Summary

9. Induction machine

9.1 Structure and operation

The induction machine (or "asynchronous machine") is the machine most widely used in industrial environments. One can found three types of applications:

- fixed speed applications
- variable speed applications without strict requirements for dynamic
- high dynamic variable speed applications.

The implementation of these last two applications is basically based on the coupling of the motor with an electronic converter, able to regulate separately voltage and frequency. The first one is usually realized by connecting the machine to the grid, directly.

From a construction point of view, the induction machine has a laminated stator on which a three-phase winding is mounted: it consists of three phases displaced by 120 degrees from each other.

The rotor, laminated, can, conversely, have two types of structures:

- wound rotor: also on the rotor, a three-phase winding is placed: its terminals are brought on the stator, for the necessary connections, by means of three sliding contacts (three rings and three brushes); in particular, during normal operation, the rotor windings are closed in short circuit;
- squirrel cage: the structure is made by ferromagnetic material, laminated, and by some conducting bars; they are closed in short-circuit by means of two circular rings, placed on both ends of the rotor.

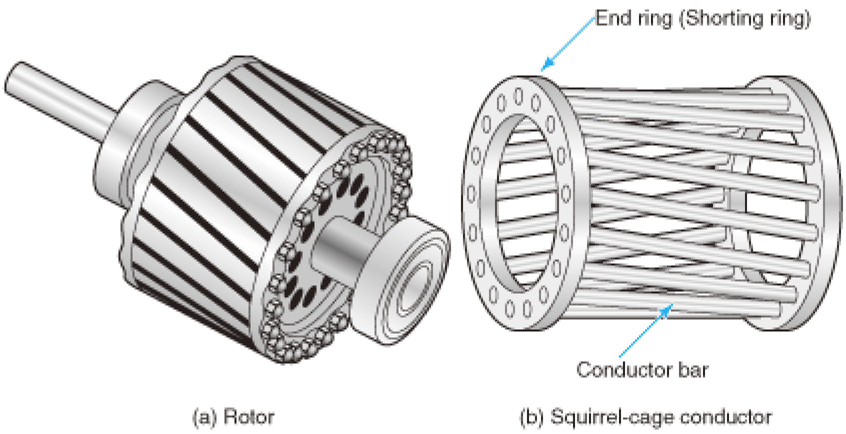


Figure 9-1: Squirrel cage (*www.nidec.com*)

Suppose you supply the stator windings with a three-phase sinusoidal AC voltage. Therefore three currents (with a displacement of 120° each other) begin to flow in the three windings. At the same time, a magnetic flux arises in the air gap, whose value, for the superposition principle, can be calculated as the composition of the fluxes created by each current.

Consider, as a reference, the magnetic structure shown in Figure 9-2, characterized by only two poles (wound rotor, open circuit).

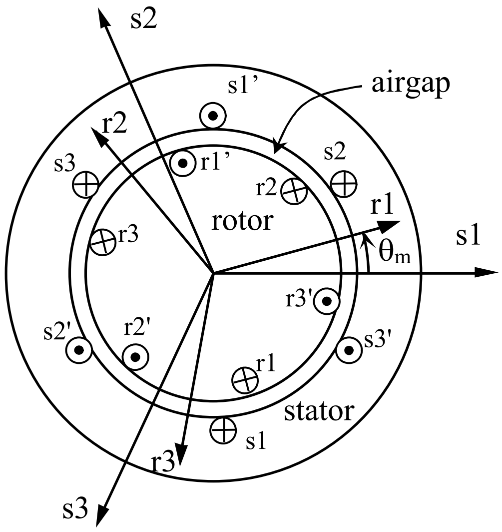


Figure 9-2: Reference structure

The currents in the three windings, at steady-state, are:

$$i_1(t) = \sqrt{2} \cdot I_{rms} \cos(\omega t)$$

$$i_2(t) = \sqrt{2} \cdot I_{rms} \cos\left(\omega t - \frac{2}{3}\pi\right)$$

$$i_3(t) = \sqrt{2} \cdot I_{rms} \cos\left(\omega t - \frac{4}{3}\pi\right)$$

where I_{rms} represents the rms value of the stator current and ω the frequency of the sine wave (in Italy with f = 50Hz, ω = 314.15 rad/s).

These currents can be represented by the corresponding space phasor:

$$\overline{i(t)} = \sqrt{\frac{2}{3}}\left[i_1(t) + \overline{\alpha} \cdot i_2(t) + \overline{\alpha}^2 \cdot i_3(t)\right]$$

where $\overline{\alpha} = e^{j\frac{2}{3}\pi}$

In case of a symmetrical and balanced three-phase system, as in this case, it results:

$$\overline{i(t)} = \sqrt{3} \cdot I_{rms} \cdot e^{j\omega t}$$

The rotating magnetic flux, due to this current, induces, into the windings of the stator and rotor, sinusoidal electromotive forces (emf), proportional to the maximum value of the flux, to the speed ω and to the number of conductors in the windings. One can therefore say that the machine behaves like a transformer with its secondary winding open, where a rotating magnetic flux links periodically the stator and rotor windings, causing the following electromotive forces (E_s is the emf induced in the stator, E_{ro} is the one in rotor):

$$E_s = K \cdot \omega \cdot \Phi \cdot N_s$$

$$E_{ro} = K \cdot \omega \cdot \Phi \cdot N_r$$

where K is a suitable coefficient, ω is the speed of the magnetic field, Φ is the magnetic flux, N_r and N_s represent the number of effective conductors of the stator and rotor windings.

The equivalent circuit of the machine is similar to that of a transformer.

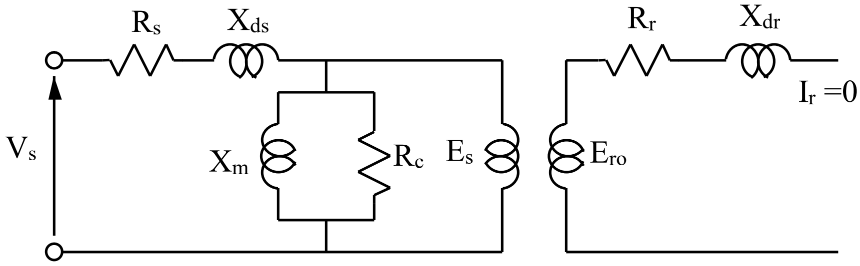


Figure 9-3: Equivalent circuit of an induction machine with open rotor

When you short-circuit the rotor terminals, a current in the rotor windings (due to the emf) arises. The frequency of these currents is the same of E_{ro}, that is ω. These currents creates a rotor flux which is rotating at ω speed. Therefore, in the airgap there are two fluxes, at the same speed: the flux due to the stator current and the flux due to the rotor ones. Like an electromagnetic joint, a torque arises and the rotor begins to rotate.

