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Lab Electrical Power Engineering I

Test 3: Induction machine with squirrel cage rotor and slip ring rotor

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1 Experiment purpose

This experiment deals with the construction and the operation modes of an induction machine and illustrates the main differences between a squirrel cage rotor and a slip ring rotor.

At first the operational performance of the induction machine with squirrel cage rotor is measured by means of a reversing operation. Then the reversing operation of the induction machine with slip ring rotor is analyzed with different starting resistances. During the measurement of the operational performance of the loaded machine, the rotational speed of the induction machine with slip ring rotor will be reduced with the help of a load machine. Finally the experiment deals with load tests at different torque.

2 Experiment preparation

2.1 Construction and operation modes of induction machines

The induction machine is a very important AC machine. It is mostly used as a motor. The stator and the rotor are made of laminated steel sheets with stamped in slots. The stator slots contain one symmetrical three-phase winding, which can be connected to the three-phase network in star or delta connection. The rotor slots carry either a symmetrical three-phase winding or a short-circuited squirrel cage winding.

The stator of a simple induction machine has 6 slots per pole pair, in each case one for the forward and one for the backward conductor for each phase winding. Generally, the winding is carried out with a large number of pole pairs ($p > 1$) and distributed in different slots ($q > 1$).

Figure 1 shows the principal construction of an induction machine. The connection to the three-phase mains is shown in figure 2.

If the induction machine is supplied from the three-phase network with the frequency f_1, the symmetrical currents generate a rotational field at synchronous speed n_1 in the air gap of the machine. This rotational field induces currents with frequency f_2 in the rotor conductors. The rotor currents generate a rotational field, which rotates with the rotational difference speed n_2 relative to the rotor and with the rotational speed $n_1 = n + n_2$ relative to the stator. So the frequency condition is fulfilled. According to Lenz´s law, the rotor currents tend to compensate its generation cause, i.e. the relative movement between the stator and the rotor. The rotor currents and the stator rotational field that revolves at synchronous speed, act together to generate a torque, which has the intention of driving the rotor in the direction of the stator field and the rotor speed equal to the speed of the stator field. The rotor can never reach exactly the

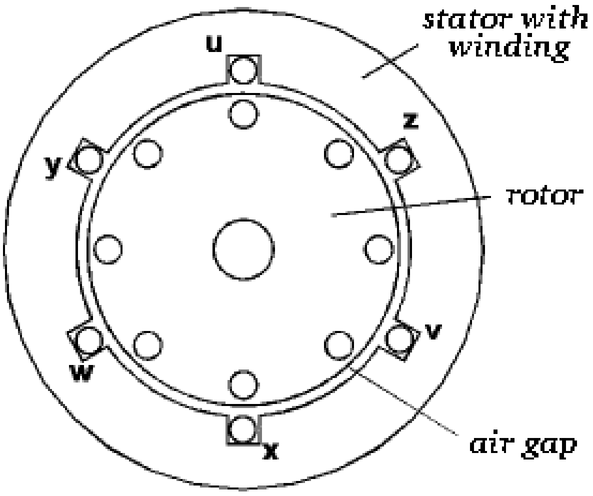

Figure 1: Schematic construction principle of an induction machine

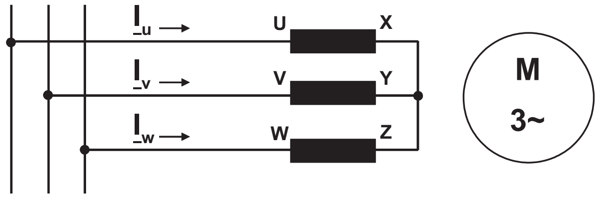

Figure 2: Connection of an induction machine

synchronous speed, because otherwise there would be no relative movement between the rotor and the stator rotational field, and the induction effect would be terminated. Therefore the rotor has a certain slip s to the stator rotational field, i.e. the rotor rotates asynchronously. Thereby it is named as asynchronous induction machine. The slip increases with the required torque.

Synchronous rotational speed:

$$n_1 = \frac{f_1}{p}$$

Rotational speed of the rotor:

$$n$$

Slip:

$$s = \frac{n_1 - n}{n_1} = \frac{f_2}{f_1}$$

2.2 Squirrel cage rotor and slip ring rotor

We can distinguish induction machines according to the type of the rotor between a squirrel cage rotor and a slip ring rotor.

The squirrel cage rotor has bars in the slots, whose ends are connected to the short-circuit rings (see figlaeuferarten). The number of the rotor phases is $m_2 = N_2$. Since there is no more access to the rotor winding, there is no possibility to influence the operational performance. The rotor bars and the short-circuit rings in large machines are made of copper, while in small machines the whole cage consists of aluminium. The induction machine with squirrel cage rotor is the most frequently used type of electrical machine, since it is simple, robust and cheaper than those with slip ring rotor. The squirrel cage rotor can be implemented only if the network tolerates a starting current of 4...7 times I_N and the heating during the start-up is not too large.

The slip ring rotor carries similarly a three-phase winding with a phase number $m_2 = 3$ in the stator. The ends of the winding are let outside and connected to slip rings. The rotor windings can be either short-circuited directly through brushes or through a series resistance, or supplied with an additional voltage. Hereby the rotational speed can be adjusted. The connection of a series resistance in the rotor circuit increases the real part of the starting current and also the starting torque while switching on. When a direct current is supplied to the slip rings, the machine can operate as synchronous machine.

Figure 3 indicates the principal difference between a slip ring rotor and a squirrel cage rotor. The following statements are valid both for a slip ring and a cage rotor.

