SILESIAN UNIVERSITY OF TECHNOLOGY
FACULTY OF ENERGY AND ENVIRONMENTAL ENGINEERING

TESTS ON THE INDUCTION MOTOR

(E-15)

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XIII. TESTS ON THE INDUCTION MOTOR

1. Aim of exercise

The aim of this exercise is to determine no-load and short-circuit characteristics of the induction squirrel-cage motor. The measurements will also make it possible to find the values of parameters of the motor equivalent circuit diagram elements.

2. Introduction

The induction machine is an electric machine used to transform electrical energy into mechanical energy or vice versa. The energy transformation takes place via a magnetic field. Generally, induction machines are machines in which voltage in the rotor circuit arises due to electromagnetic induction (without an external power supply). A simplified diagram of the cross-section of the induction squirrel-cage motor structure is presented in Fig. 1.1.

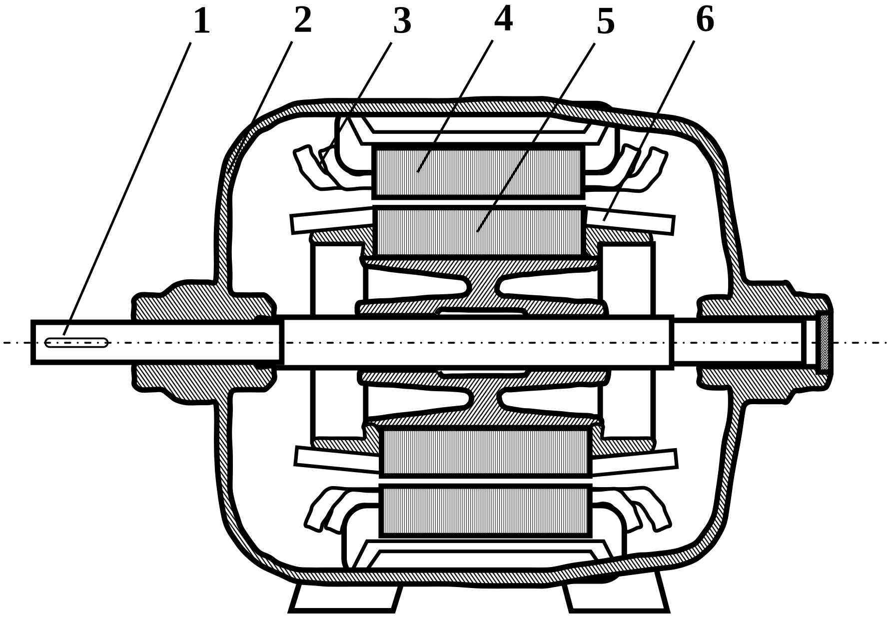
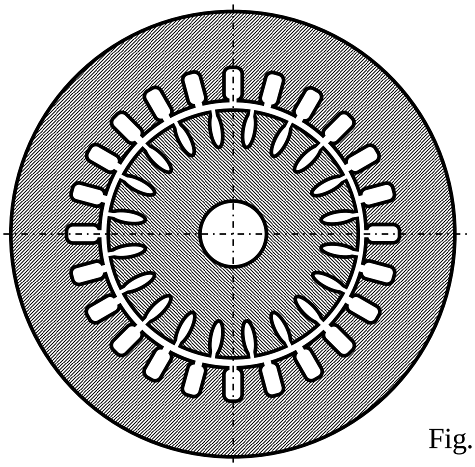


Fig. 1.1. Simplified cross-section of the induction squirrel-cage machine

Each rotating machine has a stationary part – the stator – which includes the rotating part – the rotor. The rotor is fixed on a shaft {1} with bearing relative to the machine frame {2}. The magnetic circuit of a rotating machine (unlike the one of a transformer) is composed of two parts: the stator core {4} and the rotor core {5}, separated from each other with an air gap. The stator and rotor cores are made of a pack of metal sheets insulated from each other. The core sheets feature slots, with an example shape as shown in Fig. 1.2, where the stator winding {3} and the rotor winding {6} are placed. Machines with a three-phase winding, referred to as wound-rotor motors or slip-ring motors, feature slip-rings and brushes which make it possible to connect the rotor circuit to the starter or the rotational speed governor. A simpler and cheaper squirrel-cage machine features a winding made of bars held together by rings attached to both ends of the bars. This type of a squirrel-cage winding is shown in Fig. 1.3.



