Research Article

Performance Comparison of Permanent Magnet Synchronous Motor with Different Magnet Configuration Used in Electric Vehicle

Bektas Aybars Balta, Engin Aycicek, Mustafa Gurkan Aydeniz and Haci Dedecan

Abstract— **Due to the depletion of fossil fuels, increasing environmental pollution, and global warming, the use of electric vehicles is becoming more widespread. Electric vehicles offer numerous advantages, including high efficiency, quiet and vibration-free operation, and being environmentally friendly. Electric motors provide high power density and a wide torque-speed range. Therefore, many engineering studies, analyses, and comparisons are conducted for electric motors used in electric vehicles. In this study, modeling and analyses of interior permanent magnet synchronous motors with different magnet configurations were carried out, taking as a reference an interior permanent magnet synchronous motor used in a mass-produced and well-selling electric vehicle. At the end of the study, structures with different magnet configurations were compared in terms of performance characteristics such as torque, torque ripple, and efficiency.**

Index Terms—**Electric vehicles, interior permanent magnet synchronous motor, torque, finite element analysis**

I. Introduction

DUE TO the depletion of fossil fuels, increasing environmental pollution, and the rising impact of global warming, the use of electric vehicles has become increasingly widespread. Vehicles with internal combustion engines significantly contribute to air pollution, particularly in large cities. Electric vehicles are a good alternative to reduce environmental pollution and achieve zero emissions [1]. Electric vehicles offer many advantages, such as high efficiency, quiet and vibration-free operation, and being environmentally friendly. Moreover, with the advancement of electric motor, battery, and controller technologies, interest in electric vehicles continues to grow. Electric motors provide high power density, high efficiency, and a wide torque-speed range.

Numerous studies have been conducted on the electric motors used in electric vehicles. Hashemnia and Asaei compared various motors used in electric vehicle applications, including direct current motors, asynchronous motors, permanent magnet synchronous motors, switched reluctance motors, and brushless direct current motors, in terms of power density, efficiency, cost, and maintenance. They concluded that permanent magnet synchronous motors and brushless direct current motors are suitable for electric vehicle applications due to their advantages, such as high efficiency and power density [2]. Yıldırım et al. compared different types of electric motors and drivers used in electric vehicles based on factors such as efficiency, cost, weight, cooling, maximum speed, reliability, fault tolerance, power level, and vehicle acceleration time. Their findings indicated that brushless direct current motors and asynchronous motors are advantageous in terms of cost, while permanent magnet synchronous motors are superior in terms of efficiency and power density [3].

Rind et al. examined traction motors used in electric and hybrid electric vehicles with different configurations and structures, along with high-performance sensorless speed control methods, revealing the advantages and disadvantages of electric motors in these vehicles [4]. Krings and Monissen conducted a study on the preferred designs, performance characteristics, and future concepts of electric traction motors used in electric and hybrid electric vehicles [5]. Kim et al. proposed a new optimization method to enhance the performance of an interior permanent magnet synchronous motor with a V-shaped permanent magnet rotor. They developed optimal designs using this method and validated their proposed optimization through tests on prototype motors [6].

F. Rong and D. Manfeng designed and analyzed a 30 kW V-shaped interior permanent magnet synchronous motor for an electric bus. Following the analysis, prototype production and

Bektas Aybars BALTA, is with ASELSAN A.S., Ankara, Turkey, (e-mail: abalta@aselsan.com).
https://orcid.org/0009-0001-8591-6127

Engin AYCICEK, is with Department of Electrical Engineering University of Yıldız Technical, Istanbul, Turkey, (e-mail: eaycicek@yildiz.edu.tr).
https://orcid.org/0000-0002-4295-9063

Mustafa Gurkan AYDENIZ, is with Department of Electrical Engineering University of Yıldız Technical, Istanbul, Turkey, (e-mail: aydeniz@yildiz.edu.tr).
https://orcid.org/0000-0003-1104-6752

Haci DEDECAN, is with ASELSAN A.S., Ankara, Turkey, (e-mail: hdedecan@aselsan.com).
https://orcid.org/0009-0005-4859-5853

Manuscript received Oct 1, 2024; accepted Dec 16, 2024.
DOI: 10.17694/bajece.1559038

tests demonstrated that the motor met the desired performance and characteristics [7]. Liu et al. performed design and comparative analysis of interior permanent magnet synchronous motors (IPMSMs) with different rotor topologies, concluding that the V-shaped IPMSM has advantages over other topologies [8]. Yan et al. compared different rotor structures of interior permanent magnet synchronous motors for light electric vehicles using finite element analysis. They also produced prototypes and conducted experimental tests, showing that the motor with a V-shaped magnet is advantageous in terms of average torque, wide speed range operation, field-weakening capability, and high efficiency compared to other structures [9]. Zhou et al. designed and compared four different rotor topologies of permanent magnet synchronous motors with the same core dimensions and amount of permanent magnet material. They found that EPMSMs offer higher starting torque, partly due to the reluctance torque effect, and are superior in terms of torque ripple, efficiency, and demagnetization resistance [10].

