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Parametric analysis on the effect of V-type rotor magnet geometry on the dynamic performance of PMSMs

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ABSTRACT

The research examines how different dimensions of V-type permanent magnet synchronous motor (PMSM) magnets influence the magnetic flux between the rotor and the stator system because matching these dimensions optimizes the magnetic flux for better torque production. As long as the magnet size stays within the right dimensions, it builds greater flux density, which leads to better torque output and better efficiency. Research confirms that flow barriers strengthen engine capabilities. The research applies parametric optimization to find the perfect magnet shapes while showing how they boost electric vehicle motors to meet their requirements. Our tests with finite element method (FEM) show how changing magnet dimensions affects performance. Researchers adjust magnetic measurements frequently until the optimal setup of 50 mm thick by 4.5 mm wide emerges. Their action boosts flux density, which improves motor torque and energy capacity. At these optimal dimensions, the engine achieved 95% efficiency with precise flow barrier adjustments that helped increase torque output while reducing unstable electricity output.

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1. INTRODUCTION

The permanent magnet synchronous motor (PMSM) is a vital member in many applications, ranging from electric vehicles (EVs) to renewable energy systems. Particularly as cars move towards electric power, there is a growing need to enhance the characteristics of electric motors, mainly in EVs [1]-[3]. In the world of electric vehicles, fine-tuning the size of the magnets in the rotor becomes extremely significant [4]. This tuning not just influences the profile of the motor, it gives the modification between a high and low performing machine. However, it is not just about the actual lengths of those magnets, it is also important to analyze the generated electromagnetic forces, dynamic performance, in addition to the mechanical structure of these machines. Enhancing motor efficiency, reducing losses, and boosting overall performance are essential goals in optimizing the rotor magnet's structure. However, classical approaches for scheming these structures often depend on simple prototypes or trial-and-error methods [5], [6]. Meeting these requirements is considered an essential factor to sufficiently understand how these motors work. EVs require high torque density (TD) to deliver effective and high performance [2]-[7]. Increasing the thickness of magnets can deliver heavy magnetic fields, which deliver a higher torque density. This is vital for accomplishing the preferred speeding up during driving in an EV. In conjunction with TD, power density (PD) is also an essential factor in EVs; thicker magnets give a higher PD by supporting the motor to produce more power within a certain volume or weight restraint. This is important for attaining the preferred speed and performance in EVs [8]. Tests have shown that magnetic synchronous motors (PMSM) with V-type magnets significantly affect the torque performance of the machine design. In newly used electric cars, which determines the overall efficiency of the car is determined. The magnetic circuit for this type of motor is being designed by researchers. It contributes to reducing cogging torque, which is unwanted torque that affects the movement of the engine [9].

The modern methods of researchers, which is the reason for writing this paper, show one of the recent developments in using asymmetric geometric designs to build a rotating part (V-type) and magnetic poles that work to contribute and improving the distribution of the rotating magnetic field within the air gap of the engine, which leads to improving operating efficiency and reducing noise and vibrations from by reducing the ripple factor of the machine torque. Many analyses are used with computer simulation (FEM) to optimize geometric variables in the PMSM, with the angle and space of the magnets. This contributes to achieving an ideal balance between high torque and low energy ingesting, which increases the efficiency of the motor and extends its lifetime, particularly in changing operating locations such as in electric cars [10]. The dimensions of rotor magnets in PMSMs play an important role during the design stage due to their direct effect on the motor's performance.

The size and shape of the magnets are the key parameters that impact the torque, power density, and efficiency of the motor. Previous Studies had shown that adjusting the PM dimensions, specifically the width and depth, could significantly affect the torque features and total efficiency of PMSMs [11]. In PMSMs, the mass and length of the PM structures have a distinguished impact on the torque, efficiency, and power density of the motor. Studies have verified that extensive magnet scales and fewer magnets per pole can lead to higher motor torque, while using heavier magnets can improve motor efficiency [11]. Additionally, the diameter, length, and turns per coil of the machine are serious parameters that affect torque, power, and efficiency, where the three factors increase with machine length. Nevertheless, a limited increase in efficiency and power may not be considered in the linearly increasing torque. This emphasizes the difficult relationship between magnet dimensions and PMSM performance [12], [13].

