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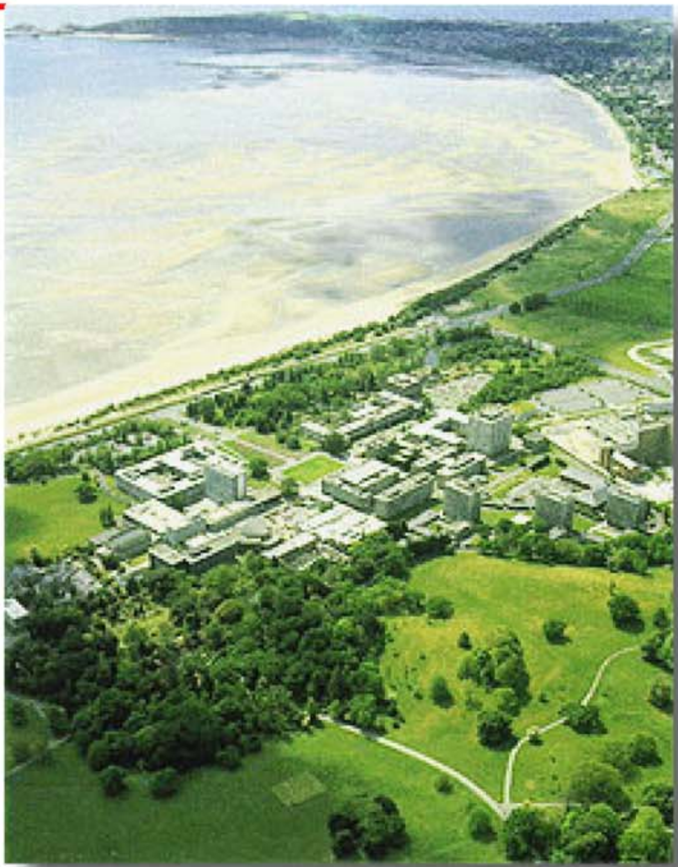

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FEM ANALYSIS OF SINGLE-PHASE SHADED-POLE MOTOR

Lidija Petkovska, Milan Cundev, Vasilija Sarac

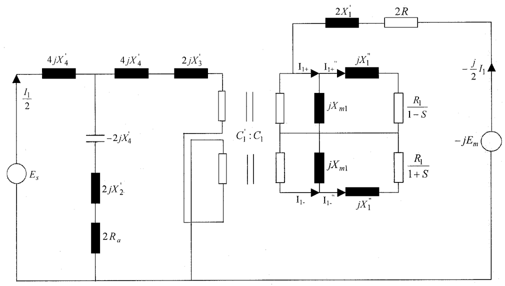
"Sts. Cyril & Methodius" University, Faculty of Electrical Engineering

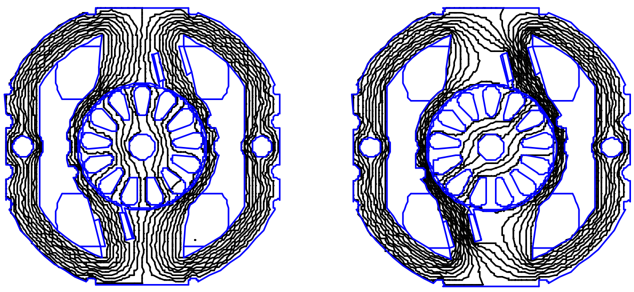
Karpos II bb, P.O.B. 574, 1000 Skopje, Macedonia