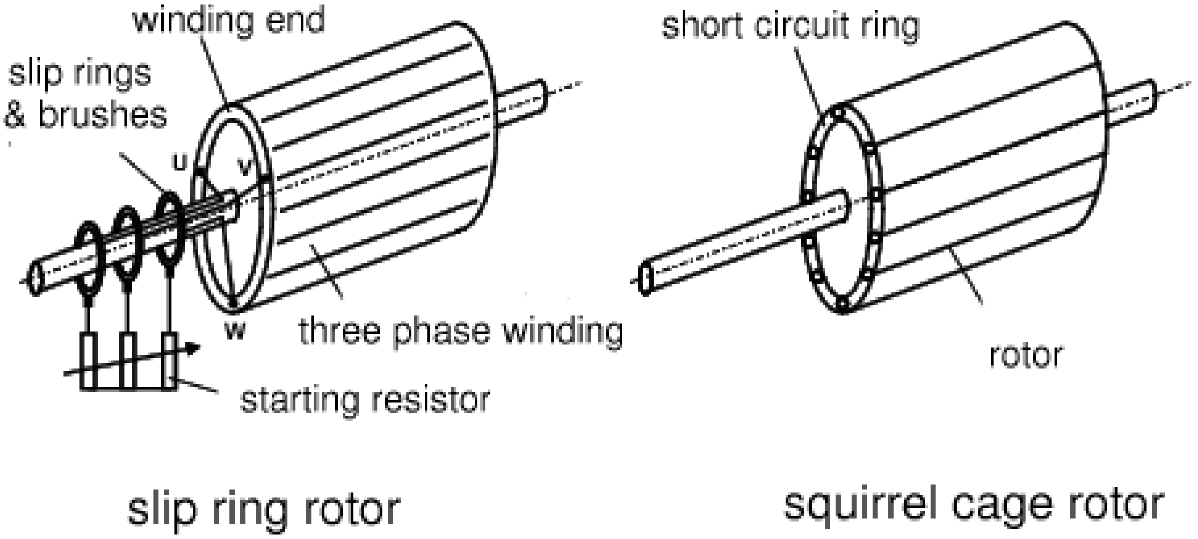

Figure 3: Rotor structure of induction machines

2.3 Basic equations and equivalent circuit diagram

The stator and rotor of the induction machine both are equipped with a symmetrical three-phase winding. Because of the symmetry it is sufficient to take only one phase into consideration.

Every phase of the stator and the rotor winding has an active resistance of R_1 and R_2, as well as a self-inductance of L_1 and L_2.

The windings of the stator and the rotor are magnetically coupled through a mutual inductance M.

Since the current flowing in the stator winding has the frequency f_1 and the current flowing in the rotor winding has the frequency f_2, then at the rotor speed n,

- currents induced from the stator into the rotor have $f = f_2$
- currents induced from the rotor into the stator have $f = f_1$.

According to this, voltage equations for the primary and secondary sides can be derived. The equivalent circuit diagram after the conversion of the rotor parameters on the stator side is presented in figure 4 .

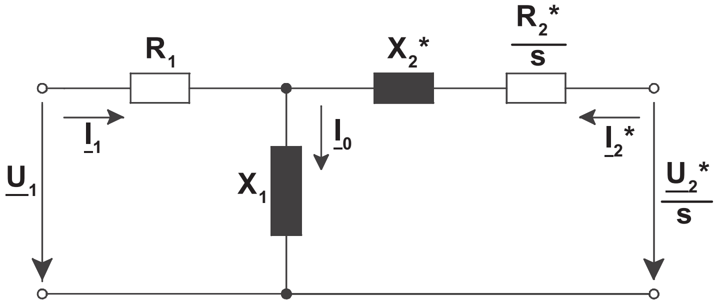

Figure 4: Equivalent circuit diagram of induction machine

The voltage and current equations are:

$$\underline{U}_1 = R_1 \cdot \underline{I}_1 + j \cdot X_1 \cdot \underline{I}_0$$

$$\frac{\underline{U}_2^*}{s} = \frac{R_2^*}{s} \cdot \underline{I}_2^* + j \cdot X_2^* \cdot \underline{I}_2^* + j \cdot X_1 \cdot \underline{I}_0$$

$$\underline{I}_0 = \underline{I}_1 + \underline{I}_2^*$$

With this equivalent circuit diagram, the operational performance of an induction machine can be completely described. This diagram is purposely used for the operation with a constant stator flux linkage, as well as for the operation on network with constant voltage and frequency.

For normal machines with the network frequency $f_1 = 50$ Hz, the stator resistance R_1 can be neglected:

$$R_1 = 0$$

At normal operation the windings of slip ring rotor are also short - circuited through slip rings and brushes like the squirrel cage rotor. As far as the skin effect in squirrel cage rotor is neglected, the operational performance for both types of the rotor construction is the same:

$$U_2^* = 0$$

So the voltage equations of the induction machine are:

$$\underline{U}_1 = j \cdot X_1 \cdot \underline{I}_0$$

$$\underline{U}_1 = -\frac{R_2^*}{s} \cdot \underline{I}_2^* - j \cdot X_2^* \cdot \underline{I}_2^*$$

$$\underline{I}_0 = \underline{I}_1 + \underline{I}_2^*$$

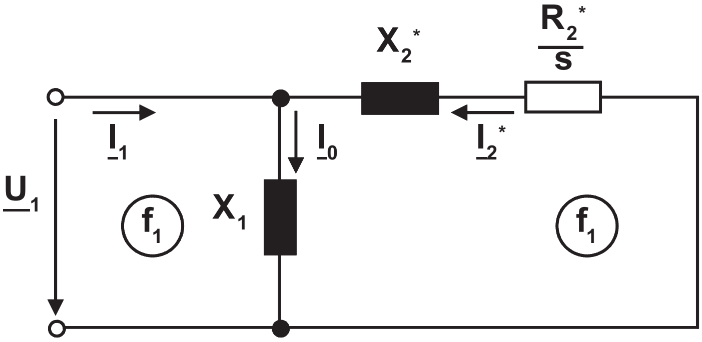

Figure 5: Equivalent circuit diagram of induction machine

This leads to a simplified equivalent circuit diagram in Figure 5, with which the research of the basic operational performance of the induction machine can be carried out.

