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Influence of Number of Varied Parameters on Torque of Single Phase Optimized Motor Models

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***Abstract*— Different optimized motor models of Single Phase Shaded Pole Motor are presented in this paper. Each of them is obtained by successive increase of number of varied motor parameters, starting from three up to five varied motor parameters while motor outer dimensions remain unchanged. Motor models are analyzed regarding electromagnetic phenomena inside the motor using Finite Element Method. Transient motor characteristics of speed, torque and currents are analyzed by the aid of simulation models built in SIMULINK. Based on result comparison conclusions for different motor models are derived regarding their performances.**

***Index Terms*— Magnetic Field Density, Magnetic Field Distribution, Optimized Motor Models, Transient Characteristics**

I. INTRODUCTION

Method of Genetic Algorithms (GA) is used for optimization of Single Phase Shaded Pole Motor (SPSPM) 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, product of company Micron-Tech. The arrangement of the motor magnetic core and windings is presented in Figure 1.

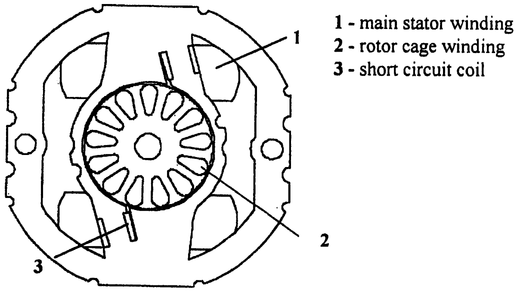


Figure 1: Motor's cross-section

GA method is heading towards maximization of chosen target function, in this case electromagnetic torque. Three new motor models, aiming to larger electromagnetic torque, are derived with successive increase of number of varied motor parameters, taking into consideration the constrain motor outer dimensions to remain unchanged. Electromagnetic field inside the motor for all motor models is obtained from Finite Element Method (FEM) in time harmonic domain i.e. f =50 Hz and for different operating regimes: no-load, rated load and locked rotor. Motor analysis is extended with respect to previous author's works [1] resulting in motor transient characteristics of speed, torque and stator current by building a simulation model of SPSPM in Simulink. On that way complex motor analysis is performed by involving analytical, optimization, numerical and simulation tools and adequate conclusions regarding all motor models are derived.

II. OPTIMISATION RESULTS

GA method is contemporary stochastic method for optimization which enables the most favorable solution of certain optimization problem to be created on fast and effective 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. Since the object of investigation is motor, electromagnetic torque is one of the most important characteristics and it is adopted to be the target function for optimization. Optimization is performed for one motor operating point in this case rated load meaning slip s_n=0.16.

Another important thing is to make the right choice of variable parameters and to put them in reasonable prescribed limits of variation. In this paper three new optimized motor models are derived by gradual increase of number of varied parameters starting from basic motor model (BM). Ranges of variation of motor parameters are placed in the following constrains:

- Current density in the stator winding Δ (5÷10) [A/mm^2];
- Magnetic flux density in the air-gap B_δ (0.4÷0.45) [T];
- Angle of the rotor skewing α_{sk} (15÷20) [deg].
- Shading portion of stator pole a (0.2÷ 0.3) [p.u.];
- Width of stator pole b_p (10÷20) [mm];

First motor model (M1) is using first three parameters as varied ones. Second motor model (M2) in addition to the first three ones is using shading portion of stator pole as forth varied parameter while all a.m. five parameters are varied in the third motor model (M3).

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. After the optimization procedure is completed, the results are presented in tables and on diagrams. In Table I the comparison of most important motor parameters, at rated load conditions for BM, M1 M2 and M3 is presented. In Table II the comparison of motor performance characteristics at rated load conditions is presented.

