EXPERIMENTAL INVESTIGATION

Laboratory test # 3/1

# Study of induction motors construction and principle

## *1. Calculation of rated data*

Table

Ratings of induction motor

| Nameplate data | | | | | | | Calculated data | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $U_{1r}$ V | $I_{1r}$ A | $P_r$ W | $n_r$ rpm | $\eta_r$ % | $\cos\varphi$ | $f_{1r}$ Hz | $2p$ | $n_1$ rpm | $s_r$ | $\Omega_r$ $\frac{rad}{s}$ | $M_{2r}$ N⋅m | $P_{1r}$ W |
| | | | | | | | | | | | | |

The synchronous rotational frequency $n_1$ is assumed equal the nearest to the rated motor rotational frequency greater value of the values obtained by calculation by expression

$$n_1 = \frac{60 f_{1r}}{p},$$

where pole pairs number $p$ is consequently taken equal to 1, 2, 3, 4, … .

Poles number $2p$ is assumed equal to the value suitable the found rotational frequency $n_1$.

The rated rotor angular speed

$$\Omega_r = \frac{\pi n_r}{30}.$$

The rated motor torque

$$M_{2r} = \frac{P_r}{\Omega_r}.$$

The motor slip under full load

$$s_r = \frac{n_1 - n_r}{n_1}.$$

The active power consumed by the stator winding under full load

$$P_{1r} = \sqrt{3} U_{1r} I_{1r} \cos\varphi,$$

where $U_{1r}$ is the rated line-to-line voltage, $I_{1r}$ is the rated line current.

*2. Determination of the phase winding terminals*

Determination of the phase winding terminals is accomplished accordingly to the circuit diagram shown in Fig. 1.

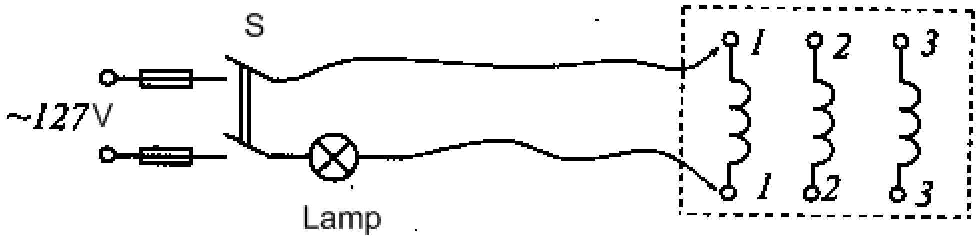


Figure 1

*3. Machine terminals marking*

The machine terminals marking is performed with the help of circuit shown in Fig. 2.

When start lead of one phase and start lead of another phase (or end lead of one phase and end lead of another phase) of two of three phases are connected together the voltmeter connected across the third phase reading is zero.

If start lead of one phase and end lead of another phase are connected the voltmeter gives reading differing of zero.

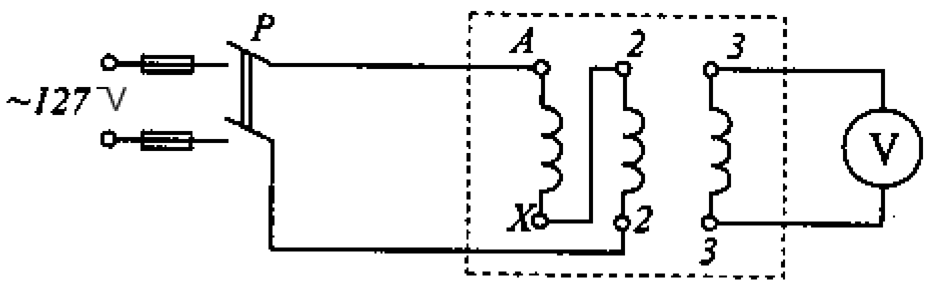


Figure 2

The principle of terminals marking is explained by Fig. 3.

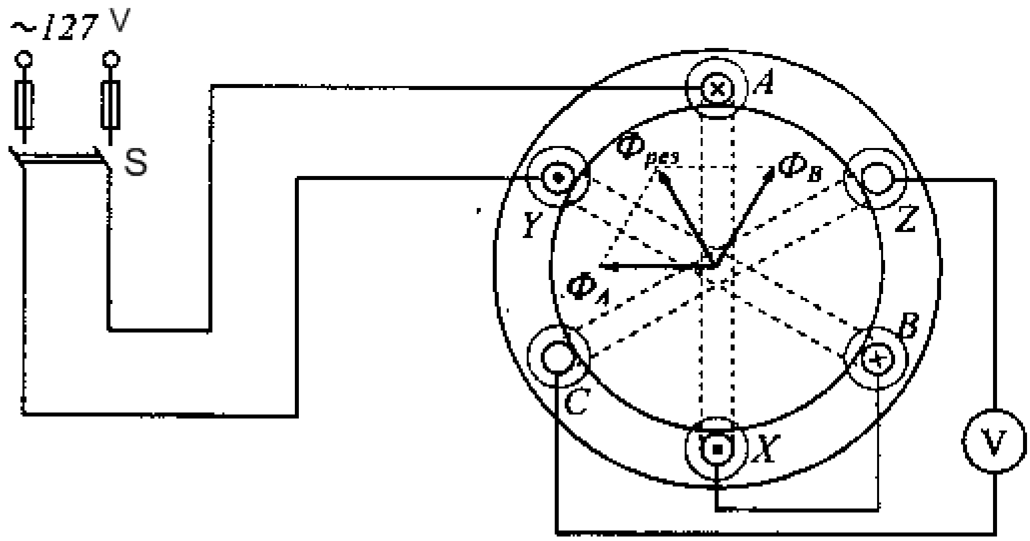


Figure 3

EXPERIMENTAL INVESTIGATION

Laboratory test # 3/2

# INVESTIGATION OF THREE-PHASE INDUCTION MOTOR USING DATA OF NO-LOAD AND SHORT-CIRCUIT TESTS

***Aim of the training*** is study of a wound rotor induction motor performance using experimental data of no-load and short-circuit.

***Work program:***

1. Study of the motor construction.
2. Measurement of the phase stator windings resistance.
3. Carrying out the no-load test.
4. Carrying out the short-circuit test.
5. Plotting the motor equivalent circuit
6. Plotting simplified circle diagram.
7. Determination of data and plotting the motor operating characteristics and speed-torque curve.
8. Analysis of experimentally obtained induction motor characteristics.
9. The report execution.

***The work procedure***

*Stage 1 Study of the motor construction*

Study construction of the motor that is subject to testing.
Using the motor nameplate data fill in the Table 1.

Table 1

Motors manufacturer data

| Motor type | Stator winding connection | $U_{1r}$ | $I_{1r}$ | $P_r$ | $n_r$ | $\eta_r$ | $\cos\varphi_r$ | $I_{2r}$ | $U_{2r}$ |
|---|---|---|---|---|---|---|---|---|---|
| - | - | V | A | kW | rpm | % | - | A | V |
| | | | | | | | | | |

*<u>Stage 2</u> Measurement of the phase stator windings resistance*

Measurement of the stator windings resistance is performed at direct current by method of ammeter and voltmeter according to the circuit shown in Fig. 1. The circuit should be checked by the instructor.

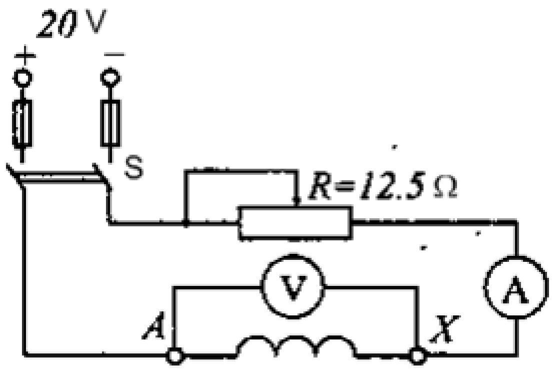


Figure 1 Measurement of phase stator windings resistance

Determination of the resistance is fulfilled on the basis of measurements at three different current values made separately for each of three phases.

The result of phase resistance determination must be found as average value of all the results obtained at every of the measurements. It should be reduced to the windings working temperature of 75º C. The measurement and calculation results are to be filled in Table 2.

Table 2

Data of measurement and calculation of stator phase winding resistance

| Winding phase | Measured | | | Calculated | | |
|---|---|---|---|---|---|---|
| | $U$ | $I$ | $t_{amb}$ | $R_{1ph}$ | $R_1$ | $R_{1,75°}$ |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
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| | | | | | | |

Denotation in the table:

$t_{amb}$ is the ambient temperature while the measurements;

$R_{1ph}$ is resistance of each the phase;

$R_1$ is average phase resistance calculated on the basis of the measurements;
$R_{175°}$ is the phase average resistance reduced to the working temperature.

*<u>Stage 3</u> Carrying out the no-load test*

Connect the circuit according to Fig. 2 after selection of the needed values of the current transformers ratio and the resistance of additional series resistors in the wattmeter voltage circuit basing on the instruments circuit limitations.