2.4 Operational performance

Power balance

To define the powers, the power balance of the machine will be analyzed.

The power input is:

$$P_1 = 3 \cdot U_1 \cdot I_1 \cdot \cos\varphi_1$$

Since there are no losses in the stator with $R_1 = 0$, the total input active power is transferred through the air gap to the rotor as the air-gap power:

$$P_D = P_1 = 3 \cdot \frac{R_2^*}{s} \cdot \underline{I}_2^{*2}$$

In equivalent circuit diagram, this air-gap power is also in form of the active power of the resistance $\frac{R_2^*}{s}$. The rotor resistance itself causes copper losses:

$$P_{el} = 3 \cdot R_2 \cdot I_2^2 = 3 \cdot R_2^* \cdot I_2^{*2} = s \cdot (3 \cdot \frac{R_2^*}{s} \cdot I_2^{*2}) = s \cdot P_D$$

As a result, the mechanical power delivered to the shaft of the induction machine is only the difference between the air-gap power and the copper loss in the rotor:

$$P_{mech} = P_D - P_{el} = (1 - s) \cdot P_D$$

Torque

Maximal value of the torque is signified as breakdown torque:

$$M_{kipp} = \frac{3 \cdot p}{\omega_1} \cdot \frac{U_1^2}{2 \cdot X_2^*}$$

The slip that occurs at the maximal torque is called breakdown slip.

$$s_{kipp} = \frac{R_2^*}{X_2^*}$$

If the torque is referred to the maximal torque, then we get the Kloss´s equation:

$$\frac{M}{M_{kipp}} = \frac{2}{\frac{s_{kipp}}{s} + \frac{s}{s_{kipp}}}$$

According to this equation, the torque can be presented as a function of the slip or the rotation speed. Figure 6 shows this relationship.

An induction machine has three operation modes:

- Motor (the rotor rotates slower than the rotation field):

$$M > 0, n > 0, 0 < s < 1$$

- Generator (the rotor rotates faster than the rotation field):

$$M < 0, n > n_1, s < 0$$

- Braking operation (the rotor rotates in reverse direction to the rotating field:

$$M > 0, n < 0, s > 1$$

Efficiency

By neglecting the copper losses in the stator $R_1 = 0$ the efficiency of an induction machine at rated operation is:

$$\eta_N = \frac{P_{ab}}{P_{auf}} = \frac{P_{mech,N}}{P_{D,N}} = \frac{(1 - s) \cdot P_{D,N}}{P_{D,N}} = 1 - s_N$$

To obtain a higher rated efficiency, the rated slip s_n should be as small as possible. In practice, under the consideration of the stator copper losses and the iron losses, the efficiency reaches a value between 0.8 - 0.95.

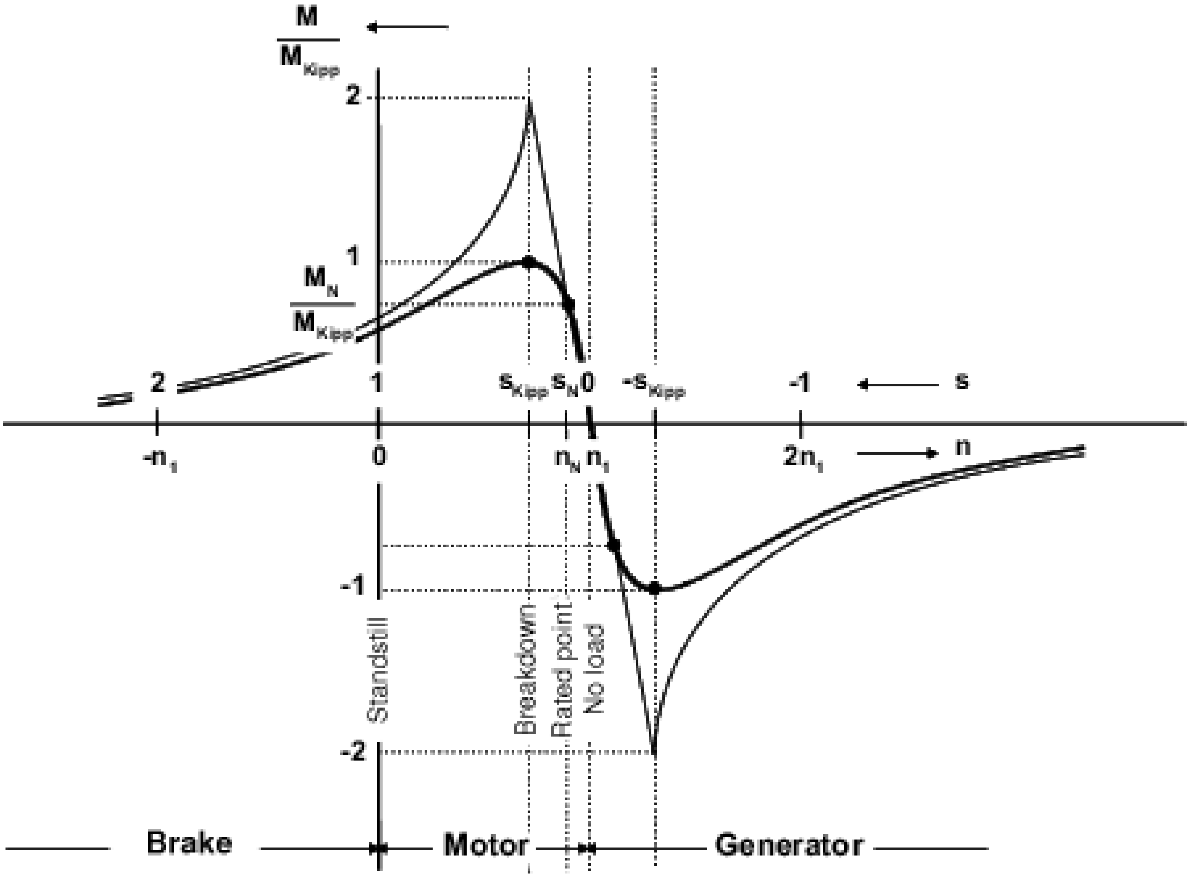

Figure 6: Operational performance of induction machine

2.5 Circle diagram

Circle diagram

The circle diagram of an induction machine is the orbit of the stator current.

