Comprehensive Analysis of Key Parameters Influencing Permanent Magnet Synchronous Motor Performance

V.Nakhaei[1], F.Zare*[2]

[1] Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran, postal code: 8415683111, mobile: 0989136085295, tell: 031 33912210, email address: v.nakhaee@ec.iut.ac.ir

[2] Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran, postal code: 8415683111, mobile: 0989103003865, tell: 031 33915025, email address: fzare@iut.ac.ir, (ORCID: 0000-0002-6215-3673)

Abstract:

Permanent Magnet Synchronous Motors (PMSMs) are extensively employed in various applications, including electric vehicles, industrial machinery, and precision motion control systems, owing to their high efficiency, power density, and excellent controllability. The performance of these motors is strongly influenced by several design parameters, notably the slots-per-pole-per-phase ratio, stator winding configuration, permanent magnet arrangement, and slot opening width. This study investigates the impact of each of these parameters on key motor performance metrics, such as output torque and torque ripple. In this study, the effects of each parameter on output torque and torque ripple are examined individually and in combination .Simulation results demonstrate that appropriate optimization of these factors can significantly enhance the motor's electromagnetic performance. Based on these findings, an improved motor structure is proposed, and its performance is compared to that of the initial design.

Keywords: PMSM, number of slots per pole per phase, winding configuration, permanent magnet, slot opening, torque, torque ripple.

1. Introduction

With the rapid growth of industry, the demand for electric motors—one of the most critical components in industrial processes—is steadily increasing [1]. Various sectors, including automotive, aerospace, robotics, and energy production, rely heavily on electric motors for their operations. While electric motors come in a variety of types depending on the application, Permanent Magnet Synchronous

Motors (PMSMs) are among the most suitable choices when high speed and power are required [2]-[5].

These motors utilize permanent magnets in the rotor, eliminating the need for external excitation. Consequently, they offer higher power density, lower losses, and improved efficiency compared to conventional induction motors [6]-[9].

There are various types of permanent magnet motors, each designed and optimized to meet specific application requirements [8]. Among them, the Surface-Mounted Permanent Magnet Synchronous Motor (SPMSM), in which magnets are directly mounted on the rotor surface, is widely used in applications where low cost and simple design are priorities, due to its straightforward structure and reduced manufacturing expenses [10]. In contrast, the Interior Permanent Magnet Synchronous Motor (IPMSM), where magnets are placed inside the rotor, provides better performance at both low and high speeds and has higher starting torque. Furthermore, lower torque ripple in IPMSM usually leads to a smooth torque output [12]-[14].

Optimizing and enhancing PMSM performance, as one of the key industrial motors, has a direct impact on industrial growth by improving motor efficiency, extending its lifespan, and reducing both weight and volume [15]-[16]. While all components of a motor contribute to its overall performance, their impact varies in significance. Optimizing and refining each of these components can collectively improve the motor's performance. Moreover, these parameters significantly affect performance both individually and through their interactions. Analyzing their interactions can lead to more accurate and optimized results [17]-[19].

Motor winding is a critical design element that significantly influences a motor's performance, efficiency, and operational lifespan [19]. It directly affects current distribution, torque generation, torque ripple, speed control, and energy loss. Moreover, selecting an appropriate winding configuration can help prevent issues such as excessive vibration, noise, and premature failures, thereby ensuring optimal motor performance [120]- [21]. One of the key challenges in motor design is the optimal selection of q (the number of slots per pole per phase). An appropriate choice of q can enhance magnetic field distribution, reduce cogging torque, improve the quality of the electromotive force (EMF), and mitigate harmonic distortion [22]. These improvements contribute to increased efficiency, reduced energy losses, and an extended motor lifespan [23].

Studying the magnet, as one of the most critical components of a motor, can provide valuable insights into performance optimization [24]. Moreover, the material used for the magnet has a direct impact on the motor's overall performance. The selection of magnetic material influences not only the motor's power density and efficiency but also affects key characteristics such as torque, performance stability under varying load and speed conditions, and overall operational efficiency [25]-[28].

In this paper, the impact of various factors such the number of slots per pole per phase, magnet arrangement, and the type of winding on the performance of SPMSM is examined. The primary goal is to optimize the motor design by analyzing and comparing these parameters to improve torque performance and reduce torque ripple.

2. Structure of Studied PM Servo Motor

The studied PMSM is illustrated in Fig. 1(a). As shown, the rotor is positioned inside the stator. The stator contains 36 slots, while the rotor has a simple structure with no windings, and the permanent magnets (PMs) are mounted on its outer surface. Samarium–Cobalt magnets (SmCo28) are used in the rotor, which are well known for their high thermal stability, excellent corrosion resistance, and strong magnetic performance. These properties make them a suitable choice for high-temperature or harsh operating environments, contributing to the reliable performance of the motor under demanding conditions. The stator is equipped with a three-phase full-pitch winding, as depicted in Fig. 1(b) (with only two phases shown for clarity). The geometric dimensions of the proposed PMSM are provided in Table I.

3. Principle of Operation

Mathematical models are essential for analyzing PMSM performance, providing valuable insights into motor operation and behavior, while also reducing the need for expensive experiments. These models, developed in the d-q reference frame, enable analysis of key factors such as winding type, slot-per-pole-per-phase (q), and winding distribution, and their impact on torque, voltage ripple, and dynamic response.

The key equations governing the motor are as follows:

$$v_q = r_s i_q + \frac{d\lambda_q}{dt} + \lambda_d \frac{d\theta_r}{dt} \qquad (1)$$

$$v_d = r_s i_d + \frac{d\lambda_d}{dt} + \lambda_q \frac{d\theta_r}{dt} \qquad (2)$$

$$\lambda_q = L_q i_q + L_{mp} i_{kq} \qquad (3)$$

$$\lambda_d = L_d i_d + L_{md} i_{kq} + L_{md} i_m \qquad (4)$$

Where v_q and v_d are the terminal voltages along the q and d axes, r_s is the stator winding resistance, and i_q and i_d are the stator currents. λ_q and λ_d represent the flux linkages, and θ_r is the rotor angle.

The electromagnetic torque, which is derived from the stored magnetic energy in the machine, is given by the following equation:

$$T = \frac{\partial \omega_m}{\partial \theta} \qquad (5)$$

Where T is the electromagnetic torque, ω_m is the stored magnetic energy, and θ_r is the mechanical angle.

