A review of modeling techniques and structural topologies for double stator permanent magnet machines

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Article Info

Article history:

Received Sep 7, 2024
Revised Jan 9, 2025
Accepted Mar 1, 2025

Keywords:

Design optimization
Efficiency improvement
Electromagnetic performance
Halbach array
Hybrid methods
Torque characteristics

ABSTRACT

This study reviews the advancements in double-stator permanent magnet machines (DSPMM) with a focus on modeling techniques, design variations, and performance optimization. The research categorizes existing DSPMM modeling methods, including numerical approaches like finite element method (FEM) and boundary element method (BEM), as well as analytical approaches such as analytical subdomain method (ASM), magnetic equivalent circuit (MEC), and Maxwell's equation approach (MEA). These methods improve analytical accuracy, computational efficiency, and address challenges like magnetic saturation and electromagnetic interactions. Structural innovations, including segmented rotor-stator techniques, Halbach arrangements, and soft composite materials, enhance torque density, reduce cogging torque, and optimize magnetic flux distribution, contributing to higher energy efficiency and reduced noise. Supported by software tools like Ansys Maxwell and JMAG-designer, this study identifies optimal DSPMM configurations for various applications, including electric vehicles and renewable energy systems. The findings emphasize the potential of DSPMM for efficient, high-performance electric machines while highlighting the need for further research on transient effects and advanced cooling systems to improve thermal stability.

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1. INTRODUCTION

The increasing demand for efficient and sustainable energy solutions has driven significant advancements in electric machine technology, with the double stator permanent magnet machine (DSPMM) emerging as a key area of research. Leveraging a dual-stator design, DSPMM enhances the utilization of magnetic flux, leading to improved output power, higher power density, lower torque ripple, and reduced losses, resulting in greater efficiency, lower energy consumption, and reduced operating costs [1]. Optimized designs enable DSPMM to achieve lower iron losses and concentrated windings, further enhancing power density and torque capacity [2]. Its ability to evenly distribute the magnetic field and minimize magnetic losses ensures stable and consistent power output, making DSPMM ideal for renewable energy applications such as wind turbines and hydroelectric plants [3]-[6]. Additionally, it is widely used in industrial sectors for actuators, servo motors, compressors, and equipment drive requiring precision and efficiency [7]. In electric vehicles (EVs), DSPMM serves as the prime drive motor, offering the high efficiency and power density needed for optimal performance [8], [9], while in the aerospace sector, it powers actuator systems, fuel pumps, and flight controls, meeting the demands for high performance in weight- and space-constrained environments [10].

While DSPMM offers many advantages, there are still some challenges in achieving optimal performance. Ahmad *et al.* [11] identified issues such as magnetic saturation, aversion to air gaps, and electromagnetic interactions between stators as the main obstacles to maximizing DSPMM efficiency, as they inhibit the increase in the magnetic field as the current increases, leading to a decrease in maximum torque and efficiency, as well as an increase in energy loss. Kim *et al.* [12] also highlight that the electromagnetic coupling between the inner and outer stators can create unwanted flux harmonics, affecting the efficiency and stability of machine operation. Gao *et al.* [13] submitted that iron losses, including hysteresis losses and eddy currents, increased in the DSPMM design due to the high magnetic flux generated by the two stators. This effect affects efficiency at high speeds and requires high-quality magnetic core material to reduce it.

Based on the above problems, such as magnetic saturation, reducing iron loss, optimizing stator interaction to reduce flux harmonics, and improving efficiency, this literature review aims to systematically analyze and improve the in-depth understanding of DSPMM, so as to solve these problems and obtain a highly efficient and performance-oriented DSPMM design. This study consists of several parts, part 1 discusses the purpose of the research, part 2 categorize and evaluate existing DSPMM modeling techniques, identifying the most effective methods to improve performance, with numerical approaches such as the boundary element method (BEM) or finite element method (FEM) as well as analytical approaches such as the analytical subdomain method (ASM) method and magnetic equivalent circuit (MEC), Maxwell's equation approach (MEA). In part 3, this review will explore the structural design variations of DSPMM, helping to identify the best geometric configurations for stators, rotors, or other magnetic elements to arrive at specific configurations that can improve efficiency, torque production, torque density, and power density. The last part is the conclusion of the research results, through a comparative analysis of previous research. It is hoped that this review provides a basis for the selection of the best method, thereby obtaining a DSPMM design that has high efficiency and performance and encourages innovation for a wider range of DSPMM applications in various industries.

2. MODELLING METHODS

In a DSPMM, magnetic flux and magnetic field are important quantities that can be obtained from the machine geometry, the magnetic properties, and the applied current. Magnetic flux is essential for determining engine performance, including rear electromotive force (EMF) and torque. Analytical models for predicting magnetic field distributions often involve solving partial differential equations in multiple subdomains as in (1) and (2) [14], [15].

$$\phi = \int_s B \, . \, dS \tag{1}$$

Where ϕ is the magnetic flux, B is the magnetic field density, S is the surface area through which the magnetic field line passes, and dS is the differential area vector on the surface S. To obtain the specific flux density distribution B in the DSPMM, we can use the Maxwell equation and solve the Laplace/Poisson equation for each engine region, taking into account the geometry and material properties.

$$B = \frac{\mu_0 . (H+M)}{1+g} \tag{2}$$

Where μ0 is the permeability of the free space, H is the strength of the magnetic field (A/m), M is the magnetization, and g is the thickness of the air gap (m).

Relationship between magnetic flux, position of rotor and phase current in DSPMM is complex and generally not linear, this is due to several factors, such as the saturation effect [16], [17] and geometric configure ration [18]. In addition, compared to conventional three-phase electric machines, the magnetic properties of DSPMM are more complex to assess because the stator and rotor have a double central pole, and the air gap in the engine cannot spread evenly in the peripheral direction [19]. This triggers a variation in the flux trajectory dimension at the air gap, resulting nonlinear relationship between the flux trajectory and the rotor position. DSPMM regularly operate in magnetic field saturation to reach high torque densities that are nonlinear with respect to phase currents. Several studies have been conducted to model the electromagnetic properties of DSPMM [20] and this approach to electromagnetic analysis is grouped into two categories, namely numerical methods analysis and analytical methods analysis.

