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DYNAMIC EVALUATION OF SHADED-POLE MOTOR MODELS OPTIMIZED BY USING THE METHOD OF GENETIC ALGORITHMS

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Abstract- In the paper, a dynamic evaluation of three single-phase shaded-pole induction motor models is presented. At the beginning, using analytical approach with symmetrical components, a mathematical model for the basic model is developed. Accuracy of the model is verified by an experiment. Afterwards, using the Method of Genetic Algorithms and introducing as target functions electromagnetic torque and efficiency factor, two improved motor models are derived. Basic model and also the two new derived models are analyzed by using the Finite Element Method in time-harmonic domain. By developing a general simulation model of a shaded-pole motor, and applying it in Matlab/Simulink, dynamic performance characteristics of all motor models are obtained. Comparative dynamic analysis for the three motor models is carried out, proving the advantages and improvements of new optimized motor models.

1. INTRODUCTION

In the paper, 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 is analyzed. The arrangement of the motor magnetic core and windings is presented in Fig. 1.

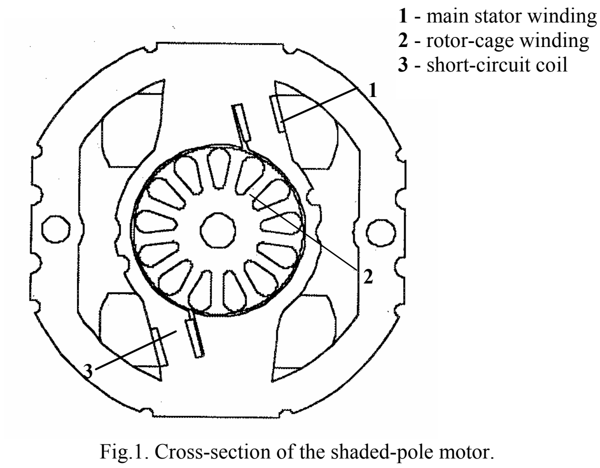


Fig.1. Cross-section of the shaded-pole motor.

At the beginning, the complex performance analysis 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 [1]. Accuracy of the shaded-pole motor model is thoroughly examined and verified by experiments.

Afterwards, the method of Genetic Algorithm (GA) is applied for optimization of the initial motor model. The authors suggest as the most interesting target functions of optimization to be considered: the electromagnetic torque and the efficiency factor [2].

The analysis of the motor models is achieved with numerical 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 based 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 optimized models is done.

2. OPTIMIZATION BY THE METHOD OF GENETIC ALGORITHMS

A. *Optimization 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:

• 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}]. Ranges of variation of input parameters are defined in separate input file which is an integral part of the originally developed software program GA-ODEM which operates under C++ programming language. In second file which is by software means linked to input file motor mathematical model is input which enables calculation of target functions. The program is adjusted to create 6000 generations of each varied parameter and as an output program GA-ODEM gives a set of most favorable values of varied parameters with which is achieved the largest target function.

B. Optimization results

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

In Table 1, 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.

In Table 2, the most important output parameters are presented comparatively at rated slip.

Table 1
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

Table 2
Comparison of 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

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.

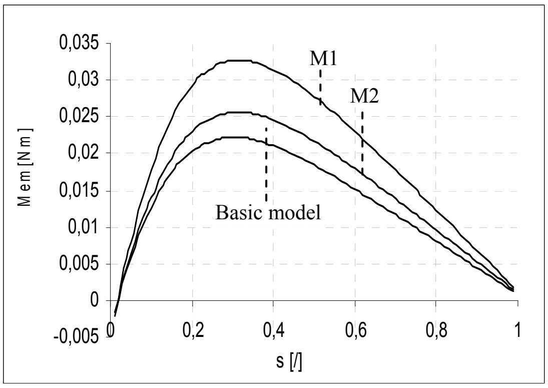


Fig. 2. Comparative characteristics M_{em}=f(s).