Preconditions are:

- $\underline{U}_1$ is in y-axis
- the rotor is short-circuited
- $R_1 = 0$

The locus of the stator current I_1 is a circle. The middle point of the circle lies on the negative imaginary axis (y-axis), the diameter of the circle is $(\underline{I}_\infty - \underline{I}_0)$. Figure 7 shows the circle diagram of the induction machine.

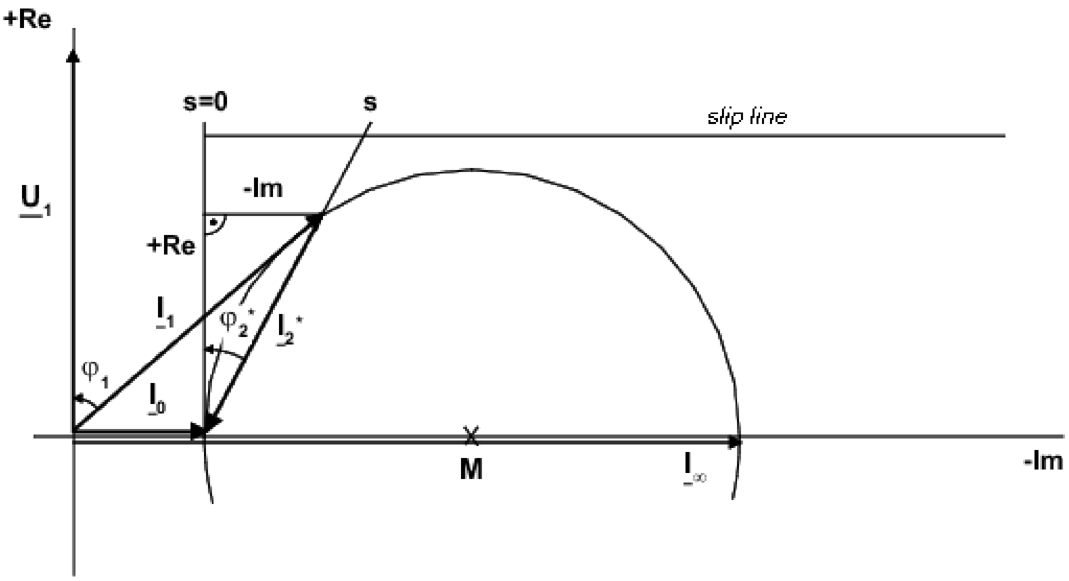

Figure 7: Circle diagram of an induction machine

Parameterization

For the construction of slip a tangent to the circle at the point I_0 should be drawn. The slip line is an arbitrary straight line parallel to the x-axis (-Im axis). The extension of the line I_2 will divide the slip line proportional to the slip.

For the parameterization another point besides the no-load point must be known.

Power in the circle diagram

From the circle diagram of induction machine it is not only possible to read the current I_1 for any operating point,but it is also possible to directly determine the torque M, the air-gap power P_D, the mechanical power P_{mech} and the electrical power P_{el} from the line segments.

The different powers are shown in the circle diagram in figure 8. The straight line through $s = 0$ and $s = 1$ is called *mechanical power line*.

Operating ranges and specific operating points

The three operation modes of induction machines are represented in the circle diagram as follows:

- Motor operation: $0 < s < 1$
- Braking operation: $1 < s < \infty$
- Generator operation: $s < 0$

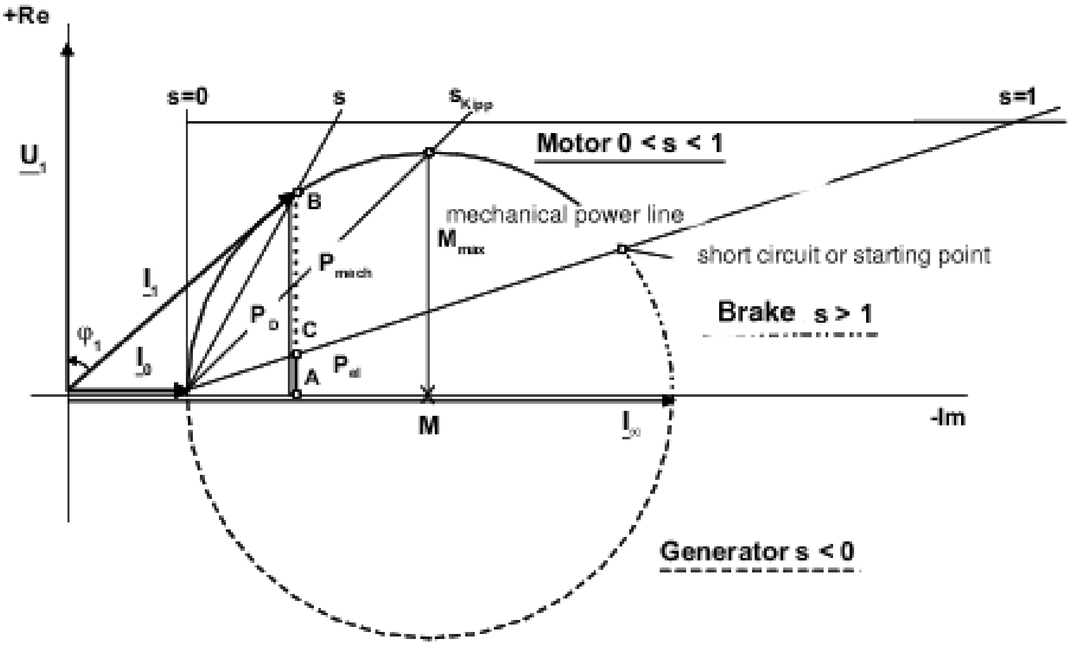

Figure 8: Power in the circle diagram

The following points can be distinguished:

