Ministry of Education and Sciences of Ukraine

«Zaporizhzhia Polytechnic» National University

STUDY OF MAGNETIC AMPLIFIERS

Methodical instructions for the laboratory works on the subject:
“Fundamentals of the Theory of Electrical Apparatus”

for the students of the specialty 141:
"Electrical Power, Electrical and Electromechanical Engineering"
(educational program **“Electric and Electronic Apparatus”**

2022

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Introduction

General Insight into Magnetic Amplifiers

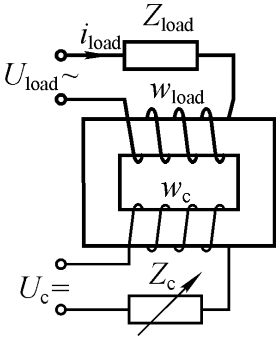
The *magnetic amplifier* (MA) is derived from the fundamental saturable reactor, which was first described in 1901. This device was identified as a mean of regulating an electric current by the use of a variable-inductance saturable reactor. Thus, the prime component of all magnetic amplifiers is the *saturable reactor* representing an electromagnetic element in which the inductance of its load winding is variable in a wide range. The term magnetic amplifier is usually determined as a circuit device consisting of combinations of saturable reactors, rectifiers, resistors, and conventional transformers used to secure control or amplification, whereas a saturable reactor (or transductor) is the reactor alone regardless of how it is used.

As differentiated from electromagnets, in which inductance of the magnetizing winding is varied under changing the operating airgap in the magnetic circuit, in saturable reactors, the inductance of its load winding is varied under changing the magnetic conditions of its magnetic core affected by the biasing flux that is excited by a control winding.

For a long time magnetic amplifiers had a very extensive and different applications in such areas as measuring technologies, control systems for powerful electric installations, AC and DC generators and motors, relay protection and automatic devices etc.

Now, the application area of magnetic amplifiers has significantly reduced because of the development of semiconductor and microprocessor-based devices. Nevertheless, after some, sometimes unreasonable, fascination with the semiconductor devices, magnetic amplifiers taken a worthy place and even continues to develop. An illustrative example is the designing new equipment, such as, a series of the DC controllable shunt reactors for reactive power compensation in electrical networks 35–500 kV that, for the first time in world practice, is developed and produced by a group of companies with the participation of JSC ZTR.

Magnetic amplifiers offer a wide variety of advantages. It is first high reliability because ones are static (free from movable parts) devices; ones save own operability in a wide range of temperatures, and under kick and vibration conditions. Magnetic amplifiers, as differentiated from semiconductor amplifiers, save high operating ability at high and ultrahigh frequencies. Performances of the magnetic amplifiers practically are not dependent upon the temperature and power network voltage.



Simplest saturable reactor connected in circuit

The operation of a saturable reactor is based on the properties of *B-H* curve, which behaves as a highly non-linear curve. The magnetic circuits of saturable reactors are mainly made of soft-magnetic materials having a very narrow hysteresis loop. In this situation, the magnetic state of their magnetic circuits can be considered with the help of an average hysteresis-less *B-H* curve. The simplest saturable reactor contains a magnetic circuit, usually free from air-gaps, and two windings: load and control ones as shown in Figure. *Load winding* w_{load} is inserted into the load circuit fed from AC power source. *Control winding* w_{c} is inserted into the control circuit fed from DC power source. If the active resistance of the load winding is neglected, the load current will be expressed as:

$$\dot{I}_{\text{load}} = \frac{\dot{U}_{\text{load}}}{Z_{\text{load}} + j\omega L_{\text{load}}},$$

where L_{load} is the inductance of the load winding expressed as follows:

$$L_{\text{load}} = w_{\text{load}}^{2} \Lambda_{\text{m.c.}} = w_{\text{load}}^{2} \mu\mu_{0} \frac{S_{\text{m.c.}}}{l_{\text{av}}},$$

where $\Lambda_{\text{m.c.}}$ is the total permeance of the magnetic circuit;

$S_{\text{m.c.}}$ is the cross-sectional area of the magnetic circuit;

l_{av} is the average length of the magnetic flux line in the magnetic circuit;

μ_0 is the magnetic constant;

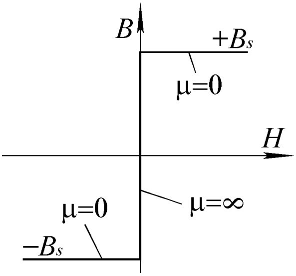
μ is the relative permeability of the magnetic circuit material.

Since values S_{mc} and $l_{\text{m.av}}$ are invariable for a particular reactor, the inductive reactance of its load winding will be dependent only on the relative permeability μ that is determined by the magnetic state of the magnetic circuit (i.e., by the flux density magnitude). The relative permeability can be varied by the so-called *magnetic biasing* due to the direct current flowing through the control winding producing a DC component of the flux Φ_0 and a DC component of the flux density B_0, respectively.

When the current through the control winding equals to zero, that is, magnetic bias is not available $B_0 = 0$, then μ is very high, and $\omega L_{\text{load}} >> Z_{\text{load}}$, and therefore the current in the load circuit is very small. When the current through the control winding is available, the magnetic circuit is biased ($B_0 \neq 0$).In this case, if the operating section of the *B-H* curve all cycle of the power voltage corresponds to low value of the relative permeability μ, then $\omega L_{\text{load}} << Z_{\text{load}}$ and the current through the load circuit is entirely defined by the load impedance Z_{load}. Hence, variation of the relative permeability μ under magnetic bias results in changing the impedance of the load winding in a wide range. Thus, the load winding behaves as contact-less switching element, which makes and breaks the load circuit.

The main difficulty to analyze the operation of saturable reactors lies in high non-linearity of the B-H curve. Therefore, various simplifications are used, such as linearized or ideal saturable reactor.

