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Design and Performance Analysis of an Outer-Rotor PMaSynRM

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Anahtar Kelimeler

Elektrik Motor Tasarımı
Demagnetizasyon Analizi
Dış Rotorlu KMSM
Tahrik Motoru
Traction Motor
MD-SRM

Graphical/Tabular Abstract (Grafik Özet)

In this study, unlike the commonly used inner-rotor PMaSynRMs in the literature, the design and electromagnetic performance analysis of an outer-rotor PMaSynRM are presented. / Bu çalışmada, literatürde yaygın olarak kullanılan iç rotorlu MD-SRM'lerden farklı olarak, dış rotorlu bir MD-SRM tasarımı ve elektromanyetik performans analizi sunulmaktadır.

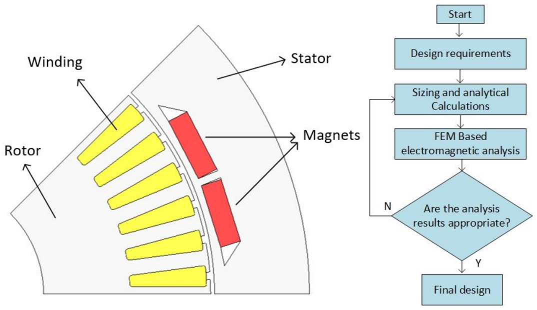

***Figure A**: a) Cross-section of the outer-rotor PMaSynRM b) The flowchart of the proposed motor design / **Şekil A**: a) Dış rotorlu MD-SRM'nin kesiti, b) Önerilen motor tasarımın akış şeması*

Highlights (Önemli noktalar)

- *Outer-rotor permanent-magnet-assisted synchronous reluctance motor / Dış rotorlu kalıcı mıknatıs destekli senkron relüktans motor*
- *Torque performance under different phase currents / Farklı faz akımlarında tork performansı*
- *Demagnetization performance under different phase currents / Farklı faz akımlarında demagnetizasyon performansı*

Aim (Amaç): *This study aims to design and electromagnetic performance analysis outer-rotor permanent-magnet-assisted synchronous reluctance motor / Bu çalışma, dış rotorlu, kalıcı mıknatıs destekli senkron relüktans motorunun tasarımını ve elektromanyetik performans analizini amaçlamaktadır.*

Originality (Özgünlük): *This study presents the outer-rotor PMaSynRM design for use in electric propulsion vehicles. / Bu çalışma, elektrik tahrikli araçlarda kullanılmak üzere dış rotorlu MD-SRM tasarımını sunmaktadır.*

Results (Bulgular): *The presented PMaSynRM, exhibiting low demagnetization risk and high performance, can be utilized as a traction motor in electric vehicles. / Geliştirilen MD-SRM modeli düşük demagnetizasyon riski ve yüksek performans sergilemesi sebebiyle elektrikli araçlarda tahrik motoru olarak kullanılabilir.*

Conclusion (Sonuç): *The conducted study resulted in obtaining an PMaSynRM design without the risk of demagnetization, featuring a maximum torque exceeding 35 Nm and achieving 90% efficiency at rated conditions. / Yapılan çalışma sonucunda demagnetizasyon riski olmayan, maksimum momenti 35 Nm üzerinde, anma noktasında %90 verime sahip olan bir MD-SRM tasarımı elde edilmiştir.*

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Abstract

Permanent magnet synchronous motors (PMSMs) are consciously used as traction motors in electric vehicles (EVs) and hybrid electric vehicles (HEVs). The rotor position (inner-rotor, outer-rotor) and topology of PMSMs significantly impact their torque profile, efficiency, and demagnetization characteristics. This article focuses on designing an outer-rotor permanent-magnet-assisted synchronous reluctance motor (PMaSynRM) under traction motor requirements and investigating its electromagnetic performance using the finite element method (FEM). This study's primary challenge is achieving optimal machine performance, considering high maximum torque and the risk of demagnetization at low levels. The design, derived from analytical calculations, was subjected to Finite Element Method (FEM) analyses. These analyses investigated motor performance in terms of efficiency, the ability to generate torque at different drive currents, and the risk of demagnetization. As a result of the study, the proposed PMaSynRM design was obtained that provides an adequate demagnetization performance even under 300% loading, has a maximum torque exceeding 35 Nm, and achieves an efficiency of 90% at rated conditions.

