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OPTIMIZATION AND ANALYSIS OF AN INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR

OPTIMIZACIJA IN ANALIZA SINHRONSKEGA MOTORJA S POTOPLJENIMI TRAJNIMI MAGNETI

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Keywords: Cogging torque, efficiency, interior permanent magnet motor, optimization, performance characteristics

Abstract

This paper aims to optimize an interior permanent magnet synchronous motor and analyze the operating characteristics of optimized models compared to the starting model. The optimization is done by optometric analysis, i.e., four motor parameters are selected and varied within certain boundaries, allowing new motor models to be obtained from each combination of these parameters. The best candidates are selected, i.e., models concerning the efficiency and cogging torque. The optimized models have improved efficiency and cogging torque compared to the starting model.

Povzetek

Namen članka je prikazati optimizacijo sinhronskega motorja s potopljenimi trajnimi magneti in analizirati delovne karakteristike optimiziranega modela v primerjavi z začetnim modelom. Metoda optimizacije je optometrična analiza, kar pomeni, da so izbrani štirje parametri motorja, ki se spreminjajo znotraj določenih meja, omogočajoč nove modele motorja iz kombinacij izbranih parametrov. Izbrani so najboljši kandidati, tj. najboljši modeli z vidika izkoristka in preskočno reluktančnega momenta. Optimizirani modeli imajo boljši izkoristek in preskočno reluktančni moment v primerjavi z začetnim modelom.

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1 INTRODUCTION

Interior permanent magnet synchronous motors (IPMM) have wide applications in the electromotive industry, machine tools, and applications where high speeds are required, i.e., spindle drives. Compared to surface permanent magnet synchronous motors (SPMM) they are more robust, due to the construction of the rotor. No bandage is required to keep the magnets in place at high speeds, as the magnets are buried inside the rotor. Less magnet material is needed for the same torque density. Finally, they have good field weakening capabilities compared to SPMM, i.e., they can maintain constant power over a wide speed range, making them a good candidate for propulsion in electric cars *[1]*. The impact of various motor parameters, such as inductance per d–axis, permanent magnet flux linkage, pole pairs, and maximum current on torque-speed characteristics, has been analyzed in *[2]-[5]*. For applications in e-mobility the smooth operation of the motor is paramount. Therefore, one of the research focuses is minimizing the cogging torque. It can be achieved by optimizing the stator and rotor shape, as stated in *[6]* and *[7]*. The IPMM can be found in several topologies regarding the design of the rotor. We will name some of them: I, V, U, 2U, VV-, V, and V- topologies. Each topology has an impact on the motor`s operating characteristics (cogging torque, torque, efficiency), as it is analyzed in *[8]*, *[9]*. Besides cogging torque, efficiency is vital in motor usage and operation.

The detailed experimental study concerning the variations of the characteristics of IPMM when load, speed, and/or magnetization conditions vary, is presented in *[10]*. The optimization, i.e., the minimization of the cogging torque by Finite Element Analysis (FEA), is presented in *[11]*. The accuracy, advantages, and difficulty level of 2D and 3D FEA of IPMM are presented in *[12]*. Finding the best motor design is often a challenging, time-consuming task. Therefore, in this paper, a software module is used for designing the motor, where four parameters (the number of conductors per slot-CPS, magnet width-MW, magnet thickness-MT, and pole embrace-EMB), are varied within certain boundaries. The pole embrace has been defined as the ratio of the actual magnet arc distance in relation to the maximum possible arc distance. The cross-section of the analyzed motor is presented in Fig. 1.

