Study of Low Power Alternating Current Motors by Functional and Energy Aspect

Ion Vlad[*], Aurel Campeanu[*], Sorin Enache[*], Monica-Adela Enache[*]
[*]University of Craiova/Faculty of Electrical Engineering, Craiova, Romania, ivlad@em.ucv.ro
[*]University of Craiova/Faculty of Electrical Engineering, Craiova, Romania, acampeanu@em.ucv.ro
[*]University of Craiova/Faculty of Electrical Engineering, Craiova, Romania, senache@em.ucv.ro
[*]University of Craiova/Faculty of Electrical Engineering, Craiova, Romania, menache@em.ucv.ro

Abstract - **The objectives followed in the frame of this paper are to approach comparatively the two types of motors, from the view point of operation performances and of exploitation expenses obtained with them (asynchronous motor and permanent magnet synchronous motor), with the help of some specialized computation softwares. That is why the two motors are built in identical conditions, in order to analyze by comparison the load operation characteristics, the active and reactive electrical energy consumption. The study lately developed regarding the optimization of alternating current electrical machine include especially the problem of efficiency and power factor increase. The utilization of permanent magnets having high specific energies for building low power synchronous motors influenced the machine performances, the machine cost and the exploitation cost. In case of drives using alternating current motors the exploitation costs can be reduced by choosing correctly the driving motor. In order to enlarge the sale market of the energetically efficient motors, the producers have aimed at proving that the motors having high efficiency might be an attractive alternative for customers. In the frame of the aided conception, the computer becomes a numerical laboratory for the prototypes construction, without costs and deadlines, specific to a real execution. The utilization of permanent magnet synchronous motor reduces the consumption of active electrical energy with 7.9%, reduces the consumption of reactive electrical power very much, resulting a total cost which is lower with 23.9%.**

Keywords: *asynchronous motors, permanent magnet synchronous motors, modelling, simulation.*

I. Introduction

Studies show that over half of the electrical energy that is produced is used for supplying electrical motors, the most part for the asynchronous ones. The permanent magnets made of rare earths have impelled the researches in the field of electrical machines by finding new topologies, which are to replace the classical electrical machines [1-2], [6]. The construction of permanent magnet synchronous motors, starting from the classical structure, for which the electromagnetic excitation system has been replaced with permanent magnets, was a progress in the field.

The utilization of permanent magnets made of rare earths has led to exceptional performances, by miniaturization, by compact and reliable equipments, having low consumption of materials and requiring low energy operation consumptions [3], [7], [19].

The problems given by the electrical machines design and construction take into account to choose the most suitable permanent magnets for the considered type. The increase of the electrical machines performances has imposed the utilization of permanent magnets with high specific energies which influence the performances as well as the exploitation and cost price [13], [17-18], [20]. At this moment there are not optimum motors from all the view points, different optimization criteria imposing sometimes contradictory conditions.

It is imposed to develop some efficient procedures for improving the performances of the existing low power electrical motors (asynchronous and permanent magnet synchronous ones).

In order to enlarge the sale market for energetically efficient motors, the producers have aimed at proving that the motors having high efficiency might be an attractive alternative for customers [5], [8], [9], [15].

In these circumstances, the theme approached in this research is a subject of interest for engineering.

II. Design of Low Power Alternating Current Motors

A. Mathematical model of the motor

It is known that the electromagnetic stresses and the main constructive dimensions are very important in the alternating current motors design (asynchronous and permanent magnet synchronous ones), with major effects upon the operation characteristics and the exploitation cost. The synchronous motor we analyzed has permanent magnets on the rotor and exterior stator having the same construction as the one of the asynchronous motor.

B. Analyzed criterion and the objective function

The mathematical models used for the design of the two types of motors, for establishing the operation characteristics, for determining the costs (fabrication, exploitation and total) are known in the literature.