Connection of the stator winding (Y or Δ) is selected basing on the rated voltage values given in the nameplate data.

The no-load test is performed at the motor running without any load on its shaft. In this case the motor slip is almost zero, and its speed is practically equals the motor synchronous speed.

Determine the instruments scale division values and fill them in Table 3.

Table 3

Instruments scale division values

| $C_V$ | $C_A$ | $C_W$ |
|---|---|---|
| V/div | A/div | W/div |
| | | |

After checking the circuit by the instructor, start the motor and take readings of the instruments. Before starting, the rheostat in rotor circuit should be put in and should be gradually put out to zero while starting. The rheostat handle must not be remained at intermediate position.

After filling the instruments readings in Table 4, switch the circuit off and calculate phase voltage and current, losses and parameters of the no-load condition filling them in the same Table.

Table 4

Data of no-load test

| Measured | | | | | Calculated | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $U_{1,l-l}$ | $I_{A0}$ | $I_{C0}$ | $P_{10}$ | $P_{20}$ | $U_{10}$ | $I_{10}$ | $P_0$ | $\Delta p_c$ | $\Delta p_{mech}$ | $Z_m$ | $R_m$ | $X_m$ |
| V | A | A | W | W | V | I | W | W | W | Ω | Ω | Ω |
| | | | | | | | | | | | | |

The quantities denotation:

$U_{10}$, $I_{10}$ is the stator phase voltage and current under no-load respectively;

$P_0 = P_{10} + P_{20}$ is active power consumed under no-load. Should be determined with account of the summand signs;

$\Delta p_c$ is the motor magnetic loss under rated voltage;

$\Delta p_{mech}$ is mechanical loss;

$Z_m$, $R_m$, $X_m$ are the motor no-load parameters.

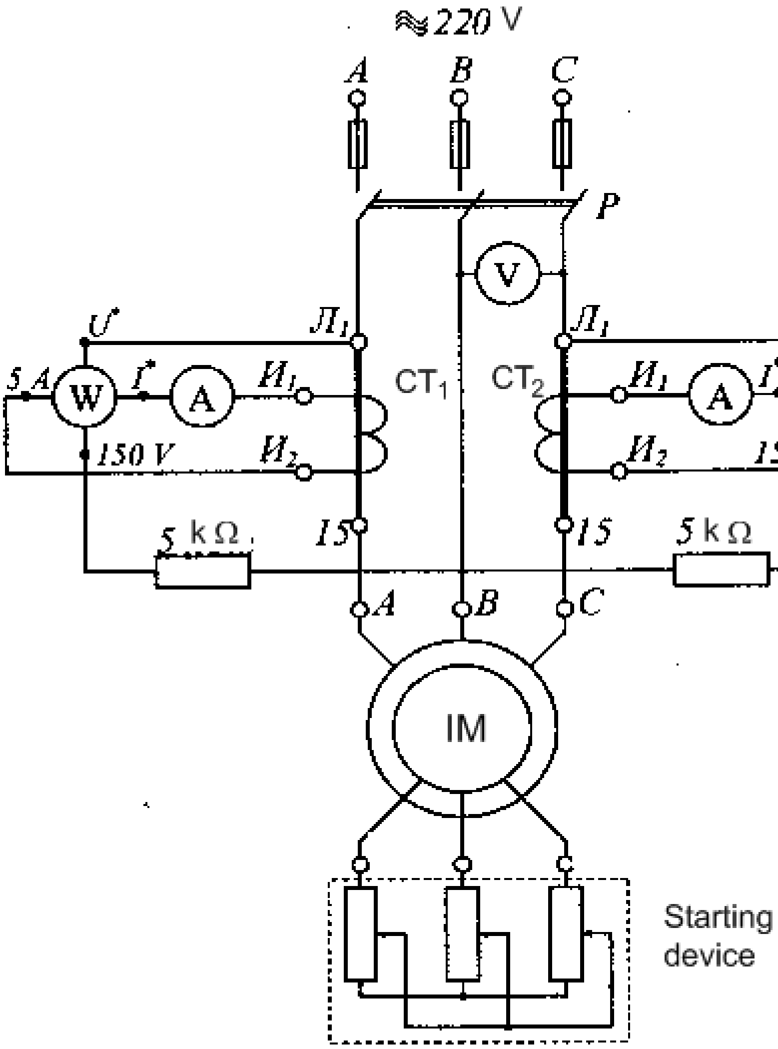


Figure 2 Motor circuit at no-load test

*<u>Stage 4</u> Carrying out the short-circuit test*

*Attention!* The short circuit test has to be carried out under reduced voltage at which the stator current does not exceed its rated value.

Connect the circuit according to Fig. 3. Select the needed value of the current transformers ratio. Line-to-line voltage supplying the stator winding under the test does not exceed 70 V. Therefore, if the voltage limit of the wattmeter is not less than this value, the additional series resistor in the wattmeter circuit is not necessary. Determine the instruments scale values and fill them into Table 5.

Table 5

Instruments scale division values

| $C_V$ | $C_A$ | $C_W$ |
|---|---|---|

| V/div | A/div | W/div |
|---|---|---|
| | | |

After checking the circuit connection by the instructor, ascertain that the mains supply voltage is zero, block the rotor, switch the circuit on, whereupon increase the supply voltage till the stator current becomes equal or some less the rated value.

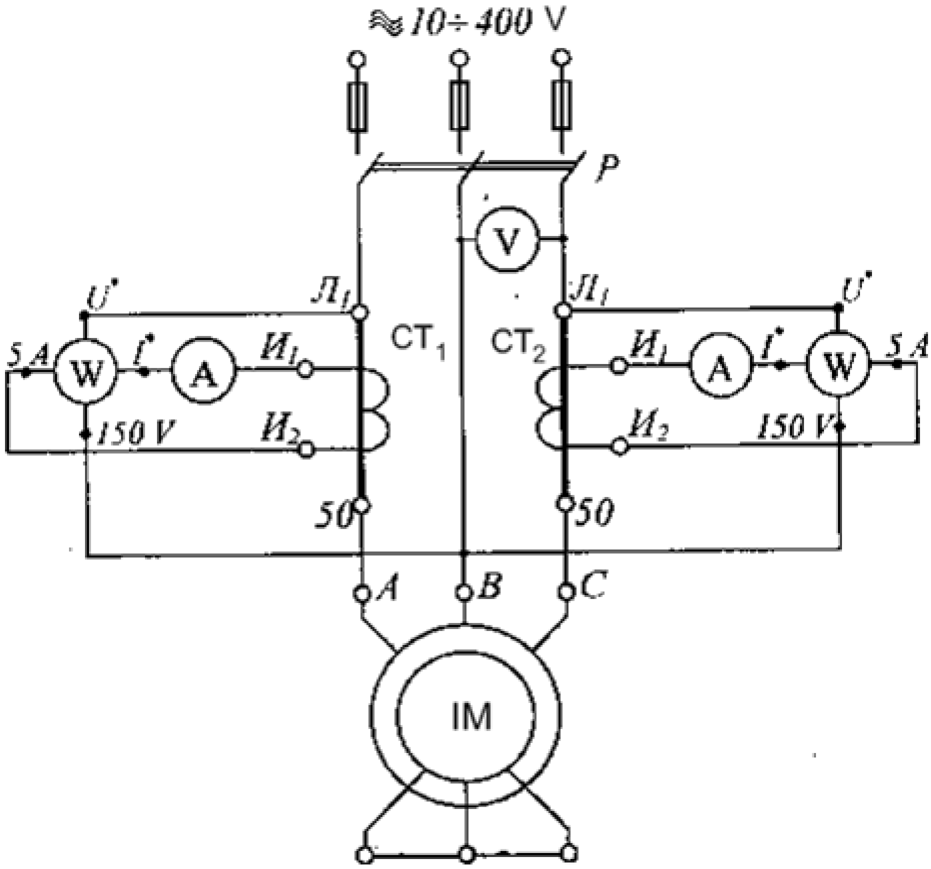


Figure 3 Motor circuit at short-circuit test

Take the instruments readings and fill them in the Table 6. Switch off the circuit.

Table 6

Data of short-circuit test

| Measured | | | | | Calculated | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $U_{s,l-l}$ | $I_{sA}$ | $I_{sC}$ | $P_{1s}$ | $P_{2s}$ | $U_s$ | $I_s$ | $P_s$ | $R_s$ | $R_{s75}$ | $R'_{2,75}$ | $X_s$ |
| V | A | A | W | W | V | A | W | Ω | Ω | Ω | Ω |
| | | | | | | | | | | | |

Using the data of measurement, calculate values of the stator phase voltage and current $U_s$ and $I_s$, active power $P_s$ consumed by the motor under short-circuit condition as the sum of the wattmeter readings with account of their signs, the equivalent motor resistance and reactance $R_s$ and $X_s$ under condition of short-circuit (or rotor-blocked) test, resistance $R_{s75}$ related (or reduced) to the working temperature of 75℃ , and the rotor phase resistance referred to the stator (primary) phase winding and reduced to the working temperature $R'_{2,75}$.