The torque is calculated using the current components along the d- and q-axes, as shown in the equation:

The torque is derived from the current components along the d- and q-axes, as outlined below:

$$T = \frac{3}{2}\frac{p}{2}\{(L_d - L_q) i_d i_q + (L_{md} i_{kd} i_q - L_{mq} i_{kq} i_d) + L_m i_m i_q\} \qquad (6)$$

Where L_q and L_d are the inductances along the q- and d-axes, L_{md}, L_{mq}, and L_m are the inductance components, i_m is the magnetizing current, and T is the electromagnetic torque.

This simplified model presents the key equations and parameters relevant to motor operation. The focus remains on the essential components—voltage, flux linkages, and torque calculations—without going into the full derivations and ancillary equations that are already well-known in the literature.

4. Finite Element Analysis

Finite element method is the most accurate method for study the performance of electrical machines. To study the performance of the proposed PMSSM, finite element analysis is employed. Fig. 2 (a) shows the flux density, mesh, and flux lines of the proposed PMSSM.

As shown in the figure, the core flux density is lower than the saturation level of stator core material. Additionally, the simulation meshing is clearly visible and provides high accuracy. Moreover, the magnetic field intensity is presented as one of the motor's analytical characteristics.

Fig. 3 shows the torque of the proposed PMSSM. As it can be seen, the average torque is 9.45 Nm . And the torque ripple is 0.38 Nm .

As seen in the above figure, the proposed PMSSM exhibits high torque density and low torque ripple. However, to further enhance torque density and reduce torque ripple, design improvements have been made, and the physical parameters of the proposed PMSM will be optimized.

5. Design improvement

The performance of an electric motor is influenced by various factors, including geometric design, material properties, winding configuration, magnet type, and control strategy. One major challenge is minimizing torque ripple, which can lead to noise, vibrations, and efficiency loss. Torque ripple reduction can be achieved by optimizing slot design, adjusting magnet arrangement, employing advanced control methods, and selecting appropriate magnetic materials. Additionally, precise phase current regulation and the reduction of magnetic field harmonics significantly enhance motor performance. In this section, the effects of q, winding arrangement, slot opening, and magnet structure on the performance of the proposed PMSSM are studied.

5.1. number of slots per pole per phase

Increasing the value of q, which represents the number of slots per pole per phase, significantly impacts the performance of electric motors [20]. One of the key advantages of increasing q is the reduction of spatial harmonics in the magnetic field, which leads to lower torque ripple, improved power factor, and higher motor efficiency [21]. Additionally, better current distribution in the stator windings minimizes undesirable inductive effects. Furthermore, increasing q helps lower noise and mechanical vibrations by ensuring a more uniform winding distribution and a smoother magnetic field. However, a higher number of slots also increases manufacturing complexity and production costs, creating challenges in design and assembly. Therefore, selecting an optimal q value requires balancing motor performance improvements with production cost considerations. The impact of q on torque and torque ripple is clearly evident in the results presented in Fig.4.

As illustrated in the figure above, an increase in the number of slots per pole per phase (q) leads to a noticeable enhancement in torque output, while also reducing the torque ripple. This is due to the improved distribution of the magnetic field and more uniform current flow, which results in smoother and more consistent torque generation. However, increasing the value of q can introduce mechanical challenges, particularly due to the reduction in tooth width, which may lead to higher mechanical stresses and potential issues with the structural integrity of the stator.

Taking these factors into consideration, the optimal value of q for the proposed Permanent Magnet Synchronous Motor (PMSM) is selected to be 3. This value strikes a balance between achieving a desirable reduction in torque ripple and maintaining the mechanical feasibility of the motor, ensuring both high performance and structural stability.

5.2. Slot Opening

Fig. 5 shows the proposed PMSSM with different slot opening values. As seen in this Figure, the slot opening is narrowed, reducing the feasibility of inserting the winding into the slot during manufacturing.

The effect of slot opening on the value of torque and torque ripple is given in Fig.6.

As seen in the figure above, the slot opening does not significantly affect the overall torque output, but it plays a crucial role in reducing torque ripple. Minimizing torque ripple leads to a more stable and consistent torque output, enhancing the motor's operational efficiency.

Torque ripple is a common source of noise and vibration in motors, and reducing it is essential for applications requiring smooth motion. By optimizing the slot opening, these issues can be effectively mitigated, improving the motor's performance, particularly in applications where noise and vibration reduction are critical.

5.3. Magnet structure

The structure of permanent magnets has a significant impact on the performance of electric motors, affecting torque, efficiency, and controllability. It affects the distribution of the magnetic field in the air gap of the motor, thereby influencing parameters such as torque, torque ripple, efficiency, and controllability. The type and arrangement of magnets can determine axial inductances, the generation of unwanted harmonics, and even performance at high speeds. In surface-mounted permanent magnet synchronous motors (SPMSM), the magnetic flux density and the amount of torque depend on the design of the magnets. Proper magnet placement can prevent the generation of undesirable harmonics in the back electromotive force (EMF) and reduce losses. One advanced magnet design technique is the Halbach array, where the magnets are arranged in such a way that the magnetic field is enhanced on one side and reduced to zero on the other. This design increases the magnetic flux density, torque, and efficiency of the motor, while also reducing the motor's size and weight, improving performance at high speeds, and enhancing overall efficiency. In Halbach array design, three main structures exist: Continuous Halbach, Sinusoidal Halbach, and Ideal Halbach. Together with the simple magnet structure, these four different configurations can be simulated and tested to assess their impact on the motor's output. The four different configurations can be observed in the Fig.7.

These four magnet structures affect torque and ripple differently due to variations in magnetic field lines. Another important factor in selecting the magnet type is the manufacturing and cutting challenges, which may make some structures inaccessible. The Parallel structure is a simple design that is easy to manufacture, but it does not offer optimal torque and ripple performance. On the other hand, the ideal pattern structure is highly efficient in terms of magnetic properties and significantly reduces torque ripple. However, its manufacturing challenges, including magnet orientation, make it difficult to produce.

Fig. 8 shows the torque and torque ripple for these different magnet structures.

As observed in the figure, the arrangement of permanent magnets significantly affects both torque and torque ripple. Different magnet configurations result in variations in magnetic field lines, which in turn influence the motor's performance. In addition to increasing torque, the proper magnet arrangement can reduce torque ripple and provide smoother operation.

Among these configurations, the ideal Halbach array offers the lowest torque ripple and the highest torque. However, it presents significant manufacturing challenges, particularly in magnet orientation. On the other hand, the simple parallel structure is the easiest to manufacture but results in the highest torque ripple, with suboptimal torque performance. Therefore, the choice of magnet arrangement depends on application priorities, balancing between optimizing performance and manufacturing simplicity.

