Magnet shape optimization of brushless machine by Self – Organizing Migrating Algorithm

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Abstract- **The paper deals with AC motor optimization. Optimized machine is three phases 14kW Surface Mount Permanent Magnet (SMPM) machine intended to work with servo amplifier. The optimization is based on Self Organizing Migrating Algorithm – SOMA with strategy "All to One".**

Artificial intelligence algorithms are effective methods for searching global extremes of the objective functions. Target is to achieve maximum efficiency of SMPM, minimize losses and increase output power of the machine. As optimized parameters the diameters of magnet shape and length of air gap were chosen. The optimization algorithm is created in MATLAB, SPEED laboratory is used as solver, communication link is provided by ActiveX. Improved efficiency leads into reduced losses and lower temperature rise. Motor torque is calculated via a circular path integral of the Maxwell stress tensor in ANSYS program. The Maxwell stress tensor provides a convenient way of computing forces acting on bodies by evaluating a surface integral.

I. INTRODUCTION

This paper deals with a complex optimization of the synchronous machine electromagnetic circuit with permanent magnets (SMPM) to achieve minimal THD of generated voltage and to achieve maximal electro-magnetic torque of the machine. In other words the optimization is focused on the efficiency increasing. Whereas the SMPM is enclosed machine the temperature analysis was performed and loss dependences on the overall efficiency were investigated. Main part of optimization process was created in program MATLAB. Optimized engine is designed, solved and optimized in program SPEED Laboratory.

For the optimization is used the self-organizing migrating algorithm (SOMA), which is type of genetic algorithm used for optimization of these problems [1], SOMA has been previously applied on the complex vibration power generator [2] where the vibration generator was optimized to the maximal generated output power in the minimal volume of generator. SOMA has several strategies. In this work is used strategy "All to one".

Several approaches to designing a permanent magnet machine those make use of optimization algorithms, DUAN Y. and col. in [4] demonstrated optimization method Partical Swarm Optimization (PSO) on the design SMPM where PSO is applied to find the optimal solutions of the design with respect to certain user defined objective function.

In the literature [5], [6] either deterministic methods and in [7], [8] stochastic methods have been presented. Arash Hassanpour Isfahani presented in [9] optimization of permanent magnet material for a constant torque and an extension in speed and torque. Literature [10], [11] deals with optimization SMPM on the area optimization electric control respectively optimal design and optimization PM motor for low speed direct – driven.

II. TECHNICAL INFORMATION

Synchronous motor with permanent magnet is a classical salient-pole synchronous AC motor with approximately sine-distributed windings, Fig. 1. The magnets can be mounted on the rotor surface or they can be imbedded to the rotor, more information is adduced in [3], basic parameters are in Table I.

Table I
PARAMETERS OF ANALYZED MACHINE

Parameter	Value	Unit
power	14,2	kW
BUS voltage	640	VDC
torque	54	Nm
number of poles	10	-
speed	2500	rpm

Stator windings are distributed in 12 square shaped slots over 10-pole rotor. This configuration allows creating windings with very short endturns without crossing and helps to reduce copper losses in inactive winding parts. On the other hand, 12/10 combination limits winding to just two parallel paths only.

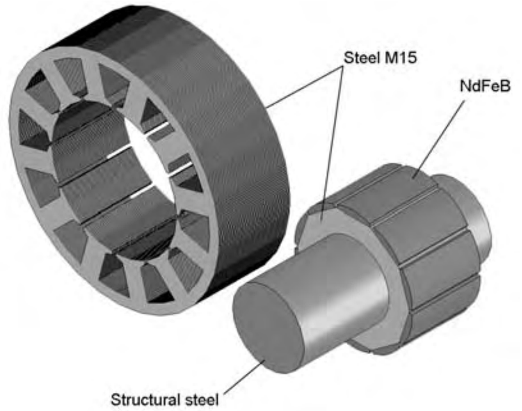

Fig. 1. SMPM machine geometry.

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Parameters of winding are shown in Table II and the Fig. 2. indicates a vector diagram of individual coil EMFs. Material of the stator and rotor is made of magnetic steel grade M15 with 0.35 mm thickness, shaft material is a standard structural steel grade 11. The material permanent magnets NdFeB was chosen.

