OPTIMIZATION OF INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR USING EVOLUTIONARY OPTIMIZATION ALGORITHM

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Abstract: The development of the interior permanent magnet synchronous motor has drawn a big interest over the last decade. This is due to the use of this kind of machine in the automotive industry, thanks to the machine high efficiency and high overload capability compare to other machine types. Using artificial intelligence or evolutionary optimization algorithms is possible to optimize the motor with maximum efficiency, lowest torque ripple and highest average torque, because a huge ammount and variety of geometry combinations are tested. This paper is focused on the overview of generally used optimization algorithms and optimization is demonstrated on Self-Organizing Migrating Algorithm (SOMA). Cost function and weight coefficients are also presented and used for optimization.

Keywords: Maxwell, SOMA, Optimization, evolutionary optimization algorithm, Finite element analysis, Interior permanent magnet

1 INTRODUCTION

A various topologies can be found in the branch of the synchronous machines. The basic criteria, that separates synchronous machines into three groups is the excitation. In the past, the current-excited topologies dominated, mostly due to use of synchronous generators in power plants or alternators in automotive industry. Situation has started to change in last three decades with development of permanent magnet (PM) excited machines. This is mostly due to the research of rare-earth magnets and control algorithms, that drives motor at the highest possible efficiency. Also the pure-reluctance machines are drawing attention in the last two decades, because of the lower-cost and relatively high effiecy. [1].

In the sub-branch of the permanent magnet exited machines, machines can be divided due to a PM placement into surface permanent magnet (SPM) machines and interior permanent magnet (IPM) machines. IPM have many advantages over the SPM topologies. SPM and IPM topologies are presented in the Figure 1. Firstly, the mounting of the PM is easily done just by creating the “iron pockets” inside the rotor iron, where magnets are fixed witout use of any fixing component (eg. fixing glue). Second main advantage is the IPM robustness towards demagnetization in machine fault-state operations, such as short-circuit between windings or short-circuit between winding and housing of the machine. Also some topologies of IPM machines can deliver torque not only from the PM flux, but also from the rotor saliency. Electromagnetic torque in the PM-excited synchronous motor, considering the magnetic saliency, can be estimated according to equation 1.

$$T_{\mathrm{elm}} = \frac{3}{2} p \left[\lambda_{\mathrm{PM}} i_{\mathrm{d}} + (L_{\mathrm{d}} - L_{\mathrm{q}}) i_{\mathrm{d}} i_{\mathrm{q}} \right] \tag{1}$$

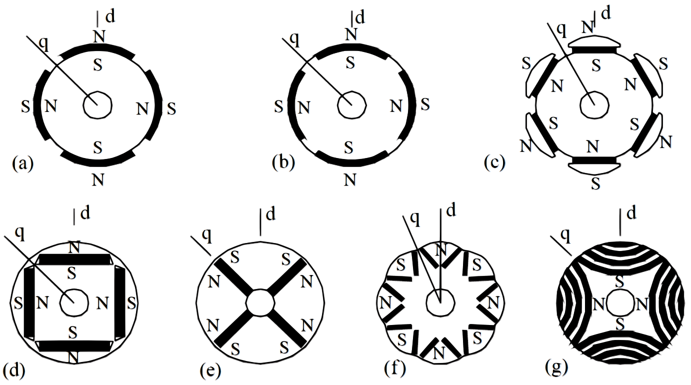
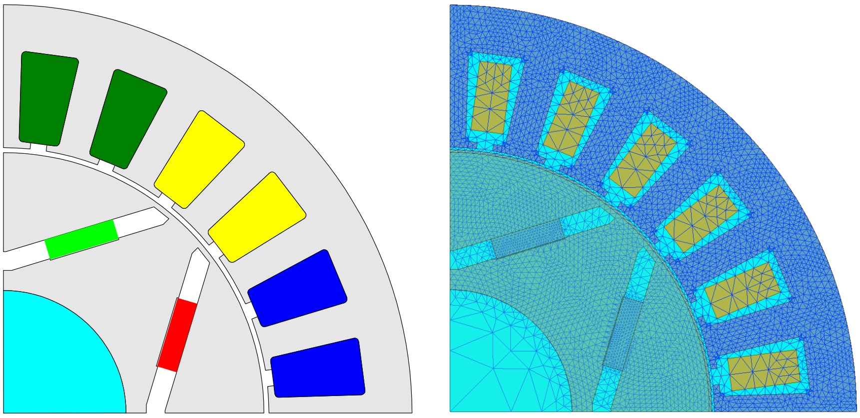


Figure 1: PM synchronous machines toplogies. a) Rotor-surface-mounted magnets, b) magnets embedded in the surface, c) pole shoe rotor d) tengentially emgedded magnets, e) radially embedded magnets, f) two magnets per pole in the V position, g) synchronous reluctance rotor equipped with permanent magnets [2]

2 MACHINE UNDER STUDY

The IPM in the V-shape PM arrangement will be investigated and optimized in this paper, mainly because of the advantages described in chapter 1. The optimized machine has 4 poles and 24 slots equiped with integral-slot winding and tranversally laminated rotor. Key parameters of the motor and the motor cross-section are depicted in the Figure 2 and Table 1.