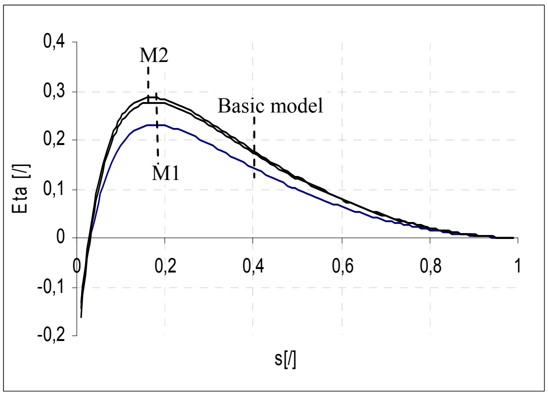


Fig. 3. Comparative characteristics η=f(s).

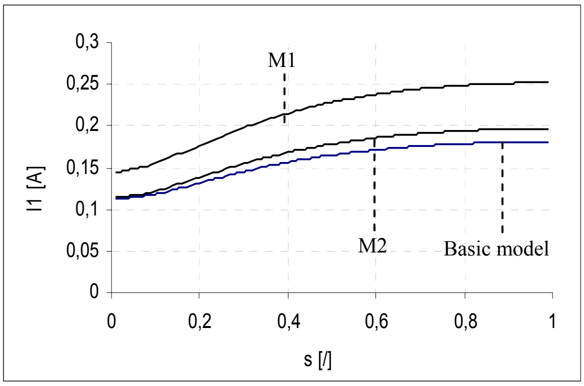


Fig. 4. Comparative characteristics I_1=f(s).

3. FINITE ELEMENT ANALYSIS OF MOTOR MODELS

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 (FEM). 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.

Electromagnetic field calculation is usually a non-linear magnetostatic problem which is solved in the terms of magnetic vector potential **A**. However, when analyzing 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 are oscillating 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 current supply frequency f=50Hz, while the rotor slip is changing with load. 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:

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

Corresponding to the compound configuration of the motor, both in electrical and magnetic sense, and taking into consideration the particular meaning of the slip *s*, a motor model suitable for FEM application is derived [3]. Exact motor geometry is input in software pre-processing part and materials in complete motor cross-section are defined. Calculations of magnetic flux distribution as well as magnetic flux density are preformed taking into consideration the magnetic material non-linearity. Boundary conditions are defined and in this case are chosen to be Dirichlet boundary conditions **A**=0. In each motor domain mesh density is defined by the program user. Subprogram femm.exe gives as output mesh of finite elements. In Fig. 5 is presented mesh in BM consisted of N=16549 nodes and E=32447 elements.

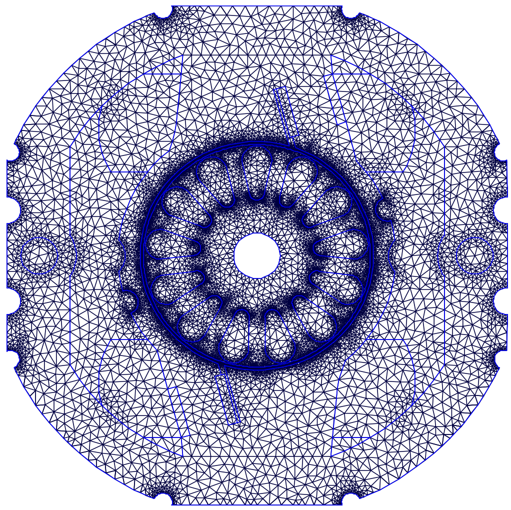


Fig. 5. Finite element mesh in the motor cross-section.

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 optimized models, is presented in Figures 6, 7 and 8, 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.

