Acemp 2004

International Aegean Conference on
Electrical Machines and Power
Electronics

26 - 28 MAY 2004

İSTANBUL - TÜRKİYE

ACEMP 2004

International Aegean Conference
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Dynamic Evaluation of Shaded Pole Motor Models Optimised by Using Method of Genetic Algorithm

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Abstract

In this paper, an extended analysis of three different models of a single phase shaded pole motor is carried out. Starting with a basic model, and by using the well established optimisation method of Genetic Algorithm (GA), two optimised motor models are derived. A special emphasis is put on the development of appropriate models of the shaded pole motor for application of particular analysing method. The magnetic field analysis is based on the application of Finite Element Method (FEM). The optimised motor models show improvements regarding the saturation of particular parts of the magnetic core. The dynamic analysis of the motor is performed on the basis of the dynamic characteristics determined by using Matlab/SIMULINK Method (MSM). From this analysis, the shaded pole motor basic model and two new derived optimised models, are discussed and evaluated.

1 Introduction

In the paper is analysed a model of a small single phase shaded pole motor, with rated data: U_n=220 V; f_n=50 Hz; I_{1n}=0.125 A; P_{1n}=18 W; n_n=2520 rpm; 2p=2. The arrangement of the motor magnetic cores and windings is presented in Figure 1.

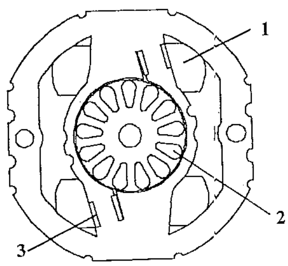


Figure 1: Cross-section of the shaded-pole motor

At the beginning, the complex performance analysis [1],[2] is carried out on the original motor, adopting it as basic model - BM. The mathematical model is developed by an application of the revolving field theory. Accuracy of the shaded pole motor model is thoroughly examined and verified by experiments.

Afterwards, the method of Genetic Algorithm (GA) is applied for optimisation of the initial motor model. The authors suggest as the most interesting target functions of optimisation to be considered: the electromagnetic torque and the efficiency factor [4].

The analysis of the motor models is proceeding with analytical calculation of their performance characteristics. By using the time harmonic FEM, magnetic flux distribution in the middle cross section of the models is computed and presented.

Dynamic analysis is carried out basing on transient characteristics for the three motor models, simulated by using Matlab/SIMULINK Method (MSM). Comparative dynamic analysis of the motor models is presented; an evaluation of improvements and advantages for two optimised models is done.

2 Optimisation by Method of GA

2.1 Optimisation Procedure

At the design stage of an electric motor, all efforts are focused to the achievement of desired motor features in faster, more economical and more reliable way. The main task of optimization procedure is to improve its performance characteristics by simple modifications. The optimization procedure is always searching for an extreme of the function: maximum or minimum of its value. In order to provide the derived solution to be practically acceptable, certain requirements should be satisfied; that means some important electrical or magnetic quantities, such as windings current density Δ [A/mm^2], or the air-gap magnetic flux density B_δ [T], must have values inside the prescribed limits. During optimization procedure the main task is to define and to select the most suitable target (objective) function of optimization.

As the most interesting, two different target functions are introduced [4]:

- Knowing that electromagnetic torque is one of the most important quantities of the motors, the first idea is to use its value as target function; the derived optimal model will be model 1 – M1.
- The efficiency factor of electric motors, through minimization of losses, is always aiming towards greater values; naturally, other interesting target function is the efficiency factor; the derived optimal model will be model 2 – M2.

It is obvious that definition and selection of two target functions in such way, means that searching for an extreme of function is always a maximizing problem. In the both cases variable parameters of the optimization procedure are accepted to be: current density of the main stator winding Δ [A/mm^2]; wire diameter of the winding d_{Cu} [mm]; number of turns of main winding W; air-gap magnetic flux density B_δ [T]; angle of the rotor skewing α_{sk} [^{0}].

Basing on experience and skills, as well as the expected results, the variation of the most important variables is placed in the following constraints: the current density in stator winding Δ=5÷10 [A/mm^2]; the air-gap magnetic flux density B_δ=0.4÷0.45 [T]; the angle of rotor skewing α_{sk}=15÷20 [^{0}].