The two fluxes are combined, in the airgap, in a single common flux. The common flux is moving at ω speed, and the relative speed ω_s between the stator and the common flux is equal to ω. The relative speed between the rotor and the common flux is no more ω (due to the rotation of the rotor), but ω_{slip}, equal to the difference between the actual speed of the rotating flux and the rotor speed ω_m.

Accordingly, the value of rotor emf becomes:

$$E_r = K \cdot \omega_{slip} \cdot \Phi \cdot N_r = x \cdot E_{ro}$$

$$x = \frac{\omega_{slip}}{\omega} = \frac{\omega - \omega_m}{\omega}$$

where "x" is called "slip" (*scorrimento*) and is equal to the ratio of the relative speed (ω_{slip}) and speed of the rotating flux ω.

When ω_m tends to ω (so the slip goes to zero, $x \Rightarrow 0$), the induced rotor electromotive force goes to zero; in fact, the rotor, rotating at the same speed of the rotating flux, does not cut new flux lines (the flux linked with the rotor is constant and its derivative is zero).

For mechanical speed different from zero, the equivalent circuit of the rotor windings is:

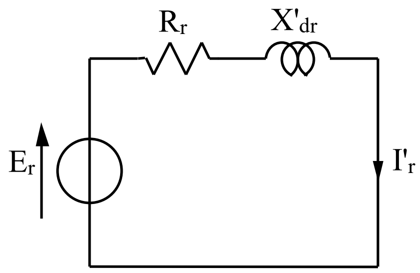


Figure 9-4: Equivalent circuit of an induction machine when $\omega_m \neq 0$

From the above, the operating frequencies are two: one for the stator ($\omega_s = \omega$) and one for the rotor ($\omega_r = \omega - \omega_m = \omega_{slip} = x\,\omega$). The new rotor leakage reactance X'_{dr} is calculated at ω_r, while the open circuit reactance X_{dr} was calculated at ω. That means:

$$\frac{X'_{dr}}{\omega_r} = \frac{X_{dr}}{\omega}$$

$$X'_{dr} = \frac{X_{dr}}{\omega}\omega_r = X_{dr}\frac{\omega - \omega_m}{\omega} = xX_{dr}$$

If you divide all the quantities (voltage, resistance and reactance) by the slip "x", the module of the rotor current does not change (the ratio between the voltage and the impedance does not depend on the slip value).

$$\overline{E_r} = (R_r + jX'_{dr})\overline{I'_r}$$

and

$$\overline{E_r} = x\overline{E_{ro}} = (R_r + jxX_{dr})\overline{I'_r}$$

$$\overline{E_{ro}} = (\frac{R_r}{x} + jX_{dr})\overline{I_r}$$

where I_r has the same amplitude of I'_r but is a phasor at a different frequency: ω (instead of ω_r), the same frequency of the stator quantities.

Since the two circuits of stator and rotor are now at the same frequency, they can be represented by a single equivalent circuit, similar to that of a transformer. In order to have the same approach of a transformer, we choose a different way to measure the rotor current I_r.

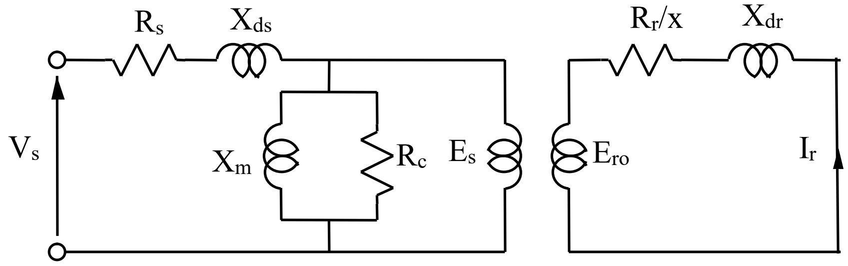


Figure 9-5: Equivalent circuit of an induction machine

Note that the involved parameters have the following physical meaning:

- R_s resistance of the stator windings: identifies the Joule losses in the stator copper
- X_{ds} stator leakage reactance: it represents the portion of the magnetic flux, linked with the stator windings, that does not link the rotor windings; it is equal to ωL_{ds}
- X_m magnetizing reactance: it identifies the need for a current to magnetize the entire magnetic circuit; that is ωM
- R_c this resistance represents the iron losses due to magnetic phenomena of hysteresis and eddy currents
- R_r rotor winding resistance: identifies the Joule losses in the rotor conductors
- X_{dr} rotor leakage reactance (calculated at the frequency of the stator ω): it represents the portion of the magnetic flux, linked with the rotor windings, that does not link the stator windings; it is equal to ωL_{dr}

The ideal transformer, in Figure 9-5, allows the transfer of the rotor leakage reactance and rotor resistance to the stator side. This gives the so-called five parameters equivalent circuit (the iron losses are neglected) of the induction machine (Figure 9-6).

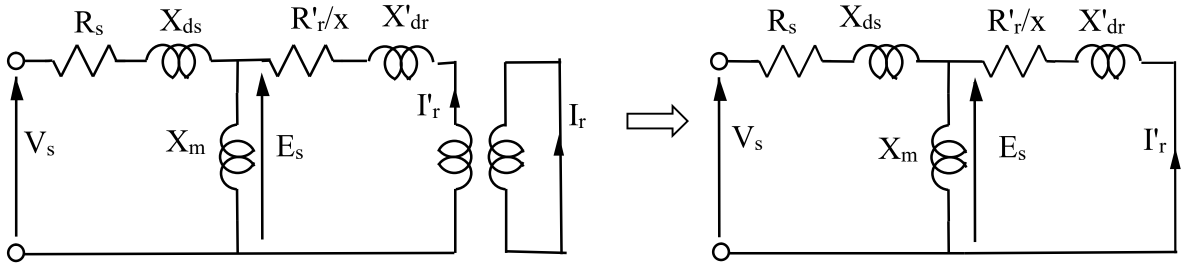


Figure 9-6: five parameters equivalent circuit

The parameters R'_r and X'_{dr} are obtained by the respective R_r and X_{dr}, multiplying them by the square of the transformation ratio $k=E_s/E_{ro}$. The current I'_r is equal to I_r/k.

The steady state equations of the machine are:

$$\overline{v_s} = R_s \cdot \overline{i_s} + j\omega L_{ds}\overline{i_s} + \overline{E_s} = R_s \cdot \overline{i_s} + j\omega L_{ds}\overline{i_s} + j\omega M(\overline{i_s} + \overline{i'_r})$$

$$0 = \frac{R'_r}{x} \cdot \overline{i'_r} + j\omega L'_{dr}\overline{i'_r} + \overline{E_s} = \frac{R'_r}{x} \cdot \overline{i'_r} + j\omega L'_{dr}\overline{i'_r} + j\omega M(\overline{i_s} + \overline{i'_r})$$

which may become:

$$\bar{v}_s = R_s \cdot \bar{i}_s + j\omega L_s \bar{i}_s + j\omega M \overline{i'}_r$$
$$0 = \frac{R'_r}{x} \cdot \overline{i'}_r + j\omega L'_r \overline{i'}_r + j\omega M \bar{i}_s$$

with $L_s = L_{ds}+M$ and $L'_r = L'_{dr}+M$.