*Stage 5 Plotting the motor equivalent circuit*

Draw the simplified motor equivalent $\Gamma$ -circuit indicating parameters obtained at no-load and short-circuit tests.

*Stage 6 Plotting motor simplified circle diagram*

It is recommended to use for plotting the circle diagram a chart-paper sheet of A4 size.

After definition of the current scale factor, plot the motor simplified circle diagram marking on it the lines of electromagnetic, useful output and input powers $P_{em}$,$P_2$ and $P_1$ respectively, the line of the motor electromagnetic torque $M$, the scales of motor power factor $\cos\varphi$, slip $s$ and efficiency $\eta$.

*Stage 7 Determination of data and plotting the motor operating characteristics and speed-torque curve*

Find values of the scale factors $m_P$ and $m_M$ for determination power and electromagnetic torque by the circle diagram.

Using the circle diagram, determine values of the motor consumed input power $P_1$, stator current $I_1$, electromagnetic torque $M$, slip $s$, rotor rotational frequency $n$, efficiency $\eta$ and power factor $\cos\varphi$ at specified values of the motor useful power on the shaft $P_2$. It is recommended to assume the shaft power values for determination the values of quantities needed to plot the operating characteristics equal to $P_{2*} = 0, 0.25, 0.5, 0.75, 1.0, 1.25$ relative units.

The found quantities values, needed for plotting the motor operating characteristics fill in Table 7.

Table 7

Data for plotting induction motor operating characteristics obtained from circle diagram

| Point | $P_2$ | | | $P_1$ | | $I_1$ | | $M$ | | $s$ | $n$ | $\eta$ | $\cos\varphi$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $m_P=$ … kW/mm | | | | | $m_I=$ … A/mm | | $m_M=$ … Nm/mm | | - | rpm | - | - |
| | Rel. | mm | kW | mm | kW | mm | A | mm | Nm | | | | |

| | unit | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | | | | | | | | | | | |
| 2 | 0.25 | | | | | | | | | | | |
| 3 | 0.50 | | | | | | | | | | | |
| 4 | 0.75 | | | | | | | | | | | |
| 5 | 1.00 | | | | | | | | | | | |
| 6 | 1.25 | | | | | | | | | | | |

Plot the operating characteristics of the induction motor $M = f(P_2)$, $n = f(P_{2)}$, $s = f(P_2)$, $I_1 = f(P_2)$, $P_1 = f(P_2)$, $\cos\varphi = f(P_2)$, $\eta = (P_2)$ by the data of Table 6 using one mutual system of coordinate axes.

By the circle diagram, find data for plotting the motor *rotational frequency-torque curve* and fill them in Table 8.

Table 8

Data for plotting rotational frequency-torque curve

| Point | $M$ | | s | n | Notes |
|---|---|---|---|---|---|
| | $m_M$= … Nm/mm | | - | rpm | |
| | mm | Nm | | | |
| 1 | | | | | No-load condition |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | Full load |
| 6 | | | | | |
| 7 | | | | | |
| 8 | | | | | Critical point |
| 9 | | | | | |
| 10 | | | | | |
| 11 | | | | | Short-circuit condition |

Data for the first six lines of Table 8 are to be taken from Table 7. Using data of Table 8, plot the motor rotational frequency-torque curve.

### <u>Stage 8</u> *Analysis of experimentally obtained induction motor characteristics*

Analysis of the data, obtained experimentally with the help of the circle diagram which has been plotted by the data obtained from the motor no-load and rotor-blocked tests, is performed by comparison them with the motor rated values given in the nameplate data (see Table 9).

Table 9

Comparison of motor nameplate and experimentally obtained data

| Quantity | Unit of measurement | Rated value by nameplate | Experimentally obtained value | Deviation in % |
|---|---|---|---|---|
| $P_{1r}$ | kW | | | |
| $I_{1r}$ | A | | | |
| $M_r$ | Nm | | | |
| $n$ | rpm | | | |
| $\eta$ | - | | | |
| $\cos\varphi_1$ | - | | | |

Deviations of experimental data are found as difference between the experimentally obtained and nameplate values in per cent of the nameplate values. If deviation magnitude of experimental value exceeds 10%, the value experimentally obtained at the study conditions has to be considered as unsatisfactory.

*Stage 9 The report execution*

The report must contain:

1. The work title, its aim and program.
2. The motor nameplate data (Table 1).
3. Test circuits (Fig. 1, 2, 3).
4. Experimental and calculated data (Tables 2, 3, 4, 5, 6, 7, 8).
5. The motor equivalent circuit.
6. The machine circle diagram.
7. Plots of operating characteristics and rotational frequency-torque curve.
8. Comparison of motor nameplate and experimentally obtained data (Table 9).

***Methodical guideline***

*To stage 2*

Reducing of the rotor phase winding resistance to normal working temperature is made by the expression:

$$R_{1,75^\circ} = R_1[1 + \alpha_R(75 - t_{amb})]$$

where $\alpha_R$ is the temperature coefficient of resistance. For copper conductors $\alpha_R = 0.0043\ 1/℃$

*To stage 3*

The stator phase current under no-load test $I_{10}$ is assumed equal to average value of phase currents defined by the measured line currents $I_{A0}$ and $I_{C0}$ with account with the stator winding connection.

The active power consumed by the machine under no-load operation is determined as $P_0 = P_{10} + P_{20}$ where $P_{10}$ and $P_{20}$ are the wattmeter readings. Take into account that in the case of balanced three-phase voltage system at the indicated in Fig. 2 phase sequence the reading $P_{20} > 0$ and the reading $P_{10} > 0$ if the phase current lags the phase voltage by the angle $\varphi < 60°$, $P_{10} = 0$ if $\varphi = 60°$ and $P_{10} < 0$ if $\varphi > 60°$.

The amount of the magnetic and mechanical losses is found as

$$\Delta \mathrm{p}_c + \Delta \mathrm{p}_{mech} = P_0 - 3R_1 I_{10}^2.$$

Magnetic and mechanical losses are assumed equal. Therefore,

$$\Delta \mathrm{p}_c = \Delta \mathrm{p}_{mech} = \frac{P_0 - 3R_1 I_{10}^2}{2}.$$

The motor no-load parameters are calculated by the expressions:

$$Z_m = \frac{U_{10}}{I_{10}}, \; R_m = \frac{P_0 - \Delta \mathrm{p}_{mech}}{3I_{10}^2}, \; \mathrm{X}_m = \sqrt{Z_m^2 - R_m^2}.$$

The power factor at no-load is equal to

$$\cos\varphi_0 = \frac{P_0}{3U_{10}I_{10}}.$$

*To stage 4*

To find short-circuit current and power values under sort-circuit condition at the rated voltage use the expressions

$$I_{sr} = I_s \frac{U_{1r}}{U_s}, \quad P_{sr} = P_s \left(\frac{U_{1r}}{U_s}\right)^2.$$

The power factor under short-circuit:

$$\cos\varphi_s = \frac{P_s}{3U_s I_s}.$$

Short-circuit parameters:

$$Z_s = U_S/I_s, \quad R_{s,75} = R_s[1 + \alpha_R(75 - t_{amb})], \quad X_s = \sqrt{Z_s^2 - R_{s,75}^2}\,.$$

where $R_s = {P_s}/{(3I_s^2)}$ is short-circuit resistance under the test conditions at the ambient temperature $t_{amb}$ .

The rotor phase resistance referred to the stator side and reduced to the normal working temperature:

$$R'_{2,75} = R_{s,75} - R_{1,75}.$$

The stator phase leakage reactance and the rotor phase leakage reactance referred to the stator side:

$$X_1 \cong X'_2 \cong {X_s}/{2}\,.$$

*<u>To stage 5</u>*

The motor simplified equivalent Г-circuit is sown in Figure 4. This circuit is used for construction of the simplified circle diagram. Write down the values of the motor parameters obtained in stages 2, 3, 4 on the equivalent circuit plot.

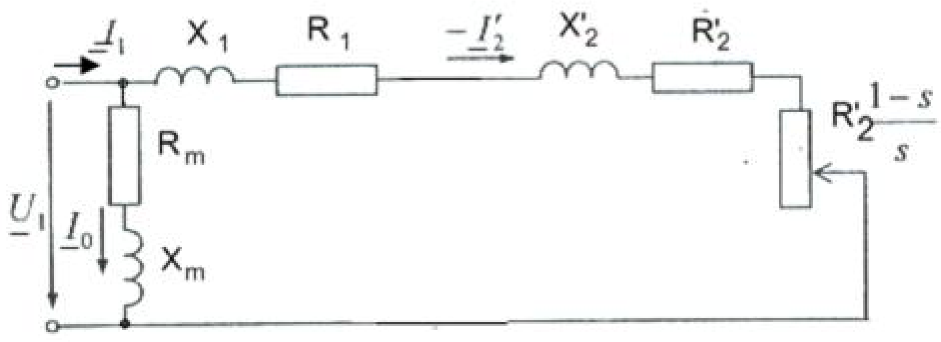


Figure 4 Simplified equivalent Г-circuit of the induction machine

*<u>To stage 6</u>*

It is recommended to use for plotting the circle diagram (Fig. 5) a chart-paper sheet of A4 size.