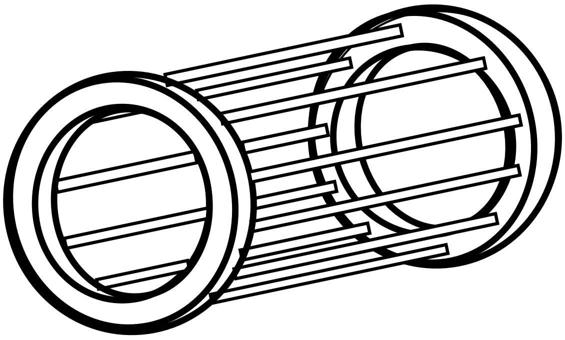


Fig. 1.3. The winding of an induction squirrel-cage machine

Fig. 1.2. Core metal sheets with slots

Squirrel-cage motors are the most common types of electric machines. This results from their numerous advantages such as simple structure, low price, reliability and long service life without the need to carry out any maintenance operations. Until recently, the biggest disadvantage of compact squirrel-cage motors used to be problems related to start-up and rotational speed adjustment. Owing to the application of frequency converters and smooth start-up devices, the performance of squirrel-cage motors in this respect has now become comparable to that of the best direct current motors.

Both types of induction motors (the wound-rotor motor and the squirrel-cage motor) feature the same principle of operation. The stator windings supplied with a three-phase current produce a circular magnetic field rotating relative to the stationary stator with synchronous speed n_S.

$$n_S = \frac{f_1}{p}\left[\frac{1}{s}\right] = \frac{60 \cdot f_1}{p}\left[{}^{obr}\!/_{min}\right], \tag{1}$$

where:

f_1 – frequency of the stator supply current,

p – number of pole pairs of the magnetic field (natural number depending on the stator winding).

For example, for network frequency $f_1 = 50$ Hz and for one pair of poles ($p = 1$) the synchronous speed is $n_S = 3000$ rpm (for $p = 2$, $n_S = 1500$ rpm etc.).

The rotating magnetic field produced by the stator currents induces in the (initially) stationary windings of the rotor electromotive forces which cause current to flow in the closed circuit of the rotor. The rotating magnetic field of the stator has an impact on the leads conducting current in the rotor, which produces an electromagnetic moment being the rotor shaft torque. The rotor starts to rotate and its speed increases relative to the stator and decreases relative to the rotating magnetic field. At the same time, the values of electromotive forces induced in the rotor windings diminish and the torque becomes smaller. Consequently, under a certain load, the rotational speed stabilizes with value n smaller than synchronous speed n_S. The difference between synchronous speed n_s and rotational (operating) speed n referred to synchronous speed is called **slip s**.

$$s = \frac{n_S - n}{n_S}. \qquad (2)$$

When the rotor is blocked ($n = 0$), the slip value is one ($s = 1$); if the rotor rotated with synchronous speed ($n = n_s$), the slip would be zero ($s = 0$).

The fact that the rotor of the induction motor may not rotate with synchronous speed n_s (for this speed value the electromagnetic moment is zero) is the reason why induction machines are also referred to, on equal terms, as asynchronous machines. The asynchronous motor speed expressed by means of slip is defined by the following dependence:

$$n = \frac{f_1}{p}(1 - s). \qquad (3)$$

Frequency f_2 of the current induced in the rotor circuit depends on the difference between the speeds of the field and rotor ($n_s - n$) and, if expressed by means of slip, is as follows:

$$f_2 = (n_S - n) \cdot p. \qquad (4)$$

Taking dependences (1) and (3) into account, the following is obtained as a result:

$$f_2 = f_1 \cdot s. \qquad (5)$$

2.1. Equivalent circuit diagram of an induction machine (one phase)

The analysis of the operation of electric machines (as it was already mentioned in the chapter "Tests on the transformer") may be performed conveniently based on the equivalent circuit diagram. There is a very close similarity in the making of an equivalent circuit diagram of an electric machine and of a transformer. The following elements are taken into consideration in the equivalent circuit diagram of an induction machine:

- $X\underline{\boldsymbol{\mu}}$ – magnetizing reactance related to the rotating main magnetic flux $\underline{\mathbf{\Phi}}$,
- X_{1R} – magnetizing reactance related to magnetic leakage flux $\underline{\mathbf{\Phi}}_{\mathbf{1R}}$ in the stator,
- X_{2R} – inductive reactance related to magnetic leakage flux $\underline{\mathbf{\Phi}}_{\mathbf{2R}}$ in the rotor,
- R_{Fe} – equivalent core-loss resistance in the stator,
- R_1 – winding resistance of the stator,
- R_2 – winding resistance of the rotor.

The core-loss and the insulation loss in the rotor, as well as capacity currents and leakage currents are ignored in the equivalent circuit diagram. The equivalent circuit diagram of an induction machine is presented in Fig. 1.4.