TABLE I

COMPARISON OF MOTOR PARAMETERS

BM	M1	M2	M3
Δ=8 [A/mm^2]	Δ=5.364 [A/mm^2]	Δ=5.0025 [A/mm^2]	Δ=5 [A/mm^2]
B_δ=0.404 [T]	B_δ=0.449 [T]	B_δ=0.449 [T]	B_δ=0.449 [T]
α_{sk}=17 [^{0}]	α_{sk}=15.0005 [^{0}]	α_{sk}=15.008[^{0}]	α_{sk}=15.003[^{0}]
a=0.25	a=0.25	a=0.2	a=0.2
b_p=16 [mm]	b_p=16 [mm]	b_p=16 [mm]	b_p=12 [mm]
d_{Cu}=0.14 [mm]	d_{Cu}=0.2 [mm]	d_{Cu}=0.18 [mm]	d_{Cu}=0.18 [mm]
W=3488 turns	W=3132 turns	W=3131 turns	W=3131 turns
R_1=492.98 Ω	R_1=243.4 Ω	R_1=297.6 Ω	R_1=272.8 Ω
X_1=498.17 Ω	X_1=410.153 Ω	X_1=366.04 Ω	X_1=354.6 Ω
R_2=497.04 Ω	R_2=362.579Ω	R_2=362.38 Ω	R_2=362.38 Ω
X_2=76.71 Ω	X_2=61.85 Ω	X_2=70.7 Ω	X_2=78.6 Ω
R_3=18474 Ω	R_3=14895.61 Ω	R_3=22414.36 Ω	R_3=21564.47 Ω
X_3=127.53 Ω	X_3=102.83 Ω	X_3=100.87 Ω	X_3=98.93 Ω
X_{12}=2163.3 Ω	X_{12}=1744.36 Ω	X_{12}=1992.92 Ω	X_{12}=2216.56 Ω
X_{13}=175.91 Ω	X_{13}=141.84 Ω	X_{13}=145.48 Ω	X_{13}=173.95 Ω

TABLE II

COMPARISON OF MOTOR PERFORMANCE CHARACTRISTICS

Quantity	BM	M1	M2	M3
Stator current I_1 [A]	0.125	0.168	0.161	0.157
Shaded coil current I_3[A]	0.0063	0.0083	0.0057	0.0061
Rotor current I_2 [A]	0.0878	0.117	0.1176	0.117
Power factor cosφ [/]	0.654	0.586	0.641	0.643
Input power P_1 [W]	18.11	21.67	22.73	22.276
Output power P_2 [W]	4.149	6.177	7.0368	7.693
Efficiency factor η [/]	0.229	0.285	0.309	0.345
Torque M_{em} [mNm]	18.075	25.7	29	31.5

From presented results in Table II it can be concluded that optimized motor models have increased electromagnetic torque and efficiency factor while power factor is kept on the same level compared to basic model, for rated operating point. In Table III is presented percentage improvement of electromagnetic torque and efficiency factor in optimized motor models compared to basic motor model.

TABLE I III

IMPROVMENTS IN OPTIMIZED MOTOR MODELS

Mem [mNm]			
BM	M1	M2	M3
18.075	25.7	29	31.5
η [%]			
BM	M1	M2	M3
0.229	0.285	0.309	0.345
Improvement compared to basic model [%] for M_{em}	42	60	74
Improvement compared to basic model [%] for η	24.45	34.93	50.65

From Table III it is evident that in optimized motor models two improvements are achieved in the same time: enlarged electromagnetic torque and efficiency factor. Obtained improvements are only result of variation of inner motor dimensions while motor outer dimension remain unchanged which is important from application point of view i.e. motor mounting position.

For better understanding of the behavior of all shaded pole motor models, comparative performance characteristics of electromagnetic torque M_{em}=f(s), efficiency factor η=f(s), power factor cosφ=f(s), main stator winding current I_1=f(s), shading coil current I_3=f(s) and rotor current I_2=f(s) with respect to motor slip-s are presented in Figures 2, 3, 4, 5, 6, and 7 consequently.