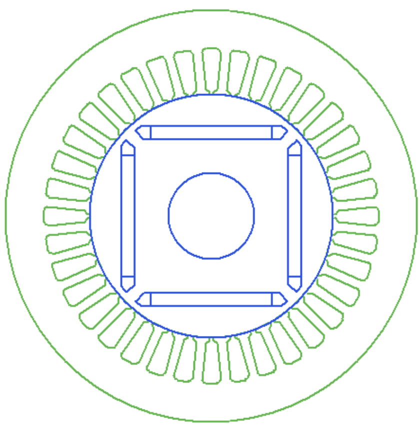


Figure 1: *Cross-section of the motor*

These four parameters' variations and combinations resulted in 840 new models. For each model, the operating characteristics are calculated: efficiency, cogging torque, weight of the magnet material, current, etc. This allows the designer to select the most optimal model in terms of several parameters, like efficiency, cogging torque, and permanent magnet consumption, thus avoiding misleading conclusions regarding the optimal design of the motor when optimization is done with optimization methods that consider only one objective function. The design gained using one objective optimization function is not always the most optimal design when other motor characteristics are analyzed. The evaluation of various motor designs that consider several operating characteristics by optometric analysis in the Ansys program allows a broader perspective of the analyzed problem, allowing the most optimal solution to be selected for several operating characteristics.

2 OPTIMIZATION

Four parameters (the number of conductors per slot-CPS, magnet width-MW, magnet thickness-MT, and pole embrace-EMB) are selected to be varied within specific ranges. The parameters are selected considering that the magnet dimensions and motor winding impact the motor efficiency and cogging torque considerably. Beside that, the magnet weight and consumption of permanent magnet material impact the motor`s price significantly, so the variation of the main magnet dimensions allows for finding the cost-effective model of the motor. The ranges of variation of parameters are presented in Table 1.

Table 1: *Ranges of variation of parameters*

Parameter	Range of variation	Step
CPS (/)	87-93	1
MT (mm)	3-7	1
MW (mm)	45-48	1
EMB (/)	0.83-0.88	0.01

The optimal designs are selected from the 840 new models derived from each combination of the four varied parameters. The first design is selected according to the highest efficiency factor, but, simultaneously, the cogging torque and magnet weight should be smaller than the initial design (BM). This design will be referred to as OM1. The second design is selected according to the smallest cogging torque, a bigger efficiency, and a smaller magnet weight than the initial design. This design will be referred to as OM2. The comparison of models BM, OM1, and OM2 is presented in Table 2. The analysis constrains all motor models to have the same output power, i.e., output torque.

Fig. 2 presents the efficiency comparison for all three models in Table II. The comparison of cogging torque for the three models is presented in Fig. 3. The air gap flux density and air-gap power for all models are presented in Fig. 4 and Fig. 5.

Table 2: *Comparison of initial and optimized models*

Parameter	BM	OM1	OM2
CPS (/)	90	90	87
MW (mm)	48	45	45
MT (mm)	5	3	3
EMB (/)	0.85	0.86	0.88
Current I_1 (A)	5.3	4.96	5.15
Stator resistance R_1 (Ω)	2.46	2.46	2.38
Wire diameter d_a (mm)	0.81	0.81	0.81
Stator slot fill factor (%)	73.4	73.4	70.97
Output power P_2 (W)	2200	2200	2200
Input power P_1(W)	2443	2414	2421
Power factor $\cos\varphi$(/)	0.98	0.99	0.99
Copper losses P_{cu} (W)	208	182	189
Core losses P_{FE} (W)	13	10.2	10.2
Rated speed (rpm)	1500	1500	1500
Output torque (Nm)	14	14	14
Torque angle (degree)	54.6	67.4	68.2
Max. output power (W)	6259	4379	4474
Frictional and windage losses P_{fw} (W)	22	22	22
$M_{cogging}$ (Nm)	0.593	0.44	0.136
η (%)	90	91.1	90.9
m_{magnet} (kg)	0.84	0.47	0.47