Linearized saturable reactor is that in which the permeability of its magnetic core is accepted invariable during the power supply cycle. Then, its load winding is considered as a linear inductance controlled by the current flowing through the control winding. Although such simplification of a saturable reactor is qualitatively valid, it improperly describes actual physical processes; therefore, it has limited usefulness.



Ideal magnetization curve

Ideal saturable reactor is that in which the actual magnetization curve of its magnetic core is substituted by *ideal B-H* curve that represents a broken line as shown in Figure.

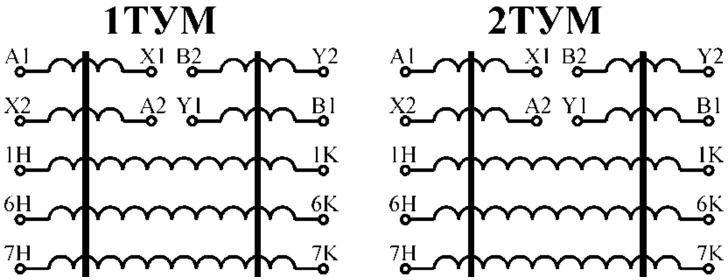
According to an ideal *B-H* curve, the flux density in the core cannot be more than its saturation value B_s. Accordingly, the magnetic core can be in two states: re-magnetization or saturated one. The core is in *re-magnetization state*, when the flux density in the core is less than saturation flux density B_s in absolute value (the core is non-saturated). The core is in *saturation state*, when the flux density in the core equals to the saturation flux density B_s (the core is saturated). In the first case the relative permeability μ and, respectively, the load winding inductance L_{load} are infinitely high and, hence, the current in the load circuit equals to zero. In the second case the relative permeability μ and, respectively, load winding inductance L_{load} are zero and, hence, the load impedance will determine the current in the load circuit.

Laboratory Equipment

The laboratory works for the study of saturable reactors and magnetic amplifiers are carried out on the laboratory table that contains the power supply unit and all-purpose laboratory panel. The power supply unit includes automatic circuit breaker QF to energize the table, as well as individual automatic breakers and toggle switches to switch the corresponding power sources.

The terminals of the power sources are arranged under the laboratory panel. For measuring operations during a laboratory work, all-purpose instruments are used placed on the laboratory table. Electrical connections in accordance with the circuits of the laboratory works are performed with the help of wires with relevant terminations. To form circuit nodes it is necessary to use the terminal blocks arranged on the panel's face.

The saturable reactors to be studied of types ТУМ А4-11 or ТУМ А3-11М are particularly mounted on all-purpose laboratory panel. The terminals of their windings are arranged on the panel's face; its appearance is shown in Figure. Performance data of the saturable reactors windings are represented in table.



Appearance of the saturable reactors on the laboratory panel face

Safety Instructions

1. Prior to perform the cycle of laboratory works, students must be instructed in safety precautions and laboratory regulations, as well as strongly fulfill appropriate instructions. Students who have not been instructed are not permitted to perform the laboratory works.

2. In the cause of laboratory work, wiring a circuit and switching operations are allowable only in the case the QF automatic breaker is in off-position. All autoformers here must be zeroed.

Performance data of the windings of the saturable reactors

Designations of terminals of the windings	**Name of the quantity**	**The magnitude of the quantity**	
		ТУМ-А4-11	**ТУМ-А3-11М**
1Н-1К	Rated current (midvalue), A	0,152	0,283
	Continuous current (midvalue), A	0,33	0,66
	Resistance at 20°C, Ohm	1,6	2,6
2Н-2К	Rated current (midvalue), A	0,021	0,0213
	Continuous current (midvalue), A	0,052	0,055
	Resistance at 20°C, Ohm	1,6	2,6
3Н-3К	Rated current (midvalue), A	0,009	0,0061
	Continuous current (midvalue), A	0,074	0,055
	Resistance at 20°C, Ohm	108	186
4Н-4К	Rated current (midvalue), A	0,009	0,0078
	Continuous current (midvalue), A	0,052	0,055
	Resistance at 20°C, Ohm	170	158
5Н-5К	Rated current (midvalue), A	0,009	0,0078
	Continuous current (midvalue), A	0,052	0,055
	Resistance at 20°C, Ohm	170	158
6Н-6К	Rated current (midvalue), A	0,009	0,0078
	Continuous current (midvalue), A	0,1	0,09
	Resistance at 20°C, Ohm	100	110
7Н-7К	Rated current (midvalue), A	0,009	0,0078
	Continuous current (midvalue), A	0,1	0,09
	Resistance at 20°C, Ohm	100	110

3 It is stringently unallowable to energize the circuit without the permission of the teacher or laboratory assistant.

4. Prior to measuring operations, the measuring instruments must be adjusted to the appropriate functioning mode (ammeter or voltmeter).

5. In the cause of trial measurements, it is necessary to pay attention to the ultimate currents and voltages of the measuring instruments and saturable reactor windings, represented in table I.1, especially when the reactor transits to saturation state.

6. In the cause of working measurements, the indications of the instruments should be monitored not permitting off-scale readings.

Preparation for the Laboratory Works and their Performance

In order to perform a laboratory work timely and successfully, the student must qualitatively prepare for them beyond the scheduled study. During the preparation, the student must study corresponding theoretical fundamentals, as well as construct a circuit diagram for experimental study according to the subject of laboratory work.

Just after the beginning of the scheduled study, the circuit diagram for experiments must be agreed with the teacher. After completion of the experiments, prior to disassemble the circuit, the derived findings must be checked by the teacher.

The findings derived in the laboratory work must be represented in the report designed in compliance with ДСТУ 3008: 2015. The report must include:

a) title-page with the name of the laboratory work;
b) purpose of work;
c) circuit diagram of experimental study;
d) formulas required for calculations according to the task;
e) tables with experimental and calculated findings;
f) plotted graphical dependencies and measured time diagrams according to the task;
g) conclusions on the work.

The student must submit and protect own report.