The diagram construction is made in the following order:

1) Cartesian rectangular coordinates axes are plotted. The stator phase rated voltage vector $U_{1r}$ is overlaid on the ordinate axis being plotted in an arbitrary scale.
2) Choose the current scale $m_I$, A/mm of integral value so that the length of the vector $I_{sr}$ be in the bounds of 200 … 300 mm.
3) Plot the no-load point $H$ laying off the segments representing scaled active and reactive no-load current components: segment $OH_1$ representing the reactive component $I_{10react}$ is laid out by the abscissa

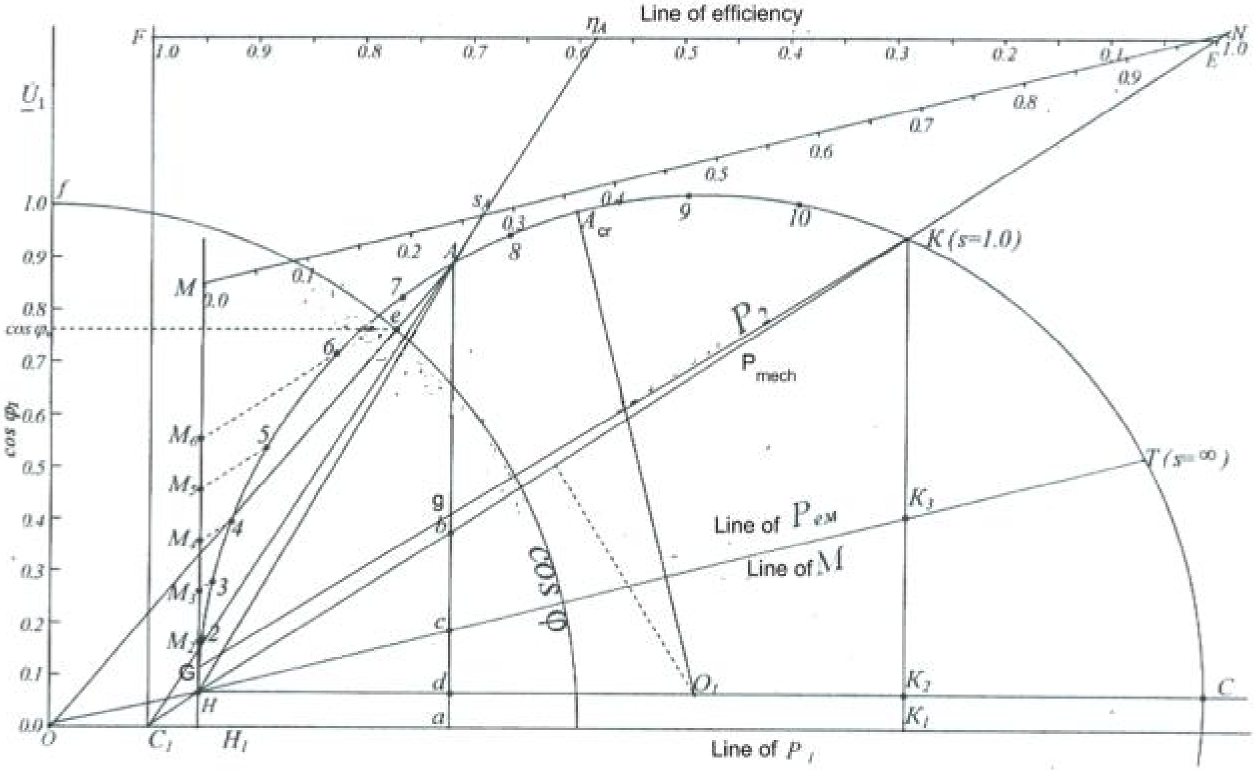


Figure 5 Circle diagram of asynchronous machine

axis, segment $H_1H$ representing the active component $I_{10act}$ is laid off parallel to the vector $U_{1r}$. The segment $OH$ represents the vector $I_{10}$.

4) Plot the short-circuit point $K$ laying off the segments representing scaled active and reactive short-circuit current components: segment $OK_1$ representing the reactive component $I_{sr,react}$ is laid out by the abscissa axis, segment $K_1K$ representing the active component $I_{sr,act}$ is laid off parallel to the vector $U_{1r}$. The segment $OK$ represents the vector $I_{sr}$.
5) Plot the straight line $HC$ parallel to the abscissa axis.
6) Draw the current circle. For that, plot the straight line $HK$ and find the point dividing the segment $HK$ in half. Restore the perpendicular from that point. The point $O_1$of it intersection with the line $HC$ is the current circle center. Its radius equals the length of the segment $O_1H_1$. The obtained circle is the locus of the stator phase current vector terminus at different values of the machine slip occurring at different values of the shaft torque and steady speed.

Assume that at some load the stator current vector terminus is in the point $A$. The segment $OA$ represents the stator current vector $I_1$ which value is equal to $I_1 = OA \cdot m_I$, A. The referred value of the rotor phase current is $I'_2 = HA \cdot m_I$ .

Different points of the current circle meets different definite values of the motor load $P_2$ and, consequently, of the slip $s$. The no-load point $H$ meets the slip $s = 0$, the short-circuit point $K$ – the slip $s = 1$. The circle section between $H$ and $K$ represents the complete set of conditions while the machine operates as a motor ($0 < s < 1$).

The point $T$ meets the conditions of the machine operation at infinite speed: $n = -\infty$ ($s = -\infty$) in generator condition and $n = +\infty$ ($s = +\infty$) in condition of electromagnetic brake. The circle section between $K$ and $T$ represents the complete set of conditions while the machine operates as electromagnetic brake ($1 < s < +\infty$). The part of the circle between the points $H$ and $T$ meets conditions of generator ($0 > s > -\infty$).

To find position of the point $T$, it is necessary to divide the segment $KK_2$ of the vertical line passing through the point $K$ in the ratio

$$\frac{K_3K_2}{KK_2} = \frac{R_{1,75}}{R_{s,75}}.$$

Finding from this ratio length of the segment $K_3K_2$ we determine position of the point $K_3$. Drawing the line $HK_3$ till it crossing to the circle find the point $T$.

With the help of the circle diagram the data needed for plotting the induction motor operating characteristics and the speed-torque curve may be obtained.

There are some special lines in the diagram having particular names:

- The line of the consumed power $P_1$- the straight line $H_1K_1$
- The line of the electromagnetic power $P_{em}$ and the electromagnetic torque – the straight line $HT$
- The line of mechanical power $P_{mech}$ - the line $HK$

- The line of shaft power $P_2$ - the line *GK*. The segment *HG* is scale representation of the sum of mechanical and additional losses. The additional losses to a first approach may be neglected.

The electric active power consumed by the motor, the mechanical shaft power and electromagnetic power equal:

$$P_1 = Aa \cdot m_P, \quad P_2 = Ag \cdot m_P \, , \; P_{em} = Ac \cdot m_P$$

where $m_P = 3U_{1r}m_I 10^{-3}$, kW/mm is the power scale factor.

Length of the segment *HG* equals $HG = \Delta p_{mech}/m_P$ where $m_P$ is defined in *stage 2*.

The electromagnetic torque is equal to

$$M = Ac \cdot m_M$$

where $m_M = \frac{m_P}{\Omega_1} = \frac{m_P 10^3 p}{2\pi f_1}$, Nm/mm is the electromagnetic torque scale factor.

The critical condition of the motor operation at which the electromagnetic torque is maximum (the appropriate slip value is called the critical slip and is denoted as $s_{cr}$) meets the point $A_{cr}$ of the circle. This point is found as tangent point of the line, parallel to the line of electromagnetic torque *HT*, to the circle.

The motor efficiency is defined as

$$\eta = \frac{P_2}{P_1} \, .$$

It is convenient to determine it with the help of the efficiency scale which is constructed in the following way. The straight line *KH* is prolonged to both sides. It crosses the abscises axis in the point $C_1$. The perpendicular $C_1F$ to the abscises axis is restored from the point $C_1$. Above the current circle the line *FE* parallel to the abscises axis is drawn so that the segment could be divided into 10 equal parts. The segment *FE* is the scale of the motor efficiency which zero mark is in the point *E*, and the unity mark – in the point *F*. The scale may divided with some step, for example, with the step of 0.1. To determine the efficiency value, it is necessary to draw the straight line through the points $C_1$ and the working point (*A*) and to read the efficiency value $\eta_A$.

For determination of the slip for any motor operating condition, the scale of slip may be used. This scale is built as follows. The perpendicular to the abscises axis is held through the point *H*. Above the current circle, the line *MN* parallel to the electromagnetic power line *HT* is drawn so that the segment *MN* could be conveniently divided in 10 equal parts. This segment is the slip scale, it is marked as shown in Fig. 5. If the working point on the current circle is given (for example, the point *A*), the slip value may be determined by this scale. For that, the line *HA* is drawn till it crosses the slip scale. The crossing point determines the sought-for value of the slip.