The study we performed here aims at emphasizing how the electrical energy consumption in exploitation can be decreased by choosing the driving motor adequately [4], [13]. That is why, the exploitation cost criterion has been chosen and the objective function has resulted:

$$f(\bar{x}) = C_e = C_{ea} + C_{er} = N_{ou} T_{ri} (c_{el.a} \Sigma p + c_{el.r} \Sigma q) \quad (1)$$

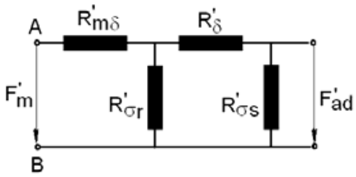
where: C_e –exploitation expenses, C_{ea} – cost of the active electrical energy lost in the machine, C_{er} – cost of the consumed reactive electrical energy, N_{ou} –number of annual operation hours; $c_{el.a}$, $c_{el.r}$ –costs of one kWh of active electrical energy, respectively reactive energy; T_{ri} –time of the investment recovery; Σp, Σq –total losses of active and reactive power in rated load operation.

III. RESULTS, SIMULATIONS AND CONCLUSIONS

Two low power motors are simultaneously analyzed: an asynchronous motor and a permanent magnet synchronous motor. For a correct comparison it has been established that the two motors have the same rated data: P_N= 1.0 kW –rated power, U_N=380 V –rated voltage, n_1=1000 r.p.m. –synchronism speed, the same electromagnetic stresses A_m=195 A/cm; B_m=0.66 T; $J_{1.m}$=3.4 A/mm^2; $J_{2b.m}$=2.6 A/mm^2; $J_{2i.m}$=2.1 A/mm^2; B_{j1m}=1.25 T, B_{j2m}=1.0 T, and the same main constructive dimensions: D_m=110mm, δ_m=0.18 mm; β_{c1m}=0.42.

The fabrication and exploitation costs have been computed on the basis of the existing documentation [11-14]. Figure 1.a presents a cross section of rotor and the arrangement of the permanent magnets. Figure 1.b presents the equivalent magnetic circuit of the rotor, in per unit, with the following meaning of the notations: F'_m –magnetic voltage between the magnet poles, F'_{ad} –magnetic voltage on the axis *d*, $R'_{m\delta}$ –reluctance of the technological air-gap, R'_δ -air-gap magnetic reluctance, $R'_{\sigma r}$ –magnetic reluctance of the space between the pole base of two adjacent poles, $R'_{\sigma s}$ –magnetic reluctance of the stator leakage circuit.

a)



b)

Fig.1. a) Rotor of permanent magnet synchronous motor; b) equivalent magnetic circuit in per unit.

To dimension the permanent magnet and to establish the optimum operation point on the return line are actions depending on the magnetic circuit configuration and they are a difficult stage [10].

The optimization procedure proposed as an invention numerically solves all the stages regarding the graphic construction, establishing the magnet dimensions and the useful flux. The points defining the per unit demagnetization curve of the permanent magnet we used, $B'=f(H')$, are computed by the relation:

$$B' = \frac{1 - H'}{1 - \alpha_{mg} H'} \tag{2}$$

where we have the variable H' =(0 ÷ 1.0), and the return coefficient of the magnet:

$$\gamma_{mg} = \frac{BH_{max}}{B_r H_c} \qquad \alpha_{mg} = \frac{2\sqrt{\gamma_{mg}} - 1}{\gamma_{mg}} \tag{3}$$

The inductor magnetic field is achieved by rare earths based permanent magnets [16-18], [20], NeFeB which have a middle remanent magnetic induction and very high intensity of the coercive magnetic field and maximum magnetic energy.

The procedure of design-optimization carried out here solves in a short time, by numerical methods and iterations, all the stages necessary for establishing the magnet dimensions and the optimum operation point, so that the difference between the useful flux and the flux established in the design stage is maximum 1%. The simulations performed here have brought quantitative and qualitative information very necessary for adjusting the mathematical model, for finishing the parameters and the constructive solution.