Dış Rotorlu MD-SRM Tasarımı ve Performans Analizi

Makale Bilgisi

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Öz

Kalıcı Mıknatıslı Senkron Motorlar (KMSM) tahrik motoru olarak elektrikli (EA) ve hibrit elektrikli (HEA) araçlarda yaygın olarak kullanılmaktadır. KMSM'lerin rotor pozisyonu (iç rotorlu, dış rotorlu) ve mıknatıs yerleşim topolojisi, tork profili, verimi ve demagnetizasyon özellikleri üzerinde önemli bir etkiye sahiptir. Bu makalenin ana amacı tahrik motoru isterlerine uygun bir şekilde dış rotorlu Mıknatıs Destekli Senkron Relüktans Motor (MD-SRM)'nin tasarımı ve elektromanyetik performansının sonlu eleman yöntemi (SEY) ile analiz edilmesidir. Bu çalışmadaki temel zorluk, yüksek maksimum tork ve düşük demagnetizasyon riski açısından en iyi makina performansını elde etmektir. Analitik hesaplamalar ile elde edilen tasarımın SEY analizleri yapılmış ve motor performansı verimlilik, farklı sürücü akımlarında tork üretme kabiliyeti ve demagnetizasyon riski araştırılmıştır. Yapılan çalışma sonucunda %300 yüklenme durumunda demagnetizasyon riski olmayan, maksimum momenti 35 Nm üzerinde, anma noktasında %90 verime sahip olan bir MD-SRM tasarımı elde edilmiştir.

1. INTRODUCTION (GİRİŞ)

Electric Vehicles (EVs) and hybrid Electric Vehicles (HEVs) are optimal solutions for reducing carbon emissions, contributing to environmental preservation, and achieving high-energy efficiency in transportation. Therefore, research studies on these vehicles and their components have increased in recent years [1-3]. Indeed, the electric motor stands out as a critical component in EVs and HEVs, directly impacting the vehicle's range and performance.

Due to their advantages, such as high power density and efficiency, Permanent Magnet Synchronous Motors (PMSMs) are widely preferred in EVs and HEVs [4]. PMSMs are generally designed in two different topologies. The first is the Surface

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Permanent Magnet Synchronous Motor (SPMSM), where magnets are located on the rotor surface, and the second is the Interior Permanent Magnet Synchronous Motor (IPMSM), where magnets are embedded within the rotor. In contrast to SPMSMs, IPMSMs can produce a high reluctance torque component [5]. IPMSMs with high reluctance torque production capability are also referred to as Permanent-Magnet-Assisted Synchronous Reluctance Motors (PMaSynRMs). This reluctance torque capability allows PMaSynRMs to generate the same torque with less magnet volume than SPMSMs. The magnet placement geometry is the most crucial factor influencing the reluctance torque component. Hence, numerous studies in the literature regarding magnet geometries commonly used in PMaSynRMs, such as V-shaped, double V-shaped, U-shaped, and Delta-shaped, are illustrated in Figure 1. These studies are summarized below.

Xiangdong and colleagues conducted a comparative study on four different PMaSynRM rotor topologies. It has been noted that the V-shaped geometry possesses the highest reluctance torque component, while the Tangential-type exhibits the highest average torque and the lowest cogging torque, torque ripple, and Total Harmonic Distortion (THD%) [5]. Ling and colleagues performed performance analyses on a motor with five different rotor geometries: Tangential-type, V-shaped, double V-shaped, Delta-shaped, and U-shaped. They presented the results comparatively, and the motor with a V-shaped rotor has been found to outperform its competitors when evaluated for the lowest demagnetization risk, the lowest manufacturing cost of rotor sheet ($), and the highest saliency ratio [6]. Sheng-Ching and colleagues conducted a design optimization study to increase the torque of a V-shaped motor with a rated power, speed, and torque of 34 kW, 2250 Rpm, and 144.3 Nm, respectively [7].

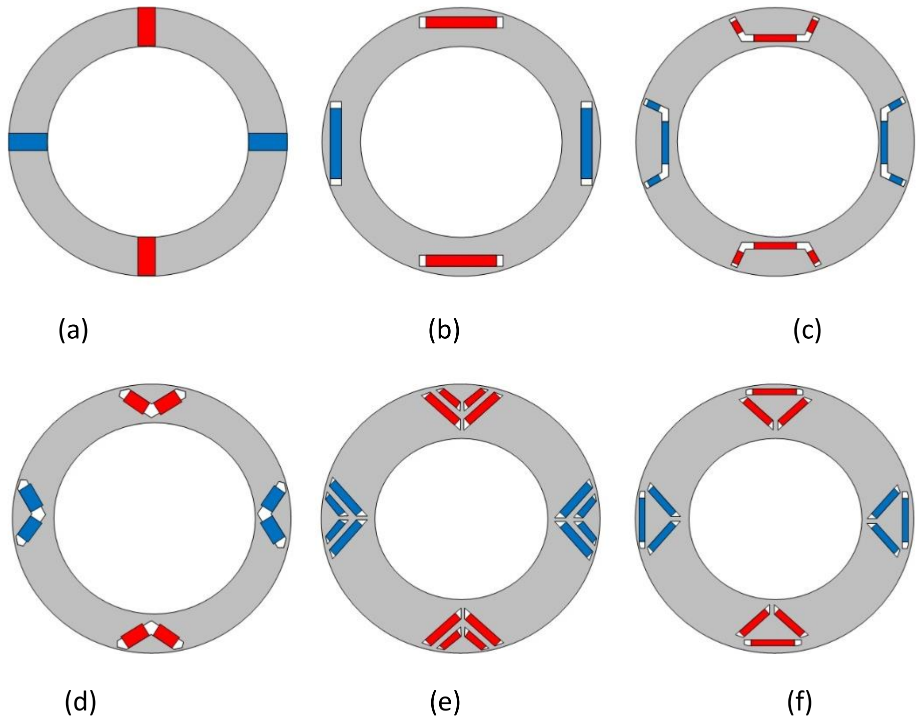


Figure 1. Cross-sections of six basic PMaSynRM models. (a) Spoke-type. (b) Tangential-type. (c) U-shaped.(d) V-shaped. (e) Double V-shaped. (f) Delta- shaped (Altı temel MD-SRM kesiti)

