SRTTU

Journal of Electrical and Computer Engineering Innovations
(JECEI)
Journal homepage: http://www.jecei.sru.ac.ir

JECEI

Research paper

Design Optimization of the Delta-Shape Interior Permanent Magnet Synchronous Motor for Electric Vehicle Application

***S. Nasr*[1]*, B. Ganji*[1,*]*, M. Moallem*[2]**

[1]*Faculty of Electrical and Computer Engineering, University of Kashan, Kashan, Iran.*

[2]*Faculty of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran.*

Article Info

Article History:
Received 25 July 2022
Reviewed 16 October 2022
Revised 28 October 2022
Accepted 07 November 2022

Keywords:
Interior permanent magnet synchronous motor
Electromagnetic modeling
Design optimization
Torque ripple reduction
Finite element method

[*]Corresponding Author's Email Address: *bganji@kashanu.ac.ir*

Abstract

Background and Objectives: Due to exclusive advantages of the permanent magnet synchronous motors (PMSMs) such as large torque/power density, high efficiency and wide speed range in constant power region, special attention has been paid to these motors especially for electric vehicle (EV) application. A conventional type of PMSMs which is more suitable for EV application is the interior permanent magnet synchronous motors (IPMSM). The main objective of the present paper is design optimization of this type of PMSM to increase efficiency and reduce torque ripple which are important for EV application.
Methods: Using different shape design optimization methods including rotor notch, flux barrier and skewed rotor, design optimization of the delta-shape IPMSM is done and an optimized design is suggested first. One of the most important factors affecting the performance of the IPMSM is the magnet arrangement in the rotor structure. Based on the design of experiments (DOE) algorithm, optimal values of some design parameters related to magnet are then determined to improve more the motor performance of the suggested structure.
Results: The simulation results based on finite element method (FEM) are provided for a typical high-power IPMSM to evaluate the effectiveness of the proposed technique. In comparison to the initial design, 7% increase of average torque, 50% reduction of torque ripple and 1.4% increase of efficiency are resulted for the optimized motor.
Conclusion: Using the proposed hybrid design optimization procedure (shape design optimization with optimum design parameters), significant improvement of some characteristics related to the delta-shape IPMSM including efficiency, average torque and torque ripple is resulted and this conclusion is desirable for EV application.

Introduction

In order to solve the problems related to the conventional vehicles such as environment and noise pollutions, special attention has been paid in recent decades to use of the EVs. In addition, the cost of charging an EV is less than the petrol or diesel cars and this can be considered as energy saving due to the limitations of fossil fuels. One of the essential requirements of EVs is to select an appropriate electric motor. In comparison to other types of electric motors, the PMSMs have larger torque/power density due to the presence of magnetic in the motor structure. In addition, efficiency and saving of battery capacity are high in these motors. Therefore, this type of the motor is an appropriate candidate for EV applications [1]-[5]. Nowadays, these motors are used more effectively than the past because of advance permanent magnet (PM)

Doi: 10.22061/jecei.2022.9207.587

materials and modern control methods. There are different rotor topologies for the PMSMs and one of them is IPMSM in which the rare-earth PMs are used to achieve high performance.

This type of PMSM produces high power density due to its utilization of both reluctance torque and electromagnetic torque. In addition, it has a more robust structure that is desirable for EV application. In comparison to the surface-type PMSM in which PMs are located on the surface of rotor, the magnetic flux of the air-gap for the IPMSM contains more harmonics and consequently it has higher torque ripple. Therefore, multi-objective design optimization of the delta-shape IPMSM is considered in the present paper with the aim of reducing torque ripple and improving average torque and efficiency simultaneously which are essential for EV application.

Significant research has been conducted on different design aspects of the IPMSM. A design optimization method is introduced in [6] to minimize torque ripple of the IPMSM. The effect of a rotor skew on performance of IPMSM has been studied in [7]. The most important factors affecting the performance of IPMSM are the arrangement and shape of PMs used in the rotor structure. In addition, some design parameters such as pole-arc to pole-pitch ratio [8], flux barrier topology [9] and number of layers [10] can impact the performance significantly. The multi-layer IPMSM is introduced in [11] for EV application and it is showed that the three-layered motor has lower torque ripple and core loss than two-layered structure due to reduction of the harmonics of air-gap flux density. An IPMSM with ∇+U shape rotor topology is introduced in [12] for EV applications and it is demonstrated that its efficiency is better than V and ∇ shape machines. The impact of PM topology on core loss and efficiency has been also evaluated in this reference. The shapes of the rotor notch and flux barriers could significantly change the electromagnetic characteristics of the IPMSM. In [13], torque ripple of IPMSM is reduced using putting notches on the rotor surface. Optimal design of the PMSM for hybrid electric vehicles (HEVs) is considered in [14] to maximize the energy efficiency. An analytical model is also developed in this reference to determine the geometrical parameters and predict quickly the efficiency.

