MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

National University "Zaporizhzhia Polytechnic"

# METHODICAL INSTRUCTIONS

to laboratory works on
"THEORY OF ELECTRICAL DRIVE"

in English for students of the branch "Electrician" 141 (specialty
"Electrical energy, electrical engineering and electromechanics")
for all forms of education

Part 2

2023

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# CONTENT

# 1 LABORATORY WORK № 4

## Research of heating of the electric motor in a long operating mode of the work

The purpose of the laboratory work: an experimental research of process of heating and induction motor cooling in a long operating mode of comparison of theoretical and experimental dependence. Excess of temperature of the motor over ambient temperature from a time of heating and cooling.

### 1.1 General theory

Analysis of a thermal condition of electric motors is one of the major problems originating at designing or maintenance of any system of the electric drive. The electric motor can heat up only to the temperature which is not exceeding admissible temperature of its class. Observance of the installed restrictions connected with load-carrying capacity, provides standard service life of the electric motor. Excess of admissible temperatures conducts to a premature failure of isolation of windings. So, for isolation of the class A the excess of an admissible reheat temperature on (8 - 10) C$^{o}$ reduce the isolation service life (and, hence, the electric motor as a whole) approximately in twice. The analysis of a thermal condition of the electric motor allows to estimate the extent of its loading by power. If motor heating is close to standard and does not exceed it, it shows the optimum use of an installed capacity of the motor. In this case the electric drive has the best technical and economic indexes of work, first of all efficiency and a power factor. Heating of the motor below admissible, tells about underloads of the motor or about its overestimated nominal power in comparison with the necessary one. Work of such electric drive will be characterized by low power parameters.

Thus, the estimation of a thermal condition of electric motors is an important technical and economic problem. At transformation of electric energy in mechanical (or on the contrary) the energy part is lost in the motor: on overcoming of resistance of windings to an electric current leakage, on reversal magnetization of a steel and eddy currents in a steel, on a friction in bearings and on ventilation. All this energy loss educes in the form of warmth. Its part is given to an ambient environment, another is store up in motors and causes increasing in its heating. Exact research of processes of heating and cooling of motors is a challenge. The motor is the number of details and the joints of a difficult configuration executed from various materials that causes their various heat capacity and a heat transfer. Conditions of heating of separate parts of the motor are unequal, and the direction of thermal flow depends on power setting. So, at a power stroke a current consumed by the motor is small, and heating of windings will be less than steel heating, in the loaded condition windings are heated up and the thermal flow from a steel to windings changes the direction on the opposite. Therefore research of thermal processes in the electric drive theory is made with such assumptions: the motor is observed as the homogeneous body have infinitely big heat conductivity and equal temperature in all points; the convective heat exchange in environment is proportional to the first extent of a difference of temperatures of the motor and an environment; an environment has an infinitely big thermal capacity, that is in the course of motor heating its temperature does not change, its factor of a convective heat exchange does not depend on motor temperature.

Equation of thermal balance of the motor at constant load:

$$\Delta Pdt = A\tau dt + Cdt,$$

where P − power of losses in the motor, W; t − year; A − motor convective heat exchange, i.e. quantity of heat given by the motor in an environment for unit of time at a difference of temperature equals 1°; τ − excess of temperature of the motor over ambient temperature, °C; C − a thermal capacity of the motor, i.e. quantity of heat which is necessary for a motor increase of temperature on 1°C. For motors excess of temperature of a winding over ambient temperature of 35°C (for moderately cold climatic zone) is rationed that matches to motor standard power.

The solution of the equation on T at the set assumptions looks like:

$$\tau = \tau_{set} \cdot (1 - e^{-t/T_H}) + \tau_{in} e^{-t/T_H} ,$$

where $\tau_{set}$, $\tau_{in}$ − the settled and initial values of excess of temperature of the motor over ambient temperature, °C, accordingly; $T_н$ = C/A − time constant of heating of the motor, s.

At $T_{in} = 0$ equation becomes:

$$\tau = \tau_{set}(1 - e^{-t/T_H}) .$$

For cooling process at the disconnected motor the equation looks like:

$$\tau = \tau_{in} \cdot e^{-t/T_{cool}} ,$$

where $T_{cool}$ – cooling time constant, s.

The previous equations show that at the accepted assumptions processes of heating and motor cooling proceed according to exponential law to the established temperature at which there is a thermal balance, i.e. all warmth which is educed in the motor, is given to the environment and, hence, the motor temperature does not change. This condition can be written down in the form of the equation:

$$\Delta P dt = A \tau_{set} dt$$

As a result:

$$\tau_{set} = \frac{\Delta P}{A} .$$

Value $\tau_{set}$ can be defined on an experimental curve of heating, using a method of three points, based on properties which states that temperature increase for equal periods are proportional to distance of points on a curve of heating from a line of the settled temperature $\tau_{set}$. If to mark out excess of temperature of the motor over ambient temperature during the moments $t_1$, $t_2$, $t_3$ (at condition that $t_2$ - $t_1$ =$t_3$ - $t_2$) as $\tau_1$, $\tau_2$, $\tau_3$ accordingly:

$$\Delta\tau_1 = \tau_2 - \tau_1;$$
$$\Delta\tau_2 = \tau_3 - \tau_2;$$

We can write proportion:

$$\frac{\tau_{set} - \tau_1}{\tau_{set} - \tau_2} = \frac{\Delta\tau_1}{\Delta\tau_2} .$$

Solving this equations on $\tau_{set}$ we gain a design formula for calculation of $\tau_{set}$ by the specified three points:

$$\tau_{set} = \frac{\Delta\tau_1\tau_2 - \Delta\tau_2\tau_1}{\Delta\tau_1 - \Delta\tau_2} .$$

Time constant $T_H$ of heating is defined by a condition that at t ≈ $3T_{н}$,

$\tau = 0{,}95\ \tau_{set}$. For a saving of time only a part of a curve of heating is borrowed and defined by the same three points

$$T_H = \frac{\Delta t}{\ln(\Delta\tau_1 / \Delta\tau_2)} .$$

Time constant of cooling $T_{cool}$ is define by this equation, using a method of three points of an experimental curve of cooling. The measurement of temperature is a significant influence on the accuracy of the experiment. Generally used thermocouples, laid in various parts of the engine, but it should be borne in mind that it is impossible to directly contact the thermocouple with the wire winding, and the electrical insulation is simultaneously and thermal insulation. This leads to the fact that the temperature in the winding grows initially faster than the theoretical curve, and only at $t \geq 0.5Tn$ the actual curve approaches the exponential.

It is more accurate to measure the temperature in the winding by the resistance method, but for this time it is necessary to disconnect the engine from the grid during the measurements, which violates the established mode of its operation. Therefore, they are usually limited to two control measurements of the winding resistance in the cold and heated state of the engine. The equation that relates the resistance and temperature in the winding is obtained:

$$R_{to} = R_{нс}(1 - \alpha_0 t_2{}^o) .$$

where $R_{to}$, $R_{нс}$ − resistance of a winding at temperature accordingly to $t^o$ and $t^o = 0^oC$, Ohm;

$\alpha_o = 1/234$ − temperature coefficient of resistance, I / $^oC$.

If resistance $R_1$ is known at ambient temperature $t^0{}_{oc}$ than resistance

$$R_2 = R_1 \frac{1+\alpha_0 t_2{}^o}{1+\alpha_0 t_{нс}{}^o} .$$

Calculating the equation for $t^0{}_2$, we obtain the calculation formula for calculating the temperature of the winding of the motor by changing its resistance:

$$t_2{}^o = \frac{R_2 - R_1}{R_1}\left(\frac{1}{\alpha_0} + t_{нс}{}^o\right) + t_{нс}{}^o .$$

For calculation of temperature excess we have the expression:

$$\tau = t_2{}^o - t_{нс}{}^o = \frac{R_2 - R_1}{R_1}\left(\frac{1}{\alpha_0} + t_{нс}{}^o\right) .$$

The rate of growth of temperature depends on the exponent. The ratio of heat to heat transfer has a unit time and is called a constant heating time, s:

$$T = \frac{C}{A} .$$

If at start-up the motor has initial temperature, equal to ambient temperature ($\tau_{in} = 0$), the equation will be

$$\tau = \tau_{set}(1 - e^{-t/T_н}) .$$

Graph of this function is shown in figure 1.1. From it is easy to understand physical sense of time constant of heating T. To do it we draw a tangent to a curve in a point matching to origin of coordinates. Any tangent to a curve characterizes speed of observed process. We observe triangle ODE, from this triangle follows that

$$tg\alpha = \frac{ED}{OD} = \frac{\tau_{set}}{t_1} .$$

From the other side:

$$tg\alpha = \frac{d\tau}{dt}\Big|_{t\to 0} .$$

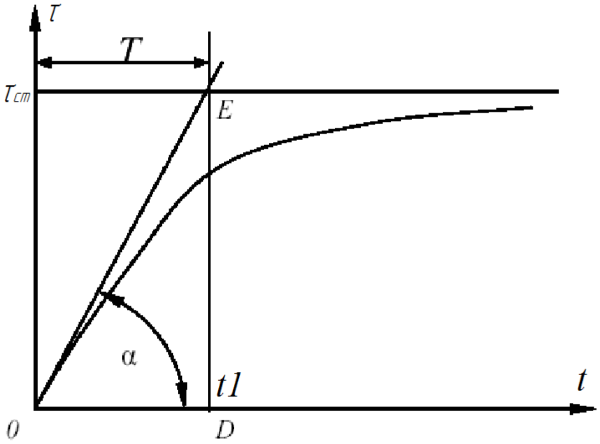


Figure 1.1 – Graph of the function.

From the equation it follows that the derivative from temperature by a time equals:

$$\frac{d\tau}{dt} = \frac{\tau_{set}}{T} e^{-t/T_{н}} .$$

If the process is studied at t → 0, the equation is written as

$$\frac{d\tau}{dt} = \frac{\tau_{set}}{T_{н}} .$$

From comparisons of previous equations follows, $t_1 = T$ that is the projection of a tangent to an axis of abscissa is numerically equal to time constant of heating T. It is defined as a time during which the motor with ideal isolation (without a heat transfer) heats up to such temperature to what it would heat up in usual conditions for an unlimited time. For practical calculations duration of heating, accept t = (3 - 5) T.

Already at t = 3T the motor practically heats up to installed temperature at $t = 3T$ $\tau = 0{,}93\ \tau_y$, at $t = 5T$ $\tau = 0{,}99\ \tau_y$.

At the tests for the established temperature, take a temperature such that during the time of the machine heats the latter no more than 1°C.