Husain and Lee examined the designs of interior permanent magnet synchronous motors with different magnet configurations for high-speed traction applications. They compared motors with V-shaped, double-layer V-shaped, and U-shaped magnets, all designed with the same stator, highlighting the advantages and disadvantages of each configuration [11]. Finally, Murali et al. investigated the design and comparison of different rotor topologies for permanent magnet synchronous motors commonly used in electric vehicles. They used ANSYS Maxwell software to compare the motors in terms of performance characteristics such as air gap flux density, cogging torque, and efficiency [12].

The performance of Interior Permanent Magnet Synchronous Motors (IPMSMs) with different rotor designs has been widely studied, with most research focusing on optimizing geometric parameters and flux-weakening capabilities. However, this study takes a more practical approach by analyzing real-world performance metrics like torque, torque ripple, and efficiency, tailored to the specific needs of electric vehicle (EV) applications. By doing so, it not only highlights the strengths of different rotor designs but also offers valuable insights for improving IPMSM performance in EVs.

This study contributes to the literature by presenting a detailed comparison of the performance of IPMSM configurations (V-shaped, flat-shaped, and U-shaped). A comprehensive modeling and optimization process were conducted using ANSYS Maxwell software to thoroughly examine the effects of different configurations on parameters such as torque, torque ripple, and efficiency. In this process, the superior performance of the V-shaped configuration in terms of torque ripple is particularly significant for electric vehicles requiring low noise and high driving comfort. Furthermore, the high torque generation capacity of the flat-shaped configuration provides an advantage for applications involving heavy load transportation or requiring high traction power.

II. MODELING OF REFERENCE MOTOR AND DIFFERENT CONFIGURATIONS

Electric vehicles require high performance in terms of high torque density, high power factor, high efficiency, a wide constant power range at high speeds, high torque capacity at high speeds, and high maximum speed. Additionally, the motors used in these applications must feature compact size, low weight, low cost, and high reliability. For these reasons, permanent magnet synchronous motors (PMSMs) are predominantly preferred in electric vehicles. In this study, the 50 kW, 8-pole V-shaped interior permanent magnet synchronous motor (IPMSM) found in the mass-produced and high-selling Toyota Prius model is chosen as the reference. The specifications of the reference IPMSM are provided in Table 1 [13,14].

TABLE I
SPECIFICATIONS OF REFERENCE IPMSM

Maximum torque	400 Nm
Nominal speed	1200 rpm
Stator outer diameter	269.24 mm
Stator inner diameter	161.9 mm
Number of stator slots	48
Rotor outer diameter	160.4 mm
Rotor inner diameter	110.64 mm
Axial length	83.82 mm

When examining the values of the stator inner diameter and rotor outer diameter provided in Table I, it can be observed that the air gap of the motor is 0.75 mm. Additionally, the magnetic material of the stator and rotor in the reference IPMSM is M19-29G, while the permanent magnets are NdFeB N36Z. Since the reference IPMSM has 8 poles and 48 stator slots, the number of slots per pole is 6. The stator winding configuration consists of 8 coils connected in series per phase, with 9 turns in each coil. Each turn contains 13 wires, with a thickness of AWG 19.

Based on this information, the reference IPMSM was modeled in two dimensions using ANSYS Maxwell software. The different configurations studied—V-shaped, flat-shaped, and U-shaped IPMSMs—were modeled with the same stator dimensions, winding configuration, rotor dimensions, magnetic material type, and permanent magnet material type as the reference IPMSM. The optimization process was designed to ensure that the rotor configurations being studied achieved performance comparable to the reference motor. To do this, key parameters such as the distance between poles (Rib), magnet thickness, magnet width, and the distance of the magnets from the rotor's inner diameter (O) were adjusted within specific ranges, considering the physical constraints of the rotor design.

For the V-shaped IPMSM, the optimization parameters were adjusted as follows:

- The distance between poles (Rib) was varied between 2–8 mm in 1 mm increments,
- Magnet thickness between 5.5–7.5 mm in 0.5 mm increments,
- Magnet width between 36–40 mm in 1 mm

increments, and

- The distance of the magnets from the rotor inner diameter (O) between 4.5–7.5 mm in 1 mm increments.