When the analysis of motor is carried out with finite element method (FEM), use of the optimization algorithms such as the particle swarm optimization (PSO) and genetic algorithm (GA) are usually time-consuming methods. In this case, the DOE method can be used properly for the optimization due to the high computational speed [15]-[17]. Using the response surface method (RSM) and the Taguchi method, design optimization of the IPMSM for electric compressors of air conditioners used in EVs is done in [18] to maximize efficiency and minimize cogging torque. Based on the combination of DOE method and Taguchi's method, an optimization procedure for a submersible PMSM is introduced in [19] to have the maximum efficiency and minimum cogging torque.

As indicated above, a multi-objective design optimization of the IPMSM is proposed here to reduce torque ripple while efficiency and average torque are improved. Hence, the main contributions of the paper can be summarized as developing a multi-objective optimization of an IPMSM by using shape design, type of winding and DOE technique for optimum magnet design. The rest of the paper is organized as follows: The proposed design optimization method is described clearly in next section.

To evaluate the effectiveness of this design optimization method, it is applied to a typical IPMSM suitable for EV application and related simulation results are given in the third section of the paper. Finally, the last section highlights the main contributions and conclusions of the paper.

Design Optimization Methods

Various shape design optimization methods have been already introduced in the literatures by which performance IPMSM can be improved. Some of them are described briefly in the following. Using the Hairpin winding and the DOE method, a new design optimization procedure is also proposed and it is introduced in this section.

A. Shape Design Optimization Methods

This paper focuses on the shape design optimization of the delta-shape IPMSM for high-speed traction application and comparison of different rotor topologies is considered.

As shown in Fig. 1, four different rotor structures with the same stator are designed. Use of notch on rotor is a conventional method for reducing torque ripple of PMSMs as done in [20]. According to the position of the notch on the rotor, different topologies have been chosen for the IPMSM in this reference and an average value of 37% was illustrated for torque ripple reduction. When a notch is located on the rotor surface, it leads to stepping the air-gap and consequently the cogging torque and torque ripple could be reduced.

This approach can be also suggested for the delta-shape IPMSM as observed from comparison between Fig. 1a and Fig. 1b.

Flux barrier in motor structure is also an effective method for average torque improvement and torque ripple reduction [9].

To improve torque waveform of the IPMSM, different symmetric flux barrier shapes are introduced in [21]. The Taguchi method is also used to optimize the design parameters. Compared to the initial design, torque ripple is decreased by 50% and average torque is increased by 8.2% for the introduced model.

Also, the shape and number of barriers can affect the value of cogging torque and torque ripple [22]. Due to reduction of magnetic flux-leakage, flux barrier can also improve the produced power.

Fig. 1c shows how the flux barrier is used for the discussed IPMSM. When the barrier is included in the structure of the motor, magnetic flux in the air-gap is increased and therefore the average torque can be improved. Moreover, the cogging torque/torque ripple can be also reduced using the skewed stator/rotor as done in [23]-[25]. The impact of different rotor skew patterns on torque ripple and average torque for an IPMSM is evaluated in [7]. Significant reduction of torque ripple (about 68%) is resulted in this research while average torque is also reduced a little (2%). The manner of skewing the rotor for the discussed delta-shape IPMSM is shown in Fig. 1d. As illustrated from this figure, 4 layers are considered here that there is a specific displacement between them.

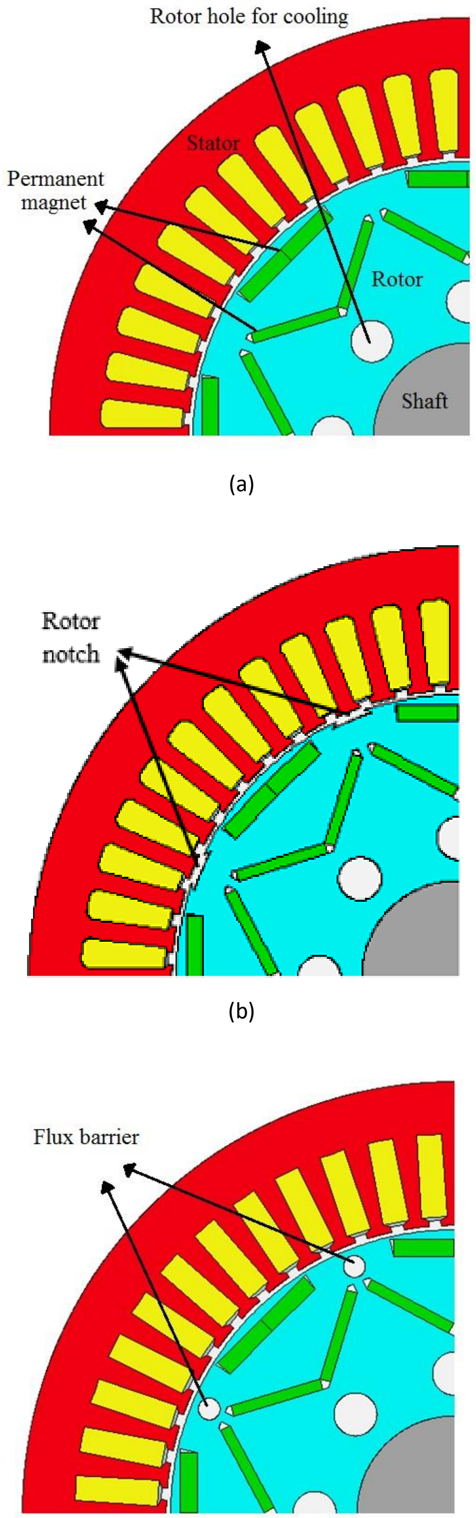
B. The Proposed Design Optimization Method