A. Analysis of the operation characteristics

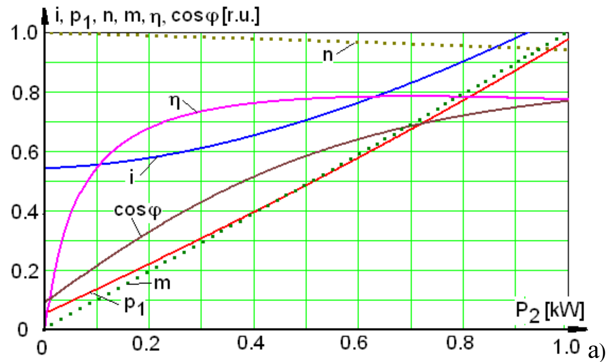
In order to emphasize the comparison between the two types of motors (asynchronous motor and permanent magnet synchronous motor), which have the same rated data, the same electromagnetic stresses and the same constructive dimensions, the operation characteristics will be analyzed below. In figure 2 there are presented these characteristics in per unit, for the two motors, when the load does not exceed the rated value.

The notations used here have the following meaning: p_1 -input power (red colour), i -current (blue colour), n -speed (green colour and dotted line), m -torque (black colour and dotted line), η -efficiency (pink colour), cosφ -power factor (brown colour). The characteristics m, p_1=f(p_2) for the two types of motors have the same shape (linear) and approximately the same values.

Owing to the high consumption of reactive power, the current curve of the asynchronous motor is much over the synchronous motor. At the same time, at the permanent magnet synchronous motor we see that the curves of efficiency and power factor are almost constant over all the operation range and the values are higher than in the case of asynchronous motor.

In conclusion, the operation characteristics presented before show that the permanent magnet synchronous motor is superior to the asynchronous one. In Fig. 3 there are plotted the operation characteristics of the two motors, when the load might reach P_2= 2.0*P_{2N} (a random overload for a short time).

The characteristics keep the same form for the two motors, but they have higher values for efficiency and power factor in case of permanent magnet synchronous motor. In order to carry out an efficient analysis, there are presented curves of the same nature in the same graphic: I_{as}, I_s=$f(P_2)$, currents curves (Fig.4), P_{1as}, P_{1s}=$f(P_2)$ input power curves (Fig.5), M_{as}, M_s=$f(P_2)$ electromagnetic torques curves (Fig.6), n_{as}, n_s=$f(P_2)$ speed curves (Fig.7), η_{as}, η_s=$f(P_2)$ efficiency curves (Fig.8), cosφ_{as}, cosφ_s=$f(P_2)$ power factor curves (Fig.9).



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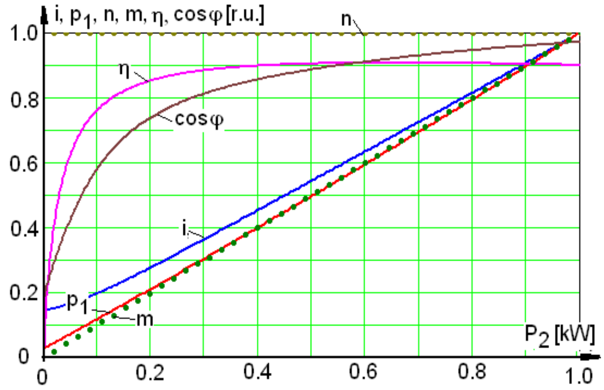

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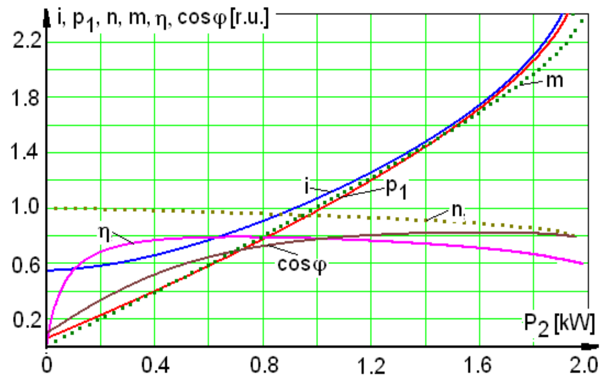
Fig. 2. Load operation characteristics for: a) asynchronous motor, b) permanent magnet synchronous motor.