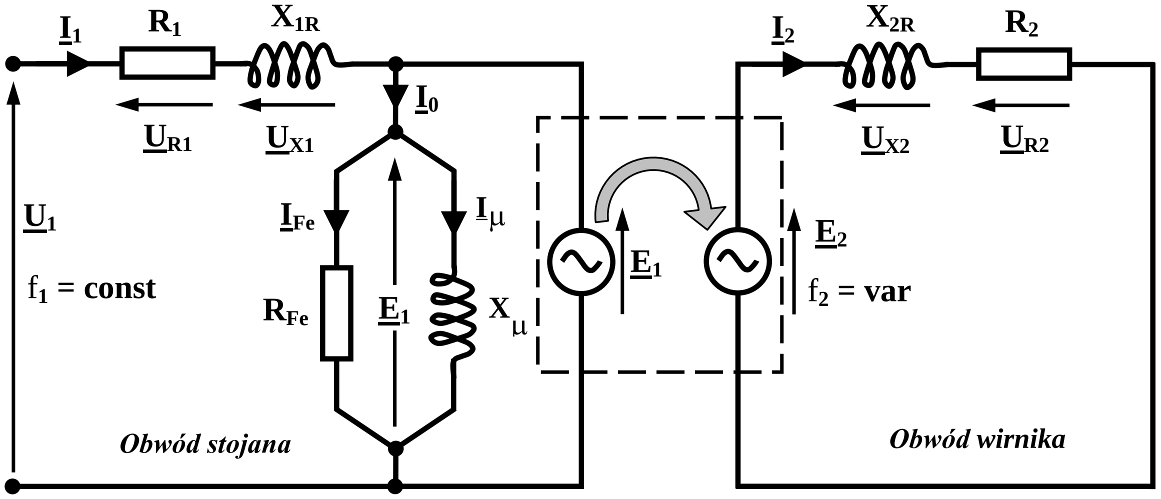


Fig. 1.4. Equivalent circuit diagram of an induction machine (form I)

do rysunku: Stator circuit/ Rotor circuit

Special attention should be drawn to the fact that a change in the rotor shaft rotational speed n (which means a change in slip s) involves a change in the rms value and the frequency of current $\underline{I}_2$ in the rotor circuit, in the rms value and the frequency of electromotive force $\underline{\mathbf{E}}_2$ induced in the rotor and in the value of the rotor circuit inductive reactance X_{2R}. In order to build an equivalent circuit diagram of an induction machine where the rotor circuit is connected to the stator circuit (form II), it is insufficient to just convert the rotor side parameters to the stator side. First, an equivalent rotor has to be introduced with frequency f_2 equal to the stator frequency f_1. In this equivalent rotor, which is stationary relative to the stator and in which $f_2 = f_1$, the equivalent parameters have to be determined which are dependent on the variable value of slip s. Physically, the state when $f_2 = f_1$ is the short-circuit state of an induction machine, which means, in the case of a squirrel-cage motor, that voltage is supplied to the stator winding and the rotor is blocked (as at any start). The value of the electromotive force induced in the stator under these conditions is E_{20}. The electromotive force induced in N_2 turns of a blocked rotor is $E_{20} = \sqrt{2}\pi f_1 N_2 \Phi$. In the same rotor rotating with rotational speed n, the electromotive force is $E_2 = \sqrt{2}\pi f_2 N_2 \Phi$. Taking (5) into account, the following may be written:

$$E_2 = E_{20} \cdot s \qquad . \tag{6}$$

Limiting the considerations to a compact squirrel-cage motor only, the rotor current dependence may be written in the following form:

$$I_2 = \frac{E_2}{\sqrt{R_2^2 + X_{2R}^2}} . \tag{7}$$

Taking (5) into account, the value of reactance X_{2R} is determined for frequency f_1, which is marked as X_{20R}:

$$X_{2R} = 2 \cdot \pi \cdot f_2 \cdot L_2 = 2 \cdot \pi \cdot f_1 \cdot s \cdot L_2 = s \cdot X_{20R} . \tag{8}$$

Introducing (8) into (7), the following is obtained:

$$I_2 = \frac{E_{20} \cdot s}{\sqrt{R_2^2 + X_{20R}^2 \cdot s^2}} = \frac{E_{20}}{\sqrt{\left(\frac{R_2}{s}\right)^2 + X_{20R}^2}} \qquad . \tag{9}$$

It results from dependence (9) that the change in the slip of a real machine is taken into account by resistance element $\frac{R_2}{s}$, whose value may be presented as a sum of the real winding resistance R_2 of the rotor and of the term dependent on the slip and representing the load of the motor shaft with active power $\frac{R_2}{s} = R_2 + R_2 \frac{1-s}{s}$.

Having completed all this, an equivalent circuit diagram of an induction machine is obtained with an equivalent rotor supplied with a current with network frequency f_1.

The equivalent circuit diagram of a squirrel-cage motor (before the rotor parameters are converted to the stator side) is shown in Fig. 1.5.