The various shape design optimization methods described above are applied to a typical delta-shape IPMSM and their impacts on the motor performance (average torque, torque ripple and efficiency) are evaluated. Then, the most effective method is selected. For this selection, two other changes are also considered in design of motor to improve more its performance. This hybrid approach is defined here as the proposed design optimization method. The two above-mentioned changes are use of the Hairpin winding and determination of the optimal values of some important design parameters explained in the following.

I. The Hairpin winding

Similar to other types of electric motors, thermal issue of the IPMSM needs to be considered in design optimization of the motor especially for traction application due to the high-speed operation. It must be noted that energy saving achievement and cooling system volume reduction are resulted by improvement of the efficiency and reduction of power losses in electrical vehicle. The Hairpin winding has been introduced in [26] to improve the efficiency through the reduction of copper losses. It can also decrease the spatial harmonics because variation of the air-gap flux is lower. These variations lead to reduction of torque ripple, iron loss and vibration/noise [27].

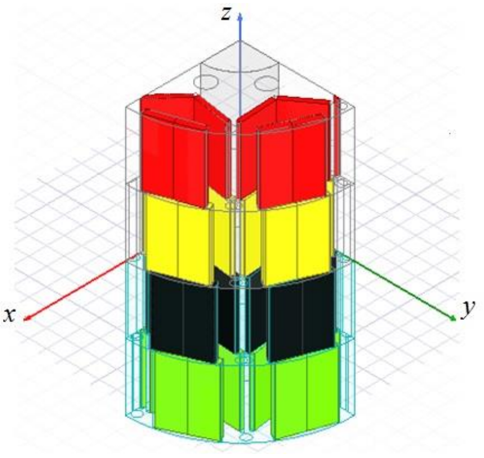
The Hairpin winding compared with the stranded winding can also result in a higher fill factor up to 0.75. Using the Hairpin winding is desirable when high efficiency/power density is required [28]. Therefore, the hairpin winding is considered here to improve the performance of the delta-shape IPMSM. Fig. 2 shows obviously the difference between the stranded winding and the Hairpin winding.



(a)

(b)

(c)



(d)

Fig. 1: Different topologies considered for the discussed IPMSM: (a) conventional structure, (b) using notch in the rotor, (c) using flux barrier in the rotor and (d) skewed rotor.

(a) (b)

Fig. 2: Different windings: (a) stranded winding, (b) Hairpin winding.

II. *Optimum design parameters*

Three important design parameters for PM including the magnet thickness, the magnet bar width, and the pole V angle in two layers depicted in Fig. 3 are selected here and their optimal values are determined to have the best performance. Based on the DOE method, this optimization is done and the Minitab software is used for implementation of this method. Since the design optimization of the delta-shape IPMSM (Fig. 1a) is considered here, it must be noted that the optimum values of six design parameters must be determined in the process of optimization. In order to find the optimum values, the Taguchi method is employed here as one of the best DOE methodologies. Since a minimum number of experiments are required for the Taguchi method, it is an appropriate optimization method when the optimal design of the motor is done using FEM. In recent years, this method has been applied to the design optimization of electric motors such as PMSMs [17]. In this method, the design factors are selected first and every factor takes its value. The orthogonal table is established and the experiments are then designed to obtain influence of factors and their different levels on optimal output. Finally, the mean value and signal-to-noise ratio (SNR) is utilized to obtain the best combination of levels [29]. As shown in Table 1, three different levels are considered for every parameter. The ranges of variables for each factor are shown in this table. It must be noted that these ranges are derived using the Nissan Leaf IPM motor described in [30].

According to the number of factors and the levels of each factor, the number of required experiments and how to combine the levels of factors in each experiment are specified using the Taguchi orthogonal arrays. The obtained results are summarized in Table 2. For three selected levels, the number of possible combinations is 729 (36). As seen obviously from this table, the Taguchi method has significantly reduced the number of tests required from 729 to 27 tests. Due to the long time of the simulations done with FEM, this reduction saves significant time to achieve the optimal point. The Taguchi method determines the optimal point according to the results of this limited number of experiments and using statistical calculations. For the experiments listed in Table 2, analysis of the motor with FEM should be carried out to calculate the average torque, torque ripple and efficiency.

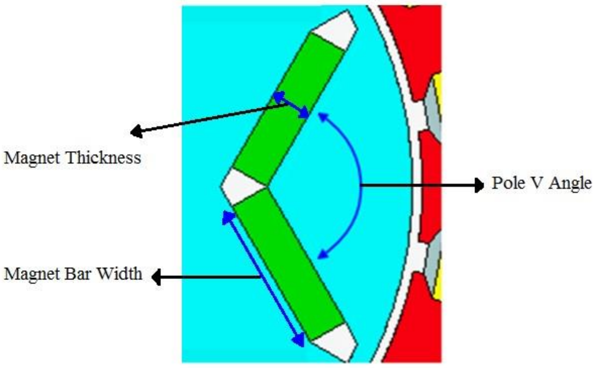


Fig. 3: Design parameters selected for main orthogonal array.

