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Design Optimization of Permanent Magnet Synchronous Motors: An Analytical Review and Case Study

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ABSTRACT

Permanent Magnet Synchronous Motors (PMSMs) are widely used in industrial and electric vehicle applications for their high efficiency, compact size, and precise controllability. However, cogging torque remains a key issue, causing vibration, noise, and performance loss, especially at variable speeds. This study presents a Finite Element Analysis (FEA)-based parametric optimization approach to improve the magnetic and structural performance of a 20-kW, 138-V, 6-pole PMSM. Instead of heuristic algorithms, the method refines key geometric parameters such as magnet thickness, pole embrace, and pole offset that strongly affect flux distribution, torque, and vibration. Using ANSYS Maxwell, simulations analyze their effects on efficiency, air-gap flux density, and cogging torque. Results indicate a decrease in cogging torque from 7.56 Nm to 4.74 Nm and an approximate 15% enhancement in efficiency, leading to improved torque smoothness and more uniform magnetic flux distribution. The study highlights the importance of precise geometric optimization for higher performance and lower noise.

Sabit Mıknatıslı Senkron Motorların Tasarım Optimizasyonu: Analitik Bir İnceleme ve Durum Çalışması

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ÖZ

Kalıcı Mıknatıslı Senkron Motorlar (SMSMler), yüksek verimlilikleri, kompakt boyutları ve hassas kontrol edilebilirlikleri nedeniyle endüstriyel ve elektrikli araç uygulamalarında yaygın olarak kullanılmaktadır. Ancak, vuruntu torku, özellikle değişken hızlarda titreşim, gürültü ve performans kaybına neden olan önemli bir sorun olmaya devam etmektedir. Bu çalışma, 20 kW, 138 V, 6 kutuplu bir SMSM'nin manyetik ve yapısal performansını iyileştirmek için Sonlu Elemanlar Analizi (FEA) tabanlı bir parametrik optimizasyon yaklaşımı sunmaktadır. Sezgisel algoritmalar yerine, yöntem akı dağılımını, torku ve titreşimi güçlü bir şekilde etkileyen mıknatıs kalınlığı, kutup kucaklaması ve kutup ofseti gibi temel geometrik parametreleri iyileştirir. ANSYS Maxwell kullanılarak yapılan simülasyonlar, verimlilik, hava boşluğu akı yoğunluğu ve vuruntu torku üzerindeki etkilerini analiz eder. Sonuçlar, vuruntu torkunda 7.56 Nm'den 4.74 Nm'ye bir düşüş ve verimlilikte yaklaşık %15'lik bir artış olduğunu, bunun da iyileştirilmiş tork düzgünlüğüne ve daha düzgün manyetik akı dağılımına yol açtığını göstermektedir. Çalışma, daha yüksek performans ve daha düşük gürültü için hassas geometrik optimizasyonun önemini vurgulamaktadır.

1. INTRODUCTION

PMSMs are commonly used in many areas such as automotive, aerospace, robotics, and industrial applications due to their high efficiency, fast torque responsiveness, and advantages of compact design [1-3]. PMSMs offer higher energy efficiencies and a wider torque-speed band than induction motors, making them especially prominent in low- and high-speed applications [1]. The design of PMSMs, however, is quite complicated and optimization techniques are required to achieve the most suitable motor parameters for the given operating conditions [2,4]. The main aim of the optimization process is to fine-tune motor parameters to strike a balance between various performance metrics, including minimizing torque ripple, managing thermal conditions, and ensuring cost-effectiveness. For this reason, optimization is necessary to increase the energy efficiency and power density of the motor, especially in high-performance applications such as electric vehicles and aviation.

Jeong et al. focused on the optimized design of PMSMs with hybrid-type permanent magnets, which not only improved performance but also enhanced reliability [4]. Lee et al. succeeded in enhancing the magnetic performance of the motor by using modified particle swarm optimization (PSO) and mesh adaptive direct search (MADS) methods in PMSM design [5]. Candelo-Zuluaga et al. emphasized the importance of optimization in PMSM design to reach the target torque-speed-efficiency map and demonstrated how this process improved the overall performance of the motor [6]. Dang et al. conducted a design optimization study on a nonsalient high-speed PMSM tailored for electric vehicle applications. Initially, they developed a one-dimensional analytical model, which was subsequently validated for the most critical point of the driving cycle using finite element analysis. The paper details the design methodology and presents results through a specific application [7]. Giangrande et al. demonstrated the design and testing of PMSMs for aerospace electromechanical actuator (EMA) applications, emphasizing the need for robust and lightweight designs [8]. Wang et al. presented in their studies that metaheuristic algorithms such as genetic algorithms (GA), PSO and MADS are effective in optimizing surface PMSM designs [9]. Qiang et al. explored the use of fuzzy PID controllers in PMSM servo control systems, demonstrating their effectiveness in achieving precise control [10]. Hou et al. proposed a composite super-twisting sliding mode control strategy based on a novel disturbance observer, which significantly improved speed regulation in PMSMs [11]. Additionally, Liu et al. addressed flux-weakening control in dual three-phase PMSM drive systems, focusing on copper loss minimization to enhance efficiency [12]. In direct drive applications, machine learning methods such as support vector regression (SVR) are being increasingly used to improve torque density and to minimize torque ripple. These techniques, in conjunction with sophisticated models that incorporate high-order space harmonics, provide more precise performance predictions and efficient design optimization [13]. In PMSM design optimization, improving efficiency and gear torque characteristics are among the focal points. Methods such as Kriging models and genetic algorithms have shown outstanding performance in dealing with these issues. By using finite element analysis (FEA) and rotor shape optimization, the efficiencies and the dynamic performance of electric vehicle electric compressors can be significantly improved [14].