Another equivalent circuit may be obtained considering the fact that the rotor is generally in short circuit and rotor quantities are not measurable: it is possible to introduce a change of variables by introducing an ideal transformer with a turns ratio equal *to* $H = v_r^*/v'_r = i'_r/i_r^*$.

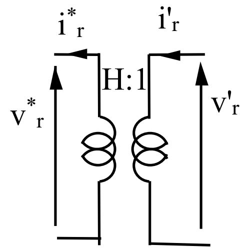


Figure 9-7: introduction of an ideal transformer

The equations become:

$$\bar{v}_s = R_s \cdot \bar{i}_s + j\omega L_s \bar{i}_s + j\omega M H \bar{i}_r^*$$
$$\bar{v}_r^* = H \overline{v'}_r = 0 = H\left(\frac{R'_r}{x} \cdot H \bar{i}_r^* + j\omega L'_r H \bar{i}_r^* + j\omega M \bar{i}_s\right)$$

and

$$\bar{v}_s = R_s \cdot \bar{i}_s + j\omega L_s \bar{i}_s + j\omega M H \bar{i}_r^*$$
$$0 = \frac{R'_r}{x} \cdot H^2 \bar{i}_r^* + j\omega L'_r H^2 \bar{i}_r^* + j\omega M H \bar{i}_s$$

Adding and subtracting the term $j\omega M H \bar{i}_s$ in the first equation and $j\omega M H \bar{i}_r^*$ in the second one, we obtain:

$$\bar{v}_s = R_s \cdot \bar{i}_s + j\omega L_s \bar{i}_s + j\omega M H \bar{i}_r^* + j\omega M H \bar{i}_s - j\omega M H \bar{i}_s$$
$$0 = \frac{R'_r}{x} \cdot H^2 \bar{i}_r^* + j\omega L'_r H^2 \bar{i}_r^* + j\omega M H \bar{i}_s + j\omega M H \bar{i}_r^* - j\omega M H \bar{i}_r^*$$

and

$$\bar{v}_s = R_s \cdot \bar{i}_s + j\omega\left(L_s - MH\right)\bar{i}_s + j\omega M H\left(\bar{i}_s + \bar{i}_r^*\right)$$
$$0 = \frac{R'_r}{x} \cdot H^2 \bar{i}_r^* + j\omega\left(L'_r H^2 - MH\right)\bar{i}_r^* + j\omega M H\left(\bar{i}_s + \bar{i}_r^*\right)$$

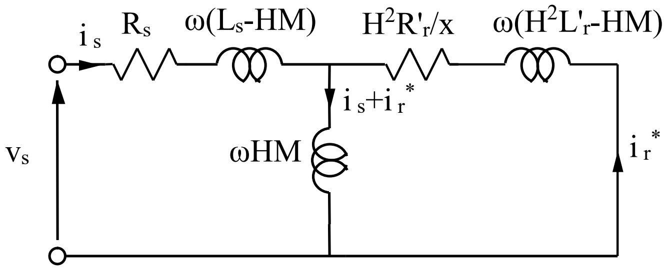


Figure 9-8: five parameters equivalent circuit with a fictitious ideal transformer

If you consider H=1, you have the classical five parameters model.

Putting $H = M/L'_r$ we obtain the four parameters equivalent circuit, with sthe hort-circuit inductance L_{ks} of the stator:

$$\bar{v}_s = R_s \cdot \bar{i}_s + j\omega L_{ks}\overline{i_s} + j\omega M^*(\overline{i_s} + \overline{i_r^*})$$
$$0 = \frac{R_r^*}{x} \cdot \overline{i_r^*} + j\omega M^*(\overline{i_s} + \overline{i_r^*})$$

where

$$L_{ks} = L_s - HM = L_s - \frac{M^2}{L'_r}$$
$$M^* = HM = \frac{M^2}{L'_r}$$
$$R_r^* = R'_r H^2 = R'_r \frac{M^2}{L'^2_r}$$

which corresponds to the equivalent circuit of Figure 9-9.

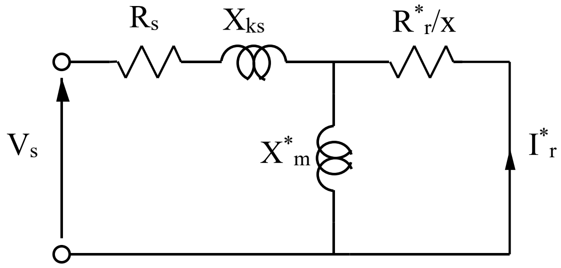


Figure 9-9: four parameters equivalent circuit, leakage on the stator side

However, you can also choose H= L_s/M. In this case, you have:

$$\bar{v}_s = R_s \cdot \bar{i}_s + j\omega M^\#(\overline{i_s} + \overline{i_r^\#})$$
$$0 = \frac{R_r^\#}{x} \cdot \overline{i_r^\#} + j\omega L_{kr}\overline{i_r^\#} + j\omega M^\#(\overline{i_s} + \overline{i_r^\#})$$

where

$$L_{kr} = L'_r H^2 - MH = \frac{L_s^2}{M^2} L'_r - L_s$$
$$M^\# = HM = L_s$$
$$R_r^\# = R'_r H^2 = R'_r \frac{L_s^2}{M^2}$$

which corresponds to the equivalent circuit of Figure 9-10.

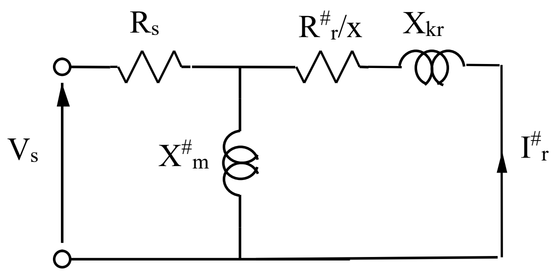


Figure 9-10: four parameters equivalent circuit, leakage on the rotor side

Regards to the fluxes, the five parameters model provides the following relationship between fluxes and currents (ignoring the quotes):

$$\overline{\psi_s} = L_s \cdot \overline{i_s} + M \cdot \overline{i_r}$$
$$\overline{\psi_r} = L_r \cdot \overline{i_r} + M \cdot \overline{i_s}$$

while, for the four parameters one (stator side), it results:

$$\overline{\psi_s} = L_{ks} \cdot \overline{i_s} + \overline{\psi_r}$$
$$\overline{\psi_r} = M^* \cdot (\overline{i_s} + \overline{i_r})$$

and, for the rotor side, it results:

$$\overline{\psi_s} = M^\# \cdot (\overline{i_s} + \overline{i_r})$$
$$\overline{\psi_r} = L_{kr} \cdot \overline{i_r} + \overline{\psi_s}$$

Finally, pay attention to the winding rotor again. The equivalent circuit of the rotor must be able to represent the active power transfer from the stator to the rotor through the airgap: it is the sum of the rotor losses and the mechanical power actually provided by the machine.