Determination of constant temperature of heating of stator winding of asynchronous engine in laboratory conditions. To do this, it is necessary to remove and build part of the constant heating curve τ = f (t) of the stator winding. The heating curve is removed at a steady load on the sfaft of the engine for 40-60 minutes. The constructed heat curve for the time interval shown is shown in figure 1.5.

Select the abscissa on the axis, for example, three points $t_1$, $t_2$ and $t_3$ corresponding to the same time intervals:

$$\Delta t_1 = t_2 - t_1;$$
$$\Delta t_2 = t_3 - t_2.$$

On axes of ordinates to find points of temperatures $\tau_1$ $\tau_2$ and $\tau_3$ matching to them, which are defined as:

$$\Delta\tau_1 = \tau_2 - \tau_1\,;$$
$$\Delta\tau_2 = \tau_3 - \tau_2\,.$$

From points $\tau_1$ and $\tau_2$ at the left to put abscissas, equal to ordinates $\Delta\tau_1$ and $\Delta\tau_2$. The ends of these pieces connect by a straight line and continue during the intersection with an axis of ordinates. The intersection point $\tau_{y1}$ estimates a value of constant temperature of a winding. For the purpose of more exact finding $\tau_{set}$ repeat the construction 2-3 times. For this purpose on the same graph (figure 1.2) choose new points on the axes of abscissa matching to other time periods. Repeating construction, find constant temperature $\tau_{y2}$. Once again repeating construction for the third variant of the chosen periods on an axis of abscissa, find constant temperature $\tau_{y3}$.

$$\tau_{ycm} = \frac{\tau_{y1} + \tau_{y2} + \tau_{y3}}{3}\,.$$

Definition of time constant of heating of a winding of the stator. For this purpose it is possible to use one of three methods. A method of three points. Substituting into equation the abscissas of three points matching to equal time periods (figure 1.2) solve it concerning time constant T:

$$T = \frac{\Delta t}{23\ln\frac{\Delta\tau_1}{\Delta\tau_2}}\,.$$

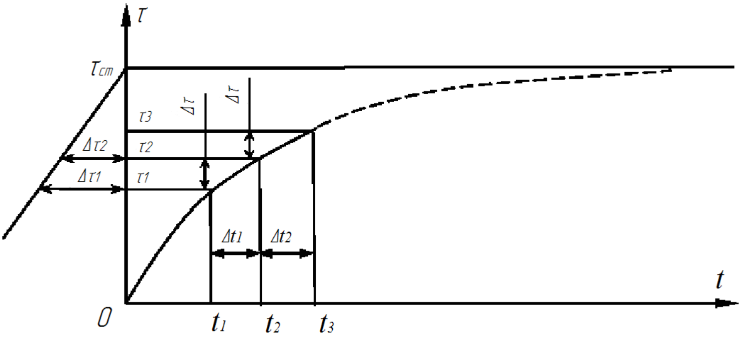


Figure 1.2.

Repeating calculation for three various sections, find T.

Method of tangents. On the graph of part of the heating curve (constructed in the same way as the finding of a constant temperature), build three tangent to the intersection with a line corresponding to the found average steady temperature $\tau_{\text{усер}}$ (figure 1.3). By determining the graphically constant heating time for each of the tangent $T_1$, $T_2$, and $T_3$, find the average constant time of heating

$$T = \frac{T_1 + T_2 + T_3}{3}.$$

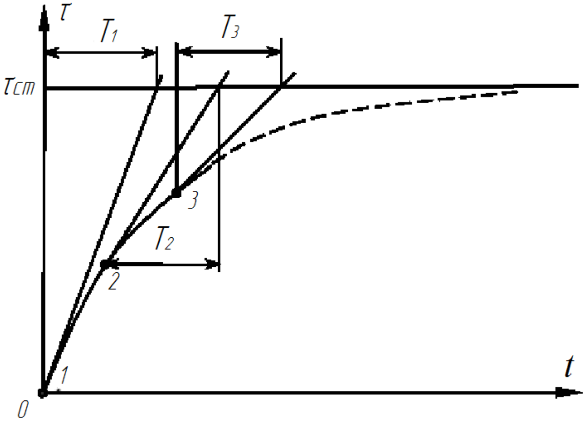


Figure 1.3.

Graphical method. Substitute in the equation values of a time of heating $t_1 = T$, $t_2 = 2T$; $t_3 = 3T$ etc. Gain excess heat temperature (over average temperature) accordingly $\tau = 0{,}63\ \tau_у$; $0{,}85\ \tau_у$; $0{,}95\ \tau_у$, etc.

Build on the graph of the heating curve (constructed similarly to the case of finding the set temperature) along the axis of the ordinates of the particle from the average steady state $\tau_{уср}$ ($0{,}63\ \tau_{усер}$; $0{,}85\ \tau_{усер}$; $0{,}95\ \tau_{усер}$).

Find the corresponding heating time $T_1$, $2T_2$, $3T_3$ on the abscissa axis (figure 1.4). On the received values of the heating time, determine the average value of the constant heating time. For example, to set aside on the ordinates axis values $0{,}63\ \tau_{уср}$ and $0.85\ \tau_{уср}$. According to these values, find the appropriate heating time T1 and 2T2 on the abscissa axis. Determine the constant heating time

$$T = \frac{T_1 + \frac{2T_2}{2}}{3}.$$

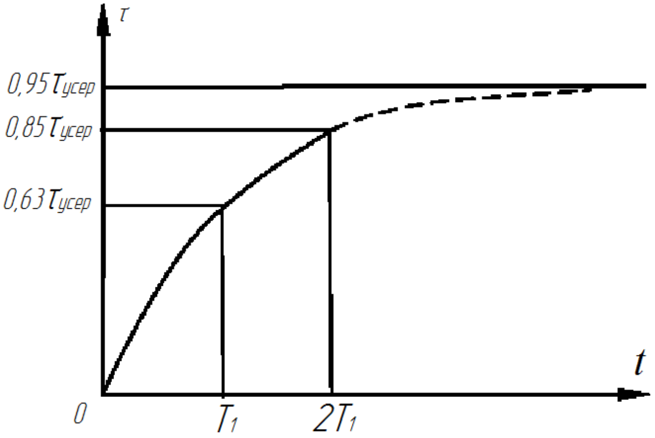


Figure 1.4.

Methods of measurement of temperature:

The accuracy of the results is significantly influenced by the methods of measuring the temperature. Measuring the temperature of the active steel of the engine using thermocouples gives quite satisfactory results. However, the temperature of windings with the help of thermocouples can only be determined approximately, because it is impossible for direct contact of thermocouples with the wire. It is desirable here to have indirect methods, for example, the method of measuring the ohmic resistance.

It is known that the resistance of the conductor during heating increases accordingly with the following equation:

$$R_{t2} = R_{t1} \cdot (1 + \alpha_T \cdot t)\,,$$

where $R_{t2}$ – resistance of a winding at the end of the experiment that is at winding temperature $t_2$;

$R_{t1}$ – resistance of a winding in the beginning of the experiment, that is at winding temperature $t_1$;

t – increase of a heating temperature of a winding during experiment $t = t_2 - t_1$;

$\alpha_T$ – the factor depending on a material of a winding, for example, for copper $\alpha_T = 1/234{,}5$, and for aluminium $\alpha_T = 1/245$.

It is possible to calculate this equation concerning of temperature of a winding at the end of the experiment $t_2$:

$$\tau = t_2 - t_1 = \frac{Rt_2 - Rt_1}{Rt_1} \cdot \left(\frac{1}{\alpha_T} + t_1\right),.$$

$$t_2 = \frac{Rt_2 - Rt_1}{Rt_1} \cdot \frac{1 + \alpha_T t_1}{\alpha_T}\,.$$

or as exceeding of winding temperature over the ambient temperature.

## 1.2 Program of the work

1.2.1. Study the main statements of the theory of engine heating, prepare a report on the passport data of electric machines, with the circuit of installation, the table.

1.2.2 Study the laboratory setup.

1.2.3 Make an experiment, write down the measurement results.

1.2.4 Construct the experimental dependence τ = f (t) by the average values of the thermocouple.

1.2.5. Calculate the excess of the engine temperature above the ambient temperature in the heated state by the results of measuring the resistance in the winding. Set the received value to the graph. Construct a graph for the obtained values.

1.2.6 Calculate the set value of the excess temperature and set it in the graph $\tau = f(t)$.

1.2.7 Determine the constant heating time $T_н$ and $T_{охол}$.

1.2.8 Calculate and set the theoretical dependences of heating and cooling in the graph $\tau = f(t)$, compare them with the experimental ones, make conclusions of the work.

## 1.3 The description of the laboratory installation

The installation diagram is shown in figure 1.5 as well as on the laboratory panel. Investigated object is an asynchronous engine M1 with a short-circuited rotor, loaded with a DC generator M2. The load of the generator is performed by resistance Rн. The generator excitation winding is fed from the rectifier UZ1 through the regulatory rheostat R4. Nominal parameters of the induction motor: $P_n$ = 1,1 kW; $U_n$ = 380 V; $I_{1n}$ = 2,8 A; $2_p$ = 6; η=0,77; cosφ = 0,78; diagram of connections is Y. Nominal parameters of the generator: $P_n$ = I kW; $U_n$ = 110 V; $I_{an}$ = 11,7 A; n = 1000 rev/min; η = 0,78. The tested engine is connected to the network ~ 380V through the automatic switch QF1 and contacts KM2.3 of linear contactor KM2.

The circuit provides two means of changing the temperature of the engine: by the thermocouple and measuring the resistance in the winding of the DC stator. Four thermocouples, in turn, connected to the microprocessor system of measurement, are located as follows: № 4 - in the groove of the rotor, № 1 - in the winding, № 2 - in the yoke, №3 - on the engine body. Thermal electromotive force of thermocouples is measured by the PS1 installed on the circuit. To measure the resistance on the stand there is an independent source of constant voltage V = 15 V, which can be connected to the stator winding with the help of Buttons SB5 «И» (measurement). To prevent the simultaneous feeding of the stator windings of the variable and constant voltage, mutual interlocking of the buttons Sb5 and S56 "П" (start) is provided. Button SB7 "C" (stop) turns off the engine.

## 1.4 Order of the work execution

1.4.1 Obtain the permission of the teacher to conduct the experiment.

1.4.2 Measure engine winding resistance in cold condition. To do this, turn on the stand by pressing the SB1 button ("On"), turn on S2 and QF1. Set the S5 switch to the "Length" position, then press SB5 ("I") to switch on the KM3 contactor and record the readings of the PA1, PV1 devices with two different values of current, changing it with R3 rheostat.