Table II
PARAMETERS OF WINDING

Parameter	Value
turn(s)	74
coil pitch	8
parallel path	2
layer(s)	2
winding type	concentric

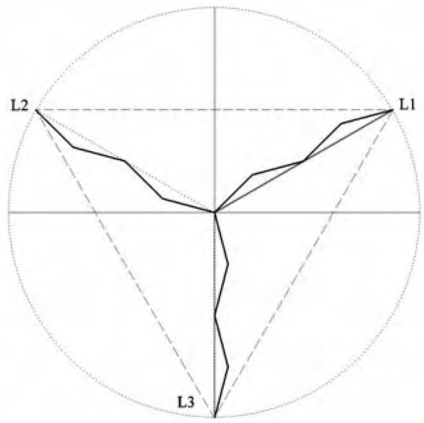

Fig. 2. Displays a vector diagram of individual coil EMFs.

III. OPTIMIZATION PROCESS

A. Optimization structure

Optimization structure is shown on Fig. 3.

INPUT – includes all parameters coming into optimization, parameters controlling SOMA are well described in [1]. As optimized parameters the BetaM, Gap, Rmo, LM have been selected, see Fig. 4.

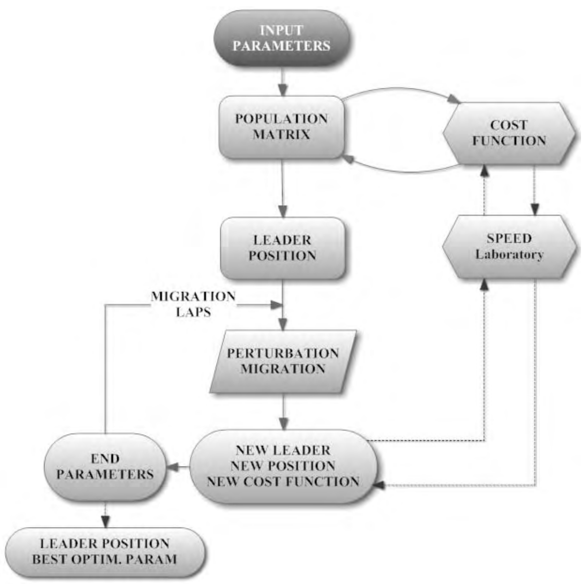

Fig. 3. Optimization structure.

In the next phase the ***POPULATION MATRIX*** is formed. Population matrix members are evaluated by ***COST FUNCTION*** – for combinations of optimized parameters, the electromagnetic torque, output torque, output power, efficiency and THD are calculated by ***SPEED***. Cost function has to be converging to zero. From population matrix, the best member with lowest cost function value is selected and marked as ***LEADER*** with its matrix location.

Next, the SOMA algorithm is executed. From population matrix are sequentially selected members migrating to leader (All to One strategy). Their path is sequentially crossed and mutated – ***PERTURBATION.*** In each round of migration the fitness check is performed, the SPEED solver is executed and cost function is evaluated. If mutated member has better cost value then current leader, then it becomes leader for next rounds.

This process is repeated till the end condition is reached – ***END PARAMETERS***. Last round with leader member contains the optimal solution.

B. Self-Organizing Migrating Algorithm – SOMA

Soma is stochastic search algorithm for global optimization. Main aim of this algorithm is searching global extreme of a cost function, were global extreme will be maximum or minimum. A definition of a suitable cost function (fitness function) is very important for successful optimization. This algorithm is very robust in his fast convergation to global extreme. The algorithm can use several strategies and our optimization uses strategy AllToOne. This strategy is based on migration of individuals moving toward to leader, which is selected for actual migration lap.

C. Optimization parameters

For this simple problem the optimization parameters has been chosen. Optimization parameters (OP) are chosen on the base geometric dimensions of magnetic circuit, in Fig. 4. displays one magnet.

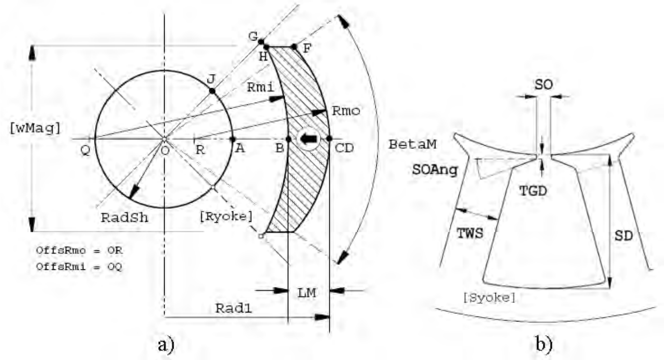

Fig. 4. Machine geometry: a) type of rotor BreadLoaf 2; b) slot, [12].

