

## THE AXIAL AIR-GAP THREE-PHASED ASYNCHRONOUS MOTOR

Arif MAMMADOV<sup>1</sup>, Neculai GALAN<sup>2</sup>

*În lucrare se prezintă un motor cu întrefier axial care a fost realizat efectiv. Elementele noi se referă la distribuția polilor pe cele două statoare prin realizarea adecvată a înfășurărilor statorice și sunt evidențiate unele probleme tehnologice. Sunt prezentate elemente constructive, modul de funcționare și s-a elaborat modelul matematic unde s-au precizat modalitățile de calcul a parametrilor electrici pentru acest motor. Motorul prezintă o serie de avantaje în raport cu motoarele clasice: consumul de materiale este mai mic; economie de energie când funcționează la sarcină variabilă; posibilitatea de a fi construit cu două viteze de sincronism dacă cele două statoare nu sunt alimentate simultan; posibilitățile de frânări succesive. Schema echivalentă este prezentată în reperul general K și sunt arătate modalitățile de particularizare pentru alte sisteme de referință.*

*It presents a motor with axial air-gap which has been manufactured practically. The new elements concern the two stators poles disposition as well as the winding building and some technological elements. One has presented the building manner, the operating mode, and the elaborating mathematical model where the electrical parameters calculation way becomes concrete for this new motor. The motor we have proposed gets real advantages: less material; less energy for variable load; opportunity to be manufactured with two synchronism speeds on the condition the two stators not be supplied simultaneously; possibility of successive brakes. The equivalent circuit are presented in the general reference K and one shows the manner they can be particularized in other reference systems.*

**Keywords:** axial motor, mathematical model, electrical parameters

### 1. Introduction

The essential constructive structures of the asynchronous motor are: radial air-gap asynchronous motor largely employed nowadays and axial air-gap asynchronous motor used especially in laboratory tests, catalogues about this motor one not yet published by the manufacturer. The constructive structures are obtained from the same components but in different geometric forms. The researches effectuated have carried out the axial air-gap motor permits an

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<sup>1</sup> Dr.eng., Dept. of Electrical Engineering, University POLITEHNICA of Bucharest, Romania

<sup>2</sup> Prof., Dept. of Electrical Engineering, University POLITEHNICA of Bucharest, Romania

important reduction of the manufacturing prize compared to the radial air-gap motor; the explanation of this reduction is: reduced consummation of materials, fabrication technology simpler grace to the “sandwich” construction, gauge dimensions smaller. One of the important advantages is an maintenance improved. Unhappily one has little experimental data concerning the axial air-gap motor confirming completely all presented above. The electrical machines fabrication methods are characterized by continuous lines and their modification in order to build the axial air-gap motor requires important funded capitals. The paper will present both theoretic elements and experimental data.

## 2. The magnetic cores and windings of the motor

The new elements are concerning the pole position of the two stators, the obtaining of the winding in some three-phased winding zone as well as any technological elements. The building form can be an advantage for an employing in the electrical traction.

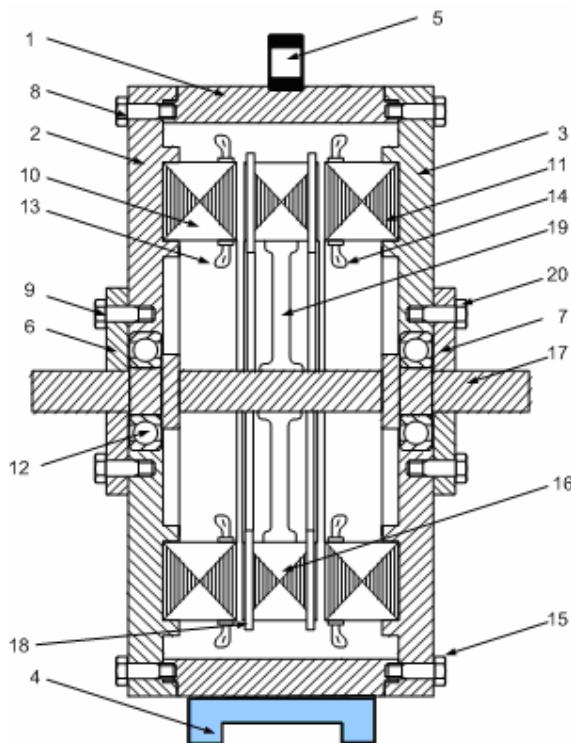


Fig.1. Longitudinal section through the axial air-gap machine:

1 – frame; 2, 3 – end shields; 4 – mast assembly; 5 – piece for raising; 6, 7 – boots for bearing; 8, 9, 15, 20 – screws; 10, 11 – stator cores; 12 – bearing; 13, 14 stator windings; 16 – rotor core; 17 – shaft; 18 - short-circuited winding; 19 – insulant bar.

In Fig.1 one presents the axial air-gap machine generally conceived as it was a prototype, the machine being a low powered one, used in experiments. From Fig. 1 results the disposition mode end shields play the role to consolidate mechanically all the system, the two stators have coils conceived in such a way to form groups of coils which have independent operating, the rotor being a disk provided with short-circuited winding

In order to obtain high results in this motor operating, it is necessary the north poles and respectively south poles engendered by the two stators windings to be the same axis, that means face to face, in this case the field lines are crossing twice the air-gap as well as in the case of the classical machine. If the poles disposed face in face have different polarity, the field lines are crossing the entire rotor in the axial direction and these lines cross four times the air-gap leading to an increase of the magnetization current. One considers machine as having the poles of same sign disposed face to face.