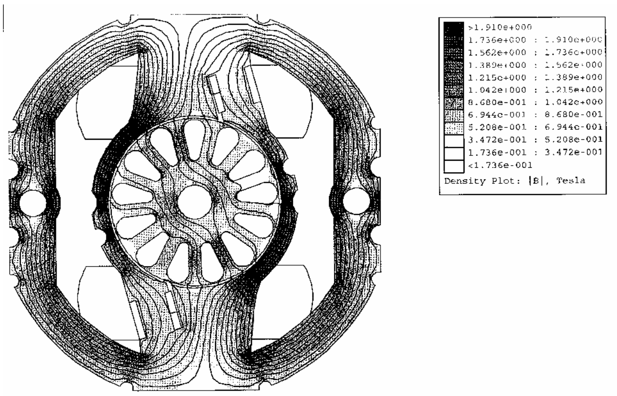


Fig. 6. Magnetic field distribution in basic model – BM.

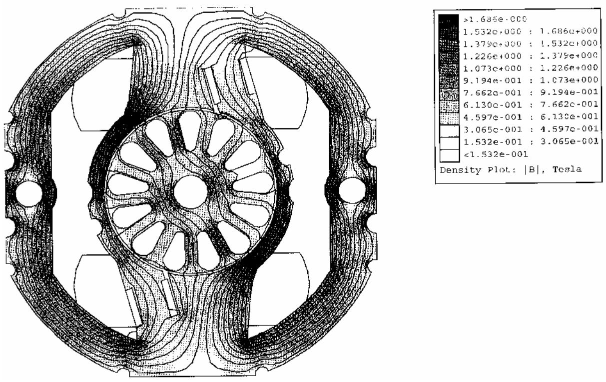


Fig. 7. Magnetic field distribution in model 1 – M1.

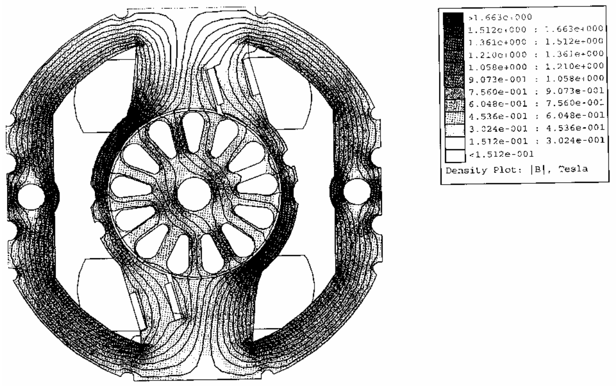


Fig. 8. Magnetic field distribution in model 2 – M2.

FEM software enables the rotation of rotor by grouping all elements from rotor circuit into one group and moving the corresponding group for arbitrary angle. Magnetic filed distribution in Figures 6,7 and 8 is presented for rotor 0° degree position.

4. DYNAMIC PERFORMANCE CHARACTERISTICS

A. 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:

$$U_{qs} = U_{as}\cos\theta + U_{bs}\sin\theta \tag{3}$$

$$U_{ds} = U_{as}\sin\theta - U_{bs}\cos\theta \quad . \tag{4}$$

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.

$$\begin{aligned}
i_{qs} &= \frac{1}{L_{lqs}+L_{mq}}\int U_{qs} - \frac{r_{qs}}{L_{lqs}+L_{mq}}\int i_{qs} - \frac{L_{mq}}{L_{lqs}+L_{mq}} i_{qr}^{'s} \\
i_{ds}^{'} &= \frac{1}{L_{lds}^{'}+L_{mq}}\int U_{ds}^{'} - \frac{r_{ds}^{'}}{L_{lds}^{'}+L_{mq}}\int i_{ds}^{'} - \frac{L_{mq}}{L_{lds}^{'}+L_{mq}} i_{dr}^{'s} \\
i_{qr}^{'s} &= \omega_r\int i_{dr}^{'s} + \frac{\omega_r L_{mq}}{L_{lr}^{'}+L_{mq}}\int i_{ds}^{'} - \frac{r_r^{'}}{L_{lr}^{'}+L_{mq}}\int i_{qr}^{'s} - \frac{L_{mq}}{L_{lr}^{'}+L_{mq}} i_{qs} \\
i_{dr}^{'s} &= -\omega_r\int i_{qr}^{'s} - \frac{\omega_r L_{mq}}{L_{lr}^{'}+L_{mq}}\int i_{qs} - \frac{r_r^{'}}{L_{lr}^{'}+L_{mq}}\int i_{dr}^{'s} - \frac{L_{mq}}{L_{lr}^{'}+L_{mq}} i_{ds}^{'}
\end{aligned} \tag{5}$$