OP ***Gap*** is length of air gap, ***Rmo***, ***BetaM*** is pole arc, ***wMAG*** is width across one magnet, ***LM*** is length of magnet in the direction of magnetization. Other parameters are not included into optimization process and that is why they are not calculated.

IV. Machine Design Optimization

Today, demands on the electric machines efficiency are being increased, that leads to effort to reduce losses in the machines. These losses could be minimized by suitable electromagnetic circuit design including mutual stator to rotor shape, therefore any single component affects the losses and efficiency. Target of optimizing is to minimize losses by changing the permanent magnets shape, keeping the other parts of electromagnetic circuit, this leads to improvement of efficiency without changing outer dimensions.

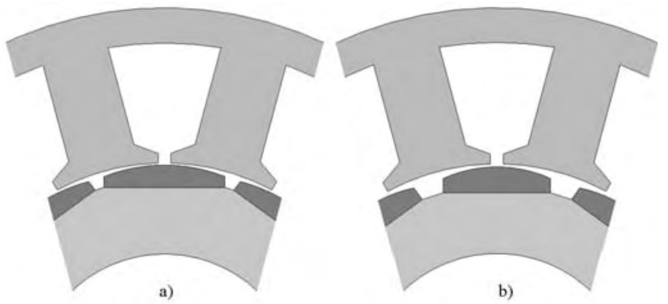

Fig. 5. Machine design optimization: a) original; b) optimizing.

Cross-section of original and optimized electromagnetic design with new magnet shape is shown in Fig. 5. New magnet shape causes reduction of magnet losses and reduces its heating.

A. *Loss reduction*

Magnetic circuit losses reductions are shown in Table III. As a result due to optimization the total losses are significant smaller. Magnet losses, mechanical losses and core losses were decreased approximately about 41% respectively 20% and 6%.

Whereas stator winding was not includes into optimization part therefore winding losses are constant.

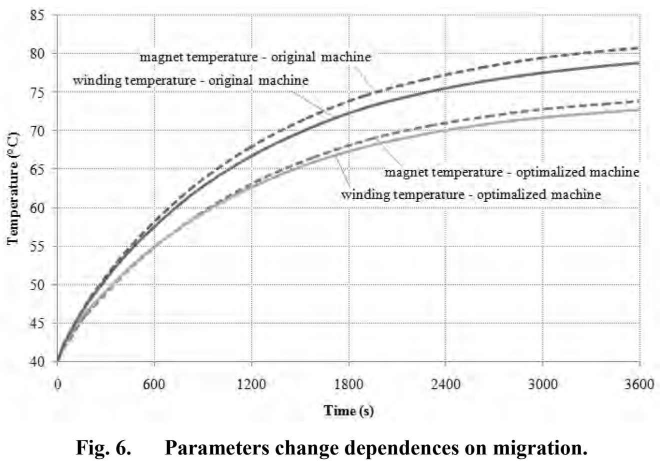

Fig. 6. Parameters change dependences on migration.

The temperature analysis was done by FEMM for detecting dependence between magnet diameters and machine overall temperature rise. Ambient temperature was set up on 40°.

The temperature dependences of original and optimized machine are shown on Fig. 6. Temperature was solved on terms nominal speed 2500rpm by nominal current approximately 50A. Performed optimization (minimize of total losses, Table III) was achieved temperature drop about $\Delta T = 10°C$ via magnets and winding. Simulation time was 3600s.

Table III
Loss Reduction

Name	Rate	Unit
winding	0,00	%
core	6,27	%
magnet	40,94	%
mechanical	22,83	%
total	**14,52**	**%**

B. *Torque calculation*

This part is dedicated to the electromagnetic field calculation by finite element method in ANSYS – calculates torque on a body in a magnetic field (TORQ2D; TORQC2D).

TORQ2D invokes an ANSYS macro which calculates torque on a body in a magnetic field. The body must be completely surrounded by air (symmetry permitted), and a closed path passing through the air elements surrounding the body must be available. A counterclockwise ordering of nodes on the PPATH command will give the correct sign on the torque result. This macro is valid for 2-D planar analysis. TORQC2D is used for a circular or cylindrical body such as a rotor in an electric machine.