Phone: + 389 2 399-145   Fax: + 389 2 364-262

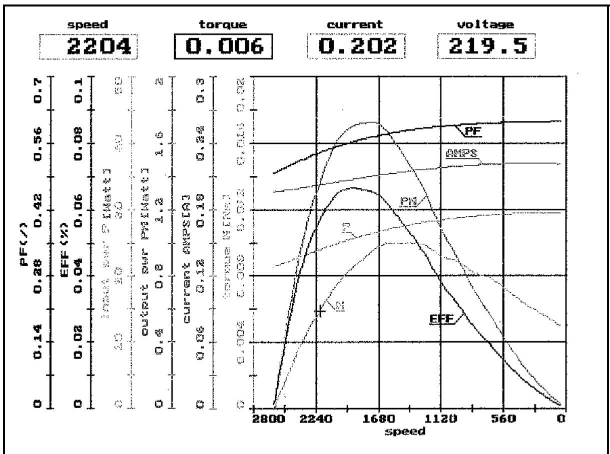
e-mail: lidijap@cerera.etf.ukim.edu.mk

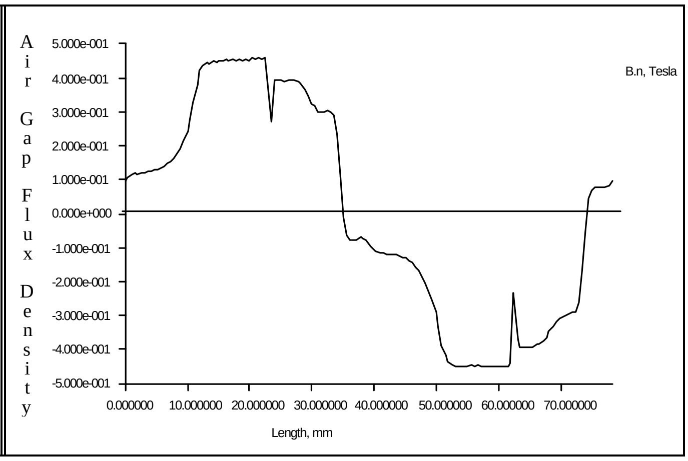
The development of automatic control drives, robotics and computer techincs, as well as different appliances, recently has caused an appearance and an expansion of palette special different types of fractional hosepower motors with enormous possibilities for their applications, hence interesting for research. The design and performance analysis of these motors are considerably different from the design and performance of the classic ones, although their operation bases on the same principles of electromechanical energy conversion. The single-phase shaded-pole motor is well recognized as simple in construction but complicated to analyze. The exact analytic methods are alomost improper. Compared to other types of induction motors, it is more complicated by the fact that there exist three mutually coupled windings and an eliptic rotating magnetic field. In this paper it will be presented an improved performance analysis of the shaded pole motor 2p=2, 24 W, 2200 rpm. on the basis of the circuit and resolving field theory with an emphasis to the Finite Element Method application. Starting from the eliptic character of the rotating field, the circuit modelling of shaded pole motor is carried out according to the revolving field theory. By coupling the phenomena caused by the forward and backward components of the magnetic field in the air-gap, the equivalent circuit is derived in the presented form. According to revolving field theory electromagnetic torques is going to be calculated from the circuit parameters.





The authors suggest the methodology and an improved performance analysis of the shaded pole motor, based on the circuit model and finite element method application. For that purpose, in the FEM model, the shaded pole motor is considered quasistatically. The currents of the main stator winding coil, the shading ring, as well as the rotor cage winding, are modelled at rated load conditions. In the paper. the results are compared with the experimentally obtained ones. A deepened analysis of influence of the shading portion of the pole, will be presented in the full paper, too.





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FEM ANALYSIS OF SINGLE-PHASE SHADED POLE MOTOR

Lidija Petkovska, Milan Cundev and Vasilija Sarac

"Sts. Cyril & Methodius" University, Faculty of Electrical Engineering, Macedonia

ABSTRACT

In this paper a methodology for an improved performance analysis of a shaded pole motor is presented. They are used different approaches to the computation of the motor characteristics. On the basis of the resolving field theory, a circuit model of the motor is derived. The FEM model of the motor is also developed. By using the Finite Element Method, a set of calculations is carried out and the distribution of the magnetic flux density in the air gap is obtained. A deepened analysis of influence of the shading portion of the pole is presented too. The shaded-pole motor is also studied experimentally. The obtained results, are mutually compared. They show a reasonable agreement.

INTRODUCTION

The development of different devices and appliances, has caused an expansion of special types of fractional horsepower motors (micro-motors) with enormous possibilities for their applications, hence, interesting for research. A design and a performance analysis of these motors are considerably different from the design and the performance of the classic ones, although their operation bases on the same principles of the electromechanical energy conversion. One of these particular motors is the shaded-pole motor which appertains to the class of the asymmetrical single-phase induction motors.