2.1 Optimisation Results

After the optimization procedure is completed, the results are presented in tables and on diagrams.

In Table 1. the most important output parameters of a shaded pole motor are presented comparatively.

In Table 2. the comparison of motor performance characteristics, at rated load conditions, meaning at slip s=0.16 for BM, and the two new derived models M1 and M2, is presented.

Table 1. Comparison of main motor parameters

BM	M1	M2
Δ=8 [A/mm^2]	Δ=5.346 [A/mm^2]	Δ=5.17 [A/mm^2]
B_δ=0.404 [T]	B_δ=0.449 [T]	B_δ=0.40035 [T]
α_{sk}=17 [^{0}]	α_{sk}=15 [^{0}]	α_{sk}=15 [^{0}]
d_{Cu}=0.14 [mm]	d_{Cu}=0,2 [mm]	d_{Cu}=0,18 [mm]
W=3488 turns	W=3132 turns	W=3520 turns
R_1=492.98 Ω	R_1=243.44 Ω	R_1=330.51 Ω
X_1=498.17 Ω	X_1=410.15Ω	X_1=515.83 Ω
R_2=497.04 Ω	R_2=362.58 Ω	R_2=457.99 Ω
X_2=76.71 Ω	X_2=61.85Ω	X_2=78.12 Ω
R_3=18,474 Ω	R_3=14895 Ω	R_3=18814 Ω
X_3=127.53 Ω	X_3=102.83 Ω	X_3=129.87 Ω
X_{12}=2163.3 Ω	X_{12}=1744 Ω	X_{12}=2202 Ω
X_{13}=175.91 Ω	X_{13}=141.84 Ω	X_{13}=179.13 Ω

Table 2. Comparison of motor performance characteristics

Quantity	BM	M1	M2
Stator current I_1 [A]	0.126	0.168	0.131
Shaded coil current I_3 [A]	0.0063	0.0083	0.0065
Rotor current I_2 [A]	0.0878	0.1175	0.092
Power factor cosφ [/]	0.654	0.586	0.592
Input power P_1 [W]	18.11	21.63	17.14
Output power P_2 [W]	4.149	6.177	4.731
Efficiency factor η [/]	0.229	0.285	0.276
Torque M_{em} [mNm]	18.075	25.76	20.28

The result of GA optimization is lower current density in the main stator winding in both new derived models of the motor. This fact leads to greater diameter of winding wire, resulting in lower resistance of the stator and rotor windings; finally, currents, and consequently the static torque, as well as the output power, are increased.

For better understanding the behavior of all shaded pole motor models, comparative performance characteristics of electromagnetic torque M_{em}=f(s), efficiency factor η=f(s) and the main stator winding current I_1=f(s), are presented in Figures 2, 3 and 4.

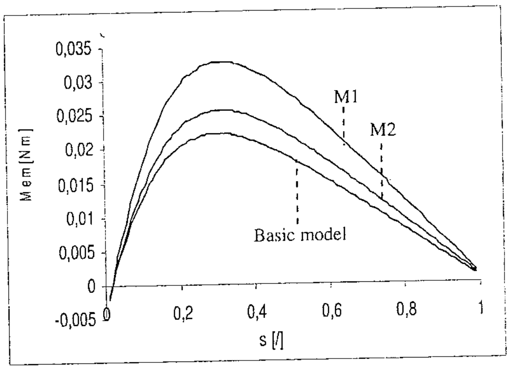


Figure 2: Comparative characteristics M_{em}=f(s)

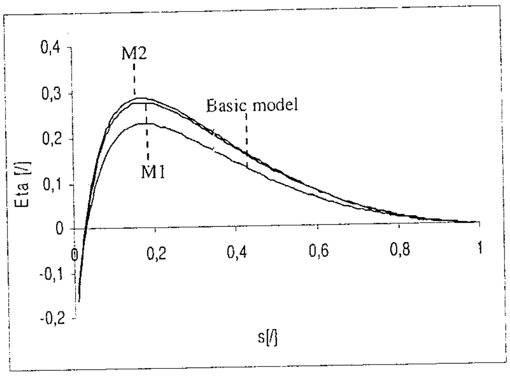


Figure 3: Comparative characteristics η=f(s)