In particular, since the term R_r/x is greater than R_r, the term

$$P_{gap} = 3 \cdot \frac{R_r}{x} \cdot I_r^2$$

includes either the losses in the copper of the rotor windings and the mechanical power transmitted to the shaft.

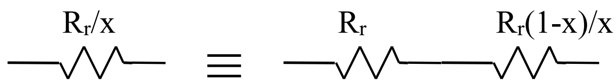
But the Joule rotor losses are:

$$P_r = 3 \cdot R_r \cdot I_r^2$$

So, by isolating the power losses term, we get:

$$P_m = 3 \cdot \frac{R_r}{x} \cdot I_r^2 - 3 \cdot R_r \cdot I_r^2 = 3 \cdot \left(\frac{1}{x} - 1\right) \cdot R_r \cdot I_r^2 = 3 \cdot \left(\frac{1-x}{x}\right) \cdot R_r \cdot I_r^2$$

that identifies the mechanical power at the output of the machine.



9.2 Torque-speed curve

In order to achieve a meaningful relationship between torque and speed, some simplifying assumptions are required.

Consider the four parameters model (leakage on the rotor side) of Figure 9-10 where the superscript $^\#$ are not reported.

As the stator resistance R_s assumes very low values, the voltage drop on this resistance is very low, so the error given by the change of position of R_s after the magnetizing reactance X_m is limited.

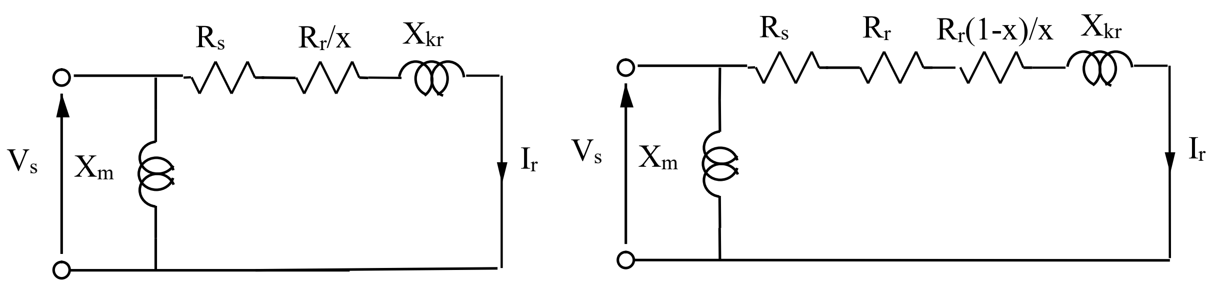


Figure 9-11: four parameters equivalent circuit, leakage on the rotor side, (R_s jumped)

The mechanical power P_m, as said before, is the power "losses" in the fictitious resistance $R_r(1-x)/x$:

$$P_m = 3 \cdot \left(\frac{1-x}{x}\right) \cdot R_r \cdot I_r^2$$

The electromagnetic torque is:

$$T_e = \frac{P_m}{\Omega_m}$$

where Ω_m is the mechanical speed (in the mechanical world). So $\Omega_m = \omega_m/n_p$ (ω_m is the mechanical speed in the electrical world and n_p is the number of pole pairs).

Call $\Omega_o = \omega/n_p$ the no load speed (synchronous speed). It results $\Omega_m = (1-x)\,\Omega_o$.

So the torque expression becomes:

$$T_e = \frac{P_m}{\Omega_m} == 3 \cdot \left(\frac{1-x}{x}\right) \cdot \frac{R_r \cdot I_r^2}{(1-x)\Omega_o} = 3 \cdot \frac{R_r \cdot I_r^2}{x} \frac{1}{\Omega_o} = \frac{P_{gap}}{\Omega_o} = 3 \frac{R_r \cdot I_r^2}{x} \frac{n_p}{\omega}$$

It means that the torque may be calculated as the ratio between the power transmitted from stator to rotor (P_{gap}) and the speed of the flux (in the mechanical world).

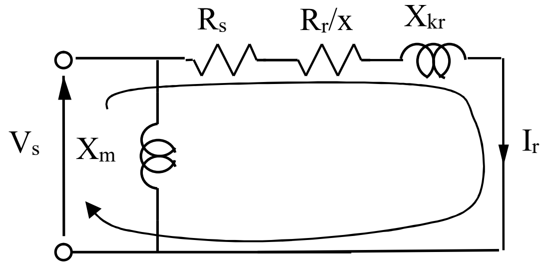


Figure 9-12: Loop for the Kirchhoff's Voltage Law

Solving the KVL applied to the loop (see Figure 9-12) we obtain the expression of the rotor current (now we choose the versus of the rotor current different from the transformer secondary current versus)

$$\overline{I_r} = \frac{\overline{V_s}}{R_s + \frac{R_r}{x} + jX_{kr}}$$

and

$$I_r = \frac{V_s}{\sqrt{\left(R_s + \frac{R_r}{x}\right)^2 + X_{kr}^{\ 2}}}$$

or

$$I_r^2 = \frac{V_s^2}{\left(R_s + \frac{R_r}{x}\right)^2 + X_{kr}^{\ 2}}$$

so

$$T_e = 3 \frac{R_r}{x} \frac{n_p}{\omega} \frac{V_s^2}{\left(R_s + \frac{R_r}{x}\right)^2 + X_{kr}^{\ 2}}$$

This expression shows the trend of the torque as a function of slip "*x*", and then, in another scale, as a function of speed ($\Omega_m = (1-x)\,\Omega_o$).

For high values of the slip "x" (x≈1), the term $\left(R_s + \frac{R_r}{x}\right)$ is negligible respect to X_{kr}, so the torque is inverse proportional to the slip: $T_e \approx 3\frac{R_r}{x}\frac{n_p}{\omega}\frac{V_s^2}{X_{kr}^{\ 2}}$. The value of the torque at slip=1 is called Starting Torque: $T_{st} = 3R_r\frac{n_p}{\omega}\frac{V_s^2}{(R_s + R_r)^2 + X_{kr}^{\ 2}}$ (slip=1 means that the rotor speed is 0).