The motor power factor may be found from the circle diagram as follows. Put the line segment *Of* on the ordinate axis, and put the scale on it in the bounds of 0 and 1.0 with the step of 0.1 and designate the obtained marks with the numerical values. The segment serves as the scale of $\cos\varphi$. Draw a quarter of a circumference by radius *Of* in the first quarter of the coordinate plane. The obtained circumference ark is the line of $\cos\varphi$. Connect the coordinate origin $O$ and the working point $A$ on the circle diagram with the straight line and find the point $e$ of the line $OA$ intersection with the line of $\cos\varphi$. Find the point $e$ projection on the scale of $\cos\varphi$ and make the scale reading of $\cos\varphi$ value.

*To stage 7*

As it was said above, the operating characteristics of the induction motor $M = f(P_2)$, $n = f(P_2)$, $s = f(P_2)$, $I_1 = f(P_2)$, $P_1 = f(P_2)$, $\cos\varphi = f(P_2)$, $\eta = (P_2)$ by the data of Table 7 using one mutual system of coordinate axes. The scale factors for these quantities are chosen so that the plots fill the coordinate plane sufficiently and scale readings may be easily made.

Approximate form of graphics is shown in Fig. 6.

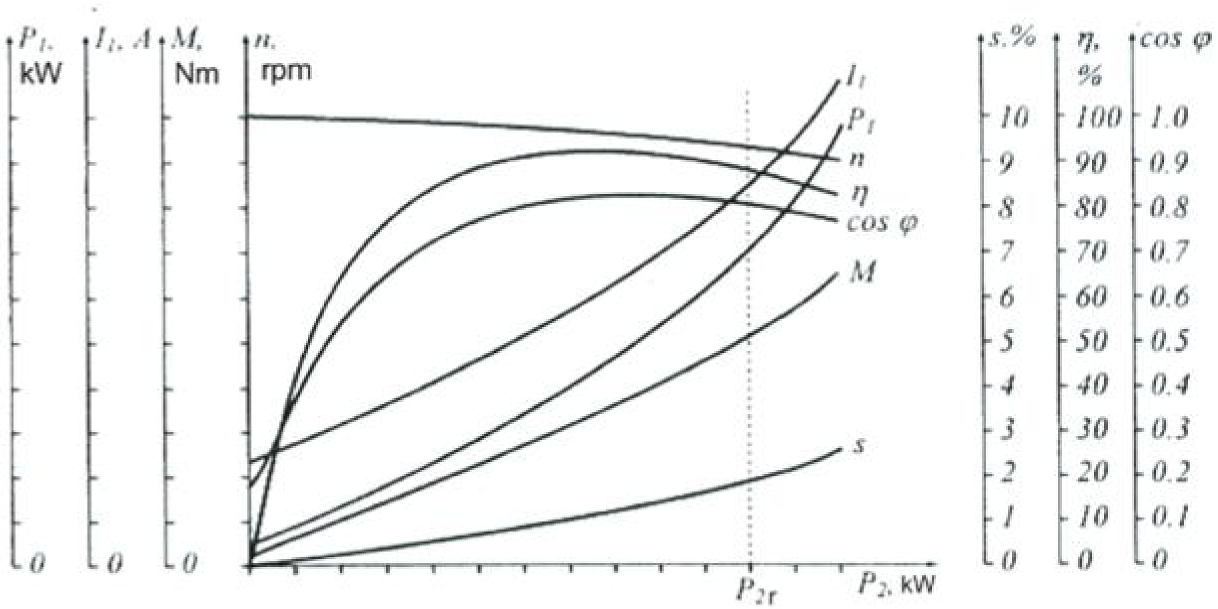


Figure 6 Operating characteristics of the induction motor (approximate form)

Using the data of Table 8, plot the rotational frequency-torque curve of the motor. An approximate form of the curve is shown in Fig. 7.

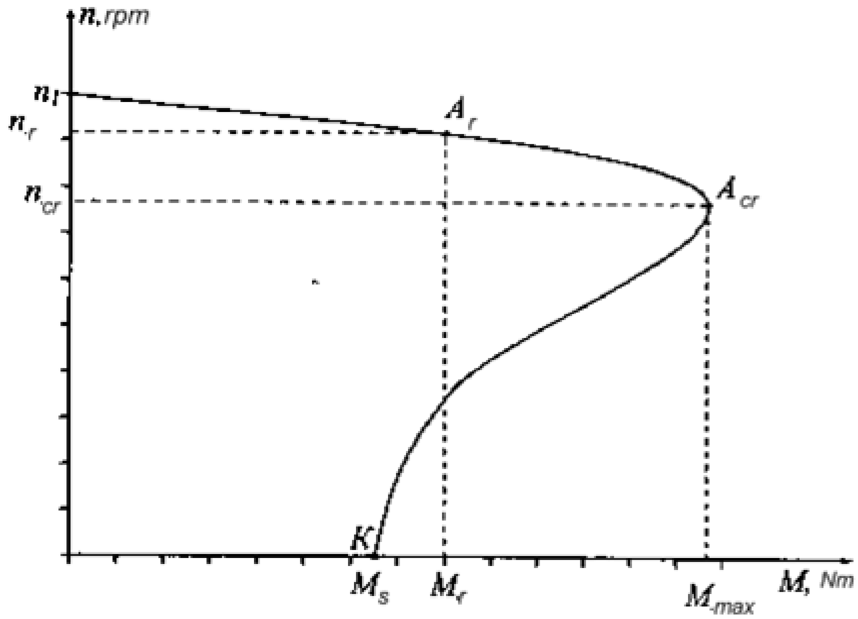


Figure 7 Rotational frequency-torque curve of induction motor (approximate form)

***Test questions***

1. What is the aim of the induction motor testing under no-load and short-circuit conditions?
2. What are the required conditions for carrying out the motor no-load test?
3. What are the required conditions for carrying out the motor short-circuit test?
4. How to recalculate the data of short-circuit test for the rated voltage?
5. Why is the no-load current of an induction motor relatively large in comparison with power transformer?
6. Explain the order of the current circle construction and stator and rotor current determination with it help.
7. How to build the lines of the consumed, electromagnetic, mechanical and shaft power and how to find these quantities with the help of the circle diagram?
8. How to find a value of electromagnetic torque with the help of the circle diagram?
9. How to find the motor slip and efficiency with the help of the circle diagram?
10. How to find the maximum electromagnetic torque using the circle diagram?
11. What sections of the circle diagram do relate to the motor, generator and electromagnetic brake operating conditions?
12. What is the critical slip of an induction motor?
13. What values does take the slip in different operating conditions?
14. Why do parameters of the wound rotor winding not depend essentially on the speed?

EXPERIMENTAL INVESTIGATION

Laboratory test # 3/3

## Investigation of induction motor working properties using method of direct loading

***Aim of the training*** is study of technique of electric machines operating characteristics by their direct loading for assessment of induction machines working properties.

***Work program:***

10. Study the test bench.
11. Calculation of the loading torque.
12. Running of the test, experimental data processing and plotting the operating characteristics.
13. The report execution.

***The work procedure***

*Stage 1 Study the test bench*

The test bench for testing a cage induction motor is fed by a three-phase power supply line and equipped with a starter unit, a measurement unit for connection an ammeter for alternate measurement current in the line conductors $A$ and $C$ and one wattmeter for measurement the power consumed by the motor with application the two-wattmeter method using one wattmeter alternately connected into the three-phase circuit to obtain two readings for determination of the three-phase motor consumed power, an electromagnetic brake with adjustable torque applied to the motor shaft, and a gage for measurement the motor shaft rotational frequency. Study the test bench diagrammatic view (Fig. 1) and its arrangement.

Fill the induction motor to be tested nameplate data in the Table 1.

Table 1

Nameplate data of the tested induction motor

| Motor type | Stator winding connection | Rated power $P_r$ | Rated line voltage $U_{1lr}$ | Rated line current $I_{1lr}$ | Rated frequency $f_{1r}$ | Rated rotor rotational frequency $n_r$ | Rated efficiency $\eta_r$ | Rated power factor $\cos\varphi_r$ |
|---|---|---|---|---|---|---|---|---|
| - | - | kW | V | A | Hz | rpm | % | - |
| | | | | | | | | |