The body must be centred about the global origin and must be surrounded by air elements. The air elements surrounding the path at radius RAD must be selected, and elements with a high-permeability material should be unselected prior to using the macro. This macro is valid for 2-D planar analyses only. For a harmonic analysis, the macro calculates the time-average torque. Radial symmetry models are allowed, i.e., the model need not be a full 360° model, [13].

The torque is calculated via a circular path integral of the Maxwell stress tensor. The Maxwell stress tensor provides a convenient way of computing forces acting on bodies by evaluating a surface integral.

$$\vec{F}_{MX} = \int \left(\vec{\vec{T}}_E + \vec{\vec{T}}_M \right) \cdot d\vec{S} \tag{1}$$

where: $\vec{\vec{T}}_E$ electric Maxwell stress tensor

$\vec{\vec{T}}_M$ magnetic Maxwell stress tensor

C. *Results*

The graphic output with several representative parameters from this optimization study is shown in Fig. 7. Each of parameters is in relative values it means relative change of absolutely values in compare with original parameters. In fig is shown the change of efficiency dependences on the optimization parameters in actual migration lap.

Optimization parameters were optimized by SOMA other parameters such as efficiency, total losses and output power were calculated in SPEED, those parameters are very important for design of electrical and mechanical part of the machine.

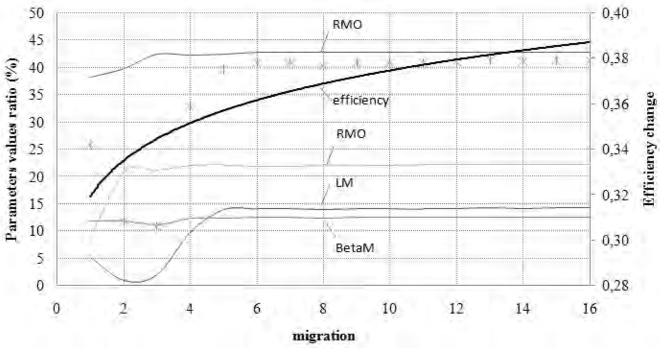

Fig. 7. Parameters change dependences on migration.

All fitness factors have approximately equivalent effect to the fitness function. A calculated value of the fitness function in equation (2) depends on a choice of individual function coefficients A, B, C, D. For complex optimization is necessary to enter into the fitness function with the request to maximal efficiency, torque and minimal overall losses.

$$\text{CostFcn} = A \cdot THD + \frac{B}{Torque} + \frac{C}{Efficiency} + D \cdot Losses \qquad (2)$$

The shape of cost function curve after 16 migrating laps is shown Fig. 8. By this type of task the last migration lap is the best of solution of whole optimization. Values and convergence speed of cost function are strongly behavior via function coefficients.

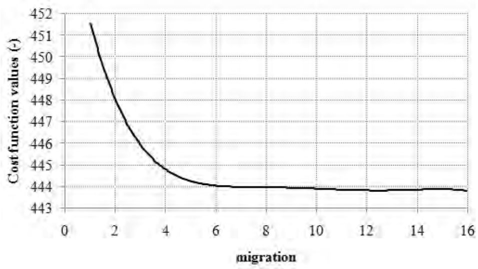

Fig. 8. Parameters change dependences on migration.

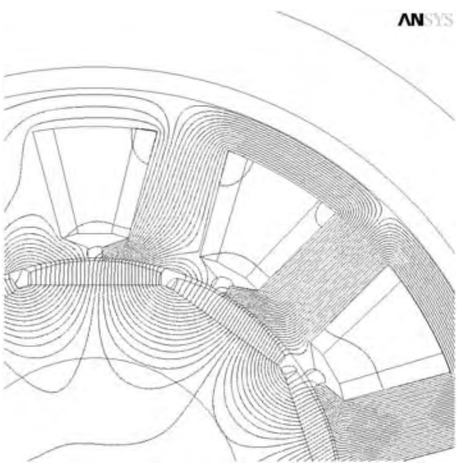

Fig. 9. FluxLines of original machine design.