PHYSICAL MODEL OF SHADED-POLE MOTOR

The rated data of the shaded pole motor under consideration are: 220 [V] voltage supply, 24 [W] input power, 2200 rpm speed and 2p=2 number of poles. The authors suggest a methodology for an improved and deepened performance analysis of the shaded pole motor. The cross section of the motor is presented in Fig. 1.

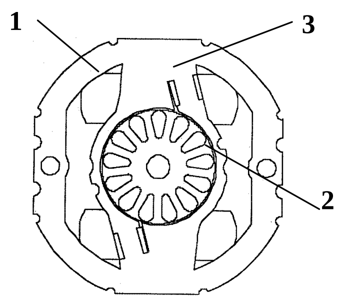

Fig. 1. Cross-section of the shaded pole motor

Compared to other types of induction motors, the shaded-pole motor is more complicated by the fact that there exist three mutually coupled windings and an asymmetrical elliptic rotating magnetic field. The application of exact analytical methods is almost improper. Many authors over the past made a lot of research efforts for an analysis and the design of this motor. But, so far, obviously, it has not been established an universal method of analysis [1]-[5].

The first winding is the main stator winding (1) and the second one is the bar squirrel cage rotor winding (2); the third winding is the auxiliary stator winding with one shading coil per pole (3). One pole pitch of the shaded pole motor, in a developed view, is presented in Fig. 2.

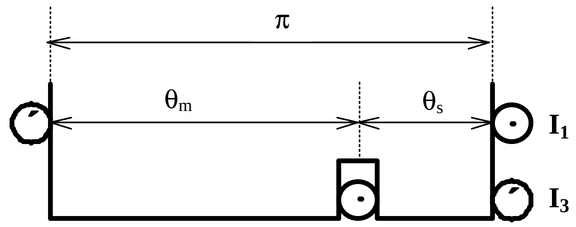

Fig. 2. Developed view of a motor pole pitch

The pole of the motor is spanned to a pole pitch angle of π el.rad. The angle q_s is shaded pole arc in the el.rad., meaning the shading pole portion. The angle q_m is considering the non-shaded part of the pole arc in el.rad., too. The common effect of the two stator windings to the rotor circuit is equivalent to that when the first (main) winding only is carrying the current $I_s = I_1 - I_3$, where, I_1 and I_3 are the main stator winding current and the shading coil current in primary terms, respectively.

CIRCUIT MODEL OF SHADED-POLE MOTOR

Starting from the elliptic character of the rotating field, the modeling of shaded pole motor is carried out according to the revolving field theory. By coupling the phenomena caused by the forward and backward components of the magnetic field in the air-gap [1], the common equivalent circuit is derived in the form presented in Fig. 3.

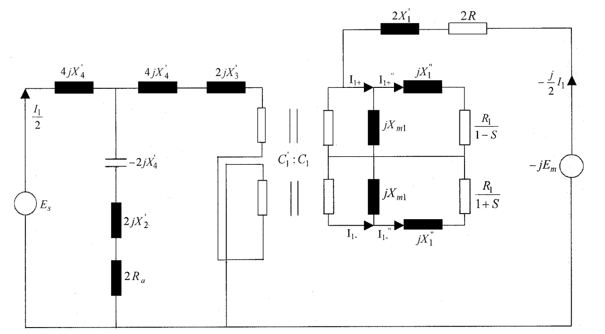

Fig. 3. Equivalent circuit of the shaded pole motor based on the revolving field theory

Note that the signs "+" and "-" are used for the forward and backward sequence components, respectively; although both currents and impedances are not specially marked, they are comprehended as complex quantities.

According to the revolving field theory the forward and the backward components of the auxiliary circuit currents are calculated as follows:

$$I_{1+} = \frac{1}{2}\left[(I_1 - I_3)\frac{C_1^{'}}{C_1} - jI_1\right] \qquad (1)$$

$$I_{1-} = \frac{1}{2}\left[(I_1 - I_3)\frac{C_1^{'}}{C_1} + jI_1\right] \qquad (2)$$

where: $C_1 = C sin(\theta_m/2)$ is the effective number of conductors of the main stator winding;
$C_1^{'} = C sin(\theta_s/2)$ is the effective number of conductors of shading coil, i.e. the auxiliary stator winding;
C is the actual number of the main stator winding conductors.