Table 1: Controllable factors and values

	Level 1	Level 2	Level 3
A = pole v angle 1 [°]	124	150	180
B = pole v angle 2 [°]	118	124	130
C = magnet bar width 1 [mm]	13.5	13.9	14.3
D = magnet bar width 2 [mm]	20.6	21.3	21.5
E = magnet thickness 1 [mm]	3.4	3.9	4.4
F = magnet thickness 2 [mm]	2.1	2.6	3.1

Using the experiments designed by the Taguchi method and after analyzing them, the optimal combination of levels for factors and values of average torque, torque ripple and efficiency at the optimal point are obtained. For instance, the mean value of the effect of level 2 of the factor B on average torque is calculated using (1).

Table 2: Orthogonal array

	A	B	C	D	E	F
1	1	1	1	1	1	1
2	1	1	1	1	2	2
3	1	1	1	1	3	3
4	1	2	2	2	1	1
5	1	2	2	2	2	2
6	1	2	2	2	3	3
7	1	3	3	3	1	1
8	1	3	3	3	2	2
9	1	3	3	3	3	3
10	2	1	2	3	1	2
11	2	1	2	3	2	3
12	2	1	2	3	3	1
13	2	2	3	1	1	2
14	2	2	3	1	2	3
15	2	2	3	1	3	1
16	2	3	1	2	1	2
17	2	3	1	2	2	3
18	2	3	1	2	3	1
19	3	1	3	2	1	3
20	3	1	3	2	2	1
21	3	1	3	2	3	2
22	3	2	1	3	1	3
23	3	2	1	3	2	1
24	3	2	1	3	3	2
25	3	3	2	1	1	3
26	3	3	2	1	2	1
27	3	3	2	1	3	2

According to Table 2, the average effect related to level 2 of the factor B is obtained from nine experiments including 4, 5, 6, 13, 14, 15, 22, 23 and 24 where the factor B is set on level 2. For the other factors, the mean value of the effect of the levels on the mean torque, torque ripple and efficiency are obtained in a same way.

$$T_{B2}=(T_{avg}(4)+ T_{avg}(5)+ T_{avg}(6)+ T_{avg}(13)+ T_{avg}(14)+ T_{avg}(15)+ T_{avg}(22)+ T_{avg}(23)+ T_{avg}(24))/9 \qquad (1)$$

The Taguchi experiments use the SNR to identify control factors that reduce variability. In general, the term of signal refers to the mean value of output and the term of noise indicates the undesirable value. Therefore, higher values of the SNR identify setting of the control factors that minimize the effects of the noise factors. In addition, analysis of variance (ANOVA) can be useful to determine the influence of any given input. The ANOVA analysis can also be utilized to demonstrate the mean response magnitudes of controllable process parameters. To perform the ANOVA, the sum of squares must be calculated. The goal of variance analysis is to optimize two or more factors simultaneously. The sum of squares of each of the factors (SSF) should be obtained in the first step of the variance analysis to choose the optimum levels.

Simulation Results

The proposed design optimization method is applied to a typical delta-shape IPMSM (Fig. 1a) whose specifications are given in Table 3 and simulation results are presented in this section.

Based on FEM using Maxwell software, analysis of this motor for speed of 4000 rpm and the maximum current 323.5 A is carried out and average torque, torque ripple and efficiency are obtained 175.8 Nm, 17.2% and 96.3 %, respectively.

Table 3: Motor specifications

Number of phases	3
Number of poles	8
Diameter of stator	198 mm
Diameter of rotor	130 mm
Air-gap	1 mm
Stack length	150 mm
Maximum speed	10000 RPM
RMS phase current	323.5 A
Rated torque	185 N.m
Permanent magnet material	N30UH
Core material	M250

A. The Results Related to the Shape Design Optimization Methods

Using the different shape design optimization methods described in the second section of the paper, some design optimizations are done for the discussed IPMSM and simulation results obtained for the considered operating point are summarized in Table 4. Compared with the initial design (average torque=175.9 Nm, torque ripple=17.3% and efficiency=96.3 %), this table shows that the models 1 and 2 reduce both average torque and torque ripple.

To have the best performance, it must be explained that the number of rotor layers and the mechanical degree for the skewed rotor are selected 4 and 1.875°, respectively.

With regard to the values obtained for the initial design, it is illustrated from Table 4 that the model 2 has better performance (higher average torque, lower torque ripple and the same efficiency). Since these improvements are desirable for EV application, the model 2 is considered and its performance is improved more using the proposed design optimization method. The related simulation results are presented in next subsection.