For low values of the slip "x" (x≈0), the term $\frac{R_r}{x}$ is very high so R_s and X_{kr} are negligible: $T_e \approx 3\frac{R_r}{x}\frac{n_p}{\omega}\frac{V_s^2}{\left(\frac{R_r}{x}\right)^2} = 3x\frac{n_p}{\omega}\frac{V_s^2}{R_r}$; this means that for low slip the relationship between torque and slip is linear.

The trends of the torque as a function of slip and speed are shown in Figure 9-13 and Figure 9-14 respectively. The torque expression is valid also per negative value of the slip, so for speed higher than the synchronous speed, where the machine is working like a generator.

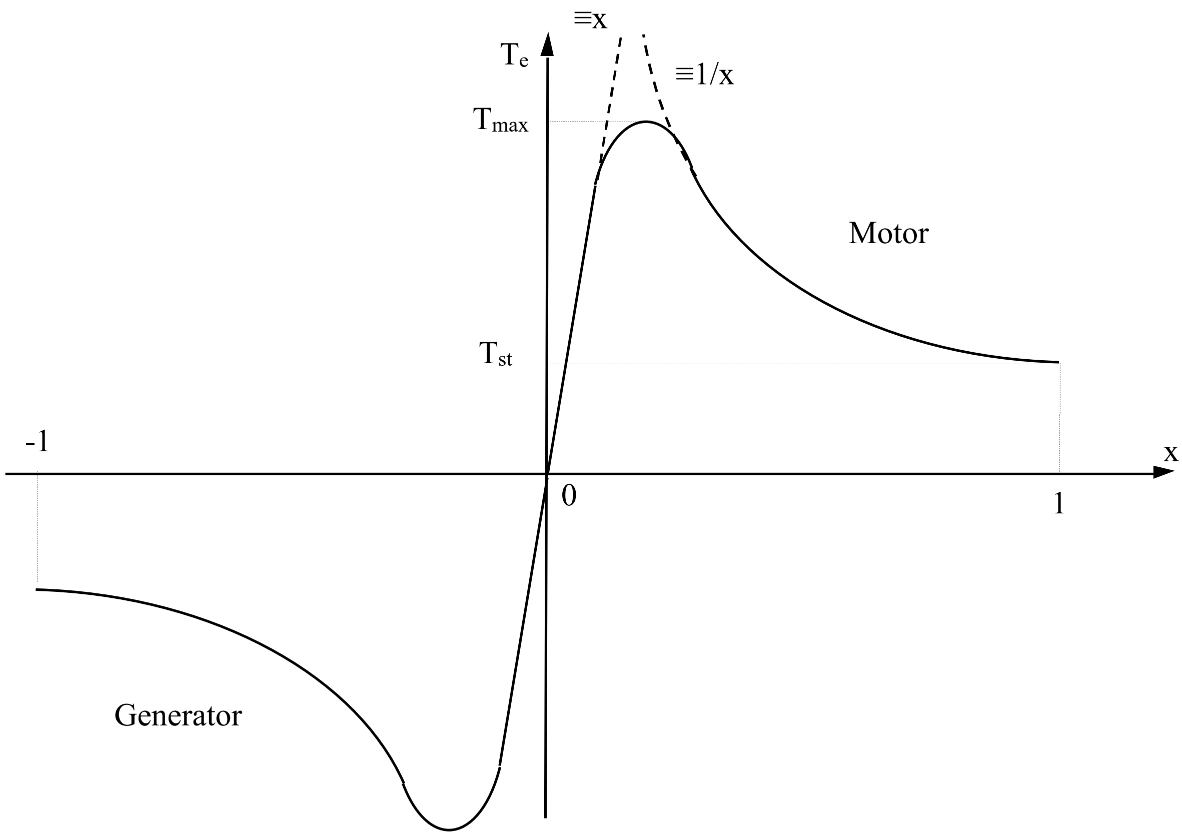


Figure 9-13: Torque/slip curve

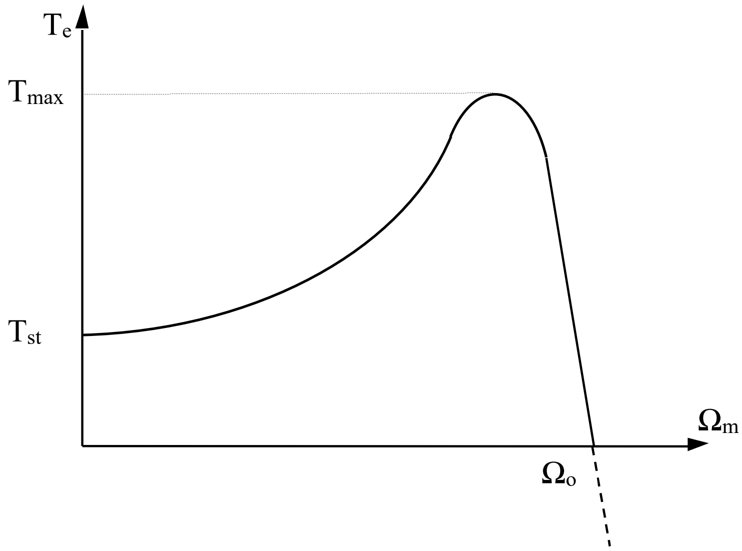


Figure 9-14: Torque/speed curve for a motor [Ω_m=(1-x) Ω_o]

The slip at which the torque is at its maximum value is when the power dissipated on R_r/x is maximum. This is true when R_r/x_{max} is equal to the module of the impedance "seen" by R_r/x (maximum power transfer principle): $Z = \sqrt{R_s^{\ 2} + X_{kr}^{\ 2}} = \dfrac{R_r}{x_{max}}$ so $x_{max} = \dfrac{R_r}{Z} = \dfrac{R_r}{\sqrt{R_s^{\ 2} + X_{kr}^{\ 2}}}$.

The maximum torque (*breakdown torque*) is (x_{max} usually assumes low values):

$$T_{max} = 3\frac{R_r}{x_{max}}\frac{n_p}{\omega}\frac{V_s^2}{\left(R_s + \dfrac{R_r}{x_{max}}\right)^2 + X_{kr}^{\ 2}} = 3Z\frac{n_p}{\omega}\frac{V_s^2}{(R_s + Z)^2 + X_{kr}^{\ 2}} \approx 3Z\frac{n_p}{\omega}\frac{V_s^2}{Z^2 + X_{kr}^{\ 2}} =$$

$$= 3\sqrt{R_s^{\ 2} + X_{kr}^{\ 2}}\frac{n_p}{\omega}\frac{V_s^2}{R_s^{\ 2} + X_{kr}^{\ 2} + X_{kr}^{\ 2}} \approx 3X_{kr}\frac{n_p}{\omega}\frac{V_s^2}{2X_{kr}^{\ 2}} = 3\frac{n_p}{\omega}\frac{V_s^2}{2X_{kr}} = 3\frac{n_p}{\omega^2}\frac{V_s^2}{2L_{kr}}$$

where R_s is considered negligible respect to X_{kr}.