Dalcalı conducted a design optimization for a V-shaped PMaSynRM, considering crucial geometric parameters such as magnet geometry and flux barriers based on cost and efficiency criteria. Three designs were obtained based on the criteria of maximum output power, maximum efficiency/cost ratio, and maximum efficiency. The study results revealed that the motor optimized for maximum output power resulted in low efficiency and high cost, while the motor developed for maximum efficiency ended up with high costs. The study results indicate that the criterion of maximum efficiency/cost ratio is the most suitable approach [8]. Wang and colleagues conducted analyses of five different rotor topologies, which include surface, V-shaped, Tangential-type, two-segment Tangential-type, and a hybrid geometry of V-shaped and Tangential-type. The analyses presented the comparative values of back EMF, magnet mass, iron loss, and torque ripple for the different motors. The analyses revealed that the topology with the highest torque production per unit magnet mass is the V-shaped [9].

When evaluating the studies in the literature, PMaSynRM has been seen widely used in the literature for the last years. However, it is observed that these studies have predominantly focused on inner-rotor PMaSynRMs. Additionally, upon reviewing the literature, it can be observed that each of the PMaSynRMs presented in Figure 1 above has its own advantages and disadvantages relative to one another. The V-shaped inner-rotor topology stands out when considering parameters such as low demagnetization risk, low production cost, and a high reluctance torque component. Therefore, this study introduces a distinctive V-type outer-rotor PMaSynRM design, differing from the literature.

Additionally, examining the studies on outer-rotor PMSM from the literature reveals a predominant focus on surface-mounted structures [10-13]. When examining outer-rotor PMSM, it is observed that these motors effectively meet the demand for high torque at low speeds and are suitable for direct drive applications. However, their saliency ratios are 1 (or close to 1), so these motors do not provide a sufficient reluctance torque component [14]. Additionally, they are not the most suitable candidates for variable-speed applications due to their low field-weakening capabilities [15].

In this study, unlike the commonly used inner-rotor PMaSynRMs in the literature, the design and electromagnetic performance analysis of a V-shaped outer-rotor PMaSynRM are presented. Efficiency map, torque-speed performance, demagnetization characteristics under different drive currents, and magnetic flux distributions of the proposed design have been examined.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Design Requirements (Tasarım Gereksinimleri)

The design of traction motors requires specific design criteria compared to industrial motors. These can be summarized as high maximum torque for acceleration, low volume due to high power density, and high efficiency across a wide speed and torque range [4]. The design requirements considered in this study are given in Table 1 below.

Table 1. Targeted design requirements (Hedeflenen tasarım gereksinimleri)

DC Supply Voltage (V)	72
Peak Current (A)	150
Maximum Torque	>30
Slot Fill Factor	%45
Base Speed	2000 Rpm
Rated Torque	10 Nm
Torque Ripple Rate	<10
Efficiency Rated Power	%85
Rated Current Density	<6

Current and voltage limits were selected considering the requirements of light EVs. The ability of the traction motor to produce high maximum torque is crucial for the climbing and acceleration capabilities of the vehicle. Therefore, the maximum torque value should be at least 300% of the rated. The outer-rotor PMaSynRM design flowchart that meets the given requirements is shown in Figure 2.

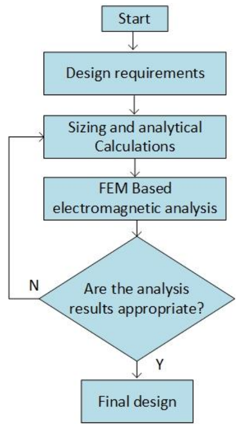


Figure 2. The flowchart of the proposed motor design (Önerilen motor tasarımın akış şeması)

Initially, analytical calculations were conducted to obtain a design meeting the requirements. Some of these calculations are provided in the next section. Subsequently, FEM analyses were performed to examine and verify the motor's performance based on the obtained results, and the outcomes are presented. JMAG Designer 22.1 was used for analysis studies on a computer with an i5-10400 CPU and 8GB of RAM.