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5.4. winding arrangement

Changing the stator windings directly affects axial inductances L_q, L_d, influencing motor performance by altering harmonic generation, torque ripple, and efficiency. Proper winding design can reduce magnetic field harmonics, minimize torque ripple, and improve overall efficiency. Additionally, distributed windings produce a more sinusoidal voltage waveform, optimizing high-speed operation by reducing losses and preventing core saturation.

In this paper stator windings are classified based on three types pitch: full-pitch, fractional-pitch (one-third and one-fifth). In full-pitch winding, the distance between the two sides of a coil equals the distance between two magnetic poles (180 electrical degrees), resulting in higher induced voltage. This type of winding is commonly used in high-power motors due to its superior electromagnetic performance but requires more copper wire, increasing cost and motor size.

In fractional-pitch winding, the coil span is smaller than the full pitch, which helps reduce certain harmonics. In one-third pitch (1/3) winding, the angle between the two sides of the coil is 60 electrical degrees. This method reduces higher-order harmonics, optimizes wire usage, and minimizes copper losses, but the induced voltage is lower compared to full-pitch winding. In one-fifth pitch (1/5) winding, the angle between the coil sides is 36 electrical degrees, primarily used to suppress fifth-order harmonics. Although it reduces the induced voltage and torque, it is beneficial in synchronous motors and generators where harmonic reduction is crucial. Fig. 9 shows the different winding arrangements for the proposed PMSSM.

Various winding configurations were simulated to analyze their impact on output parameters. This simulation has been conducted for different values of q, the effect of winding arrangement on torque and torque ripple for different number of q is given in Fig.10.

As shown in the figure above, the 1/5 winding exhibits the minimum torque ripple, while its torque is close to that of the full-pitch winding. Therefore, the mentioned winding can be employed for the proposed motor. Additionally, a plot of torque and torque ripple as a function of the value of q for various winding configurations is provided.

As concluded in the previous section, increasing q improves both torque and torque ripple, provided mechanical considerations are taken into account. However, the impact of the q is also dependent on the winding type. The full-pitch winding provides the highest torque across all q values, but it comes with increased torque ripple. The combination of q value and winding type can lead to optimal performance in terms of both torque and ripple, depending on the specific application requirements.

As shown in this section, various parameters of the PMSM can significantly affect its performance. In the following section, the optimized PMSM is presented and compared with the initial design.

6. Optimized motor

Considering manufacturing constraints and design requirements, the optimal value for the slot per pole per phase parameter (q) was determined to be 3. This choice leads to a stator configuration with 54 slots, which is favorable in terms of manufacturability and magnetic field distribution.

Further analysis of the slot geometry revealed that a slot opening of 1 mm provides optimal performance in terms of magnetic flux penetration.

In addition, a winding configuration designed to eliminate the 5th harmonic, combined with an ideal Halbach array magnet structure, places the motor at its optimal operating point. This combination results in high torque output with minimal torque ripple, which is particularly critical for applications sensitive to torque fluctuations, such as precision drives or high-speed propulsion systems.

The results obtained from electromagnetic simulations confirm the effectiveness of this design. The average torque and torque ripple under nominal operating conditions are seen in Fig.11.

As seen in this figure, the torque and torque ripple for the optimized design are 14.652 Nm and 0.04 Nm, respectively, representing a 55.2% increase in torque and an 89.47% reduction in torque ripple compared to the initial design.

7. Conclusion

In this study, the impact of several key design parameters on the performance of a three-phase surface-mounted permanent magnet synchronous motor (SPMSM) was comprehensively analyzed. The results indicated that these parameters significantly influence both average torque and torque ripple, with optimizations leading to improved motor performance, particularly in high-precision servo drive applications. Specifically, applying the optimal parameter design to the proposed PMSM can increase torque by 55.2% and reduce torque ripple by 89.47%.

This paper investigates the optimization of key parameters for a three-phase permanent magnet synchronous motor (PMSM), with the primary innovation lying in the introduction of a comprehensive approach to model the combined effects of different parameter combinations, not only individually but also in interaction with one another. Unlike previous studies that typically analyze the effects of each parameter separately, this research achieves more accurate results by analyzing the interactions between parameters, which can lead to enhanced electromagnetic performance. Additionally, the simultaneous optimization of magnet arrangement, winding configuration, and slot-to-pole ratio has resulted in increased torque and a significant reduction in torque ripple, which is crucial for high-precision applications such as servo drives. These innovations contribute to the development of motor designs with better efficiency, more stable performance, and reduced noise and vibration.

One of the main limitations of this study is the exclusive reliance on finite element simulations as the tool for evaluating motor performance. While this method provides accurate insights into motor behavior, it may not fully capture all the complexities encountered in real-world operating conditions, such as thermal effects, material degradation, and non-ideal operating scenarios. Additionally, the study has focused primarily on specific parameters, such as the magnet arrangement and the winding configuration, potentially overlooking factors like electromagnetic interference or the influence of control strategies.

Future research should include experimental validation of the simulation results under real operating conditions to confirm the accuracy of the predictions made in this study. Moreover, the impact of other factors such as thermal effects, mechanical wear, and varying load conditions should be investigated to gain a more comprehensive understanding of the motor's long-term performance. Advanced optimization algorithms that consider a broader range of parameters, including operational variability, could be useful in developing more efficient and robust motor designs. Furthermore, research into the potential integration of adaptive control strategies for real-time motor performance optimization could improve dynamic performance and transient conditions, ensuring more stable and reliable operation across various applications.

Reference

[1] Husain *et al*., "Electric Drive Technology Trends, Challenges, and Opportunities for Future Electric Vehicles," in *Proceedings of the IEEE*, vol. 109, no. 6, pp. 1039-1059, June 2021, doi: 10.1109/JPROC.2020.3046112.

[2] C. Candelo-Zuluaga, J. -R. Riba, A. G. Espinosa and P. T. Blanch, "Customized PMSM Design and Optimization Methodology For Water Pumping Applications," in *IEEE Transactions on Energy Conversion*, vol. 37, no. 1, pp. 454-465, March 2022, doi: 10.1109/TEC.2021.3088674

[3] S. Pillai, A. Forsyth, M. Abdalmagid et al. "Investigating the Effects of PWM Currents on a High-Speed PMSM for an Aerospace Application," *2023 IEEE Transportation Electrification Conference & Expo (ITEC)*, Detroit, MI, USA, 2023, pp. 1-6, doi: 10.1109/ITEC55900.2023.10186909.