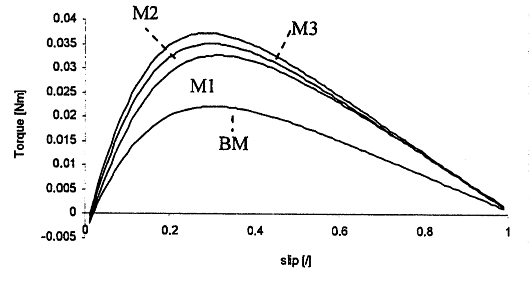


Figure 2: Comparative characteristics M_{em}=f(s)

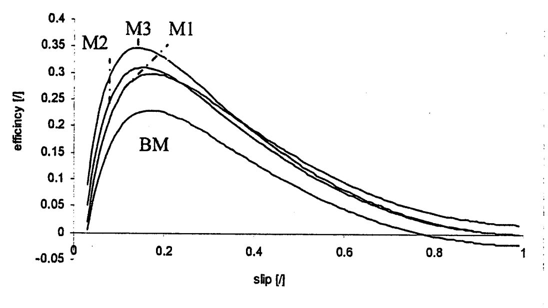


Figure 3: Comparative characteristics η=f(s)

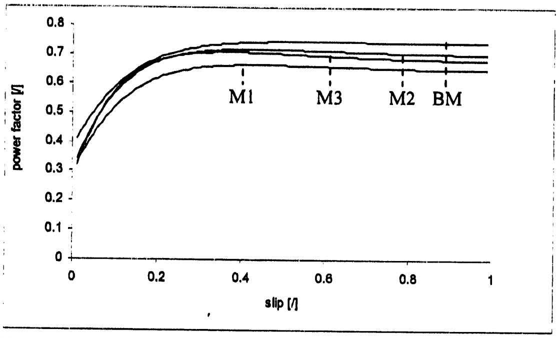


Figure 4: Comparative characteristics cosfi=f(s)

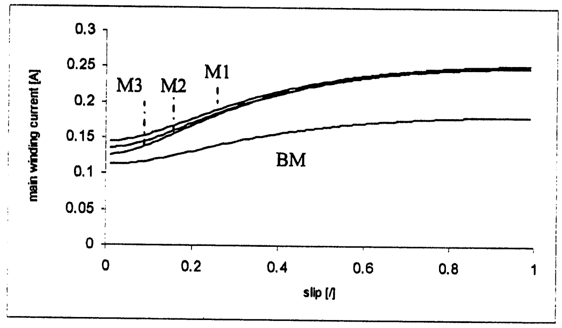


Figure 5: Comparative characteristics I_1=f(s)

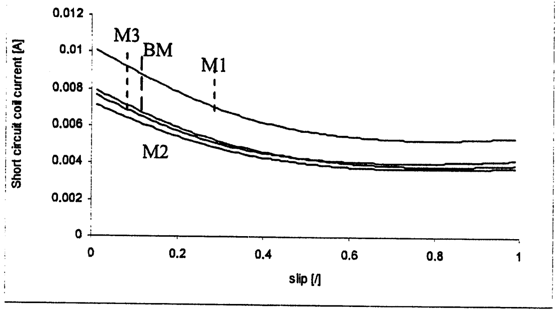


Figure 6: Comparative characteristics I_3=f(s)

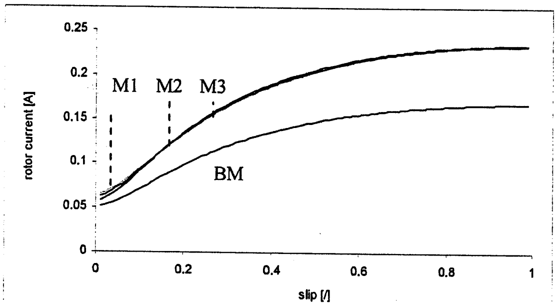
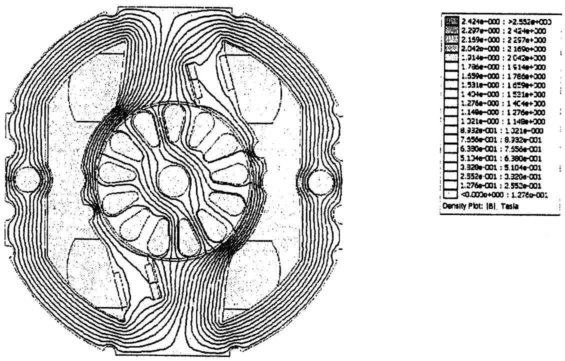