The magnetic field lines have the following sketch: stator core where the field lines get the form of a circle arc being in a perpendicular plan on the machine axis; are crossing twice the air-gap in the axial direction and close themselves by the rotor core surrounding the rotor winding, the form of the field line in the rotor core being similar to that in the stator core. If one does the intersection of a coaxial cylinder with the axis of the machine and the machine magnetic system, the magnetic field lines engendered by a coil has the form presented in Fig. 2.

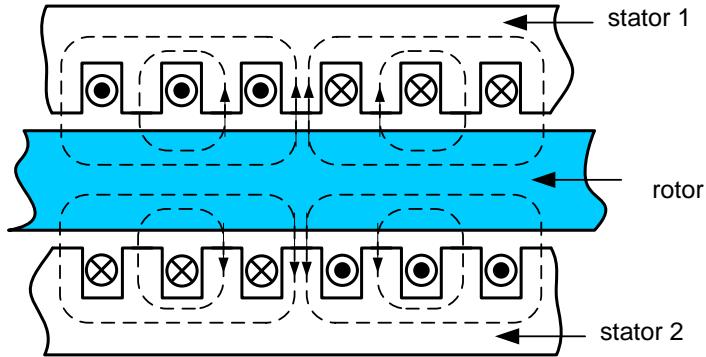


Fig. 2. The inductor magnetic field lines.

In Fig. 2 one shows on internal of the ferromagnetic core displayed in plan. The magnetic structure is repeated on each cylindrical surface included between the diameters  $D_{ex}$  and  $D_{in}$  of the magnetic core. The magnetic field structure has the same form for the three-phased winding, but in this case the magnetic field is a rotating one having as angular speed  $\Omega = 60 f_1/p$ .

By the analyze of the Fig.2 one has to remark that the inductor field lines engendered by the two stators do not cross the rotor median plan, that means the

inductor magnetic fields engendered by the two stators do not interact, being completely separated; consequently, the median plan presence shows that this asynchronous motor is the equivalent of two classical motors. As building, the two motors have the same rotor with two short-circuited windings laid in slots disposed in the two plans surrounding the rotor. One remarks that on the same axis one can lay many stators function of the useful power required (similar to the axial air-gap synchronous motor building). The end stators are similar to these of the Fig. 1, but the inner stators have two three-phased windings laid in slots disposed in the two plans surrounding the stator. One can obtain some advantages concerning the material used for this asynchronous motor.

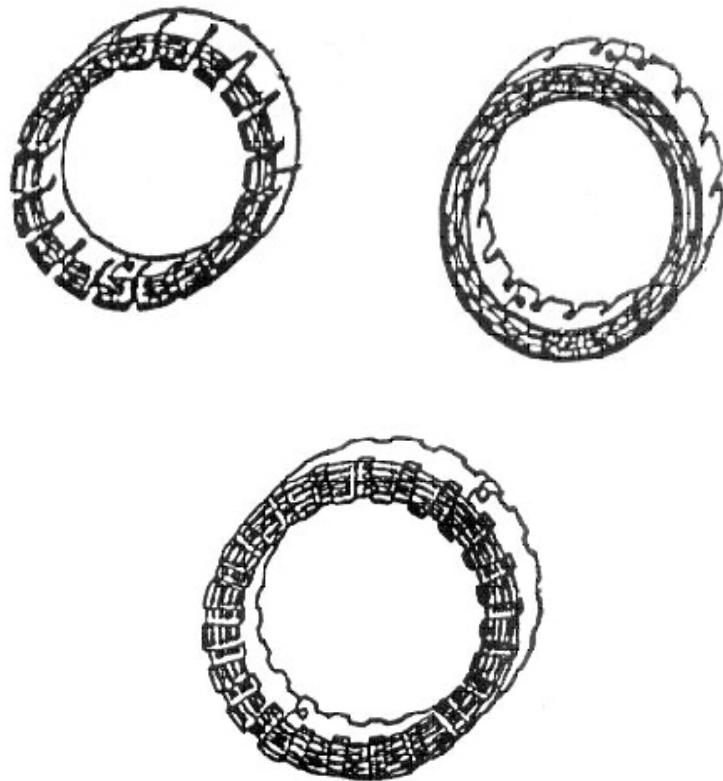


Fig. 3. The stator cores and rotor core.

The two stators magnetic core 1 and 2 as well as the rotor core have been manufactured by rolling of the iron electrotechnical sheets having 0,5 mm as thickness and being isolated by oxidation; the rotor gets slots on his both faces

(Fig. 3). In Fig. 4 one presents the three-phased stator winding disposed in the radial slots of the stator obtained by 6 modules noted motor 1...motor 6; these modules are independent and each one can operate independently as elementary motors. Three modules are disposed on the stator 1 and the following three modules are disposed on the stator 2.