1.4.3 Start the test engine, for which the contactor KM2 must be switched on by the SB6 button.

1.4.4 Turn on QF2. By varying the current of the generator's oscillation with the rheostat M, set the PW1 wattmeter to 360 Watts.

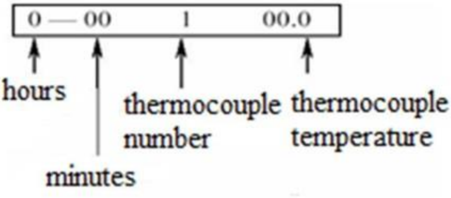
Connect the test recording device by setting the switch S1 to the upper position. Start the countdown and record the performance of all instruments by performing the following tasks.

Before starting, the device must be switched on for 1-2 minutes.

To reset the timer, press the RESET button. When pressing the RESET button on the internal memory, the previous indications of the thermocouples are also erased.

The temperature of the thermocouples begins to be recorded every 2 minutes, immediately after the supply voltage is supplied.

The following information is located on the device screen:



To view the next temperature of desired thermocouple the "Select thermocouple" button is used.

With the flashing cursor of the thermocouple on the screen there is a real time (hour-minute) that has passed since the last click of the "RESET" button.

To look at the temperature of the thermocouples earlier (but not before pressing the "RESET" button) the "Forward" and "Back" buttons are used; if the time on the screen is less than real, the timer cursor does not flash on the screen. When measuring the engine's heating, maintain the load on the PW1 wattmeter unchanged and record the instrument values at the time points specified in table 1.1.

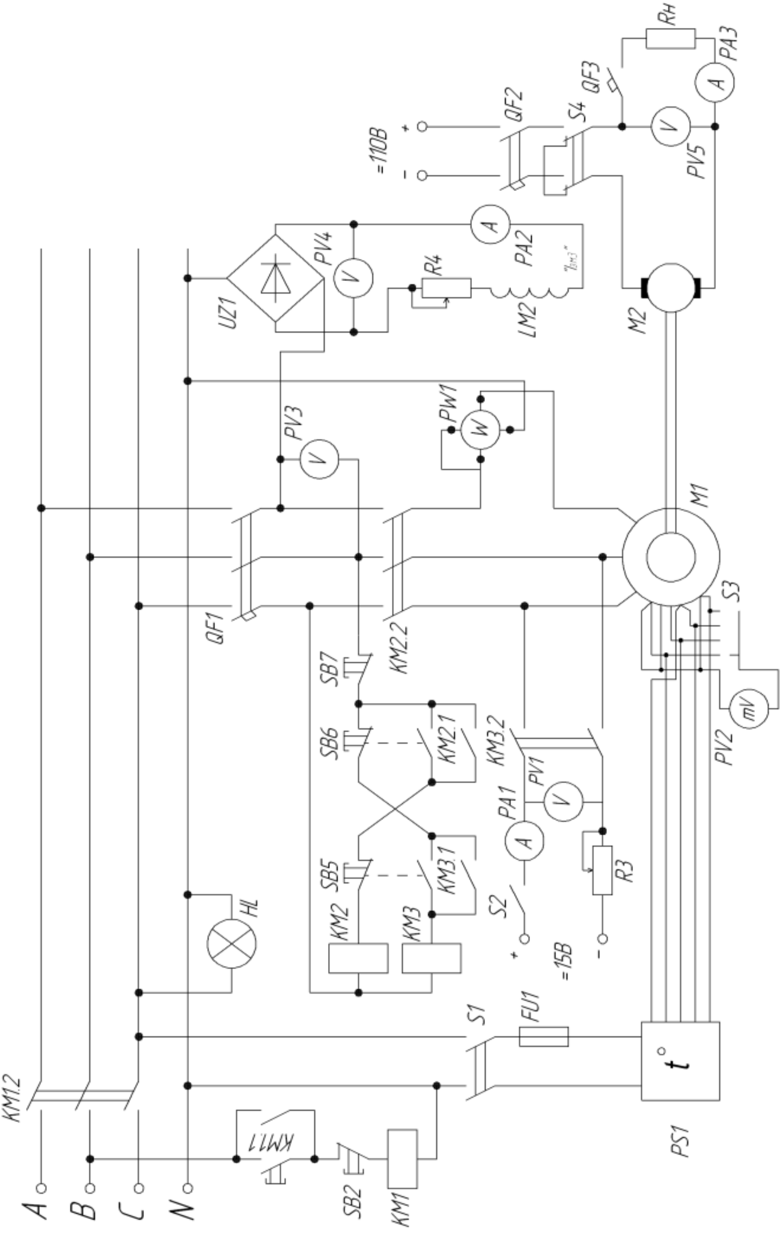

A
B
C
N
KM1.2
KM1.1
SB2
KM1
QF1
HL
S1
FU1
PS1
t°
KM2
KM3
SB5
KM3.1
SB6
KM2.1
SB7
KM2.2
KM3.2
S2
+
=15В
−
PA1
A
PV1
V
R3
PV2
mV
S3
M1
PV3
V
PW1
W
UZ1
PV4
V
R4
LM2
PA2
A
M2
=110В
−
+
QF2
S4
QF3
V
PV5
A
PA3
RН

Figure 1.5.

Table 1.1 − Results of measurement and calculations.

| Time | Measurement | | | | | | | | Calculation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | W, Вт | $T_{\text{ос}}$, C | $U_{1}$, B | $I_{1}$ A | Termocouples | | | | $\tau_{\text{сер}}$, C | $R_{\text{ex}}$, З | $\tau_{\text{обм}}$. З | $\tau_{\text{теор}}$. C° |
| | | | | | 1 | 2 | 3 | 4 | | | | |
| | | | | | C° | | | | | | | |
| 0 | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 15 | | | | | | | | | | | | |
| 20 | | | | | | | | | | | | |
| 30 | | | | | | | | | | | | |
| 40 | | | | | | | | | | | | |
| 50 | | | | | | | | | | | | |
| 60 | | | | | | | | | | | | |

1.4.5 Measure the resistance of the winding in the heated state similar to that carried out in a cold state. The measurements on thermocouples continue until t = 60 minutes.

At time t1 = 40 minutes after removing the indicators of the thermocouple turn off the engine with the SB7 button ("C"), turn off the QFl and QF2.

1.4.6 When the work is completed, switch S1 to the lower position, remove the power from the stand by pressing the SB2 button ("Off").

1.4.7 Instructions for the calculations:

- The average value of the thermocouples for constructing the graph= f (t) is defined as the arithmetic average value for each time point specified in table 1.1;
- exceeding of the engine temperature above the ambient temperature determined by the formula (1.12);
- determine the steady-state value of the temperature exceeding by the formula (1.9);

- constant time Tн calculate by the formula (1.8) for the moments of time 20, 30, 40 minutes, Тохол - for 40, 50, 60 minutes;
- calculate theoretical dependences by the formulas (1.2) or (1.3) and (1.4).

## 1.5 Content of the report

The report should have a circuit of installation, passport data of electric machines, a table with experimental data and results of calculations, as well as graph of dependence $\tau = f(t)$ constructed by the results of the experiment and the calculations, the conclusions on the work.

## 1.6 Control questions

1.6.1 What physical content has a constant heating time and what does its value depend on?

1.6.2 Are there constant heating and cooling times? What is it caused?

1.6.3 How is the heat balance equation written?

1.6.4 When the engine temperature becomes constant and what does its value depend on?

1.6.5 What is heat capacity?

1.6.6 How to calculate the temperature by changing the winding resistance?

1.6.7 In which sequence should I turn on the installation?

1.6.8 Specify the assignment of all elements of the installation circuit.

1.6.9 What is more heated at idling and in operating modes, steel or stator winding?

# 2 LABORATORY WORK № 7

## Control of starting and braking of an induction motor with short-circuited rotor

The purpose of the laboratory work: to study the modes of starting and braking an asynchronous motor with a short-circuited rotor by comparative analysis of various methods of braking of the asynchronous motor with short-circuited rotor.

### 2.1 General theory

Start mode is characterized by the consumption of energy from the network and the presence of the forced components of the magnetizing current and magnetic flux. Electromagnetic moments during the transition from engine mode to braking mode have a changeable character and the main task here is to limit their maximum. To do this, in accordance with the established control principle, to reduce the rate of change of the magnetic flux by one of three methods:

- limitation of the derivative of the flow in time;
- reduction of the limit of magnetic flux changes due to limitation of its constant value;
- due to creation of its some initial value.

For engines with short-circuited rotor, the essential value in terms of the electric drive have multiplicities of the initial torque and the initial starting current.

In fig. 1.1 exemplary natural characteristics of the engine with a normal short-circuited rotor are given. These characteristics indicate that the motor with short-circuited rotor, consuming a very large current from the network, has a relatively low initial start-up moment. Multiplicity of initial starting torque of engines is

$$K_{in} = \frac{M_{in}}{M_n} = 1 \div 1.8 .$$

Multiplicity of a starting current is

$$K_I = \frac{I_{in}}{I_n} = 5 \div 7 .$$

Absence of proportionality between the engine moment and the stator current during start-up (figure 2.1) occurs due to a significant decrease in the magnetic flux of the engine and a decrease in the power factor of the secondary circuit at start-up.

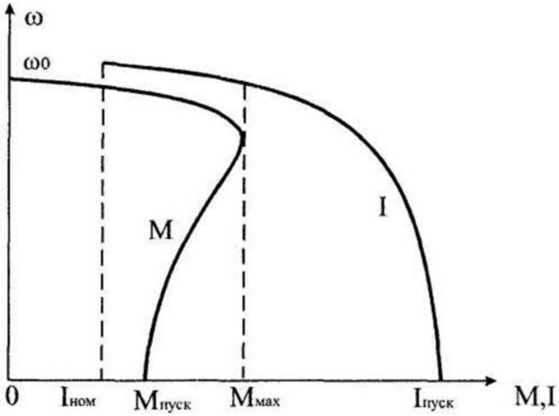


Figure 2.1 – Natural characteristics of the motor with short-circuited rotor.

For increasing of the initial starting torque and reducing of the starting current, motors with short-circuited rotors of special constructions are used. All braking regimes are generating, but differ from each other by the processes of transforming of the mechanical energy of the drive into an electric one. Therefore, the nature of the process of braking is mainly determined by the kind of exciting energy. Excitation of the braking regime in such classical means of braking, as plugging and dynamic, comes from sources of alternating current and direct current.

Plugging can be obtained by switching two phases of the stator winding. The rotor thus rotates against the direction of motion of the field and gradually slows down. If an additional variable resistance is introduced into the stator circuit, it is possible to adjust the braking current, moment and time of the engine stop. Obtained characteristics are shown in figure 2.2.