r_{qs}, r'_{ds} and r'_r are resistances of main winding, short circuit coil and rotor, winding respectively. L_{lqs}, L'_{lds}, L'_{lr} and L_{mq} are inductances of main winding, short circuit coil, rotor winding and mutual inductance between stator and rotor circuits. In (4) parameters of short circuit coil and rotor winding are referred to main stator winding.

In order simulation model to be complete it is necessary to add the equation for electromagnetic torque:

$$M_{em} = J\left(\frac{2}{P}\right)\frac{d\omega_r}{dt} + M_s \tag{6}$$

where: J is constant of inertia, M_S is load torque, P is number of pair of poles.

On the other hand electromagnetic torque can be found from:

$$M_{em} = \frac{P}{2} L_{mq}\left(i_{dr}^{'s} i_{qs} - i_{qr}^{'s} i_{ds}^{'}\right). \tag{7}$$

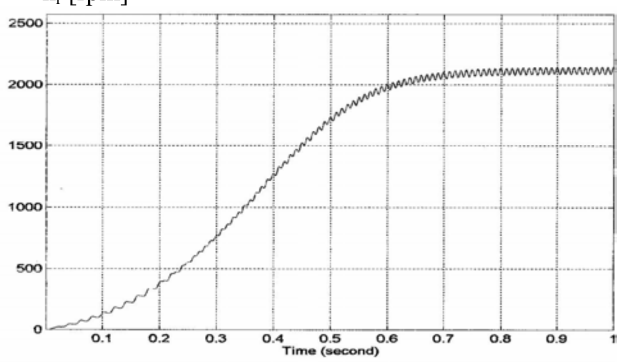
From (5) and (6) can be derived:

$$\frac{d\omega_r}{dt} = \frac{P^2 L_{mq}}{4J}\left(i_{dr}^{'s} i_{qs} - i_{qr}^{'s} i_{ds}^{'}\right) - \frac{P}{2J} M_s \,. \tag{8}$$

Eqs. (5) and (8) are used to simulate transient performance characteristics of the shaded-pole motor, i.e to develop Simulink motor model.

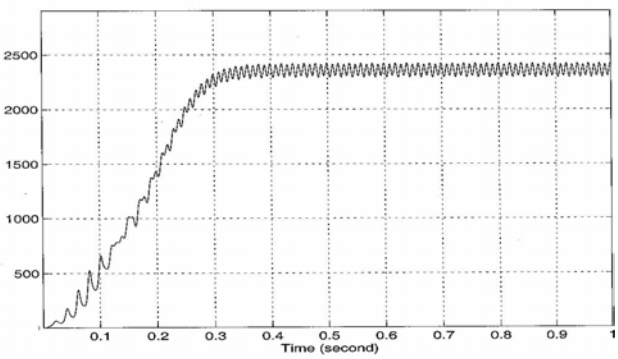
As the motor is assigned for fan driving, having the static torque characteristic $Ms=k \cdot n_r^2$, the start-up transient characteristics at rated load are presented in Figs. 9, 10 and 11. Performance characteristics at rated load are obtained by involving the feed-back link in Simulink motor model per rotor speed n_r. Constant k is obtained form intersection of characteristic Mem=f(s) and load characteristic of fan for all three motor models. This motor operational point is the most interesting taking into consideration that optimization procedure was performed for rated load operational point.