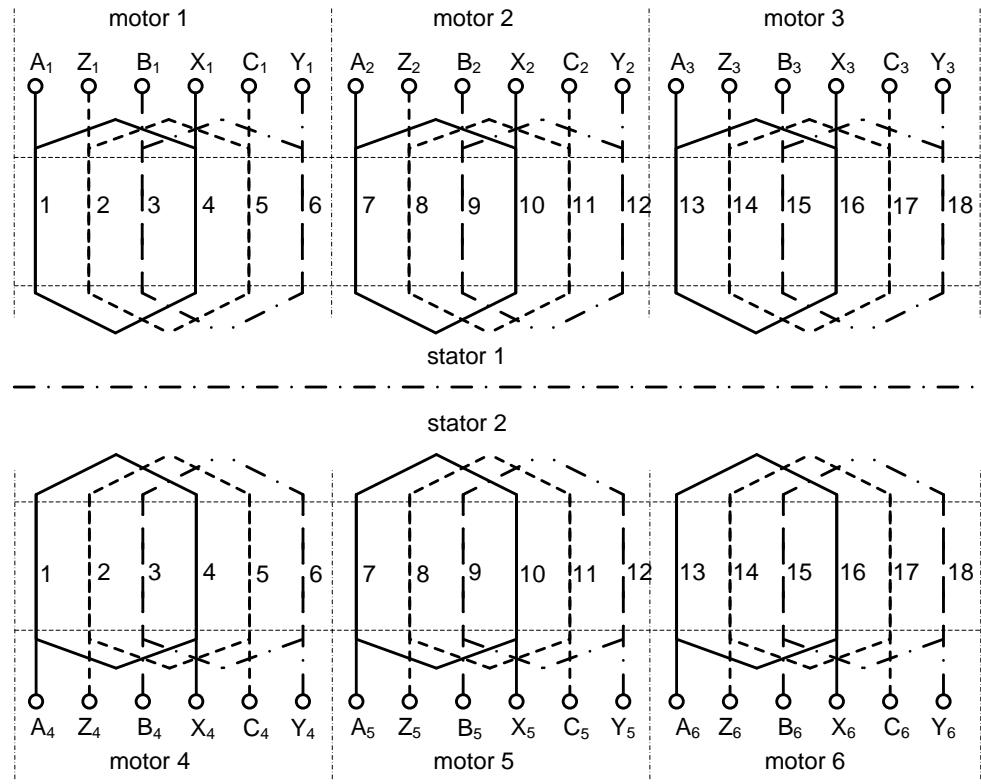


Fig. 4. Stator winding.

One disadvantage of this kind of motor is the mounting of the armatures on the machine shaft (stator 1, stator 2 and rotor), the armature surfaces limiting the air-gap have to be plane and exactly perpendicular to the machine shaft. Otherwise, the axial air-gap does not be constant on the entire surface and magnetic forces appear as unilateral attraction  $F_0$  which can incline the armatures in regard with the machine shaft and an uniform air-gap is not assured any more.

In order to decrease really the axial forces  $F_0$  it is necessary the elementary motors are operating in pair number, equally disposed upon the two stators and the magnetic axis of the elementary windings, face to face, to be coincided.

### 3. Voltage equations and torque equations in arbitrary reference-frame

This equation has the same structure for a classical machine, but in the electrical parameters calculation (resistances and reactances) there are any special mentions determinate by the geometrical dimensions different for the windings overhang.

Introduction of the spatial phasors in the mathematic model of the three-phased asynchronous machine permits to obtain a simple model, physic rigorous interpretations and to identify new solutions in the electrical drives. The spatial phasors are correlated to the reference systems and are defined in the own reference system stator or rotor system. Finally, the mathematic model is written in general reference (for the steady state are considered the synchronous reference). In Fig. 5 one presented the reference systems employed in the electric machines theory, the electric angles are represented as well. FS – the fix stator reference system; FR – the fix rotor reference system and the general reference K having the angular speed  $\Omega_k$ . If  $\Omega_k = \Omega_1$  (synchronism speed) then the reference system K becomes the reference system synchronous noted by  $K_0$ .

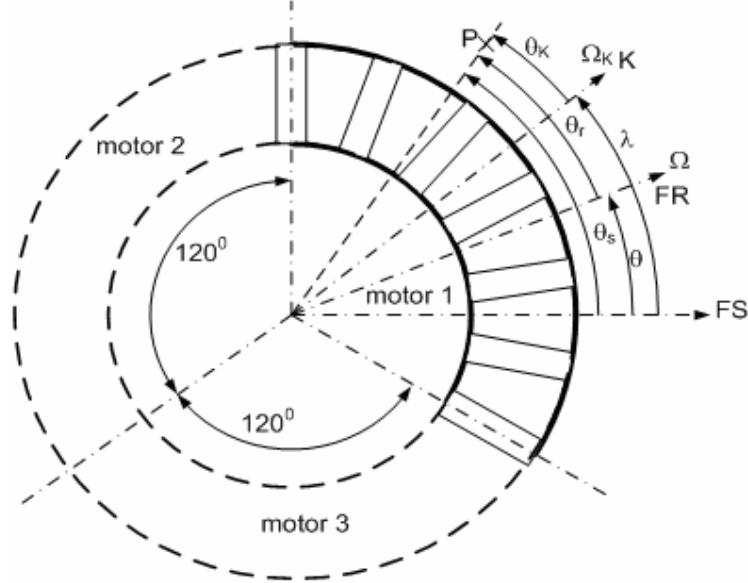


Fig. 5. The reference systems employed in the asynchronous machine theory.

