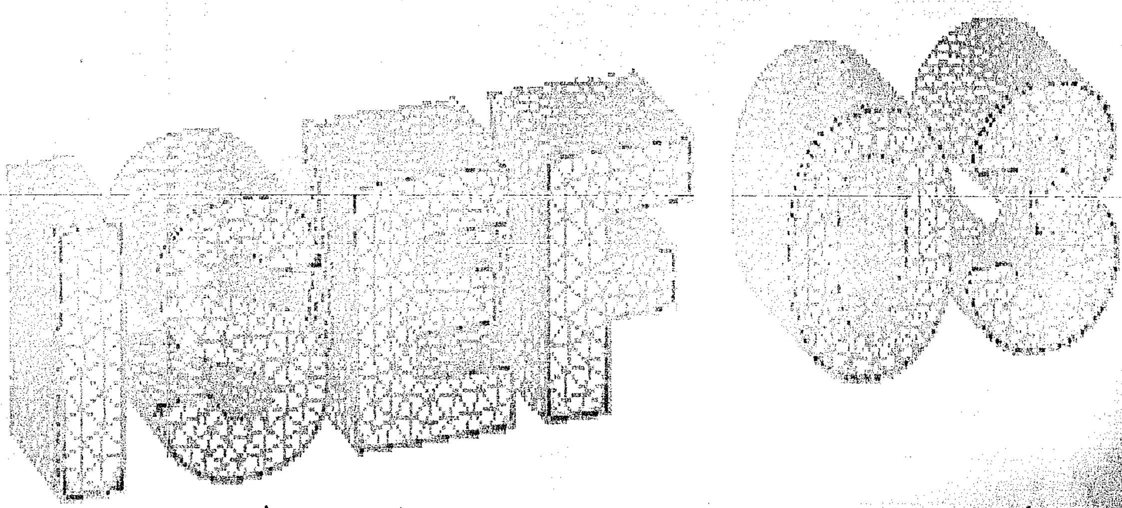
XI INTERNATIONAL SYMPOSIUM ON ELECTROMAGNETIC FIELDS IN ELECTRICAL ENGINEERING

ISEF 2003



SEPTEMBER 18-20, 2003

MARIBOR, SLOVENIA

The Symposium is organised by:

- Research group Applied Electromagnetics, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia
- University of Maribor, Slovenia
- Institute of Mechatronics and Information Systems, Technical University of Lodz, Poland
- Department of Fundamental Research, Electrotechnical Institute, Warsaw, Poland

VOLUME 1

ORAL SESSION:
ELECTROMAGNETIC ENGINEERING 2 (EE-2, Computational Techniques) [14.00-16.00]
Chairman: Prof. J. A. Tegopoulos

POSTER SESSION:
COUPLED FIELDS AND SPECIAL APPLICATIONS (CFSA) [14.00-16.00]
Chairman: Prof. A. Savini

thursday morning
thursday afternoon
friday afternoon
saturday morning

NON-LINEAR TIME HARMONIC ANALYSIS OF A SHADED-POLE MICROMOTOR

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Abstract - When analysing induction machines, considering their AC excitation, the air-gap magnetic field is always a time-varying quantity. In such case, the non-linear time harmonic analysis by using FEM (Finite Element Method) should be applied. In the paper, the results of FEA (Finite Element Analysis) of a shaded-pole micromotor, as a challenging object of investigation, are presented. An accurate calculation of the air gap flux linkage and magnetic co-energy is performed and the characteristics are presented on diagrams. The electromagnetic static torque is calculated at different currents, and its characteristic is derived and presented, as well. The numerically calculated values of static electromagnetic torque are compared with the measured ones, proving the applied FEA as quite accurate. In addition, the comparison with the analytically obtained value is presented, too. Dynamic behaviour of the motor is analysed on the basis of transient characteristics.