n_r [rpm]



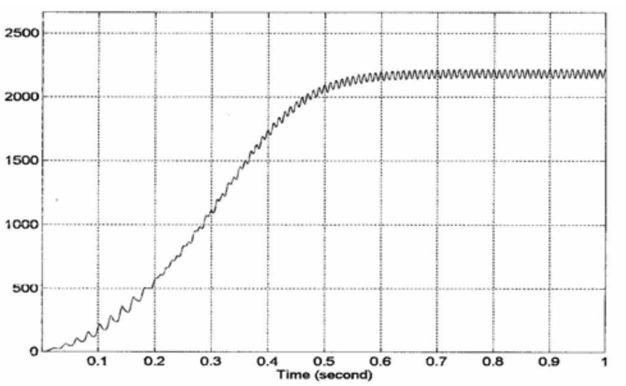
(a) BM

n_r [rpm]



(b) M1

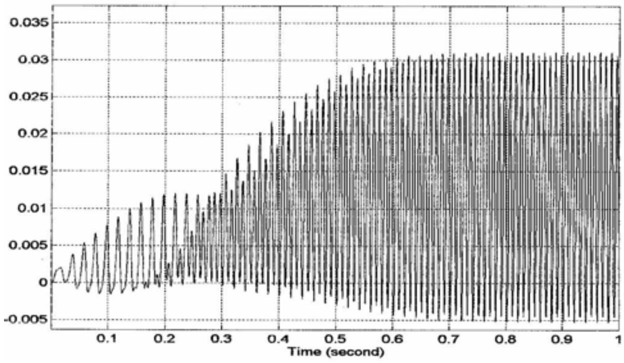
n_r [rpm]



(c) M2

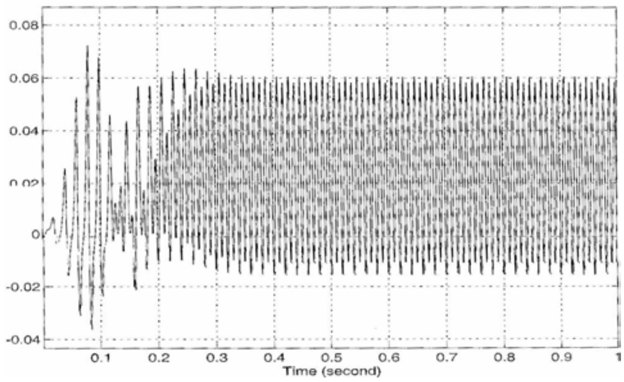
Fig. 9. Rotor speed n_r=f(t) at rated load start-up.

M_{em} [Nm]



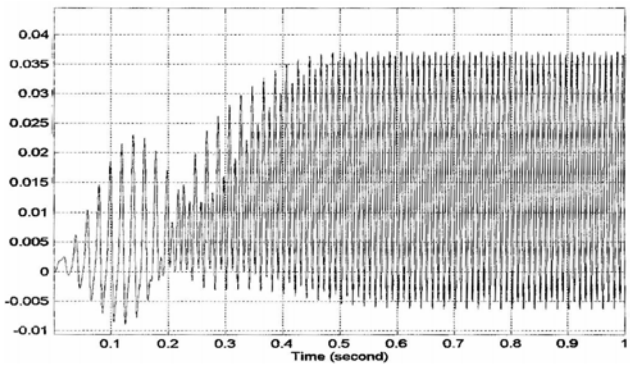
(a) BM

M_{em}[Nm]



(b) M1

M_{em}[Nm]