2.1. Numerical methods analysis

Numerical method analysis has become a major tool in optimizing electrical machines, as well as in DSPMM which has a significant effect on the analysis of electromagnetic, enabling the simulation, and solving of complex problems in electromagnetic analysis [21], [22]. The methods most frequently used in numerical analysis are the boundary element method and the finite element method [23]. Using this method, the properties and dynamics of DSPMM can be evaluated with a high degree of reliability. In addition, various stator and rotor orientations also allow for magnetic field calculations, thus allowing accurate prediction of the magnetization properties of the DSPMM. To solve Maxwell's equations in complex geometry and boundary conditions, numerical methods are used. Some commonly used numerical methods are:

2.1.1. Finite element method (FEM)

The finite element method (FEM) is a powerful numerical technique for solving partial differential equations, especially in electromagnetic problems. This method works by delimiting the problem domain into small, simple elements. The main advantages of FEM include modelling flexibility, which allows it to handle complex geometries and material properties, as well as sparse matrix solutions, which allow for efficient storage and computing. It is widely used in analyzing electromagnetic fields in devices such as antennas, sensors, and waveguides, providing insights into performance characteristics such as radiation patterns and field distribution [24], temperature distribution in the generator. Thermal and electromagnetic models are validated by simulation [3] as well as determine distribution of magnetic flux and electromagnetic performance of various DSPMM topologies. An analysis of electromagnetic and structural characteristics needs to be carried out to determine the overall impact of changes in design and direction of magnetization that affect motor performance [25].

Finite element simulation is highly effective in analyzing the distribution of magnetic fields in no-load motor operation allowing researchers to evaluate and optimize the machine design before physical implementation, ensuring high efficiency, thermal stability, and optimal field distribution. Research conducted by Yang *et al.* [26] find that the simulation results show that the magnetic field line of the motor passes through the rotor iron in the radial direction, not through the circular direction iron core of the rotor, so does not experience saturation, and under the no-load condition, the inner stator teeth maximum magnetic flux density is 1.6187 T and the outer stator teeth of the motor is 1.6735 T. Figure 1 showing the results of finite element simulation in magnetic field distribution in no-load motor operation on the designed motor Figure 1(a) shows that the neat and symmetrical flux line trajectory shows that the design of this machine has an optimal magnetic field distribution and Figure 1(b) shows that the density of the magnetic flux is uniformly distributed in the machine around the stator so that overload does not occur which causes overheating.

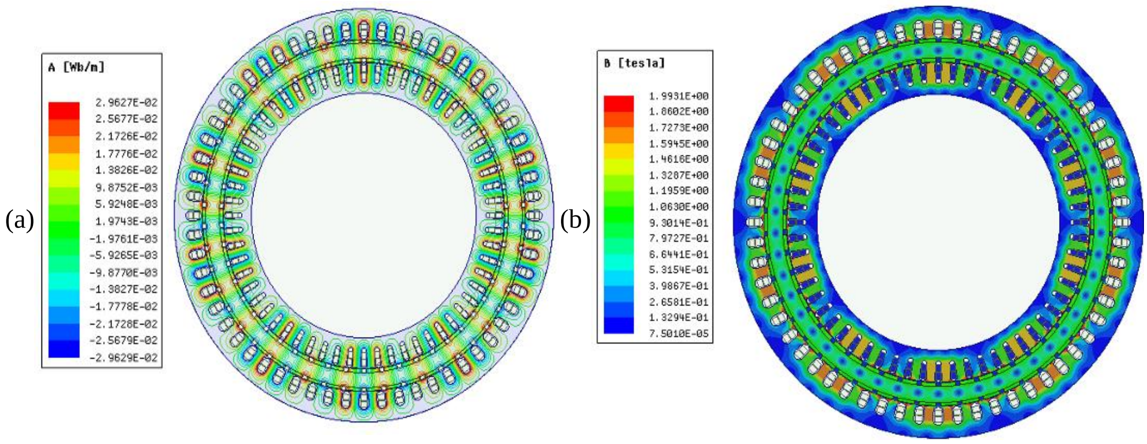

Figure 1. Finite element simulation in magnetic field distribution on motor design: (a) line distribution of the magnetic field flux under condition without load and (b) cloud graph of condition magnetic flux density without load [26]

Finite element analysis (FEA) is used to analyze the influence of key machine parameters on output torque and torque ripple [27], electromagnetic performance, and characteristics of the machine [28]. Maxwell simulation is used to validate design results based on parameters optimized with FEA [1], also it can evaluate electromagnetic performance, structural integrity, and thermal distribution, leading to optimal design. Modelling the magnetic field inside the machine, allowing prediction of flux density and field distribution

[29]-[31] to determine the mechanical and electromagnetic performance of the engine, including torque and efficiency [32]-[34]. This is important to ensure that the machine meets performance specifications and operates efficiently under a wide range of load conditions [35]. By simulating different design configurations, FEA helps identify potential issues such as force ripples and magnetic imbalances. This predictive capability allows design makers to make precise adjustments before physical prototypes are made, thereby reducing the risk of costly design defects [36].

In addition to electromagnetic simulations, FEA is used to evaluate thermal behavior and structural integrity. Understanding how temperature variations affect the performance and service life of machine components is essential, especially in applications that are expected to experience high thermal loads [37]. FEA helps optimize the use of materials, especially permanent magnets. By analyzing the distribution of magnetic fields and performance metrics, designers can minimize the amount of magnet material required while maintaining performance, which is essential for cost-effective production [38]. FEA provides a high level of detail and accuracy in electromagnetic field modelling in DSPMM. This precision is essential for optimizing design parameters, such as the shape and placement of permanent magnets, stator and rotor geometry, and overall machine topology.

2.1.2. Boundary element methods (BEM)

The boundary element method (BEM) offers high accuracy and efficient unconstrained problem modeling by using integral equations to represent boundary conditions, allowing for precise analysis of electromagnetic characteristics such as magnetic field distribution and interactions in double-stator permanent magnet machines [39], [40]. The boundary element method (BEM) offers significant advantages over FEA method in the DSPMM study. One of the main advantages of BEM is just requires a surface mesh the boundary, so there is no need to use a volume mesh that covers all space, including air gaps, this reduces the dimensions of the structure matrix and reduces computational time [41]. The boundary integral method can accurately and efficiently solve electromagnetic smooth boundary problems in two dimensions [41], [42]. Iron and copper are analyzed using finite element methods to handle nonlinearities and eddy currents, while boundary element methods are used on the air gaps between moving parts, utilizing Green's functions in free space to allow for linear motion with periodic time [43].

Sathyan *et al.* [44] used BEM to measure the sound pressure near the motor and the sound pressure level that is produced according to varying frequencies, as shown in Figure 2. Figure 2(a) shows the distribution of acoustic pressure in Pascal units (Pa) distributed around the motor. The interference pattern of acoustic waves indicates that the motor produces sound of varying intensity in the surrounding area. Figure 2(b) indicates the level of sound pressure in decibels (dB) at the same frequency around the motor, it indicates that the strongest sound spreads in a particular direction around the motor.