For the flat-shaped IPMSM, the following ranges were explored:

- Rib was varied between 3.5–7.5 mm in 1 mm increments,
- Magnet thickness between 6–8 mm in 0.5 mm increments,
- Magnet width between 38–40 mm in 0.5 mm increments, and
- O between 8–12 mm in 1 mm increments.

For the U-shaped IPMSM, the optimization ranges were defined as:

- Rib between 8–13 mm in 1 mm increments,
- Magnet thickness between 6–8 mm in 0.5 mm increments,
- Magnet width between 42–44 mm in 0.5 mm increments, and
- O between 2.5–5.5 mm in 1 mm increments.

For each configuration, the goal was to find parameter combinations that provided performance similar to the reference motor. Once suitable configurations were identified, detailed analyses were carried out. This careful approach ensured that the optimization process was both thorough and aligned with practical design considerations. The final dimensions of the optimized configurations and the reference IPMSM are provided in Table 2.

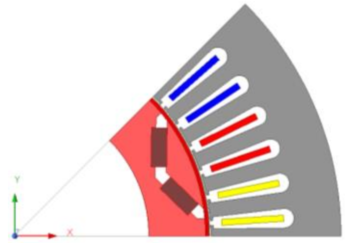
TABLE II
FINAL PARAMETRIC DIMENSIONS

	Reference IPMSM	V-shaped IPMSM	Flat-shaped IPMSM	U-shaped IPMSM
Rib	14 mm	4 mm	4,5 mm	10 mm
Magnet Width	32 mm	38 mm	38,5 mm	42 mm
Magnet Thickness	6,5 mm	7,5 mm	6 mm	6 mm
O	7,3 mm	7,5 mm	12 mm	3,5 mm

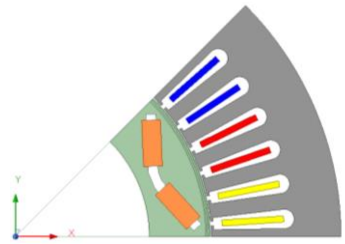
The images of the IPMSMs modeled in ANSYS Maxwell are shown in Fig. 1.

After creating the models, analyses were conducted in ANSYS Maxwell to obtain performance characteristics such as torque, torque ripple, cogging torque, and efficiency. These analyses were performed using the finite element analysis (FEA) method. Torque, torque ripple, and efficiency analyses were carried out with a supply current of 250A and a speed of 1200 rpm. Cogging torque analyses were conducted at a speed of 1 degree per second without any power supply. The torque values obtained from the analyses are presented in Fig.2.

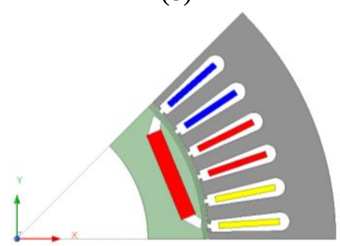
As seen in Fig.2, the flat-shaped IPMSM achieves the highest torque value at 279.85 Nm. The V-shaped IPMSM reaches 264.7 Nm, surpassing the reference IPMSM, which has a torque value of 245 Nm. The U-shaped IPMSM, however, produces the lowest torque at 232.1 Nm. The torque ripple values obtained under the same conditions are shown in Fig.3.



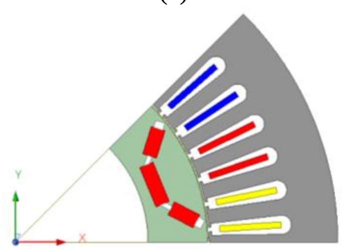
(a)



(b)



(c)



(d)

Fig.1. Final motor models (a) Reference IPMSM (b) V-shaped IPMSM (c) Flat-shaped IPMSM (d) U-shaped IPMSM