PMSM design optimization is a procedure to increase the performance and efficiency of the motor. In this optimization procedure, various algorithms and techniques are used. As shown in Figure 1, evolutionary algorithms like Genetic Algorithms (GA), Particle Swarm Optimization (PSO) and Differential Evolution (DE) use population-based searching strategies to obtain better results in motor design. Goal-based optimization algorithms optimize motor parameters to reach a given goal performance or efficiency value. On the other hand, heuristic algorithms use problem domain-specific information and experiences to produce fast and efficient solutions. By a combination of these methods, high performance and efficiency can be achieved in PMSM optimization.

In this study, the design and optimization of a PMSM are performed using ANSYS Maxwell, a finite element analysis software for electromagnetic systems. Unlike the optimization algorithm frequently employed in the literature, this study adopts a parametric optimization methodology. The effectiveness of the parametric optimization method is both computational efficiency and the ability to systematically optimize many design parameters. This method offers significant advantages in enhancing motor performance, reducing torque ripples, and minimizing electromagnetic losses. Similarly, Wiesheu et al. demonstrated substantial improvements in reducing material costs, torque ripples, and losses through spline-based rotor and stator shape optimization within an isogeometric analysis framework [15]. Chen and Lee performed a detailed parametric sensitivity analysis on an Interior PMSM with a V-shaped magnet structure, revealing how rotor geometric variations impact key electromagnetic characteristics such as average torque, torque ripple, cogging torque, power density, power factor, and efficiency across different speed ranges [16]. In conclusion, parametric optimization serves as a powerful tool in PMSM design, facilitating informed decision-making and enabling designers to achieve targeted performance metrics while potentially reducing development and production costs.

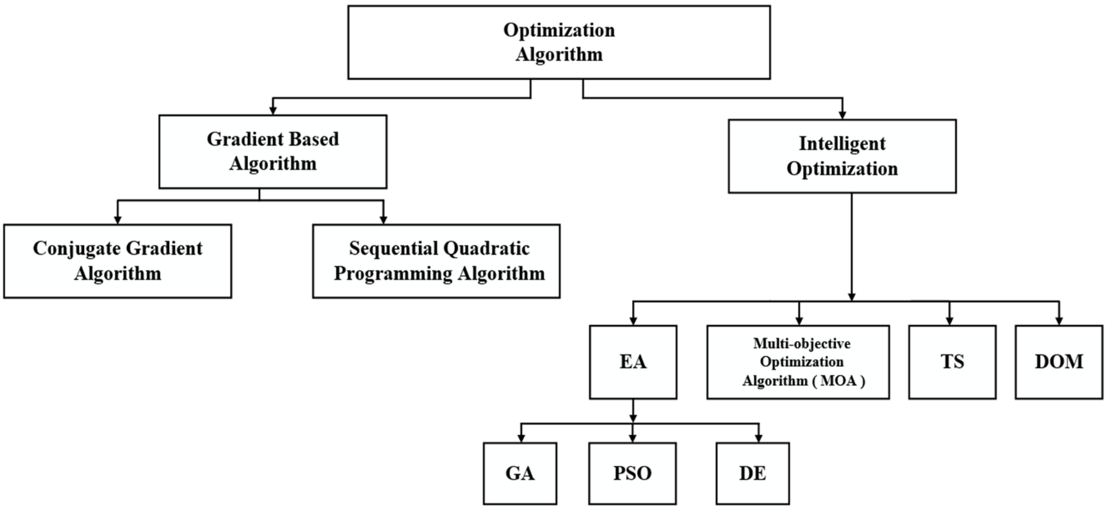


Figure 1. Optimization algorithm for PMSM designs

The study introduces a parametric optimization strategy focused on critical geometrical parameters that have a direct influence on the motor's magnetic field distribution specifically, magnet thickness, pole embrace, and pole offset. The proposed optimization scheme enhances the overall performance efficiency of the PMSM while simultaneously achieving a substantial reduction in cogging torque, one of the main sources of vibration and noise in electric motors. By methodically adjusting these key parameters, the study ensures an improved balance between electromagnetic torque generation and mechanical stability, leading to a more stable and efficient operation.

2. OPTIMIZATION METHODS PERFORMED IN THE PMSM FIELD

2.1. Genetic Algorithm

PMSMs are widely used in various industrial applications due to their high efficiency, power density, and reliability. However, designing an optimal PMSM requires a balance between multiple conflicting objectives, such as efficiency maximization, weight reduction, and cost minimization. Traditional design methodologies often fall short in addressing the complexity of this multi-objective problem. Therefore, advanced optimization techniques such as Genetic Algorithms (GAs) have gained popularity for PMSM design optimization.

Cvetkovski and Petkovska utilized GA for optimizing specific power density, demonstrating its effectiveness in balancing performance metrics [17]. Similarly, Mutluer and Bilgin compared GA with PSO in PMSM design, concluding that GA provides robust and globally optimal solutions [18]. Avdeev and Osipov applied GA for PMSM parameter identification under noisy conditions, showing that GA-based optimization improves accuracy and robustness [19]. Furthermore, Guo et al. (2010) introduced hybrid and interval-based GA approaches, which enhanced solution precision and convergence speed [20]. Additional studies highlight the use of GA in high-speed PMSM designs, focusing on power density and loss minimization [21]. Karnavas and Korkas implemented GA for optimizing radial flux PMSM, demonstrating improved efficiency and reduced material costs [22]. In another study, Mallik et al. used GA to design an energy-efficient induction motor, highlighting its applicability to PMSMs as well. They found that GA could effectively optimize efficiency and cost parameters while adhering to manufacturing constraints [23].