Figure 7: Comparative characteristics I_2=f(s)

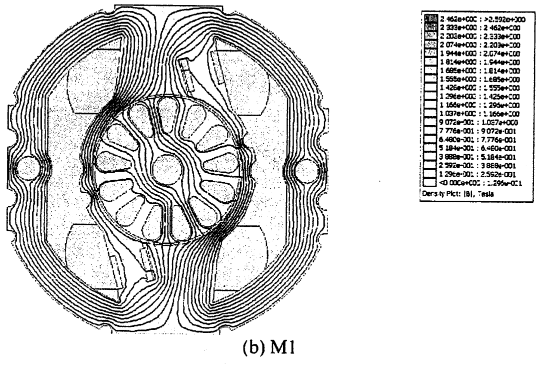
III. FINITE ELEMENT METHOD RESULTS

In order to be analysed electromagnetic phenomena inside the motor FEM method is used which enables two different approaches: magneto-static and time-harmonic approach [2]. Before starting the FEM analysis motor model is defined by inputting the exact motor geometry in software program FEM 4.7. Afterwards properties all materials inside the motor are defined. Very important issue is defining the boundary conditions on outer motor geometry and in this case are used Dirichlet-boundary conditions. In magnetostatic approach all electromagnetic quantities are time constant and they are analysed in certain moment of time, i.e. at frequency f=0 Hz, while in time harmonic magnetic approach all electromagnetic quantities are analysed at frequency f=50 Hz. In time-harmonic motor model only stator current is input in motor model and consequently currents in short circuit coil and rotor winding are freely induced. On that way analyse of electromagnetic phenomena inside the motor is closer to the real electromagnetic process inside the machine when it is supplied with voltage 220 V, 50 Hz. Time harmonic analysis in 2D domain will be performed on SPSPM for characteristic operating regimes no-load and rated load. 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 into magneto-dynamic i.e. non-linear time harmonic problem. When rotor is moving, the rotor quantities oscillate at slip frequency. Properties of all materials are input in motor model. Beside inputting the magnetization curve as B=f(H) also the lamination of magnet material is input as well as fill factor. The result of this model is that one can account for laminations with hysteresis and eddy currents.

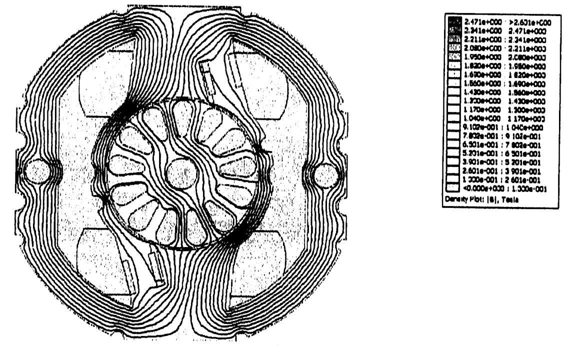
After preparing the motor model programs is run and post-processing results such as magnetic field distribution in motor's cross section as well as spatial distribution of flux density in the middle air gap line are obtained. In Figure 8 is presented magnetic field distribution in the cross section of the shaded pole motor at no –load i.e slip s_0=0,004 for basic motor model as well as for optimized motor models.