1. Laboratory work №1.

Study of the Magnetization Curve of Ferromagnetic Material

The duration of the laboratory study is 4 hours

1.1 Purpose of the work

The purpose of this laboratory work is to find experimentally the basic parameters of the magnetization curve of ferromagnetic material.

1.2 Subject of the study

Qualitative properties and characteristics of electromagnetic components and systems are substantially defined by the properties of ferromagnetic materials to be used. That is why the selection of ferromagnetic material is a highly responsible stage in designing of electric apparatus in general and its electromagnetic components in particular.

The fundamental characteristic, which features the properties of ferromagnetic material, is its static *magnetization curve* or *B-H curve*. It is the dependency the flux density *B* of the magnetic field vs its intensity *H*. It has very complex behavior: it is first highly non-linear, and secondly, non-single-valued, that is, it has hysteresis as shown in Figure 1.1.

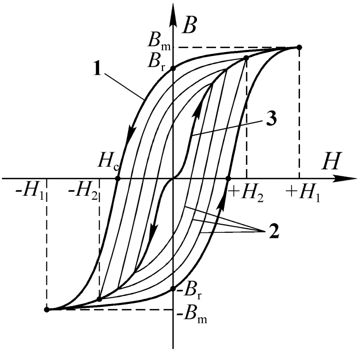


Figure 1.1 – Typical *B-H* curve of a ferromagnetic material

The magnetization curve of a ferromagnetic material usually includes the following main elements:

1 is ***major hysteresis loop*** featured by *saturation flux density* B_m corresponding to its tips, *residual* or *remanent flux density* B_r, and *coercive force (coercivity)* H_c;

2 is ***minor symmetric subloops***;

3 is ***fundamental (initial) magnetization curve***, which coincide with the tips of the symmetric subloops.

It should be pointed out that initial magnetizing a ferromagnetic material (i.e., from zero flux density) follows to the fundamental *B-H* curve. If the value of the magnetic intensity follows to non-symmetric cycle, then the magnetization curve will follow the so-called ***asymmetric hysteresis subloop***.

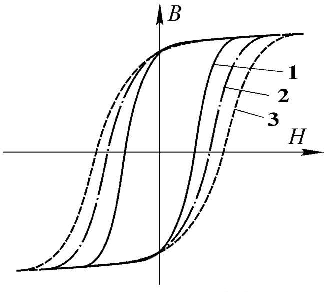


Figure 1.2 – Static and dynamic hysteresis loops.

As already noted, the magnetization curve considered above represents a static characteristic obtained at steady-state external magnetic field. However, in actual magnetic circuits, the re-magnetization of ferromagnetic materials frequently occurs at sufficiently high rate of change of the external field. In this case, the *B-H* curve behaves somewhat differently representing the so-called *dynamic B-H curve* or *dynamic hysteresis loop*.

The behavior of dynamic curve is first dependent on the rate of change of the external magnetic field. Figure 1.2 shows the static magnetization curve 1, when $dH_1/dt = 0$, and dynamic magnetization curves 2 and 3 measured at different rates of change of the magnetic intensity. Dynamic hysteresis loops are characterized by a lag of change of the flux density *B* under changing the magnetic intensity *H*. The more rate of change of the intensity is, the more will be the lag of the flux density: $0 < dH_2/dt < dH_3/dt$. The lag of dynamic magnetization curves takes place due to:

- firstly, the *magnetic viscosity* phenomena of ferromagnetic materials, which is explained by the lag in the orientation of the domains under rapid changing the external magnetic field intensity;
- secondly, *eddy currents* that excite magnetic field, which, according to Lenz rule, interferes with changing of the external field.

The components of magnetic circuits are usually made of *soft-ferromagnetic materials* featured by very narrow hysteresis loop, that is, the materials with high permeability and low coercive force. In engineering calculations, the non-single-valuedness of *B-H* curve is neglected, and the characteristic is determined by its fundamental curve. In such cases, the relation between the flux density and intensity of the magnetic field is expressed as follows:

$$B = \mu_a H = \mu\mu_0 H$$

where μ_a is the magnetic permeability;

μ is the relative permeability;

μ_0 is the magnetic constant or permeability of vacuum.

There following ferromagnetic materials are extensively used in electromagnetic systems of electric apparatus: electrical-sheet steels, qualitative structural steels, steel castings, cost irons, special iron-nickel and iron-cobalt alloys.

1.3 Task

1.3.1 Construct a circuit diagram for the experimental study of *B-H* curve; this should be made in the preparation for the work before scheduled study.

1.3.2 Experimentally determine currents and voltages required to calculate the *B-H* curve of the saturable reactor magnet core.

1.3.3 Calculate the *B-H* curve parameters of the magnet core and plot the corresponding graphical diagrams.

1.3.4 According to the experimental and calculation findings, determine what material is used in this magnetic circuit.

1.4 Methodical instructions

1.4.1 To perform item 1.3.1, it is necessary to use a textbook (see “Reference List”) and lection texts. The circuit diagram should contain all measuring instruments required to perform the experiments.

1.4.2 To measure the *B-H* curve of the core, use both load windings of saturable reactor ТУМ-А4-11 or ТУМ-А3-11М.

1.4.3 For the sake of convenience of mounting and checking the circuit wiring, the circuit diagram should have designations of windings’ terminals, as well as numbers of nodes.

1.4.4 The circuit diagram constructed must be agreed with the teacher.

1.4.5 Item 1.3.2 should be performed in the following order:

a) assemble the circuit using a power source with adjustable phase voltage: phase "A" (terminals 4 and 5); or phase "B" (terminals 4 and 6); or phase "C" – (terminals 4 and 7); the assembled circuit wiring must be necessarily checked by the teacher or laboratory assistant;

b) all-purpose instruments, used in the laboratory study, must be positioned to the relevant operation mode (AC ammeter or AC voltmeter), as well as the widest measuring range;

c) make the main automatic circuit-breaker QF and the corresponding circuit-breaker of AC power source (chosen phase);

d) with the help of the corresponding autoformer step the supply voltage up to the maximal value, then adjust optimal measuring ranges of the measuring instruments;

e) stepping down the power voltage, make 10–12 working measurements; the derived findings should be written in table 1.1; in the process, the *B-H* curve should be measured in more detail in the range of its knee.