2.2. Basic Design Equations (Temal Tasarım Eşitlikleri)

Sizing calculations are the starting point for designing electric machines. Three independent variables are used to determine the size of the electric motor. These are the shape ratio (SR), the torque per rotor volume (TRV), and the torque density (TD) [16]. These variables are used to determine the rotor diameter, core length, and stator diameter of the motor. SR, TRV, and TD can be expressed by the following equations, respectively:

$$SR = \frac{L_{STK}}{D_R}, \ TRV = \frac{T_{MAX}}{\frac{\pi}{4}D_R^2 L_{STK}}, \ TD = \frac{T_{MAX}}{\frac{\pi}{4}D_S^2 L_{STK}} \quad (1)$$

L_{STK} represents the core length, T_{MAX} is the maximum torque, D_S is the stator outer diameter, and D_R is the rotor diameter. These three parameters are also employed as independent variables in the design process when calculating the motor's geometric parameters, such as stator slot geometry, magnet geometry, and stator back iron distance. After dimension calculation, some design equations used to achieve the requirements specified in Table 1 are as follows. The equations in the d-q reference plane for PMaSynRM are as follows [17].

$$U_d = i_d R_s + L_d \frac{di_d}{d_t} - w_e L_q i_q \quad (2)$$

$$U_q = i_q R_s + L_q \frac{di_d}{d_t} - w_e L_d i_d + w_e \varphi_{pm} \quad (3)$$

In this context, U_d and U_q represent the stator voltage components in the direct and quadrature axes, i_d and i_q stand for the stator current components in the direct and quadrature axes, φ_{pm} designates the magnet flux linkage, w_e is the electrical angular velocity, L_d and L_q are the self-inductance components in the d-q axes, and R_s is the stator winding resistance. The electromagnetic torque generated by the motor can be computed using the following formula [18, 19].

$$T_e = \frac{3}{2} p [\varphi_{pm} i_q + (L_d - L_q) i_d i_q] \quad (4)$$

Here, p represents the number of pole pairs. In PMaSynRM, the motor torque consists of two components: the magnet torque and the reluctance torque.

$$T_{magnet} = \frac{3}{2} p \varphi_{pm} i_q \quad (5)$$

$$T_{reluctance} = \frac{3}{2} p (L_d - L_q) i_d i_q \quad (6)$$

In IPM motors, the saliency ratio L_d/L_q directly influences the amount of reluctance torque, as seen in Eq. 6. The variation of the two torque components and the total output torque of a typical PMaSynRM, depending on the current phase angle is presented in Figure 3 below. The reluctance torque component, typically depicted in the torque-current angle graph, varies depending on the geometry of the magnet inside the rotor and the flux barriers.

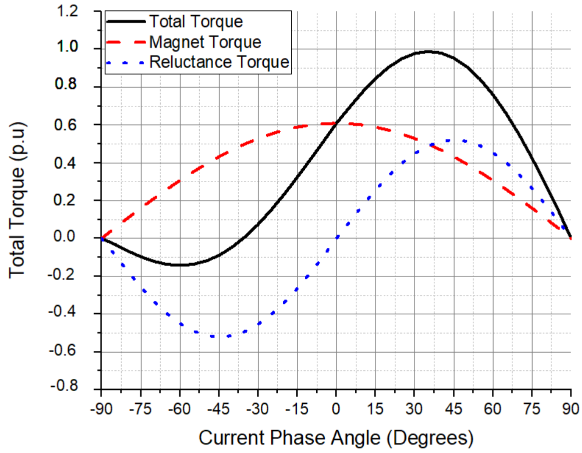


Figure 3. The torque component of a PMaSynRM
(MD-SRM'nin tork bileşenleri)

Torque ripple is also an important performance parameter for electric motors and can be expressed as the equation below [20].

$$T_{ripple} = \frac{T_{pp}}{T_{avg}} x100\% \quad (7)$$

Where T_{pp} and T_{avg} are peak-to-peak torque and average torque, respectively. The efficiency of the motor can be calculated as follows:

$$\eta = \frac{P_e}{P_e + P_{loss}} x100\% \quad (8)$$

Here, P_e represents the electromagnetic power, and P_{loss} is the motor losses.

2.3. Specification of the Designed Motor
(Tasarlanan Motorun Özellikleri)

As a result of the calculations and FEM analyses conducted in line with the design requirements, the overall geometry of the PMaSynRM, as shown in Figure 4, has been obtained.