In order to be clear and in order to have the same notations as in classic theory, the axes of the references have moved with  $90^\circ$ , the axis of the references have the axial direction. The angles signification results in Fig. 5.

The mathematic model is written in the reference K whose angular speed per unit is  $\nu_K$ . To be mentioned the basic torque expression  $M_b$  can be correlated to the nominal torque  $M_n$ :

$$M_b = \frac{3}{2} p \frac{U_{sb} I_{sb}}{\omega_b} = \frac{3}{2} \frac{U_{sb} I_{sb}}{\Omega_b} = \frac{P_n}{\eta_n \Omega_b \cos \varphi_{sn}} = \frac{M_n (1-s)}{\eta_n \cos \varphi_{sn}} \quad (1)$$

In the last expression of the basic torque  $M_b$  one has considered  $\Omega_k = \Omega_1$ ; one remarks the magnitude  $M_b$  differs from the nominal torque  $M_n$  and  $M_b > M_n$ . The notations being known, in magnitudes per-unit, one can write the mathematical model as follows:

$$\begin{aligned} u_{sK} &= r_s i_{sK} + j \nu_K \psi_{sK} + \frac{d\psi_{sK}}{d\tau}; \\ \psi_{sK} &= x_{s\sigma} i_{sK} + x_\mu i_{\mu K} = x_s i_{sK} + x_m i_{rK}'; \\ 0 &= r_r i_{rK}' + j(\nu_K - \nu) \psi_{rK}' + \frac{d\psi_{rK}'}{d\tau}; \\ \psi_{rK}' &= x_{r\sigma} i_{rK}' + x_\mu i_{\mu K} = x_r i_{rK}' + x_m i_{sK}'; \\ i_{\mu K} &= i_{sK} + i_{rK}'; \quad H \frac{d\nu}{d\tau} = m - m_2; \quad \nu = \frac{\omega}{\omega_b}; \quad \nu_K = \frac{\omega_K}{\omega_b}; \quad (2) \\ m &= \frac{M}{M_b} = \psi_{sd} i_{sq} - \psi_{sq} i_{sd}; \quad m_2 = \frac{M_2}{M_b}; \quad H = \frac{J\omega_b^2}{pM_b} \\ e_{st} &= -\frac{d\psi_{sK}}{d\tau}; \quad e_{sm} = -j \nu_K \psi_{sK}; \quad e_{rt}' = -\frac{d\psi_{rK}'}{d\tau}; \\ e_{rm}' &= -j(\nu_K - \nu) \psi_{rK}' \end{aligned}$$

In the equations (2) one has carried out the transformation e.m.f.  $e_{st}$ ,  $e_{rt}$ , as well as the motion e.m.f.  $e_{sm}$ ,  $e_{rm}$ .

The mathematical model (2) is to be applied at each three-phased coils group, operating as an elementary motor when they are connected in parallel.

The stator leakage reactance,  $X_{s\sigma}$ , has two components determinated by the different geometry of the two stator windings overhang. The rotor leakage reactance components,  $X_{r\sigma}$ , is different by the ring zones leakage reactances and

the rotor resistance,  $R_r$ , components is different as well as by the short-circuited rotor ring zones resistance:

$$\begin{aligned} X_{s\sigma} &= X_{\sigma,a} + X_{\sigma,e} + X_{\sigma,i} = X_{\sigma c} + X_{\sigma,i} ; \quad X_{\sigma c} = X_{\sigma,a} + X_{\sigma,e} \\ X_{r\sigma}^{\prime} &= X_{\sigma,b}^{\prime} + X_{r\sigma,e}^{\prime} + X_{r\sigma,i}^{\prime} = X_{\sigma f}^{\prime} + X_{r\sigma,i}^{\prime} ; \quad X_{\sigma f}^{\prime} = X_{\sigma,b}^{\prime} + X_{r\sigma,e}^{\prime} \\ R_r^{\prime} &= R_{r,b}^{\prime} + R_{r,e}^{\prime} + R_{r,i}^{\prime} = R_{rf}^{\prime} + R_{r,i}^{\prime} ; \quad R_{rf}^{\prime} = R_{r,b}^{\prime} + R_{r,e}^{\prime} \end{aligned} \quad (3)$$

the index e concerns the outer diameter  $D_e$  and the index i the inner one  $D_i$ . When the electrical parameters are expressed in magnitudes per unit they are written in small letters:

$$x_{s\sigma} = x_{\sigma c} + x_{\sigma,i} ; \quad x_{r\sigma}^{\prime} = x_{\sigma f}^{\prime} + x_{r\sigma,i}^{\prime} ; \quad r_r^{\prime} = r_{rf}^{\prime} + r_{r,i}^{\prime} \quad (4)$$