The system matrix in boundary element method (BEM) is described as requiring $O(N^2)$ memory storage, which is notably higher than finite element analysis (FEA), which typically requires $O(N)$ memory. This is due to the solid structure of the system matrix used in BEM, which lacks the symmetry and diagonal dominance that can simplify computations in FEA [45]. The boundary element method (BEM) is a powerful tool in DSPMM design, especially for analyzing the magnetic field around the machine. Its advantages in computing efficiency and precision in handling terrain extending far from the machine make it a perfect fit for this application, however, for analyses involving complex internal geometry, BEM is often used in conjunction with other methods such as FEA to obtain more thorough and accurate results. By combining BEM with FEA, FEA can be used to analyze areas of high geometric complexity inside a motor, while BEM can handle outside areas and constraints, which often have non-trivial boundary conditions. The hybridization of this methodology allows for nonlinear analysis, making it a viable solution for DSPMM electromagnetic analysis [46].

Based on the results of the above discussion, it is known that the FEM-BEM hybrid approach can improve the accuracy of the analysis to the FEM for complex internal geometries and the simulation shows an ideal and symmetrical distribution of the magnetic field in the DSPMM with a safe flux density, preventing saturation and overheating. BEM is used to analyze external fields with high computational efficiency, while ensuring temperature stability through thermal analysis and reducing noise through acoustic approaches. Design optimization for energy efficiency, permanent magnet material savings, and the application of hybrid methods to electric machines are examples of the results of this study. In the future, research can concentrate on the development of FEM-BEM for faster computing, experimental validation, machine learning integration for design optimization, and the development of new cooling systems to improve the thermal stability of DSPMM.

(a)

(b)

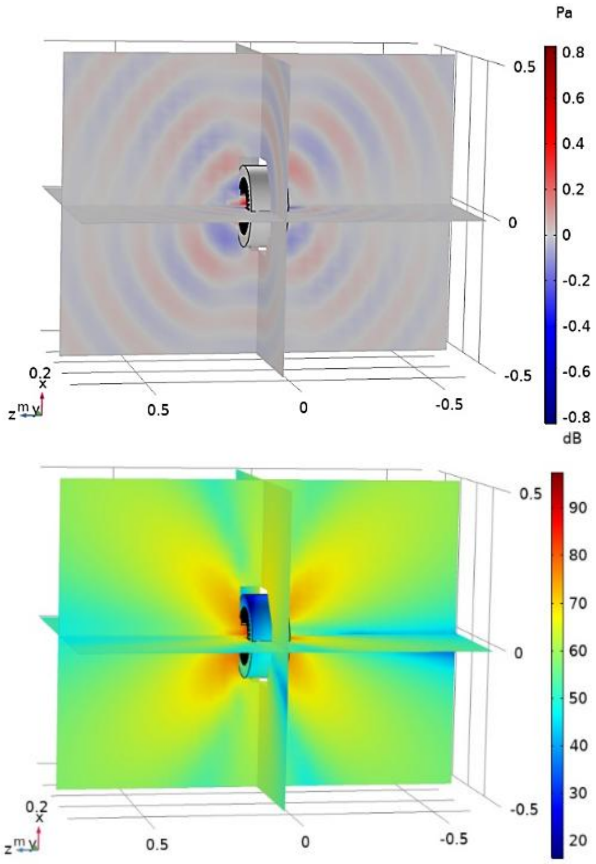

Figure 2. The level of sound pressure in the air: (a) pressure distribution (Pa) off-motor, with frequency 2016 Hz and (b) the level of sound pressure produced (dB) off-motor at frequency 2016 Hz [44]

2.2. Analytical methods analysis

In the design process of double-stator permanent magnet machines (DSPMM), analytical methods are an important tool to obtain optimal results. This method involves mathematical modelling and analysis to predict the performance and behavior of machines under various operating conditions. The following are some of the main functions of analytical methods in designing DSPMM. The analytical methods used in the calculations for double-stator permanent magnet machines mainly focus on modelling the distribution of magnetic fields, optimizing design parameters, and validating performance through numerical techniques. Here are the key analytical approaches:

2.2.1. Analytical subdomain method (ASM)

In this technique, the machine is divided into several parts to simplify the analysis of the magnetic field and its electromagnetic parameters. This method allows the calculation of the distribution of magnetic fields on machines with complex geometries, such as a double stator configuration [46]. This method simplifies the complex geometry of these machines into manageable subdomains, thus allowing for efficient magnetic field computing and performance characteristics, and converts the sample into a finite subdomain in a two-dimensional (2D) plane and applies analytic potential vector magnetization to each subdomain with partial difference [47], [48].

The model subdomains have the ability to affect the opening of slots, permanent magnets, and slot shapes, and the accurate prediction of magnets and slots has good accuracy. Preview study [49] subdomain analytical model is used to calculate the effect of tooth tips in predicting the magnitude of the armature reaction field in surface-mounted permanent-magnet (SMPM) machines and Tiang *et al.* [50] taking into account different magnetization patterns (e.g., radial and parallel magnetization) and considering the effects of tooth tip and slotting and can predict the electromagnetic flux performance of the machine by considering saturation effect on the rotor core [51]. By analyzing the effects of different design parameters, these models can help identify optimal configurations that increase efficiency, reduce cogging torque, and improve overall performance [52]. Subdomain model analytics were proposed by Said *et al.* [53] as an effective tool for the preliminary investigation of the distribution of electromagnetic features and magnetic fields in open circuits or armature responses in electric machines. Table 1 shows that, with very minor exceptions, the results of the study conducted using the subdomain model are remarkably similar to those obtained by FEA. The analytical method is used for the initial design, then FEA is used to validate and modify the results. The percentage of errors (all below 1%) shows that the analytical model implies that the accuracy of the analytical model is quite reliable.

The complexity of machine DSPMM geometry requires effective analysis methods such as harmonic response for performance evaluation. The subdomain model can measure the accurate flux density distribution at load for the DSPMSM machine and electromagnetic capabilities of the machine taking into account the tooth tip effect [54]. Analytical subdomain models are used to predict the magnetic field distribution during open circuit, armature reaction, and related electromagnetic parameters. To solve Maxwell's equations directly at PM, air gap, and stator location, a subdomain approach is used using separation of variables [55]. The distribution of the magnetic field and electromagnetic parameters in a double stator radial type permanent magnet vernier machine (DSRTVM) was identified using an approach that divides the field domain into many subdomains, with Laplace and Poisson equations in each subdomain [56].