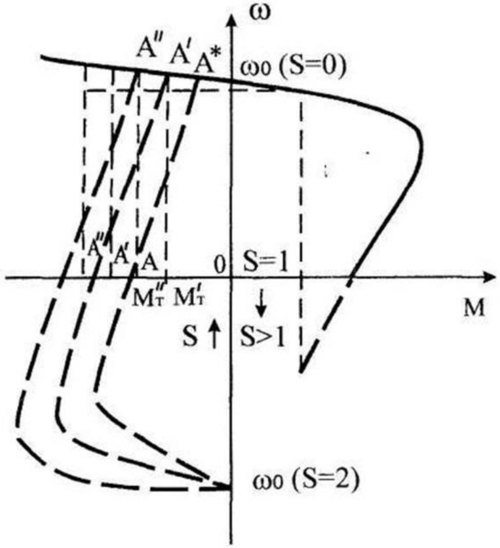


Figure 2.2 – Characteristics of plugging mode.

If the engine was working at a speed of $\omega_c$, then at an off-switch (we consider the magnetic field to be non-inertial) the speed remains unchanged, and the moment changes the sign, that is, it becomes braking (point C). Sliding in this case is more than one (for ω = 0, S = 1). Indeed, substituting the sliding in the formula $\omega_0 = -\omega_0$ (the direction of the field changes), we obtain:

$$S = \frac{-\omega_0 - \omega}{-\omega_0} = \frac{\omega_0 + \omega}{\omega_0} > 1;$$

$$(1 \le S \le 2).$$

At point C, the engine must be disconnected, otherwise a reverse motion (reversal) occurs. By varying the value of the braking current, we obtain different values of the initial (M 'and M ") and the effective moments of braking, that are proportional to the area, limited by the curve M = f (ω) in the second quadrant, which means that the time of braking will be changed. For this purpose, the rheostat R is included in each phase.

Passing through the winding of a stator, a constant current forms a stationary field, the main wave of which gives a sinusoidal distribution of induction.

In the rotary rotor there is an alternating current that creates its field that is stationary relative to the stator. As a result of the interaction of the total magnetic flux with the rotor current, an alternating current arises, which creates its field, which depends on the stator's MMF and the angular speed of the rotor. An exemplary look at the characteristics of various stator currents are shown in figure 2.3.

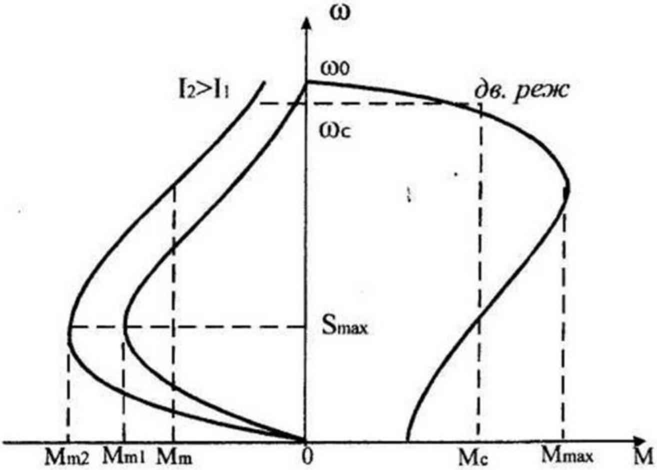


Figure 2.3 – Characteristics of the drive in a dynamic braking regime.

With an increase in current, an effective braking torque increases and, as a result, braking time decreases. Braking regimes may also be obtained without consuming excitation energy from constant sources and, therefore, in the absence of the forced components of the current of magnetization and magnetic flux.

One of the means of braking, which does not consume the power of excitation from the network, is a condenser, based on the use of capacitive self-excitation of the asynchronous machine. Excited by the stator, the machine at a given angular velocity generates the energy emitted in the form of heat in rotor circuit. Such braking circuit have not yet been widely used due to the high cost of capacitors.

Regulation of dynamic characteristics allows to achieve the partial optimization of individual braking regimes, but does not eliminate the known significant defects of each of the four considered main means of braking of asynchronous motors with short-circuited rotor. So, dynamic braking is not very effective due to the small braking torque developed by the engine in the high speed zone. Condenser braking, on the contrary, generating significant brake moments at high angular velocities, generally stops at low angular velocity.

## 2.2 Program of the work:

2.2.1. Study the circuit of starting and braking of asynchronous motor.

2.2.2. Remove the experimental dependence of the engine's braking time on the braking current flowing in the stator winding of the engine in plugging, dynamic and condenser modes.

2.2.3. Make a conclusion about the effectiveness of the braking means of the asynchronous motor.

## 2.3 Description of the laboratory installation

The main element of the circuit shown in figure 2.4 is an asynchronous motor M with a short-circuited rotor. Activation of the machine in the motor mode is carried out by the contactor KM1, in the plugging mode – by contactor KM2, in the dynamic braking mode – by contactor KM3, condenser braking – by contactor KM4. The commands for switching on, switching off of the engine and selecting the braking mode are carried out with buttons SB1 - SB6, which feeds (or removes) power from the coils of the auxiliary relays KH1 - KH4. In turn, the contacts of the relay KN1 - KN4 supply (or remove) the voltage from the windings of the corresponding power contactors KM1 - KM4. S1, S2 tumblers are designed for voltage supply of time relays KT1, KT2. The power supply to the engine control circuit is supplied by the QF1 switch. The engine is shut down with the SB1 button.

## 2.4 Preparation to the laboratory work

The student must be prepared in advance for future work. To do this it is necessary to study a theoretical information, to study the procedure of work, to write down the report.

Before starting the laboratory work, the student shows the teacher a work piece of the report and answers questions according to the laboratory work execution. Unprepared students are not allowed to perform laboratory work and work it out in the prescribed manner.

### 2.5 Order of the work execution

2.5.1. Write down the passport data of the researched engine (table 2.1).

Table 2.1 – Passport data of the investigated motor.

| Parameter | Units | Nominal data |
|---|---|---|
| Type | — | |
| Power | kW | |
| Number of phases | — | |

2.5.2. Feed the laboratory setup. Switch on QF1 and press SB2 ("Start") button. This will activate K1, and then the KM1 launcher, which by its power contacts will turn on the engine and will have the self-supply. Simultaneously with the shutdown of the engine with the SB1 button, turn on the stopwatch and measure the free time (without braking). Write down data of measurements to the table. 2.2.

Table 2.2 − Measurement data.

| | | | | | |
|---|---|---|---|---|---|
| Plugging mode | I, A | | | | |
| | *t*, s | | | | |
| Regime of dynamic braking with independent excitation | I, A | | | | |
| | *t*, s | | | | |
| Regime of dynamic braking with self-excitation | I, A | | | | |
| | *t*, s | | | | |
| Free time | *t*, s | | | | |

2.5.3. With fully introduced rheostats R1, R2, R3 start the engine. Put the engine in plugging mode by pressing the SB4 button and simultaneously turn on the stopwatch. At the moment of reducing the speed of the engine shaft to zero, lock the braking time by repeatedly pressing the stopwatch. Turn off the engine. Write down in table 2.2 value of the current in the stator winding of the engine that corresponds to the moment of engine transition to braking mode, and time of plugging.

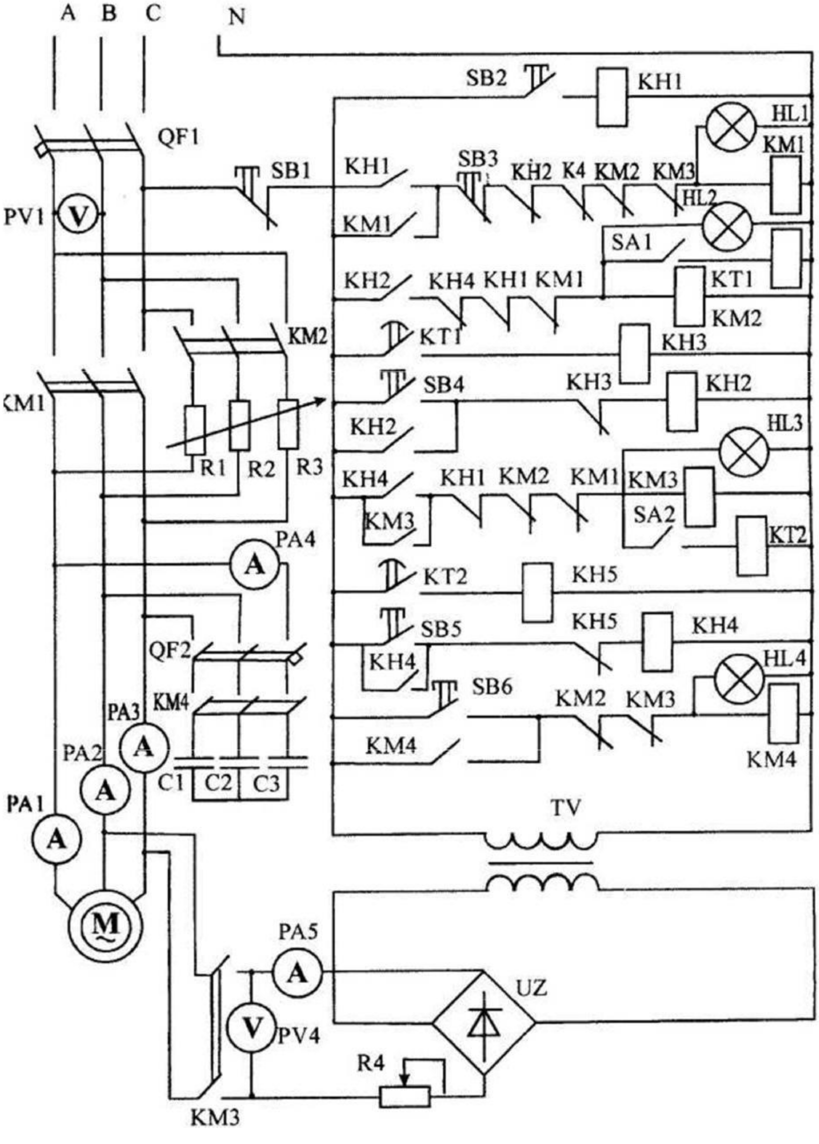


Figure 2.4 − Circuit of the laboratory installation.

2.5.4. Repeat experiment 3 by setting the braking currents (3-4 values) on the labels on the rheostats R1, R2, R3. Turn off the engine. Return rheostat to its original state. Construct graph $t_т = f(I_г)$ (braking).