- No-load: $s = 0, n = n_1$: No-load current lies on the x-axis and should be as small as possible considering the absorbed reactive power of the induction machine.
- Breakdown point: At this point the induction machine has the maximum torque. This is the peak point of the circle, the real part and imaginary part of the current I_2^* are the same.
- Starting- or short-circuit point: $s = 1, n = 0$: At the start-up of the machine the short-circuit current I_{1K} is several times the rated current I_{1N}. So it has to be limited. Typical values are $I_{1K} = 5...7 \cdot I_{1N}$.
- Ideal short circuit: $s = \infty, n = \infty$: This is the largest theoretically occuring current which also lies on thex-axis. The values reached in practice are $I_\infty = 5...8 \cdot I_{1N}$
- Optimum operating point: The rated point is chosen at the point where cosφ_1 is maximum. This is fulfilled if the rated current line is a tangent to the circle. In practice the optimum value can not be always kept exactly.

2.6 Rotation speed adjustment

The most important method for the rotation speed adjustment follows from the basic equation

$$n = \frac{f_1}{p} \cdot (1 - s)$$

Increase of the slip

Adding resistances in the rotor circuit of the slip ring rotor machines can increase the slip. The circle diagram of the induction machine will stay preserved, if the resistance of the rotor R_2 is increased by the addition of series resistor R_V. Hereby only the slip parameterization is changed. It is valid:

$$s_2 = s_1 \cdot (1 + \frac{R_V}{R_2^*})$$

With a series resistance of R_V^* and at a certain slip s_2 the same circle point and therefore the same torque and current as at the slip s_1 can be obtained. So it is possible, for example, to start up the machine with maximum torque. However, this method has great losses because the efficiency $\eta = 1 - s$ decreases.

Change of the number of pole pairs

In squirrel cage rotor machines, which are not bounded to a fixed pole number, pole change alterates the rotational speed. For this purpose, two three-phase windings with different pole numbers are placed in the stator, but only one of them can be in operation. Alternatively, the tapped winding with possibility of pole changing can be used. This permits a change of the rotational speed at a ratio of 2:1 by switching two coil groups from serial to parallel connection. However this method allows to change the rotation speed only in very large steps.

Change of the supply frequency

This method requires a power converter. The power is supplied from the three-phase network, rectified, transmitted over a DC voltage-link and fed to a power inverter which will supply the induction machine with variable frequency and voltage. The adjustment of frequency and voltage enables an ideal regulation of the rotational speed with small losses. Fig. 9 shows a schematic diagramm of such a device.

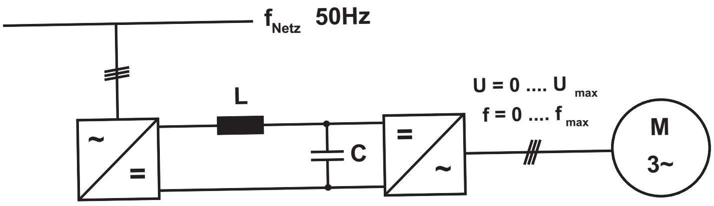

Figure 9: Change of the supply frequency

2.7 Skin effect in squirrel cage rotor

Due to the skin effect when supplying with alternating current the current in the bars is pressed towards the air gap with increased frequency. The cause lies in the slot leakage flux. In induction machines this skin effect is used to improve the starting performance.

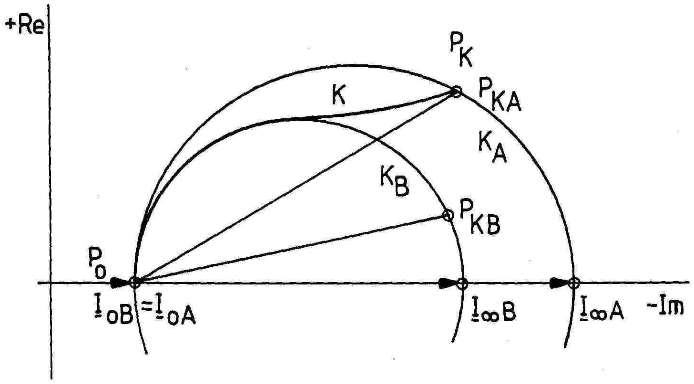

Figure 10: Starting and operational performance in circle diagram

Figure 10 shows the starting and operational preformance of the induction machine. At the starting point the frequency of the rotor current is equal to the network frequency. The skin effect appears in therotor bars, which causes the increase of R_2' and the decrease of $X_{2\sigma}'$. The increase of R_2' is responsible for the shift of starting point in the direction of breakdown point, while the decrease of $X_{2\sigma}$ extends the circle diameter. As the motor starts rotating, the skin effect will be more and more weak and finaly disappear at the rated operation point. The locus of the stator current can be determined from the starting circle K_A and the operation circle K_B. Strictly speaking, a new circle must be constructed for every operating point.