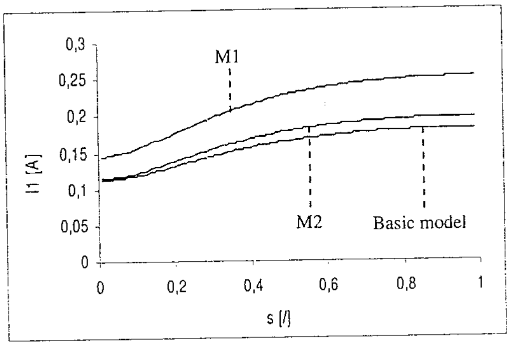


Figure 4: Comparative characteristics I_1=f(s)

3 FEM Analysis of Motor Models

3.1 Magnetic Field Computation

The best way to get inside the motor under consideration and to "see" the magnetic field distribution in the shaded-pole motor is to apply the Finite Element Method. This method is widely used as a powerful numerical tool for electromagnetic field computation and analysis of electrical machines.

By using this contemporary method it is possible to determine the exact value of the magnetic flux density (B) in each particular part of the motor's cross-section, allowing the "week" parts of magnetic core to be uncovered; afterwards the necessary improvements in the design can be done.

The most frequently, FEM is used as non-linear magnetostatic case problem, 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, considered as non-linear time harmonic problem. Even more, when rotor is moving, its quantities oscillate at slip frequency; quite different from the stator frequency; the direct implementation of the non-linear harmonic analysis isn't correct. The problem is solved by adjusting the rotor bars conductivity σ, corresponding to the slip. Hence, the non-linear harmonic analysis, by using FEM, is performed at fixed supply frequency f=50Hz in the stator windings, while the rotor slip is changing with load [1].

The most useful results obtained by FEM, are certainly at rated rotor speed n_r=2520 rpm, defining the rated slip s=0.16. The magnetic field distribution in this case, in the middle cross section of the basic model - BM of the shaded pole motor, and the two optimised models, is presented in Figures 5, 6 and 7, respectively. As can be seen from the figures, the peak-value of the flux density, corresponding to the weakest point in the motor's cross section is significantly decreasing in the new derived models, in comparison to the basic model. Maximum values of the flux density for all three models are:

- Basic model - BM: $B_{max} = 2.0833$ [T]
- Model 1 – M1: $B_{max} = 1.8389$ [T]
- Model 2 – M2: $B_{max} = 1.8145$ [T]

Lower values of the flux densities are certainly more desirable, since the saturation of magnetic core in critical parts such as magnetic bridges is avoided, and the core losses are decreasing with its square.