2.5.5. Rebuild and check the circuits for automatic switching using the time relay. Set the time relay KT1 $t \leq 8$ s when the machine is off. Run the engine, then press the SB4 button and the switch S1 simultaneously. When the time relay KT1 is turned on, in a given time it will turns off K2 and KM2, KM1. Disconnection of KM2 should occur at the moment when the rotor stops (if necessary, adjust the KT1 relay, having previously turned off the QF1 machine). Turn off the engine.

2.5.6. Start the engine. To transfer the engine to dynamic braking mode, apply a constant current to the stator SB5, turn on the stopwatch and measure the braking time. Turn off the engine.

2.5.7. Start the engine, increasing the current of braking with a rheostat, repeat the test for 5-6 times according to paragraph 2.5.6. These measurements should be written down in the table 2.2. Construct a graph $t_т = f(I_г)$.

2.5.8. For a given braking current, find the braking time and set it to the KT2 time relay (when the QF1 is turned off). Run the engine and press the SB5 button simultaneously with S2. At the same time the KT2 time relay will be switched on and starts counting. Over the time, the KT2 contact closes, K5 will be turned on and off with its unlocking contact, then KM3 will shut down. Choose the KT2 so that the shutdown of the circuit occurs at the moment when the rotor stops. Turn off the engine.

2.5.9. Study the process of condenser braking, turn on the QF2 machine and, by pressing the button, start the engine. Press the SB3 button and use the stopwatch to measure the engine braking time, then clear the PA4 ammeter reading when the engine is turned into braking mode.

## 2.6 Content of the report:

The report must contain: the scheme of the laboratory installation; a table with the engine's passport data, a table with the results of the research;

graphs of functions $t_{\text{т}}=f(I_{\text{г}})$ for the investigated braking regimes; conclusions on the effectiveness of the investigated modes of braking.

## 2.7 Control questions

2.7.1. Explain the control circuit for starting and braking the asynchronous motor with short-circuited rotor in general, and the features of its individual elements.

2.7.2 How is the electric lock and self-resetting of the relay elements of the circuit carried out.

2.7.3 Features of the mechanical characteristics of the asynchronous motor in braking modes.

2.7.4 Peculiarities of starting of IM with a short-circuit rotor.

2.7.5 Nominal data of the investigated IM with short circuited rotor.

2.7.6 Physical sense of the plugging mode.

2.7.7 Write the equation and show the graph of the characteristics of the IM in the engine mode and braking mode.

2.7.8 Sense of dynamic braking.

2.7.9 How the circuit works when the engine starts up.

2.7.10 How the circuit works, providing dynamic braking with independent excitation and self-excitation.

2.7.11 Fields of use of the braking modes.

2.7.12 Time relay with clock mechanism.

2.7.13 How the circuit works, providing plugging mode.

2.7.14 What main logical operations are basic when writing basic logical equations (functions) describing elementary discrete processes.

2.7.15 Explain the principle of writing logical equations of control circuits on relay-contact elements.

2.7.16 Explain the basic principles of constructing contactless control circuits.

2.7.17 Explain the basic rules for the implementation of principle electric circuits on logical elements.

# 3 LABORATORY WORK № 20

## Research of speed-torque (mechanical) characteristics of the electric drive of lifting of the crane on the basis of the induction motor with a phase rotor and the power control unit

The purpose of the work: to study the circuit design of control of the electric drive of the mechanism of lifting of the crane, to take experimental characteristics of the induction drive in traction and brake modes; to define a moment of resistance on the motor shaft.

## 3.1 General theory

Mechanical electric drive characteristic can be built by several values ω and M, where ω is the angular speed of rotation of the shaft of the motor, M is the moment developed by the motor.

For conditions of the given work angular speed is defined experimentally, and the motor moment is a design quantity:

$$M = 9{,}81 \frac{GR_d}{i \cdot z_n} \text{ , N·m,}$$

where $G$ - is a load weight, kg;

$R_d$ - is a drum radius, m;

$i$ - is a reductor gear ratio;

$z_n$ - is an efficiency of transmissions.

The first pair of values ($\omega_1$, $M_1$), as it is known, is defined by synchronous angular speed of the motor in the synchronous speed $\omega_1 = \omega_0$ and value of moment $M_1 = 0$.

Synchronous speed is defined by the formula:

$$\omega_{\text{sinh}} = \frac{2\pi f}{p} \text{, rad/s,}$$

where $f$ - is a network frequency, Hz;

$p$ - is a number of pairs of poles of the motor, $p = 3$.

It is necessary to remember, that in the formula of definition of the moment $z_n$ is a variable value and depends on weight of a lifted load. In (11) the following technique for calculation of efficiency at any loading on coefficients $b$, $c$ , $d$ is offered:

$$z_n = f(b,c,d) = \frac{1}{1+b/d+c},$$

where $b = \frac{M_0}{M_H} = k\frac{1-z_{nom}}{z_{nom}(1+k)}$ - coefficient of constant losses;

$c = \frac{\Delta M_{per}}{M} = \frac{1-z_{nom}}{z_{nom}(1+k)}$ - coefficient of variable losses;

$d = \frac{M_1}{M_{nom}} = \frac{G+G_0}{G_{nom}+G_0}$ - coefficient that considers the change of a load weight.

In the given formulas following designations are accepted:

$M$ , $M_{nom}$ , $M_1$ , $M_{per}$ are actual and nominal moments, the moment of idling and the moment of variable losses accordingly; $G$, $G_{nom}$, $G_0$ are weight of actual and nominal loads, weight of the mechanism without weight ( $G_{nom}$=500 kg, $G_0$=20 kg).

The estimation of magnitude $k$ is reduced to the relation of coefficients of constants and variable losses in mechanism transmission $k=b/c$. In calculations it is recommended to choose such values of $k$=1,2…1,5.

For crane low power mechanisms $k$ = 1,2 (1). At nominal loading (kg) the coefficient is equal 1. In the conditions of the given work the loading of the lift is always less than nominal. For this reason γ< 1 and it should be counted for each load weight.

An instance: a load weight $G$ =(90+90) kg, $G_0$ =20 kg, $G_{ном}$=500kg.

For these conditions:

$$d = \frac{G+G_0}{G_{nom}+G_0} = \frac{20+90+90}{500+20} \approx 0,4;$$

$$c = \frac{1-z_{nom}}{z_{nom}(1+k)} = \frac{1-0,7}{0,7(1+1,2)} \approx 0,2;$$

$$b = k\frac{1-z_{nom}}{z_{nom}(1+k)} = 1,2\frac{1-0,7}{0,7(1+1,2)} \approx 0,24.$$

Hence,

$$z_n = f(b,c,d) = \frac{1}{1+b/d+c} = \frac{1}{1+0,24/0,4+0,2} \approx 0,55.$$

Magnitude of the moment developed by the motor is equal:

$$M = 9{,}81\frac{(G+G_0)R_d}{i\cdot z_n} = 9{,}81\frac{(20+90+90)\cdot 0{,}0825}{58\cdot 0{,}55} \approx 5{,}1\text{N·m}.$$

### 3.2 Description of the laboratory setup

The electric control circuit of the lift drive is shown in figure 3.1.

Installation consists of an induction motor with a phase rotor, the reductor, disk shortrun brakes with an electromagnet, a drum with a wire rope, suspension brackets with one moving block, control and protective equipments.

Motor data: type МТОИП-6, $P_n$ =1,4 kW, $n_n$ = 1000rev/min,
$U_n$ = 380V, $I_n$ = 5,3 A, $z_n$ = 0,885, $\cos\varphi_n$ = 0,65.

The reductor with cylindrical wheels (three-stage) with the general transmission relation $i_p$ = 29. The polyspast that consists of one moving block, increases the transmission coefficient to $i$ = 58. Efficiency of all transmission links at a rated load $z_n$ = 0,7. At the loading close to 25% from nominal, efficiency drops to 0,5.

Drum radius is $R_\delta$= 82,5 mm.

Control of the electric drive is carried out by means of control unit KKT-61 that has eleven positions of the handle. The circuit of turning on of resistance in motor phases is symmetric, also it is applied for the movement and turning of mechanisms. But for small cranes and for lifting mechanisms is admitted to apply the symmetric circuit.

The load weight: 1 plate weighs 90 kg, a suspension bracket - 20kg.

### 3.3 Execution of the laboratory work

The speed-torque characteristic of an induction motor with a phase rotor is not rectilinear, but on a section of an operating characteristic with synchronous speed to a rated load it is very close to a straight line and that is why can be built on two points: synchronous speed and speed of any loading.

Synchronous speed is defined by formula:

$$\omega_{\text{sinh}} = \frac{2\pi f}{p}.$$

The second point is determined by tacho-generator parameters, then the moment on the motor shaft is defined by formula

$$M = \frac{GR_d}{i \cdot z_n}\ .$$

where $G$ - is a load weight, N;
$R_d$ - is a drum radius, m;
$i$ - is a reductor and polyspast gear ratio;
$z_n$ - is an efficiency of transmission.

If loading is less than nominal, the efficiency is calculated or it is necessary to define it on a curve.

3.3.1 Set the control unit handle in a zero position and switch on the device.

3.3.2 Fasten a necessary weight and pull down doors, then move the control unit handle in the first position "lifting".

3.3.3 Fix the data of the steady motion of a weight upwards, write them down to the table.

3.3.4 Stop the drive by putting the handle of the control unit to zero position.

3.3.5 Lower a weight in a plugging mode or in modes of power or generative lowering, then fix the received data to the same table.

3.3.6 Take characteristics of a drive on lifting for all weights and for all positions of the handle of the control unit on which lifting of the given weight is possible.

3.3.7 Characteristics of brake lowering of loads in a plugging mode is possible to gain only for the biggest weights in the first positions of lifting.

3.3.8 Research the power lowering of a small weight (or an empty hook) for all five positions of "lowering" control unit.

3.3.9 General lowering of a load is gained at big loads in all "lowering" positions.

3.3.10 If at lifting of loads or a hook the contact of finite turning on KBB is switched on and the drive is stopped abnormally, then you need to put the control unit handle to zero condition in order to return the circuit to a normal state (thus the contactor L should not be switched on). Then push an emergency button "AB" and switch on contactor L. Pressing the contactor button, set the control unit handle in any "lowering" position and wait while KBB will not be free. After that put the handle in a zero position and brake a weight.