Introduction

The single phase shaded pole induction motor has found wide application being built-in many household devices, due to its simple construction, as well as the capability for sustaining overloading locked rotor position, since the value of short circuit current is very close to the value of rated current. Contrary to these facts, the researches found the motor as rather complicated for analysis since there exist three mutually coupled windings and elliptic rotating magnetic field. The motor under consideration is shaded-pole motor, type AKO-16, produced by "Mikron" with rated data: U_n=220V@50Hz; P_{1n}=18W; I_{1n}=0.125A; 2p=2; n_n=2520 rpm. In order to calculate electromagnetic characteristics non-linear iterative procedure is applied in time harmonic domain, meaning the supply frequency f_n=50Hz. By using nonlinear time harmonic FEM calculation, when the main stator winding is energised with currents corresponding to different loading conditions i.e. slips, while currents both in the stator shading coils and the rotor bars are induced, the magnetic field distribution in the motor is determined. The analysis of the motor behaviour is proceeding with the main performance characteristics.

Electromagnetic Field of Shaded-Pole Motor

Problem definition

The Finite Element Method is widely used for electromagnetic field calculations in electrical machines, in general. It is usually used as a non-linear magnetostatic problem which is solved in the terms of magnetic vector potential **A**. However, when analysing induction machines, considering their AC excitation, the air-gap magnetic field is always a time-varying quantity. In materials with non-zero conductivity eddy currents are induced; consequently, the field problem turns to magnetodynamic, i.e. non-linear time harmonic problem. Even more, when rotor is moving, the rotor quantities oscillate at slip frequency, quite different from the stator frequency, and the direct implementation of the non-linear time harmonic analysis is improper. The problem is solved by adjusting the rotor bars conductivity σ, corresponding to the slip. Hence, the non-linear time harmonic analysis, by using FEM, is performed at fixed stator winding supply frequency f=50Hz, while the rotor slip is changing with load. When field is time varying, in materials with non-zero conductivity eddy currents are always induced. In that case following partial equation is going to be solved numerically:

$$\nabla \times \left(\frac{1}{\mu(B)} \nabla \times A \right) = -\sigma \dot{A} + J_{src} - \sigma \nabla V \qquad (1)$$

where J_{src} represents the applied current sources. The additional voltage gradient ∇V in 2-D field problems is constant over conducting bodies. FEM considers the equation (1) for the problems in which the field is oscillating at the single (fixed) frequency; its developed form in the 2-D domain of the motor, yields the diffusion equation for time harmonic problems which FEM is actually solving:

$$\frac{1}{\mu}\frac{\partial^2 A}{\partial x^2} + \frac{1}{\mu}\frac{\partial^2 A}{\partial y^2} = -J_{src} + j\omega\sigma A \qquad (2)$$

Preprocessing - Mesh generation

In FEM preprocessing step, the shaded-pole motor geometry is modelled. Materials in all motor domains are defined, and their characteristics are input. The current sources and boundary conditions are included in the model, as well. The mesh of finite elements, consisted of 16,552 nodes and 32,667 elements is generated, and presented in Fig.1. The special attention is paid on the mesh refinement in the air gap, and a more detailed view of the mesh in this region is presented in Fig.2.

