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OPTIMIZATION AND ANALYSIS OF INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR

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Abstract: The optimization of the interior permanent magnet syncrnous motor and analysis of operating characteristics of optimized models in comparison to the starting model is the objective of this paper. Optimization is done by optimetrics analysis i.e. four motor parameters are selected and varied within certain boundaries al-lowing out of each combination of these varied parameters, new motor models the be obtained. The best candidates i.e. models with respect to the efficiency and cogging torque are selected. The optimized models have improved efficiency and cogging torque with respect to the starting model.

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

INTRODUCTION

Interior permanent magnet synchronous motors (IPMM) have wide application in electromotive industry, machine tools and applications where high speeds are required i.e. spindle drives. In comparison 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 on place at high speeds as the magnets are buried inside the rotor. The less magnet material is needed for the same torque density and finally they have good field weakening capabilities in comparison to SPMM, i.e. they can maintain constant power over a wide speed range, which makes them a good candidate for the propulsion in electrical cars [1]. The impact of various motor parameter such as: inductance per d –axis, permanent magnet flux linkage, pole pairs and maximum current on torque-speed characteristics has been analysed in [2]-[5]. For applications in e-mobility the smooth operation of the motor is of a paramount importance. Therefore, one of the research focuses is the minimization of the cogging torque. It can be achieved by optimizing stator and rotor shape, as it sated in [6], [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- topology. Each topology has an impact on motor operating characteristics (cogging torque, torque , efficiency) as it is analyzed in [8], [9]. Besides cogging torque, efficiency also plays the important role in motor usage and operation. The detailed experimental study with respect to the variations of the characteristics of IPMM when load, speed and/or magnetizations 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 is presented in [12]. Finding the best design of the motor is often a challenging time consuming task. Therefore, in this paper a software module is used for designing the motor, where four parameters (number of conductors per slot-CPS, magnet width-MW, magnet length-ML 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 analysed motor is presented in Fig. 1.

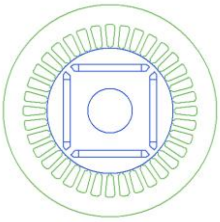

Fig.1 - *Cross-section of motor.*

The variation of these four parameters and their combinations resulted in 841 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, permanent magnet consumption thus avoiding the misleading conclusions with respect to the optimal design of the motor when optimization is done with optimization methods that take into consideration only one objective function. Gained design by using one objective function of optimization is not always the most optimal design when other motor characteristics are analysed. The evaluation of various motor designs that take into consideration several operating characteristics by optimetrics analysis in Ansys program allows broader perspective of analysed problem, allowing the most optimal solution in terms of several operating characteristics to be selected.

OPTIMIZATION

Four parameters (number of conductors per slot-CPS, magnet width-MW, magnet length-ML and pole embrace-EMB) are selected to be varied within certain ranges. The selection of parameters is done considering that the magnet dimensions and motor winding has considerable impact on motor efficiency and cogging torque. Besides that, the magnet weight and consumption of permanent magnet material has significant impact on motor price, so the variation of the main magnet dimensions allows finding the cost effective model of the motor. The ranges of variation of parameters are presented in Table I.

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Table I

Ranges of variation of parameter

Parameter	Range of variation	Step
CPS (/)	83-93	1
MT (mm)	3-7	1
MW (mm)	45-48	1
EMB (/)	0.83-0.88	0.01

Out of the obtained 841 new models, derived from each combination of the four varied parameter, the optimal designs are selected. First design is selected according to the highest efficiency factor but in the same time 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 in accordance to the smallest cogging torque, the bigger efficiency and the 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 II. The analysis constrain is all motor models to have same output power i.e. output torque.