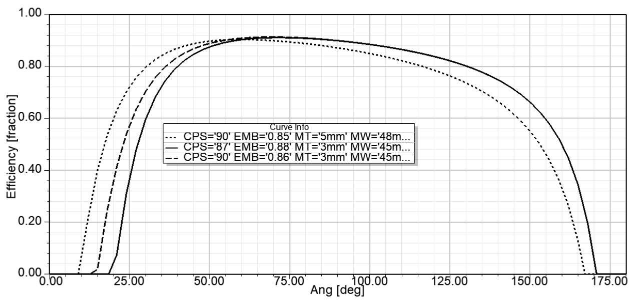


Figure 2: *Efficiency of three models*

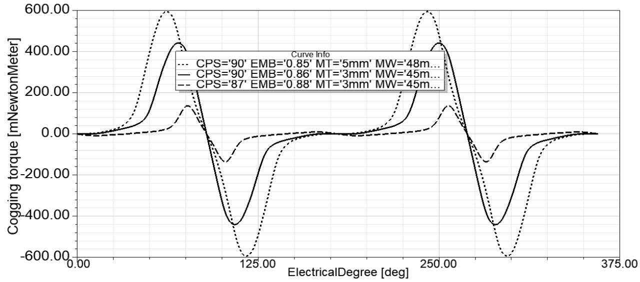


Figure 3: *Cogging torque of three models*

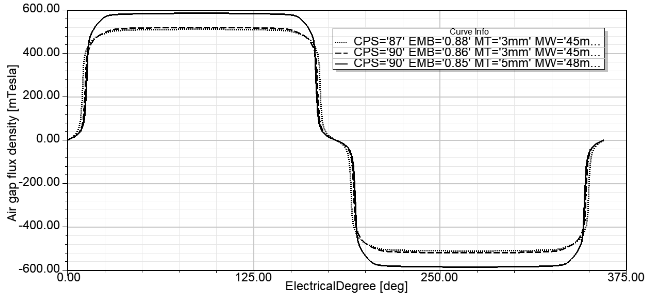


Figure 4: *Air gap flux density of three models*

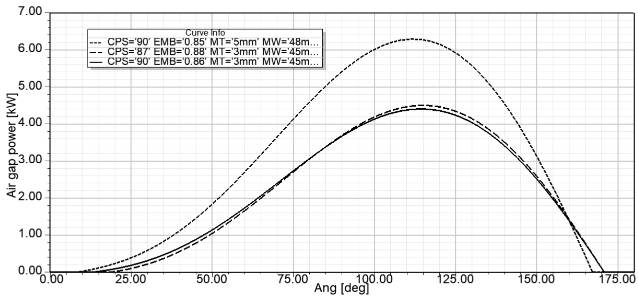
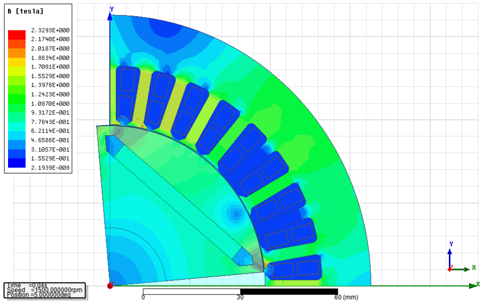
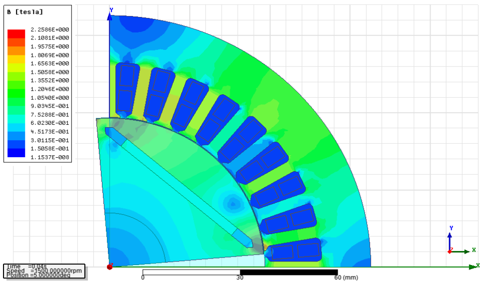


Figure 5: *Air gap power of three models*

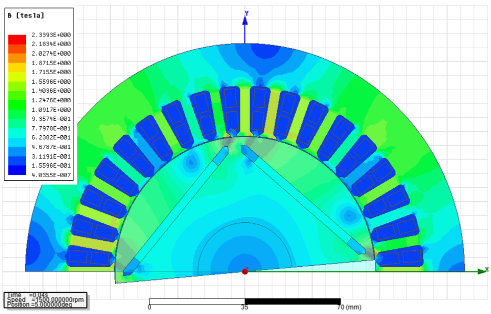
The motor analysis proceeds with FEA to determine the motor cross-section's magnetic flux density. The FEA determines the areas of the motor core where saturation occurs, thus providing valuable data for the motor designers. The flux density distribution for all models for the rated load operating conditions is presented in Fig. 6.