#### 4. Variants of the electromagnetic torque expression

For the study of the asynchronous motor dynamic in the drive systems it is necessary to express the electromagnetic torque in many variants evidently all these relationships are the same for each three-phased motor type. A first form is:

$$\begin{aligned} M &= \frac{3}{2} p \left( \psi_{sd}^* i_{sq} - \psi_{sq}^* i_{sd} \right) = \frac{3}{2} p \operatorname{Re} \left( -j \psi_{sR}^* i_{sR} \right) = \\ &= \frac{3}{2} p \operatorname{Re} \left( -j \psi_s^* i_s \right) = \frac{3}{2} p \operatorname{Im} \left( \psi_{sR}^* i_{sR} \right) = \frac{3}{2} p \operatorname{Im} \left( \psi_s^* i_s \right) \end{aligned} \quad (5)$$

« c » is the conjugated complex magnitude ; the torque M can be expressed per unit :

$$\begin{aligned} M &= \frac{3}{2} p \operatorname{Im} \left( \psi_{sR}^* i_{sR} \right) = \frac{3}{2} p \left( \psi_{sd}^* i_{sq} - \psi_{sq}^* i_{sd} \right) ; \\ m &= \frac{M}{M_b} = \left( \psi_{sd}^* i_{sq}^* - \psi_{sq}^* i_{sd}^* \right) \end{aligned} \quad (6)$$

In the axes system d and q are defined formely the stator magnetic flux  $\psi_{sK}$  by the components  $\psi_{sd}$  and  $\psi_{sq}$  and the electric current  $i_{sK}$  by the components  $i_{sd}$ ,  $i_{sq}$ ; the electromagnetic torque being represented by the vector product of the two vectors

$$\begin{aligned}\vec{M} &= \frac{3}{2} p [\vec{\psi}_{sK} \ x \ \vec{i}_{sK}] ; \ \vec{\psi}_{sK} = \vec{i} \psi_{sd} + \vec{j} \psi_{sq} ; \\ \vec{i}_{sK} &= \vec{i} \ i_{sd} + \vec{j} \ i_{sq}\end{aligned}\quad (7)$$

that means the versors plan (i, j) is superposed on the system (d, q).

The spatial phasors intervening in the electromagnetic torque formula are 6:  $\psi_{sK}$ ,  $\psi_{rK}$ ,  $\psi_{\mu K}$ ,  $i_{sK}$ ,  $i_{rK}$ ,  $i_{\mu K}$ ; the electromagnetic torque  $M$  can be expressed function of each other two of the 6 spatial phasors between which one has known relationships. One has 15 variants but will be presented only the ones used frequently.

The relationships of the magnetic fluxes and the currents permit to express the stator magnitudes  $\psi_{sK}$  and  $i_{sK}$  function of the rotor magnitudes  $\psi_{rK}$  and  $i_{rK}$ . One will obtain:

$$\psi_{sK} = \frac{1}{L_m} \left[ L_m^2 i_{rK} + L_s (\psi_{rK} - L_r i_{rK}) \right] ; \ i_{sK} = \frac{1}{L_m} (\psi_{rK} - L_r i_{rK}) \quad (8)$$

Effecting the calculations one obtains:

$$\begin{aligned}M &= -\frac{3}{2} p \text{ Im}(\psi_{rK}^c i_{rR}) = \frac{3}{2} p (\psi_{rq} i_{rd} - \psi_{rd} i_{rq}) ; \\ m &= \frac{M}{M_b} = \left( \psi_{rq}^* i_{rd}^* - \psi_{rd}^* i_{rq}^* \right) ; \ \vec{M} = \frac{3}{2} p [\vec{i}_{rR} x \vec{\psi}_{rK}] \end{aligned}\quad (9)$$

Similarly one obtains :

$$\begin{aligned}M &= \frac{3}{2} p L_m \text{ Im}(\vec{i}_{sR}^c \vec{i}_{rR}) = \frac{3}{2} p L_m (i_{sq} i_{rd} - i_{sd} i_{rq}) ; \\ m &= \frac{M}{M_b} = x_m \left( i_{sq}^* i_{rd}^* - i_{sd}^* i_{rq}^* \right) ; \ \vec{M} = \frac{3}{2} p L_m [\vec{i}_{rR} x \ \vec{i}_{rK}] \end{aligned}\quad (10)$$

In the electromagnetic torque  $M$  expression one can introduce the magnetization current  $i_{\mu K}$ , as well the magnetization flux  $\psi_{\mu} = w_{es} \psi_{\mu K}$ :

$$\begin{aligned}
 \psi_{sK} &= L_s i_{sK} + L_m i_{rK} = L_{s\sigma} i_{sK} + \psi_\mu \Rightarrow M = \frac{3}{2} p \operatorname{Im} \left( \psi_\mu^c i_{sR} \right) \\
 \psi_{rK} &= L_r i_{rK} + L_m i_{sK} = L_{r\sigma} i_{rK} + \frac{1}{k} \psi_\mu \Rightarrow M = \frac{3}{2} p \frac{L_m}{L_s} \operatorname{Im} \left( \psi_\mu^c i_{rK} \right) \quad (11) \\
 i_{\mu K} &= i_{sK} + i_{rK} \Rightarrow M = \frac{3}{2} p L_m \operatorname{Im} \left( i_{\mu R}^c i_{rR} \right)
 \end{aligned}$$

The expression of these variants for the electromagnetic torque permit to obtain whatever expression function of the magnitudes demanded; one can introduce the rotor magnitudes refer to the stator winding:  $\psi_{rK} = k \psi_{rK}$  and  $i_{rK} = k i_{rK}$ .