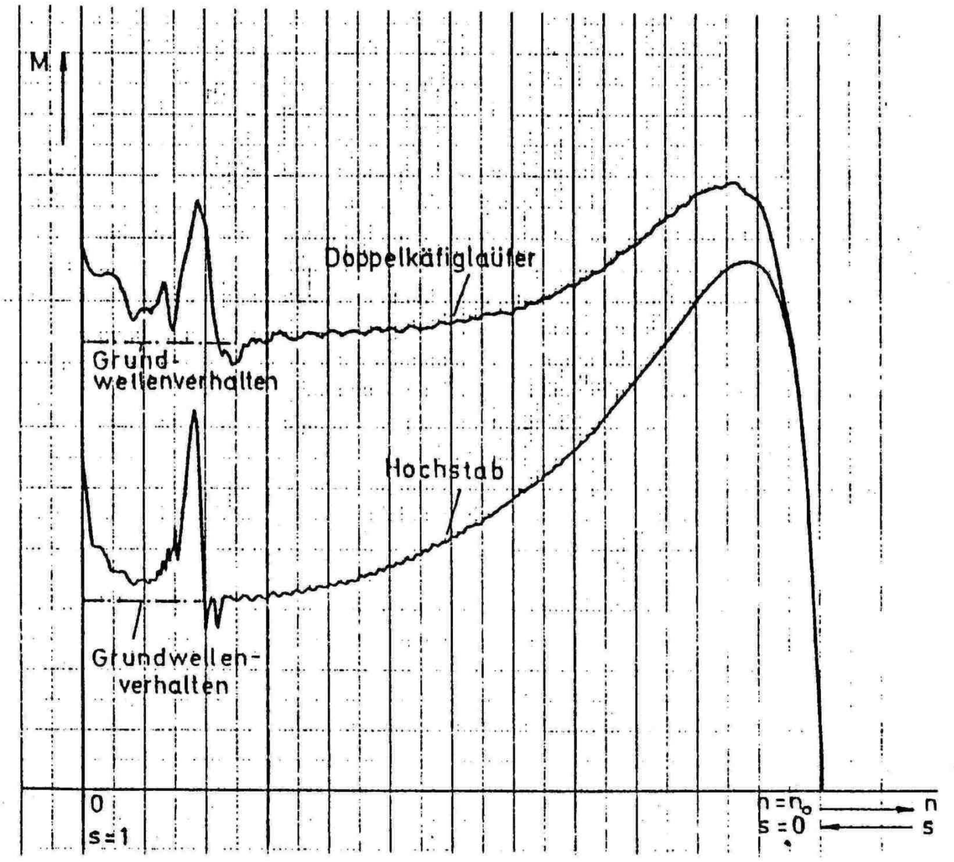

Figure 11: Start-up of induction machine

2.8 Speed-/torque characteristic in the range $0 \leq s \leq 1$

At the analysis of the machine performance with calculations through the single phase equivalent circuit diagram only the fundamental wave of the induction is taken into consideration. Effects of higher harmonics are considered in the form of double interlaced leakage, merely as increase of leakage, while at the calculation of the torque all the harmonics are not considered. The measurement of the rotation speed/torque characteristic shows that the torque curve in the area close to the short-circuit point can not be explained good enough only with the fundamental wave (performance). In order to get this disturbing torque, the effect of higher harmonics must be considered. Figure 11 shows the startup of induction machines.

3 Experiment realization

3.1 Safety requirements

Because the applied voltage amounts up to 400 V the laboratory orders must be **strictly** respected, particulary these ones:

1. Set up and change of circuit connections are allowed only under **no voltage conditions**.
2. Before the beginning of operation the superintendent must be consulted and **every** connection must be inspected.
3. Adjustment of variable capacitors must be performed under no voltage conditions.
4. Before the experiment every participant must inform himself about the location and function of the emergency devices.
5. Nominal values of the test machine can be exceeded only for a short period of time. Read the nominal values of the machine from the rating plate on the machine.

	Pendulum machine		induction machine
U_N		U_N	
I_N		I_N	
n_{max}		n_N	
M_{max}		P_N	
f_{max}		$\cos\varphi_N$	

3.2 Induction machine with suqirrel-cage rotor

3.2.1 Reversion of induction machine with suqirrel-cage rotor

Experimental set up

1. Connect the pendulum machine to the induction machine with suqirrel-cage rotor.
2. Connect the induction machine in star connection on the 230 V network.
3. Plug the PC on the RS 232-interface of the control unit of the pendulum machine.

Experiment realization

1. Reverse the induction machine from $n = -1500\,min^{-1}$ to $n = 1500\,min^{-1}$, using n-start and n-stop on the control unit. Record the reversing characteristic graphically.
2. Explain the obtained characteristic:

3.3 Induction machine with slip ring rotor

3.3.1 Reversion of induction machine with slip ring rotor

Experimental set up

1. Connect the pendulum machine to the induction machine with slip ring rotor.
2. Connect the slip ring in star connection with the serial resistance and the induction machine in star connection on the 230V network.
3. Plug the PC to the control unit.

Experiment realization

1. Reverse the induction machine from $n = -1500\,min^{-1}$ to $n = 1500\,min^{-1}$, using n-start and n-stop on the control unit. Record graphically the reversing characteristics for $R = 0\,\Omega$ and $R = 2,75\,\Omega$.
2. Explain the obtained characteristics and compare this with the characteristic of the induction machine with squirrel-cage rotor.

3. Reverse analogically the induction machine from $n = -1000\,min^{-1}$ to $n = 3000\,min^{-1}$ using n-start and n-stop on the control unit and record graphically the characteristics for $R = 0\,\Omega$ and $R = 0,5\,\Omega$.
4. Explain the obtained characteristics and mark the operating ranges of the induction machine.

3.3.2 Load measurement at changing speed

Experimental set up

Connect two wattmeters in Aron-connection with the machine clamps.