3.3.11 Take and build a natural speed-torque characteristic at Rp=0 and G=Var, carrying out consecutive lifting and lowering of various weight according to the table.

| Position of a handle | $G_1$, N | Velocity | | $I_1$, A | $U_1$, V | Calculating data | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Pos. | $\omega_1$, 1/s | | | $\eta_н$ | $\eta$ | $M_C$, Hm | Rp, Ohm |
| 1 “lift” | | | | | | | | | |
| 1 “lift” | | | | | | | | | |
| 1 “lift” | | | | | | | | | |
| and so on | | | | | | | | | |
| 1 “lowering” | | | | | | | | | |
| 1 “lowering” | | | | | | | | | |
| 1 “lowering” | | | | | | | | | |
| and so on | | | | | | | | | |

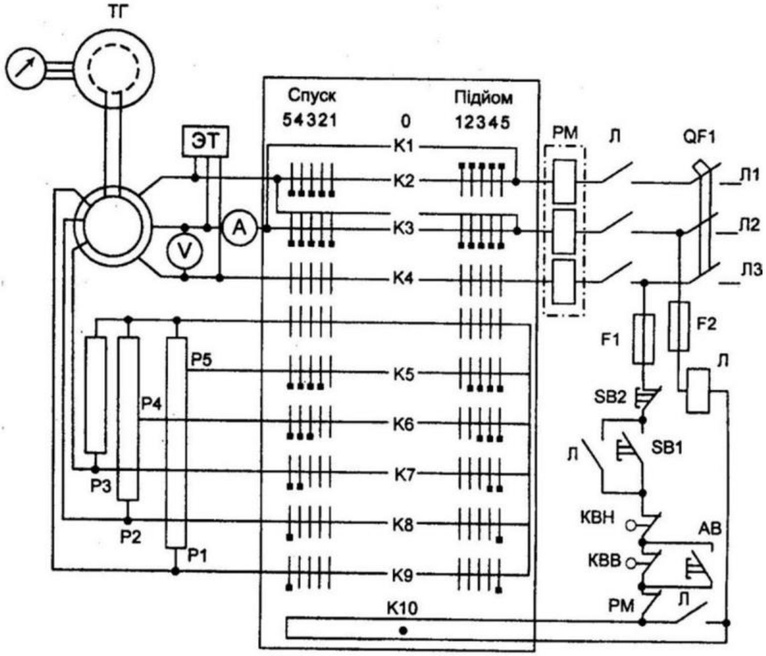


Figure 3.1 - Electric drive of the mechanism of lifting of the crane. The electric basic circuit.

3.3.12 Take and build rheostat speed-torque characteristics at G=Var and Rp=Var, carrying out lifting and lowering of weights according to table.

| Weight, kg | | Speed | | | | | | Calculations | | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| | | lifting | | | lowering | | | | | |
| | | Pos. | N, rev/min | ω, rad/s | Pos. | N, rev/min | ω, rad/s | $\eta_к$ | $M_{ИДМ}$ | |
| 5 | 20+0<br>20+90<br>20+90+90<br>20+90+90+90<br>20+90+90+90+90 | | | | | | | | | Natural charac-teristic |
| 4 | 20+0<br>20+90<br>20+90+90<br>20+90+90+90 | | | | | | | | | 1st rheostat charac-teristic |
| 3 | 20+0<br>20+90<br>20+90+90 | | | | | | | | | 2nd rh.ch. |
| 2 | 20+0<br>20+90 | | | | | | | | | 3rd rh.ch. |
| 1 | 20+0 | | | | | | | | | |

## 3.4 Turning on of the laboratory setup

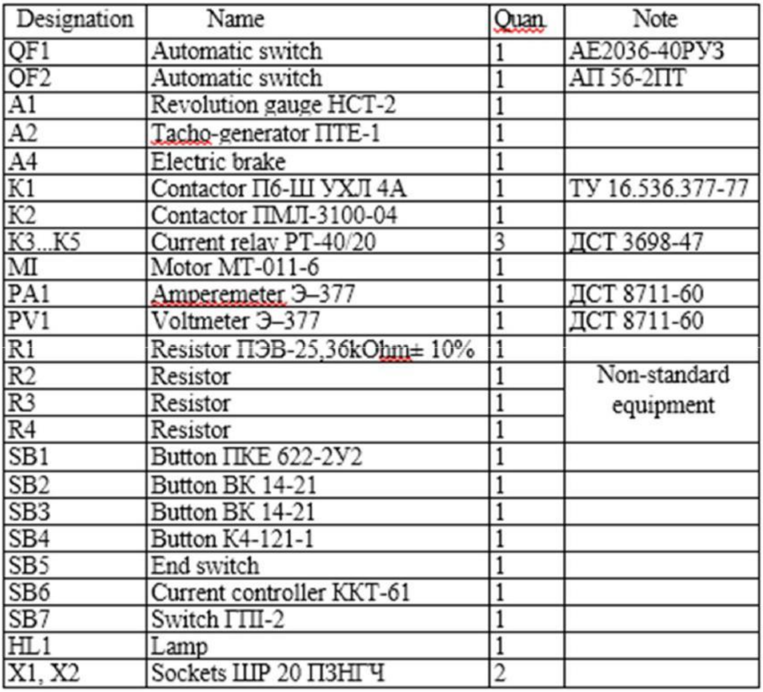
3.4.1 Before switching on of the setup make sure that: any of four load plates is not fixed; enclosure doors are pulled down and the lower blocking finite switch is pushed; the handle of the controller is in zero position.

3.4.2 Switch on command controller to the 2nd position and during the lifting (G0=20 kg) fix constant tachometer indications. Turn the command controller handle to zero position and put the toggle switch to "Lifting" position.

3.4.3 Switch on the circuit breaker 11 and push the button SB1.1 "Start". Make sure that the toggle switch under a tachometer is put in "lifting" position.

3.4.4 For suspension bracket lowering switch on command controller to the 2nd position and fix tachometer indications. After lowering of a weight turn the control unit handle to zero position and switch on the toggle switch to "lifting" position. Repeat tasks 3.4.3-3.4.4 for the 3rd and the 5th positions of command controller and return a suspension bracket to the initial position, push the button SB1.2 "Stop".

3.4.5 Lift a fence door, fix one load plate and repeat tasks 3.4.2-3.4.4.



| Designation | Name | Quan. | Note |
|---|---|---|---|
| QF1 | Automatic switch | 1 | АЕ2036-40РУЗ |
| OF2 | Automatic switch | 1 | АП 56-2ПТ |
| A1 | Revolution gauge НСТ-2 | 1 | |
| A2 | Tacho-generator ПТЕ-1 | 1 | |
| A4 | Electric brake | 1 | |
| K1 | Contactor П6-Ш УХЛ 4А | 1 | ТУ 16.536.377-77 |
| K2 | Contactor ПМЛ-3100-04 | 1 | |
| K3...K5 | Current relay РТ-40/20 | 3 | ДСТ 3698-47 |
| MI | Motor МТ-011-6 | 1 | |
| PA1 | Amperemeter Э–377 | 1 | ДСТ 8711-60 |
| PV1 | Voltmeter Э–377 | 1 | ДСТ 8711-60 |
| R1 | Resistor ПЭВ-25,36kOhm± 10% | 1 | |
| R2 | Resistor | 1 | Non-standard equipment |
| R3 | Resistor | 1 | |
| R4 | Resistor | 1 | |
| SB1 | Button ПКЕ 622-2У2 | 1 | |
| SB2 | Button ВК 14-21 | 1 | |
| SB3 | Button ВК 14-21 | 1 | |
| SB4 | Button К4-121-1 | 1 | |
| SB5 | End switch | 1 | |
| SB6 | Current controller ККТ-61 | 1 | |
| SB7 | Switch ГП-2 | 1 | |
| HL1 | Lamp | 1 | |
| X1, X2 | Sockets ШР 20 П3НГЧ | 2 | |

3.4.6 If during the lifting of loads the switch KBB operates, it is necessary:

- to set the control unit handle to a zero position and to push simultaneously buttons КіП АВ;

- to switch on command controller on lowering to release the end switch of KBB;
- to set the handle to a zero position.

### 3.5 Content of the report

3.5.1 Name of the work.
3.5.2 Purpose of the work.
3.5.3 Electric circuit of the setup.
3.5.4 Results of experimental researches in table form and graphic characteristics.
3.5.5 Static model of the electric drive and its description.
3.5.6 Functional diagram of the drive and its description.
3.5.7 Structurally-algorithmic circuit of the drive and its description.
3.5.8 Conclusion.

### 3.6 Control questions

3.6.1 What are mechanical and electromechanical characteristics?
3.6.2 Under what conditions the characteristic is natural.
3.6.3 How the critical moment and sliding are changed at changing of resistance in a rotor chain.
3.6.4 What is the speed-torque characteristic equation?
3.6.5 Count the equations of the natural characteristic according to passport data, and graphically build this characteristic.
3.6.6 What brake regimes are known in motors with a phase rotor? Build their speed-torque characteristics.
3.6.7 Name speed control modes and build their mechanical characteristics.
3.6.8 What is the dependence of the moment of the motor from supplied voltage?
3.6.9 If the induction motor changes sliding from negative value to sliding of more than 1, in what regimes does the motor work? Build speed-torque characteristics for all these regimes.
3.6.10 What three conditions are necessary for obtaining the generator operating mode with energy output to a network in synchronous motors?
3.6.11 Describe the mode of forced electrical braking.

# 4 LABORATORY WORK № 23

## Variable-frequency induction electric drive

The purpose of the laboratory work:

a) to study the laws of variable-frequency control and regulation and the properties of frequency regulation;

b) experimental removals of control and load characteristics at control laws $\frac{U}{f} = const$, $\frac{U}{\sqrt{f}} = const$;

c) construction of static model of the frequency roller drive; construction of the functional circuit diagram of the drive; construction of the structurally-algorithmic circuit of the drive.

## 4.1 General theory

Type of mechanical characteristic is determined by the idling speed, critical moment, sliding and starting moment. Speed of ideal idling (synchronous speed) is defined as:

$$\omega_0 = \frac{2\pi f}{p},$$

where $\omega_0$ – synchronous speed;
$f$ – frequency of a current of the power supply;
$p$ – number of pairs of poles of the motor.

From this expression it is clear that synchronous speed of the motor directly proportional to frequency of the current supplied to the motor.

Critical moment and sliding are defined by following expressions:

$$M_k = \frac{3 \cdot p}{4 \cdot \pi \cdot f} = \frac{U^2}{r_1 \pm \sqrt{r_1^2 + (x_1 + x_2^{'})^2}},$$

$$S_k = \pm \frac{r_1^{'}}{\sqrt{r_1^2 + (x_1 + x_2^{'})^2}},$$

where $r_1$, $x_1$ – active and an inductive reactance of stator dispersion;

$r_2$ , $x_2$ – active and inductive reactance of dispersion of a rotor which is led to the stator;

$p$ – number of poles;

$f$ – frequency of a feed current;

$U$ – supply voltage;

$M_k$ – critical moment;

$S_k$ – critical sliding.