Table I

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 cosφ(/)	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 toque (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

In Fig. 2 is presented comparison of efficiency for all three models, given in Table II. The comparison of cogging torque for the three models is presented in Fig. 3. In Fig. 4 and Fig. 5 is presented the air gap flux density and air-gap power for all models. The motor analysis proceeds with FEA for determining the magnetic flux density in motor cross-section. The FEA determines the areas of motor core where saturation occurs, thus providing a valuable data for the motor designers. The flux density distribution for all models for rated load operating condition is presented in Fig. 6.

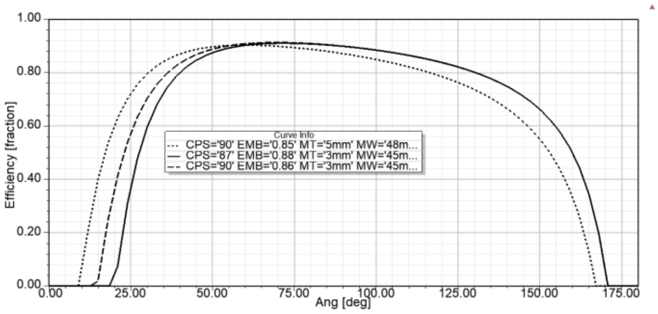


Fig.2 - *Efficiency of three models.*

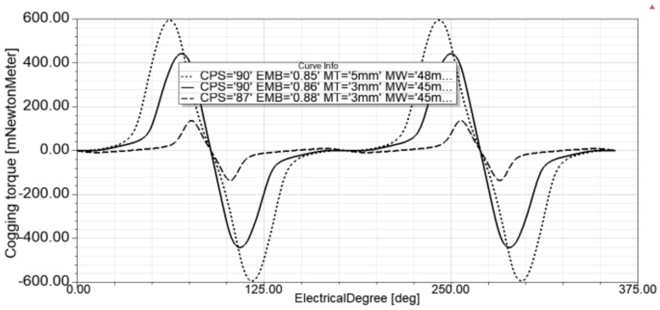


Fig.3 - *Cogging torque of three models.*

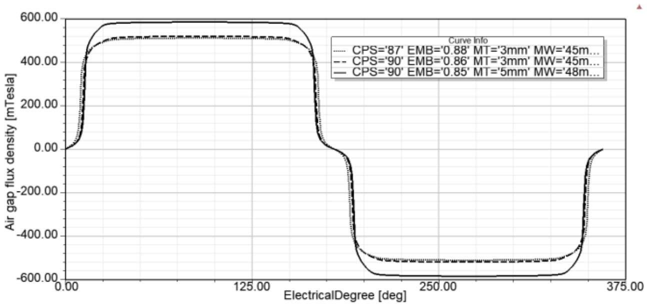


Fig.4 - *Air gap flux density of three models.*

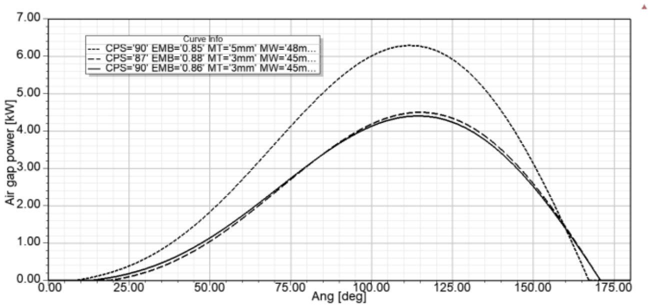
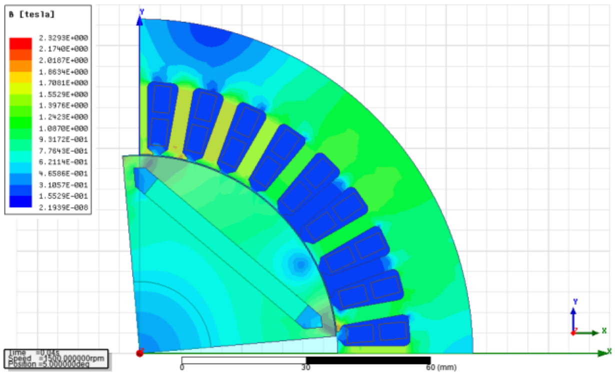
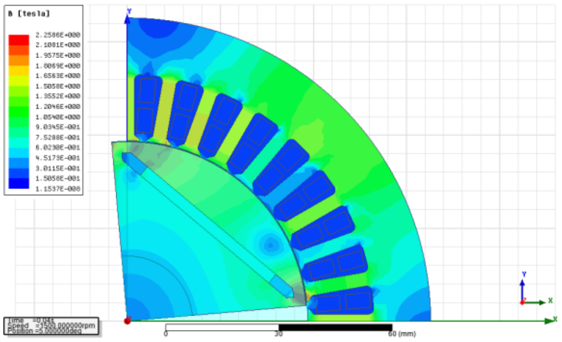