The optimized subdomain analytical model is used to estimate distribution of magnetic fields in permanent magnet machines, taking considering the impact of stator slots and gear tips and can provide highly accurate results in calculating the distribution of magnetic fields and other electromagnetic parameters during open circuit conditions, armature reactions, and operating conditions at load for dual stator machines. Subdomain models and finite element analysis, when compared able to reduce computational time without sacrificing the accuracy of the results. This technique is effective for exploring topologies and optimizing the design of double stator engines with various structural configurations and slot-pole combinations.

Table 1. Performance output comparison [53]

Data	Analytical (%)	FEA (%)	Error (%)
Maximum outer airgap flux density, B_{og} [T]	0.793	0.792	0.13
Maximum inner airgap flux density, B_{ig} [T]	0.837	0.836	0.12
Maximum line-line back-emf, $\mathcal{E}_{line}$ [V]	278.4	276.6	0.65
Maximum phase back-emf, $\mathcal{E}_{phase}$ [V]	139.29	138.6	0.5
Average output torque, T_o [Nm]	23.45	23.29	0.69
Average output power, P_o [W]	1475.9	1465.9	0.68

2.2.2. Magnetic equivalent circuit (MEC)

The analysis of electromagnetic circuits in DSPMM focuses on understanding the magnetic interactions and performance characteristics of the machines. This analysis is important because of the unique configuration of the DSPMM, which typically has two stators and one rotor, allowing for increased efficiency and torque density compared to single-stator designs. The equivalent magnetic circuit technique used to analyze DSPMM magnetic circuits, by simplifying the analysis and representing the machine as an equivalent circuit, allowing for easier calculation of magnetic flux and reluctance across various components [57], [58], using lumped nonlinear adaptive parameters representing the reluctance of individual parts of the machine and creating a magnetic circuit by changing the magnetic field. By simplifying the magnetic components of the machine into equivalent circuits, it can efficiently calculate parameters such as magnetic flux, reluctance, and EMF.

Figure 3 explain that the equivalent magnetic circuit used to explain the differences between the 12/10 flux switching permanent magnet (FSPM) machines and shows that the equivalent reluctance of the double stator flux switching permanent magnet (DSFSPM) machine is twice that of the 12/10 FSPM, Figure 3(a) describes the physical structure and design concept of DSFSPM, where passive rotors are applied to facilitate fabrication and improve efficiency. Using the equivalent model, Figure 3(b) presents an analytical representation of the magnetic field, which facilitates the analysis of electromagnetic machine performance. This shows that these analytical methods and equivalent models can be used to facilitate the development and optimization of DSFSPM machines.

The MEC model was used to optimize torque control in permanent magnet synchronous machine (PMSM), allowing for the systematic calculation of magnetic saturation effects and non-sinusoidal characteristics [59]. Analyzed the magnetic circuits of four types of double-stator permanent magnet synchronous motors (DSPMSM) with different rotor structures [60]. EMC functions to model and calculate magnetic parameters such as magnetic flux and reluctance (magnetic resistance) in different parts of the motor. This EMC model helps in understanding how magnetic fields interact inside the motor, particularly between the stator and the inner and outer rotors.

In a double-sided axial flux permanent magnet machine (AFPMM), the flux density is acquired by finding out every source of flux and reluctance and flux sources using the MEC reluctances network [61]. Predicts the magnetic flux distribution, flux density, electromagnetic force, and other performance parameters of the linear motor being studied. This method is also integrated with other numerical calculation techniques to obtain more accurate results [62]. The results of the application of the MEC method show that this approach is able to provide a good prediction of motor performance, including flux distribution and electromagnetic force calculation, which is then validated with FEA simulation results.

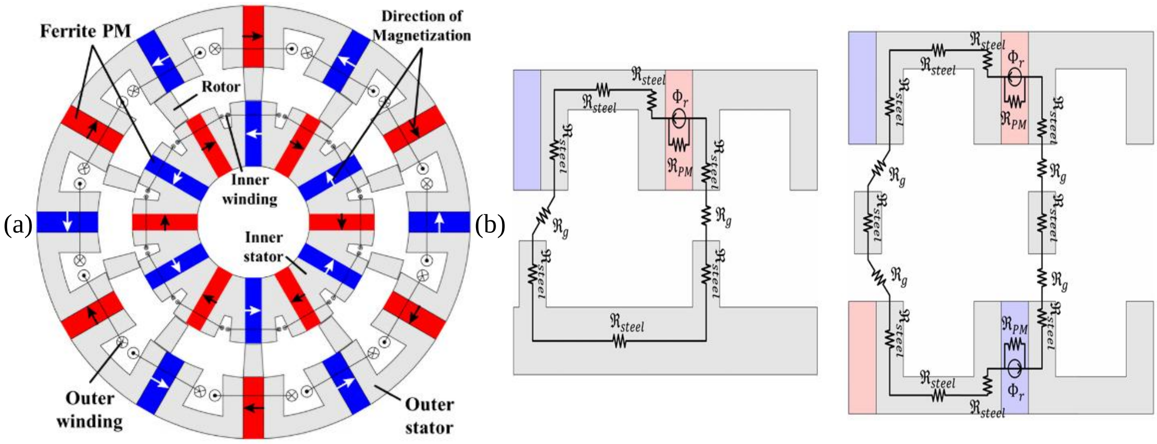

Figure 3. Double stator flux switching permanent magnet machine: (a) cross section and (b) magnetic equivalent circuit [58]

The MEC method used demonstrates flexibility and accuracy in analyzing motors with these complex configurations, thus providing a solid basis for further optimization and development. By modelling the errors that occur in the engine rotor, such as demagnetization, eccentricity, and imbalance [63]. This method makes it possible to take into account any changes in the magnetic flux path, which is very important in analyzing rotors-related errors. Thus, MEC helps to provide a more precise representation distribution of magnetic field under fault conditions, which is important for further diagnosis and prevention of errors in PMSM.

MEC simplifies the magnetic network by approximating magnetic paths as reluctances, often neglecting the intricate non-linearities like saturation and magnetic hysteresis. Wymeersch *et al.* [64] introduced a dynamic reluctance management for repairs in highly saturated conditions or where tooth tips and slot effects are prominent. The articles [65], [66] stated that MEC often ignores secondary phenomena such as eddy currents, harmonics, and stray losses so that it can result in significant errors in the calculation of losses and prediction of flux distributions, especially in designs with distributed windings or unconventional geometries.