[4] Y. Yu, S. Xie, F. Chai, et al. "Analysis and Suppression of Core and PM losses in Fractional-Slot Permanent Magnet Vernier Machine and PMSM for In-Wheel Application,06 March 2025" in *IEEE Transactions on Industry Applications*, doi: 10.1109/TIA.2025.3548602

[5] Ashouri-Zadeh, A., and Zahra Nasiri-Gheidari. "Force Ripple Reduction Methods for Tubular Permanent Magnet Linear Machines." *Scientia Iranica* (2023). https://scientiairanica.sharif.edu/article_23313.html

[6] M. A. Hebri *et al*., "Electromagnetic Study of High Power Density : PMSM for Automotive Application," *2022 International Conference on Electrical Machines (ICEM)*, Valencia, Spain, 2022, pp. 28-34, doi: 10.1109/ICEM51905.2022.9910916

[7] J. -W. Jung, D. -H. Jung and J. Lee, "A Study on the Design Method for Improving the Efficiency of Spoke-Type PMSM," in *IEEE Transactions on Magnetics*, vol. 59, no. 2, pp. 1-5, Feb. 2023, Art no. 8200205, doi: 10.1109/TMAG.2022.3170089

[8] N. Murali, S. Ushakumari and M. V. P, "Performance comparison between different rotor configurations of PMSM for EV application," *2020 IEEE REGION 10 CONFERENCE (TENCON)*, Osaka, Japan, 2020, pp. 1334-1339, doi: 10.1109/TENCON50793.2020.9293844.

[9] Marousi Noushabadi, Mahmoud, Saeid Javadi, et al . "Design and modeling of an axial flux permanent magnet consequent pole machine." *Scientia Iranica* (2024). https://scientiairanica.sharif.edu/article_23625.html

[10] H. Murakami, Y. Honda, H. Kiriyama, et al. "The performance comparison of SPMSM, IPMSM and SynRM in use as air-conditioning compressor," *Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat. No.99CH36370)*, Phoenix, AZ, USA, 1999, pp. 840-845 vol.2, doi: 10.1109/IAS.1999.801607.

[11] Nobahari, Amin, et al. "Permanent Magnet Design for Torque Ripple Reduction in PM-Assisted Synchronous Reluctance Motors." *Scientia Iranica* (2024). Doi: https://scientiairanica.sharif.edu/article_23744.html

[12]M. R. Rahman, S. Choi and H. -G. Kim, "A High-Speed Rare-Earth Free IPM with Carbon Composite Wrapped Rotor," *2024 IEEE Energy Conversion Congress and Exposition (ECCE)*, Phoenix, AZ, USA, 2024, pp. 5017-5023, doi: 10.1109/ECCE55643.2024.10861214.

[13] Y. Shimizu, S. Morimoto, M. Sanada et al."Investigation of Rotor Topologies for Reducing Torque Ripple in Double-Layer IPMSMs for Automotive Applications," in *IEEE Transactions on Industrial Electronics*, vol. 70, no. 8, pp. 8276-8285, Aug. 2023, doi: 10.1109/TIE.2023.3234129

[14] A. M. Ajamloo, A. Ghaheri and R. Nasiri-Zarandi, "Design and Optimization of a New TFPM Generator with Improved Torque Profile," *2019 International Power System Conference (PSC)*, Tehran, Iran, 2019, pp. 106-112, doi: 10.1109/PSC49016.2019.9081559.

[15] A. Amini, M. KhajueeZadeh and A. Vahedi, "Reliability and Lifetime Analysis on Permanent Magnet Motors in Elevator: Case Study PMA-SynRM & IPMSM," *2023 3rd International Conference on Electrical Machines and Drives (ICEMD)*, Tehran, Iran, Islamic Republic of, 2023, pp. 1-6, doi: 10.1109/ICEMD60816.2023.10429474.

[16] Sundaram, Maruthachalam, et al. "Design and FEM Analysis of High-Torque Power Density Permanent Magnet Synchronous Motor (PMSM) for Two-Wheeler E-Vehicle Applications." International Transactions on Electrical Energy Systems 2022.1 (2022): 1217250. doi: 10.1155/2022/1217250

[17] X. Sun, Z. Shi, G. Lei, et al."Analysis and Design Optimization of a Permanent Magnet Synchronous Motor for a Campus Patrol Electric Vehicle," in *IEEE Transactions on Vehicular Technology*, vol. 68, no. 11, pp. 10535-10544, Nov. 2019, doi: 10.1109/TVT.2019.2939794

[18] Abedini Mohammadi, Abdolmajid, et al. "Post-fault Model of Six-phase PMSMs with an Open-circuit Fault." *Scientia Iranica* (2025). Doi: https://scientiairanica.sharif.edu/article_23811.html

[19] A. Wallace, A. von Jouanne, P. Andrews, et al. "The effects of voltage and winding abnormalities on the measured performance of induction motors," *IAS '97. Conference Record of the 1997 IEEE Industry Applications Conference Thirty-Second IAS Annual Meeting*, New Orleans, LA, USA, 1997, pp. 196-200 vol.1, doi: 10.1109/IAS.1997.643027.

[20] W. Zhao, Q. He, W. Tian, et al."Investigation of Winding Configuration on Electromagnetic Vibration in Modular Dual Three-Phase PM Machine," in *IEEE Transactions on Industrial Electronics*, vol. 71, no. 2, pp. 1257-1267, Feb. 2024, doi: 10.1109/TIE.2023.3262876

[21] A. S. Abdel-Khalik, S. Ahmed and A. M. Massoud, "Effect of Multilayer Windings With Different Stator Winding Connections on Interior PM Machines for EV Applications," in *IEEE*

Transactions on Magnetics, vol. 52, no. 2, pp. 1-7, Feb. 2016, Art no. 8100807, doi: 10.1109/TMAG.2015.2495301

[22] H. Dohmeki and Y. Shoji, "Characteristic comparison of PMSM by slot/pole ratio," *2005 International Conference on Electrical Machines and Systems*, Nanjing, China, 2005, pp. 251-254 Vol. 1, doi: 10.1109/ICEMS.2005.202523.

