S. Chand Publishing, 2016.
6. Chapman, Stephen J. Electric Machinery Fundamentals. 5th ed., McGraw Hill, 2020.
7. Floyd, Thomas L. Electronics Fundamentals: Circuits, Devices & Applications. 11th ed., Pearson Education, 2022.
8. Fundamentals of Electrical Engineering by Don Johnson. Internet resource. Path to the resource: https://www.circuitbread.com/textbooks/fundamentals-of-electrical-engineering-i https://open.umn.edu/opentextbooks/textbooks/337
9. Mulukutla S.Sarma. Introduction to Electrical Engineering. Internet resource. Path to the resource: https://svbitec.files.wordpress.com/2013/09/introduction-to-electrical-engineering.pdf
10. L.Hima Bindu. Basic Electrical Engineering. Internet resource. Path to the resource: https://www.griet.ac.in/nodes/BEEE.pdf
11. Basic Electrical Engineering. Digital Notes. Internet resource. Path to the resource: https://mrcet.com/downloads/digital_notes/HS/Basic%20Electrical%20Engineering%20R-20.pdf

Attachments

№	*Greek letters*		
1	*Α*	*α*	*alfa*
2	*Β*	*β*	*beta*
3	*Γ*	*γ*	*gamma*
4	*Δ*	*δ*	*delta*
5	*Ε*	*ε*	*epsilon*
6	*Ζ*	*ζ*	*dzeta*
7	*Η*	*η*	*eta*
8	*Θ*	*θ,*	*teta*
9	*Ι*	*ι*	*jota*
10	*Κ*	*κ*	*kapa*
11	*Λ*	*λ*	*lambda*
12	*Μ*	*μ*	*miu*
13	*Ν*	*ν*	*niu*
14	*Ξ*	*ξ*	*ksi*
15	*Ο*	*ο*	*micron*
16	*Π*	*π*	*pi*
17	*Ρ*	*ρ*	*ro*
18	*Σ*	*σ,ς*	*sigma*
19	*Τ*	*τ*	*tau*
20	*Υ*	*υ*	*ipsilon*
21	*Φ*	*φ*	*fi*
22	*Χ*	*χ*	*hi*
23	*Ψ*	*ψ*	*psi*
24	*Ω*	*ω*	*omega*

Physical values designation and units

Value	***Designation***	***Dimension***
Resistance	*R*, Ω	***Om***
Reactance	*X*, Ω	***Om***
Impedance	*Z*, Ω	***Om***
Conductance	*G, Sm*	***Simens***
Susceptance	*B, Sm*	***Simens***
Admittance	*Y, Sm*	***Simens***
Capacity	*C, F*	***Farada***
Inductance	*L, H*	***Henry***
Inductance mutual	*M, H*	***Henry***
Electromotive force	*E, V*	***Volt***
Potential	*φ, V*	***Volt***
Voltage	*V, V*	***Volt***
Current	*I, A*	***Amper***
Active power	*P, W*	***Watt***
Reactive power	*Q, VAr*	***Volt-Amper reactive***

Total power	*S, VA*	***Volt-Amper***
Magnetomotive force	*F, A*	***Amper***
Magnetic induction	*B, T*	***Tesla***
Magnetic field tension	*H, A/m*	***Amper per meter***
Magnetic stream	Φ, *Wb*	***Weber***
Linkage	ψ, *Wb*	***Weber***
Magnetic permeability (absolute)	μ_a,, *Гн/м*	***Henry per meter***
Magnetic permeability (relative)	μ	
Magnetic constant	μ_0, *Гн/м*	$\boldsymbol{4\pi \cdot 10^{7}}$
Frequency	*f, Hz*	***Herz***
Angular frequency	ω, *rad/s*	***radian per second***
Length	*1, m*	***meter***
Hight, depth	*h, m*	***meter***
Layer	δ, *d, m*	***meter***
Arial	*S*, m^2	***square meter***
Magnetic resistance	R_m	
Number of turns	*w*	
Force	*F, N*	***Newton***
Work (energy)	*W, J*	***Joule***
Charge	*Q, C*	***Coulomb***

Content