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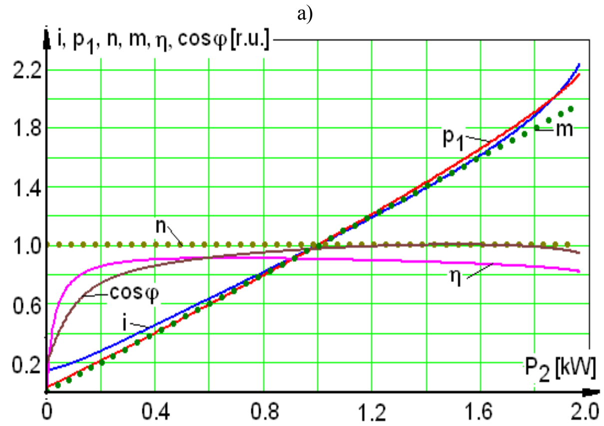

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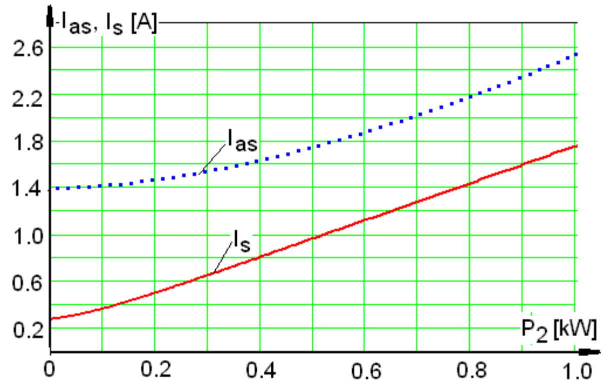
Fig. 3. Operation characteristics in temporary overload regime for: a) asynchronous motor, b) permanent magnet synchronous motor.



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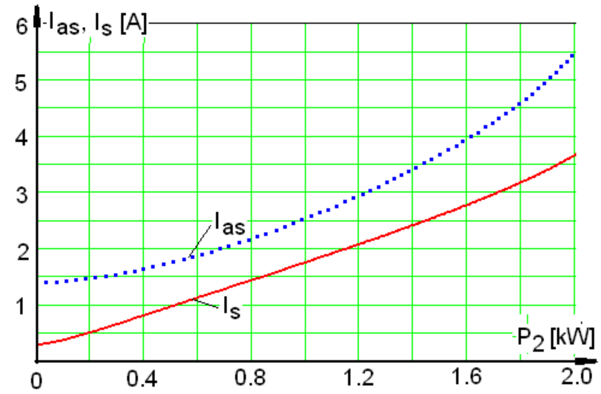

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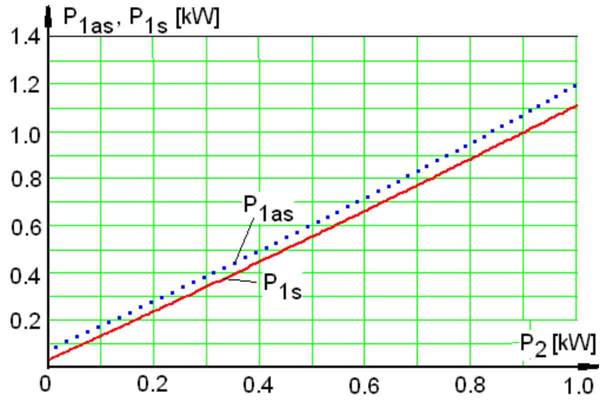
Fig. 4. Variation curves of the currents (i_{as} –asynchronous motor, i_s – permanent magnet synchronous motor, for: a) rated load, b) overload.