Experiment realization

1. Start up the machine at 230 V network and lower the speed using the pendulum machine, as it is given in tables 1 and 2.
2. Measure the speed n, the torque M_P of the pendulum machine, the power P_P of the pendulum machine as well as the power P_{w1} and P_{w2} of the induction machine (Aron-connection) for $R = 0\,\Omega$ and $R = 1,25\,\Omega$.

Analysis

1. Calculate the power $P_A = P_{w1} + P_{w2}$ of the induction machine and the power factor $\cos\varphi = \cos\left(\arctan(Q/P)\right)$ with $Q = \sqrt{3} \cdot (P_{w1} - P_{w2})$.
2. Sketch P_A und P_P, $\cos\varphi$ and M_P for $R = 0\,\Omega$ and $R = 1,25\,\Omega$ in separate graphs and explain them.

n/min^{-1}	P_{w1}/W	P_{w2}/W	P_P/W	M_P/Nm	P_A/W	Q_A/W	$\cos\varphi$
1500							
1480							
1460							
1440							
1420							
1400							
1380							
1360							

Table 1: Load-case measuring, $n = const$, $R = 0\,\Omega$

n/min^{-1}	P_{w1}/W	P_{w2}/W	P_P/W	M_P/Nm	P_A/W	Q_A/W	$\cos\varphi$
1500							
1480							
1460							
1440							
1420							
1400							
1380							
1360							

Table 2: Load-case measurement, $n = const$, $R = 1,25\,\Omega$

Figure 12: Diagram $P_A,\ P_P = f(n)$ for $R = 0\,\Omega$ and $R = 1,25\,\Omega$

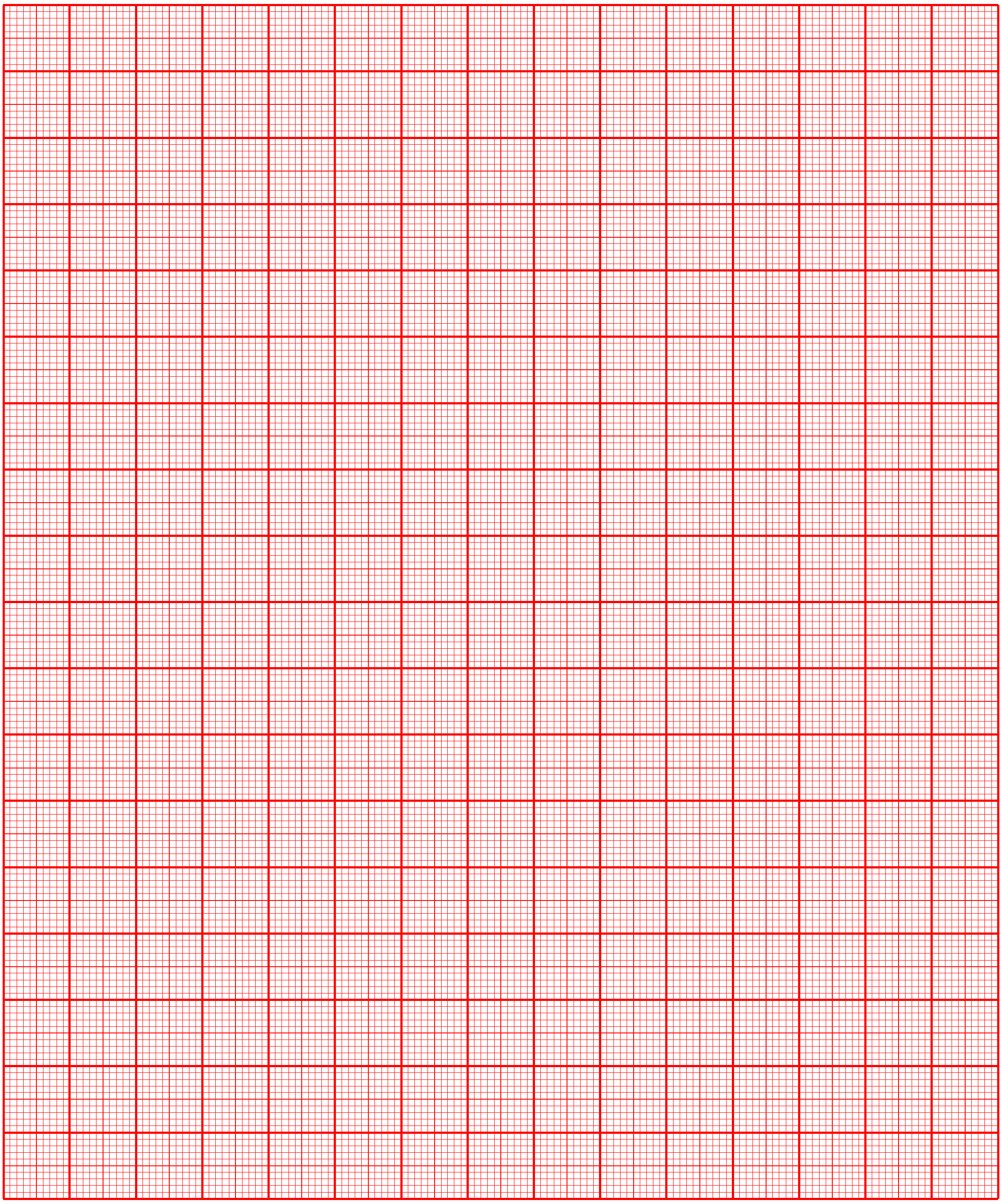

Figure 13: Diagram $\cos\varphi = f(n)$ for $R = 0\,\Omega$ and $R = 1,25\,\Omega$

Figure 14: Diagram $M = f(n)$ for $R = 0\,\Omega$ and $R = 1,25\,\Omega$

3.3.3 Load measurement at changing torque

Change the torque of the pendulum machine according to the tables 3 and 4 and measure the speed n, the power of the pendulum machine P_P, as well as the power P_{w1} and P_{w2} of the induction machine (Aron connection) and the current I for $R = 0\,\Omega$ and $R = 1,25\,\Omega$.