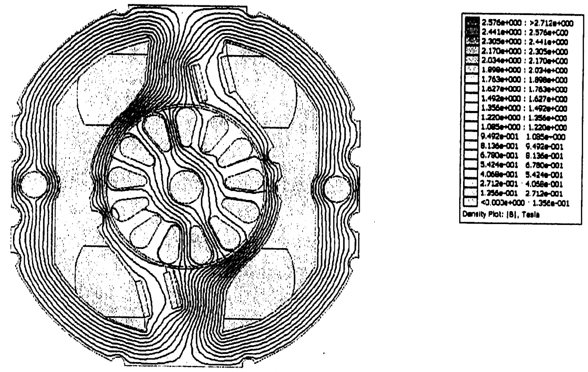
(a) BM



(b) M1



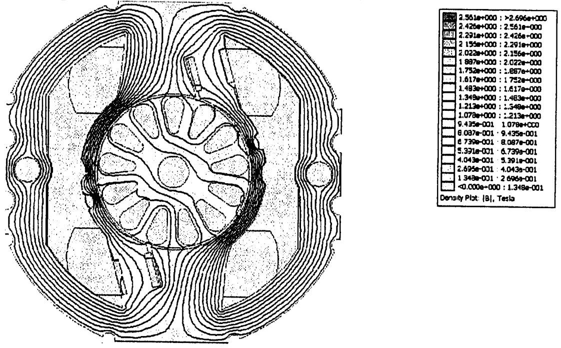
(c) M2



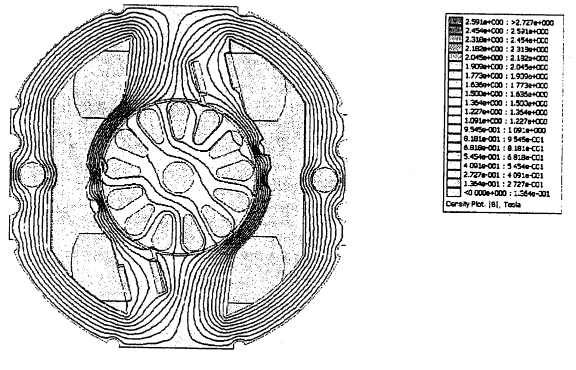
(d) M3

Figure 8: Magnetic field distribution at no load

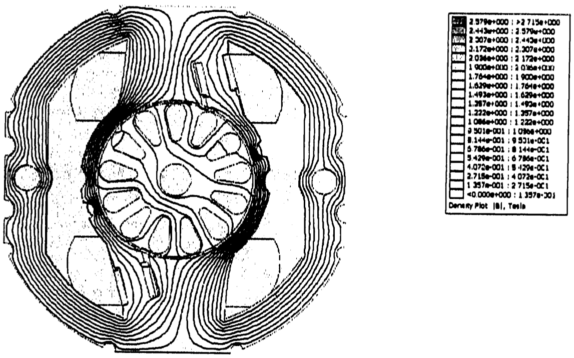
In Figure 9 is presented magnetic field distribution in the cross section of the shaded pole motor at rated load i.e slip s_n=0,16 for all motor models.