(a) (b)

Figure 2: Initial geometry a) and Maxwell model with mesh b)

Parameter	Symbol	Value
Rated output torque	T_{N}	28 Nm
Rated line-to-line voltage	U_{S}	400 V
Nominal power factor	PF	0.87
Rated speed	n	1500 min^{-1}
Stator outer diameter	D_{out}	200 mm
Stack length	L_{stk}	120 mm
Number of slots/poles	Q_{s}/2p	24/4

Table 1: Key parameters of the tested machine

The FEA analysis will be done in ANSYS Electronic Destkop software, the initial geometry results are shown with the optimized geometry data in the Figure 3. Initial torque characteristic and induced voltage are presented in the Figure 5. Average torque, torque ripple and first harmonic peak value of the induced volage and total induced voltage harmonic distortion between the lines are shown with the results of the optimization in the Table 3.

3 OPTIMIZATION ALGORITHMS

Optimization algorithm (OA) can be in general defined as a list of steps or procedures, that lead to the minimalization of objectives evaluating the quality of the population member. Algorithm steps and procedures are usually related to an algorithm working principle, it can be the reproduction in case of genetic algorithm (GA) or migration in self-organizing migrating algorithm (SOMA) or travel sequences in ant colony optimization. Objectives are chosen to estimate quality of the machine, that can be objectively evaluated, objectives such as average torque, torque ripple and efficiency are usually chosen in electrical machines optimization process. Example of the objective, in this case average torque with the desired value is shown in equation 2. In case of cost function minimization process, besides the objectives, the weight objectives coefficients are needed to be define. The weight coefficients are puting emphasis on speccific objective that is desired more than on others. For instance, if the torque ripple minimization in the optimization process is desired more than other objectives, higher coefficient is used. Cost function is then defined as a sum of the objectives multiplied by the corresponding weight coefficients as shown in equation 3.

$$Obj_{T_{\text{avg}}} = 1 - \frac{T_{\text{member}}}{T_{\text{desired}}} \tag{2}$$

$$cost\_function = \sum_{i=1}^{n} Obj_i \cdot weight_i \tag{3}$$

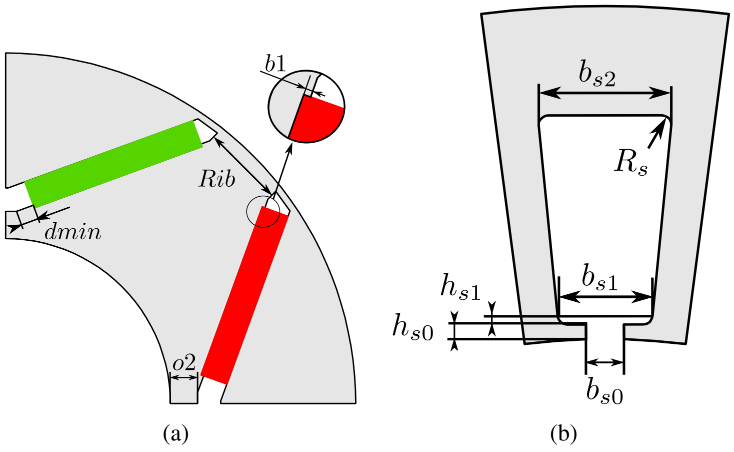
3.1 SELF-ORGANIZING MIGRATING ALGORITHM

Self-orginizing migrating algorithm (SOMA) developed by I. Zelinka in 1999 at Tomas Bata University in Zlin [3], will be used in this paper. Choice of the algorithm was based on a previous author experience, where the SOMA converged faster to a optimal solution, which was very close to the result from GA optimization. SOMA works on a principle of pack of wolves searching for food. Always one member of the pack is closest to the food and other pack members are traveling towards him. Firstly the initial population is generated and evaluated, then the leader with the lowest cost function (closest to the “food”) is selected and other members are traveling towards the leader.

Advantage of this algorithm is the fast convergence to the minimal value of the cost function, which is usually found within 2 migrations while considering 50 inital population members. The disadvantage is that, SOMA has a tendecy to converge towards the local minimum instead of the global one. This disadvantage can be reduced with multiple run sequences of the optimization process, that ideally leads to the same result or with generating sufficient (usually around 50) number of initial members of the population.

3.2 OPTIMIZED PARAMETERS

Optimized parameters of the geometry are listed separately for rotor and stator on Figure 3. 10 parameters were optimized in total, 4 parameters of the rotor and 6 of the stator. Objective function was constructed from 4 objectives with their weights listed in Table 3. From the Table 3 is obvious, that the biggest emphasis was put on the torque ripple T_{rip} and average torque T_{avg}, because these objectives are either in direct or indirect relationship with efficiency and total harmonic distortion ($THD_{\text{L-L}}$). Table 2 and 3 depict the results of the optimization regarding the geometry parameters changes and objectives. While Figure 4 and 5 are showing the results of the geometry, torque and voltage characteristics optimization.