[23] D. Wu and Z. Q. Zhu, "Influence of Slot and Pole Number Combinations on Voltage Distortion in Surface-Mounted Permanent Magnet Machines With Local Magnetic Saturation," in *IEEE Transactions on Energy Conversion*, vol. 30, no. 4, pp. 1460-1471, Dec. 2015, doi: 10.1109/TEC.2015.2436065

[24] Mafi, Hanieh, Ebrahim Afjei, et al ."Design of coaxial magnetic gear utilising a novel permanent magnet Halbach array structure." *IET Electric Power Applications* 15.3 (2021): 299-309. https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/elp2.12021

[25] I. Petrov and J. Pyrhonen, "Performance of Low-Cost Permanent Magnet Material in PM Synchronous Machines," in *IEEE Transactions on Industrial Electronics*, vol. 60, no. 6, pp. 2131-2138, June 2013, doi: 10.1109/TIE.2012.2191757.

[26] Rezaee-Alam, Farhad. "Performance Analysis of Slotless Axial Flux Permanent Magnet Machines with Skewed Magnets under Loading Condition." *Scientia Iranica* (2024). Doi: https://scientiairanica.sharif.edu/article_23657.html

[27] T. Liu, S. Huang, Q. Deng, Q. Pu, et al. "Effect of the number of slots per pole on performance of permanent magnet generator direct-driven by wind turbine," *2011 International Conference on Electrical Machines and Systems*, Beijing, China, 2011, pp. 1-4, doi: 10.1109/ICEMS.2011.6073738.

[28] H. Zhou, W. Tao, C. Chen, et al. "Analysis and Comparison of Even-Order Back EMF Harmonics of Fractional-Slot Concentrated-Winding Consequent Pole Permanent Magnet Vernier Machines," in *IEEE Transactions on Transportation Electrification*, vol. 10, no. 1, pp. 1969-1981, March 2024, doi: 10.1109/TTE.2023.3262980.

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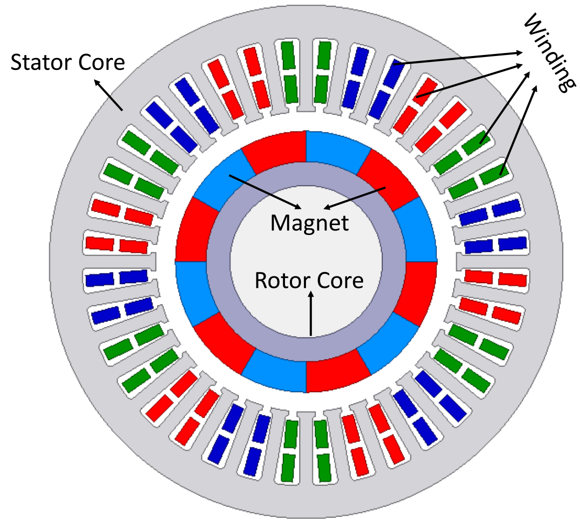
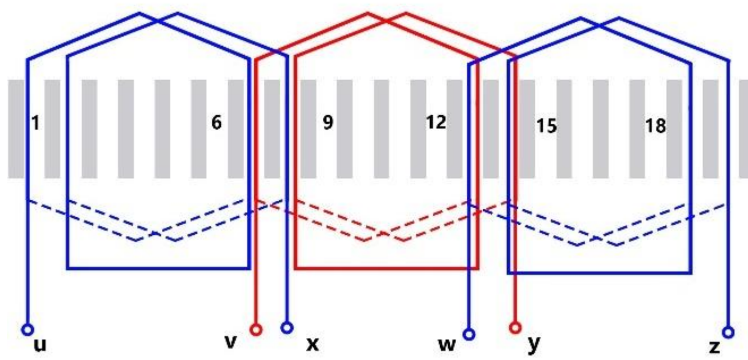


(a)



(b)

Fig.1: a) The structure of proposed PMSSM b) Stator winding arrangement

Table.I: physical dimension of proposed servo PMSM

parameter	value
Stator / rotor outer diameter	118 / 60 mm
Airgap length	4.5 mm
Stator slot height	17 mm
Stator tooth width	3 mm
Slot opening	1.9 mm
Magnet depth	7 mm
Motor length	435mm
Stator Material	M250-25A
Magnet Material	SmCo28