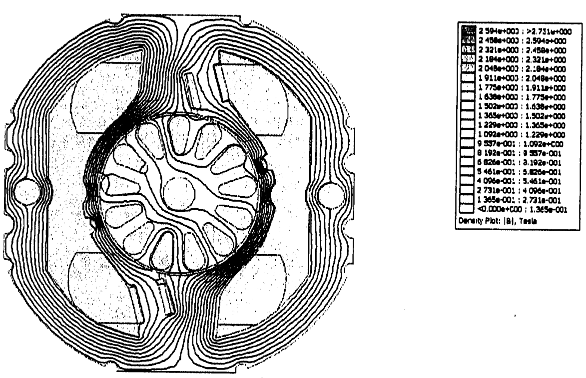
(a) BM



(b) M1



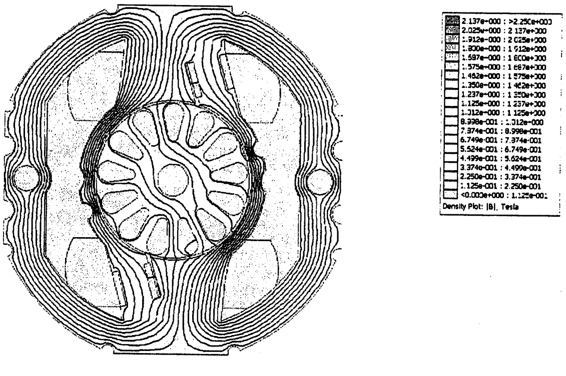
(b) M2



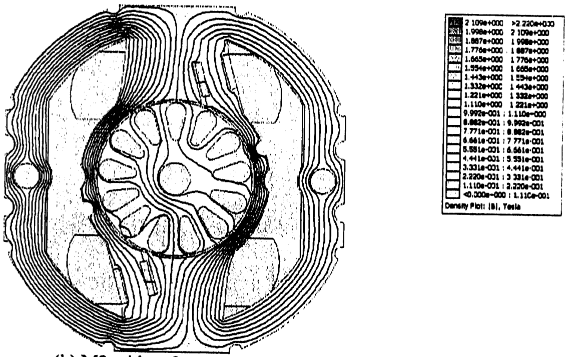
(b) M3

Figure 9: Magnetic field distribution at rated load

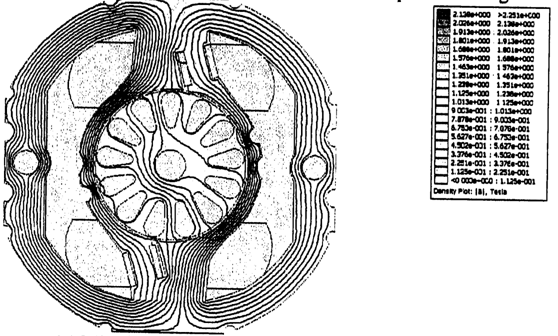
From presented results it can be concluded that in optimized motor models maximal value of magnetic induction in some critical points of magnetic core is slightly increased. In general it can be concluded that all motor models are experiencing high saturation in the region of stator bridge. Therefore it was taken into consideration the fact that in second and third optimized motor model-M2 and M3 dimensions of stator pole are variable i.e. in model M2 shading portion of stator pole is decreased while in model M3 width of stator pole is decreased. Consequently in stator pole and bridge teen steel laminations are replaced with soft magnetic powders which enable decreased value of maximal magnetic induction i.e. considerable decrease of saturation in the region of stator bridge. Obtained results are presented in Figure 10.



(a) M1 with soft magnetic powder in stator pole and bridge



(b) M2 with soft magnetic powder in stator pole and bridge



(c) M3 with soft magnetic powder in stator pole and bridge

Figure 10: Magnetic field distribution at rated load in optimized motor models with soft magnetic powder in stator bridge and pole

IV. SIMULATION RESULTS

Analysis of motor transient performance characteristics is performed by the aid of simulation software Simulink for Matlab. For that purpose simulation model was developed where as a first step all variables from two phase system are transformed in a d,q system which in this case is stationary.

Basic equations for modeling the transient performance characteristics of SPSPM are given (1)-(3):

$$i_{qs} = \frac{1}{L_{lqs}+L_{mq}}\int U_{qs} - \frac{r_{qs}}{L_{lqs}+L_{mq}}\int i_{qs} - \frac{L_{mq}}{L_{lqs}+L_{mq}} i'^{s}_{qr}$$

$$i'_{ds} = \frac{1}{L'_{lds}+L_{mq}}\int U'_{ds} - \frac{r'_{ds}}{L'_{lds}+L_{mq}}\int i'_{ds} - \frac{L_{mq}}{L'_{lds}+L_{mq}} i'^{s}_{dr} \qquad (1)$$

$$i'^{s}_{qr} = \omega_r \int i'^{s}_{dr} + \frac{\omega_r L_{mq}}{L'_{lr}+L_{mq}}\int i'_{ds} - \frac{r'_r}{L'_{lr}+L_{mq}}\int i'^{s}_{qr} - \frac{L_{mq}}{L'_{lr}+L_{mq}} i_{qs}$$

$$i'^{s}_{dr} = -\omega_r \int i'^{s}_{qr} - \frac{\omega_r L_{mq}}{L'_{lr}+L_{mq}}\int i_{qs} - \frac{r'_r}{L'_{lr}+L_{mq}}\int i'^{s}_{dr} - \frac{L_{mq}}{L'_{lr}+L_{mq}} i'_{ds}$$

where i_{qs}, i'_{ds}, i'^{s}_{qr} and i'^{s}_{dr} are transformed stator rotor currents into stationary d.q system consequently. r_{qs}, r'_{ds} and r'_r are resistances of main stator winding, short circuit coil and rotor winding respectively. L_{lqs}, L'_{lds} and L'_{lr} are inductive resistances of main stator winding, short circuit coil and rotor winding respectively while L_{mq} is mutual inductance between reference stator and rotor windings.