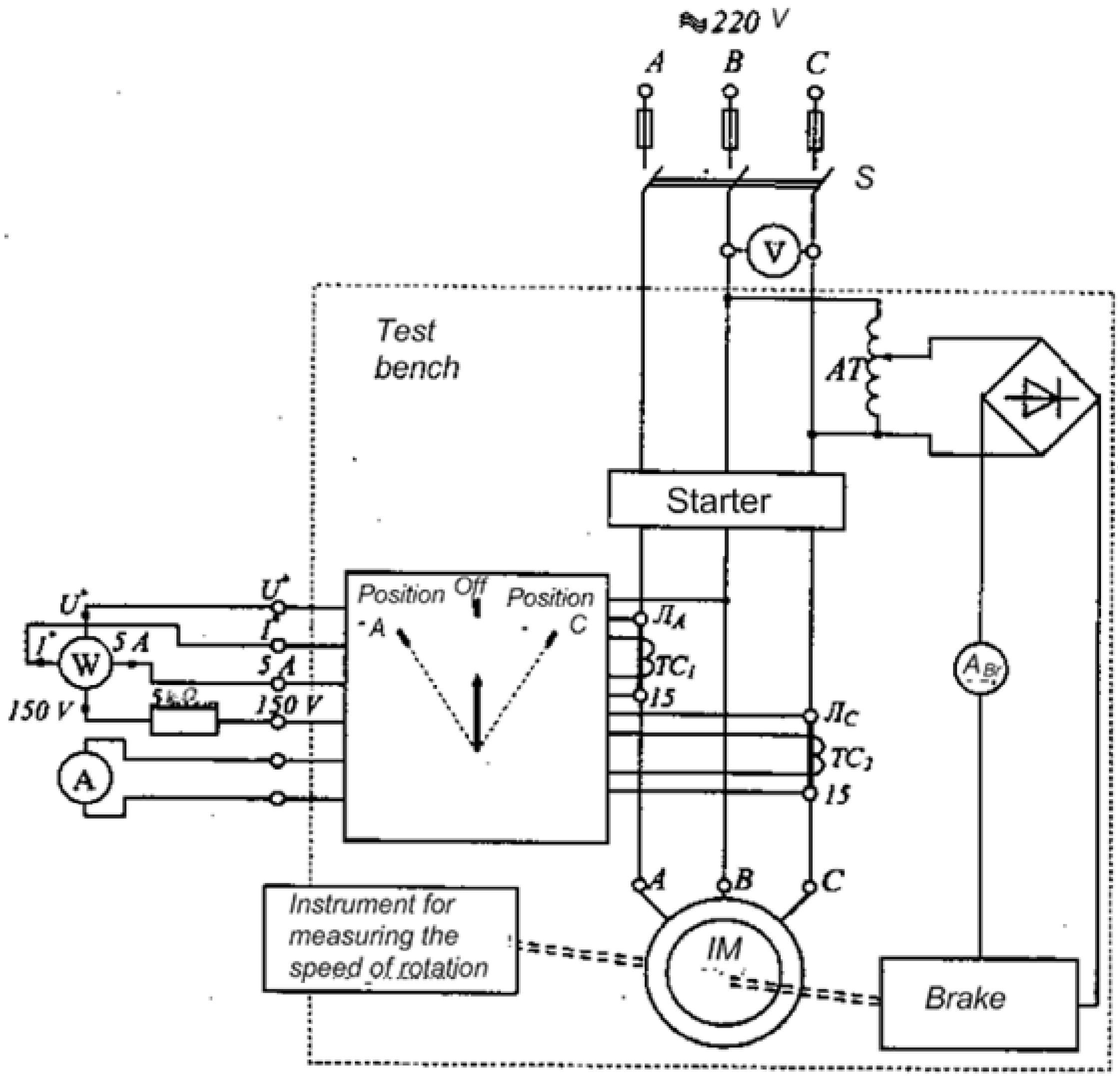


Figure 1 Test bench diagrammatic view

*<u>Stage 2</u> Calculation of the loading torque*

It is recommended to apply to the motor shaft in turn the braking torque from the range:

$$M_b = (1.20, 1.00, 0.75, 0.5, 0.25, 0)M_r$$

where $M_r$ is the rated torque of the tested induction motor.

The rated torque of the induction motor is found using its nameplate data as

$$M_r = \frac{30P_r10^3}{\pi n_r}, \text{Nm}$$

where the values of $P_r$ in kW and $n_r$ in rpm are taken from Table 1.

The found values of the braking torque write down in Table 2 (see Stage 3).

*Stage 3 Running of the test, experimental data processing and plotting the operating characteristics*

*! Attention!* Be careful with the brake disk. The disc is accessible though some measures for contact protection are provided. *Avoid touching the steel brake disc! It is dangerous!* While running the test the disk rotates with high speed. During and for a long enough time after the test the disk temperature exceeds 100°C.

In the course of test the desirable braking torque value is established by adjustment of the current flowing through the electromagnetic brake field coil with the help of adjustable autotransformer *AT* (Fig. 1).

The wattmeter current circuit and ammeter are connected through the current transformers which transformation ratio equal to 3. In the wattmeter voltage circuit the additional resistor may be available. That must be taken into consideration at the instruments scale division values determination.

Connect the circuit according to Fig.1. Set the minimum current through the brake coil and start the motor. After the start, set the braking torque equal to $M_b = 1.20 \cdot M_r$ and fill the quantities reading into first line of Table 2. Measurement of currents and taking the wattmeter readings is made at two positions of the interchanging switch of the measurement unit.

Then, setting in turn other braking torque $M_b$ values calculated in *Stage 2* read the instruments and fill the values of torque and the instruments readings in the following lines of Table 2.

Table 2

Measured and calculated data for plotting operating characteristics

| Point number | Measured | | | | | | | Calculated | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $M$ | $n$ | $U_{1l}$ | $I_A$ | $I_C$ | $P_{pos.A}$ | $P_{pos.C}$ | $P_2$ | $I_{1l}$ | $P_1$ | $\eta$ | $\cos\varphi$ | $s$ |
| | Nm | rpm | V | A | A | W | W | W | A | W | % | - | - |
| 1 | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | | |

Calculate the quantities indicated in the right side of the table.

Using data of Table 2 plot the induction motor operating characteristics $P_1 = f(P_2)$, $I_{1l} = f(P_2)$, $M = f(P_2)$, $n = f(P_2)$, $\eta = f(P_2)$, $\cos\varphi = f(P_2)$ and $s = f(P_2)$ where $P_1$ is electric power consumed by the motor from the supply network, $I_{1l}$ is the stator line current, $M$ is the motor torque on shaft, $n$ is the shaft rotational frequency, $\eta$ is the efficiency, $\cos\varphi$ is the power factor, $s$ is the slip and

$P_2$ is useful mechanical power on the shaft. For plotting characteristics use one mutual coordinate axes system.

*Stage 4 The report execution*

The report on the test should include:

1. The title of the test and its aim
2. The motor nameplate data (Table. 1)
3. Calculation the loading torque values
4. Measured and calculated data for plotting operating characteristics (Table 2)
5. Calculation the data under full load included in Table 2
6. The induction motor operating characteristics plotted in mutual coordinate axes.

***Methodical guideline***

*To stage 1*

Loading the motor is made with the help of electromagnetic brake. The brake has pivoted field system which can turn on its stationary shaft. The field coils situated on the poles having forked shoes. The field coils are connected to the output terminals of the rectifier fed from the autotransformer with adjustable transformation ratio. The brake field current is controlled by turning the autotransformer knob. This causes variation of the alternating voltage impressed to the rectifier input that brings in turn the direct current flowing through the brake field coils variation.

The solid steel disc is fixed on the induction motor shaft and rotates with it. The disc periphery enters into the space between the brake pole shoe faces and, therefore, cuts the magnetic flux in the course of rotation. The eddy currents occur. Interaction of the eddy currents with the field flux causes the brake electromagnetic torque, tending to turn it in the direction of the motor rotation. Eccentrically fixed weight is attached to the brake field system. When the brake electromagnetic torque turns the field system, the weight counter-torque appears. As the counter-torque increases with the angle of rotation the rotating and braking torques become balanced after the field systems takes a certain position due to its rotation under action of the rotating torque. After the field system takes the position of equilibrium, the value of the torque may be count on the scale of the braking device with an arrow attached to the moving field system of the brake.

The torque enthralling the brake moving field system is the braking moment for the motor as it is transmitted to the induction motor shaft through the braking disc. At the motor rotation with a steady-state speed the braking and electromagnetic torques acting on the shaft are counterbalanced, and the value of the braking torque read on the scale of the braking device equals the useful torque on the motor shaft.

*To stage 3*

Calculation of the quantities needed for plotting the induction motor operating characteristics is made by the following expressions:

$$P_2 = M\frac{\pi n}{30} = 0.105Mn, W; \; P_1 = P_{pos.A} + P_{pos.C}, W;$$
$$\eta = \frac{P_2}{P_1}100, \%; \; \cos\varphi = \frac{P_1}{\sqrt{3}U_{1l}I_{1l}}; s = \frac{n_1 - n}{n_1}$$

where $n_1$ is the motor synchronous rotation speed found as the next to the rated speed value from the synchronous rotation speed series determined for the motor rated frequency.

***Test questions***

1. What kind of dependence may be called an operating characteristic of electric motor?
2. What losses affect the efficiency of an induction motor?
3. How does the rotor core loss depend on the induction machine slip?
4. Is the dependence of the torque on an induction motor shaft against the useful power the linear function?
5. What is a motor efficiency under no-load operation? Explain the answer.
6. What is the motor power factor value at no-load? Explain.
7. In what bounds of the slip is the induction motor operation at constant torque on the shaft stable?
8. What does happen if the induction motor load torque exceeds the motor maximum torque?
9. What range of the load torque is considered as normal operating range of an induction motor?
10. Why are general purpose induction motors designed so that their rated slip value does not exceed a few per cent?