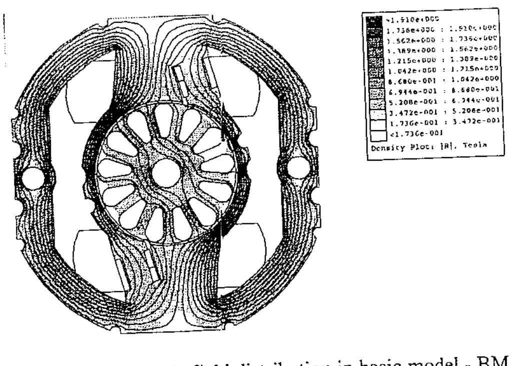


Figure 5: Magnetic field distribution in basic model - BM

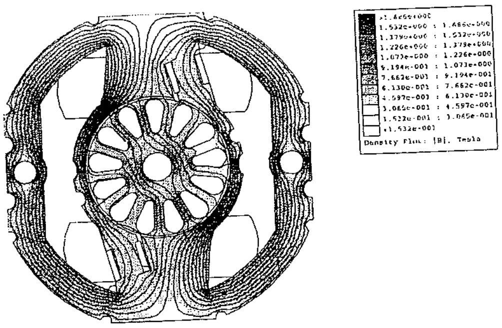


Figure 6: Magnetic field distribution in model 1 – M1

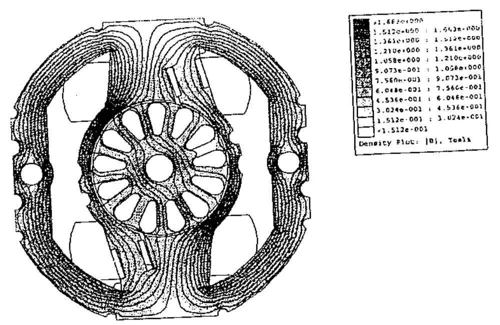


Figure 7: Magnetic field distribution in model 2 – M2

4 Dynamic Performance Characteristics

4.1 Simulink Model

Matlab/SIMULINK is widely known and accepted simulation tool which enables to display and to analyse dynamic performance characteristics. When simulation methods are used, main emphasis has to be stressed on development the proper mathematical model, which will represent physical phenomena as close as possible. The derived simulation model of the shaded pole motor, suitable for implementation in Matlab/SIMULINK software tool [4], bases on d,q transformation known from the reference frame theory of single phase induction machines.

Two phase fictitiuos power supply of main stator winding is modelled by using following equations:

$$U_{qs} = U_{as}\cos\theta + U_{bs}\sin\theta \qquad (1)$$

$$U_{ds} = U_{as}\sin\theta - U_{bs}\cos\theta \qquad (2)$$

The special position of the shading ring axis – b, according to the reference axis of the main stator winding – a, is taken into account by introducing the corresponding phase shift between voltages U_{as} and U_{bs}, which in this case is found to be 43.4 [^{0}].

In order to develop the simulation motor model, voltage equations of all stator and rotor circuits are to be rearranged in the terms of motor currents and parameters: resistances and inductances of all motor windings, as well as the mutual inductances between all stator and rotor circuits.

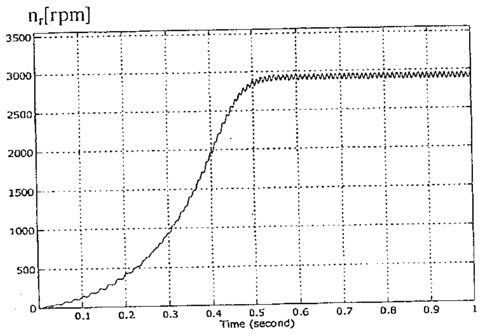
The simulation model is completed when rotor movement equation is added:

$$\frac{d\omega_r}{dt} = \frac{P^2 L_{mq}}{4J}\left(i_{dr}^{'s} i_{qs} - i_{qr}^{'s} i_{ds}\right) - \frac{P}{2J} M_s \qquad (4)$$

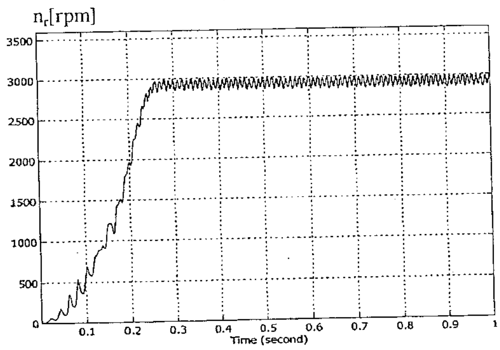
where J is inertia constant and M_S is load torque.

4.2 Dynamic Characteristics

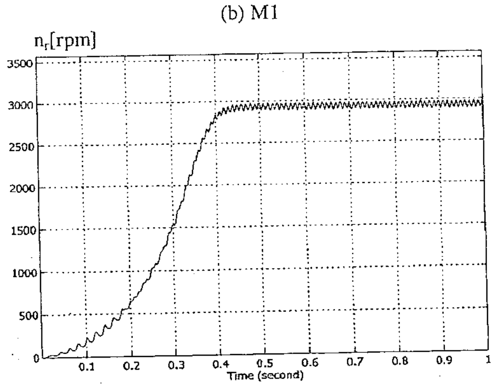
By substitution of parameters adequate for BM, M1 and M2 in the simulation model of the shaded pole motor, the dynamic characteristics are simulated and displayed on diagrams. In Figures 8, 9 and 10, are presented the characteristics during free acceleration, as follows: speed n_r=f(t), torque M_{em}=f(t) and current I_1=f(t), respectively; (a) is linked to the basic model, (b) to the model 1 and (c) to the model 2.