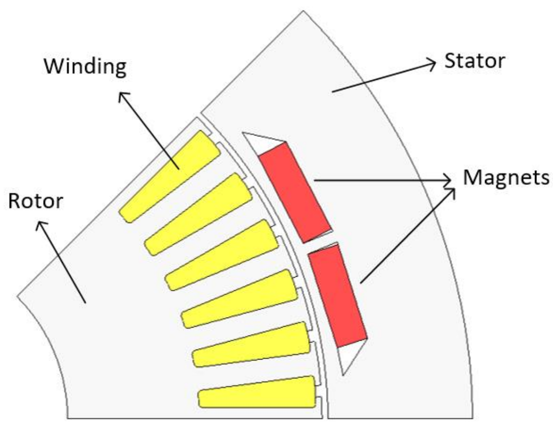
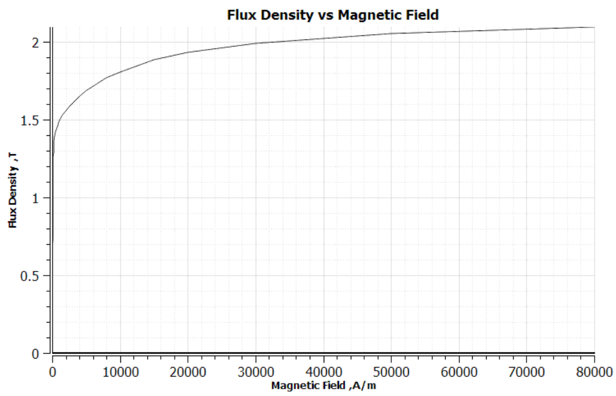


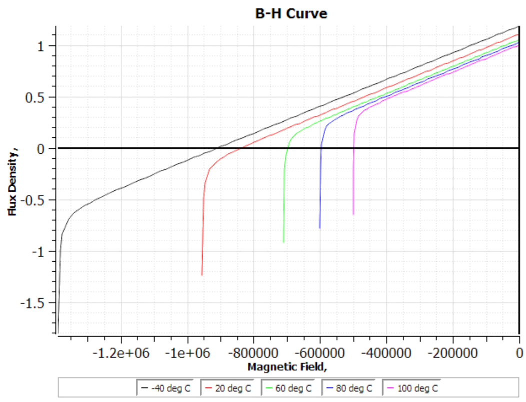
Figure 4. Cross-section of the outer-rotor PMaSynRM (Dış rotorlu MD-SRM'nin kesiti)

The general geometric dimensions of the obtained motor, the core material, materials used for magnets, and stator winding connection details are provided in the following Table 2.

Core losses contribute significantly to the overall losses of an electric motor. Silicon steel laminations with low W/kg values are typically used to minimize core losses [1]. Therefore, in this study, M270-35A material has been preferred. Additionally, for its high energy density, an N30-grade neodymium magnet has been chosen as the permanent magnet in the design. The B-H curves for the magnet and core material are given in Figure 5 below. Furthermore, slot geometries with high fill factor have been obtained for minimizing stator copper losses.



(a)

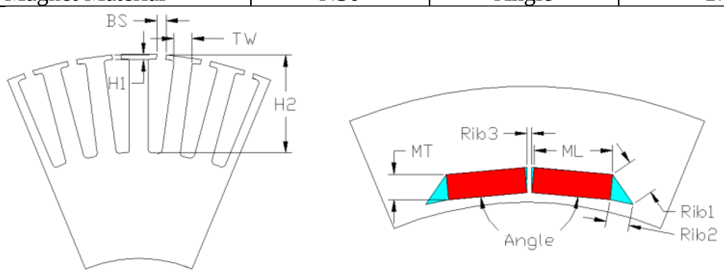


(b)

Figure 5. B-H Curve. (a) M270-35 Steel sheet. (b) N30 permanent magnet (B-H Eğrisi. (a) M270-35 Silisli sac. (b) N30 mıknatıs)

Table 2. Specıficatıon of the proposed motor (Önerilen motorun özellikleri)

Basic Motor Parameters		Geometric Parameters	
Outer radius of the Rotor	100 mm	H1 (mm)	2.5
Inner radius of the Rotor	75 mm	BS (mm)	6
Outer radius of the Stator	74 mm	TW (mm)	3.4
Inner radius of the Stator	30 mm	H2 (mm)	13.2
Axial length	50 mm	MT (mm)	4
Stator/Rotor Number	48/8	ML (mm)	12.4
Connection Type	Star	Rib1 (mm)	5.7
Number of turns	4	Rib2 (mm)	3.6
Core Material	M270-35A	Rib3 (mm)	1
Magnet Material	N30	Angle	170



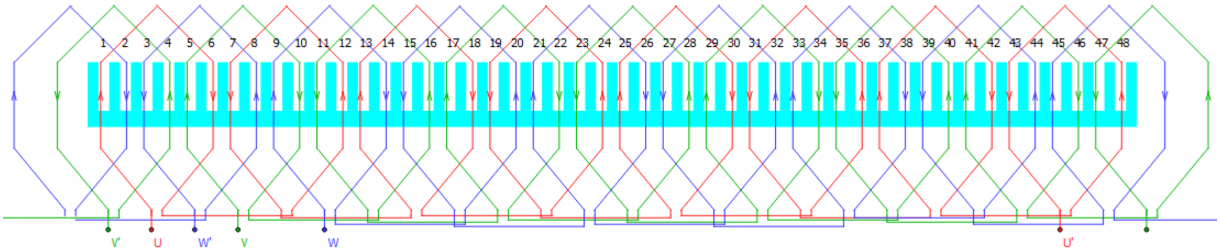


Figure 6. Winding diagram of the proposed design (Önerilen tasarımın sargı diyagramı)

To reduce copper losses in an electric motor, a fundamental method commonly employed involves increasing the slot cross-sectional area and the wire diameter, thus decreasing current density. This method is commonly applied if the motor does not have critical constraints, such as core size and magnetic circuit. In the designed motor, attention was paid to this aspect when determining the stator tooth thickness, ensuring that the area of stator slots is set to avoid core saturation. After determining the slot fill factor, decisions were made regarding the number of turns and stator winding topology, which significantly affects the rated and maximum speed, the rated and maximum torque, and the field-weakening capability of the motor. The winding diagram of the designed motor is given in Figure 6 above.