Genetic Algorithm is a powerful tool for PMSM design optimization, offering a robust and flexible approach to addressing multiobjective design challenges. The literature indicates that GA not only improves performance metrics such as efficiency and cost but also enables innovative hybrid optimization strategies.

2.2. Differential Evolution Algorithm

This section discusses the fundamental principles of DE, its application in PMSM optimization, and evaluates its effectiveness in comparison with other algorithms. Optimization techniques for PMSMs have evolved significantly over the years. Sizov et al. employed a multi-objective DE algorithm for optimizing PM AC synchronous machines, addressing multiple stator and rotor geometric variables. They demonstrated that DE achieves better efficiency and lower torque ripple compared to conventional methods [24]. Another study by Caponio et al. explored the application of Memetic Differential Evolution (MDE) in PMSM control system design, showing significant improvements in convergence speed and solution quality [25]. Zhao et al. introduced a combined approximation model with DE to optimize modular linear PM vernier machines, demonstrating enhanced performance in high-precision direct-drive applications [26]. Furthermore, Zhang et al. implemented DE in parametric modeling and optimization of spoke and V-type PM machines, highlighting its capability to systematically compare different motor topologies [27]. DE is a population-based optimization algorithm that operates through mutation, crossover, and selection operators to iteratively improve solutions. The mutation step involves creating new individuals by adding weighted differences between existing population members. The crossover step combines parent and mutated individuals to introduce diversity, while the selection step ensures that only the fittest individuals survive to the next generation [28]. DE is well-suited for PMSM optimization due to its ability to handle nonlinear constraints and multi-objective trade-offs effectively. Unlike Genetic Algorithms, DE employs direct mutation strategies without requiring crossover probabilities, making it computationally efficient and robust against local optima.

2.3. Particle Swarm Optimization

Kennedy and Eberhart first proposed PSO in 1995 [29]. Particles can reach in the direction of the optimal solution in the search space using this approach, which is predicated on the concept of swarm intelligence. In the design of permanent magnet synchronous motors, PSO is also utilized. By examining design optimization techniques for electrical devices, Lei et al. showed the efficacy of PSO in this area [30]. Zhang et al. shown how well it works to solve challenging optimization issues. Their research showed that PSO's capacity to strike a balance between exploration and exploitation has led to its widespread use in machine learning, artificial intelligence, and engineering. The authors also underlined the value of hybrid PSO techniques, which incorporate additional metaheuristic algorithms to improve solution accuracy and convergence speed [31]. Gu et al. proposed an optimization of a PMSM design to preserve a constant power speed range. An increased constant power speed range provided by the recommended optimization method has resulted in lower losses and increased efficiency over the torque-speed range [32]. Bhagubai et al. identified geometric factors such rotor radius, stator outer ring width, magnet width and length, airgap size, and shaft radius as decision variables [33]. Gong et al. offered a better PSO variant known as genetic PSO in which the original PSO's convergence rate has been increased by using genetic operators [34]. Essential parameters and feasible models for optimization are provided by the design process. As seen in Figure 2, the optimization process improves these designs using a variety of methods and techniques to get the highest performance and efficiency.

Two crucial aspects to enhancing electrical machine performance and cutting expenses are design and optimization. Process planning, inverter and controller design, electromagnetic properties, motor type, structure, material and size selection, and thermal management are all part of the design process. Optimization models are developed using the data gathered during the design stage. Using single or multi-objective models, conventional numerical techniques, clever algorithms, and hybrid approaches, the optimization process enhances the design. Optimization is more effective when multilevel approaches, transdisciplinary methods, and surrogate models are used. These two processes operate in a cycle whereby design improves optimization and optimization improves designs. This combination, particularly when combined with clever algorithms, expedites design processes and successfully resolves technical difficulties.