## 5. Simplified mathematical models of the induction machine.

One uses as well simplified mathematical models in the induction machine study which can obtain an important reduction of the volume of the calculation and a simpler physical interpretation of the results obtained

A first simplified model consists to neglected the transitive state in the stator windings, that means one neglects the transformation electromotive force (e.m.f.):

$$\begin{aligned}
 \frac{d\psi_{sd}}{dt} &= 0; \quad \frac{d\psi_{sq}}{dt} = 0 \Rightarrow u_{sd} = R_s i_{sd} - \frac{\omega_K}{\omega_b} \mathcal{E}_{sq}; \\
 &= u_{sq} = R_s i_{sq} + \frac{\omega_K}{\omega_b} \mathcal{E}_{sd}; \\
 -u_{rd}^{\dot{}} &= R_r i_{rd}^{\dot{}} - \frac{\omega_K - \omega}{\omega_b} \mathcal{E}_{rq}^{\dot{}} + \frac{p}{\omega_b} \mathcal{E}_{rd}^{\dot{}}; \quad -u_{rq}^{\dot{}} = \quad (12) \\
 &= R_r i_{rq}^{\dot{}} + \frac{\omega_K - \omega}{\omega_b} \mathcal{E}_{rd}^{\dot{}} + \frac{p}{\omega_b} \mathcal{E}_{rq}^{\dot{}};
 \end{aligned}$$

In these equations the magnetic fluxes enter the magnitudes composition having dimension of the e.m.f. named conventional e.m.f. presented under the form:

$$\begin{aligned}
\mathcal{E}_{s\ d} &= \omega_b \psi_{s\ d} = X_{s\ \sigma} \dot{i}_{s\ d} + X_{\mu} \dot{i}_{\mu\ d} = X_s \dot{i}_{s\ d} + X_{\mu} \dot{i}_{r\ d} ; \\
\mathcal{E}_{s\ q} &= \omega_b \psi_{s\ q} = X_{s\ \sigma} \dot{i}_{s\ q} + X_{\mu} \dot{i}_{\mu\ q} = X_s \dot{i}_{s\ q} + X_{\mu} \dot{i}_{r\ q} ; \\
\dot{\mathcal{E}}_{r\ d} &= \omega_b \dot{\psi}_{r\ d} = X_{r\ \sigma} \dot{i}_{r\ d} + X_{\mu} \dot{i}_{\mu\ d} = X_r \dot{i}_{r\ d} + X_{\mu} \dot{i}_{s\ d} ; \\
\dot{\mathcal{E}}_{r\ q} &= \omega_b \dot{\psi}_{r\ q} = X_{r\ \sigma} \dot{i}_{r\ q} + X_{\mu} \dot{i}_{\mu\ q} = X_r \dot{i}_{r\ q} + X_{\mu} \dot{i}_{s\ q} ; \\
\dot{i}_{\mu\ d} &= \dot{i}_{s\ d} + \dot{i}_{r\ d} ; \quad \dot{i}_{\mu\ q} = \dot{i}_{s\ q} + \dot{i}_{r\ q}
\end{aligned} \tag{13}$$

The conventional e.m.f. are replaced by their relationships function of currents (13) and obtains the matrix equation:

$$\begin{bmatrix} u_{sd} \\ u_{sq} \\ -u_{rd} \\ -u_{rq} \end{bmatrix} = \begin{bmatrix} R_s & -\frac{\omega_K}{\omega_b} X_s & 0 & -\frac{\omega_K}{\omega_b} X_{\mu} \\ \frac{\omega_K}{\omega_b} X_s & R_s & \frac{\omega_K}{\omega_b} X_{\mu} & 0 \\ \frac{p}{\omega_b} X_{\mu} & -\frac{\omega_K - \omega}{\omega_b} X_{\mu} & R_r + \frac{p}{\omega_b} X_r & -\frac{\omega_K - \omega}{\omega_b} X_{\mu} \\ \frac{\omega_K - \omega}{\omega_b} X_{\mu} & \frac{p}{\omega_b} X_{\mu} & \frac{\omega_K - \omega}{\omega_b} X_r & R_r + \frac{p}{\omega_b} X_r \end{bmatrix} \cdot \begin{bmatrix} \dot{i}_{sd} \\ \dot{i}_{sq} \\ \dot{i}_{rd} \\ \dot{i}_{rq} \end{bmatrix} \tag{14}$$

To the matrix equation one adds the move equation. If one replaces in the relationships (12) the currents function of conventional e.m.f. one will obtain a new matrix equation:

$$\begin{bmatrix} u_{sd} \\ u_{sq} \\ -u_{rd} \\ -u_{rq} \end{bmatrix} = \begin{bmatrix} \frac{R_s X_r'}{D} & -\frac{\omega_K}{\omega_b} & 0 & -\frac{R_s X_{\mu}}{D} \\ \frac{\omega_K}{\omega_b} & \frac{R_s X_r'}{D} & \frac{R_s X_{\mu}}{D} & 0 \\ -\frac{R_r X_{\mu}}{D} & -\frac{\omega_K - \omega}{\omega_b} X_{\mu} & \frac{R_r X_s'}{D} + \frac{p}{\omega_b} & -\frac{\omega_K - \omega}{\omega_b} \\ \frac{\omega_K - \omega}{\omega_b} X_{\mu} & -\frac{R_r X_{\mu}}{D} & \frac{\omega_K - \omega}{\omega_b} & \frac{R_r X_s'}{D} + \frac{p}{\omega_b} \end{bmatrix} \cdot \begin{bmatrix} \omega_b \psi_{sd} \\ \omega_b \psi_{sq} \\ \omega_b \psi_{rd} \\ \omega_b \psi_{rq} \end{bmatrix} \tag{15}$$