In this study, a distributed winding configuration has been preferred, as shown in Figure 6 above, due to its superior torque-speed characteristics, torque ripple, efficiency, and power factor compared to the concentrated winding PMSMs [22].

3. RESULTS (BULGULAR)

In this section, the results of the FEM analysis for the outer-rotor PMaSynRM are given. The distribution of magnetic flux density, efficiency map, torque-speed performance under different drive currents, and demagnetization risk analyses obtained by FEM analyses are conducted and presented. A dense mesh is applied to the stator teeth and magnets to obtain a high-accuracy analysis study, as seen in Figure 7. Although this extends the analysis time, it increases the accuracy of the results. Figure 8 shows the flux density distribution and flux lines of the stator and rotor of the proposed motor.

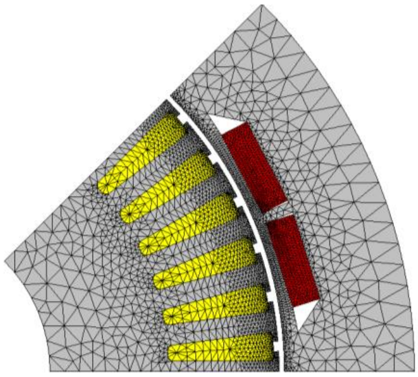


Figure 7. Distribution of mesh (Ağ dağılımı)

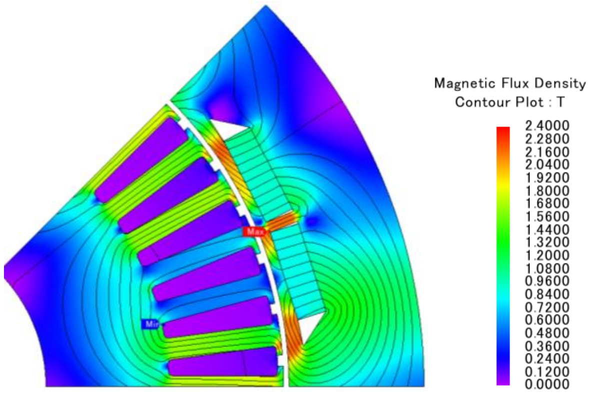


Figure 8. Distribution of magnetic flux density and flux lines (Manyetik akı yoğunluğu ve akı çizgilerinin dağılımı)

In Figure 8, it can be seen that the maximum magnetic flux density in the stator teeth is around 1.8 Tesla, while in the rotor and stator back iron regions, it is significantly lower. To minimize leakage magnetic flux in the rotor, the region between the flux barrier and the inner diameter of the rotor has been designed as short as mechanical limits allow. In the specified region, the core has been saturated to minimize leakage magnetic flux. Considering the B-H curve of the M270-35A core material provided in Figure 4-a, it is observed that the magnetic flux values meet the requirements.

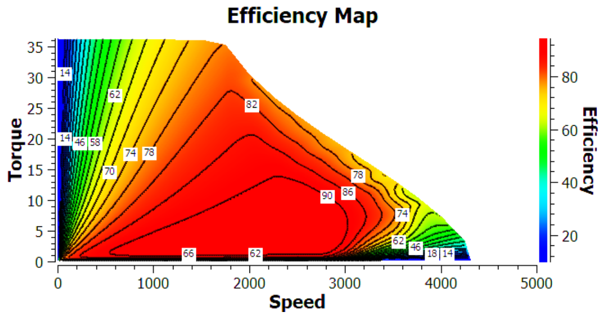


Figure 9. Efficiency map of the proposed motor (Önerilen motorun verimlilik haritası)

Analyzing the results presented in Figure 9, it is evident that the motor exhibits a maximum torque exceeding 35 Nm. Moreover, within the range of 1000 to 3000 RPM and 5 Nm to 10 Nm, the motor attains an efficiency of approximately 90%. The torque-speed characteristics of the traction motors used in EVs and HEVs are directly affected by the maximum phase current that the motor drive can supply. Figure 10 shows the output torque of the proposed motor under different drive currents. Upon careful examination of the outcomes, it becomes apparent that the torque values produced per ampere exhibit noteworthy uniformity across nearly four current density levels. It can be asserted that this situation represents another analysis output indicating that the core has not undergone saturation.