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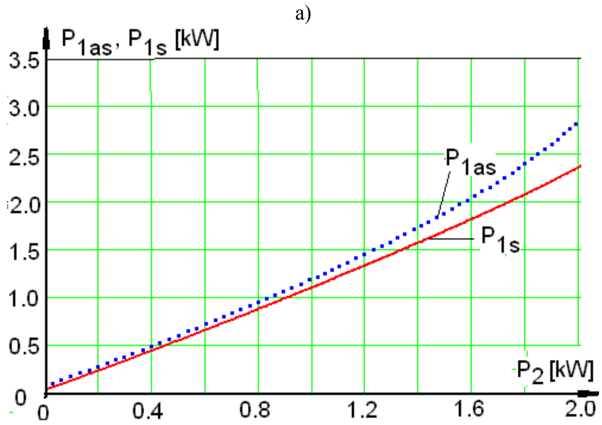

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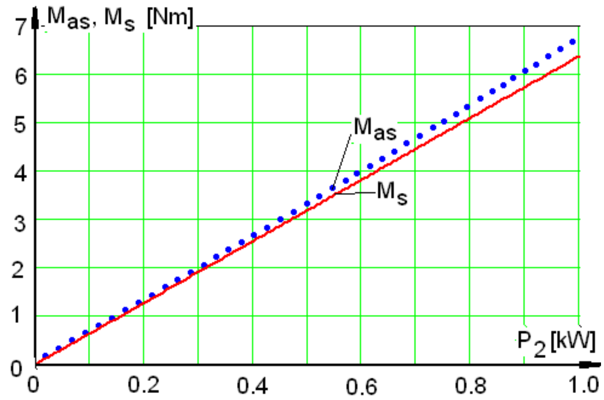
Fig. 5. Variation curves of input power (p_{1as} –asynchronous motor, p_{1s} – permanent magnet synchronous motor), for: a) rated load, b) overload.



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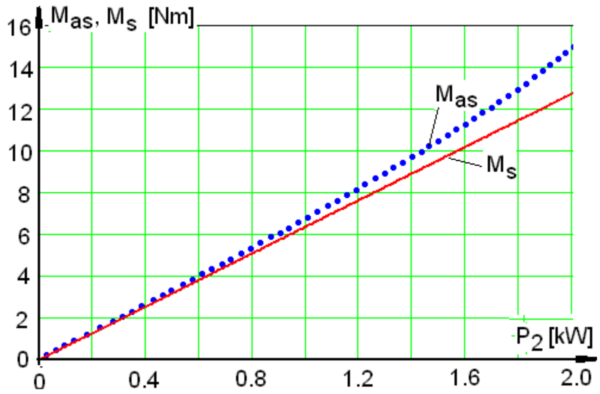

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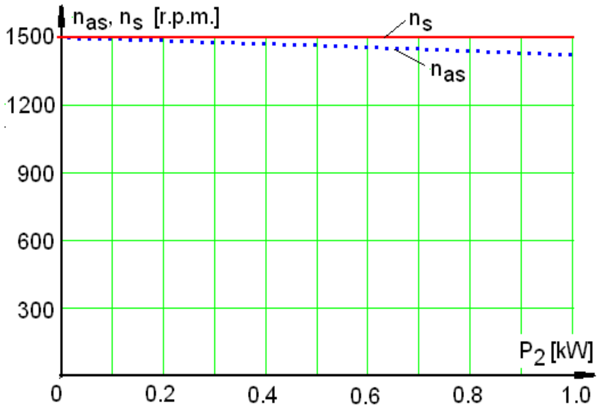
Fig. 6. Variation curves of torques (m_{as} –asynchronous motor, m_s – permanent magnet synchronous motor), for: a) rated load, b) overload.



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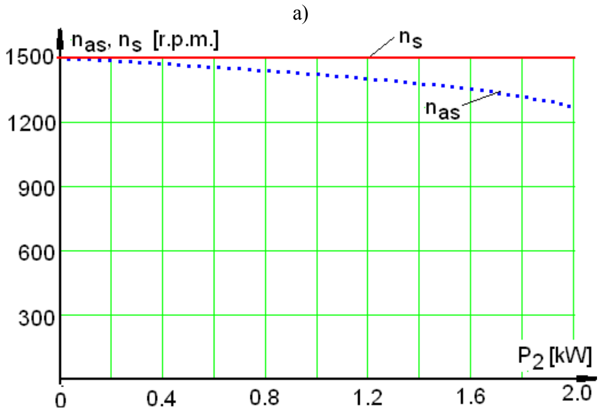