Accurately modelling radial end flux leaks using MEC can be challenging and may require modifications to the standard approach. Accuracy in predicting but not predicting, thus making MEC remain a valuable tool for DSPMSM analysis and due to computer efficiency and capability, the design provides very accurate results, especially in the early stages of the design process. However, for more detailed analysis and final design validation, a combination of MEC and FEA is often used to harness the strengths of both methods.

2.2.3. Maxwell equation approaches (MEA)

Maxwell equation approaches model is highly effective in predicting flux distribution, as in DS-PMSM, where Maxwell's equation solving allows for accurate determination of flux densities in air gaps and other regions, while being able to handle complex geometries with reliable segmentation and analysis, both in no-load and on-load conditions, it is very important to model the distribution of magnetic flux, flux density, and magnetic saturation effects, all of which affect engine performance [67], can be modelled complex geometries such as slotting effects and rotor asymmetry [68]. For surface-mounted PM machines, slot geometry and air gap field distribution are incorporated into MEA models using conformal mapping and relative air-gap permeance [69]. Utilize the conformal transform to calculate Maxwell's stress force in the air gap of the PM motor. Optimization was performed using the differential evolution algorithm (DEA), a population-based optimization method in MATLAB obtained Flux density distribution modeling in perforated air gaps resulted in accurate estimation of torque and losses and was able to predict reverse EMF, torque, and iron loss, accuracy of 4.85% in EMF, 4.41% in torque, and 4.44% in iron loss, compared to a full FEM-based solution [70], [71].

The reverse EMF and cogging torque were calculated using Maxwell's equation, then compared to the Finite Element model and experimental data on intact and partially demagnetized permanent magnets, solution of the boundary condition by reducing number of boundary variables to a single variable [72]. Maxwell's equations enable precise modeling of air gap flux and magnetomotive force (MMF) paths in both stators and accounting for their interaction through the rotor (DSPMM), Time-stepping for dynamic performance modeling in varied operating conditions [73]. The saturation and flux leakage effects as well as the longitudinal final effect are considered using equivalent magnetic networks [74]. The development of magnetic equivalent circuits (MECs) also helps in estimating motor parameters such as inductance on the -d axis and -q axis of the engine and leakage flux [75]. Finite element analysis (FEA) is often involved to compare the predicted results obtained, which are typically more accurate but require longer computational times. Thus, the use of Maxwell's equation approximation provides a balance between accuracy and efficiency in DSPMSM design and analysis.

In addition to the methods already mentioned, there are also other methods that are often used in this modelling process such as genetic algorithms used to optimize the design of double stator engines, focusing on parameters like the shape of the rotor and the number of slots [76], as well as permeance analysis, finite element simulation, and optimization algorithms to improve the design and performance prediction to achieve the desired performance characteristics. There are several shortcomings in the modelling of DSPMM, such as the inability of existing analytical and numerical models to accurately capture nonlinear behavior, in particular the complex interactions of magnetic flux, rotor position, and phase current under saturation conditions [26]. Current studies also lack consideration of dynamic and transient effects, such as sudden load changes, as well as the lack of integration of hybrid modelling techniques to improve computational accuracy and efficiency [77].

The analytical method enables accurate prediction of magnetic field distribution, optimization of design parameters, and validation of performance through the analytical subdomain method (ASM), magnetic equivalent circuit (MEC), and Maxwell's equation approach (MEA). Based on the presentation, it can be concluded that the use of hybrid methods, such as the combination of ASM and MEC with finite element simulation (FEA), focuses on transient dynamics, exploration of structures such as Halbach arrays, and utilizes software such as Ansys can solve the problems of magnetic saturation, air gap aversion, and electromagnetic interaction between the two stators. So that it can improve the computing accuracy and performance of DSPMM.

3. STRUCTURE TOPOLOGY OF DSPMM

Structural topology of the double-stator permanent magnet machine (DSPMM) is essential in determining its performance. The unique arrangement of the stator and rotor significantly affects various performance metrics, including efficiency, torque characteristics, and thermal management. In designing a double stator permanent magnet machine, an efficient construction structure and model are the foundations that must be possessed in order to produce a machine design with optimal performance. Over the past few years, numerous studies have been carried out to optimize the performance of DSPMM machines, focusing on innovative topological structure design to improve the efficiency and output power of the machine, lowering the torque ripples and torque density [78]-[80].

The segmented rotor design allows for better alignment of the magnetic field at the interface of the rotor and stator, resulting in a higher torque density. In addition to the segmentation method on the rotor, cogging torque can also be lowered by the method of combining two steps slotting (TSS) with gradually inclined surface end (GISE) on PMG [81]. Therefore, the author proposes various DSPMM topology structures to improve performance and efficiency. In this review paper, the author focuses on the comparison of segmented structures to improving performance in DSPMM. This is particularly beneficial in applications that require an abundance of initial torque or fast acceleration, such as electric vehicles [82], significantly reducing cogging torque resulting in smoother operation and better machine control [83].

Segmentation in double stator permanent magnet machines (DSPMM) is a design technique that involves dividing the main components of the machine, such as rotors, stators, and permanent magnets, into smaller parts. Much research has been done to get a more optimal design in utilizing magnetic flux, which can produce higher torque. Segmented stators and rotors in electric machines have advantages, such as simplifying the manufacturing process, allowing the use of different materials for the stator and rotor, and reducing production waste. But it also has some challenges of increased cogging torque, acoustic noise, and core losses due to changes in the material structure at the edges of the cut [84]. The segmented rotor in a DSPMM is an important design Factors that significantly influence the performance and operational characteristics of the machine, rotor segmentation also reduces the eddy currents that often occur in solid rotors, especially at high speeds and reduce power losses and improve engine efficiency. To speed up the motor design and analysis process, Wu *et al.* [54] used Ansys in FEM simulations to compare the performance of various rotor structures such as electromagnetic analysis, magnetic field distribution, torque and energy loss. Asymmetric problems can be solved effectively by using segments in stator and rotor structures. This suggests that the torque ripple can be significantly decreased concurrently, as the average output torque is not reduced. Segmented rotors increase power density by up to two times as well as reduce iron reluctance and reduce cogging torque by up to 53.48% and ripple torque by up to 67.45%, which contributes to reduced vibration and acoustic noise [85]. Park *et al.* [86] used with rotor spoke-type and rotor support rod.