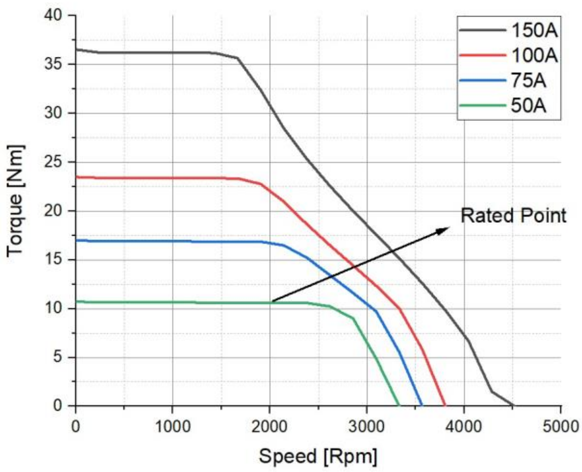


Figure 10. Torque performance under different phase currents (Farklı faz akımlarında tork performansı)

The maximum torque and speed values the motor produces also vary depending on the motor phase current. In the proposed design, the winding cross-sectional area is 10 mm². In this case, the current density at the rated point is 5 A/mm². The determined current density is a suitable value for motors operating in the S2-60 min duty cycle cooled by natural convection and belonging to the H insulation class. In permanent magnet motors, the demagnetization of permanent magnets adversely affects the motor performance [21]. Therefore, the demagnetization characteristics of these motors are a crucial parameter that needs to be examined for motor performance. Magnet temperature dramatically influences the magnet's operating point; hence, demagnetization prediction analyses were conducted at a constant ambient temperature of 40°C.

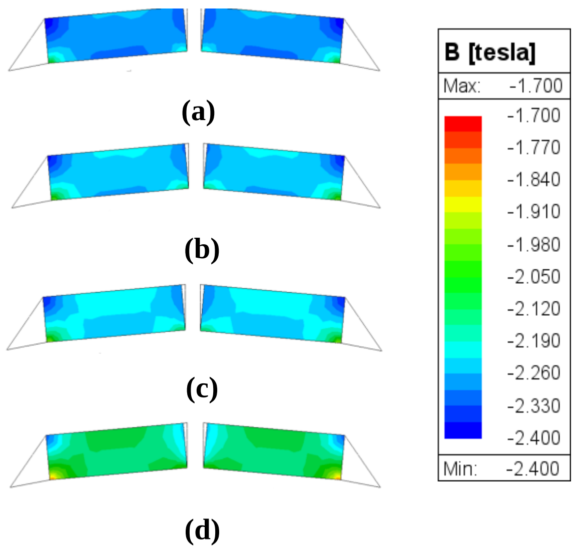


Figure 11. Demagnetization performance of the designed motor under different phase currents. (a) 50 A, (b) 75 A, (c) 100 A, (d) 150 A (Tasarlanan motorun arklı faz akımlarında demagnetizasyon performansı)

In Figure 11 above, the demagnetization risk of the magnets can be observed at four different phase currents. When the "demagnetization proximity" value is negative in these graphs with the unit Tesla, it can be regarded as there is no demagnetization risk. As the temperature increases, the risk of demagnetization will also increase. In this study, apart from the current density, the thermal performance of the motor has yet to be examined.

4. CONCLUSIONS (SONUÇLAR)

In this study, a design and analysis of a V-shaped Outer-Rotor PMaSynRM applicable to EVs and HEVs utilizing a 72V DC battery pack was conducted. The design phase was culminated and verified by electromagnetic performance analysis, assessing motor performance under various conditions.

The efficiency of the proposed motor under rated conditions was determined to be 90%, and its maximum torque was observed to exceed 35 Nm based on the performed analyses. The torque-speed characteristics of the motor were examined at phase currents of 50A, 75A, 100A, and 150A, considering the different capacity motor drives used in light electric vehicles. The approximately consistent maximum torque values per ampere across each phase current indicate that the core is not undergoing saturation. Similarly, the demagnetization performance of the magnets was examined at the specified current values. The investigation concluded that there is no risk of demagnetization in the current design.

In the further stages of this study, a design optimization study for different magnet placement geometries will be conducted, and the electromagnetic and thermal performance parameters of the optimized designs will be comparatively analyzed and presented.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Burak YENİPINAR**:** He conducted the research, analyzed the results and performed the writing process.

Araştırmayı yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

Ali SAYGIN**:** He conducted literature review and interpretation of results.

Literatür taraması ve sonuçların yorumlanması işlemini gerçekleştirmiştir.

Yusuf SÖNMEZ**:** He conducted literature review and interpretation of results.

Literatür taraması ve sonuçların yorumlanması işlemini gerçekleştirmiştir.

Cemal YILMAZ**:** He has contributed subject and article evaluation.

Konu ve makale değerlendirmesinde katkıda bulunmuştur.

Cemil OCAK**:** He has contributed subject and article evaluation.