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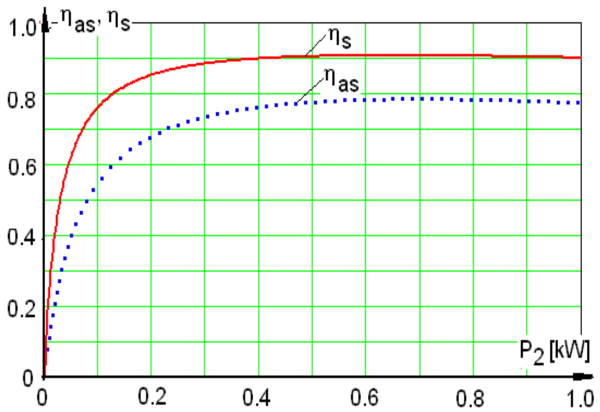
Fig. 7. Variation curves of speed (n_{as} –asynchronous motor, n_s – permanent magnet synchronous motor), for: a) rated load, b) overload.



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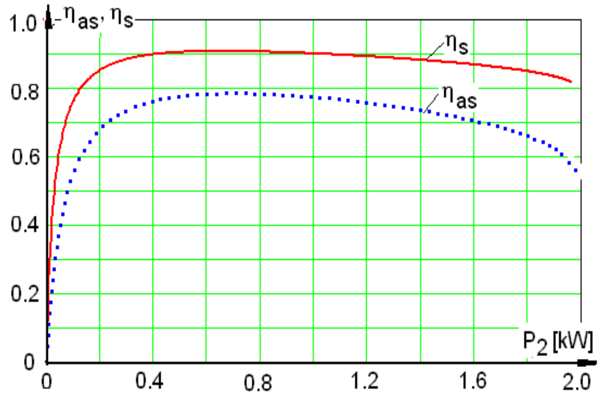

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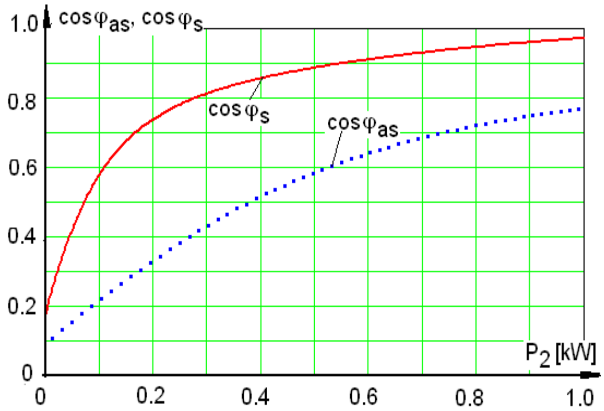
Fig. 8. Variation curves of efficiency (η_{as} –asynchronous motor, η_s – permanent magnet synchronous motor, for: a) rated load, b) overload.



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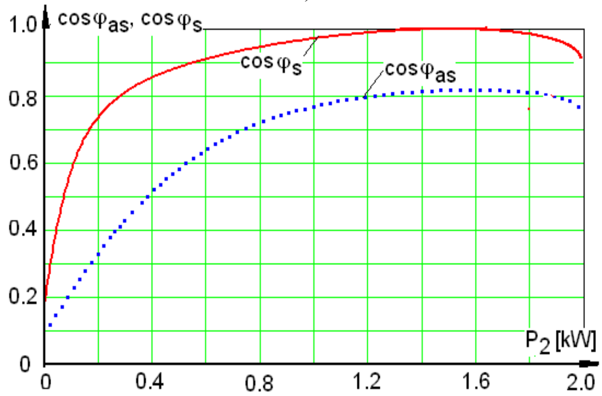

b)

Fig. 9. Variation curves of power factor ($\cos\varphi_{as}$ –asynchronous motor, $\cos\varphi_s$ – permanent magnet synchronous motor), for: a) rated load, b) overload.