Table 1.1 – Measuring and calculated findings

E, В	**I, A**	**E_u, В**	**B_m, Тл**	**$H_{ср}$, А**	**μ, Гн/м**	**μ_d, Гн/м**

1.4.6 After termination of working measurements the autoformer must be zeroed, all automatic breakers must be opened; saving assembled circuit, measured findings must be checked by the teacher.

1.4.7 To perform items 1.3.3 and 1.3.4 use the formulas and reference data represented in textbooks and reference books (see “Reference List”).

1.5 Self-checking questions

1.5.1 Call the basic parameters, which feature the properties of ferromagnetic materials.

1.5.2 What is the magnetization (*B-H*) curve and what parameters is it characterized by?

1.5.3 What is absolute (relative) magnetic permeability?

1.5.5 What is a dynamic hysteresis loop and what does it look like?

1.5.6 Explain the causes of dynamic behavior of the hysteresis loop.

2. Laboratory work № 2.
Study of AC Saturable Reactor

The duration of the laboratory study is 4 hours

2.1 Purpose of the work

The purpose of the work is to determine experimentally the fundamental characteristics and time diagrams defining the operation of AC saturable reactor.

2.2 Subject of the study

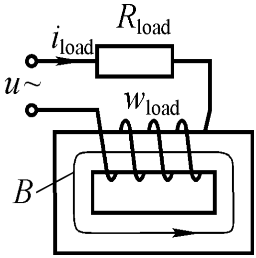


Figure 2.1 – Circuit diagram of AC saturable reactor connection

The distinctive feature of AC saturable reactor, i.e. the saturable with AC magnetic biasing, is the absence of biasing its magnetic core by direct current. Hence, the current passing through its load windings does not contain DC component. AC saturable reactors are extensively used in automatics as sensing component of electrical quantities (current, voltage, frequency, power etc.), measuring relay elements, as voltage stabilizers and others. Let us consider the operation of the simplest AC saturable reactor with one load winding connected in a circuit as shown in Figure 2.1.

The circuit is powered from AC sine source. It consists of a load winding w_{load} and a load R_{load} connected in series. The analysis of the circuit is realized with taking into consideration the following assumptions:

- the reactor magnet core under study has an ideal *B-H* curve;
- the flux density is equally distributed over the core;
- stray fluxes are not available;
- active losses in the load winding are not available;
- the circuit load is purely resistive.

For the load circuit, according to the Kirchhoff voltage law the following equation can be written:

$$U_{\mathrm{m}} \sin \omega t = iR_{\mathrm{load}} + w_{\mathrm{load}} S_{\mathrm{c}} \frac{dB}{dt}, \tag{2.1}$$

where S_c is the cross-sectional area of the magnetic circuit;

w_{load} is the number of turns of the load winding.

If during the power voltage cycle the flux density in the rector's core *B* is less than the saturation value B_s, then in compliance with ideal *B-H* curve the core all time is in re-magnetization state. Hence, the load current is zero and equation (2.1) becomes as follows:

$$U_{\mathrm{m}} \sin \omega t = w_{\mathrm{p}} S_{\mathrm{c}} \frac{dB}{dt} . \qquad (2.2)$$

Separating variables and integrating both sides of the equation, we will have the expression for the flux density in the magnet core

$$B = -\frac{U_{\mathrm{m}}}{\omega w_{\mathrm{p}} S_{\mathrm{c}}} \cos \omega t + A = -B_{\mathrm{m}} \cos \omega t + A . \qquad (2.3)$$

Let us assume that the magnetic state of the core at the initial moment corresponds to the zero value of the integration constant (i.e., $A = 0$), then:

$$B(0) = -B_{\mathrm{m}} .$$

Time diagrams characterizing the operation of AC saturable reactor are shown in Figure 2.2.

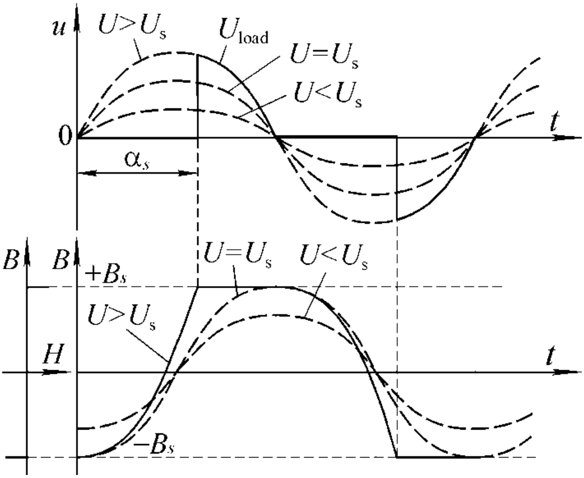


Figure 2.2 – Time diagrams of operation of AC saturable reactor

If the power voltage amplitude U_{m} is increased, the flux density amplitude B_{m} will proportionally increase. At a certain value U_{ms}, the flux density amplitude will reach the saturation value B_{s} that corresponds to the following expression (see Figure 2.2):

$$U_{\mathrm{ms}} = \omega w_{\mathrm{load}} S_{\mathrm{c}} B_{\mathrm{s}} \qquad (2.4)$$

When $U_{\mathrm{m}} > U_{\mathrm{ms}}$, the core will be in re-magnetization state only part of the half-cycle within the time interval $0 \ldots t_{\mathrm{s}}$. During this interval, the load winding is non-conductive, and, respectively, load current equals to zero and all supply voltage is applied to the load winding. At the instant t_s the core reaches saturation and remain in this state until the end of the half-cycle. During this interval, the reactance of the load winding will be zero and whole power voltage is applied to the load (see Figure 2.2).