EXPERIMENTAL INVESTIGATION

Laboratory test # 3/4

## Investigation of starting methods of cage induction motors

***Aim of the training*** is to study and investigate the starting methods used for squirrel-cage induction motors.

***Work program:***

14. Familiarization with the motor nameplate data.
15. Investigation of starting the cage induction motor by connecting directly across the feeding line.
16. Investigation of the cage induction motor ***Y-Δ*** starting.
17. Investigation of the induction motor starting with use of autotransformer.
18. Comparison of the investigated starting methods.
19. Execution of the report.

***The work procedure***

*Stage 1 Familiarization with the motor nameplate data*

Read the motor to be tested nameplate data and fill into the Table 1.

Table 1

Nameplate data of the tested induction motor

| Motor type | Stator winding connection | Rated power $P_r$ | Rated line voltage $U_{1lr}$ | Rated line current $I_{1lr}$ | Rated frequency $f_{1r}$ | Rated rotor rotational frequency $n_r$ | Rated efficiency $\eta_r$ | Rated power factor $\cos\varphi_r$ |
|---|---|---|---|---|---|---|---|---|
| - | - | kW | V | A | Hz | rpm | % | - |
| | | | | | | | | |

*Stage 2 Investigation of starting the cage induction motor by connecting directly across the feeding line*

Select the stator connection under the rated voltage.

Proceeding from the possible range of the motor starting current ratio at connection under the rated voltage equal to $\frac{I_{1l(dir),st}}{I_{1lr}} = 4 \ldots 7$, find the possible bounds of the starting line current at starting by direct connection on the rated voltage.

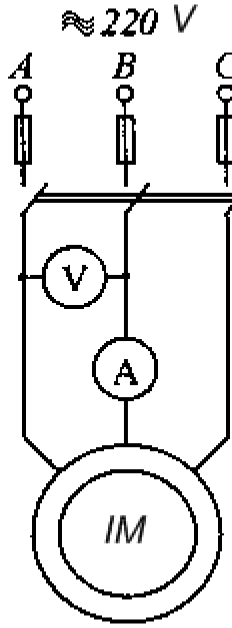


Figure 1 Direct starting squirrel-cage induction motor under rated voltage

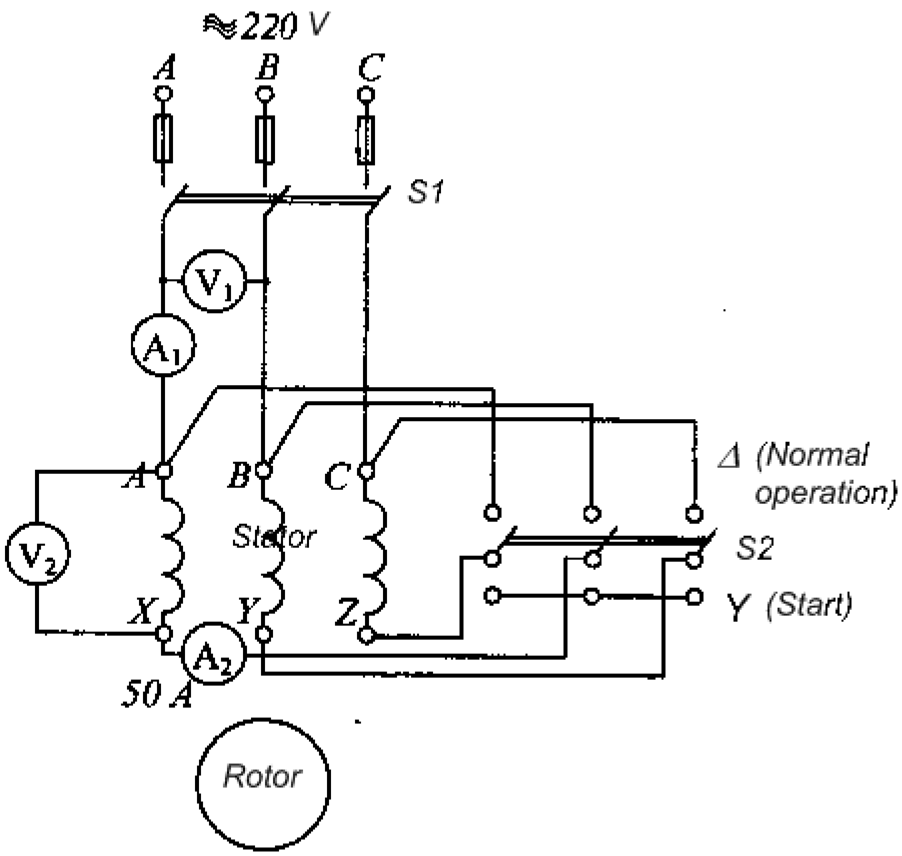


Figure 2 Starting the motor by switching connections from *Y* to *Δ*

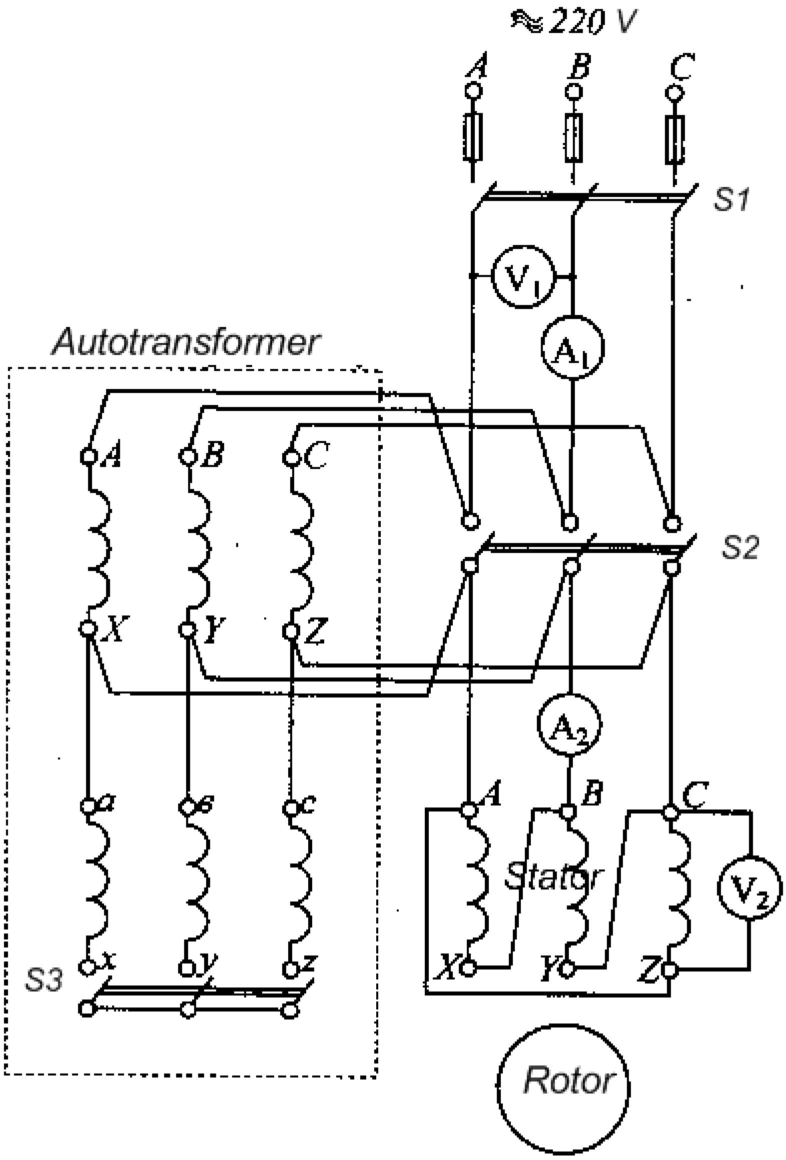


Figure 3 Cage induction motor starting with use of autotransformer

Select the automatic switch, ammeter, voltmeter and fuses for starting the motor by direct connection across the line on the rated voltage (Fig. 1). Connect the circuit.

Carry out the motor test staring without blocking the rotor paying attention to the starting current inrush.

Determine the current at the initial instant of the motor starting executing the investigation in the following order:

- Block the rotor by means of the band-brake
- Turn on the switch *S* and read the values of the stator current and voltage. To avoid the motor overheating, **release the brake not later than in 3 *s*** giving the rotor an opportunity of turning without load.

**During this time it is necessary to meter the instruments readings that must be done simultaneously by all the instruments after calming the instruments needle fluctuations around the equilibrium positions that requires 1-2 s.** Fill the instruments readings in Table 2.