These curves are plotted for a normal load, respectively for a double overload for a short time. The analysis of these curves presenting the operation in normal load and in overload for a short time shows that the asynchronous motor is much inferior.

B. Characteristics analysis from energy point of view

Another objective of the study has been to identify the quantities conditioning the exploitation cost (consumption of active and reactive electrical energy) and to establish the ways for reducing them. The reactive power consumption and its cost are established with the help of the power factor. A high reactive component causes an increase of the input current ($I=I_a+I_r$), which means an increase of the windings losses, so a higher active power consumption.

In the usual operation range $P_2=(0.75 \div 1.0)P_{2N}$, there are high differences between currents curves ($I_{as}/I_s \approx 1.83$), efficiency ($\eta_s/\eta_{as} \approx 1.154$) and power factor ($\cos\varphi_s/\cos\varphi_{as} \approx 1.33$), and in the range of the low loads these differences are much higher. These differences are found in the active and reactive electrical energy consumption, so in the exploitation cost.

The study shows that the permanent magnet synchronous motor has much higher efficiency and power factor, so it has lower electrical energy consumption.

C. Analysis of currents curves

Using the results obtained by design, with the help of an adequate program, there has been plotted the phasors diagram of current for the asynchronous motor and for the permanent magnet synchronous motor.

These diagrams emphasize the importance of the numerical models in the constructive conception and design activity at alternating current electrical machines, in the pre-determination of the important parameters and the possibility to verify the machine performances.

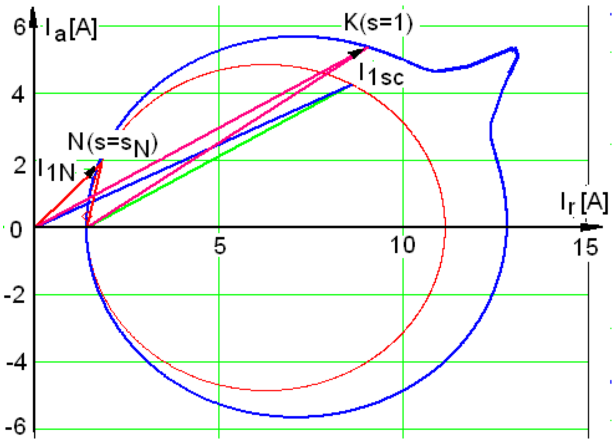

Fig. 10. Current diagram for the asynchronous motor.

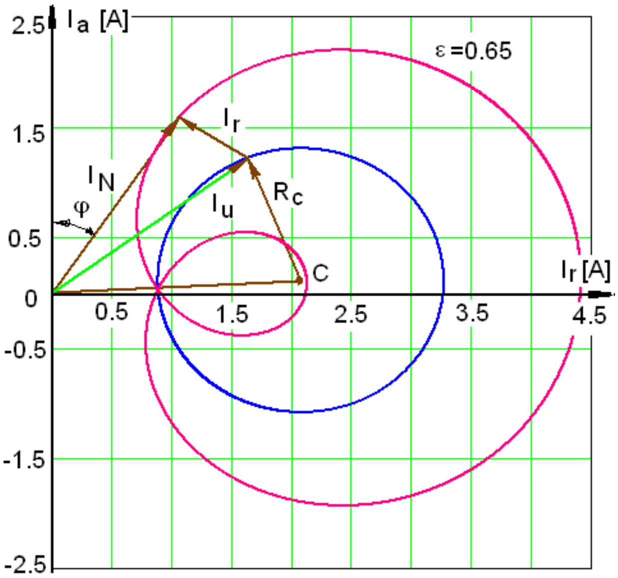

Fig. 11. Current diagram for the optimized permanent magnet synchronous motor.

In Figure 10 there is plotted the adjusted current diagram for the asynchronous motor we analyzed (blue colour), and for the machine with constant parameters (pink colour). Because the machine parameters are slightly dependent by repression and magnetic saturation, the geometric locus curve is almost a circle.

The diagram emphasizes the currents corresponding to the rated state I_{1N} (N rated point) and the starting one I_{1sc} (k short-circuit point).