One remarks the derivatives of the stator magnetic flux  $\dot{\psi}_{rd}$  and  $\dot{\psi}_{rq}$  do not appear and the rotor magnetic fluxes  $\psi_{rd}'$  and  $\psi_{rq}'$  can be envisaged as state variables. A second simplified mathematic model consists to neglect the stator as well the rotor transformation e.m.f.

$$\frac{d\psi_{sK}}{dt} = 0; \quad \frac{d\psi_{rK}}{dt} = 0 \quad (16)$$

Such a mathematical model can be employed for slow transient process presenting interest when the mechanical time constant is greater than the electric circuits time constants. In the synchronous reference frame  $K_0$  and the conditions (16) the mathematical model becomes:

$$\begin{aligned} u_{sK} &= R_s i_{sK} + j\omega_1 \psi_{sK}; \quad \omega_K = \omega_1 \\ \psi_{sK} &= L_s i_{sK} + L_m i_{rK} = L_{s\sigma} i_{sK} + w_{es} \psi_{\mu K} = \\ &= L_{s\sigma} i_{sK} + L_\mu i_{\mu K} \\ -u_{rK} &= R_r i_{rK} + j(\omega_1 - \omega) \psi_{rK}; \\ \psi_{rK} &= L_r i_{rK} + \frac{w_{es}}{w_{er}} L_m i_{sK} = L_{r\sigma} i_{rK} + w_{es} \psi_{\mu K} = \\ &= L_{r\sigma} i_{rK} + L_\mu i_{\mu K} \quad (17) \\ w_{es} \psi_{\mu K} &= \frac{w_{es}}{w_{er}} L_m i_{\mu K} = L_\mu i_{\mu K}; \\ \frac{J}{p} \frac{d\omega}{dt} &= M - M_2; \quad M = \frac{3}{2} p (\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) \end{aligned}$$

The equation system (17) coincides formerly with the equation system in steady state. To remark that to neglect the transformation e.m.f. is possible only in the synchronous reference frame  $K_0$  where the induced e.m.f. in the stator winding and in the rotor one different from zero with them the transformation e.m.f. can be neglected. If in the stator fixed reference SF or in the rotor fixed reference FR one neglects in such a way, one will obtain:

$$FS : \frac{d}{dt} \frac{\psi_s}{t} = 0 \Rightarrow u_s = R_s i_s; \quad FR : \frac{d}{dt} \frac{\psi_r}{t} = 0 \Rightarrow -u_r = R_r i_r \quad (18)$$

the relationships are absurd, that means in the respective reference frame the transformation e.m.f. can not be neglected. It is possible to neglect the transformation e.m.f. only in the reference frames where the move e.m.f. have a

significant magnitude compared with transformation e.m.f. In the synchronous reference frame  $K_0$  the stator winding has as angular speed  $\Omega_1$  and the rotor winding has as angular speed  $s\Omega_1$ ,  $s \neq 0$  and consequently relationships (16) are possible.

On the basis of the relationships (17) it results the equivalent diagram, which is similar to the diagram of steady state. The fact explains the extension of the steady state relationships towards certain transient states when the hypothesis (16) can be valuable.

## 6. The equivalent electric circuits

The equivalent electric circuits constitute an another manner of the voltage equations representation for an asynchronous machine in transient state as well as in steady state ones; these circuits represent intuitively the component elements in the machine theory permitting clear explanations of different phenomena characterizing the machine operating. For the same voltage equations system one has many equivalent circuits types. The circuits structure is the same in the case of the axial air-gap motor but modifications will appear in the electric parameters structure. In the equivalent circuits construction, the expression manner of the stator and rotor representative magnetic fluxes will be essential. One defines a rapport factor "a" which can get the magnitude of  $a = w_{es}/w_{er} = k$  - referred to the stator winding. In regard to the factor a, the magnetic representative fluxes will become:

$$\begin{aligned}
 \psi_{sK} &= x_s i_{sK} + x_m i_{rK} = (x_s - a x_m) i_{sK} + \\
 &+ a x_m \left( i_{sK} + \frac{i_{rK}}{a} \right) = x_{sa} i_{sK} + a x_m i_{aK} ; \\
 a \psi_{rK} &= a x_r i_{rK} + a x_m i_{sK} = a^2 \left( x_r - \frac{x_m}{a} \right) \frac{i_{rK}}{a} + \\
 &+ a x_m \left( i_{sK} + \frac{i_{rK}}{a} \right) = \dot{x}_{ra} \frac{i_{rK}}{a} + a x_m i_{aK} \quad (19) \\
 x_{sa} &= x_s - a x_m ; \quad \dot{x}_{ra} = a^2 \left( x_r - \frac{x_m}{a} \right) ; \quad i_{aK} = i_{sK} + \frac{i_{rK}}{a} ; \\
 a = k &\Rightarrow x_{sa} = x_{s\sigma} ; \quad \dot{x}_{ra} = \dot{x}_{r\sigma} ; \quad i_{aK} = i_{\mu K}
 \end{aligned}$$

For  $a = k$  the reactances get the classic theory signification;  $x_{s\sigma}$  - stator leakage reactance;  $x'_{r\sigma}$  - rotor leakage reactance referred to the stator winding;  $k x_m = x_\mu$  - magnetization reactance;  $i_{aK} = i_\mu$  - magnetization current.