(a) BM

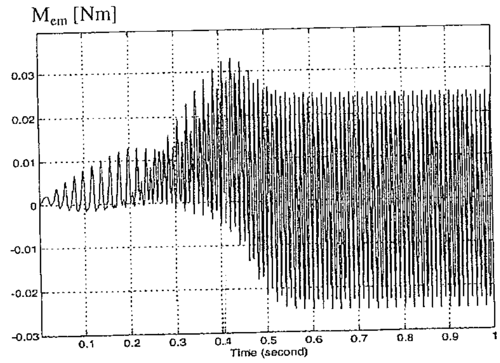


(b) M1

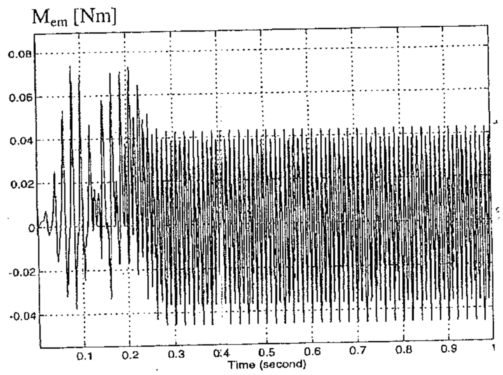


(c) M2

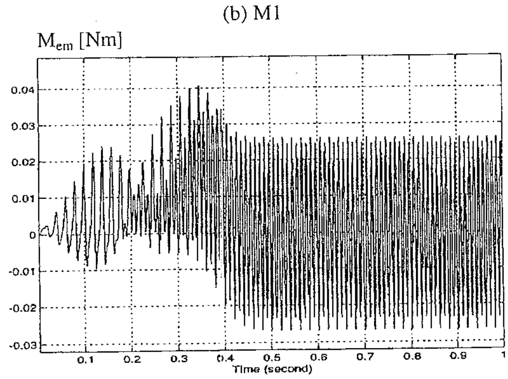
Figure 8: Rotor speed n_r=f(t) at free acceleration



(a) BM

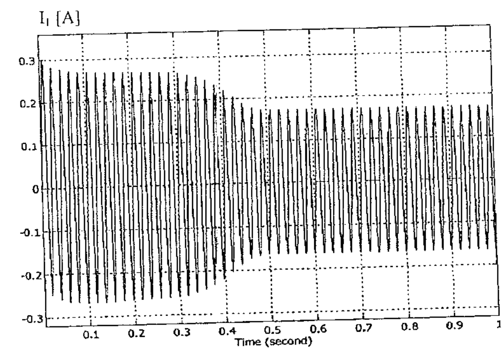


(b) M1

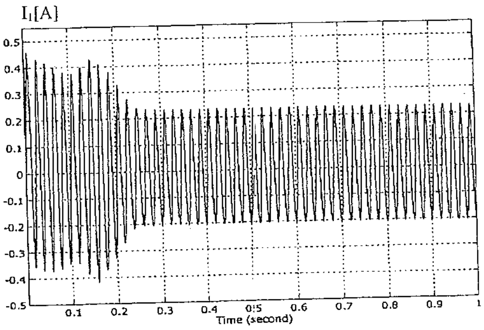


(c) M2

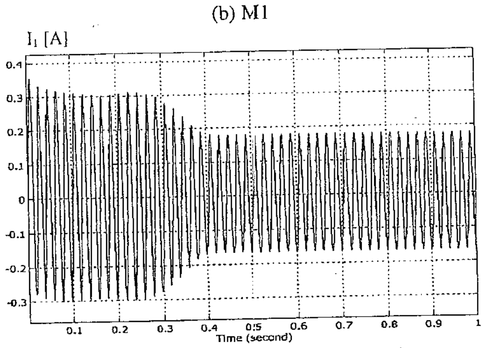
Figure 9: Torque M_{em}=f(t) at free acceleration