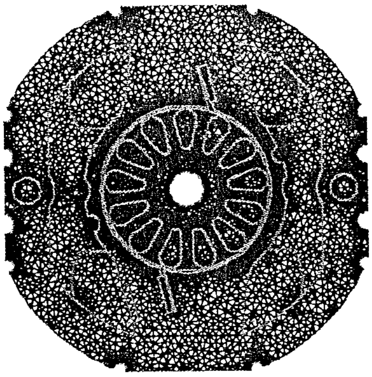


Fig.1 Mesh of finite elements in shaded-pole motor

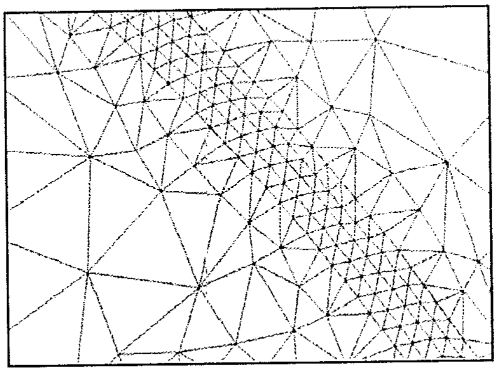
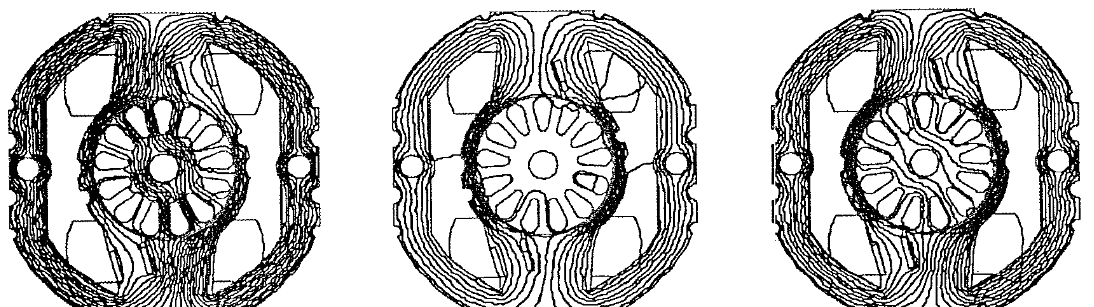


Fig.2 Detailed view of the air-gap mesh

Processing - Magnetic field problem solution

In Fig.3 the magnetic flux distribution in the middle cross section of the shaded-pole motor, at the following operating modes, is presented: (a) no load at current I_0=0.111A and slip s=0; (b) locked rotor (start-up) at current I_k=0.135A and slip s=1.0; (c) rated load at current I_n=0.125A and slip s=0.16.



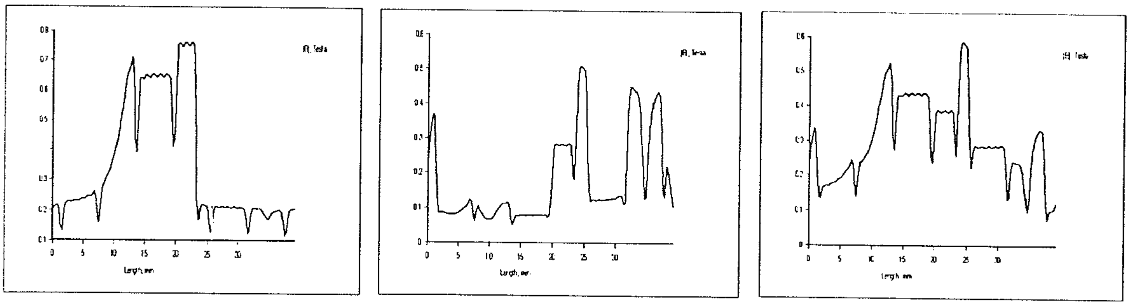
(a) no-load (b) locked rotor (c) rated load

Fig.3 Flux distribution in the middle cross-section of the shaded-pole motor

The number of flux lines in Fig.3 is selected to be proportional to the field strength, and the difference of the field intensity can be seen. In time varying magnetic problems analysis, the magnetic field is always oscillating at the arbitrary given fixed frequency (f=50Hz). Apart from the line frequency, the rotor quantities in a shaded-pole motor oscillate at slip frequency, quite different from the stator one. When applying FEM, this problem is solved by adjusting the rotor bars conductivity σ corresponding to the slip, simply by multiplying it with s. The non-linear FEM harmonic analysis offers a possibility to get "inside" the shaded-pole motor, to find the "week" parts and to improve its design features.