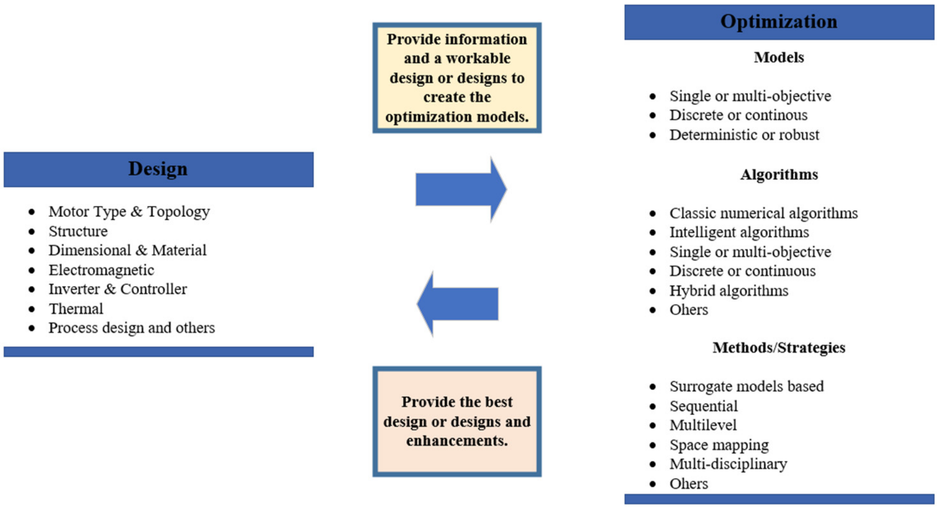


Figure 2. Electrical machine design and optimization

2.4. Tabu Search Algorithm

Tabu Search (TS) is a metaheuristic search method employing local search methods for mathematical optimization. It was created by Fred W. Glover in 1986 [35] and formalized in 1989 [36, 37].TS guides a local heuristic search procedure to explore the solution space beyond local optimality, emphasizing adaptive memory and responsive exploration [35]. TS applications include electric motor optimization. Yazdani-Asrami et al. designed a Permanent Magnet Brushless DC Motor using a modified TS optimizer, considering losses, volume, and cost [38]. Idoumghar et al. minimized torque ripple in a three-phase switched-reluctance machine, demonstrating TS's effectiveness in improving motor performance [39]. By improving the current TS method, Ho et al. presented an improved Tabu Search (ITS) algorithm to optimize electromagnetic devices. In addition to using techniques like systematic diversification, memory retention of investigated subspaces, and an accelerated neighborhood search procedure, the ITS also includes an aspiration criterion. Thus, the ITS reached convergence in 1,842 iterations, about five times less than the number of iterations needed for the Simulated Annealing (SA) technique [40].

The solution process of the Tabu Search algorithm is illustrated in Figure 3. This process includes local search methods starting from an initial solution, barriers to local minimum, cycling problems, and strategies for reaching the global minimum. Local minimum, which are points in the solution space where the objective function reaches a reasonably low value but frequently do not correspond to the optimal solution, are distinct from global minimum. Figure 3 shows how a local minimum might trap an early solution, impeding its progress toward the global minimum.

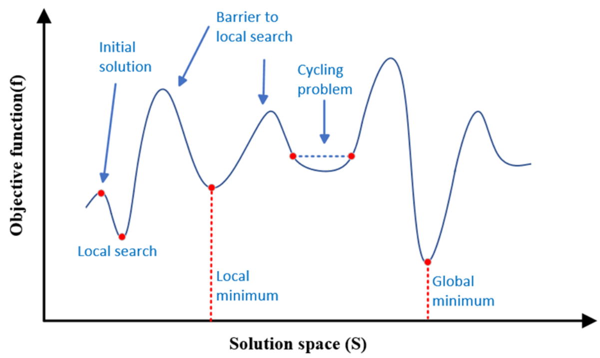


Figure 3. Tabu search algorithm solution process.

An algorithm's ability to find better solutions may be hampered by obstacles in the solution space, and conventional optimization algorithms frequently encounter these difficulties and prematurely converge at local minimum. The problem of cycling, in which the algorithm alternates between spots without making much progress, can also arise in optimization procedures. This reduces search efficiency and makes it more difficult to explore new regions of the solution space. These issues are successfully addressed by sophisticated algorithms such as TS, which avoid trapping in local minimum, prevent cycling, and intelligently guide the search process. TS improves the algorithm's capacity to go past barriers and arrive at the global minimum by more effectively traversing the solution space. These methods are essential to engineering optimization, especially in applications like electric motor optimization, where they enhance system performance, lower expenses, and lessen unintended consequences in challenging optimization issues.

2.5. Multi-Objective Algorithm

PMSMs are extensively used in industry due to their high efficiency and their successful performance in various applications. However, it is challenging to optimize the layout of these engines as they have conflicting objectives. These targets include maximizing efficiency and torque while also minimizing flyback and torque swelling. To help overcome these difficulties, academics and engineers have developed multi-objective algorithms (MOAs) to optimize the design and performance of PMSMs. By considering the competing goals of efficiency, cost, torque performance and stability simultaneously, MOAs help to carefully balance these trade-offs to create designs that meet specific performance requirements while maintaining reliability and productivity.

Parekh et al. presented a hybrid representation that integrates data-driven and physics-based methodologies. Their novel approach leverages deep neural networks to forecast motor motion and optimize execution, resulting in a significant decrease in computational requirements compared to classical optimization methods. This work emphasizes the potential of integrating artificial intelligence with MOAs to improve the design flow and offers a more efficient way for motor optimization [41]. Huber et al. explored the formation of unsteady PMSM designs with machine learning techniques. Their work is focused on optimizing targets such as constant quality, which is essential for sustaining consistent motor performance. Despite encountering difficulties with instability, their work has highlighted the importance of power and stability as critical directions in motor optimization. This highlights the role of MOAs in tackling complex, multi-dimensional design challenges [42]. Gauthey et al. developed a multi-material optimization topology optimization approach for PMSM design. Their approach has facilitated the discovery of modern rotor and stator geometries, resulting in significant improvements in the motor performance. This work has resulted in novel designs that increase overall efficiency and functionality by showing how MOAs can effectively manage material distribution and structural optimization [43]. Wiesheu et al. has proposed a spline-based optimization strategy for rotor and stator designs. Their method sought to minimize material costs, decrease torque fluctuation and mitigate the mechanical failures. This approach, which is in line with the principles of MOAs, shows the potential to achieve practical and cost-effective engine design solutions while maintaining high performance standards. The spline-based method's emphasis on material efficiency and robustness underlines the MOAs' versatility in meeting various optimization objectives [15]. Figure 4 is a cross-sectional representation of the basic components and layout of an electric motor. The motor's static and moving components are expressed in different colors. The stator (orange color) is the stationary part of the motor, which generates the magnetic field and makes the rotor spin. The air gap (yellow) is between the stator and the rotor, allowing the transmission of magnetic flux. The rotor design area (red color) is the rotating component of the motor and generates the mechanical movement as a consequence of magnetic interaction. The torque matching band (black) is a region critical to optimizing the motor's torque performance. The windings and circuit elements (colored green) are located inside the stator, allowing the electric current to be conducted and the magnetic field to be created. Figure 4 is used to analyze the arrangement of the structural components in motor design and to optimize performance.