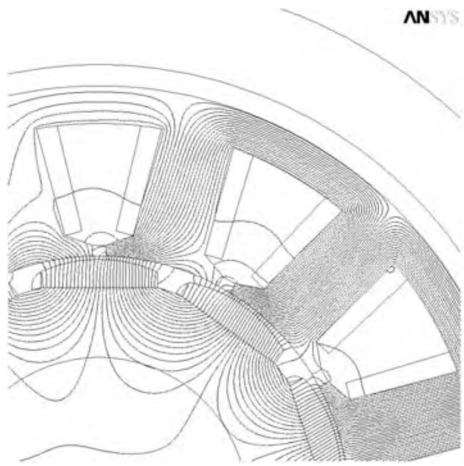

Fig. 10. FluxLines of optimized machine design.

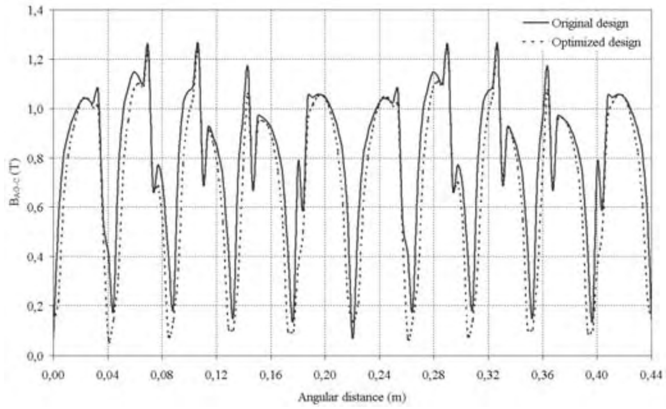

Fig. 11. Behavior of magnetic flux density (absolute value) along the airgap.

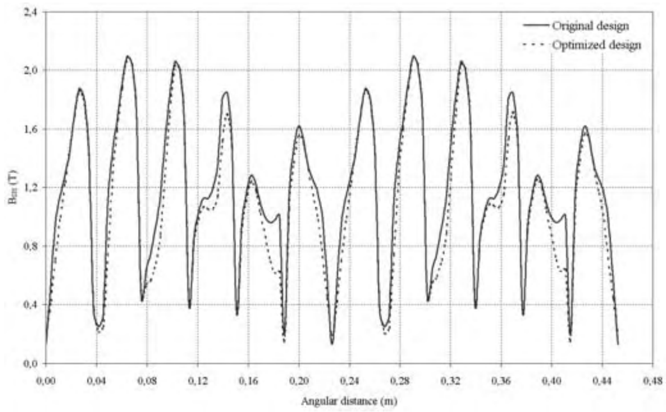

Fig. 12. Behavior of magnetic flux density (absolute value) in the middle of stator head teeth.

The magnet shape optimization affects electromagnetic field distribution (Fig. 9. , Fig. 10.) onto several directions. In case of original machine design the oversaturated areas size (OSA) was 2.66% of whole magnetic circuit and based on optimization dropped to 2.09%. Then torque provided by the Maxwell stress tensor dropped from the 58.73Nm to 55.72Nm, which represents approximately 5.1% decrease. In case of average value of magnetic flux density along air gap (Fig. 11.) dropped from 0.807 T to 0.696 T (it means 13.75% decrease) and in the middle of stator head teeth (Fig. 12.) the magnetic flux density dropped from 1.186T to 1.094T (it means 7.76% decrease).

V. CONCLUSION

The optimization process of SMPM machine is quite complex. Therefore artificial intelligence optimizing method has been used. Optimization algorithms are very efficient and fast method, to get better solution.

Design of SMPM was created in program SPEED Laboratory, applied optimization strategy SOMA – "All To One" was developed in MATLAB. It should be noted that the optimization was performed only on the rotor - magnets. If we consider all possible parameters (stator, shaft) which might be involved into the optimization process, the resulting value of THD efficiency, total losses may differ.

This type of task has been created to proof suitability and usability of SOMA algorithm for SMPM optimization and to determine the theoretical computational time optimization. On the other hand the optimization showed that SOMA was proved as a feasible way how to optimize electro - mechanical systems.

ACKNOWLEDGMENT

This work has been prepared under the support provided by research projects: CZ.1.07/2.3.00/09.0162: Knowledge and Skills in Mechatronics-Innovations Transfer to Practice; GA ČR 102/09/1875: Analysis and Modeling of Low Voltage Electric Machines.; MPO FR-TI1/082: Research and development of Permanent Magnet Servomotor.

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