Therefore, the maximum torque is inverse proportional to the square of the frequency.

By analyzing the obtained torque-speed curve, it is very important to emphasize the dependence of the torque by the square of the supply voltage.

If you increase the rotor resistance, the starting torque $T_{st} = 3R_r\dfrac{n_p}{\omega}\dfrac{V_s^2}{(R_s + R_r)^2 + X_{kr}^{\ 2}} \approx 3R_r\dfrac{n_p}{\omega}\dfrac{V_s^2}{X_{kr}^{\ 2}}$ and the slip at the maximum torque increases $x_{max} = \dfrac{R_r}{Z} = \dfrac{R_r}{\sqrt{R_s^{\ 2} + X_{kr}^{\ 2}}} \approx \dfrac{R_r}{X_{kr}}$, while the maximum torque does not change.

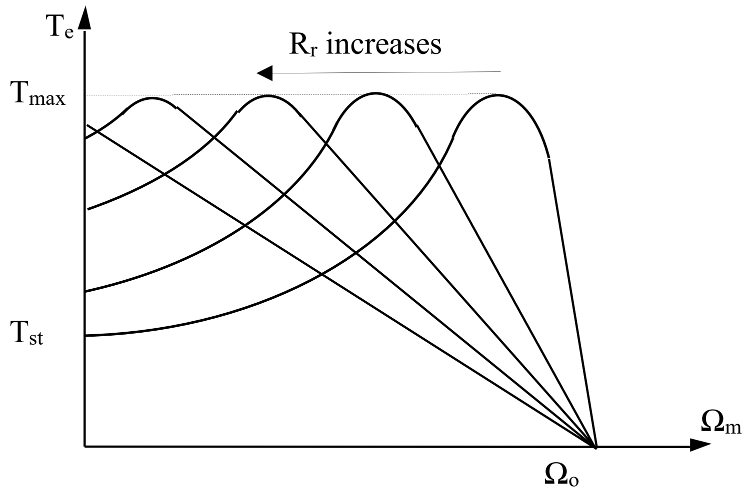


Figure 9-15: Effect of a variation of the rotor resistance

This idea is used to realize deep rotor bars or double cage bars.

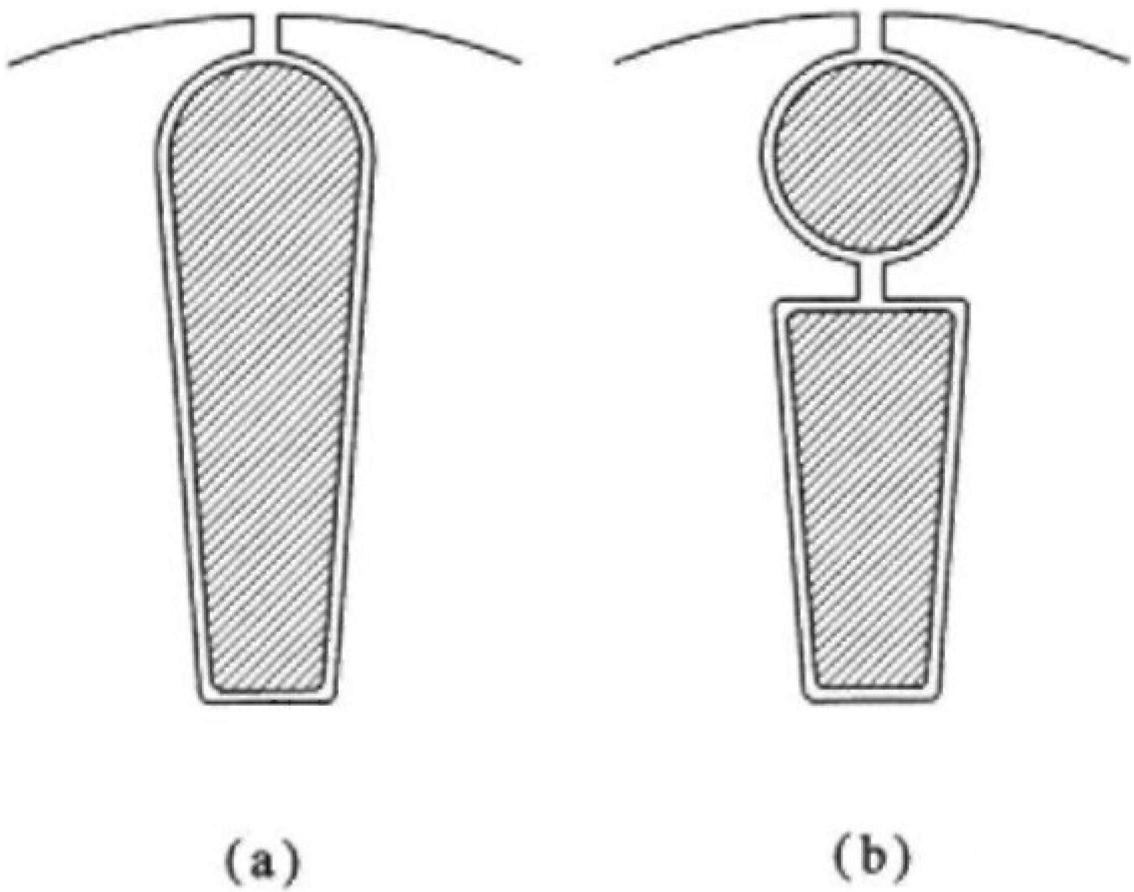


Figure 9-16: (a) deep bar, (b) double cage (*what-when-how.com*)

9.3 Operating regions as a function of voltage and frequency

jump

The operating regions of the machine are very similar to that proposed for the DC machine. In fact, the considerations on the maximum stator flux, the rated emf, the base mechanical speed (or rated) and the maximum speed are still valid for the induction machine. Figure 9-17 shows some torque-speed curves at different values of voltage and frequency.