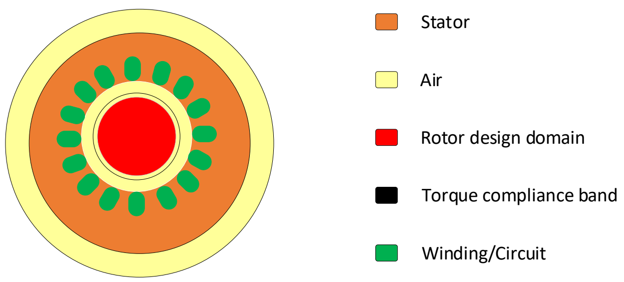


Figure 4. Schematic representation of the motor structure

These studies illustrate the potentially transformative impact of MOAs on PMSM design optimization. By integration of advanced computational techniques, machine learning and hybrid approach, the researchers have obtained substantial improvements in engine performance, cost-efficiency and safety. The capability of MOAs to balance competing targets such as material efficiency, stability and torque performance positions them as essential tools for modern engineering challenges.

2.6. Deterministic Optimization Method

Deterministic Optimization Method (DOM) has been used for electric vehicles and machinery since the 1940s. DOM has a simpler structure compared to some other methods. Instead of modifying multiple parameters simultaneously, it follows a sequential process that is repeated until the most efficient result is obtained. Efficient results are defined as the attainment of optimal values in terms of efficiency, power, torque, and various other parameters [44]. Figure 5 shows the flowchart of the DOM algorithm to analyze a PMSM.

DOM is a method of changing the air gaps between the rotor and stator, changing the fixed parts on the rotor and reducing the magnetic losses in the motor. These changes are parameters that vary depending on the type of motor and where it is used. Each one serves many different purposes. To date, many studies have been carried out on many different machines, from household machines to business machines, and all of these studies have a different purpose. Compared to stochastic measurements, DOM is more preferable as it is a more accurate way of configuring the machines and motors under study. Ahmad et al. used the DOM method to optimize the design of electric machines by taking the design parameters in order and using Finite Element Analysis (FEA) method to modify the air gaps in the motor, the thickness and thinness of the materials in the rotor and stator. In addition, they made design changes to increase torque production and to prevent the loss in magnetic flux [43]. ION et al. compared these two methods for the improvement of electrical devices in their study [45].

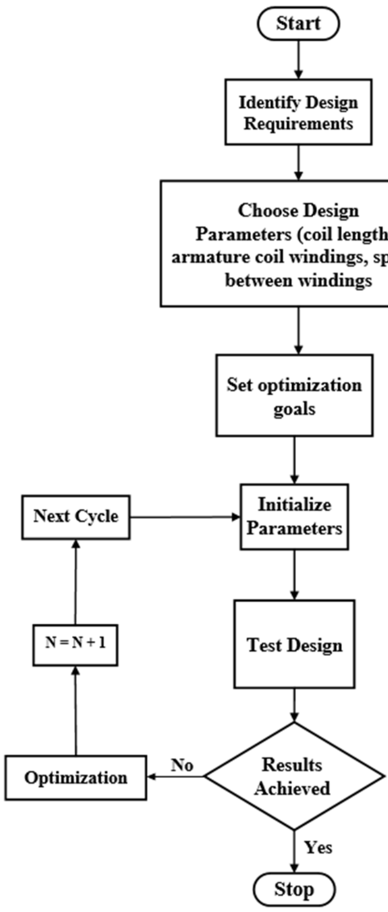
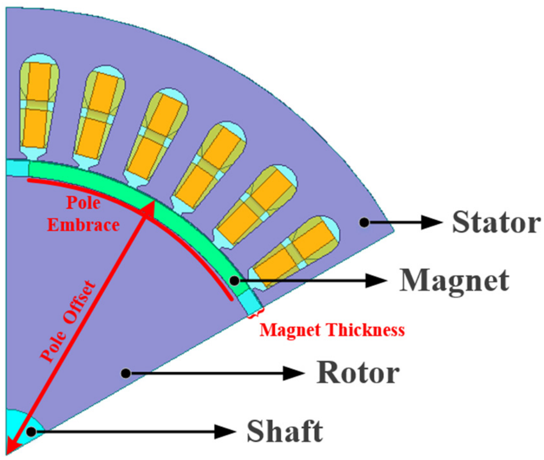


Figure 5. Flowchart of the DOM algorithm

Liu et al. proposed a design proposal using robust and deterministic optimization methods together to improve torque performance in spoke-type permanent magnet machine designs. A design was made using Monte Carlo analysis (MCA) and Design for Six Sigma (DFSS) analysis methods. As a result, they reduced the fluctuations in torque performance [46]. Wang et al. used particle swarm optimization (PSO) and deep deterministic policy gradient (DDPG) algorithms for speed control of PMSMs. First, they used the PSO algorithm to design a PI controller based on the characteristics of the motor. In the second stage, they included the DDGP algorithm and completed the online learning process quickly. They have achieved success by maintaining the balance between speed and control by counteracting the delays in the system and the inability to maintain the load [47].

3. CASE STUDY

PMSMs have notable benefits compared to conventional motors, mainly due to their compact size, reduced weight, and superior efficiency and power performance. Advances in the development of high-energy-efficiency motors have emphasized the significance of minimizing harmonic distortions in torque-time curves and variations in rotor speed. Since torque under no-load conditions contributes to speed instability and noise, its reduction is a crucial design goal, especially for applications that run at low speeds and light loads [48]. In this study, the analytical and magnetic design processes are carried out using ANSYS RMxprt and Maxwell-3D software tools. The motor being analyzed is a three-phase PMSM, featuring a 6-pole rotor and a 36-slot stator. The designed PMSM model is illustrated in Figure 6.