At the permanent magnet synchronous motor we analyzed, the current diagram $I=f(\theta)$ emphasized in figure 11 with its components, is a geometric curve called limacon (θ -internal angle of the machine).

The case $\varepsilon=0$ corresponds to the reluctance synchronous motor where the geometric locus of the phasor $I=f(\theta)$ is the circle having the centre in C and the radius R_c.

The figure also emphasizes the current lagging which is modified by the component I_r, so the power factor might be increased by dimensioning correctly the permanent magnet. The current expression contains the following components:

R_c –radius of the circle given by the asymmetry by the two axes (circle diagram for the reluctance motor);

C – phasor defining the circle centre;

$$R_c = \frac{U_1}{R^2 + X_d X_q}\frac{X_d - X_q}{2} \tag{4}$$

$$\underline{C} = \frac{U_1}{R^2 + X_d X_q}\left(R - j\frac{X_d + X_q}{2}\right) \tag{5}$$

I_r – current component given by the excitation degree of the permanent magnet.

$$\underline{I}_r = \frac{U_1}{R^2 + X_d X_q}\left[-\varepsilon(R - jX_q)e^{-j\delta}\right] \tag{6}$$

$\varepsilon=U_{E0}/U$ –defines the excitation degree of the motor.

D. Technical-economic comparison between the two types of motors

Table no.1.

Rated data/ Characteristics	Asynchronous motor	Permanent magnet synchronous motor
P_N [kW] –rated power	1.0	1.0
U_N [V] –rated voltage	380	380
n_1[r.p.m.] –synchronism speed	1000	1000
I_N [A] –rated current	2.13	1.74
M_N [Nm] –rated torque	10.02	9.48
M_{max} [r.u.] –maximum torque	2.01	1.62
M_p [r.u.] –starting torque	1.23	1.02
I_p [r.u.] –starting current	4.21	3.98
P_{1N} [kW] –active power	1.204	1.116
Q_{1N} [kVA] –reactive power	0.724	0.268
Σp [kW] –total losses	0.204	0.116
η -efficiency	0.831	0.896
$\cos\varphi$ –power factor	0.857	0.972
De –outer diameter of motor	180.3	174.7
L_e – total length of machine	184.7	176.5
m_{mg} – magnet weight	-	0.537
m_{Cu} –copper weight	3.77	4.12
m_{Fe} –iron weight	13.8	9.64
m –motor weight	21.1	17.2
C_t [E] –total cost	436	352
C_f[E] –fabrication cost	146	218
C_e [E] –exploitation cost	290	134

A classical design of motors (according to the specialty literature) led to the following results filled in the table no.1. The mathematical model used provides: consumptions of materials, costs, the total losses of machine, the important parameters necessary in the command and control systems etc.

The motors costs (total, fabrication and exploitation), are dependent upon the costs of the existing raw materials, upon the characteristics of the electrotechnical materials used, upon the fabrication technology, upon the cost of electrical energy and upon the costs of other energetic consumtions.

All these cost are variable from one period of another.

IV. CONCLUSIONS

The study carried out here has presented two motors (asynchronous motor and permanent magnet synchronous motor), which have the same rated data, the same electromagnetic stresses and the same main constructive dimensions. Consequently, the two motors are built in identical conditions and we can analyze, by comparison, the load operation characteristics, the consumption of active and reactive electrical energy in exploitation.

On the basis of this study it has been established that, for low power, the permanent magnet synchronous motor is better. Thus there are provided indications and a lot of detail elements, for one building electromechanical equipments, using an electrical motor in the driving system.

It is shown that, if the permanent magnet synchronous which has better efficiency and power factor instead of the asynchronous motor, then the consumption of active electrical energy is reduced with 7.9%, and the consumption of reactive electrical energy is reduced with 271% .

All these advantages also have a drawback by the fact that the fabrication cost of the permanent magnet synchronous motor is increased with 49.1% and the starting torque is smaller.

The study shows a total cost reduced with 23.9% for the synchronous motor owing to the low consumption of active and reactive electrical energy.

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