Known from Figure 4(a), conventional spoke-type rotors without a buffer will be difficult to use in practical applications because there are no mechanical connections connecting the rotating parts to the shaft or direct applications, and Figure 4(b). As a solution, a rotor with a stainless-steel support rod was inserted to replace the four spokes arranged placed at 90-degree intervals to hold the rotor. Thus, it can be said that segmented rotors require additional components or structural modifications, such as support rods, to be more stable and can be used effectively in real applications. Likewise, the character of the torque obtained in this form can be seen in Table 2. Table 2 is the result of a comparison of the torque characteristics of a double stator spoke permanent magnet vernier machine (DSSPMVM), overall, the Type 1 (motor without support) showed the best characteristics in terms of torque stability (low torque ripple) and low cogging resistance, followed by the Type 3 (motor with SUS430 support) which had almost similar characteristics.

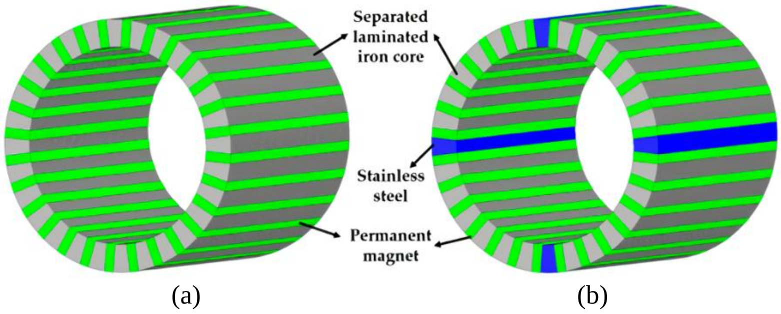

Figure 4. Structure motor: (a) without aids and (b) with aids [86]

Table 2. Comparison torque characteristic of the proposed DSSPMVM [86]

Motor type	Average torque (Nm)	Torque ripple (%)	Cogging torque Nm)
Type 1 (No support)	13.28	1.68	0.43
Type 2 (SUS304)	11.23	15.03	2.31
Type 3 (SUS430)	13.26	2.06	0.47

Type 2 (motor with SUS304 support) has poor performance due to high ripple and cogging torque values, although the average torque is lower than the other two types. This states that the offered engine (Type SUS430) has a higher average torque, lower torque ripples, and a significant decrease in torque cogging [86]. The rotor configuration using V shape IPM significantly reduces cogging torque, gear harmonic EMF, and torque ripples that are proportional to the slot slope [87]. A composite soft magnetic material is located in the stator core, and a Halbach permanent magnet two-segment is located in the rotor; good torque density and efficiency are two benefits of this design [88]. Khoshoo *et al.* [89] state that in the segmentation of the rotor, the flux gap generated can affect the performance of the machine. Another study by Zhang *et al.* [90] shows that segmented rotor designs can help in better managing eddy current losses, especially in high-speed applications.

The segmented rotor design of DSPMM has a major influence on improving the performance and operational characteristics of the machine. Rotor segmentation allows for a reduction in magnetic losses, a decrease in cogging torque, and an increase in torque density, which overall improves the efficiency and dynamic performance of the engine. The design has also been shown to reduce eddy currents and provide better thermal management, making it an attractive option for a wide range of modern applications, particularly in electric vehicles and renewable energy systems.

The DSPMM consists of two stators, which can be configure in various ways to improve performance. To reduce eddy current losses, each stator is typically constructed with a core made of laminated steel. The stator is equipped with concentrated armature windings, which may be linked in parallel or series depending on the desired output characteristics. In many designs, permanent magnets (PM) are arranged in a radius-like configuration inside a stator. This setting allows for effective flux focusing, thereby increasing the density of the air gap flux and increasing torque production. The double stator can be divided into several segments. This segmentation is usually applied to the stator teeth that hold permanent magnets and winding, so that there can be a more even distribution of flux throughout the engine, which can reduce torque ripples and improve efficiency as well as reduce vibration and noise that often occur during operation, improving the comfort and reliability of the machine [91]. States that the performance of the machine is highly based on the geometry of the machine, in order to improve the machine's electromagnetic performance. Stator segmentation causes weakening of the magnetic circuit, thus lowering the average value of the magnetic flux density (B) and will reduce iron loss. This is due to the additional air gap and the effect of cutting edges (cut-edge effect) [92].

The design of a double stator hybrid excited Halbach permanent magnet flux reversal machine with a 19-pole rotor machine, the outer stator consists of a modular E-shaped core, the PM is located on the outer and inner stator, which includes the spoke-type PM and the PM slot, proposed in [93]. With 6 inner stator teeth, it is positioned in such a way that the teeth with PM are aligned with the outer stator teeth. Spoke-type PM is tangentially magnetized and sandwiched between a modular E-shaped core.

Figure 5 presents the topology structure of a spoke-type PM. Figure 5(a) shows that the slot and spoke-PM configurations are positioned radially to generate a magnetic field. Figure 5(b) shows configurations with Halbach arrays and DC field windings to improve magnetic field control and the resulting field efficiency. This design allows for more efficient terrain control, generates more torque, reduces cogging, and improves efficiency.

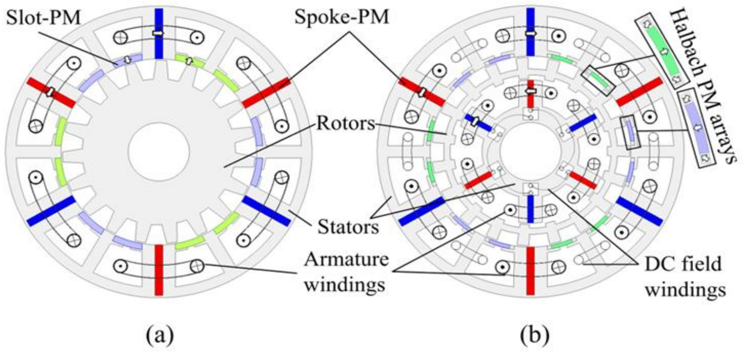

Figure 5. Topological structure of (a) standard HE-FSPM engine and (b) offered DS-HE-HPM-FS engine [93]

It is known from Figure 5 that the external stator is set up an E-shaped modular core similar to a benchmarking machine. Permanent magnets (PM) are placed on the outer and inner stators that have 6 teeth, which are arranged in parallel with the permanent magnets including the PM spoke and PM slot types. The spoken-type PM is tangentially magnetized and placed between the E shaped modular cores.

JMAG-designer version 14.0 was used on [83] DS PMSFM computers. Segmented designs generate magnetic flux levels that are 40% larger than unsegmented designs, according to flux relationship studies. With a percentage difference of 35.54% and 32.06%, respectively, the segmented design outperforms the unsegmented version on torque and power production. The collected results demonstrate that, in terms of torque and power, segmented designs outperform unsegmented designs. The engine has a greater torque density due to the partitioned stator structure, which places the PM excitation and anchor windings in the outer and inner stators independently, as well as the larger stator area [94]. Under the same conditions, the corresponding dual stator SFPM with 12 stator slots of the same size can provide a torque density that is roughly 40% lower than that of the produced 6-stator slot partitioned stator permanent magnet machine [95].