If in these expressions is neglected in comparison with $(x_1 + x_2^{'})^2$ and it is considered that $x_1 = 2 \cdot p \cdot f \cdot L_1$, $x_2 = 2 \cdot p \cdot f \cdot L_2$, where $L_1$ , $L_2$ are stator and rotor leakage inductance we obtain:

$$M_k = \frac{3 \cdot p \cdot U^2}{4\pi \cdot f \cdot 2\pi \cdot f \cdot (L_1 + L_2^{'})} = \frac{3 \cdot p}{8\pi^2 \cdot (L_1 + L_2^{'})} \cdot \frac{U^2}{f^2};$$

$$S_k = \frac{r_2^{'}}{2\pi \cdot f \cdot (L_1 + L_2^{'})} = \frac{r_2^{'}}{2\pi \cdot (L_1 + L_2^{'})} \cdot \frac{1}{f}.$$

From the gained expressions it is clear that the critical moment is proportional to a square of voltage and inversely proportional to a frequency square, and critical sliding is inversely proportional to frequency.

Dependence of a starting torque from frequency and voltage can be defined as:

$$M_k = \frac{3 \cdot p}{2 \cdot \pi \cdot f} \cdot \frac{U^2 \frac{r_2^{'}}{S}}{(r_1 + \frac{r_2^{'}}{S}) + (x_1 + x_2^{'})^2}.$$

Sliding S = 1 and the magnitude $(r_1 + \frac{r_2^{'}}{S})$ should be neglected in comparison with $(x_1 + x_2^{'})^2$ :

$$M_k = \frac{3 \cdot p \cdot r_2^{'}}{8\pi^2 \cdot (L_1 + L_2^{'})^2} \cdot \frac{U^2}{f^3}.$$

The gained expression is very approximate. From it is clear that the starting torque of the motor is directly proportional to a square of voltage and inversely proportional to a cube of frequency.

Magnitude of speed difference that matches to the critical sliding, equal to the product of synchronous speed to the critical sliding, when frequency change remains constant and equals:

$$\Delta\omega = \omega_0 \cdot S = \frac{2\pi \cdot f}{p} \cdot \frac{r_2^{'}}{2\pi \cdot (L_1 + L_2^{'})^2} \cdot \frac{1}{f} = \frac{2\pi \cdot r_2^{'}}{2\pi \cdot p \cdot (L_1 + L_2^{'})^2} = const\ .$$

Hence, at change of frequency the inclination of mechanical characteristics and an axis of the moments remains approximately constant.

Control law, i.e. the dependence between frequency and voltage at speed control of rotation of a short-circuited induction motor, depends on character of loading. When the loading moment is constant and independent on speed of rotation, the control law should provide invariable overload capacity of the motor that is actually invariable critical moment:

$$M_k = \frac{U^2}{f^2} = const\,;\ \frac{U}{f} = const\,.$$

Family of speed-torque characteristics of a short-circuited induction motor at control law $\frac{U}{f} = const$ is shown in figure 4.1.

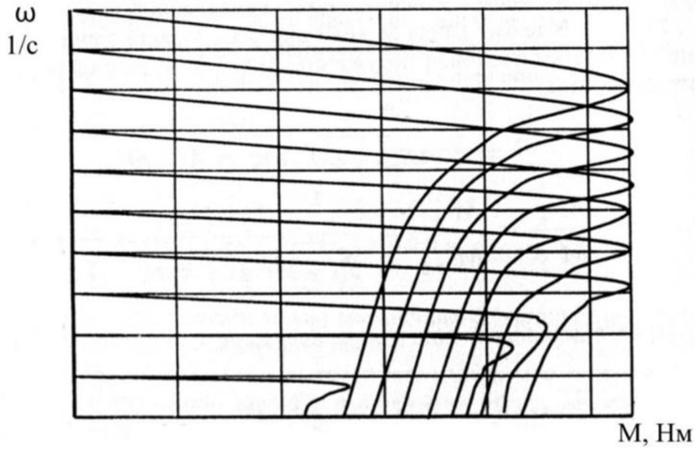


Figure 4.1 – Induction motor under frequency control by the law $U\ /\ f\ = const$ .

Regulation by any other laws at the constant loading moment cannot be effective enough. For example, if voltage decreases slower than frequency, then the motor saturation increases and lead to increase of a current of the stator and its excessive heating. If voltage decreases faster than frequency then overload capacity will decrease that can lead to violation of stability of motor work. Decrease at low frequencies of critical moments is shown in figure 4.1.

In this case when at speed control a power should remain constant, the control law can be obtained as:

$$P = const = M_1 \cdot \omega_1 = M_2 \cdot \omega_2 ;$$

$$\frac{M_1}{M_2} = \frac{M_{k1}}{M_{k2}} = \frac{U^2}{f^3} \cdot \frac{f_2^2}{U_2^2} ; \ \frac{\omega_1}{\omega_2} = \frac{f_1}{f_2} .$$

So, substituting one in another, we obtain:

$$\frac{U_1^2}{f_1^2} \cdot \frac{f_2^2}{U_2^2} = \frac{f_1}{f_2} \text{ or } \frac{U}{\sqrt{f}} = const .$$

The family of speed-torque characteristics at regulation under this law is shown in figure 4.2.

## 4.2 Description of the laboratory installation

Principal circuit of the laboratory stand is shown in figure 4.4. Installation consists of thyristor transducer of the frequency with a link of a direct current, of type ТПЧ-15: $U_с$ = 380V, output U = 230V, f = 50-60Hz, $P_н$ = 12 kW.

Speed control of induction short-circuited motor of type АОЛ31-4, $P_н$ = 0,6 kw, $n_н$ = 1410 rev/min, cos φ = 0,77, that has as loading on the constant-current generator shaft, gives energy to the loading resistance R5.

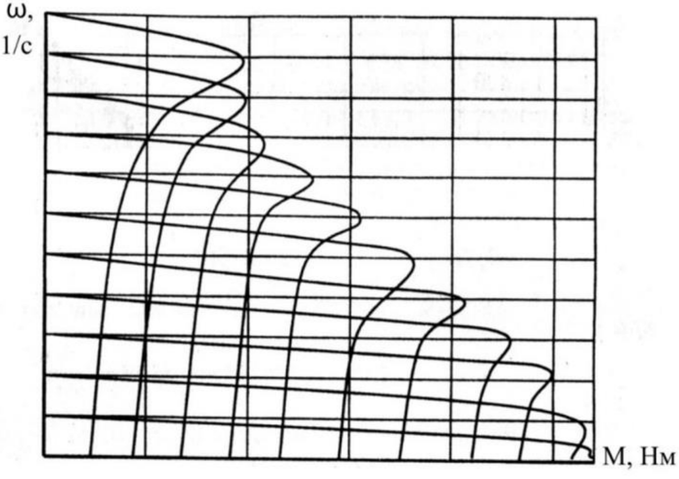


Figure 4.2 – Induction motor under frequency control by the law $U/\sqrt{f} = const$.

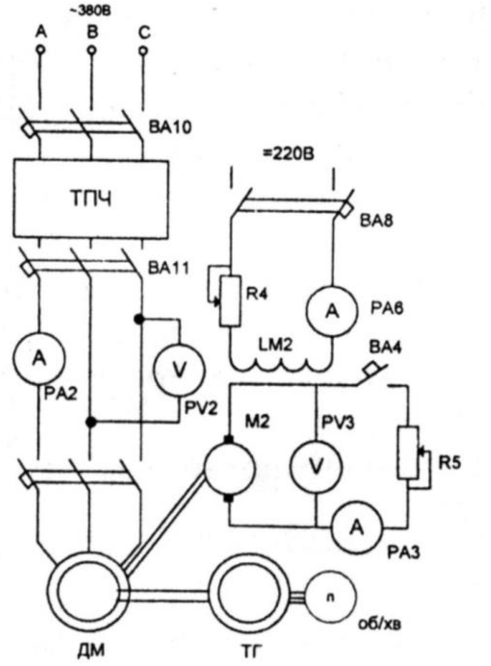


Figure 4.3 – Circuit

Current losses at $I_{nom}\, f(\omega)$, A

| n, rev/min | 200 | 400 | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1700 | 1800 |
|---|---|---|---|---|---|---|---|---|---|---|
| *I*, A | 0,66 | 0,68 | 0,7 | 0,715 | 0,73 | 0,755 | 0,78 | 0,81 | 0,82 | 0,83 |

Passport data of Г2: Type MI–32, $P_н$=0,9 kW, $n_н$=1450 rev/min;
$C_M = 1.34\ Нм\ A^{-1}$;
at $I_{зб}=2A = const$; $C_e=1.43 Нм\ A^{-1}$ .

## 4.3 Carrying out of the laboratory work

4.3.1 Studying of theoretical questions of frequency regulation of electric drives, acquaintance with the basic circuit diagram of the stand and the basic characteristics of an electric equipment. Students are obliged to study main properties of frequency control law of alternating-current drives: to study the circuit diagram of speed control of the frequency drive of an alternating current and electric equipment main properties, to remove the sketch of the basic circuit diagram of the drive at frequency regulation; to prepare the table for experimental data.

4.3.2 Conducting of an experimental part of laboratory work. Order of connection the frequency converter and actuating motor loading in work of the stand are shown in the special table which is on the stand.

$$\frac{U}{f} = const\,; \ \frac{U}{\sqrt{f}} = const\,,$$

where $U_н$ , $f_н$ − rated values: voltage (220V) and frequency (50Hz).

$$A = \frac{220}{50} = 4{,}4\,.$$

Current value of frequency has following value:

$$f_T = \frac{U_T}{A} = \frac{U_T}{4{,}4}\,,$$

or current value that matches to the current value of frequency $U_T = f_T \cdot 4{,}4$.

Some values of voltage for given value of frequency are shown in table 4.1.

Table 4.1 - Value of an output voltage of the converter.

| f, Hz | 55 | 50 | 45 | 40 | 35 | 30 | 25 | 23 | 22 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| $U_T$, V | 242 | 220 | 198 | 176 | 154 | 132 | 110 | 101,2 | 96,8 | 88 |

Order of setup of necessary value of frequency and magnitude of feeding voltage of the frequency converter at the law

$$\frac{U}{\sqrt{f}} = const\,, \ \frac{U}{\sqrt{f}} = \frac{220}{\sqrt{50}} = 31{,}1 = A_H = const\,, \ U_T = 31{,}1 \cdot \sqrt{f_T}\,.$$

Some values of voltage and frequency at control $\frac{U}{\sqrt{f}} = const$ are given in table 4.2.