The current in the main stator winding, from Fig. 3, is:

$$I_1 = \frac{U}{Z_m + Z_t + R + j\left(X_1^{'} + 2X_4^{'}\right)} \qquad (3)$$

where: $U = 220$ [V] is the supply voltage;
R is the main stator winding resistance.

According to the circuit model of the motor, the following impedances are introduced:

$$Z_{1+} = \frac{jX_{m1}\left(\frac{R_1}{1-S} + jX_1^{'}\right)}{\frac{R_1}{1-S} + j\left(X_1^{'} + X_{m1}\right)} \qquad (4)$$

$$Z_{1-} = \frac{jX_{m1}\left(\frac{R_1}{1+S} + jX_1^{''}\right)}{\frac{R_1}{1+S} + j\left(X_1^{''} + X_{m1}\right)} \qquad (5)$$

$$Z_m = \frac{1}{2}(Z_{1+} + Z_{1-}) \qquad (6)$$

$$Z_t = -\frac{j}{2}\left(\frac{C_1^{'}}{C_1}\right)(Z_{1+} - Z_{1-}) \qquad (7)$$

The variable S is introduced as the ratio of actual rotor speed n to synchronous speed of the rotating fundamental flux wave n_S. Considering that the rotor slip s is expressed by these quantities, as:

$$s = \frac{n_S - n}{n_S} \qquad (8)$$

the following equations are obvious:

$$s_+ = s = 1 - S \qquad (9)$$

$$s_- = 2 - s = 1 + S \qquad (10)$$

Also, in equations (4) and (5) R_1 is the rotor resistance and X_{m1} is the mutual reactance between the main stator winding and the short circuit coil.

There are four types of stator leakage reactances, which are included in the equivalent circuit of the motor presented in Fig. 3. The first one is the leakage reactance $X_1^{'}$, due to the leakage flux linked with the stator coil only; the second one is leakage reactance $X_2^{'}$, due to the leakage flux linked with the shading coil only; the third component links the leakage fluxes between the main winding coil and shading ring placed on the same pole. The stator leakage reactance $X_4^{'}$, linking one shading coil with two stator coils (placed on a pair of poles) due to the magnetic shunt, is the fourth component.

The circuit model of shaded-pole motor is described by the rotor parameters included in the equivalent circuit, too. The rotor leakage reactance $X_1^{''}$ is consisted by the following components: the slot reactance $X_{1slot}^{''}$, the end regions reactance $X_{1end}^{''}$, the reactance due to the slot skewing $X_{1skew}^{''}$ and the "zigzag" reactance $X''_{1zigzag}$, known as teeth leakage reactance.

The shading coil current is calculated from:

$$I_3 = I_1 \frac{Z_a - Z_t}{Z_s + Z_a + j\left(X_3^{'} + 2X_4^{'}\right)} \qquad (11)$$

In the above equation, R_a is the shading ring resistance, and the following impedances are introduced:

$$Z_a = R_a + j\left(X_2^{'} - X_4^{'}\right) \qquad (12)$$

$$Z_s = \left(\frac{C_1^{'}}{C_1}\right)^2 (Z_{1+} + Z_{1-}) \qquad (13)$$

The static electromagnetic torque is calculated from the circuit parameters, as follows:

$$M_{em} = \frac{9{,}55}{n_1}\left[\left|I_{1+}\right|^2 R_{1+} - \left|I_{1-}\right|^2 R_{1-}\right] \qquad (14)$$

In the equation (14), the currents I_{1+} and I_{1-} are calculated from the equations (1) and (2); R_{1+} and R_{1-} are the resistive components of Z_{1+} and Z_{1-} previously given by the equations (4) and (5), respectively.

Power factor of the motor is calculated as:

$$\cos\varphi = \frac{I_1}{\left|I_1\right|} \qquad (15)$$

Input power is determined from,

$$P_1 = UI_1 \cos\varphi \qquad (16)$$

while output power on the motor shaft is given by

$$P_2 = \frac{(1-s)n_s M_{em}}{9{,}55 \cdot \left(1 + \frac{p\%}{100}\right)} \qquad (17)$$

considering that usually mechanical losses of this type of the motor are *p%=15-25%* of the output power.