In this case, rms voltage across the load can be found from the following equation:

$$U_{\text{load}} = U - U_{\text{s}},$$

where U is the rms power voltage;

U_{s} is the rms voltage across the reactor defined by the following expression:

$$U_s = 4{,}44\, f w_{\text{load}} B_{\text{s}} S_{\text{c}}\,.$$

The value U_{s} is not dependent upon the supply voltage value, but depends on its frequency. Hence, the characteristics of AC saturable reactor at different frequencies of the supply voltage will be therefore as illustrated by Figure 2.3

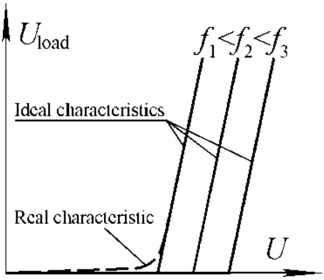


Figure 2.3 – Characteristics of AC saturable reactor

2.3 Task

2.3.1 Set up the circuit diagram for the experimental study of AC saturable reactor. It should be made in preparing to the work outside the schedule of the laboratory study.

2.3.2 Experimentally determine the dependencies $U_{\text{SR}}(U)$, $U_{\text{load}}(U)$, $I_{\text{load}}(U)$ and plot their graphical diagrams.

2.3.3 Linearize the derived dependencies and determine the saturation voltage U_{s} and the material used in the magnetic circuit.

2.3.4 Measure the time diagrams of voltages across the reactor and load at $U < U_{\text{s}}$ and $U > U_{\text{s}}$.

2.3.5 Draw conclusions on the work.

2.4 Methodical instructions

2.4.1 To perform item 2.3.1, it should be used the textbooks (see "Reference List") or lecture texts. The circuit for the experiment must contain all the necessary measuring instruments.

2.4.2 To measure the dependencies in accordance with item 2.3.2, it should be used one of the load windings of saturable reactor ТУМ-А4-11 or ТУМ-А3-11М.

2.4.3 For the sake of convenience to assemble and check, the circuit diagram should contain designations of the reactor's terminals and numbers of nodes.

2.4.4 Setup circuit diagram must be agreed with the teacher, who supervises the laboratory works.

2.4.5 Item 2.3.2 should be performed in the following order:

a) assemble the circuit; the assembled must be necessarily checked by the teacher or laboratory assistant;

b) adjust all-purpose instruments to the desired operation mode (AC ammeter or voltmeter), as well as the maximal measuring ranges;

c) close main automatic breaker QF and the phase circuit-breaker being used for the experiment;

d) step the supply voltage up to maximal value with the help of corresponding autoformer; adjust the measuring instruments to be used to optimal measuring ranges;

e) stepping down the supply voltage, make 10–12 working measurements; derived findings should be written into table 2.1; in the process, the characteristic in the bend zone should be investigated in more detail.

Table 2.1 – Measured and calculated findings

E, В	**$U_{д}$, В**	**$U_{н}$, В**	**$I_{н}$, А**

2.4.6 Item 2.3.4 should be performed in the following order:

a) turn on the oscilloscope and connect the HF-cable to its measuring input and to the terminals of the object being studied;

b) adjust the desired supply voltage ($U < U_s$ or $U > U_s$);

c) synchronize the oscillogram trace and adjust the optimal sweep on time and amplitude;

d) make a photo of the measured oscillogram traces; all traces must be equally scaled in the time and amplitude.

2.4.7 After the measurements are completed, the autoformer must be zeroed, all circuit-breakers must be opened.

2.4.8 Prior to disassemble the circuit, the derived findings should be agreed with the teacher.

2.5 Self-checking questions

2.5.1 What is AC saturable reactor?
2.5.2 Where are AC saturable reactors used?
2.5.3 Represent basic circuit designs with AC saturable reactor.
2.5.4 What is saturation voltage?
2.5.5 What is called the saturation frequency?
2.5.6 Explain the measured oscillogram traces.

3. Laboratory work №3

Study of Choke Magnetic Amplifier

Duration of scheduled laboratory study is 4 hours

3.1 Purpose of the work

The purpose of the work is to determine experimentally fundamental characteristics and time diagrams defining the operation of choke magnetic amplifier.

3.2 Subject of the study

The main component of the choke magnetic amplifier is a saturable reactor (choke) including the magnet core, which is magnetically biased by a direct current. Hence, the current flowing through the one of its windings contains a direct component. There are two extreme types of the operation of the saturable reactor: *forced magnetization* taking place in the case of a high impedance of the control circuit, and *natural* or *free magnetization*, when the control circuit impedance is low. The circuit diagram of the simplest saturable reactor with DC magnetic biasing was considered above (see Figure I.1), but it has limited application due to grave shortcomings because of the AC component of the load current induces into the control circuit. The alternating magnetic flux excited by the load winding induces in the control winding (analogically to secondary winding) alternating EMF.

If the choke operates in natural magnetization condition, the control circuit practically does not effect on the AC current component induced, and the load current will be dependent mainly upon the load resistance (as in a short-circuited transformer). In this case, the load current becomes almost unregulated by the control current, and its waveform is significantly distorted relative to sine one.

When the choke operates in forced magnetization condition, the alternating current induced from the load circuit to the control one is limited. In practical situation, the induced current can be reduced by insertion of a high resistance or reactance into the control circuit. However, such measures significantly deteriorate the technical-and-economical performances of the magnetic amplifier. Firstly, the lag is increased (i.e., response speed is reduced); secondly, the losses and expenses of material are increased; third, amplification factor reduces, and other shortcomings.

Extensive application has received the magnetic amplifier circuits with two saturable reactors. In such circuits, the AC current induced from the load circuit to the control one is eliminated by the anti-connection of the load half-windings relative to the control winding. Let us consider the simplest circuit of the choke magnetic amplifier shown in Figure 3.1.