(a) BM



(b) OM1

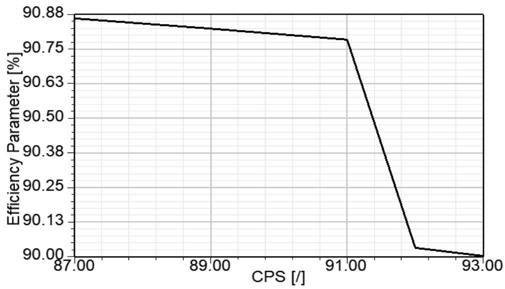


(c) OM2

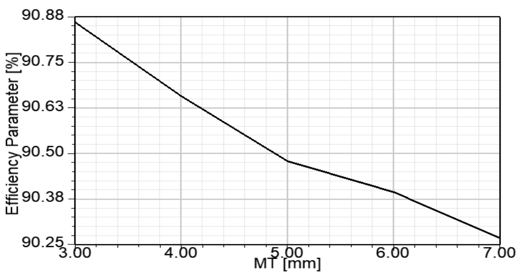
Figure 6: *Flux density distribution of three models*

3 DISCUSSION OF RESULTS

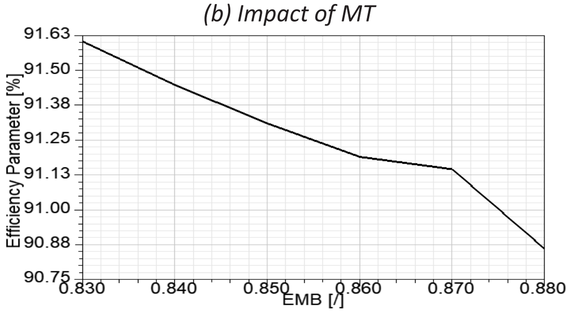
The design process of electrical machines involves various parameters regarding the electrical, magnetic, and geometric properties of the analyzed design. The ultimate goal of designers is to achieve the most optimal solution for the machine regarding several objective optimization functions with minimum costs. By varying the four parameters of IPMM, the numerous combinations, i.e., 840 combinations, are obtained from these four varied parameters, which define the new motor models. For each new model several operating characteristics are calculated simultaneously, according to which the goodness of the design is estimated. The advantage of the parametric analysis is that each model can be evaluated according to several operating characteristics that are calculated simultaneously and compared directly. The analysis aims to achieve high efficiency, minimum cogging torque, and small consumption of permanent magnet material. According to the results presented in Table 2, two models satisfy the above mentioned criteria. The model OM1 had the biggest efficiency of all models, but relatively big cogging torque. However, this design has considerably better characteristics than the starting model BM. Model OM2 had slightly decreased efficiency compared to OM1, due to the increased current and the copper losses compared to OM1, but considerably decreased cogging torque. Also, the permanent magnet's weight was reduced considerably compared to the BM, which reduces the overall costs for the motor construction. As the difference in efficiency between models OM1 and OM2 was negligible, model OM2 is the best candidate for the optimized model of BM. Therefore, the impact of each of the varied parameters on motor efficiency and cogging torque for OM2 is presented in Figs. 7 and 8 correspondingly. In the results presented in Figs. 7 and 8, the impact was analyzed of one varied parameter on efficiency and cogging torque. In contrast, the other three parameters were kept constant and equal to the values presented in Table 2.