(a) (b)

Figure 6. Designed PMSM a) 2D view, b) The pole piece of a full motor

The optimization process considers key design factors, including magnet thickness, pole embrace, and pole offset. These variables play a crucial role in shaping the motor's torque characteristics, minimizing cogging effects, and optimizing the magnetic field distribution. By integrating parametric optimization techniques for magnet thickness, pole embrace, and pole offset, the overall motor performance can be significantly improved. Magnet thickness plays a crucial role in determining the magnetic flux linkage, air-gap flux density, and torque production of the motor. Pole embrace (or pole arc ratio) represents the ratio of the pole arc to the pole pitch and directly affects the air-gap flux distribution and torque production. Pole offset refers to the angular displacement of the permanent magnets on the rotor. It is a key parameter for reducing torque ripple and cogging torque, ensuring smoother operation. By integrating parametric optimization techniques for magnet thickness, pole embrace, and pole offset, the overall motor performance can be significantly improved [49].

Parametric optimization involves systematically adjusting key design parameters to enhance motor performance metrics such as torque production, efficiency, and reduction of torque ripples. Key parameters typically considered in this optimization process include magnet thickness, pole embrace, and pole offset. Nominal design data of the PMSM is given in Table 1. PMSM optimization is carried out using the parameters listed in Table 2.

To systematically determine the optimal values of these parameters, the parametric optimization process is implemented using an iterative approach. Finite Element Analysis (FEA)-based simulations are used to analyze and refine the design. The optimization process consists of multiple iterative simulations and analysis steps to determine the optimal values for pole offset, magnet thickness, and pole embrace. Initially, the variable ranges are defined based on prior knowledge and design constraints. Then, parametric analysis is conducted using electromagnetic simulations to assess the effects of different parameter combinations on motor performance. The optimization process evaluates key performance indicators, including efficiency, air-gap flux density, total losses, and cogging torque. Higher efficiency ensures lower power losses and improved energy conversion, while optimal air-gap flux density enhances smooth torque generation and minimizes saturation effects. Additionally, reducing total losses improves overall motor performance. Lastly, minimizing cogging torque leads to smoother operation and reduced torque ripple, resulting in a more stable and efficient PMSM design.

The initial nominal efficiency of the PMSM (Permanent Magnet Synchronous Motor) is 70.46%. Through parametric optimization, parameters have been determined to increase efficiency, reduce cogging torque, and achieve the optimum air gap flux density. Figure 7 presents the 3D efficiency map. In this optimization process, two key factors are focused on reduction of cogging torque and achieving optimum air gap flux density. Cogging torque arises from irregularities in the motor's tooth structure, causing torque ripple. Reducing this ripple improves the smoothness and efficiency of the motor's operation. Optimizing the magnetic flux density in the air gap of the motor enhances its efficiency. This optimization ensures the motor operates with less energy loss, thus improving its overall performance. As a result, by optimizing these parameters, a more efficient PMSM design is obtained.

Table 1. Nameplate data of designed PMSM

Nominal data	Value
Rated Output Power (kW)	20
Rated Voltage (V)	138
Nominal Efficiency (%)	70.46
Number of Poles	6
Stator data	**Parameters**
Number of Stator Slots	36
Outer Diameter of Stator (mm)	340
Inner Diameter of Stator (mm)	225
Length of Stator Core (mm)	86
Stacking Factor of Stator Core	0.95
Slot Area (mm^2)	481.357
Rotor data	**Parameters**
Minimum Air Gap (mm)	0.5
Inner Diameter (mm)	35
Length of Rotor (mm)	400
Polar Arc Radius (mm)	112
Pole Offset (mm)	0
Mechanical Pole Embrace	0.75
Max. Thickness of Magnet (mm)	8
Permanent magnet	**Parameters**
Residual Flux Density (Tesla)	0.96
Coercive Force (kA/m)	690
Maximum Energy Density (kJ/m^3)	183
Type of Magnet	XG196/96

Table 2. Limits of parameter adjustments

Parameter range	Pole embrace (mm)	Magnet thickness (mm)	Pole offset (mm)
Minimum	0.45	4	0
Maximum	0.95	9	26