Table 4: Comparison between the shape design optimization methods

	Average torque [Nm]	Torque ripple [%]	Efficiency [%]
Initial design	175.9	17.3	96.3
Model 1 (Initial design with notch)	173.5	13.7	96.4
Model 2 (Initial design with flux barrier)	179.9	11.5	96.3
Model 3 (Model 2 + skewed rotor)	173.5	9.7	96.2

B. Performance Improvement Using the Proposed Design Optimization Method

As indicated above, the model 2 defined in Table 4 is selected as an appropriate candidate and its performance is improved more using the design optimization method proposed in the second section of the paper. The simulation results related to this improvement are presented in the following.

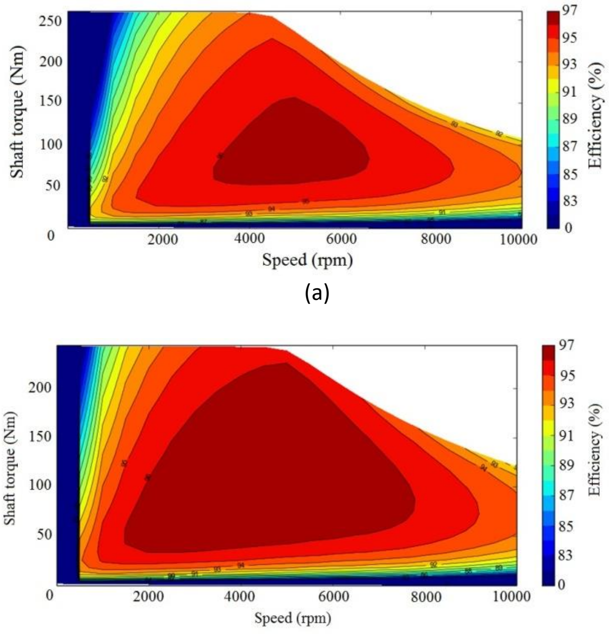
I. Results related to the Hairpin winding

Using the Hairpin winding, both thermal design and efficiency of IPMSM can be improved as discussed at above.

Since these improvements are very important for EV application, the model 2 with this type of winding is considered here and it is defined as model 4. With analysis of the model 4 for the considered operating point, the average torque, torque ripple and efficiency are obtained and they are 182.3 Nm, 8.5% and 97.5 %, respectively. Compared with the values for the model 2 (average torque=179.9 Nm, torque ripple=11.5% and efficiency=96.3 %), it is seen that all characteristics are improved using the model 4. It must be also indicated that slot area of the Hairpin winding for the model 4 is similar to that for the model 2.

As indicated above, the arrangement of the conductors for the Hairpin winding could increase the fill factor significantly. As an example, the fill factor is 0.4 for the stranded winding and 0.67 for the Hairpin winding when the areas of slots in the discussed IPMSM are 115.3 mm^2 for the two windings.

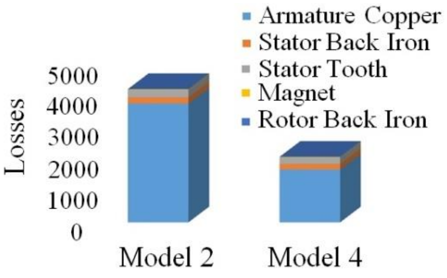
The efficiency maps of the two different models are shown in Fig. 4. The winding temperature and total losses including copper loss, core loss and magnet eddy current loss are predicted for the model 2 and the model 4 and they are shown in Fig. 5.



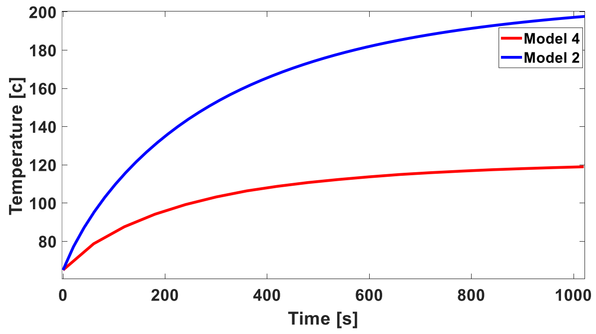
(a)

(b)

Fig. 4: The efficiency map of model 2: (a) the stranded winding, (b) the hairpin winding.



(a)



(b)

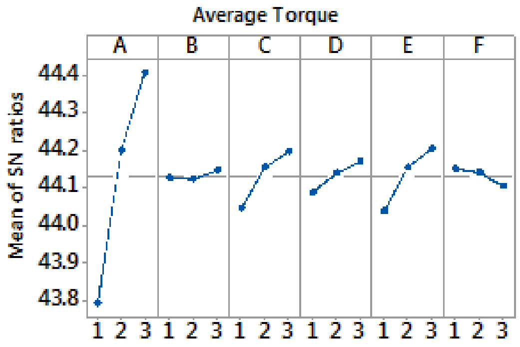
Fig. 5: The predicted winding temperature and total losses: (a) losses, (b) temperature.