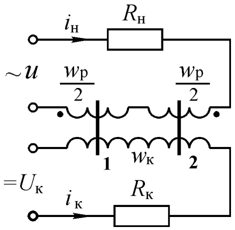


Figure 3.1 – Choke magnetic amplifier with two load windings

The magnetic amplifier contains a three-legged magnetic circuit, a load winding w_load, producing an alternating flux, placed on the side legs 1 and 2, and a control winding w_c, producing a DC component of the flux, placed on the middle leg connected with the side ones. The load winding is connected so that there is no AC component of the flux in the middle leg and, hence, the alternating current is not induced in the control circuit.

Let us consider in more detail operation of the magnetic amplifier in free magnetization. In this case, as per Kirchhoff's voltage law the equation for the load circuit with pure active load is:

$$u = i_\text{н} R_\text{н} + \frac{d\Psi_\text{р}}{dt} = i_\text{н} R_\text{н} + \frac{w_\text{р} S_\text{с}}{2}\left(\frac{dB_1}{dt} + \frac{dB_2}{dt}\right) \qquad (3.1)$$

where B_1, B_2 are the flux density in the first and second core, respectively, which vary in time according to following expressions:

$$B_1 = -B_\text{m}\cos\omega t + B_0\,; \quad B_2 = -B_\text{m}\cos\omega t - B_0\,, \qquad (3.2)$$

where B_0 is the flux density produced by the control winding (constant on value and direction).

If $|B_0| < B_\text{s}$, and $|B_\text{m}| = B_\text{s}$, then

$$B_1 = -B_\text{s}\cos\omega t + B_0\,; \quad B_2 = -B_\text{s}\cos\omega t - B_0\,, \qquad (3.3)$$

At zero time instant:

$$B_1(0) = -B_s + B_0\,; \quad B_2(0) = -B_s\,,$$

because of that the flux density in a core cannot be by the module more than B_S.

From zero time, flux density B_1 will vary according to equation (3.3). To determine B_2, let us use the equation for the control circuit

$$U_{\text{к}} = i_{\text{к}} R_{\text{к}} + \frac{d\Psi_{\text{к}}}{dt} = i_{\text{к}} R_{\text{к}} + w_{\text{к}} S_{\text{c}} \left(\frac{dB_1}{dt} - \frac{dB_2}{dt} \right).$$

According to the definition of free magnetization $R_{\text{к}} \approx 0$, then

$$w_{\text{к}} S_{\text{c}} \left(\frac{dB_1}{dt} - \frac{dB_2}{dt} \right) = 0\,; \quad \frac{dB_1}{dt} = \frac{dB_2}{dt}\,,$$

Thus, at any time instant, the difference $B_1 - B_2 = B_0 = const$ as shown in Figure 3.2.

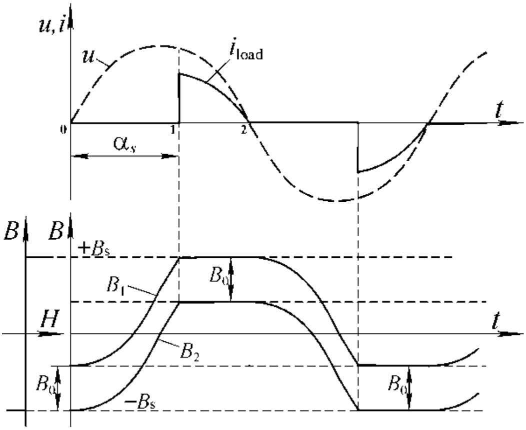


Figure 3.2 – Time diagrams of operation of choke magnetic amplifier

Accordingly, each half-cycle of supply voltage includes two distinctive time intervals:

0–1 – within this time span both cores are remagnetized that corresponds to the vertical section of the ideal *B*-*H* curve; hence, the reactance of both load windings is infinitely high and the load current equals to zero;

1–2 – within this time span the 1st core is in saturation state while in 2nd core there is no variation of the flux density; consequently, the reactance of both load windings equals to zero and the load current will be dependent upon the load resistance only.

In the second half-cycle, the process will occur in the same way. The angle corresponding the time span 0-1 is named the *saturation* or *firing angle* α_s. It can be determined from equation (3.3) and expressed as:

$$\cos\alpha_s = \frac{B_0}{B_s} - 1 .$$

In such a way, by varying the flux density B_0 in the range $0 < B_0 < 2B_s$ we can control the mean and rms value of the load current; this condition corresponds to *working operation* of the magnetic amplifier.

When $B_0 = 0$; $\cos\alpha_s = -1$; $\alpha_s = \pi$, the load winding does not conduct the load current throughout a half-cycle; this condition corresponds to *no-load operation* of the magnetic amplifier.

When $B_0 = 2B_s$; $\cos\alpha_s = 1$; $\alpha_s = 0$, the load winding conducts load current throughout whole half-cycle. In this case the mean and rms value of the load current are maximal and independent on the control current; this condition corresponds to *maximal output operation* of the magnetic amplifier.

Taking into account that $B_0 \equiv I_к$, the control characteristic of the choke magnetic amplifier will be as illustrated in Figure 3.3.

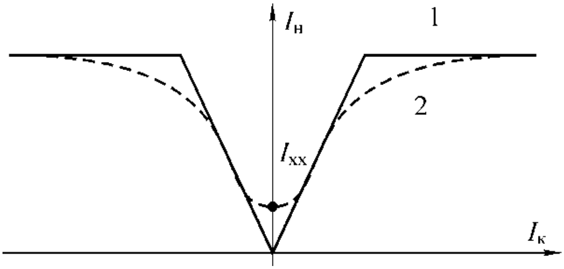


Figure 3.3 – Control characteristic of choke magnetic amplifier: 1 – ideal; 2 – real

3.3 Task

3.3.1 Draw up the circuit diagram for the experimental study of the magnetic amplifier (it should be made during preparation for the work outside the schedule of laboratory classes).