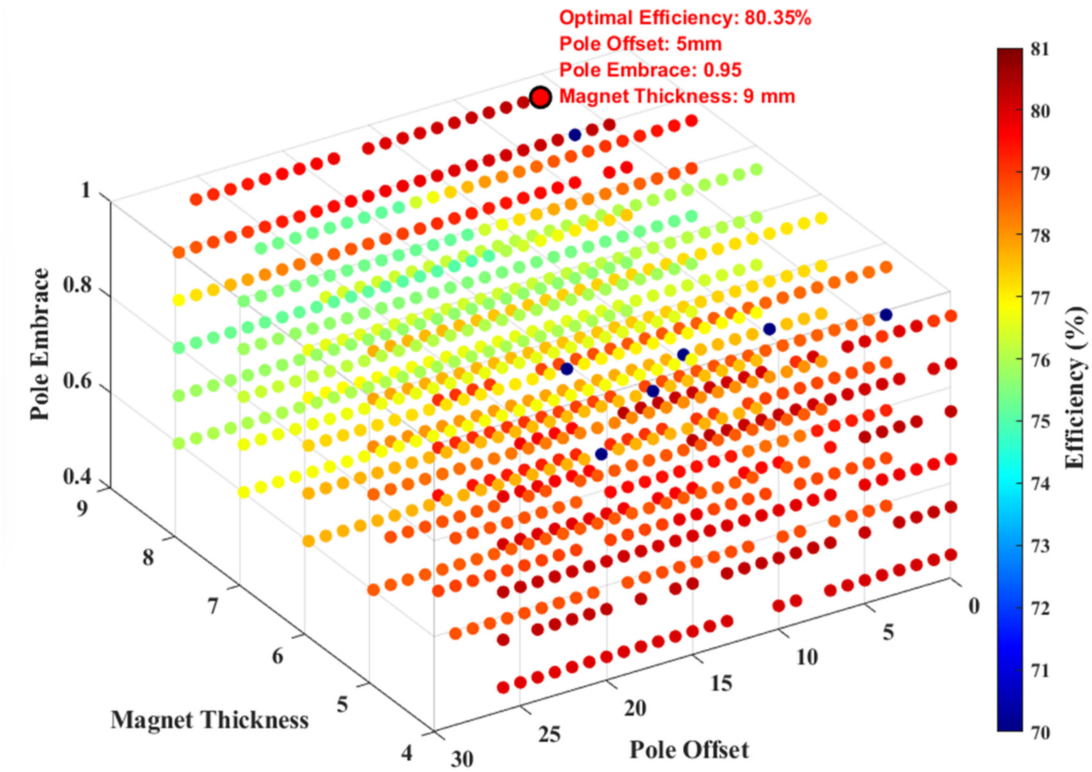


Figure 7. 3D efficiency map of the optimized PMSM

After parametric optimization, the optimal values for efficiency, cogging torque, and air gap flux density were determined to be a Pole Offset of 5 mm, a Pole Embrace of 0.95, and a Magnet Thickness of 9 mm. The maximum efficiency achieved after optimization is shown in Figure 8.

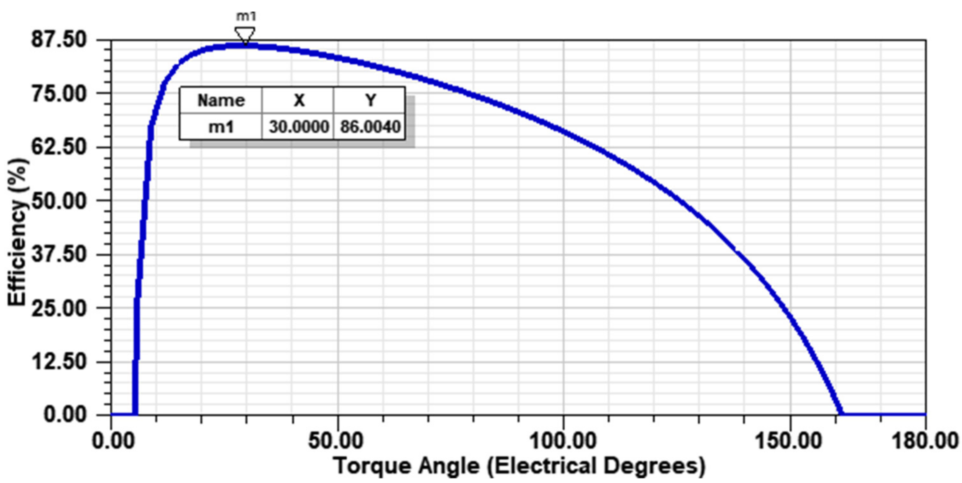
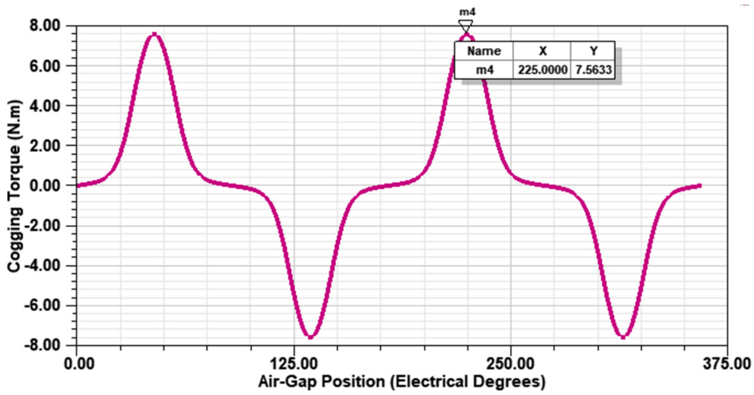
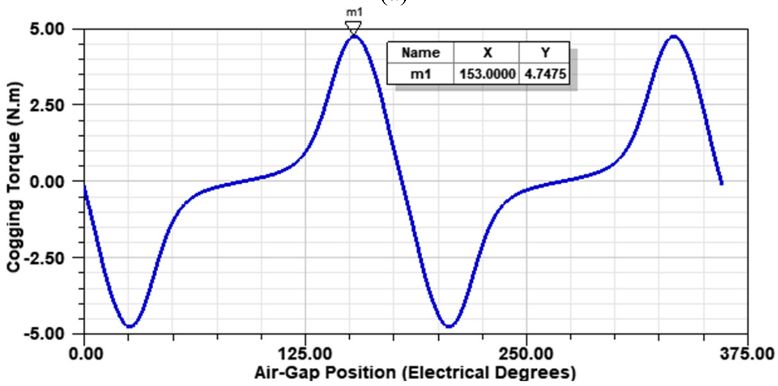


Figure 8. The maximum efficiency of the optimal PMSM

The cogging torque and air gap flux density values are thoroughly analyzed using optimized design parameters. Figure 9 illustrates the reduced cogging torque, while Figure 10 presents the optimized air gap flux density.