Output torque on the motor shaft is calculated from the expression:

$$M_2 = \frac{9{,}55 P_2}{n_s(1-s)} \qquad (18)$$

and the efficiency factor is calculated as:

$$\eta = \frac{P_2}{P_1} \qquad (19)$$

FEM ANALYSIS OF SHADED-POLE MOTOR

The Finite Element Method (FEM) in the recent years has been found as a very attractive in the design and analysis of electrical machines and electromagnetic devices. So far it has been developed a large number of program packages [6] for calculation of the magnetic field. Also, there has been done a lot of work all over the world in this subject matter.

In order to determine parameters and characteristics of the shaded-pole motor as accurate as possible, the Finite Element Method is used. All winding currents and the rotor speed have the rated values. In the post-processing step, the distribution of the magnetic flux density is obtained. Static electromagnetic torque is computed, too. The different winding reactances could be also calculated. Some of the most interesting results are presented in the next figures.

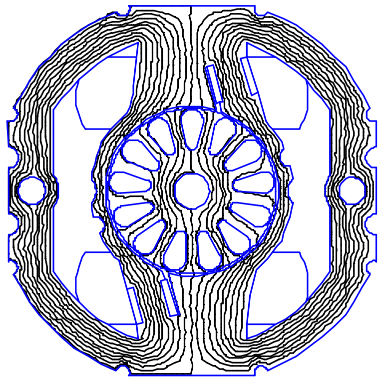

Fig. 4. Flux distribution when only the main winding is excited

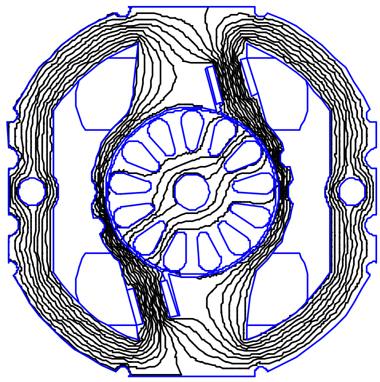

Fig. 5. Flux distribution when only the shading coil is excited

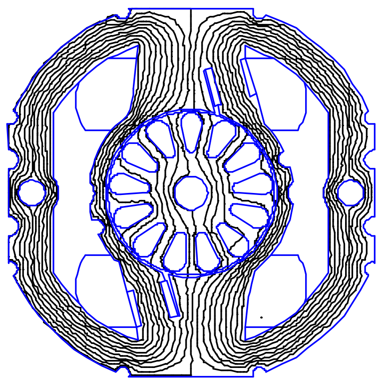

Fig. 6. Flux distribution when all motor windings are excited

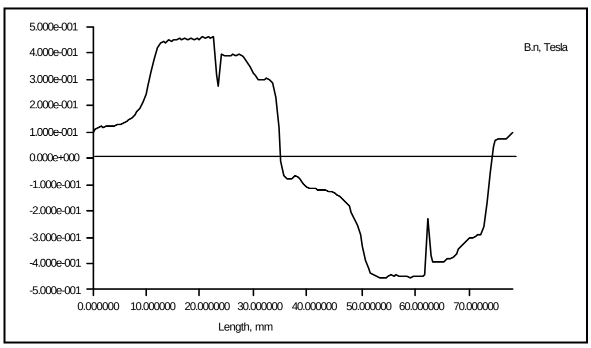

Fig. 7. Spatial distribution of the air-gap flux density when only the main winding is excited

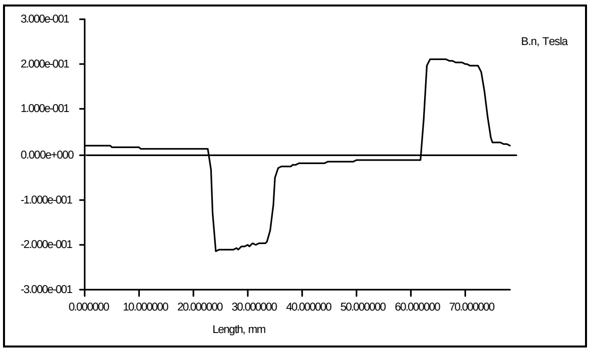

Fig. 8. Spatial distribution of the air-gap flux density when only the shading coil is excited

The previous two figures could serve as a guide, during the optimization of the shaded pole, especially when selecting the optimal shading portion of the stator pole.