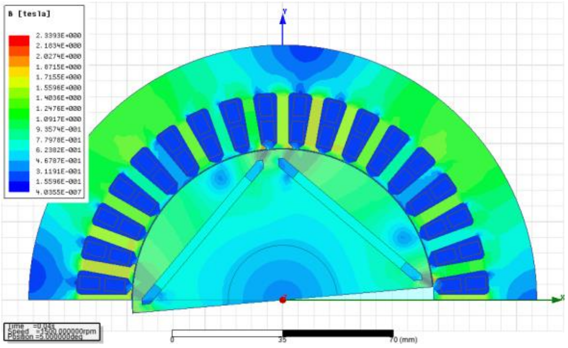
Fig.5 - *Air gap power of three models.*



(a) BM



(b) OM1

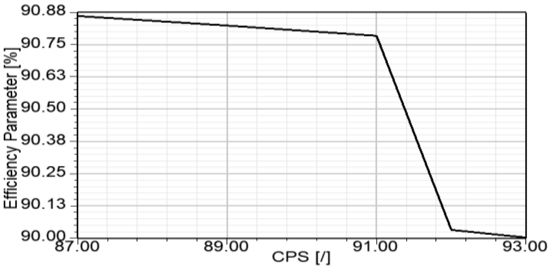


(c) OM2

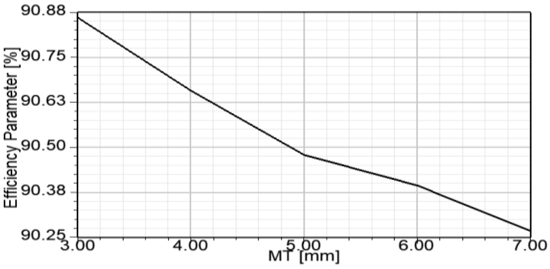
Fig.6 - *Flux density distribution of three models.*

DISCUSSION OF RESULTS

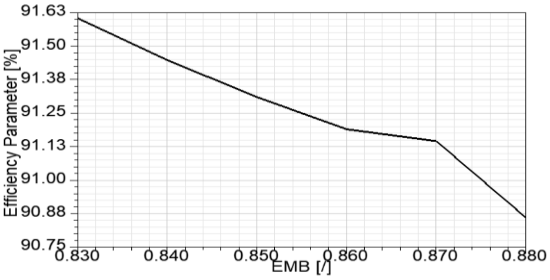
The design process of electrical machines involves various parameters regarding electrical, magnetic and geometric properties of the analysed design. The ultimate goal of designers is to achieve the most optimal solution of the machine regarding several objectives function of optimization with minimum costs. By varying the four parameters of IPMM the numerous combinations, i.e. 841 combinations, out of these four varied parameters are obtained, which define the new motor models. Simultaneously, for each new model several operating characteristics are calculated according to which the goodness of the design is estimated. The advantage of the presented parametric analysis is that each model can be evaluated in accordance to several operating characteristics that are simultaneously calculated, and directly compared. In the presented analysis the goal is to achieve the high efficiency, minimum cogging torque and small consumption of permanent magnet material. According to the results presented in Table II, two models satisfy the above mentioned criteria. The model OM1 has the biggest efficiency from all models but relatively big cogging torque. Yet, this design has considerably better characteristics than the starting model BM. Model OM2 has slightly decreased efficiency, compared to OM1, due to the increased current and the copper losses in comparison to OM1 but considerably decreased cogging torque. Also the weight of permanent magnet is considerably reduced in comparison to the BM which reduces the overall costs for the motor construction. As the difference in efficiency between models OM1 and OM2 is negligible the model OM2 could be considered as 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 of one varied parameter on efficiency and cogging torque is analysed while the rest of three parameters are kept constant and equal to the values presented in Table II.