Postprocessing - Magnetic field analysis

In Fig.4 the spatial distribution of flux density along the middle line of the air gap, for the same operating modes as previous, is presented: (a) no load, (b) start-up (locked rotor); (c) rated load.



(a) no-load (b) locked rotor (c) rated load

Fig.4 Spatial distribution of flux density in the middle air-gap line of the shaded-pole motor

In addition, air gap flux linkage per pole and magnetic co-energy for different operating modes, are computed. For non-linear field problems the air-gap flux linkage ψ_δ per pole, when excited with W number of turns, along an integration contour c is determined numerically from the expression:

$$\psi_\delta = W \cdot \phi_\delta = \oint_c A dr \tag{3}$$

The magnetic co-energy W_c is defined as:

$$W_c = \iint \left(\int_0^H B(H) dH \right) dV \tag{4}$$

The characteristics of the air gap flux linkage and the magnetic co-energy at rated load, meaning the slip 0.16 and the current 0.125A, for different rotor positions along one half of the tooth pitch, are presented in Fig.5 and Fig.6, respectively.

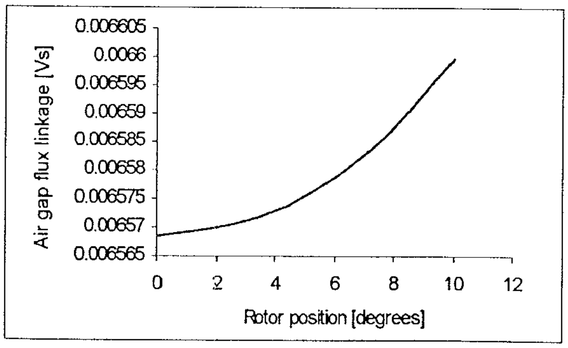


Fig.5 Air gap flux linkage for different rotor positions

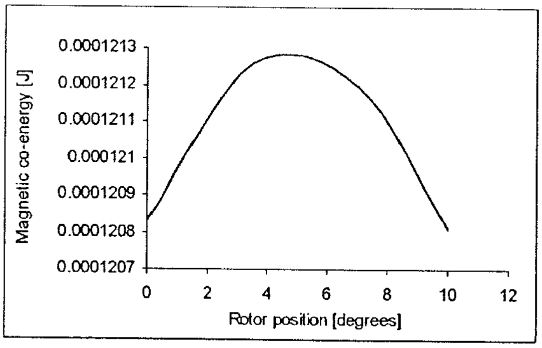


Fig.6 Magnetic co-energy for different rotor positions

Computation of electromagnetic torque

One of the most interesting parameters of the motors is always electromagnetic torque. Hence, the authors put a special attention on computation of torque and certainly,, verification of obtained results. In the previous works [1], the analytic calculation of the torque is presented in details. Here, only the results will be used for comparison.

Numerical calculation

Electromagnetic torque is calculated numerically by the electromagnetic force, via Maxwell's Stress Tensor, or via energy concept. The Maxwell Stress Method is basing on the Faraday-Maxwell theory for electromagnetic force, acting in closed surfaces. The stress tensor can be evaluated over a contour few elements away from the surface of the object - where the field solution is much more accurate. The best results are obtained by integrating along the contour a few finite elements away from any boundary or interface; as for the motor under consideration, it is previously presented in Fig.2. The torque is easily derived from the tangential component of the force, by using the following expression:

$$M_{em} = \left[\frac{r}{\mu_o} \oint_c (B_n \cdot B_t) dc \right] l_\delta \qquad (5)$$

where: B_n and B_t are normal and tangential components of the magnetic flux density; c is integration contour; r is distance of the integrating path from the centre of rotation; l_δ is axial rotor length.