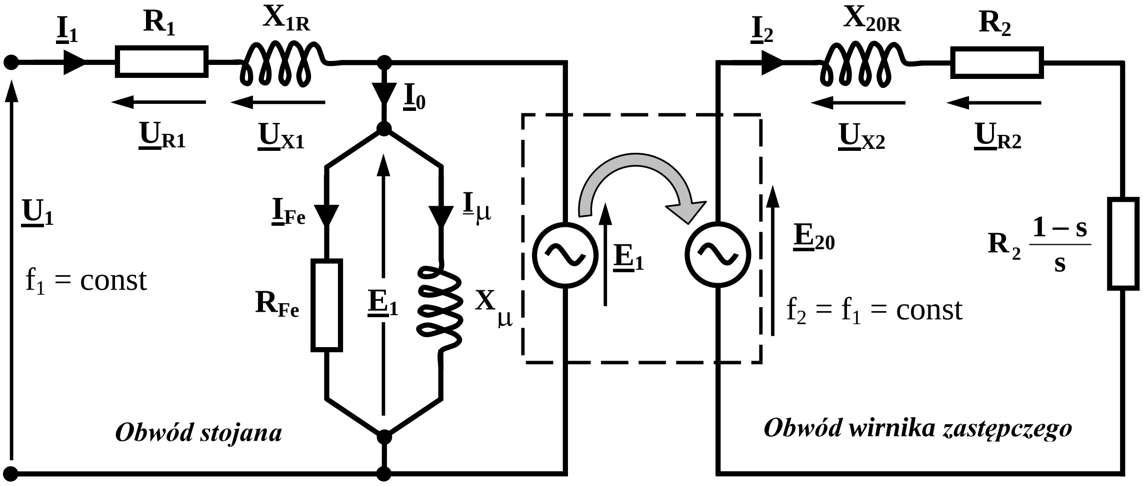


Fig. 1.5. Equivalent circuit diagram of an induction machine (form I) with the equivalent rotor

do rysunku: Stator circuit/ Rotor circuit

The conversion (calculation) of the rotor (secondary) side to the stator (primary) side is carried out using the notions of voltage ratio ϑ_U and current ratio ϑ_I defined as follows:

$$\vartheta_U = \frac{E_1}{E_{20}} = \frac{N_1 \cdot k_{U1}}{N_2 \cdot k_{U2}}, \tag{10}$$

$$\vartheta_I = \frac{N_1 \cdot k_{U1} \cdot m_1}{N_2 \cdot k_{U2} \cdot m_2} = \vartheta_U \frac{m_1}{m_2}, \tag{11}$$

where:

N_1, N_2 – number of turns,
m_1, m_2 – number of phases,
k_{U1}, k_{U2} – coefficients dependent on the type of winding

Subscripts ($_1$), and ($_2$) are used for the stator and the rotor, respectively.

Converting the rotor quantities to the stator side, the following parameters are obtained:

- representation of voltage on the secondary side to the primary side $E'_{20} = E_{20} \cdot \vartheta_U$ and generally $$U'_2 = U_2 \cdot \vartheta_U, \tag{12}$$
- representation of current on the secondary side to the primary side $$I'_2 = I_2 \cdot \frac{1}{\vartheta_I}, \tag{13}$$

- representation of the secondary side resistance to the primary side $R'_2 = R_2 \cdot \vartheta_U \cdot \vartheta_I$ or

$$R'_2 = R_2 \cdot \vartheta_U^2 \cdot \frac{m_1}{m_2}, \tag{14}$$

- representation of the secondary side reactance to the primary side $X'_2 = X_2 \cdot \vartheta_U \cdot \vartheta_I$ or

$$X'_2 = X_2 \cdot \vartheta_U^2 \cdot \frac{m_1}{m_2}. \tag{15}$$

The equivalent circuit diagram of an induction squirrel-cage machine after the rotor side has been converted to the stator side is presented in Fig. 1.6.

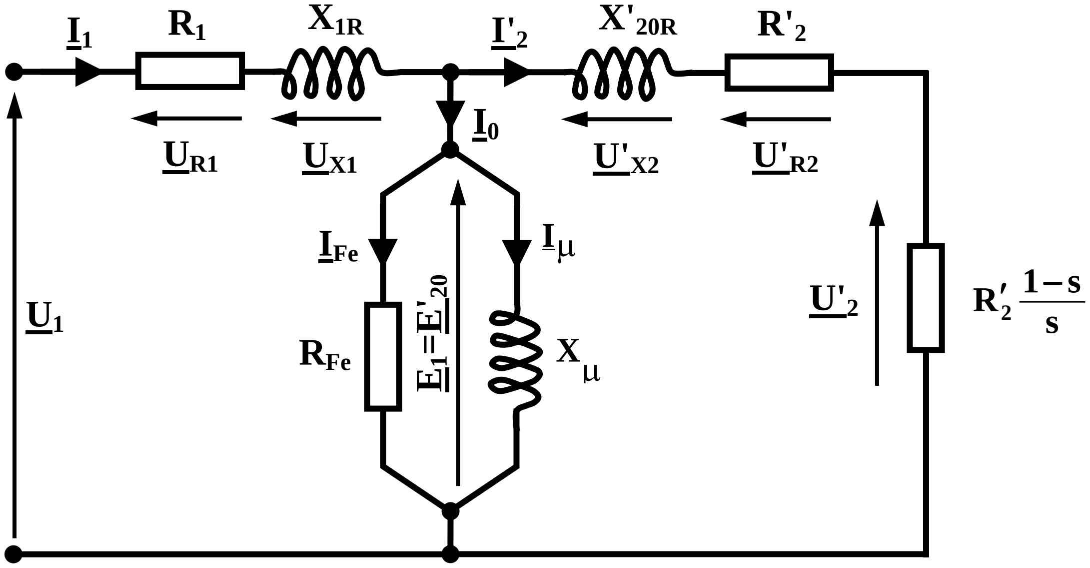


Fig. 1.6. Equivalent circuit diagram of an induction machine (form II)