3.3.2 Experimentally determine the control characteristic of the magnetic amplifier and plot its graphical diagram.

3.3.3 According to derived control characteristic of the magnetic amplifier, determine its amplification factor.

3.3.4 Measure time diagrams of the voltages across the load $u_н(t)$ for three typical types of magnetic amplifier operation: no-load, working and maximal output.

3.3.5 Make conclusions from the work.

3.4 Methodical instructions

3.4.1 To execute item 3.3.1, it should be used the textbooks (see “Reference List”) or lecture texts. The circuit diagram for the experimental study must include required measuring instruments.

3.4.2 In order to measure the control characteristic according to item 3.3.2, it should be used both load windings of the magnetic amplifier ТУМ-А4-11 or ТУМ-А3-11М, and its control winding (its terminals are designated as 6Н-6К).

3.4.3 As supply sources for the load and control circuits it is necessary to use different phases; for example, if for the load circuit you use AC supply voltage of phase “A”, then for the control circuit you should use DC supply voltage of phase “B” or “C”.

3.4.4 The load resistance in the load circuit should be accepted equal to 300 Ohms; the control winding is the load for the control circuit.

3.4.5 For convenience of wiring and checking the circuit, the circuit diagram should include designations of windings’ and supply sources’ terminals, as well as the numbers of nodes.

3.4.6 The drawn up circuit diagram must be checked by the teacher, who supervises the laboratory works.

3.4.7 Item 3.3.2 should be performed in the following order:

a) assemble the circuit; that circuit must be necessarily checked by the teacher or laboratory assistant;

b) adjust all-purpose instruments according to the desired position (ammeter or voltmeter, DC or AC), as well as the maximal measuring range;

c) close automatic circuit breaker QF and the breaker of that phase being used to supply the load circuit;

d) using the autoformer, step the supply voltage of the load circuit up to the value equal to $2E_s$ (see laboratory work №2);

e) close the breaker of that phase being used to supply the control circuit;

f) stepping up the supply voltage of the control circuit, make 10–12 working measurements; the derived findings should be entered into table 3.1; the section where the characteristic has bend must be investigated in more detail.

Table 3.1 – Measured and calculated findings

$I_{к}$, A	**$I_{н}$, A**	**$U_{н}$, B**	**$P_{н}$, Вт**

3.4.8 Item 3.3.4 should be performed in the following order:

a) turn on the oscilloscope and connect the HF-cable to its measuring input and to the terminals of the object being studied;

b) adjust the magnetic amplifier in accordance with the desired type of operation: (no-load, working, maximal output);

c) synchronize the oscillogram trace and adjust the optimal sweep on time and amplitude;

d) make a photo of the measured oscillogram traces; all traces must be equally scaled in the time and amplitude.

3.4.9 After the measurements are completed, the autoformer must be zeroed, all circuit-breakers must be opened.

3.4.10 Prior to disassemble the circuit, the derived findings should be agreed with the teacher.

3.5 Self-checking questions

3.5.1 Explain the operating principle of choke magnetic amplifier.

3.5.2 What are the shortcomings of the choke magnetic amplifier with one load winding?

3.5.3 How to reduce the AC component in the control circuit induced by the load current?

3.5.4 What is the control characteristic of the choke magnetic amplifier?

3.5.5 Show and explain the distinction between the control characteristics of the ideal and actual choke magnetic amplifier.

3.5.6 What characterizes the amplification coefficient and how is it determined?

4. Laboratory work №4

Study of Self-Saturating Magnetic Amplifier

Duration of scheduled laboratory study is 4 hours

4.1 Purpose of the work

The purpose is to determine experimentally the fundamental characteristics and time diagrams defining the operation features of self-saturating magnetic amplifier.

4.2 Subject of the study

Self-saturating magnetic amplifier differs from usual choke magnetic amplifier in that the choke magnetic core is magnetically biased not only by DC control current, but also due to DC component of the load current. The circuit of the simplest self-saturating magnetic amplifier is distinctive from the circuit of usual saturable reactor (see Figure I.1) by the presence of a rectifying component (diode) in the load circuit. Consequently, a half-waved load current passes through the load circuit. It contains DC component that produces additional magnetic biasing the core. Its degree is direct with value of the load current. It results in the same effect as the action of the feedback winding. That is why the self-saturating magnetic amplifiers are also known as *magnetic amplifiers with internal feedback*.

Conducting half-cycle for the diode is usually called *positive half-cycle*; respectively, non-conducting one is *negative* or *reset half-cycle*. It is supposed that:

- the predetermined supply voltage corresponds to the peak value of the flux density equal to B_s;

- total impedance of the control circuit is very high, so the current through the one is independent on EMF induced by the load circuit;

- diode VD offers infinitely high resistance during the negative half-cycle and zero one during the positive half-cycle;

- the core material offers an ideal rectangular hysteresis loop in steady-state conditions, however the operation of the self-saturating magnetic amplifiers is defined by the dynamic hysteresis loop shaped as parallelogram illustrated in Figure 4.1.

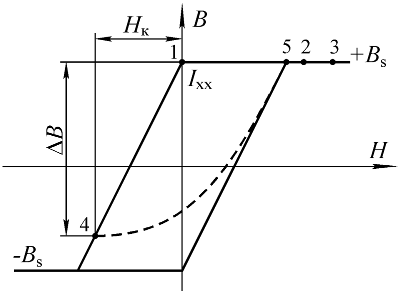


Figure 4.1 – Ideal dynamic hysteresis loop

If $I_{\text{к}} = 0$, the core is not magnetically biased by the control winding. In this case, the DC component of the load current excites the flux of density B_s in the core and its magnetization cycle corresponds to the section 1–2. In this case, the core is in saturation state the positive half-cycle and the load circuit carries maximal current determined by the load impedance only.

If $I_{\text{к}} > 0$, the magnetic flux excited by the control winding coincides in direction with the flux excited by DC component of the load current. In this case, the magnetization cycle of the core will correspond to point 3 (see Figure 4.1), and rms load current is maximal, as well as in the first case.