II. Results with consideration of the optimum design parameters

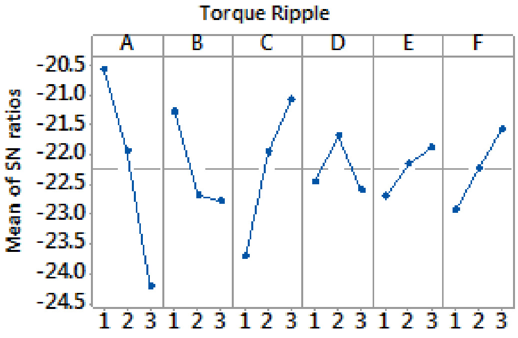
Since the model 4 has showed the best level of performance, it is selected and its performance is improved more with determining the optimum parameters of PMs as indicated above. This optimized motor is called the model 5 and the related simulation results are presented here.

For the model 5, the mean of SNR related to average torque, torque ripple and efficiency are shown in Fig. 6. According to this figure, combination of A3-B3-C3-D3-E3-F1 leads to the highest average torque. In addition, this figure shows that combination of A1-B1-C3-D2-E3-F3 is related to the lowest torque ripple and combination of A3-B3-C3-D3-E3-F2 is for the highest efficiency. In the first stage, only the third level of the factor C and E can be selected.

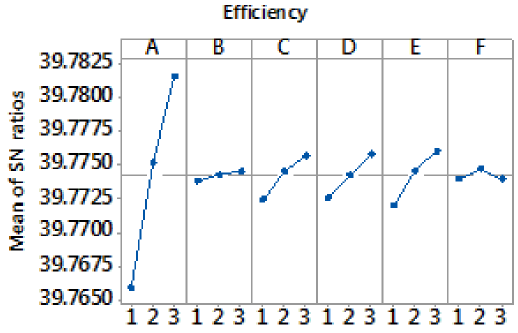
Table 5 is used to find the best level for other factors. The sum of squares of the factors is calculated and it is also given in this table. To obtain the effect of factors, the value of each factor must be divided by the total. As illustrated from Table 5, the effect of factor A on average torque is 87.61%, on ripple torque is 48.82% and on efficiency is 86.1%. Therefore, level 3 is selected between the two levels 1 and 3 of factor A. Finally, it can be seen that the best optimization combination is A3-B1-C3-D2-E3-F3.



(a)



(b)



(c)

Fig. 6: The Taguchi SNR plot for: (a) average torque, (b) torque ripple, (c) efficiency.

Table 5: Impact of the selected design parameters on motor performance

	Average torque		Torque ripple		Efficiency	
	SSF	Effect [%]	SSF	Effect [%]	SSF	Effect [%]
A	198.5	86.1	55.1	49.2	0.047	86.1
B	0.3	0.1	13.4	11.9	0.0001	0.2
C	12.1	5.2	31	27.7	0.002	3.9
D	3.2	1.4	5.8	5.2	0.002	3.7
E	15	6.5	1.4	1.3	0.003	5.8
F	1.5	0.7	5.3	4.7	0.0002	0.3

Regarding the optimized IPMSM (the model 5), the average torque, torque ripple and efficiency for the considered operating point are 187.7 Nm, 6.7% and 97.6 %, respectively. Compared with the values related to the model 4 (average torque=182.3 Nm, torque ripple=8.5% and efficiency=97.5 %), it is illustrated that motor performance has been improved more using the model 5. This improvement is more evident when the optimized IPMSM (the model 5) is compared with the initial design (average torque=175.9 Nm, torque ripple=17.3% and efficiency=96.3 %).

It must be noted that these improvements are very valuable for EV applications. The instantaneous torque waveforms predicted for two different designs (initial and the optimized motor) are also compared in Fig. 7. This figure shows obviously increase of average torque and reduction of torque ripple for the model 5 (optimal design).

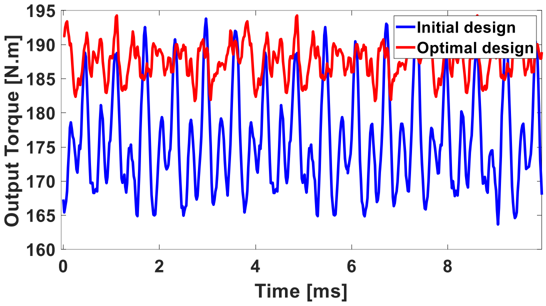


Fig. 7: The predicted instantaneous torque.

Conclusion

Using the MAXWELL, a simulation model based on FEM was developed for the delta-shape IPMSM to predict the important electromagnetic characteristics. Three different design optimization methods including consideration of notch on rotor, inserting flux barrier on rotor and having a skewed rotor were applied to a typical delta-shape IPMSM and their impacts on average torque, torque ripple and efficiency were evaluated first using FEM. Compared with initial design, it was seen that the design with flux-barrier had better performance. This design was then selected for more optimization and the optimum values of some design parameters were determined using the DOE method. In addition, the Hairpin winding was used for it instead of the conventional stranded winding. Using these two changes, significant improvement of motor performance was resulted when it was compared to the initial design (7% increase of average torque, 50% reduction of torque ripple and 1.4% increase of efficiency for the considered operating point).

Since these improvements are so valuable for an EV, the proposed design optimization method can be considered appropriately when the delta-shape IPMSM is used for this application.

Author Contributions

S. Nasr developed the model and provided the simulation results under supervision of Dr. Ganji and Prof. Moallem. The paper was written by S. Nasr and it is improved by Dr. Ganji and Prof. Moallem.