On the basis of the above expressions one builds the equivalent circuit in the reference K represented in Fig. 6. The reference changed, in the equivalent circuit are affected the moving e.m.f.  $e_{sm}$  and  $e'_{rm}$ ; for fix stator reference FS,  $\Omega_k = 0$ , consequently  $e_{sm} = 0$ ; for fix stator reference FR,  $\Omega_k = \Omega$ , consequently  $e_{sr} = 0$ .

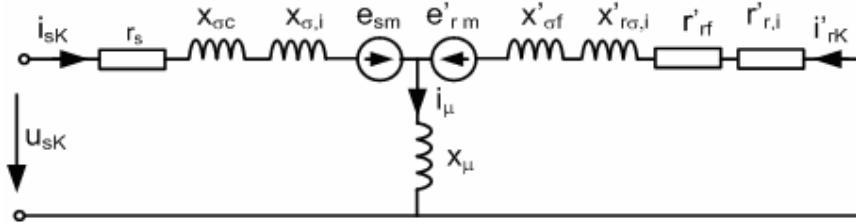


Fig. 6. Asynchronous machine equivalent circuit in the reference K.

For the case where the rotor circuit is resistive one has the following relationships:

$$a = \frac{x_m}{x_r} = \frac{L_m}{L_r} \Rightarrow x'_{ra} = 0 ;$$

$$x_{sa} = x_s^* = x_{\sigma c} + x_{\sigma, i} + \frac{1}{\frac{1}{x'_{\sigma f}} + \frac{1}{x_{r\sigma, i}} + \frac{1}{x_\mu}} \quad (20)$$

the rotor circuit reactance is nul and the stator circuit reactance  $x_{sa}$  is equal to the stator transient reactance  $x_s^*$ , the reactance being concentrated in the stator circuit. The equivalent circuit with resistive rotor circuit is largely employed in the vector control system.

The equivalent circuit is presented in the general reference K and one shows the manner they can be particularized in other reference systems.

## 7. The experimental test

We have built a prototype with 6 elementary motors (3 on each stator) and increased rotor resistance for a low power. All the elementary motors have been supplied in parallel and test have been operated in steady load. The voltage was

approximate constant and one has measured: the active power absorbed  $P_1$ , the line currents  $I_A$ ,  $I_B$  and  $I_C$ , the axis torque  $M_2$  and the rotation  $n$ . One the basis of these data one has calculated the useful power  $P_2$ , the efficiency  $\eta$  and the power factor. The data are presented in the table 1.

Table 1

**Experimental results.**

$U_{AB}$	$U_{BC}$	$U_{CA}$	$I_A$	$I_B$	$I_C$	$P_1$	$S_1$	$M$	$n$	$P_2$	$\cos\varphi$	$\eta$
V	V	V	A	A	A	W	VA	Nm	rpm	W	-	-
120	122	118	2,5	2,74	3,08	234	575	0	720	-	0,4	0
119	120	118	3,5	3,55	3,6	378	731	1,2	710	90,43	0,51	0,23
117,5	119	117	3,9	3,95	3,8	481	793	2,3	680	163,7	0,6	0,34

One remarks the rotation is relatively small (slips being big) in regard with the synchronism rotation because the rotor resistance is a big one; one has to mention that the no load operation is concerning the fact there is no useful torque at the axis but the mechanical losses are important, consequently the no load rotation is small compared to that of the synchronism. The high resultants offered by the motor can be improved if its building technology is high one.

The experimental test of the machine in a no load operation at the nominal voltage will be permit to determinate the mechanical losses  $p_{mec}$  and iron losses  $p_{Fe}$ ; if one measuret with high precision the slip  $s_0$  for the no load operation one has:  $p_{mec} = s_0 P_n / s_n$ .

The motor we have proposed offers real advantages: less materials; less energy for variable load; it is possible to build it at two synchronism speeds on condition the two stators are not supplied simultaneously; successive brakes can be obtained.

## 8. Conclusions

The motor we have proposed gets real advantages: less material; less energy for variable load; opportunity to be manufactured with two synchronism speeds on the condition the two stators not be supplied simultaneously; possibility of successive brakes.

The new elements are concerning the pole position of the two stators, the obtaining of the winding in some three-phased winding zone as well as any technological elements. The building form can be an advantage for an employing in the electrical traction.

The mathematical model has the same structure for a classical machine, but in the electrical parameters calculation (resistances and reactances) there are any special mentions determinate by the geometrical dimensions different for the windings overhang.

We have built a prototype with 6 elementary motors (3 on each stator) and increased rotor resistance for a low power. All the elementary motors have been supplied in parallel and test have been operated in steady load.

The equivalent circuit is presented in the general reference K and one shows the manner they can be particularized in other reference systems.

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