PERFORMANCE ANALYSIS

By using the developed circuit model, as well as the FEM model, the performance analysis of the shaded-pole motor under consideration is carried out. In order to prove the proposed methodology, the motor has been tested thoroughly on the computerized testing bench. The output results of the test procedure are automatically plotted on a diagram and presented in Fig. 9.

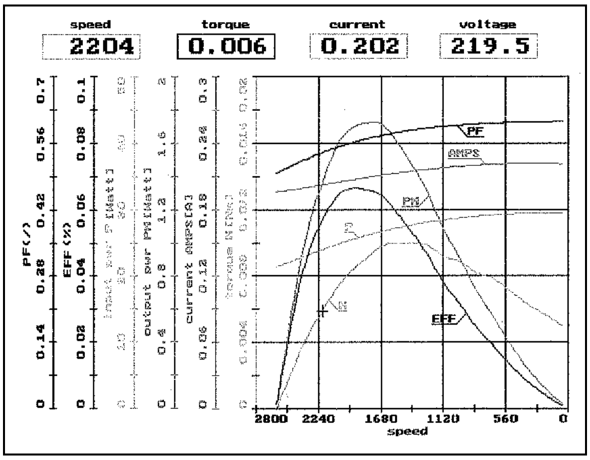

Fig. 9. Performance characteristics of the shaded pole motor obtained experimentally

After the circuit model parameters of the shaded pole motor are determined, they are included in calculations of performance characteristics by using the derived equations in previous sections. In this case as the variable parameter is accepted to be the rotor slip *s*, i.e. the quantity *S*. For better view and more evident comparison, the calculated and measured characteristics are presented on separate charts, in the following figures.

The presented characteristics show a reasonable agreement, so the proposed methodology is proved as satisfactory accurate.