Co-energy can be used in an alternative method for torque computation. To compute electromagnetic torque by using the energy concept, currents are held constant and the position of the object upon which the torque is acting (rotor), is slightly perturbed (displaced). The torque can be calculated by:

$$M_{em} = \frac{W_{c(\theta+\delta)} - W_{c(\theta)}}{\delta} \qquad (6)$$

where θ denotes the initial position of the object, usually rotor angular position, while $\theta+\delta$ is the perturbed position; δ is the magnitude of perturbation (displacement) of the rotor.

The electromagnetic torque is calculated at different currents, energizing the main stator winding, corresponding to different slips, i.e. loading conditions. Currents in the stator shading coil, as well as in the rotor bars are induced, as eddy currents. The rotor slip frequency is introduced by multiplying rotor bars conductivity σ with the respective slip value. The torque-speed characteristic at constant current is presented in Fig.7. Characteristic is achieved by applying rated current at main stator winding , while current in shaded coil is induced. Currents in rotor bars are induced for different slips.

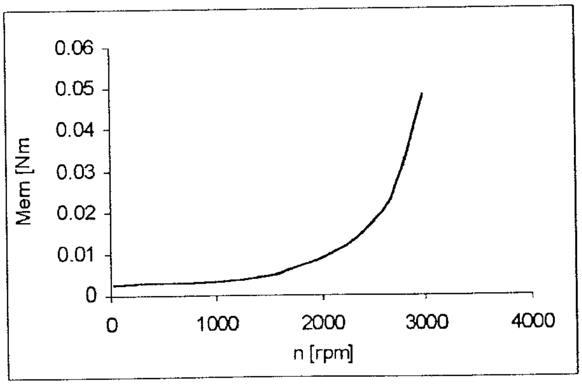


Fig.7 Constant current torque-speed characteristic

Transient performance simulation

By creating simulation model of the shaded-pole motor in the software package SIMULINK for MATLAB, the transient characteristics of electromagnetic torque [Nm] and speed [rpm] during motor start-up and free acceleration are derived and presented in Fig.8 and Fig.9, respectively.

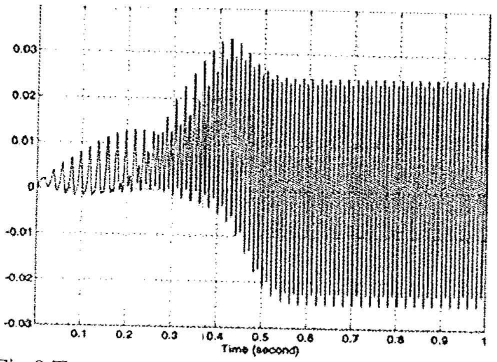


Fig.8 Torque transient performance characteristic

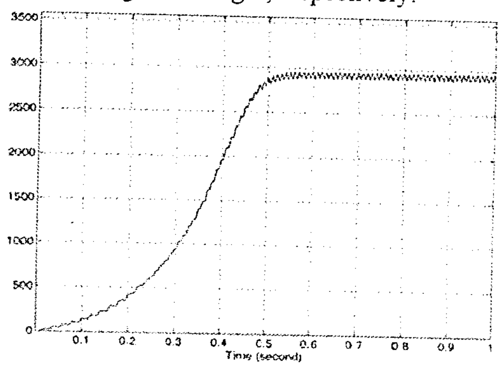


Fig.9 Speed transient performance characteristic

In order to obtain the simulated torque-slip characteristic, series of simulations at different loading torque have been done. After the transients are suppressed, the speed i.e. slip is obtained, and one point of the static torque curve is determined.

Comparative analysis

The comparative characteristics M_{em}=f(s) calculated by using different methods, as analytic circuit theory method, numerical FEM and transient simulation method, are presented in Fig.10. Some of the most interesting values are extracted and given in Table I, as well.