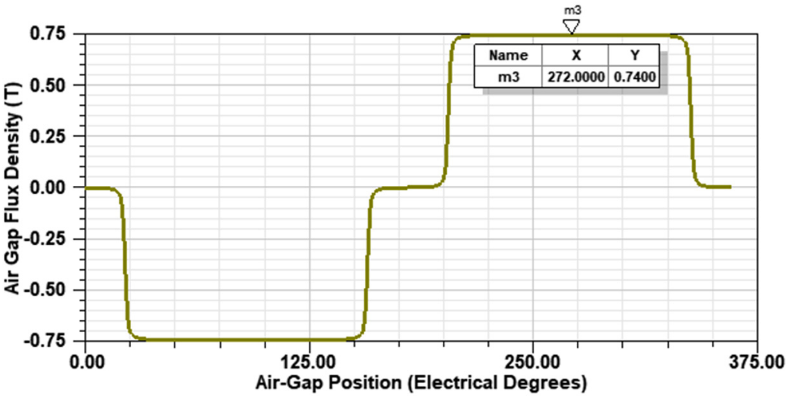


(a)

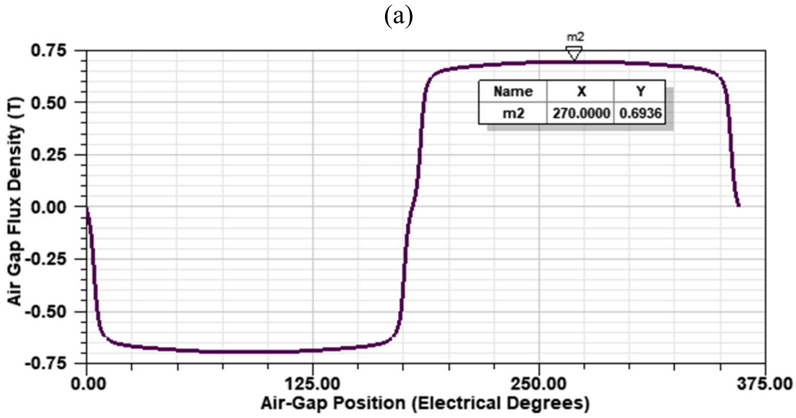


(b)

Figure 9. Cogging torque a) nominal design b) optimal design



(a)



(b)

Figure 10. Air gap flux density a) nominal design b) optimal design

The cogging torque, which is a major source of unwanted vibration and acoustic noise in PMSMs, has been significantly reduced from 7.56 Nm to 4.74 Nm through the applied optimization process. This reduction enhances the smoothness of torque delivery, contributing to quieter and more stable motor operation, especially at low speeds. Additionally, the air-gap flux density has been effectively optimized, leading to a more uniform magnetic flux distribution across the air gap. This improvement not only enhances the torque production capability of the motor but also reduces the risk of local magnetic saturation, which can degrade motor efficiency and cause thermal issues. The combined reduction in cogging torque and refinement of the flux density profile highlights the success of the design approach in achieving a high-performance, low-noise motor configuration. Moreover, following the parametric optimization process, the motor's efficiency experienced a significant improvement, increasing by approximately 15%. This enhancement reflects the effectiveness of optimizing key design parameters such as pole offset, magnet thickness, and pole embrace in reducing losses and improving electromagnetic performance. The increase in efficiency indicates a more effective energy conversion, resulting in reduced power consumption, and better overall motor performance.

The optimization process in this study led to a more uniform air-gap flux density, enhancing torque production and reducing the risk of local magnetic saturation. In comparison, Chen et al. conducted a parametric sensitivity analysis on an Interior PMSM with a V-shaped magnet structure, revealing how rotor geometric variations impact key electromagnetic characteristics such as average torque, torque ripples, cogging torque, power density, power factor, and efficiency across different speed ranges [16]. While both studies emphasize the importance of flux distribution, the current study's integration of analytical modeling with parametric optimization provides a comprehensive approach to enhancing flux uniformity. The efficiency of the motor in this study improved by approximately 15% post-optimization, a significant enhancement. In contrast, Çömezoğlu and Partal reported efficiency improvements of about 1.5% in their study on PMSMs for light electric vehicles [50]. The substantial efficiency gain in the current study underscores the effectiveness of optimizing key design parameters such as pole offset, magnet thickness, and pole embrace. Kim and Baek conducted an optimization of a 30-kW interior PMSM designed for electric vehicle applications, aiming to enhance torque characteristics through modifications to the stator and rotor geometry. Their methodology combined parametric sensitivity analysis with the progressive quadratic response surface method (PQRSM) [51]. The cogging torque presented an approximate performance compared to this study. This comparison highlights the strength of the parametric optimization method employed in this study, particularly considering that the results were achieved without the use of more intricate hybrid optimization techniques.

4. CONCLUSIONS

This study presents a FEA-based parametric optimization approach aimed at improving the magnetic-structural characteristics of a 20-kW, 138-V, 6-pole adjustable-speed permanent magnet synchronous motor for electric vehicle applications. The optimization focuses on refining magnet thickness, pole embrace, and pole offset without altering the motor’s original topology. These parameters are critical as they directly influence the electromagnetic performance, torque production, and mechanical stability of the motor. The results of parametric optimization reveal a notable increase in motor efficiency, from 70.46% to 80.35%. This significant improvement demonstrates the sensitivity of PMSM performance to these structural design parameters. Proper adjustment of pole offset, magnet thickness, and pole embrace leads to an optimal distribution of the magnetic flux in the air gap, thereby reducing losses and improving operational smoothness. The study confirms that careful tuning of these variables can lead to better energy conversion, reduced cogging torque, and enhanced thermal and vibrational performance. Looking ahead, future work will explore hybrid optimization strategies that combine parametric optimization with advanced multi-objective optimization algorithms. This integration is expected to provide more comprehensive design solutions that balance efficiency, cost, and performance under multiple constraints and objectives.

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