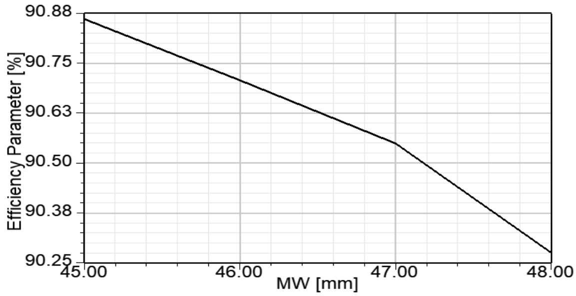
(a) Impact of CPS



(b) Impact of MT



(c) Impact of EMB

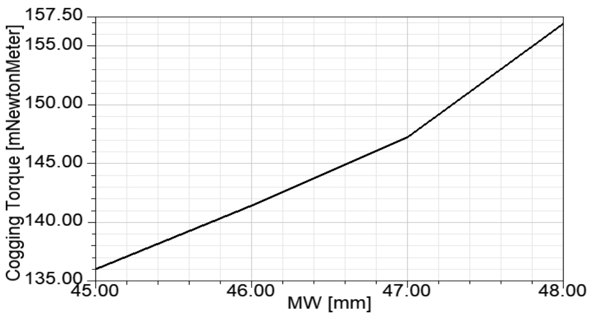


(d) Impact of MW

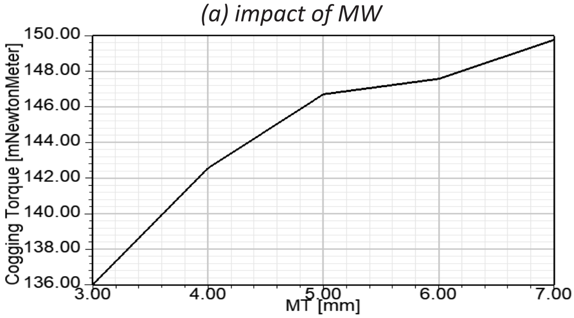
Figure 7: *The impact of varied parameters on motor efficiency*

From the results presented in Fig.7a) it can be concluded that the increase in the number of CPS decreases the efficiency. This is due to the increased resistance, which increases the copper losses. The decrease in efficiency is not linear, as the slot fill factor is set to a limited value of 75 %, so the cross-section of the copper wire is adjusted automatically when the limit of the slot fill factor is reached, which changes the stator phase resistance. The increase in the amount of magnet material, according to Figs. 7 b), c), and d) decreases the motor efficiency.

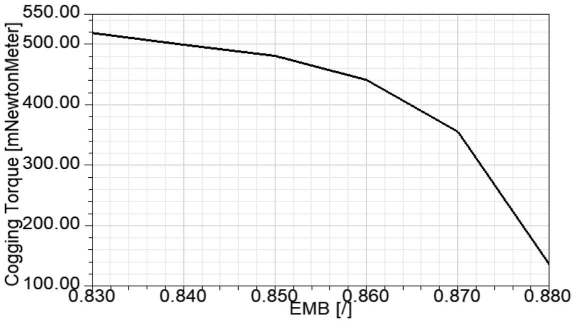
On the other hand, according to Fig. 8 c), the increase in pole embrace impacts decreasing the cogging torque significantly. Increasing magnet width and thickness increases the cogging torque (Figs. 8a) and b). The number of conductors per slot does not impact the cogging torque (Fig. 8 d).



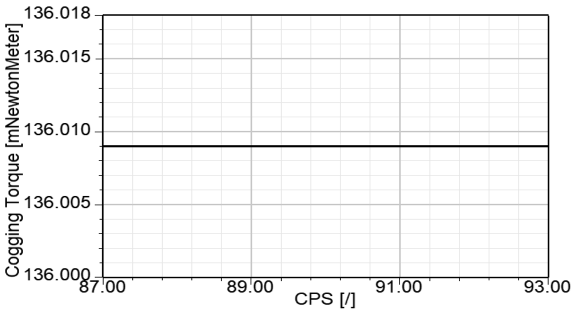
(a) impact of MW



(b) impact of MT



(c) impact of EMB



(d) impact of CPS

Figure 8: *The impact of varied parameters on cogging torque*

Fig. 6 shows that all three models were designed well, and no significant core saturation was detected. The very small parts of the stator teeth are saturated, but, generally, the flux density distribution is within the expected limits in the stator yoke, teeth and rotor core. Samarium cobalt magnets were used in all models, and, according to Fig. 6, no demagnetization of the magnets should occur.4

CONCLUSION

Energy efficiency and green technologies have become some of the most important goals of the modern society. Considering that more than the half of world-wide consumption of electricity is attributed to electrical motors, their efficiency is one of the key parameters in the design, manufacturing and usage of motors. The usage of electrical motors is extended in transportation systems, where the comfort of the passengers is of paramount importance. It is expected that the motor will operate smoothly without noise and vibrations, often present, when there is a large cogging torque. Therefore, this paper analyzes and optimizes the synchronous motor with internal magnets with respect to the efficiency and cogging torque. The most optimal combination of conductors per slot, magnet width, magnet thickness, and position of the magnets from the rotor surface is selected, resulting in a model with increased efficiency, decreased cogging torque, and magnet mass.

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