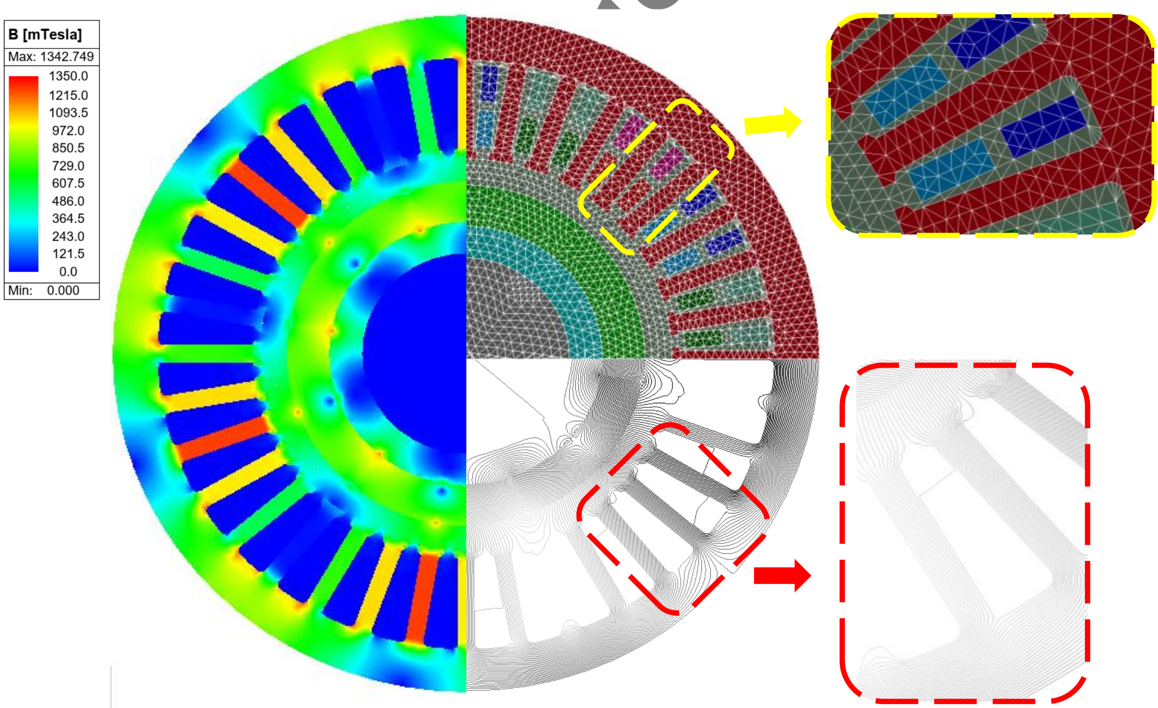


Fig.2: mesh, flux density and flux lines of proposed PMSSM

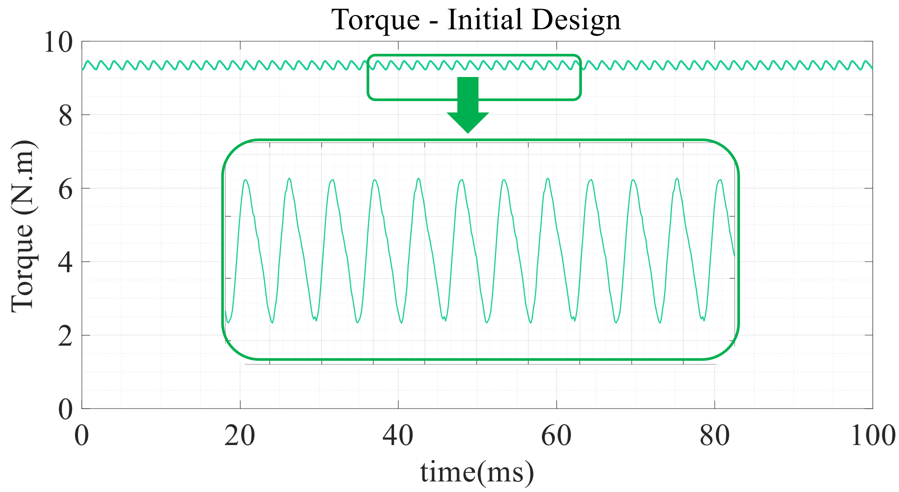


Fig.3: Torque versus time for the proposed PMSM

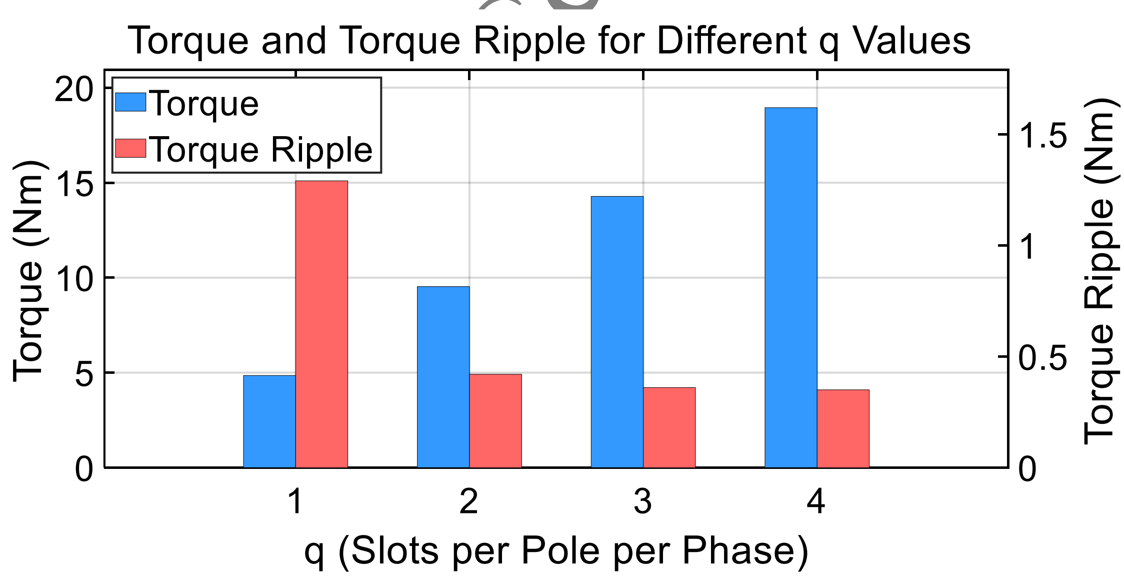


Fig.4: torque and torque ripple for different number of q

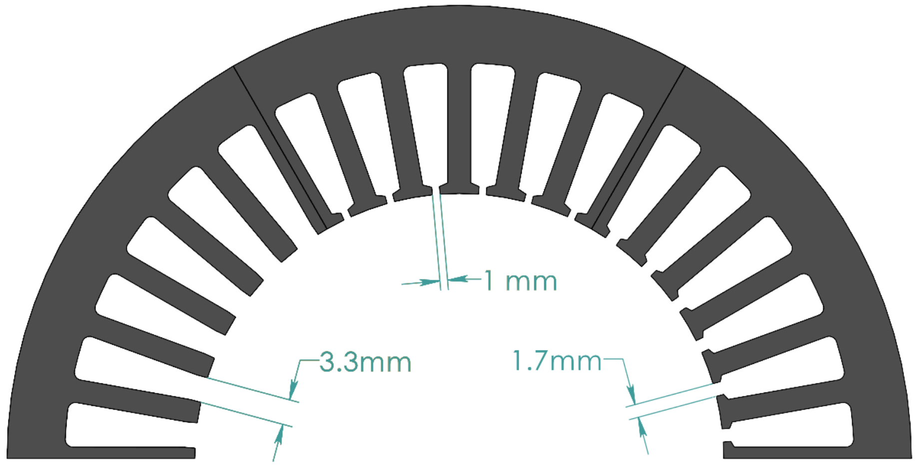


Fig.5: Proposed PMSM with different value of slot opening

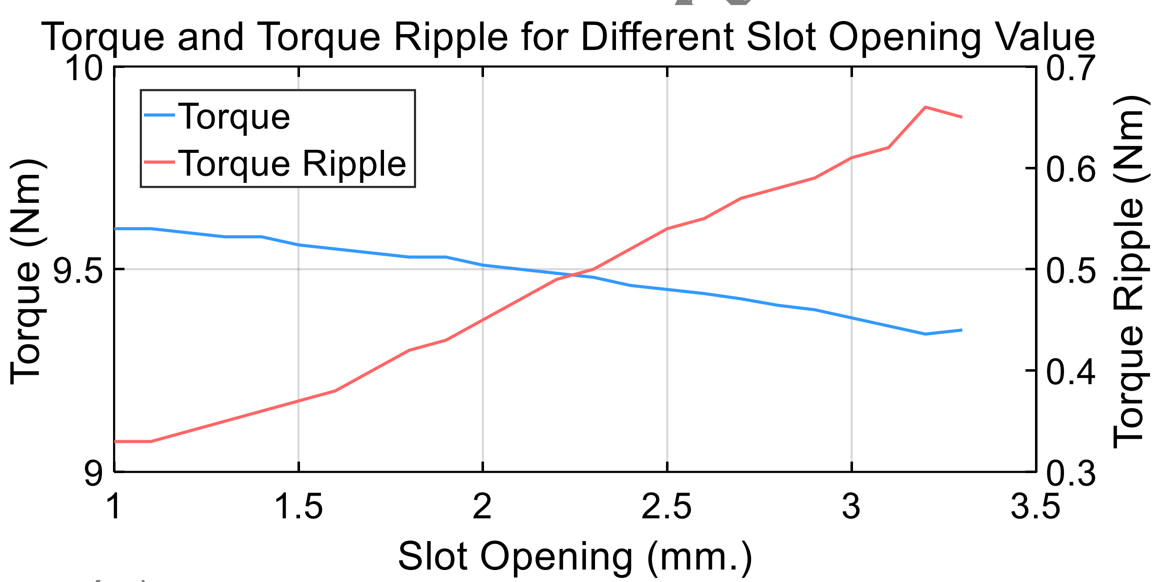