Awah [96] compared the performance of double-stator permanent magnet machines. In Figure 6(a), the permanent magnet is located on the outer stator, and the windings are located on the inner and outer stators. in Figure 6(b), the permanent magnet is located on the inner stator, and the windings are located on the inner and outer stators. In Figure 6(c), the permanent magnet is located on the inner and outer stator, and the windings are on the inner stator. From the results of the comparison, it was obtained that the machine with permanent magnets located in the inner and outer stator, and the windings were in the inner stator, had the largest total loss and the least efficiency and had the potential to be affected by demagnetization, but this machine had the best performance with the average torque and the largest electromagnetic torque and was rich in its waveform and EMF amplitude.

The DSPMM permanent magnets can be divided into several small segments mounted on the stator or rotor, which serve to optimize magnetic interaction and improve engine performance. This permanent magnetic segmentation helps to reduce eddy current losses, especially in high-speed operation [85], thereby improving the efficiency of the machine. Additionally, segmentation makes possible a more effective and controlled distribution of magnetic flux, which contributes to increased torque density and overall engine efficiency.

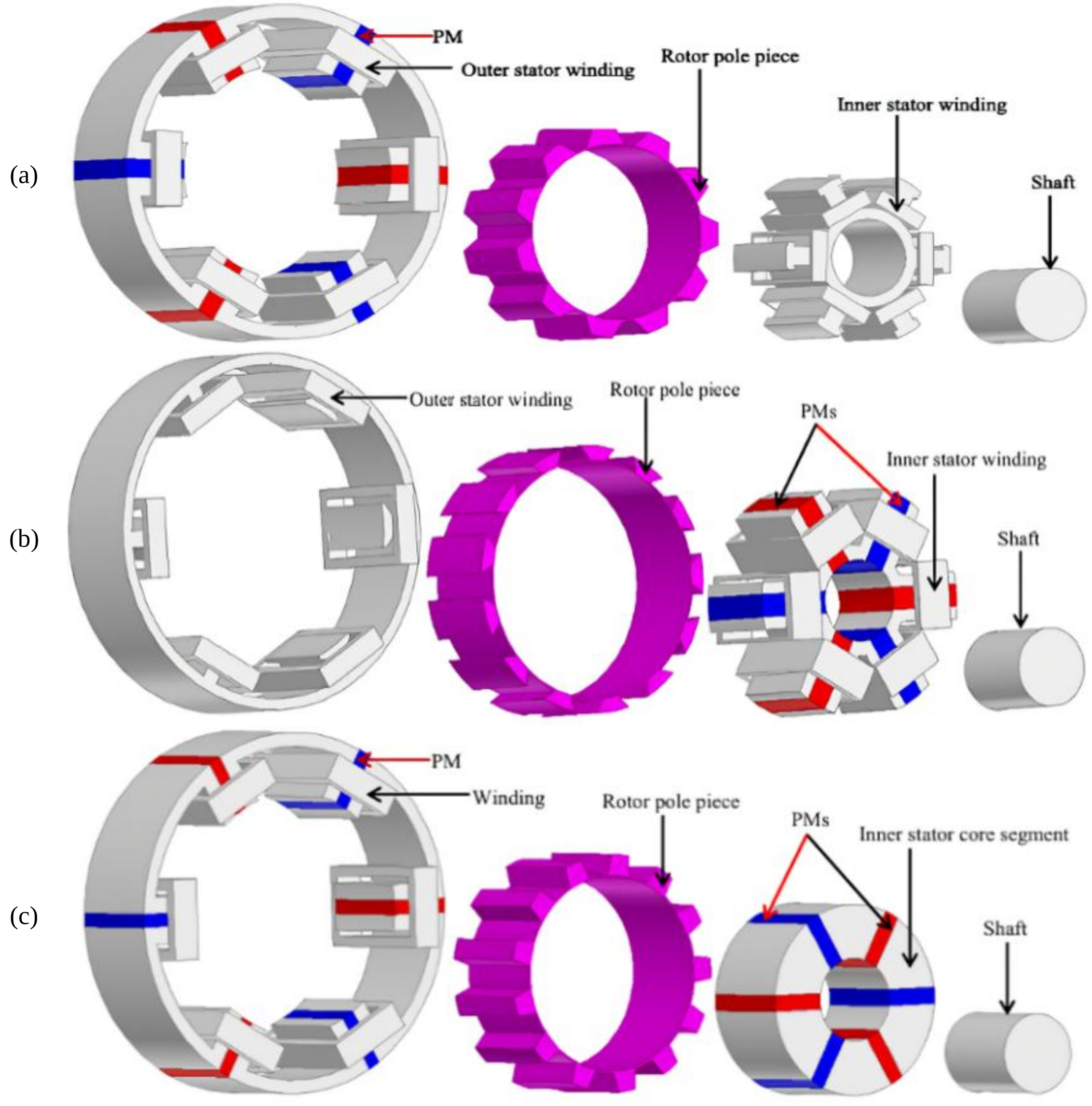

Figure 6. Location of the magnets on the internal and external stator: (a) machine construction 1, (b) machine construction 2, and (c) machine construction 3 [96]

Variation in PM inclination angles results in varying distribution of flux between the two stators, which affects the DSVPMV machine torque capacity [97]. The use of V PM V helps reduce torque ripple, increase rotor strength, enhance resistance to demagnetization, and maintain a relatively simple design [87]. With magnetic flux tending to be concentrated in one radial direction, it can result in uneven distribution of flux among the double stators, thereby reducing the efficiency of using the entire stator volume whereas the spoke-PM machine distributes the flux more evenly between the internal and external stators, which can improve the total efficiency of the machine [98]. The placement design and permanent shape of the magnet clearly have an important role in maximizing the performance of torque and other parameters, such as torque ripples and cogging torque, as conveyed in the research of Yu *et al.* [99] on the spoke-PMV machine can produce the maximum torque output of 146 Nm with a current density of 6.7 A/mm^2, whereas the V PMV engine has the least torque ripple at 5.8%. The relationship between magnetic flux and angle reflects the torque performance of motors with two types of spoke PMVM and V PM configurations. Figure 7(a) explains that V-PM produces a higher flux compared to spoke-PVM, which can be a consideration if greater torque is required. Figure 7(b) explains the cogging torque for both configurations, spoke PM and V PM. There is almost no significant difference between these two configurations in terms of cogging torque, so it can be said that they both have similar performance for these parameters.