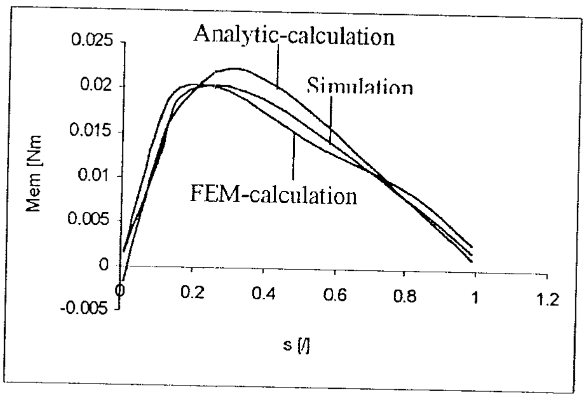


Fig.10 Comparative torque-slip characteristics

TABLE I. Torque results by different methods

Electromagnetic torque M_{em} [Nm]			
s [/]	FEM	Analytic	Simulation
0.01	0.0017808	0.001625	0.00167
0.10	0.0156608	0.012647	0.01141
0.16	0.0199774	0.018075	0.01890
0.30	0.0196288	0.022175	0.02023
0.50	0.0147680	0.018423	0.01639
0.80	0.0088368	0.008042	0.00800
0.99	0.0028912	0.001809	0.00200

Values of electromagnetic torque at rated slip (s=0.16) obtained by FEM, analytic calculation and simulation, are compared with values obtained from experiment, and presented in Table II. The error of computed torque from FEM, analytic method and simulation method, compared to the experimentally obtained value is 4.87%, 13.9 %, and 10% respectively, showing reasonable agreement and proving the FEM model as the most accurate. The values of air-gap flux obtained numerically and analytically are also given. Using FEM, the losses in the iron core sections of the motor are determined. This feature is especially useful for calculation of iron losses in harmonic problems considering that their exact calculation by using analytic methods is quite difficult and not sufficiently accurate.

TABLE II. Comparative results at rated slip s=0.16

Quantity	FEM	Analytic	Simulation	Experiment
Electromagnetic torque [Nm]	$19.977\cdot10^{-3}$	$18.075\cdot10^{-3}$	$18.9\cdot10^{-3}$	$21\cdot10^{-3}$
Air-gap flux per pole [Vs]	$2.2704\cdot10^{-4}$	$2.5574\cdot10^{-4}$	/	/
Iron losses [W]	5.891	4.84	/	6.24

From the comparison between the numerically and analytically calculated values for air-gap flux per pole the difference of 12.6% is evident. The lack of accuracy in analytical methods, certainly proves the FEM as the best approach to deepened complex field analysis of the motor. Especially, when the field problems are considered as magneto-dynamic, particular computations regarding the eddy currents and iron losses are performed. These quantities are almost impossible to be calculated or experimentally measured, so the FEM calculations are the best way for their determination.

Conclusion

Non-linear time harmonic analysis is carried out on a single phase shaded pole micromotor by using magneto-dynamic FEM. Although this special type of motor is well known for its simple construction, a complexity of its analysis arises from the existence of three magnetically coupled windings and elliptic rotating field in the motor air gap. Hence, the analytic calculations are improper, and the desired accuracy of the results can be achieved by numerical methods, only. The FEM has already found a wide range of applications and is proved to be the most accurate. From the flux plots and magnetic field distribution the motor inside can be "viewed", enabling to find week parts i.e. areas with high saturation. For this type of motor, stator bridges have been proven to be areas with high saturation; but, their existence is obvious, because they contribute toward improvement of magnetic field wave form by reducing the third space field harmonic, and consequently, improving the motor characteristics. The numerically calculated static electromagnetic torque, at rated slip s=0.16, is compared with the measured value, proving the FEM analysis as quite accurate. FEM enables also evaluation of air gap flux linkage as well as magnetic co-energy in machine air gap, quantities which are difficult to be measured or calculated by analytic methods.

Further research will be focused on determination of motor inductances using different approaches. As it is known, the analytic calculation of motor inductances is always with certain approximations, and for that reason FEM will be applied for their accurate calculation.

References

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