Electromagnetic torque is obtained from:

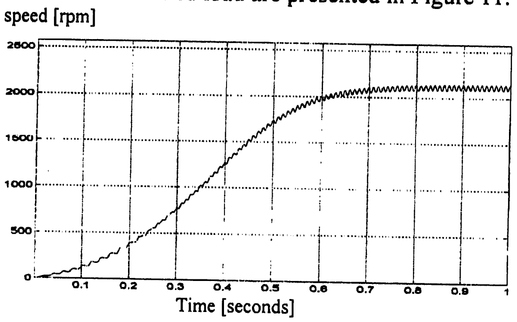
$$M_{em} = J\left(\frac{2}{P}\right)\frac{d\omega_r}{dt} + M_s \qquad (2)$$

where J is a moment of inertia [kgm^2], M_s is a load torque in [Nm] and P are the number of poles of motor.

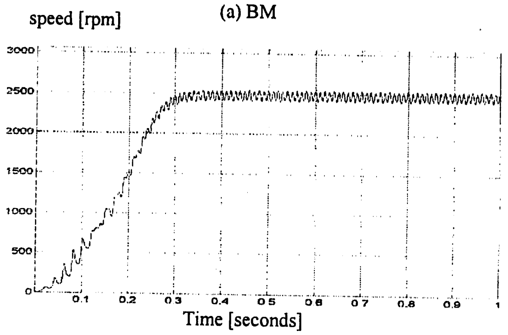
Rotor speed is obtained from:

$$\omega_r = \frac{P^2}{4J}\int i'^{s}_{dr} i_{qs} - \frac{P^2 L_{mq}}{4J}\int i'^{s}_{qr} i'_{ds} - \int \frac{P}{2J} M_s \qquad (3)$$

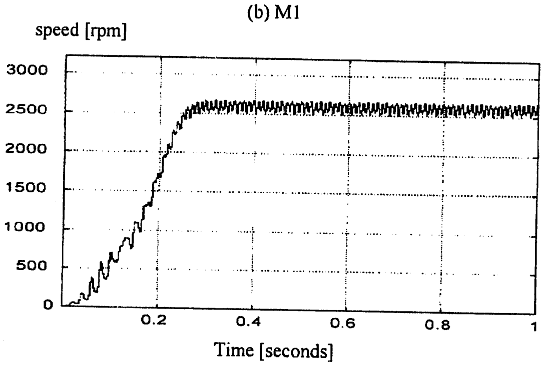
Transient performance characteristics of speed for all motor models at rated load are presented in Figure 11.



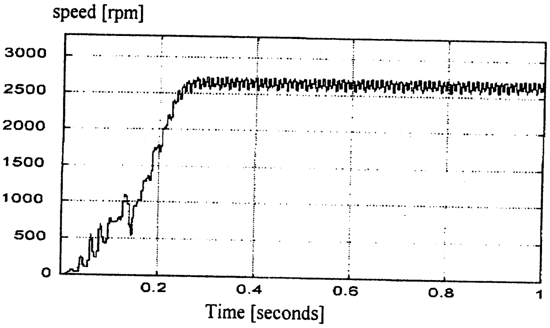
(a) BM



(b) M1



(c)M2



(d) M3

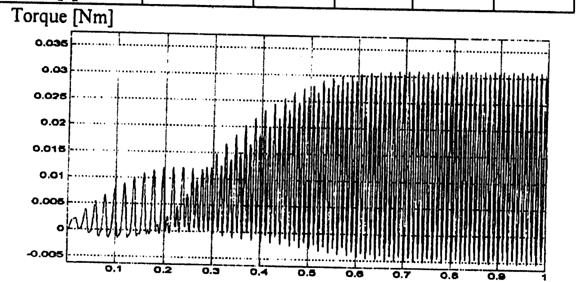
Figure 11: Transient characteristic of speed for all motor models

From the results in Figure 11 it is evident that model BM has a largest acceleration time due to the smallest electromagnetic torque while model M3 has the shortest acceleration time as a result of the largest electromagnetic torque. Obtained value of the speed from simulation after the transients are suppressed is compared to the value obtained from motor producer as well as acceleration times of all motor models. Results are presented in Table IV. Transient characteristics of electromagnetic torque for all motor models are presented in Figure 12.