(a) BM



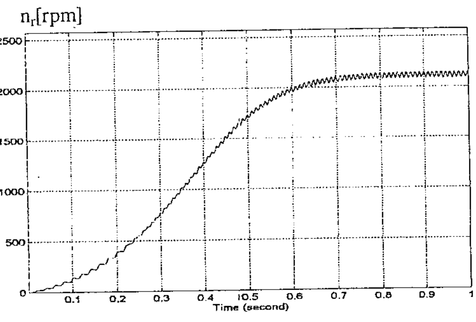
(b) M1



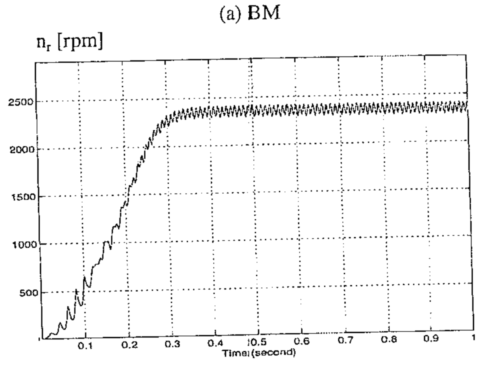
(c) M2

Figure 10: Current I_1=f(t) at free acceleration

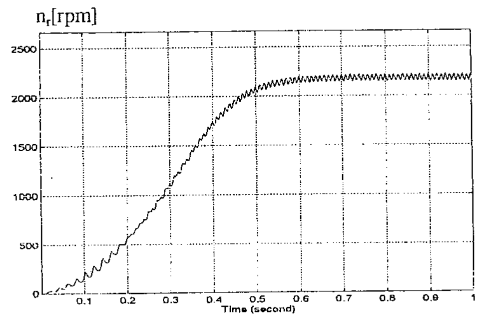
As the shaded pole motor is mainly assigned for fan driving, which load torque is considered to be $M_s=k\cdot n^2$, the next task is to simulate and to analyse starting characteristic at rated load.



(a) BM

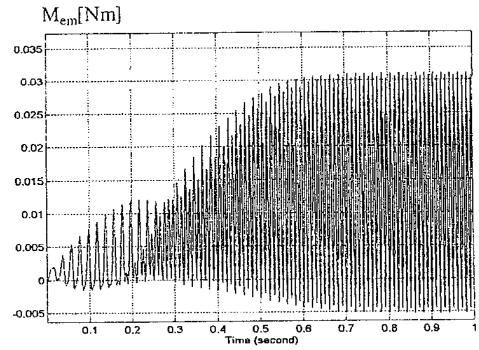


(b) M1

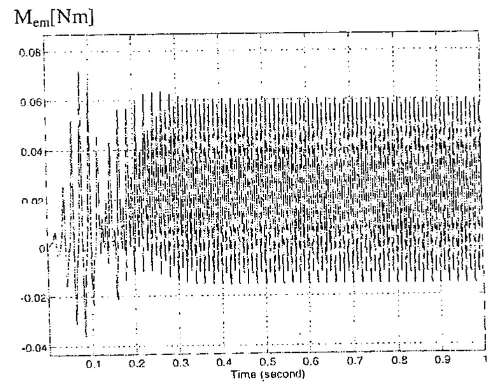


(c) M2

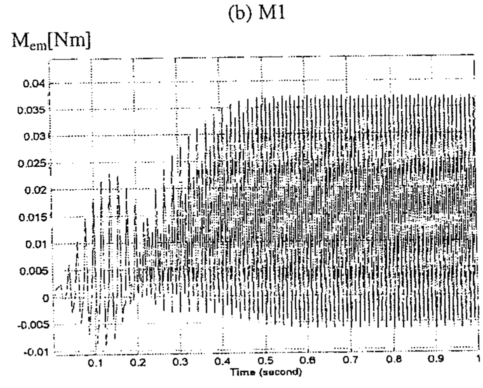
Figure 11: Rotor speed n_r=f(t) at rated load start-up