III. ANALYSIS RESULTS OF IPMSMS

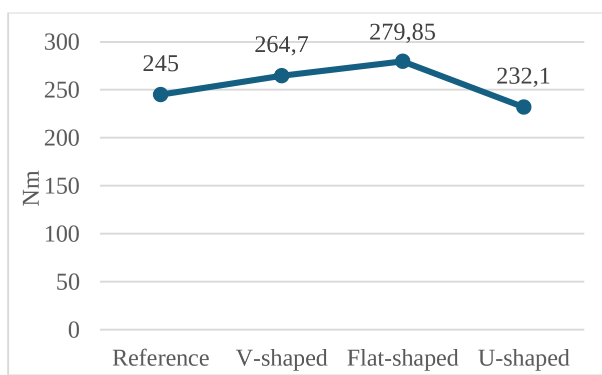


Fig.2. Torque comparison chart

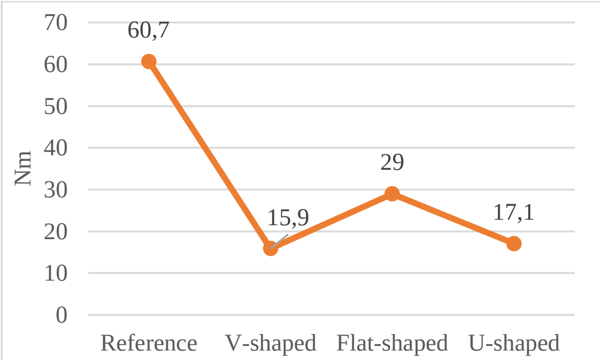


Fig.3. Torque ripple comparison chart

As seen in Fig.3, the torque ripple for the reference IPMSM is 60.7 Nm, which corresponds to 24% of the torque value. The V-shaped IPMSM exhibits a torque ripple of 15.9 Nm, or 6% of the torque value. The flat-shaped IPMSM has a torque ripple of 29 Nm, which is 10% of its torque value, while the U-shaped IPMSM has a torque ripple of 17.1 Nm, corresponding to 7% of its torque value. The V-shaped IPMSM shows the best performance in terms of torque ripple. The efficiency values obtained from the analyses are presented in Fig.4.

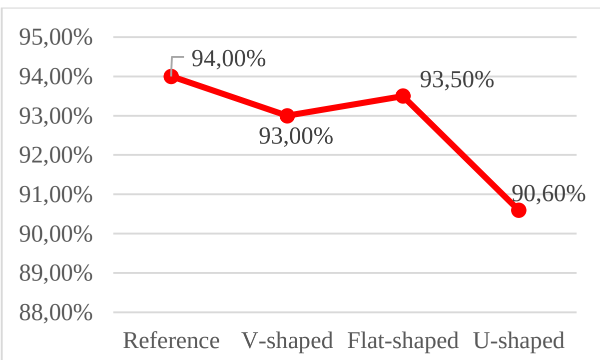


Fig.4. Efficiency comparison chart

As seen in Fig.4, the efficiencies of the reference, V-shaped, and flat-shaped IPMSMs are quite similar. The U-shaped IPMSM, however, has the lowest efficiency. Finally, the results of the cogging torque analysis are presented in Fig.5.

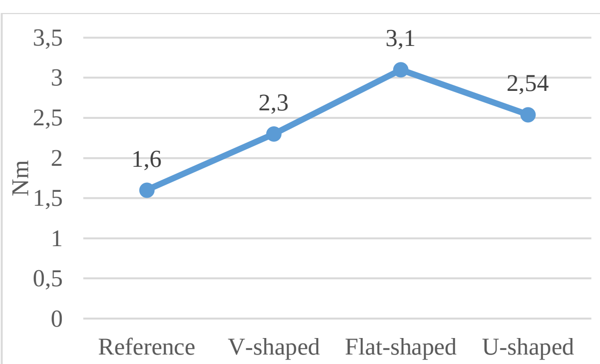


Fig.5. Cogging torque comparison chart

As shown in Fig.5, due to changes in magnet configuration and the increase in permanent magnet volumes, the cogging torque values of the V-shaped, flat-shaped, and U-shaped IPMSMs were higher than those of the reference IPMSM. However, when considering the torque and power levels, the obtained values remained within acceptable limits.

IV. CONCLUSION

In this study, the modeling and finite element analysis (FEA) of interior permanent magnet synchronous motors (IPMSMs) with different magnet configurations, commonly used in electric vehicles, were conducted using ANSYS Maxwell. Initially, the electric motor from the Toyota Prius model was selected as the reference, and its model was created and analyzed. Following this, the reference IPMSM's different magnet configurations—V-shaped, flat-shaped, and U-shaped—were modeled and analyzed. The findings of the study reveal the advantages of different IPMSM configurations in terms of various performance metrics. The flat-shaped IPMSM delivers the highest torque value of 279.85 Nm, making it particularly suitable for applications requiring high traction power. The V-shaped IPMSM, on the other hand, stands out for its low torque ripple (6.0%), addressing the needs for driving comfort and quiet operation. Meanwhile, although the U-shaped IPMSM has limitations in terms of efficiency, its low torque ripple (17.1 Nm) makes it advantageous for applications requiring precise speed control. These results will provide important guidance in the development of an optimum motor configuration suited to the various driving and design requirements of electric vehicles.