2.2. Induction motor no-load operation

Under no-load conditions an induction motor rotates with a speed close to synchronous speed ($n \approx n_S$); a slight slip arises ($s \approx 0$). The consequence of this slight slip is a very small value of current and voltage frequency $f_2 = s\, f_1$, which results in negligibly small losses in the rotor metal. The copper loss in the rotor is also negligible because current $\underline{I}_2$ flowing through the rotor winding is very small due to the very small value of electromotive force $\underline{E}_2 = s\, \underline{E}_{20}$. The power output of the motor no-load operation is close to zero (the motor shaft is under no load). The entire power P_0 taken by a motor supplied with phase voltage $\underline{U}_1$ and forcing no-load current $\underline{I}_0$ from the source is consumed to cover stator losses, including:

- stator copper loss $$\Delta P_{Cu0} = m_1 \cdot R_1 \cdot I_0^2, \tag{16}$$

- stator core loss $\Delta P_{Fe0} \approx m_1 \frac{U_1^2}{R_{Fe}}$, (17)
- mechanical loss $\Delta P_m \approx \text{const.}$ (18)

The stator core loss and the mechanical loss are independent of the motor shaft load. The entire circuit of the rotor (like the transformer secondary winding) may be ignored in the simplified equivalent circuit diagram under no-load conditions. A (simplified) equivalent circuit diagram for an induction motor under no-load conditions is shown in Fig. 1.7.

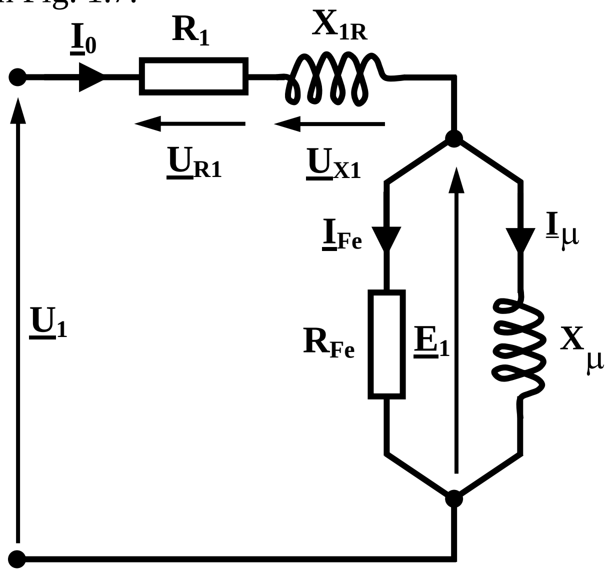


Fig. 1.7. Simplified equivalent circuit diagram for an induction squirrel-cage motor under no-load conditions

The significant value of no-load current $I_0 = (0.25 \div 0.5)I_N$ and the small value of power factor $\cos\varphi_0 = \frac{P_0}{3 \cdot U_1 \cdot I_0} \approx 0.1 \div 0.2$ under no-load conditions are the fundamental weaknesses of induction motors.

2.3. Induction motor short-circuit operation

Under short-circuit conditions an induction rotor is blocked; the rotational speed is zero $(n = 0)$ and the slip is equal to one $(s = 1)$. Therefore rotor current $\underline{\mathbf{I}}'_2$, which is approximately equal to the stator current, is strong, reaching values ten times higher than the rated current. No mechanical power is given as the rotor does not rotate. In measuring practice, the short-circuit state is realized by supplying the induction motor with voltage U_Z with a value that generates rated current I_N in the stator winding. The entire short-circuit power P_Z taken from the network is consumed to cover losses in the stator and rotor windings (copper losses). The core losses are negligible due to their slight value (especially at lowered voltage).

$$P_Z = \Delta P_{Cu1} + \Delta P_{Cu2} . \tag{19}$$

The entire lateral limb (like in the case of the transformer) may be ignored in the simplified equivalent circuit diagram under short-circuit conditions. A (simplified) equivalent circuit diagram for an induction motor under short-circuit conditions is shown in Fig. 1.8.