(a) (b)

Figure 3: Initial geometry characteristics

Parameter [mm]	Rib	dmin	b1	o2	b_{s0}	b_{s1}	b_{s2}	h_{s0}	h_{s1}	R_{s}
Initial geom.	10	20	0.2	5	4	10	14	1.5	1	1
Optim. geom	17.8	2.1	0.9	16	4.7	11	19.7	0.6	2.1	1.7

Table 2: Intitial and optimized parameters

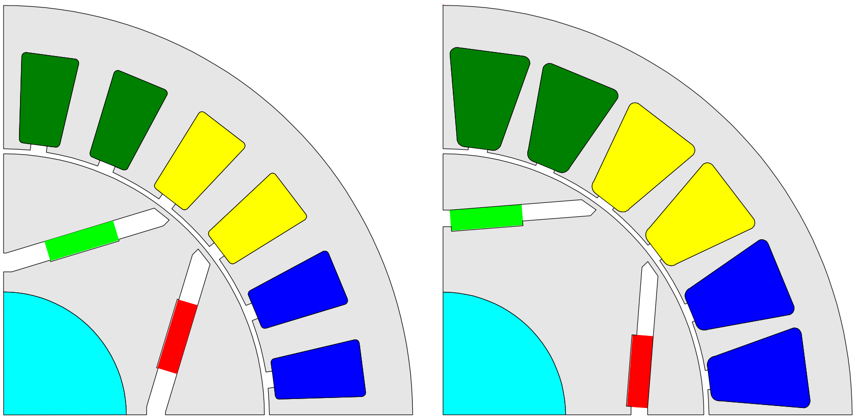
Objective	T_{avg}	T_{rip}	$U_{\text{1h,peak}}$	$THD_{\text{L-L}}$	$Cost\_function$
Initial geom.	28.13	24.36	230	14.22	136.9
Optim. geom	28.1	8.46	227.4	7.95	55.56
Weight	20	50	1	1	-
Desired value	50	10	230	5	-

Table 3: Intitial values, optimized values, weigths and desired values

4 CONCLUSION

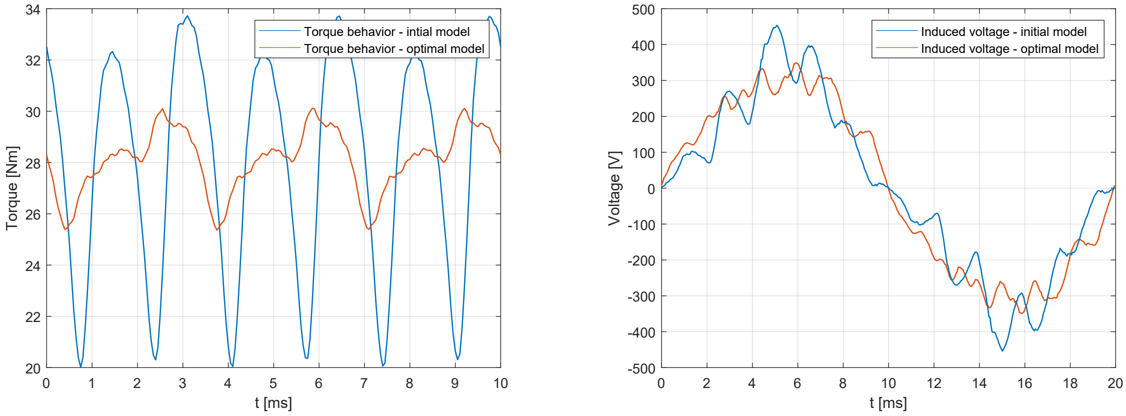
This paper firstly very briefly covers the importance of the IPM synchronous machines from the industry point of view. Later the optimization algorithms are introduced and selected SOMA algorithm is presented more thoroughly with the cost function and its weight coefficients.

It was demonstrated, that the SOMA algorithm and cost function minimalization process was sucessfully performed on the IPM machine in the ANSYS Electronics Desktop software. All of the objectives were improved and the desired T_{rip} reduction was achieved. It is worth noticing the fact, that eventhough the weight coefficient of the THD_{LL} was only equal to 1, the objective THD_{LL} was reduced from 14.22% to 7.95%. The THD_{LL} improvement is depicted also on the induced voltage characteristics in Figure 5 b). The presence of higher harmonic freqencies in the machine usually causes additional losses in winding and iron. Thus it is expected that the THD_{LL} reduction should theoretically lead to the higher machine efficiency. The biggest improvement is found in T_{rip}, which was reduced from 24.36% to 8.46%. This reduction should lower possible machine vibrations and



(a) (b)

Figure 4: Initial a) and optmized b) geometry comparison



(a) (b)

Figure 5: Comparison of initial gometry and optimal geometry characteristics, a) is torque behavior, b) is induced voltage

should result in lenghtening the machine bearings lifetime.

The optimization was done with the initial population equal to 50 members and took 4 migrations to obtain the optimal results. Cost function difference between the third and the fourth migration was only 1.5, therefore the optimization could have ended sooner with result still relatively close to the optimum. This would lead to even shorter optimization time. This paper proves the short convergency time of the SOMA algorithm, which was approximately 10 hours. To certainly prove the global optimum finding, more optimization runs would be needed.

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