(a) BM

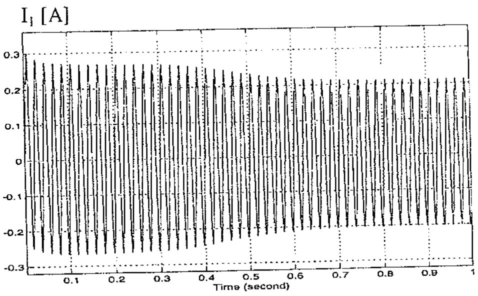


(b) M1

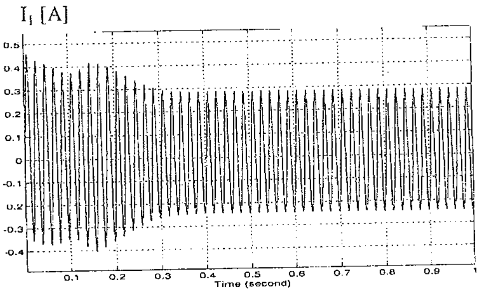


(c) M2

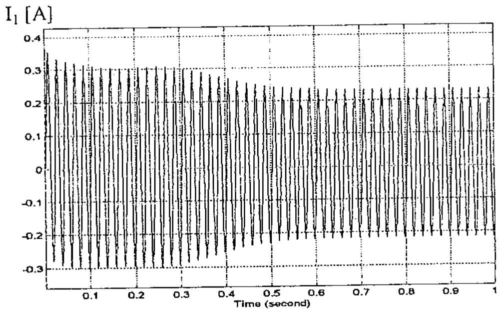
Figure 12: Torque M_{em}=f(t) at rated load start-up



(a) BM



(b) M1



(c) M2

Figure 13: Current I_1=f(t) at rated load start-up

In Figures 11, 12, and 13, the characteristics of speed n_r=f(t), torque M_{em}=f(t) and current I_1=f(t), at rated load start-up, are presented respectively; (a) is linked to the BM, (b) to the M1 and (c) to the M2.

4.3 Comparative Dynamic Evaluation

From the comparison of Figures 8 and 11 it is clearly shown that under rated loading conditions acceleration time in all the models is increasing, while the steady state speed is decreasing up to rated speed. Consequently the stator current and electromagnetic torque are of the greater value. After transients are suppressed, the static motor torque can be obtained. The torque-slip characteristics derived from the simulation models for the three motors are presented in Figure 14. As it can be expected Model 1 has the greatest torque compared to other two ones.

In addition, a comparison of stator current and rotor speed, determined from the simulations and by analytical calculations, for the two typical operating regimes, is presented in Table 3.

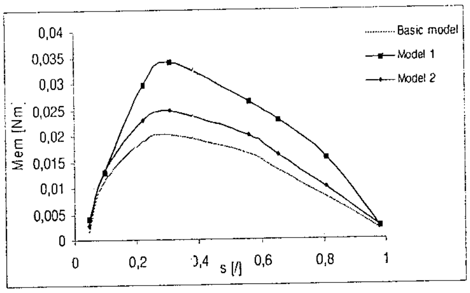


Figure 14: Simulated characteristics M_{em}=f(s)

Table 3. Comparison of current and speed

	Basic model	Model 1	Model 2
Stator current [A] at no-load			
Simulation	0.120	0.165	0.126
Analytical	0.113	0.146	0.115
Stator current I_1 [A] at rated load			
Simulation	0.141	0.190	0.148
Analytical	0.126	0.168	0.132
Rotor speed n_r [rpm] at no-load			
Simulation	2950	2980	2950
Analytic calc.	2910	2910	2910
Rotor speed n_r [rpm] at rated load			
Simulation	2100	2400	2250
Analytical	2520	2520	2520

5 Conclusion

Using GA as an attractive stochastic optimization method, and starting from basic shaded pole motor model, two new models, with two different target functions are obtained. In M1 the torque is increased for 30% and in M2 the efficiency is increased for 17%. Magnetic field calculations by FEM, show that in the new optimal models, the flux density is lower; this is more desirable with respect to the iron loss.

Dynamic analysis of the motor is carried out with models developed in Matlab/SIMULINK. From the torque-slip characteristics, it is evident that the best torque value appears in M1, the comprehensive and expected fact, considering that it is derived by using torque as target function. The new M2 has still better torque value than the basic model. New models have improved performance and dynamic characteristics.

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