Analysis

1. Calculate the power $P_A = P_{w1} + P_{w2}$ of the induction machine, the power factor $\cos\varphi = \cos(\arctan(Q/P))$ with $Q = \sqrt{3} \cdot (P_{w1} - P_{w2})$ and the efficiency $\eta = P_{ab}/P_{auf}$.
2. Sketch $\cos\varphi$, η and I for $R = 0\,\Omega$ and $R = 1,25\,\Omega$ in a graph and explain them.

M/Nm	P_P/W	P_{w1}/W	P_{w2}/W	P_A/W	Q/W	I/A	n/min^{-1}	$cos\varphi$	η
-3,0									
-2,5									
-2,0									
-1,5									
-1,0									
-0,5									
0,0									
+0,5									
+1,0									
+1,5									
+2,0									
+2,5									
+3,0									

Table 3: Load-case measuring, $M = const$, $R = 0\,\Omega$

M/Nm	P_P/W	P_{w1}/W	P_{w2}/W	P_A/W	Q/W	I/A	n/min^{-1}	$cos\varphi$	η
-3,0									
-2,5									
-2,0									
-1,5									
-1,0									
-0,5									
-0,0									
+0,5									
+1,0									
+1,5									
+2,0									
+2,5									
+3,0									

Table 4: Load-case measuring, $M = const$, $R = 1,25\,\Omega$

Figure 15: Diagram $\cos\varphi,\ \eta,\ I = f(M)$ for $R = 0\,\Omega$

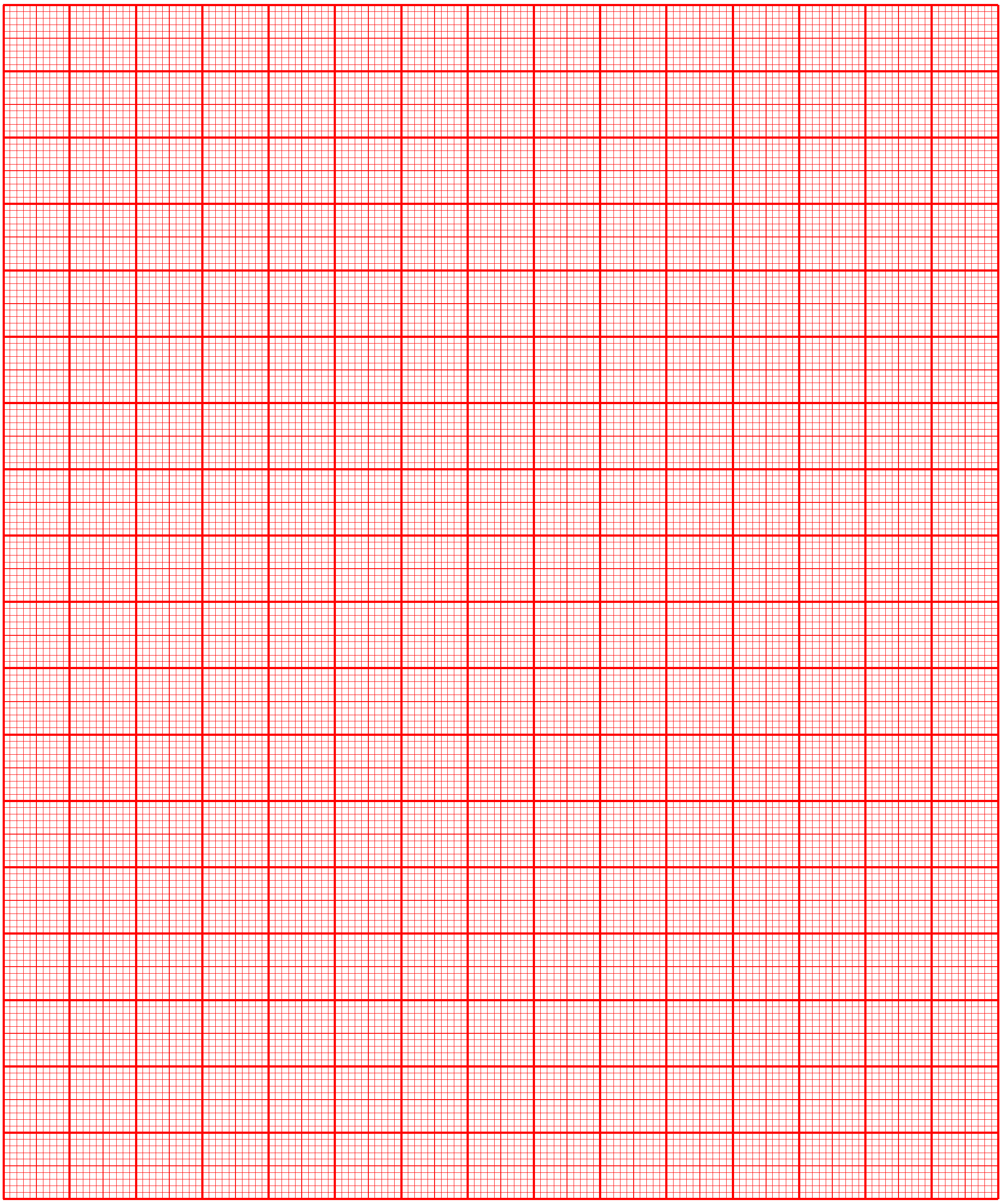

Figure 16: Diagram $\cos\varphi,\ \eta,\ I = f(M)$ for $R = 1,25\,\Omega$