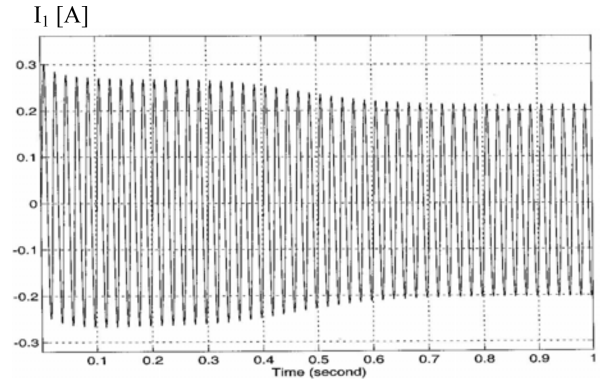


(c) M2

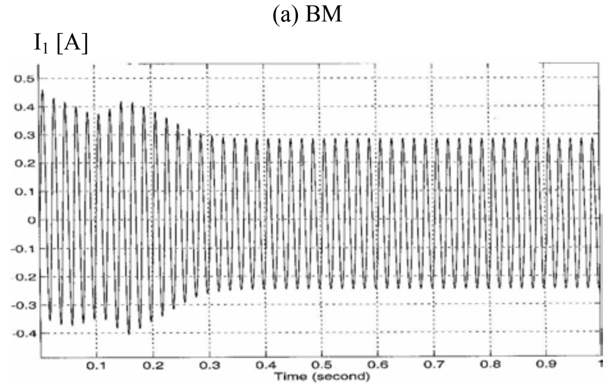
Fig. 10. Electromagnetic torque M_{em}=f(t) at rated load start-up.

B. Comparative dynamic evaluation

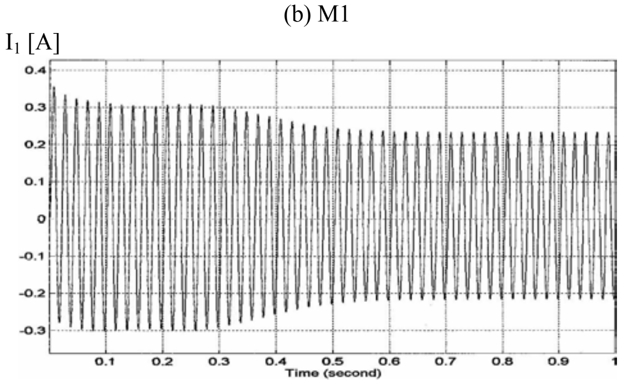
From the comparison of Figs. 8 and 11, it is clearly shown that Basic model has the largest acceleration time while optimized Model 1 has the shortest. This is comprehensive considering that Model 1 has the largest torque while Basic model has the smallest. Consequently the stator current in main excitation winding has the largest values in Model 1 while it has the smallest value in Basic model. 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 Fig. 12. As it can be expected Model 1 has the greatest torque compared to other two ones.



(a) BM



(b) M1



(c) M2

Fig. 11. Current I_1=f(t) at rated load start-up.

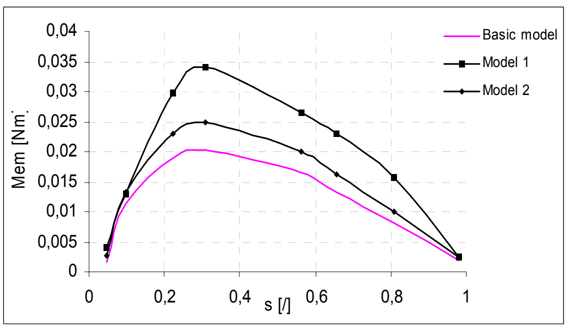


Fig. 12. Simulated characteristics M_{em}=f(s).

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.

Table 3
Comparison of current and speed by different methods

	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 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%. Improvement of electromagnetic torque is due to increased current in main excitation winding with the same time decrease of current density due to larger diameter of copper conductor. This result in lower operational losses and consequently in larger output power which further more improves the efficiency factor in both motor models.

Magnetic field calculations by FEM, show that in the new optimized 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, meaning that due to enlarged electromagnetic torque in both motor models acceleration time is shortened.

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