When $I_{\text{к}} < 0$, the magnetic flux excited by the control winding is opposite in direction to the flux excited by the DC component of the load current. In this case, at the beginning of the positive half-cycle the flux density in the core B_0 will correspond to intensity $H_{\text{к}}$ (point 4, see Figure 4.1).

During the positive half-cycle, the flux density in the core will vary in accordance with the minor hysteresis subloop 4–5–2. In the process, within the section 4–5 its relative permeability far more than 1, therefore the load winding reactance will be very high and very low current will flow through the load circuit. At point 5, the relative permeability becomes zero, and until the positive half-cycle end, the load current will be dependent on resistance $R_{\text{н}}$ only.

With advent of reset half-cycle, the diode cuts off, the current through the load circuit becomes zero, and the core during this half-cycle is demagnetized by the value ΔB. Time diagrams of the operation of self-saturating magnetic amplifier are represented in Figure 4.2.

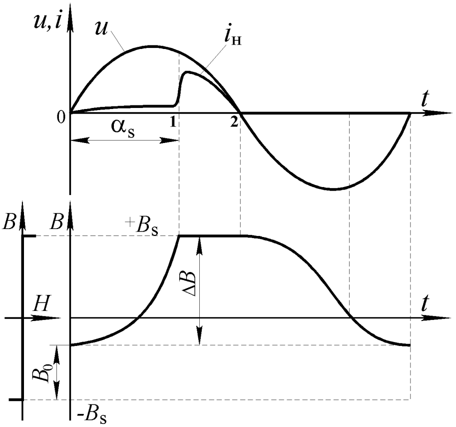
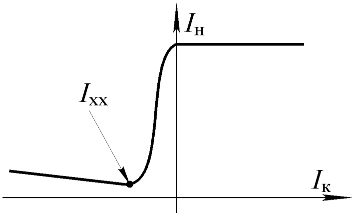


Figure 4.2 – Time diagrams of operation of self-saturating magnetic amplifier



Figurer 4.3 – Control characteristic of self-saturating magnetic amplifier

Mean and rms values of the load current are dependent on the value of *cutting angle* α_s dependent in turn on the value of the flux excited by the control winding. Consequently, taking into account that $B_0 \equiv I_к$, the control characteristic of self-saturating magnetic amplifier will be similar to that shown in Figure 4.3.

4.3 Task

4.3.1 Construct circuit diagram for the experimental study of the magnetic amplifier (it should be made outside the schedule of the laboratory study).

4.3.2 Determine experimentally the control characteristic of the magnetic amplifier and plot its graphical diagram.

4.3.3 Identify the main characteristic operating conditions of the magnetic amplifier.

4.3.4 Measure the time diagrams of the load voltage for all typical operating conditions of the magnetic amplifier.

4.3.5 Draw conclusions from the work.

4.4 Methodical instructions

4.4.1 To perform item 4.3.1, use the textbooks (see the section “References”) or lecture texts. The circuit diagram for the experimental study must include all the required measuring instruments.

4.4.2 To measure the control characteristic of the magnetic amplifier according to item 4.3.2, use a two-half-waved circuit with AC load.

4.4.3 As a supply sources, use an AC phase voltage for the load circuit and a DC supply voltage 0…12 V for the control circuit, respectively.

4.4.4 As a load for the load circuit, use the resistor of 300 Ohm resistance; the load in the control circuit is the control winding itself.

4.4.5 For the sake of convenience to wire the circuit and its checking, the circuit diagram should contain designations of windings’ and power sources’ terminals, as well as numbers of nodes.

4.4.6 The drawn up circuit diagram must be checked by the teacher, who supervises the laboratory works.

4.4.7 Item 4.3.2 should be performed in the following order:

a) assemble the circuit; the assembled circuit must be necessarily checked by the teacher or laboratory assistant;

b) adjust all-purpose measuring instruments according to the desired operation (ammeter or voltmeter, AC or DC), as well as the maximal measuring ranges;

c) close the main circuit-breaker QF and the circuit-breaker of the supply voltage of that phase, which is used for the load circuit;

d) with the help of respective autoformer, step the supply voltage of the load circuit up to the value equal to $2E_s$ (see laboratory work №2);

e) close toggle switch of the supply voltage 0…12 V; increasing the control current with the help of respective regulator, make 5–6 working measurements; derived findings enter into table 4.1.

Table 4.1 – Measured and calculated findings

$I_{к}$, A	**$I_{н}$, A**	**$U_{н}$, B**	**$P_{н}$, Вт**

f) open toggle switch of the control circuit supply source and swap the terminals of the control winding;

g) decreasing the control current with the regulator, make again 5–6 working measurements; derived findings also enter into table 4.1; the control characteristic in working and no-load operation should be measured in more detail;

h); the control characteristic should be plotted in two quadrants.

4.4.8 Item 4.3.4 should be performed in the following order:

a) turn on the oscilloscope and connect HF-cable to its measuring input;

b) connect the cable across the loading resistor of the load circuit and adjust magnetic amplifier to the desired type of operation (no-load, working, current);

c) the sweep that appears on the display should be synchronized and adjusted according to the desired scales on time and amplitude;

d) take photos of the measured displays; all displays must have the same scale in time and amplitude.

4.4.9 After completion of working measurements and operations with the oscilloscope, adjust the autoformers to zero; open all circuit breakers. Prior to disassemble the circuit, obtained findings should be agreed with the teacher.

4.5 Self-checking questions

4.5.1 Explain the operating principle of a self-saturating magnetic amplifier.

4.5.2 What is the control characteristic of a self-saturating magnetic amplifier?

4.5.3 What is the positive (reset) half-cycle?

4.5.4 Name and characterize the typical types of operation of self-saturating magnetic amplifiers.

4.5.5 Present basic circuit designs of self-saturating magnetic amplifiers.

4.5.6 Why self-saturating magnetic amplifiers are magnetic amplifiers with internal feedback?

4.5.7 Name and characterize the static and dynamic parameters of self-saturating magnetic amplifiers.

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