Fig. 6: The effect of slot opening on the torque and torque ripple of the proposed PMSSM

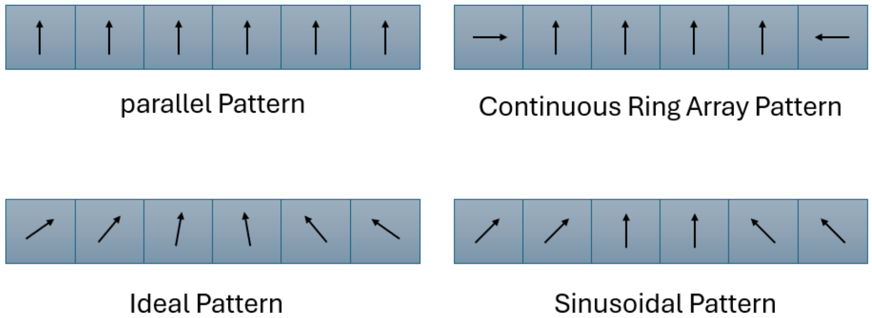


Fig. 7: Different magnet structures

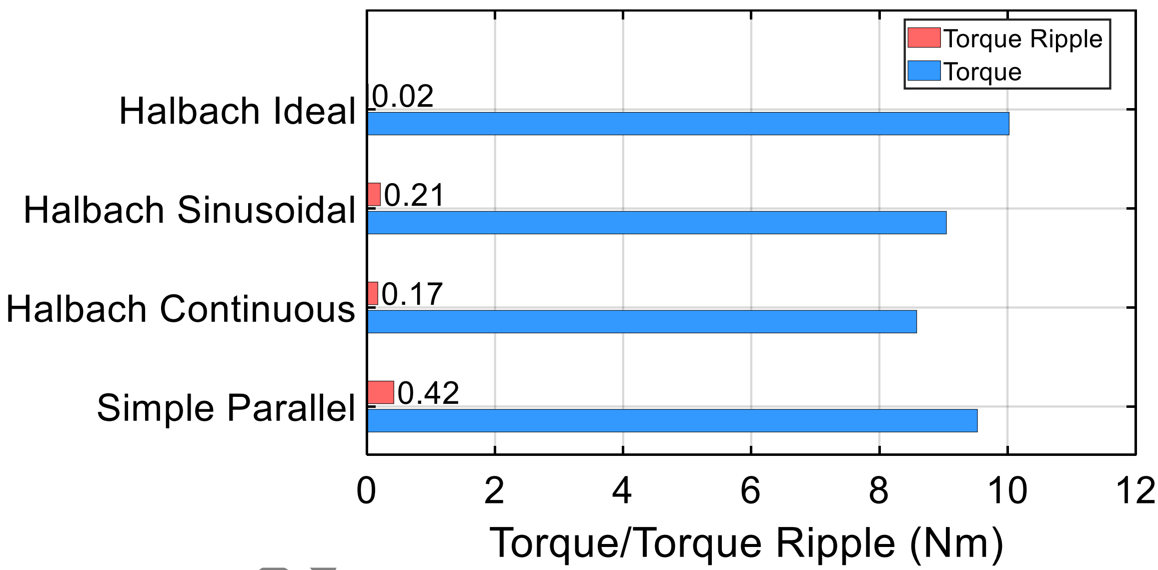
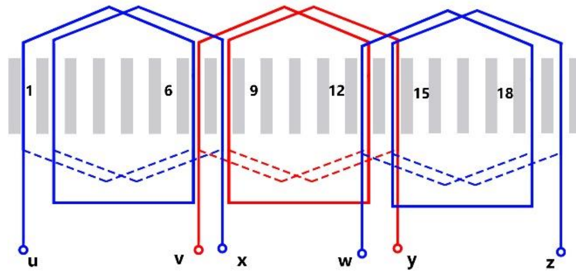
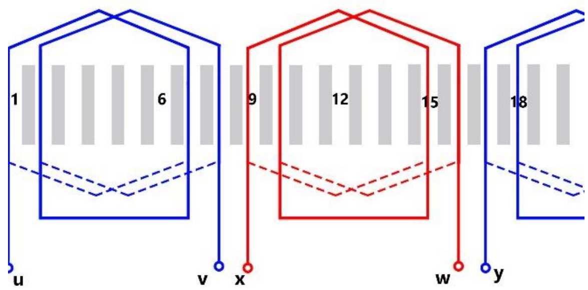


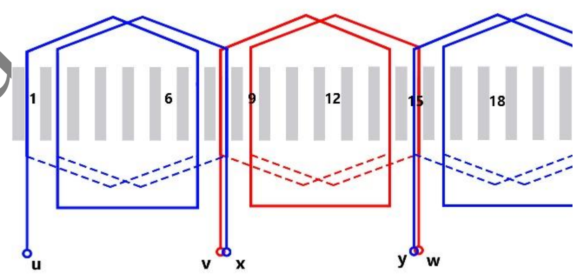
Fig.8: Torque and torque ripple for different magnet structure



(a)