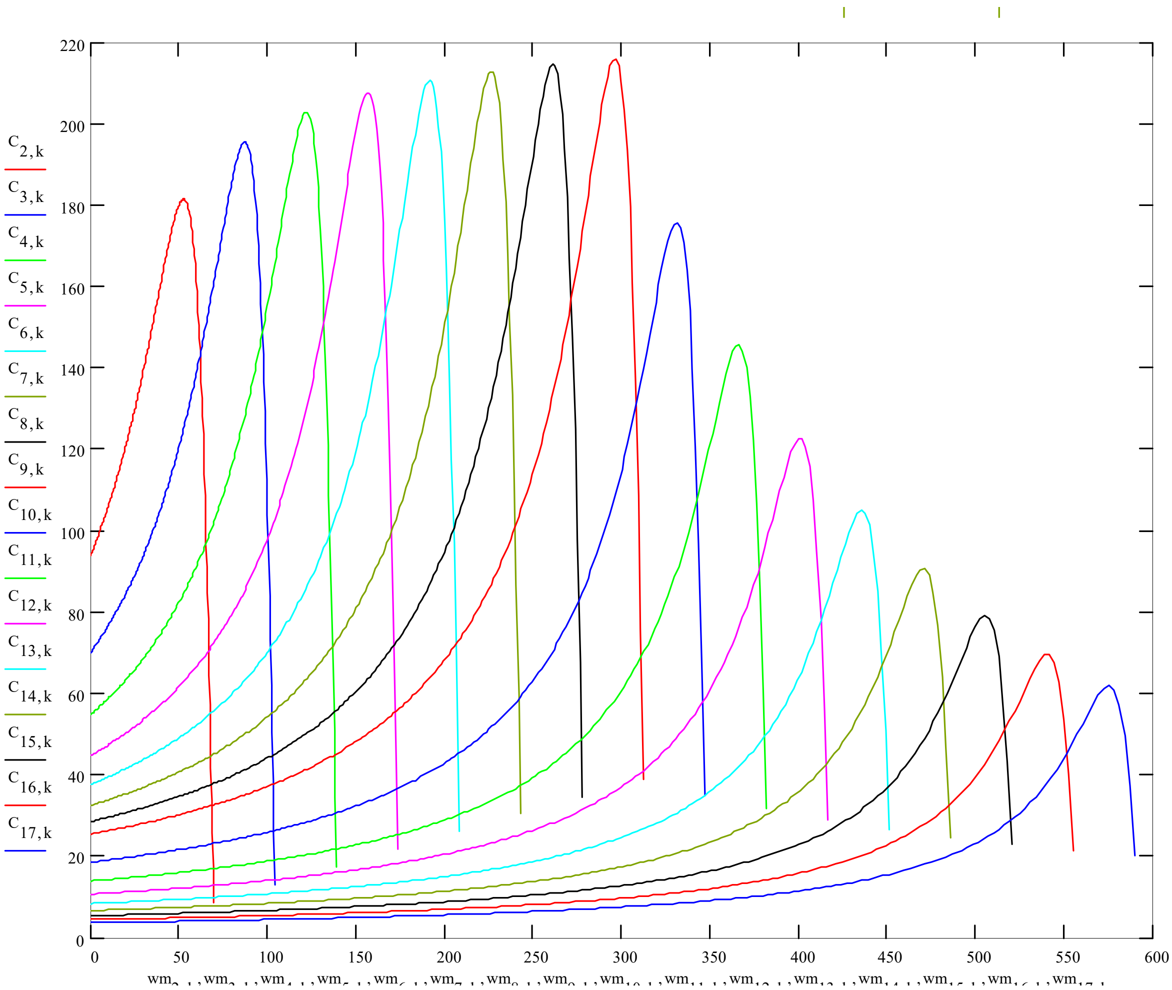


Figure 9-17: torque-speed curves as a function of voltage and frequency (symbol "*c*" means torque)

This suggests that the current, voltage and flux trends (as a function of speed) are still valid, as shown in Figure 9-18.

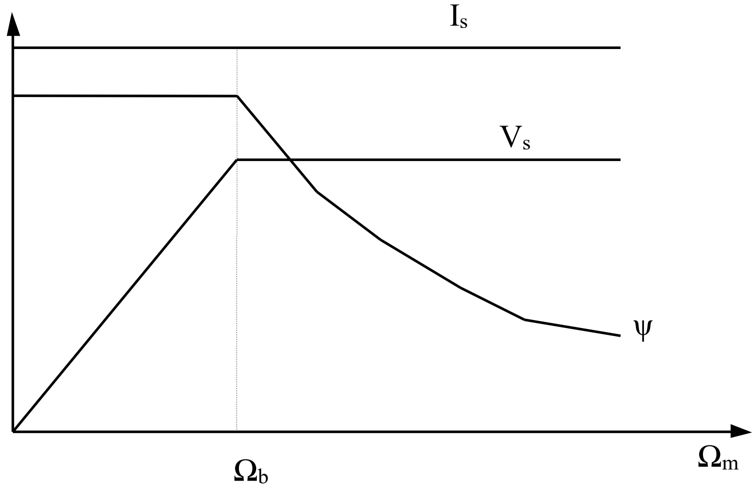


Figure 9-18: maximum allowable values of current, voltage and flux as a function of speed

The current is limited by thermal problems: Joule Losses, cooling system and service duty. The voltage is limited by insulation problem and by the maximum voltage of the power supply. The flux is limited by the saturation of the ferromagnetic materials.

However, the torque trend changes: at speeds greater than the base speed Ω_b, the rated torque decreases as $1/\Omega_m$ while the maximum torque as $1/\Omega_m^2$. There will, therefore, a speed Ω^* beyond which the limit is not imposed by the rated torque but by the maximum torque.

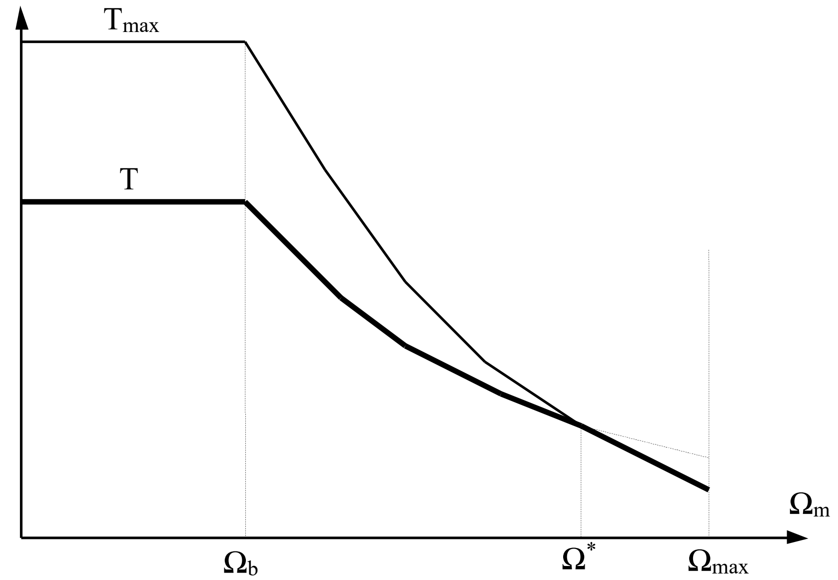


Figure 9-19: Torque-speed operating region

9.4 Tests for parameters determination

9.4.1 DC Test

Consider the four parameters model (leakage on the rotor side) of Figure 9-10 where the superscript # are not reported.