In order to maximize the utilization of magnets and extend the operating range, Halbach permanent magnet arrays are one of popular the techniques that are able to increase the torque ability at low speeds, and reduce magnetic flux leakage [100], [101], with two soft magnetic composite materials in the stator core and segments in the rotor, proved to provide advantages in terms of high torque density and high efficiency. When there is a space of gaps between segments, the waveform of flux density in the air gap and the reverse electromotive force (EMF) becomes closer to the electromagnetic torque ripple and the sinusoidal decreases when there is a certain gap between the segments. Figure 8 explains that segment gaps play an important role in determining the basic amplitude of radial components, explains the air gap flux density wave becomes more optimal if the number of segments per pole is less [102].

The torque generated is more stable and consistent during operation, and improves the overall efficiency of the machine [93]. Thus, it can be said that permanent magnetic segmentation in DSPMM improves engine performance by optimizing magnetic interaction, reducing eddy current losses, and increasing torque density and efficiency. Designs with Halbach magnets and soft magnetic composite materials have also proven to be effective, while variations in the IPM tilt angle significantly affect electromagnetic performance.

(a) (b)

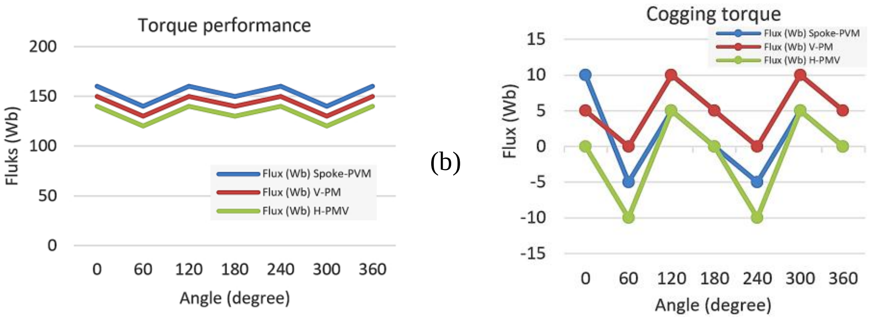

Figure 7. The torque performance comparison: (a) torque performance and (b) cogging torque

In DSPMM topology, research that explores innovative design combinations, such as the synergy of rotor and stator segmentation techniques with other innovative structures, such as Halbach magnetic arrays and soft composite materials, is still rare and often limited to specific geometric configurations, such as V-shaped rotors or radius-type rotors. This ignores other geometric variations that may significantly affect the distribution of magnetic flux, torque, and engine efficiency. In addition, understanding of dynamic and transient effects is also lacking, as most studies focus only on performance in steady-state conditions without considering responses to sudden changes in load or operating conditions. The results of this study also show that the segmented rotor design with the application of the two step slotting (TSS) technique and Halbach arrangement significantly increases the torque density, reduces cogging torque and ripple torque, and optimizes the distribution of magnetic flux, resulting in higher energy efficiency overall. This method has great potential to be applied to electric vehicles and renewable energy plants.

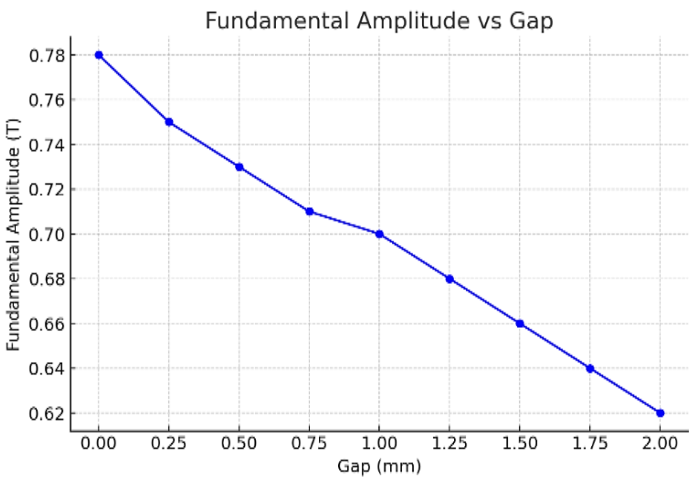

Figure 8. The impact of the segment gap on the radial component's basic amplitude [102]

4. CONCLUSION

This paper underlines the potential of DSPMM in the development of electric machine technology through innovative design and modeling approaches. The hybrid approach between the finite element method (FEM) and the boundary element method (BEM) improves analytical accuracy for complex internal geometries and computational efficiency on external fields, ensuring ideal magnetic field distribution on the double-stator permanent magnet machine (DSPMM) as well as preventing saturation, overheating, and reducing noise. This method also supports design optimization for energy efficiency, permanent magnet material savings, and the application of hybrid methods in electric machines. Analytical approaches such as the analytical subdomain method (ASM), magnetic equivalent circuit (MEC), and Maxwell's equation approach (MEA) allow for accurate prediction of magnetic field distributions, optimization of design parameters, and validation of performance, while the combination of analytical methods with finite element simulation (FEA) addresses issues such as magnetic saturation and electromagnetic interactions, thereby improving the performance of DSPMM. To support design and analysis, the use of software such as JMAG-designer-based simulations and Maxwell equation approach such as Ansys Maxwell is an innovative and renewable solution. Further research on the DSPMM that integrates design innovations, such as the segmented rotor-stator technique with a Halbach arrangement and soft composite materials, shows increased torque density, reduced cogging torque and ripple torque, and optimal magnetic flux distribution. With great potential for applications in electric vehicles and renewable energy plants, the innovative design of DSPMM offers high energy efficiency and noise reduction, although additional research is still needed to understand the dynamic and transient effects in non-steady-state operating conditions and develop new cooling systems to improve thermal stability.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the British Malaysia Institute, Universiti Kuala Lumpur (BMI-UNIKL), for providing a place to continue her doctoral studies. Furthermore, sincere appreciation is extended to Ibn Khaldun University Bogor for offering the opportunity for her to pursue her doctoral studies.

FUNDING INFORMATION

This research was supported by Universiti Kuala Lumpur through the UniKL/CoRI/str24009 research grant.

AUTHOR CONTRIBUTIONS STATEMENT

This paper was conducted with contributions from all listed authors according to the Contributor Roles Taxonomy (CRediT).

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Tajuddin Nur	✓	✓		✓		✓	✓	✓		✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state that they do not have any personal conflicts of interest or linkages that could affect the research presented in this paper.

DATA AVAILABILITY

This paper did not generate or analyze new data. Therefore, data sharing is irrelevant for this article.

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