REFERENCES

[1] Cao, Z., Mahmoudi, A., Kahourzade, S., & Soong, W. L. (2021, September). An overview of electric motors for electric vehicles. In 2021 31st Australasian Universities power engineering conference (AUPEC) (pp. 1-6). IEEE.

[2] Hashemnia, N., & Asaei, B. (2008, September). Comparative study of using different electric motors in the electric vehicles. In 2008 18th international conference on electrical machines (pp. 1-5). IEEE.

[3] Yildirim, M., Polat, M., & Kürüm, H. (2014, September). A survey on comparison of electric motor types and drives used for electric vehicles. In 2014 16th International Power Electronics and Motion Control Conference and Exposition (pp. 218-223). IEEE.

[4] Rind, S. J., Ren, Y., Hu, Y., Wang, J., & Jiang, L. (2017). Configurations and control of traction motors for electric vehicles: A review. Chinese Journal of Electrical Engineering, 3(3), 1-17.

[5] Krings, A., & Monissen, C. (2020, August). Review and trends in electric traction motors for battery electric and hybrid vehicles. In 2020 International Conference on Electrical Machines (ICEM) (Vol. 1, pp. 1807-1813). IEEE.

[6] Kim, K. C., Lee, J., Kim, H. J., & Koo, D. H. (2009). Multiobjective optimal design for interior permanent magnet synchronous motor. IEEE Transactions on Magnetics, 45(3), 1780-1783.

[7] Rong, F., & Manfeng, D. (2012, October). Optimization design and analysis of a 30kW interior permanent magnet synchronous motor used in electric vehicles. In 2012 15th International Conference on Electrical Machines and Systems (ICEMS) (pp. 1-5). IEEE.

[8] Liu, X., Chen, H., Zhao, J., & Belahcen, A. (2016). Research on the performances and parameters of interior PMSM used for electric vehicles. IEEE Transactions on Industrial Electronics, 63(6), 3533-3545.

[9] Yan, J., Yang, K., Zhang, S., Feng, Y., Chen, Y., & Yang, H. (2017). Comparative investigation of inset-type and V-type IPMSM for light electric vehicle. International Journal of Applied Electromagnetics and Mechanics, 54(4), 515-524.

[10] Zhou, C., Huang, X., Fang, Y., & Wu, L. (2018, September). Comparison of PMSMs with different rotor structures for EV application. In 2018 XIII International Conference on Electrical Machines (ICEM) (pp. 609-614). IEEE.

[11] Husain, T., & Lee, S. T. (2019, September). Design considerations for magnet configurations in IPM rotor for high speed traction applications. In 2019 IEEE Energy Conversion Congress and Exposition (ECCE) (pp. 6062-6069). IEEE.

[12] Murali, N., & Ushakumari, S. (2020, November). Performance comparison between different rotor configurations of PMSM for EV application. In 2020 IEEE REGION 10 CONFERENCE (TENCON) (pp. 1334-1339). IEEE

[13] Burress, T. A., Campbell, S. L., Coomer, C., Ayers, C. W., Wereszczak, A. A., Cunningham, J. P., ... & Lin, H. T. (2011). Evaluation of the 2010 Toyota Prius hybrid synergy drive system (No. ORNL/TM-2010/253). Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States). Power Electronics and Electric Machinery Research Facility.

[14] Staunton, R. H., Ayers, C. W., Marlino, L. D., Chiasson, J. N., & Burress, B. A. (2006). Evaluation of 2004 Toyota Prius hybrid electric drive system (No. ORNL/TM-2006/423). Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).

BIOGRAPHIES

Bektas Aybars BALTA received the B.Sc. and M.Sc. degrees in electrical engineering from Yıldız Technical University, Istanbul, Turkey, in 2015 and 2024, respectively. He is currently a system engineer at ASELSAN A.S. in Ankara, Turkey. His main research interests include electrical machine theory and design.

Engin AYCICEK received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Yıldız Technical University, Istanbul, Turkey, in 2001, 2005, and 2012, respectively. He is currently Asst. Prof. at Yıldız Technical University. His main research interests include electrical machine theory and design.

Mustafa Gurkan AYDENIZ received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Yıldız Technical University, Istanbul, Turkey, in 1995, 1998, and 2005, respectively. He is currently Lect. PhD. at Yıldız Technical University. His research interests include electrical machine theory and design.

Haci DEDECAN received the B.Sc. and M.Sc. degrees in electrical engineering from Yıldız Technical University, Istanbul, Turkey, in 2015 and 2024, respectively. He is currently a system engineer at ASELSAN A.S. in Ankara, Turkey. His main research interests include electrical machine theory and design.