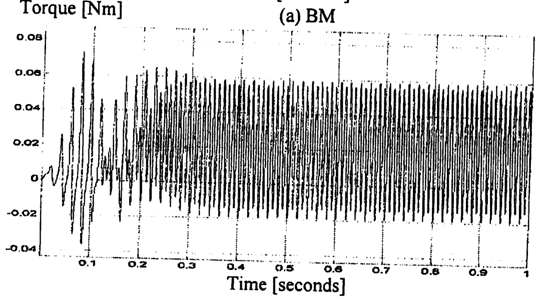
TABLE IV

COMPARISON OF TRANSIENT PERFORMANCE CHARACTRISTICS

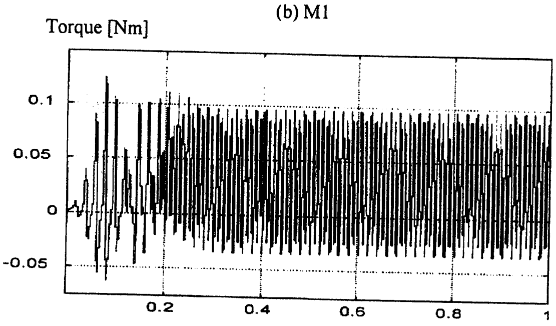
Producer data		Simulation results			
		BM	M1	M2	M3
speed [rpm]	2520	2200	2500	2550	2600
acceleration time [s]	0.6	0.7	0.32	0.27	0.25



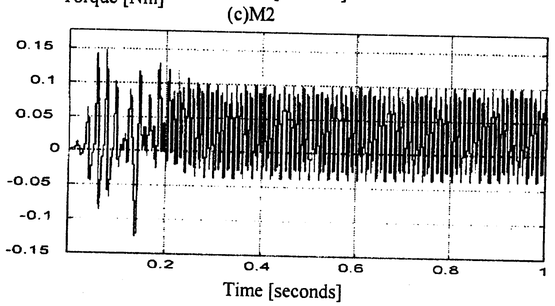
(a) BM



(b) M1



(c)M2



(d) M3

Figure 12: Transient characteristic of torque for all motor models

The comparative characteristics M_{em}=f(s) for basic motor model calculated by using different methods, as analytic circuit theory method, numerical FEM and transient simulation method, are presented in Table V.

TABLE V

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

V. CONCLUSION

Three optimized motor models of SPSPM motor were developed by gradual increase of number of varied parameters starting from three up to five varied parameters which resulted in three new motor models M1 up to M3 consequently. In all motor models outer motor dimensions remain unchanged and electromagnetic torque is adopted as target function for optimization. Optimization process resulted in increase of electromagnetic torque at rated operation point in model M1 for 42 %, in M2 for 60 % while in M3 for 74 % compared to the basic motor model. Simultaneously, in all motor models is achieved considerable increase of efficiency factor. FEM is used for obtaining distribution of magnetic field in motor cross section. FEM results proved that motor is experiencing high values of magnetic induction in some parts of stator bridge. High value of magnetic induction in stator bridge was decreased by implementing soft magnetic powders in this region of optimized motor models. On that way magnetic induction was decreased in models M1 and M3 from 2,59 T to 2,13 T and for model M2 from 2,57 T to 2,109 T. Simulink motor model was built in order motor transient performance characteristics to be obtained. Transient characteristics has proved that basic motor model has the largest acceleration time due to the smallest electromagnetic torque while optimized motor model M3 has the shortest acceleration time due to the largest electromagnetic torque. Obtained results of torque for basic motor model from different methods, analytical, numerical and simulation are compared showing especially good agreement at rated operating point. Results of speed and acceleration time from simulation have satisfactory agreement with data from the producer.

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