By means of a tester (ohmmeter) or a dc voltage/current test, the stator resistance may be easily measured: $R_s=V_{dc}/I_{dc}$.

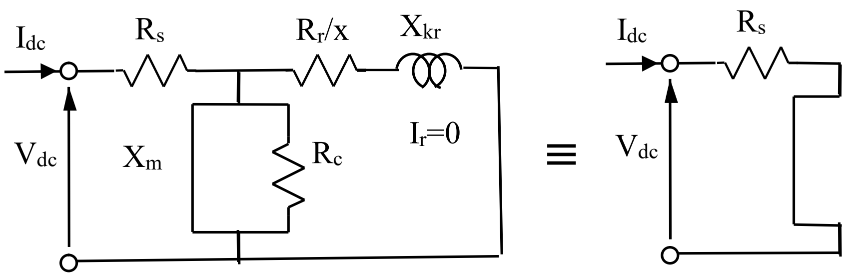


Figure 9-20: Equivalent circuit of an induction machine with a dc power supply

9.4.2 No-load Test

By means of a prime mover, you can put the machine in rotation at the synchronous speed Ω_o. The machine is supplied by the rated voltage V_n at frequency ω. In this condition, the slip is zero and R_r/x is infinite. This means that the rotor circuit is opened.

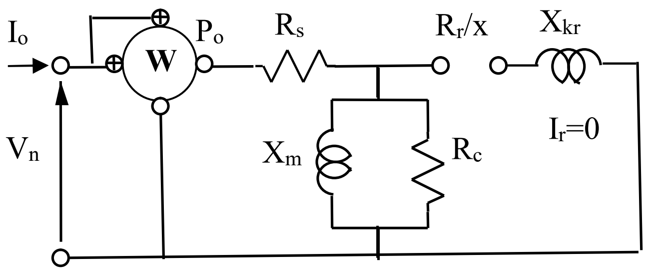


Figure 9-21: Equivalent circuit of an induction machine during no-load test

The stator resistance is already known, so as its losses $P_{rs}=3R_sI_o^2$. The core losses P_{core} (related with R_c) are: $P_{core}=P_o-P_{rs}= P_o-3R_sI_o^2$. If you consider that the voltage drop on the stator resistance is negligible, the voltage drop on R_c is the rated voltage V_n. So $R_c=3V_n^2/P_{core}$.

The apparent power is $A_o=3V_nI_o$, so the reactive power is $Q_o = \sqrt{A_o^2 - P_o^2}$ and $X_m=3V_n^2/Q_o$.

9.4.3 Blocked-rotor Test

You have to block (fix) the rotor of the machine.

The mechanical speed is zero so the slip is 1

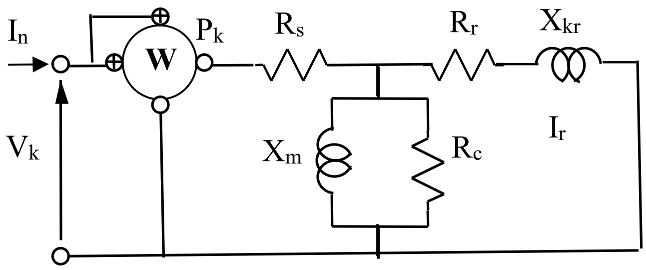


Figure 9-22: Equivalent circuit of an induction machine during blocked-rotor test

The impedance R_r+jX_{kr} is much lower than the impedance made by the parallel of jX_m and R_c. So you may consider the parallel of jX_m and R_c like an open circuit.

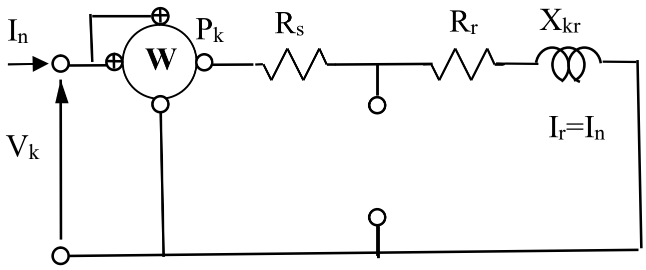


Figure 9-23: Reduced equivalent circuit of an induction machine during blocked-rotor test

The total impedance seen by the power supply is very low so the test is realized supplying the rated current to the machine (in order to save it from thermal problem): $I_k=I_n$. This is done at a very low voltage (some percent of the rated voltage), at the rated frequency.

The stator resistance is already known, so for its losses $P_{rs}=3R_sI_n^2$. The rotor losses P_r (related with R_r) are: $P_r=P_k-P_{rs}= P_k-3R_sI_n^2$. So $R_r=3\ P_r/I_n^2$.

The apparent power is $A_k=3V_kI_n$, so the reactive power is $Q_k = \sqrt{A_k^2 - P_k^2}$ and $X_{kr}=3\ Q_k/I_n^2$.

9.5 Y/D Starting

In order to reduce the starting current value, a method is the use of a switch able to change the terminals of the machine: at the beginning the machine is connected to the grid with a star (Y) connection; after a while, the connection is switched to a delta (D) connection. In the first period the voltage on the coil of the machine is the phase voltage, equal to 1/sqrt(3) of the voltage (line-line voltage) applied to the coil during the second period. The coil currents have the same ratio. But the current grid for a delta connection is sqrt(3) times the current of the coil. So the ratio between the grid current of a star connection is 1/3 of the current of a delta connection, given the same line to line voltage.

9.6 Notes on the use of squirrel-cage rotor

The foregoing considerations relate essentially to the wound rotor induction motor. However, it was mentioned, at the opening, to the possibility of using a squirrel-cage rotor. This is a simpler and more robust solution, from the construction point of view; however, that does not involve substantial changes in terms of the principle of operation and external characteristics.

The model and the equivalent circuits are equal to those of wound rotor machine.

On the other hand, the great mechanical resilience and better use of the magnetic structure have determined its success. It should be noted that there are no limits to the machine power; rather it can be overloaded due to the highest temperatures tolerable by the machine. Indeed, there is no insulation material on the rotor which may suffer thermal damage.

9.7 Rated quantities

The rated power of an induction machine working as a motor is given by the mechanical power available at the shaft, at rated operating point.

The nameplate usually reports the rated speed, in addition to the rated voltage, the rated current and the rated power or torque; usually the power factor at rated operating point and efficiency are not included.

Assuming typical values for efficiency (eg. between 70% and 90%) it is possible, with good approximation, to calculate the electrical rated power.

From the grid point of view, an induction motor is equivalent to a load that absorbs active and inductive reactive power in any operating condition.

9.8 Single-phase induction machine

next year