Acknowledgment

The authors gratefully acknowledge the ISKRA company managers for their support to develop the model and provide the simulation results.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

PMSM	Permanent Magnet Synchronous Motor
EV	Electric Vehicle
IPMSM	Interior Permanent Magnet Synchronous Motor
DOE	Design of Experiments
FEM	Finite Element Method
PM	Permanent Magnet
HEV	Hybrid Electric Vehicle
PSO	Particle Swarm Optimization
GA	Genetic Algorithm
RSM	Response Surface Method
SNR	Signal-to-Noise Ratio
ANOVA	Analysis of Variance
SSF	Sum of Squares of Factors

References

[1] F. Momen, K. Rahman, Y. Son, "Electrical propulsion system design of Chevrolet Bolt battery electric vehicle," IEEE Trans. Ind. Appl., 55(1): 376-84, 2018.

[2] X. Sun, Z. Shi, Y. Cai, G. Lei, Y. Guo, J. Zhu, "Driving-cycle-oriented design optimization of a permanent magnet Hub motor drive system for a four-wheel-drive electric vehicle," IEEE Trans. Transp. Electrif., 6(3): 1115-25, 2020.

[3] J. W. Chin, K. S. Cha, M. R. Park, S. H. Park, E. C. Lee, M. S. Lim, "High efficiency PMSM with high slot fill factor coil for heavy-duty EV traction considering AC resistance," IEEE Trans. Energy Convers., 36(2): 883-94, 2021.

[4] H. Dhulipati, S. Mukundan, Z. Li, E. Ghosh, J. Tjong, N. C. Kar, "Torque performance enhancement in consequent pole PMSM based on magnet pole shape optimization for direct-drive EV," IEEE Trans. Magn., 57(2): 8103407, 2021.

[5] A. Balamurali, A. Kundu, Z. Li, N. C. Kar, "Improved harmonic iron loss and stator current vector determination for maximum

efficiency control of PMSM in EV applications," IEEE Trans. Ind. Appl., 57(1): 363-73, 2021.

[6] D. W. Kim, G. J. Park, J. H. Lee, J. W. Kim, Y. J. Kim, S. Y. Jung, "Hybridization algorithm of fireworks optimization and generating set search for optimal design of IPMSM," IEEE Trans. Magn., 53(6): 16914097, 2017.

[7] J. W. Jiang, B. Bilgin, Y. Yang, A. Sathyan, H. Dadkhah, A. Emadi, "Rotor skew pattern design and optimisation for cogging torque reduction," IET Electr. Syst. Transp., 6(2): 126-35, 2016.

[8] F. Chai, P. Liang, Y. Pei, S. Cheng, "Analytical method for iron losses reduction in interior permanent magnet synchronous motor," IEEE Trans. Magn., 51(11): 15552769, 2015.

[9] E. Sayed, Y. Yang, B. Bilgin, M. H. Bakr, A. Emadi, "A comprehensive review of flux barriers in interior permanent magnet synchronous machines," IEEE Access, 7: 149168-149181, 2019.

[10] K. Yamazaki, M. Kumagai, T. Ikemi, S. Ohki, "A novel rotor design of interior permanent-magnet synchronous motors to cope with both maximum torque and iron-loss reduction," IEEE Trans. Ind. Appl., 49(6): 2478-2486, 2013.

[11] S. Zhu, W. Chen, M. Xie, C. Liu, K. Wang, "Electromagnetic performance comparison of multi-layered interior permanent magnet machines for EV traction applications," IEEE Trans. Magn., 54(11): 18164250, 2018.

[12] S. Zhu, Y. Hu, C. Liu, K. Wang, "Iron loss and efficiency analysis of interior PM machines for electric vehicle applications," IEEE Trans. Ind. Electron., 65(1): 114-124, 2018.

[13] G. H. Kang, Y. D. Son, G. T. Kim, J. Hur, "A novel cogging torque reduction method for interior-type permanent-magnet motor," IEEE Trans. Ind. Appl., 45(1): 161-167, 2009.

[14] D. Wei, H. He, J. Cao, "Hybrid electric vehicle electric motors for optimum energy efficiency: A computationally efficient design," Energy, 203: 117779, 2020.

[15] C. Ma, L. Qu, "Multiobjective optimization of switched reluctance motors based on design of experiments and particle swarm optimization," IEEE Trans. Energy Convers., 30(3): 1144-53, 2015.

[16] K. Li, X. Zhang, H. Chen, "Design optimization of a tubular permanent magnet machine for cryocoolers," IEEE Trans. Magn., 51(5): 8202708, 2015.

[17] J. Si, S. Zhao, H. Feng, R. Cao, Y. Hu, "Multi-objective optimization of surface-mounted and interior permanent magnet synchronous motor based on Taguchi method and response surface method," Chin. J. Electr. Eng., 4(1): 67-73, 2018.

[18] S. K. Cho, K. H. Jung, J. Y. Choi, "Design optimization of interior permanent magnet synchronous motor for electric compressors of air-conditioning systems mounted on EVs and HEVs," IEEE Trans. Magn., 54(11): 18164285, 2018.