Table 4.2 − Value of an output voltage of the converter

| f, Hz | 50 | 45 | 40 | 35 | 30 | 25 | 20 |
|---|---|---|---|---|---|---|---|
| $U_T$, V | 220 | 209 | 196 | 184 | 170 | 156 | 149 |

The given values of voltage matching the current value of frequency, are set up by means of regulator potential.

Regulating characteristic at control law $\frac{U}{\sqrt{f}} = const$ acts takes at idling of motor. Frequency of converter (table 4.1) changes by means of the regulator "speed" which is located on the converter ТПЧ-15 and registers value of speed of the motor on a tachometer, located on the stand. Results should be written down in table 4.3.

Table 4.3 – Experimental data for construction of the regulating characteristic

| f, Hz | 50 | 45 | 40 | 35 | 30 | 25 | 20 |
|---|---|---|---|---|---|---|---|
| $\omega_{dv}$, *rev/min* | | | | | | | |

Limits of change of frequency are set by the teacher.

According to the table 4.3 the regulating characteristic is constructed by the dependence $\omega_{dv} = f(f_T)$, $\frac{U}{f} = const$. Using the regulating characteristic the drive transfer coefficient by the channel of regulation is calculated.

Regulating characteristics at $\frac{U}{\sqrt{f}} = const$ acts identically to the law $\frac{U}{f} = const$, but the value of frequency and voltage are accepted according to table 4.2. The data is written down to the table 4.4.

Table 4.4 − Experimental data for construction of the controlling characteristic $\frac{U}{\sqrt{f}} = const$.

| f, Hz | 55 | 50 | 45 | 40 | 35 | 30 | 25 |
|---|---|---|---|---|---|---|---|
| $\omega_{dv}$, *rev/min* | | | | | | | |

According to the table the controlling characteristic is constructed by the dependence $\omega_{dv}=f(f_T)$ using the characteristic, the transfer coefficient by the channel of regulation is calculated.

Loading characteristic at control law $\frac{U}{\sqrt{f}}=const$.

The characteristic is taken at constant value of frequency of the converter and (table 4.1) change of a current of loading (ampermeter A3) by means of potentiometer K5. The limits of change of frequency is given by the teacher. Results should be written down in the table 4.5.

Table 4.5 − Experimental data of dependence of speed of the motor at $\frac{U}{f}=const$.

$f_T$=55Hz

| (A3), $I_3$, A | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\omega_{dv}$, *rev/min* | | | | | | | |

$f_T$=50Hz

| (A3), $I_3$, A | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\omega_{dv}$, *rev/min* | | | | | | | |

$f_T$=45Hz

| (A3), $I_3$, A | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\omega_{dv}$, *rev/min* | | | | | | | |

According to the table 4.5 loading characteristics are built, and by each characteristic hardness of the loading (mechanical) characteristic is calculated and the short analysis of properties of the drive is carried out at regulation under the law $\frac{U}{f}=const$.

Loading characteristic at control law $\frac{U}{\sqrt{f}}=const$.

The characteristic is taken at constant value of frequency of the converter and (table 4.1) change of a current of loading (ampermeter A3) by means of potentiometer K5. The limits of change of frequency is given by the teacher. Results should be written down in the table 4.6.

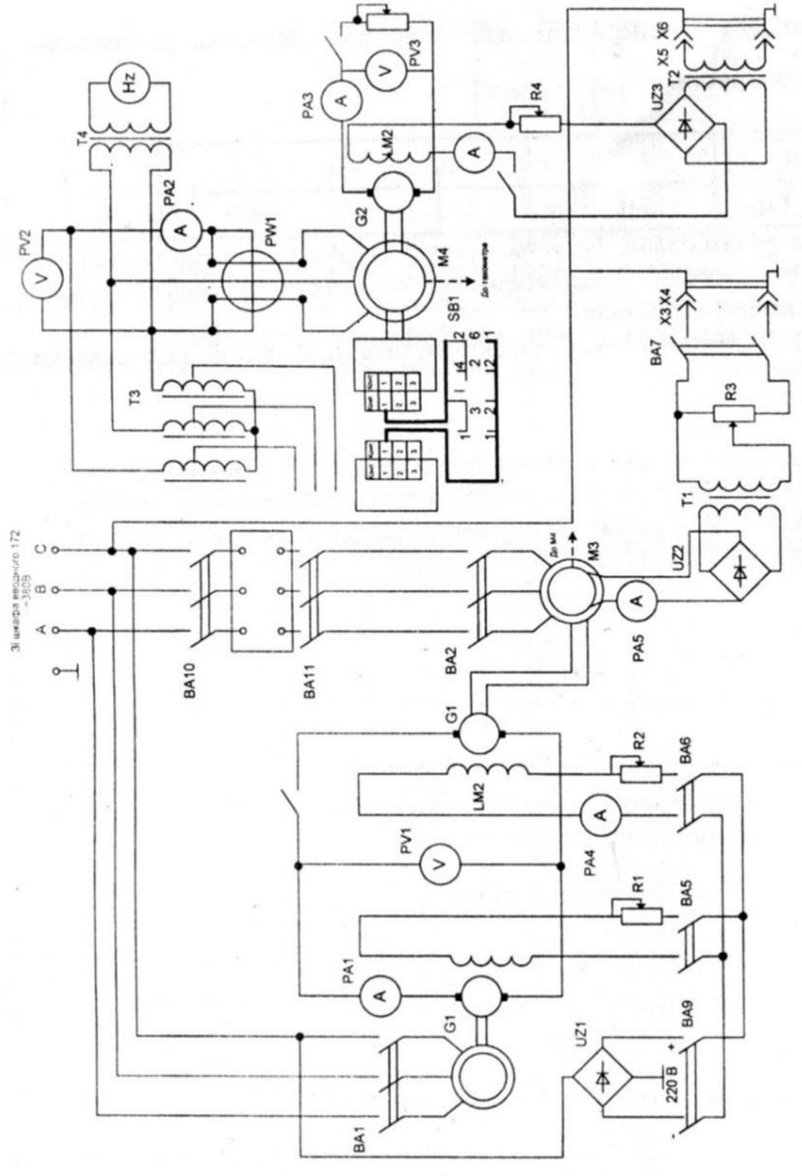


Figure 4.4 – Circuit of the laboratory panel.

Table 4.6 – Experimental data of dependence of speed of the motor at $\frac{U}{\sqrt{f}} = const$.

$f_T$=55Hz

| (A3), $I_3$, A | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\omega_{dv}$, *rev/min* | | | | | | | |

$f_T$=50Hz

| (A3), $I_3$, A | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\omega_{dv}$, *rev/min* | | | | | | | |

$f_T$=45Hz

| (A3), $I_3$, A | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\omega_{dv}$, *rev/min* | | | | | | | |

According to the table 4.6 loading characteristics are built, and by each characteristic hardness of the loading (mechanical) characteristic is calculated and the short analysis of properties of the drive is carried out at regulation under the law $\frac{U}{\sqrt{f}} = const$.

4.3.3 Functional drive circuit design is made on the basis of the principal circuit diagram of the drive and its description according to recommendations of ДСТ ЕСКД.

4.3.4 Structurally-algorithmic circuit design of the drive with frequency regulation is developed according to recommendations (1,2) on the basis of functional circuit.

4.3.5 After acquaintance with the laboratory setup it should be switched on.

4.3.6 Make calibration test of the loading generator by a following method taking into account that the induction motor speed-torque characteristic can be defined as the electromechanical characteristic of the loader $\omega=f(M)$, representing in scale the electromagnetic moment at a constant magnetic flux of a loader the dependence of speed from the electromagnetic moment $\omega=f(M_{EIM})$.

Really, at $I_{bg2}=I_{vn}=const$, i.e. at $F_{nm}=F_{ng2}=const$, electromagnetic moment is defined by expression:

$$M_{zim} = K_M \cdot F_{NM} \cdot I_A = C_M \cdot I_A,$$

where $C_м$ is the coefficient of proportionality, is defined separately at calibration test of a loader and set separately for each setup.

Thus, during the research, speed-torque characteristic of the motor in all regimes is gained by removal of the electromechanical characteristic of a loader ω = $f$ ($I_{\text{ag2}}$). For the record of losses in the loading motor a curve of the losses is removed, representing dependence of speed of the motor from loader armature current ω = $f$ ($I_{\text{ag2}}$), gained at disconnection from a network. At curve removal the loading motor is connected to the constant-current source.

For gaining of a speed-torque characteristic of the motor taking into account losses it is necessary to make the exploratory electromechanical characteristic ω = $f$ ($I_{\text{ag2}}$) and a curve of losses ω = $\varphi$ ($I_{\text{ag2}}$), and then for a resulted curve inject moment scale that is defined by expression:

$$M_м = M_i \cdot C_м ,$$

where $M_i$ − armature current scale, $C_м$ − coefficient of proportionality. According to experiences and calculations it is necessary to calculate the matching values of the drive operated on frequency law. Results are tabulated in 4.7 and 4.8.

Table 4.7 − Measured and calculated data.

| № | Measured data | | | | | | | Calculated data | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $I3$ | $U3$ | $I2$ | $U2$ | $n$ | $f$ | $I_{nom}$ | ω | n | $I_з$<br>$\pm I_{nom}$ | $M=CI$ | $M = M_B \cdot (\frac{U_H}{U_i})$ |
| | | | | | | | | | | | | |

Table 4.8 − Measured and calculated data.

| № | Measured data | | | | Calculated data | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | I3 | U3 | I2 | U2 | P | $P_b$ | $M_{\max}$ | cos φ | η |
| | | | | | | | | | |

## 4.5 Content of the report

The report of the laboratory work should contain:

- the name of laboratory work;
- the work purpose;
- general views of the laboratory stand and its description;

- the list of the equipment and a short technical data of elements and apparatuses of stand;
- the electric principal circuit of the stand and its description;
- results of experimental researches in the form of tables and characteristics and their description;
- the electric functional circuit of the drive and its description;
- the structurally-algorithmic circuit and its description;
- the conclusion;
- the list of references.

## 4.6 Control questions

4.6.1 What main joints does the thyristor transducer with a link of a direct current consist of and appointment of these links?

4.6.2 What condition is carried out at regulation of velocity of induction motor at constant moment by change of network frequency?

4.6.3 What condition is carried out at regulation of velocity of induction motor by change of network frequency if power should remain constant?

4.6.4 What does happen to the induction motor moment if network frequency is increased without changing of voltage?

4.6.5 Represent induction motor speed-torque characteristics at constant network frequency and decrease of supply voltage.

4.6.6 Represent induction motor speed-torque characteristics at constant supply voltage and frequency decrease.

4.6.7 How does the starting torque of the motor depend from network frequency?

4.6.8 How does the moment of an induction motor depend from supply voltage?

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