Table 2

Results of induction motor investigation at direct starting

| Measurement | | Calculations | |
|---|---|---|---|
| $U_{1l(dir)}$ | $I_{1l(dir),st}$ | $I_{1l(dir),st,r} = I_{1l(dir),st}\dfrac{U_{1lr}}{U_{1l(dir)}}$ | $k_{I(dir)} = \dfrac{I_{1l(dir),st,r}}{I_{1lr}}$ |
| $V$ | $A$ | $A$ | - |
| | | | |

As the voltage $U_{1l(dir)}$ under the test may occur not equal the rated value, the starting current at the rated motor voltage is determined by means of expression:

$$I_{1l(dir),st,r} = I_{1l(dir),st}\frac{U_{1lr}}{U_{1l(dir)}}.$$

Find the starting current ratio under starting by direct connection to the rated voltage:

$$k_{I(dir)} = \frac{I_{1l(dir),st,r}}{I_{1lr}}$$

*<u>Stage 3</u> Investigation of the cage induction motor Y-Δ starting*

The method is applicable if the stator winding is normally connected in *Δ* under the available network voltage (compare the inscription on the panel of network terminals and the motor nameplate data).

Select the automatic switches, ammeters, voltmeters and fuses for starting the motor by switching connections from *Y* to *Δ* (Fig. 2). Connect the circuit.

Carry out the motor test staring without blocking the rotor, switching it first in *Y* and after acceleration changing the connection to *Δ*. Pay attention to the current inrushes at the beginning of starting and at changeover to *Δ*, and cognize that acceleration of the motor is in this case slower than at direct starting.

After putting the switch *S2* into position *"Y"* and blocking the rotor by means of the band-brake, turn on the motor with switch *S1*, read simultaneously the instruments and turn off switch *S1*. Duration of ON state should be not longer than 3 *s*. Fill the instruments readings in Table 3.

Table 3

Results of induction motor investigation at starting by switching connections from *Y* to *Δ* (initial stage at connection in *Y*)

| Measurement | | | Calculations | | | |
|---|---|---|---|---|---|---|
| $U_{1l(Y)}$ | $U_{1(Y)}$ | $I_{1l(Y),st} = I_{1(Y),st}$ | $I_{1l(Y),st,r}$ | $k_{I(Y)}$ | $I_{1l(Y),st,r}/I_{1l(dir),st,r}$ | $M_{st(Y)}/M_{st(dir)}$ |
| *V* | *V* | *A* | *A* | - | - | - |
| | | | | | | |

Pay attention that while starting at connection of the stator winding in *Y* unlike the case of connection in *Δ* the line voltage $U_{1l(Y)}$ and phase voltage $U_{1(Y)}$ are unequal whereas the line and phase starting currents $I_{1l(Y),st}$ and $I_{1(Y),st}$ are equal.

Calculate and fill in Table 3 also the quantities values related to the initial stage of starting (Y-connection):

- The starting line current under the rated line voltage

$$I_{1l(Y),st,r} = I_{1l(Y),st} \frac{U_{1lr}}{U_{1l(Y)}}$$

- The starting current ratio at *Y*-connection

$$k_{I(Y)} = \frac{I_{1l(Y),st,r}}{I_{1lr}}$$

- The ratio of starting currents at *Y*-connection and direct starting

$$I_{1l(Y),st,r}/I_{1l(dir),st,r}$$

- The ratio of starting torques at *Y*-connection and direct connection

$$M_{st(Y)}/M_{st(dir)} = (U_{1l(Y)}/U_{1l(dir)})^2$$

*<u>Stage 4</u> Investigation of the induction motor starting with use of autotransformer*

As autotransformer, the three-phase transformer studied at previous laboratory classes is used. It connection is shown in Fig. 3. Transformation ratio of the autotransformer equals

$$n_A = \frac{U_{AX}+U_{ax}}{U_{ax}} = \frac{220+133}{133} = 2.65 .$$

Select the automatic switches, ammeters, voltmeters and fuses for starting the motor with use of autotransformer (Fig. 3). Connect the circuit.

Set the switches to the initial state to start the motor: the switches *S1* and *S2* – into position "off", the switch *S3* – into position "on". Then put the fuses and carry out the motor test staring without blocking the rotor in the following sequence:

- *Turn on* the switch *S1*. The voltage is impressed across the motor terminals being reduced by the autotransformer.
- After the motor acceleration to the steady speed, *turn off* the switch *S3* *then immediately turn on* the switch *S2*.

Pay attention that the motor accelerates not as fast as at use two other methods that is explained by greater reduction the voltage on the motor terminals and more considerable decrease of the starting torque. The current inrush at the beginning of start is smaller in this case on the reason of more essential voltage reduction and due decrease the current into the input circuit under the given transformation ratio of the step-down autotransformer in comparison with its output circuit.

After testing the circuit, turn the motor off by means of the switch *S1* and then restore the initial state of the switches as described above.

Block the rotor and turn on the switch S1. Read all the instruments simultaneously and turn off the motor in 3 … 5 *s*. Fill the instrument readings in Table 4.

Table 4

Results of induction motor investigation at starting with use of autotransformer

| Measurement | | | | Calculation | | | | |
|---|---|---|---|---|---|---|---|---|
| $U_{1l(AT)}$ | $U_{2l(AT)}$ | $I_{1l(AT),st}$ | $I_{2l(AT),st}$ | $I_{1l(AT),st,r}$ | $I_{2l(AT),st,r}$ | $k_{I(AT)}$ | $\frac{I_{1l(AT),st,r}}{I_{1l(dir),st,r}}$ | $\frac{M_{st(AT)}}{M_{st(dir)}}$ |
| *V* | *V* | *A* | *A* | *A* | *A* | - | - | - |
| | | | | | | | | |

Denotations used in Table 4:

$U_{1l(AT)}$ - line voltage on the primary side of the autotransformer (line network voltage);

$U_{2l(AT)}$ is the line voltage on the secondary side of the autotransformer (line voltage on the motor terminals);

$I_{1l(AT),st}$ is the starting line current in the network at testing;

$I_{2l(AT),st}$ is the starting line current in the motor circuit at testing;

$I_{1l(AT),st,r}$ is the starting line current in the network under the rated voltage;

$I_{2l(AT),st,r}$ is the starting line current in the motor circuit under the rated network voltage

$k_{I(AT)} = \frac{I_{1l(AT),st,r}}{I_{1lr}}$ is the ratio of the starting current at use of an autotransformer

$\frac{I_{1l(AT),st,r}}{I_{1l(dir),st,r}}$ is the ratio of the starting current at use the autotransformer to the starting current at direct motor connection to the rated voltage

$\frac{M_{st(AT)}}{M_{st(dir)}}$ is the ratio of starting torques under autotransformer and direct starting

*Stage 5 Comparison of the investigated starting methods*

Analyze the data obtained at use of different methods for starting the squirrel-cage induction motor (Tables 1-4), and make conclusions about their validity and also on advantages and disadvantages of these methods.

*Stage 4 The report execution*

The report should include:

7. The title of the test and its aim
8. The motor nameplate data (Table. 1)
9. Circuit diagrams (Fig. 1, 2 and 3) for starting the motor using different methods, and results of measurement and calculation (Tables 2, 3 and 4)
10. Conclusions based on analysis of results obtained at testing the induction motor direct starting under rated voltage and starting under reduced voltage.

***Methodical guideline***

*To stage 2*

Three-phase induction motor at direct connection to the network with the rated voltage draws comparatively great starting currents (to 4 … 7 times as the rated current). The starting motor torque is in this case about 1.1 … 1.4 of the rated motor torque and provides it start when the external braking torque does not exceed that value. The direct start is acceptable by the supply network conditions if the network voltage regulation caused by the starting currents relatively the rated value is not greater than 10%.

Otherwise measures preventing considerable voltage decrease must be taken. These measures may relate to a power line or to the methods of the motor starting.

Relatively starting, one of possible ways may be use of methods providing start at reduced voltage, such as starting with switching the motor stator winding being connected in *Y* with subsequent transfer to *Δ*-connection, or starting with use a step-down autotransformer that are considered in this laboratory work.

*To stages 3-4*

Starting induction motor with use *Y-Δ* connections is applicable under condition if the motor at the given network voltage must be normally connected in *Δ* and beginnings and ends of all the phases are brought into the motor terminal box. This method reduces the starting currents by three times. At the same time reduction of the starting torque is also by three times. Therefore this method may be applied when the loading torque is small enough, usually not more than 30% of the motor rated torque. The essential disadvantage of this method restricting it use for high-voltage motors is commutation overvoltage arising at shifting the winding connection.

Reduction of starting current at use of step-down autotransformers depends on the transformation ratio. The starting current decreases by $n_A^2$ times. The same is decrease of the starting torque. The start may be successfully carried out if the motor load is appropriately decreased. Selection of the autotransformer ratio is defined by the motor starting conditions.

***Test questions***

11. On what induction motor parameters does the starting current depend?
12. How may be explained that start current inrush considerably exceed the motor rated current?
13. Does the current inrush depend on the motor load on the shaft?
14. How is it may be explained that at start under *Y*-connection the current inrush decreases by three times?
15. How is it may be explained that at start under *Y*-connection the induction motor starting torque decreases by three times?
16. Why do the supply network current inrush and the motor starting torque reduce by $n_A^2$ times both at starting by means of autotransformer?
17. By what means is the current inrush reduction provided at starting wound rotor induction motors? Does the starting torque of such motors vary due to measures taken for their current inrush decrease?
18. How does the speed-torque curve of the squirrel-cage induction motor change at use of the methods providing decrease of the impressed voltage at the motor starting?