[19] J. Cui, W. Xiao, W. Zou, S. Liu, Q. Liu, "Design optimisation of submersible permanent magnet synchronous motor by combined DOE and Taguchi approach," IET Electr. Power Appl., 14(6): 1060-1066, 2020.

[20] M. H. Hwang, H. S. Lee, H. R. Cha, "Analysis of torque ripple and cogging torque reduction in electric vehicle traction platform applying rotor notched design," Energies, 11(11): 3053, 2018.

[21] Z. Pan, K. Yang, X. Wang, "Optimal design of flux-barrier to improve torque performance of IPMSM for electric spindle," in Proc. 18th International Conference on Electrical Machines and System: 773-8, 2015.

[22] T. Zhou, J.-X. Shen, "Cogging torque and operation torque ripple reduction of interior permanent magnet synchronous machines by using asymmetric flux-barriers," in Proc. 20th International Conference on Electrical Machines and System: 1-6, 2017.

[23] X. Ge, Z. Zhu, G. Kemp, D. Moule, C. Williams, "Optimal step-skew methods for cogging torque reduction accounting for three-dimensional effect of interior permanent magnet machines," IEEE Trans. Energy Convers., 32(1): 222-32, 2017.

[24] Z. Shi, X. Sun, Y. Cai, Z. Yang, G. Lei, Y. Guo, J. Zhu, "Torque analysis and dynamic performance improvement of a PMSM for EVs by skew angle optimization," IEEE Trans. Appl. Supercond., 29(2): 18352259, 2018.

[25] R. Islam, I. Husain, A. Fardoun, K. McLaughlin, "Permanent magnet synchronous motor magnet designs with skewing for torque ripple and cogging torque reduction," IEEE Ind. Appl. Ann. Meet., 45(1): 1552-59, 2007.

[26] D. Deurell, V. Josefsson, "FEA study of proximity effect in hairpin windings of a PMSM for automotive applications," MSc thesis, Chalmers University of Technology, 2019.

[27] D. S. Jung, Y. H. Kim, U. H. Lee, H. D. Lee, "Optimum design of the electric vehicle traction motor using the hairpin winding," in Proc. 75th Vehicular Technology Conference: 1-4, 2012.

[28] G. Berardi, N. Bianchi, "Design guideline of an AC hairpin winding," in Proc. XIII International Conference on Electrical Machines: 2444-50, 2018.

[29] X. Sun, Z. Shi, J. Zhu, "Multiobjective design optimization of an IPMSM for EVs based on fuzzy method and sequential Taguchi method," IEEE Trans. Ind. Electron., 68(11): 10592-600, 2021.

[30] E. Sayed, R. Yang, J. Liang, M. H. Bakr, B. Bilgin, A. Emadi, "Design of unskewed interior permanent magnet traction motor with asymmetric flux barriers and shifted magnets for electric vehicles," Electr. Power Compon. Syst., 48(6): 652-666, 2020.

Biographies

Sepideh Nasr was born in Isfahan, Iran, in 1990. She received her M.Sc. in Electrical Engineering from the Isfahan University of Technology, Isfahan, Iran, in 2016. She is currently pursuing the Ph.D. degree in the Electrical Engineering at University of Kashan in Iran. Her main research interest includes electrical and thermal design of electrical machines especially PMSM for EV application.

- Email: s.nasr@alumni.iut.ac.ir
- ORCID: 0000-0003-0974-4228
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: NA

Babak Ganji received his B.Sc. degree from Esfahan University of Technology, Iran in 2000, and M.Sc. and Ph.D. from University of Tehran, Iran in 2002 and 2009, respectively, all in major Electrical Engineering-power. He was granted DAAD scholarship in 2006 from Germany and worked in institute of Power Electronics and Electrical Drives at RWTH Aachen University as a visiting researcher for 6 months. He has been working at University of Kashan in Iran since 2009 as an Associate Professor and his research interest is modeling and design of advanced electric machine especially switched reluctance motor.

- Email: bganji@kashanu.ac.ir
- ORCID: 0000-0003-2310-215X
- Web of Science Researcher ID: NA
- Scopus Author ID: 24724058600
- Homepage: https://faculty.kashanu.ac.ir/bganji/en

Mehdi Moallem (SM'95) received the Ph.D. degree in electrical engineering from Purdue University, West Lafayette, IN, in 1989. He has been with the Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran since 1991. His research interests include design and optimization of electromagnetic devices, application of advance numerical techniques and intelligent systems to analysis and design of electrical machines, and power quality.

- Email: moallem@cc.iut.ac.ir
- ORCID: 0000-0002-5965-0978
- Web of Science Researcher ID: NA
- Scopus Author ID: 7005252934
- Homepage: https://moallem.iut.ac.ir/

How to cite this paper:
S. Nasr, B. Ganji, M. Moallem, "Design optimization of the delta-shape interior permanent magnet synchronous motor for electric vehicle application," J. Electr. Comput. Eng. Innovations, 11(2): 291-300, 2023.

DOI: 10.22061/jecei.2022.9207.587

URL: https://jecei.sru.ac.ir/article_1810.html