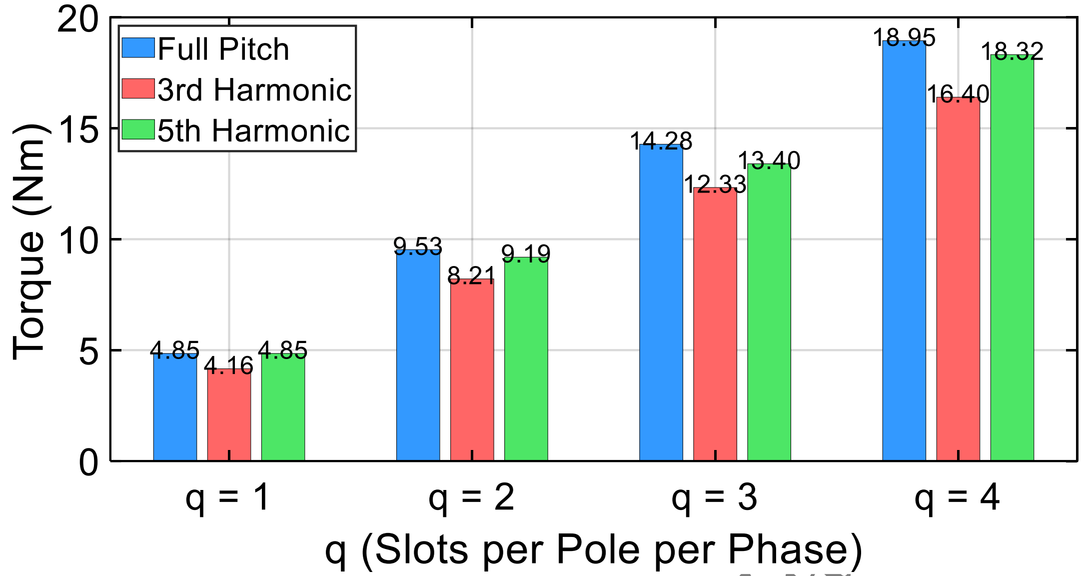


(b)

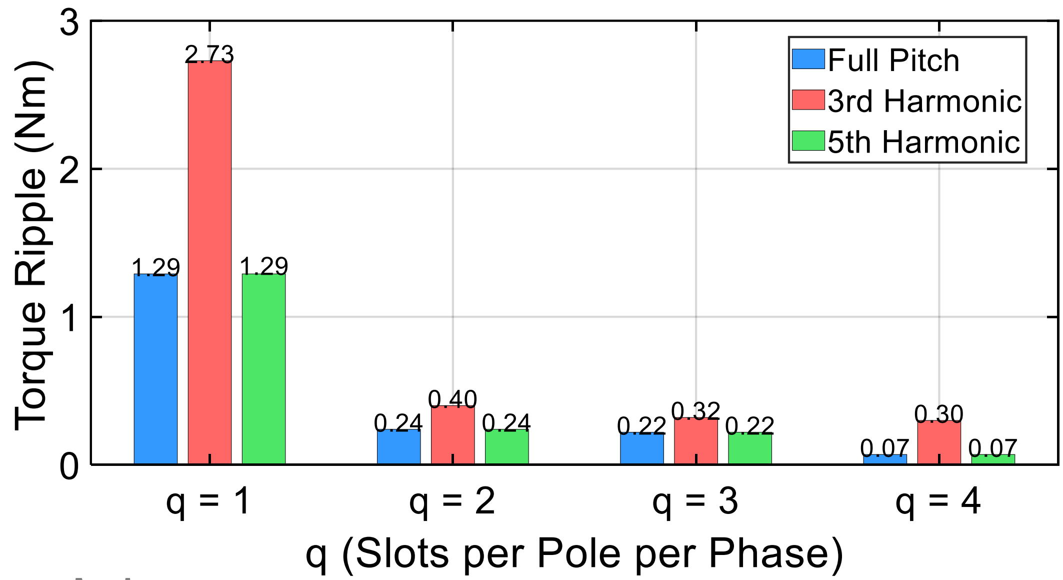


(c)

Fig.9: winding arrangement for different types of pitch: a)full pitch b) fractional (1/3) c) fractional (1/5)



(a)



(b)

Fig.10) the effect of winding arrangement on the performance of proposed PMSM a) torque b) torque ripple

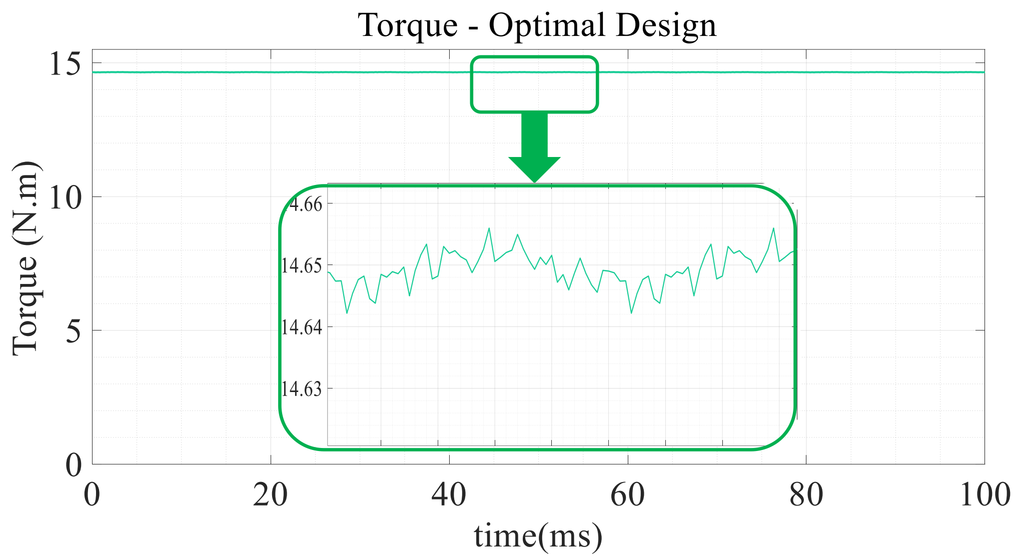


Fig. 11: Torque versus time for the optimized PMSSM

Vahid Nakhaei Madbooni received the B.Sc. degree in electrical engineering from the Isfahan University of Technology, Isfahan, Iran. He is currently pursuing the M.Sc. degree in electrical engineering (power electronics and electrical machines) at the Isfahan University of Technology. His research interests include electrical machines and related applications.

Fateme Zare received the B.Sc. degree in electrical engineering from the Sharif University of Technology, Tehran, Iran, in 2016, the M.Sc. degree in electrical engineering from the Isfahan University of Technology, Isfahan, Iran, in 2018, and the Ph.D. degree in electrical engineering from the Sharif University of Technology, in 2022. She is currently an Assistant Professor with the Department of Electrical and Computer Engineering, Isfahan University of Technology. Her research interests include design and optimization of electrical machines and electromagnetic sensors.