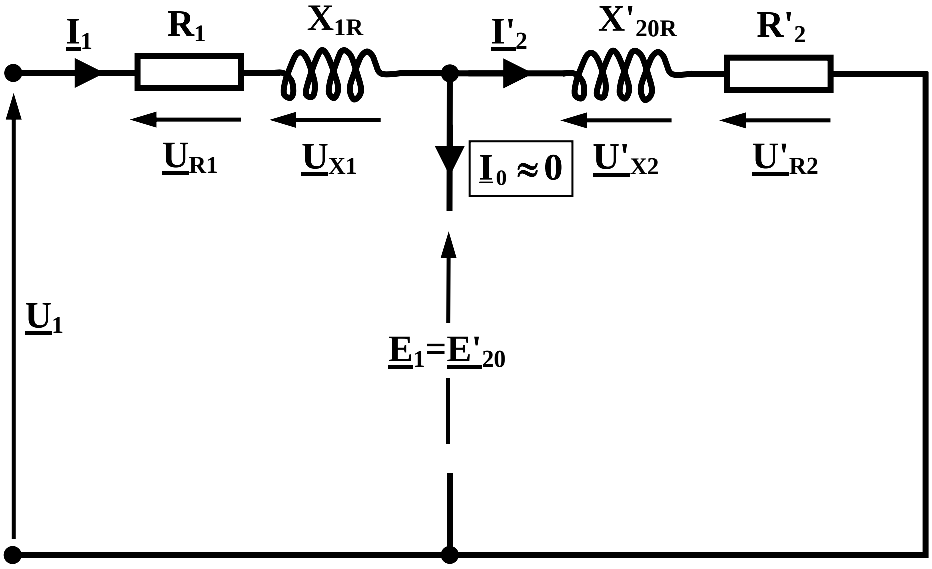


Fig. 1.8. Simplified equivalent circuit diagram for an induction squirrel-cage motor under short-circuit conditions

3. Laboratory tests and measurements

3.1. Determination of measured quantities

The following quantities are measured: the values of inter-phase voltage, of line current intensity and of active power in the supply system of an induction motor under short-circuit and no-load conditions. The measurements of the no-load operation additionally include the motor shaft rotational speed. Based on the measurement data, the following are to be found: the characteristics of the no-load and short-circuit operation and the values of parameters of the elements of the induction motor equivalent circuit diagram (one phase).

3.2. Diagram of the test stand

The test stand is supplied from an adjustable alternating current source – autotransformer ATr. The system includes the so-called measuring case which makes it possible to measure line currents (separately in each phase – three ammeters), inter-phase voltages and one phase voltage (one voltmeter with a switch), and active power of a three-phase circuit (one multi-coil wattmeter). An example measuring system using transformers and a measuring set referred to as "measuring case" is presented in Fig. 1.9.