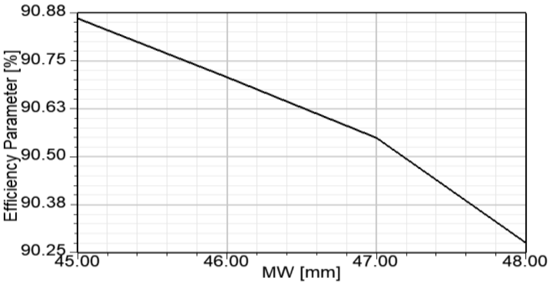
(a) Impact of CPS



(b) Impact of MT



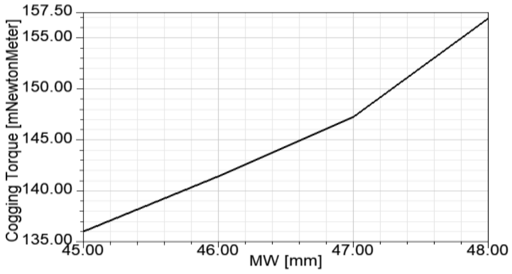
(c) Impact of EMB



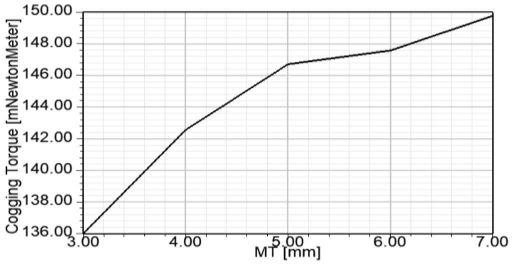
(d) Impact of MW

Fig.7 - *Impact of varied parameter on motor efficiency.*

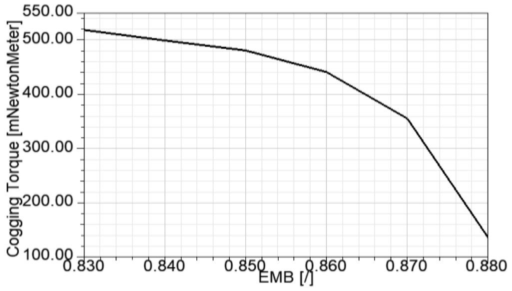
From the results presented in Fig.7a) it can be concluded that the increase of number of CPS decreases the efficiency. This is due to the increased resistance which increases the copper losses. The decrease of efficiency is not linear as the slot fill factor is set to limited value of 75 % so the cross-section of the copper wire is automatically adjusted when limit of the slot fill factor is reached, which in turn changes the stator phase resistance. The increase of 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 of pole embrace has significant impact on decreasing the cogging torque. The increase of magnet width and magnet thickness increases the cogging torque (Figs. 8a) and b). The number of conductor per slot has no impact on the cogging torque (Fig. 8 d).