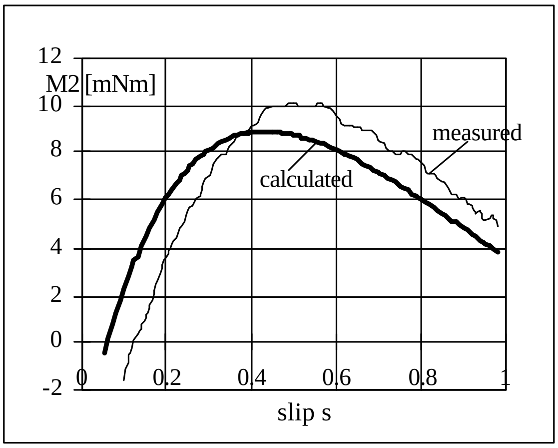

Fig. 10. Comparison of output torque characteristics

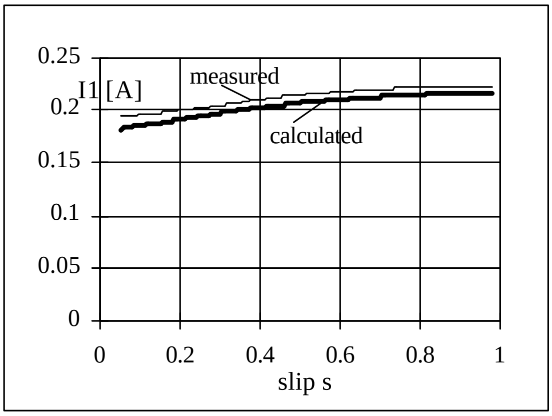

Fig. 11. Comparison of input current characteristics

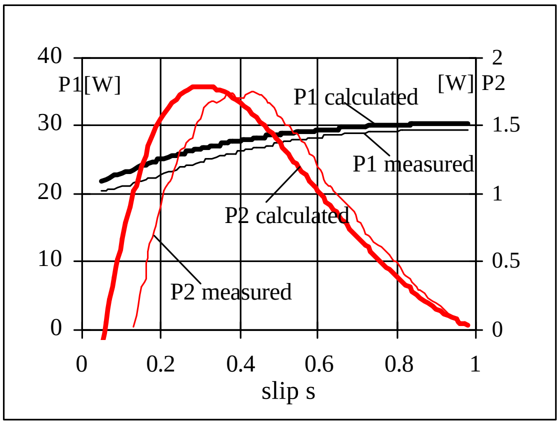

Fig.12. Comparison of input and output power characteristics

Additionally, the most interesting matter of investigation is certainly the effect of shading portion of the pole. Starting electromagnetic torque characteristic M_p, when the shaded pole arc angle is varied, is given in Fig.13. The maximum values of electromagnetic torque is attained at shading angle of the stator pole arc equal to $\theta_s = 80^0 \div 90^0$ electrical. This fact shows considerable agreement with the analyzed motor. But, knowing that the shading portion of stator pole arc is determined to be $\theta_s \approx 73^0$ electrical, it is suggested to enlarge its value.

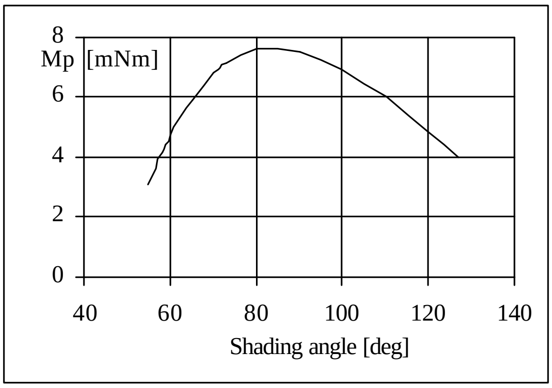

Fig. 13. Starting torque plotted against variable angle of shaded pole arc

In addition to the starting torque analysis at different angles of the shaded pole arc, it is interesting to present and to analyze the effect of the shading coil width on the starting currents in the main stator winding I_{1p} and in the shading coil I_{3p}. The calculated characteristics are presented in Fig. 14; obviously, the average value of the input starting current in the main stator winding I_{1p} is obtained exactly at the shading angle which determines the maximum values of electromagnetic torque.

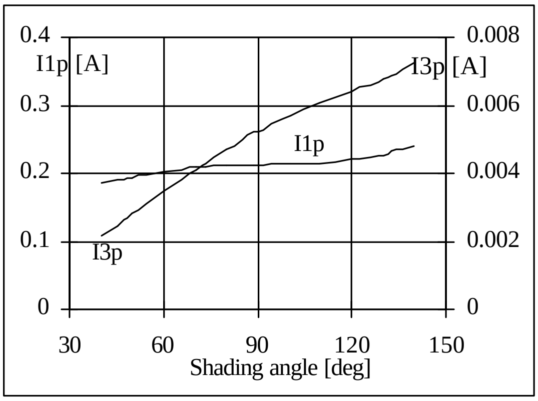

Fig. 14. Starting currents in both stator windings plotted against variable angle of the shaded pole arc

CONCLUSION

In this paper a mathematical model for calculation of shaded-pole motor performance characteristics based on the circuit and finite element model is presented. By using the method of symmetrical components in a relatively simple and fast way the performance characteristics are calculated. The obtained results are compared with experimentally obtained ones and they show very good agreement. Additionally the effect of the shaded angle variation to the electromagnetic torque and starting currents in the stator windings is analyzed.

The accuracy of calculated characteristics is highly dependent on the proper and exact determination of the motor parameters. The application of the Finite Element Method is powerful and effective approach to this task.

In the paper all calculations are accomplished considering the fundamental harmonic only. Calculations can be expanded to the higher order harmonics, especially the third, the fifth and the seventh harmonic, so an analysis of their effect on the characteristics could be done, too. This work can serve as a guide in a later investigation.

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Author's address:

Prof. Lidija Petkovska
"Sts. Cyril & Methodius" University
Faculty of Electrical Engineering
Karpos II bb, P.O.B. 574, 1000 Skopje, Macedonia
Phone: + 389 2 399-145 Fax: + 389 2 364-262
e-mail: lidijap@cerera.etf.ukim.edu.mk