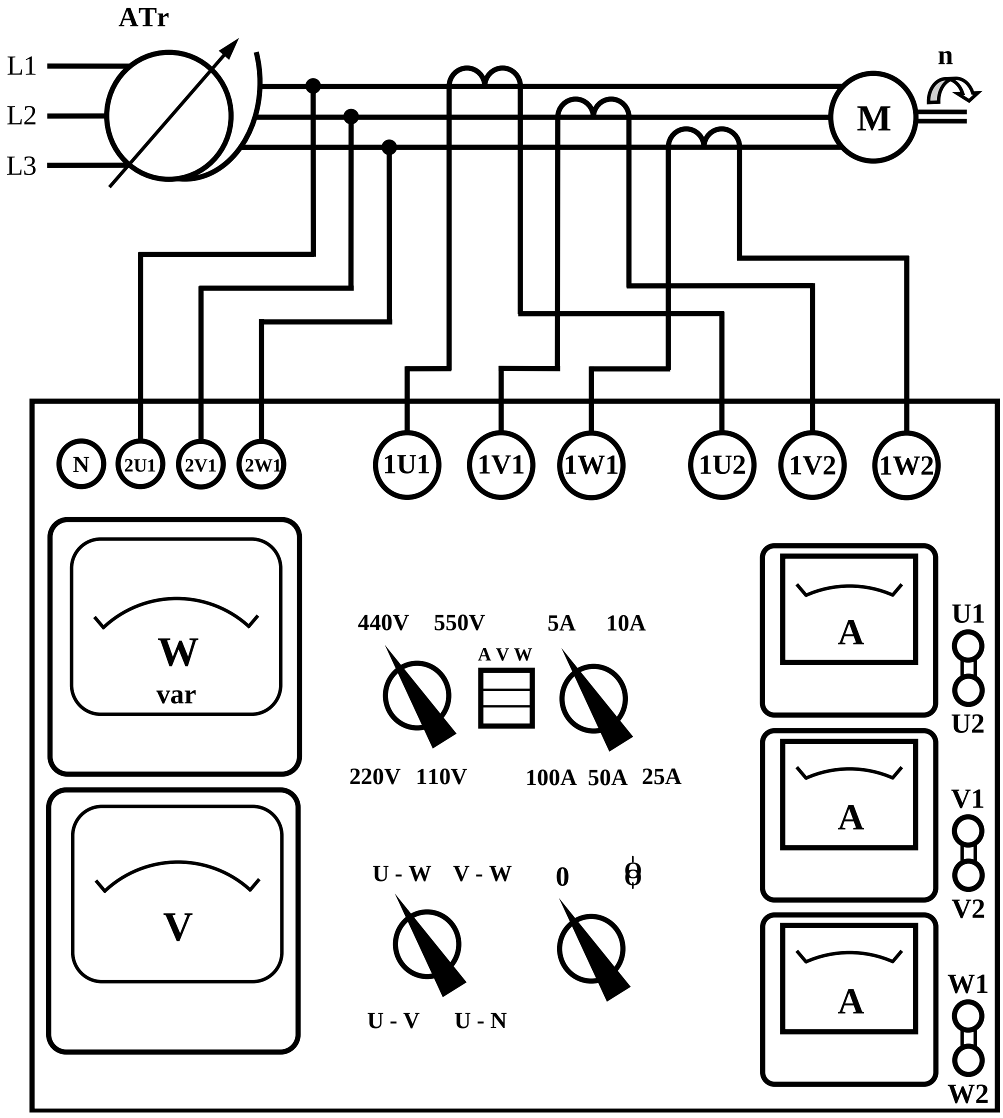


Fig. 1.9. Diagram of the measuring system with a "measuring case"

3.3. Course of exercise

1. Read and record the rated data of the motor under analysis.
2. Measure the resistance of the analyzed induction motor stator. Use a bridge or employ the technical method – as advised by the class instructor.
3. Check if the motor shaft rotates freely.
4. Check whether the range switches of the measuring case are set to the maximum values and the transformer knob – to the minimum value.
5. Turn on the stand and slowly let the motor gain speed increasing the autotransformer voltage to the value of the motor rated voltage.
6. Wait 15 minutes until the temperatures in the motor stabilize.
7. Take the no-load operation characteristic (*suggested voltage values: 400 V, 350 V, 300 V, 250 V, 200 V, 150 V, 100 V – the* ***rated voltage*** *must not be omitted*) measuring: voltages, currents, power and rotational speed. Enter the measured values in Table 1.1.

Table 1.1

The motor data plate details:																
Measurements									Calculations							
Armature phase resistance R_1								Ω								
Item	U_{UV}	U_{VW}	U_{UW}	I_U	I_V	I_W	P_0	n_0	U_0	U_0^2	I_0	$\cos\varphi_0$	s_0	ΔP_{Cu}	ΔP_m	ΔP_{Fe}
	V	V	V	A	A	A	W	1/s	V	V^2	A			W	W	W
1.																
2.																
3.																
etc.																

8. Switch off the supply and wait until the motor shaft stops.
9. Select, experimentally, the motor shaft position (at a slight value of supply voltage) at which the current intensity reaches the middle value between the minimum and maximum. **Block the motor shaft in this position.**
10. Take the short-circuit operation characteristic (*suggested voltage values: 60 V, 50 V, 40 V, 30 V, 20 V, 10 V – the value of* ***voltage at rated current, i.e. short-circuit voltage*** U^*_Z *must not be omitted*) measuring: voltages, currents and power. Enter the measured values in Table 1.2.

Table 1.2

Measurements								Calculations							
Item	$\mathbf{U_{UVz}}$	$\mathbf{U_{VWz}}$	$\mathbf{U_{UWz}}$	$\mathbf{I_{Uz}}$	$\mathbf{I_{Vz}}$	$\mathbf{I_{Wz}}$	$\mathbf{P_z}$	$\mathbf{U_z}$	$\mathbf{I_Z}$	$\cos\varphi_Z$	$\mathbf{\Delta P_{Cu1}}$	$\mathbf{R_z}$	$\mathbf{Z_z}$	$\mathbf{X_z}$	$\mathbf{\Delta P_{Cu2}}$
	V	V	V	A	A	A	W	V	A		W	Ω	Ω	Ω	W
1.															
2.															
3.															
etc.															
Short-circuit voltage U^*_Z					V		%								

4. Elaboration on measurement results

1. Fill in the computational part of Tables 1.1 and 1.2 using the following dependences:

   a) for voltages and currents U_0, I_0, U_Z, I_Z (average values of inter-phase voltages and line currents measured in three phases):

$$U_0 = \frac{U_{UV} + U_{UW} + U_{VW}}{3}, \tag{20}$$

$$I_0 = \frac{I_U + I_V + I_W}{3}, \tag{21}$$

$$U_Z = \frac{U_{UVz} + U_{UWz} + U_{VWz}}{3}, \tag{22}$$

$$I_Z = \frac{I_{Uz} + I_{Vz} + I_{Wz}}{3}, \tag{23}$$

   b) for power factors for the operation under no-load and short-circuit conditions:

$$\cos\varphi_0 = \frac{P_0}{\sqrt{3} \cdot U_0 \cdot I_0}, \tag{24}$$

$$\cos\varphi_Z = \frac{P_Z}{\sqrt{3} \cdot U_Z \cdot I_Z}, \tag{25}$$

   c) for slip under no-load conditions

$$s_0 = \frac{n_S - n_0}{n_S}, \tag{26}$$

d) for resistance, impedance and reactance (one phase) under short-circuit conditions:

$$R_Z \approx \frac{P_Z}{3 \cdot I_Z^2}, \tag{27}$$

$$Z_Z = \frac{U_Z}{\sqrt{3} \cdot I_Z}, \tag{28}$$

$$X_Z = \sqrt{Z_Z^2 - R_Z^2}, \tag{29}$$

e) for total power losses, as shown below:

the stator copper loss under no-load conditions

$$\Delta P_{Cu0} = 3 \cdot R_1 \cdot I_0^2, \tag{30}$$

the stator copper loss under short-circuit conditions

$$\Delta P_{Cu1} = 3 \cdot R_1 \cdot I_Z^2, \tag{31}$$

the rotor copper loss under short-circuit conditions

$$\Delta P_{Cu2} \approx P_Z - \Delta P_{Cu1}, \tag{32}$$

the stator core loss

$$\Delta P_{Fe0} \approx P_0 - \left(\Delta P_{Cu0} + \Delta P_m\right), \tag{33}$$

f) mechanical power loss $\Delta P_m \approx \mathrm{const}$ is assessed from characteristic

$$P_0 = f(U_0^2).$$

2. Plot the characteristic of the induction motor no-load operation P_0 in the function of the square of supply voltage (inter-phase voltage) U_0^2.
3. Plot the characteristics of the induction motor no-load operation I_0, P_0, $\cos\varphi_0$ in the function of supply voltage U_0 (*the characteristics shown in a single chart must differ in the line colour and/or type and description*).
4. Plot the characteristics of the induction motor short-circuit operation I_Z, P_Z, $\cos\varphi_Z$ in the function of supply voltage U_Z (*the characteristics shown in a single chart must differ in the line colour and/or type and description*).
5. Draw a complete equivalent circuit diagram of the induction motor (form II) and specify on it the values of the parameters determined for the rated values of current and voltage:

a) R_1 from measurements under short-circuit conditions for the rated current:

$$R_1 \approx \frac{R_Z}{2} \tag{34}$$

and, for comparison (*in parentheses*), from direct measurements (cf. 3.2.2):

b) R_{Fe}, $X_{\boldsymbol{\mu}}$ from measurements under no-load conditions for the rated voltage:

$$R_{Fe} = \frac{3 \cdot E_1^2}{\Delta P_{Fe}} \cong \frac{3 \cdot (U_1 - I_0 \cdot R_1)^2}{P_0 - 3 \cdot I_0^2 \cdot R_1 - \Delta P_m} \approx \frac{U_0^2}{P_0 - 3 \cdot I_0^2 \cdot R_1} \approx \frac{U_0^2}{P_0}, \tag{35}$$

$$X_\mu = \frac{E_1}{I_\mu} \cong \frac{U_1 - I_0 \cdot R_1}{\sqrt{I_0^2 - I_{Fe}^2}} \approx \frac{U_0}{\sqrt{3} \cdot I_0}, \tag{36}$$

c) R’$_2$ from measurements under short-circuit conditions for the rated current:

$$R_2' \cong R_Z - R_1 = \frac{\Delta P_{Cu}}{3 \cdot I_Z^2} - R_1 \approx \frac{P_Z}{3 \cdot I_Z^2} - R_1, \tag{37}$$

d) X_{1R}, X_{20R} from measurements under short-circuit conditions assuming that:

$$X_{1R} = X_{20R}' \tag{38}$$

(the assumption causes an error of $5 \div 10$ % [4]),

$$X_{1R} = R_1 \frac{\sqrt{1 - \cos^2 \varphi_Z}}{\cos \varphi_Z} = R_1 \cdot \operatorname{tg} \varphi_Z, \tag{39}$$

$$X_{20R}' = X_Z - X_{1R}. \tag{40}$$

6. Determine the values of short-circuit voltage U_Z^* and $u_{Z\%}^* = \frac{U_Z^*}{U_N} \cdot 100\%$ and record them in the last row of Table 1.2.

5. Report

The report must include:

1. The title page *(exercise name, section number, the last and first names of the students doing the exercise and the exercise date)*.
2. Rated data of the induction machine under analysis (*power, voltage, current, revolutions, power factor*).
3. Diagram of the measuring system
4. Tables listing the measurement results with calculations.
5. Charts for dependences described in 4.2–4.4 above.
6. The equivalent circuit diagram of one phase of the induction motor with values of the parameters specified in 4.5 above.
7. Remarks and conclusions (*concerning the characteristics, their deviations from theoretical characteristics, values of determined parameters of the equivalent circuit diagram, correctness of the measuring method, discrepancies between the approximate value of the resistance of the stator winding calculated under short-circuit conditions and its measured value, etc.).*