Konu ve makale değerlendirmesinde katkıda bulunmuştur.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

REFERENCES (KAYNAKLAR)

[1] Ocak, C., & Yenipınar, B. (2021). Hafif Elektrikli Araçlar için Asenkron Motor Tasarımı ve Uygulaması. Avrupa Bilim ve Teknoloji Dergisi, (26), 228-233.

[2] Kerem, A., & Gürbak, H. (2020). Elektrikli Araçlar için Hızlı Şarj İstasyonu Teknolojileri. Gazi University Journal of Science Part C: Design and Technology, 8(3), 644-661.

[3] Cao, R., Mi, C., & Cheng, M. (2012). Quantitative comparison of flux-switching permanent-magnet motors with interior permanent magnet motor for EV, HEV, and PHEV applications. IEEE Transactions on magnetics, 48(8), 2374-2384.

[4] Husain, I., Ozpineci, B., Islam, M. S., Gurpinar, E., Su, G. J., Yu, W., ... & Sahu, R. (2021). Electric drive technology trends, challenges, and opportunities for future electric vehicles. Proceedings of the IEEE, 109(6), 1039-1059.

[5] 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.

[6] Ding, L., Cheng, Y., Zhao, T., Yao, K., Wang, Y., & Cui, S. (2023). Design and Optimization of an Asymmetric Rotor IPM Motor with High

Demagnetization Prevention Capability and Robust Torque Performance. Energies, 16(9), 3635.

[7] Wang, S. C., Nien, Y. C., & Huang, S. M. (2022). Multi-objective optimization design and analysis of V-shape permanent magnet synchronous motor. Energies, 15(10), 3496.

[8] Dalcali, A. (2018). Optımal Desıgn of Hıgh Performance Interıor PM Motor for Electrıc Vehıcle. The International Journal of Energy and Engineering Sciences, 3(2), 46-54.

[9] Wang, A., Jia, Y., & Soong, W. L. (2011). Comparison of five topologies for an interior permanent-magnet machine for a hybrid electric vehicle. IEEE transactions on Magnetics, 47(10), 3606-3609.

[10] Tovar-Barranco, A., Briz, F., López-de-Heredia, A., & Villar, I. (2017, September). Comparison of permanent magnet synchronous machines with concentrated windings and different rotor configurations. In 2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe) (pp. P-1). IEEE.

[11] Shi, Z., Sun, X., Cai, Y., Tian, X., & Chen, L. (2020). Design optimisation of an outer-rotor permanent magnet synchronous hub motor for a low-speed campus patrol EV. IET Electric Power Applications, 14(11), 2111-2118.

[12] Sundaram, M., Anand, M., Chelladurai, J., Varunraj, P., Joshua Smith, S., Sharma, S., ... & Alayi, R. (2022). 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.

[13] Bdewi, M. Y., Ali, M. M. E., & Mohammed, A. M. (2022). In-wheel, outer rotor, permanent magnet synchronous motor design with improved torque density for electric vehicle applications. International Journal of Electrical and Computer Engineering, 12(5), 4820.

[14] Ghahfarokhi, P. S., & Faiz, J. (2018). Design of four pole permanent magnet motor with different rotor topologies. Journal of Electromotion, 20, 1-4.

[15] Paitandi, S., & Sengupta, M. (2020). Analysis, fabrication and detailed comparative study of surface and interior rotor PMSM prototypes of identical nominal ratings and stators. Sādhanā, 45(1), 69.

[16] Kim, H. J., Jeong, J. S., Yoon, M. H., Moon, J. W., & Hong, J. P. (2017). Simple size determination of permanent-magnet synchronous machines. IEEE Transactions on Industrial Electronics, 64(10), 7972-7983.

[17] Diab, A., Rashed, M., Li, J., Gerada, C., & Bozhko, S. (2018, November). Performance analysis of PMSM for high-speed starter-generator system. In 2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC) (pp. 1-7). IEEE.

[18] Shen, Q., Sun, N., Zhao, G., Han, X., & Tang, R. (2010, March). Design of a permanent magnet synchronous motor and performance analysis for subway. In 2010 Asia-Pacific Power and Energy Engineering Conference (pp. 1-4). IEEE.

[19] Estima, J. O., & Cardoso, A. M. (2010, September). Performance analysis of a PMSM drive for hybrid electric vehicles. In The XIX International Conference on Electrical Machines-ICEM 2010 (pp. 1-6). IEEE.

[20] Bdewi, M. Y., Mohammed, A. M., & Ezzaldean, M. M. (2021). Design and performance analysis of permanent magnet synchronous motor for electric vehicles application. Engineering and Technology Journal, 39(03 Part A), 394-406.

[21] You, Y. M., & Yoon, K. Y. (2021). Multi-objective optimization of permanent magnet synchronous motor for electric vehicle considering demagnetization. Applied Sciences, 11(5), 2159.

[22] Pop-Pîgleşan, F., Pop, A. C., & Marţiş, C. (2021). Synchronous reluctance machines for automotive cooling fan systems: numerical and experimental study of different slot-pole combinations and winding types. Energies, 14(2), 460.