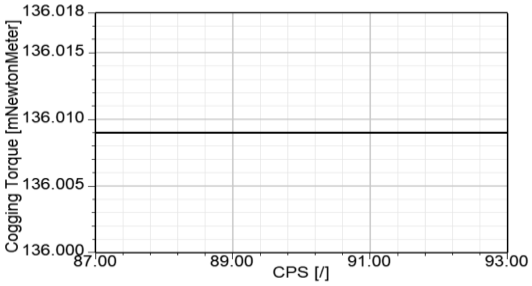
(a) impact of MW



(b) impact of MT



(c) impact of EMB



(d) impact of CPS

Fig.8 - *Impact of varied parameter on cogging torque*.

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

CONCLUSION

Energy efficiency and green technologies has become one of the most important goals of the modern society. Considering that more than the half of world-wide consumption of electricity is attributed to the 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, in this paper is analysed and optimized 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 which resulted with model with increased efficiency, decreased cogging torque and magnet mass.

REFERENCES

[1] A. Dalcali: “Optimal design of high-performance interior PM motor for electrical vehicle”, The International Journal of Energy & engineering science, Vol. 3 (2), 2018, pp. 26-35.

[2] Y. E. Shklyarskiy, A. Y. Shklyarskiy, A. S. Lutonin: “Sizing parameters of interior permanent magnet synchronous motor based on torque-speed characteristics”, Journal of Physics: Conference Series, 1753 012026, 2021.

[3] E.S. Beser: “Electrical equivalent circuit for modelling permanent magnet synchronous motor”, Journal of Electrical Engineering, Vol.72, no.3, 2021, pp. 176-183.

[4] B.-W. Jo, J.-K. Kang, C.-H. Song, K.-C. Kim: “Electromagnetic Characteristics Analysis of the Interior Permanent Magnet Synchronous Motor considering Temperature Change”, International Journal of Engineering & Technology, Vol. 7 (3.24), 2018, pp. 194-196.

[5] M. Künzler, R. Pfüger, R. Lehmann, Q. Werner: “Dimensioning of a permanent magnet synchronous machine for electric vehicles according to performance and integration requirements”, Automotive and Engine Technology Vol. 7, 2022, pp. 97–104.

[6] J.-S. Yu, H.-W. Cho, J.-Y. Choi, S.-M. Jang, S.-H Lee: ‘Optimum Design of Stator and Rotor Shape for Cogging Torque Reduction in Interior Permanent Magnet Synchronous Motors” Journal of Power Electronics, Vol. 13, No. 4, 2013, pp. 546-551.

[7] S.-e. Kim, Y.-m. You: “Optimization of a Permanent Magnet Synchronous Motor for e-Mobility Using Metamodels”, Applied Sciences, Vol. 12(3), 2022, 1625.

[8] B. M. Dinh, N. V. Anh: “Detail Design of Interior Permanent Magnet Motor for Electric Vehicle”, Proceedings of the International Conference on Industrial Engineering and Operations Management Istanbul, Turkey, March 7-10, 2022, pp. 1329-1336.

[9] L. Niu, M. Zhang: “The optimal design and research of interior permanent magnet synchronous motors for electric vehicle applications”, The Journal of Engineering, 2023;2023:e12258, pp. 1-20.

[10] M. Caruso, A. O. Di Tommaso, R. Miceli, C. Nevoloso, C. Spataro, F. Viola: “Characterization of interior permanent magnet synchronous motors for loss model algorithm identification”, 19th International Workshop on ADC Modelling and Testing , Budapest, Hungar, 2016, pp. 37-42.

[11] G. Zhang, We. Yu , W. Hua, R. Cao, H. Qiu, A. Guo: “The Design and Optimization of an Interior, Permanent Magnet Synchronous Machine Applied in an Electric Traction Vehicle Requiring a Low Torque Ripple”, Applied Science, 2019, 9, 3634;

[12] S. Naik, B. Bag, K. Chandrasekaran: “A 2D and 3D Analysis on Electromagnetic Parameters of Spoke-shape Interior Permanent Magnet Synchronous Motor Using FEM” , Periodica Polytechnica Electrical Engineering and Computer Science, Vol. 67(2), 2023, pp. 181–193.