Moreover, the electromagnetic features of V-type PMSMs are difficult to link to other issues like magnet shape, size, stator teeth, and flux barriers. Modifying the dimensions of the rotor and stator, including the number of stator winding turns in each coil, may produce variations in electromagnetic features and performance results. Modifying the performance of PMSMs by changing dimensions like length, diameter, and turns per coil can be utilized to optimize electromagnetic torque, developed power, and efficiency in the absence of wide redesigning, though careful aspects of mechanical restrictions and electromagnetic performance are essential [14], [15]. In summary, the dimensions of rotor magnets in V-type PMSMs have a superficial influence on performance parameters (torque, efficiency, and power density). Optimizing magnet dimensions is a very important aspect for high-performing PMSMs. Extensive magnet dimensions, low number of magnets/poles, and suitable length and diameter adjustments are essential factors in accomplishing preferred motor characteristics [16]-[18]. In the current study, a parametric investigation was conducted using ANSYS software, providing appreciated insights into the effects of width and thickness variations on the performance of V-type PMSM.

The results highlighted the effect of optimizing magnet dimensions to attain greater motor performance, with the best dimensions identified as 5-6 mm width and 35-40 mm thickness. These results contribute to the improvement of PMSM design and optimization for numerous engineering requests. In addition, flux barrier (FB) variation plays an essential role in enhancing the developed torque, efficiency, and minimizing ripple torque of V-type PMSM. By adjusting the FB within the motor design, several advantages can be accomplished. FB can be optimized to improve the magnetic flux distribution within the motor. By suitably inserting and modeling these barriers, the magnetic flux paths can be effectively maximizing the interaction between the stator and rotor Fluxes. This optimization improves the torque generation and increases the overall performance. Also, variation of FB helps in decreasing magnetic core losses within the motor, like hysteresis and eddy current losses. By suitably designing the FB, these losses can be abated, consequential in enhanced efficiency. Additionally, optimizing the FB can reduce the cogging torque, which means increasing efficiency by reducing the power required to cancel reluctance effects through motor operation. In the same manner, FB change can assist in reducing the ripple torque effect, which is produced due to fluctuation in developed torque through motor rotation [19]-[21]. When FB is optimized, the magnetic flux distribution becomes more uniform, generating a smooth torque. The reduction in torque ripple increases the overall performance, particularly for applications that need accurate control and smooth operation.

2. LITERATURE REVIEW

The shape of rotor magnets and stator slots considerably affects the efficiency and performance of PMSMs. Different rotor structures affect motor operation factors as cogging torque, developed torque, back EMFs, and total electromagnetic features of the motor. For example, using a slot slice made of composite materials or inserting isolated magnetic materials in slots can decrease eddy current losses and improve electromagnetic performance [22]-[24]. Furthermore, asymmetric slot positions can develop torque features and the total electromagnetic performance by adjusting the slot asymmetry [16]. Also, the width and depth of secondary slots in the stator can alter the distribution of motor internal loss, iron loss, and PM eddy current loss, provided that visions for motor design [17]. Overall, optimizing stator slot shapes is crucial for enhancing the efficiency and performance of PMSMs. Nowadays, more research efforts have pointed out the significance of rotor magnet optimization in increasing PMSM performance. The impact of magnet dimensions on PMSM efficiency several studies have sought to expand upon this foundational knowledge. The influence of magnet shape on motor efficiency also causes a reduction in the cogging torque and improves torque density [4].

The physical length of rotor magnets in interior permanent magnet synchronous motors (IPMSMs) has a great effect on their performance. Various rotor magnet designs, such as sinusoidal, eccentric, V-shaped, Nabla-shaped, and segmented bridge, influence key performance indicators like torque capability, torque ripple, efficiency, and flux density distribution [18]-[25]. Optimal rotor structures can be obtained by fine-tuning of permanent magnet dimensions. According previously mentioned types of PM, the thickness, magnet arrangement, and pole arc to pole pitch ratio, leading to enhanced torque, efficiency, and flux weakening capability over a wide speed range [20]. As mentioned earlier, finite element analysis (FEA) is normally the method employed to investigate the effects of rotor magnet dimensions varying on the PMSMs electromagnetic performance, enabling the utilized of suitable rotor geometry structures for Interior PMSMs in electric vehicles and other applications [21], [22]. Furthermore, developments in computational methods, such as finite element analysis (FEA), have allowed researchers to discover the complex structure of machine geometries in more detail [10]. FEA employed to optimize dimensions to reduce the losses and enhance torque characteristics, recent works have been used to investigate the electric machines based on advanced optimization algorithms. A genetic algorithm is employed to optimize motor shapes, reaching significant improvements in the efficiency and suppression of torque ripple [11]-[26]. Additionally, the previous works highlight the significance of considering thermal effects in machine optimization. With EVs pushing the borders of motor performance, thermal control becomes a serious issue [12]. Also, research has focused on the influence of many types of materials on motor performance. The effect of insulation materials on conductors' losses and thermal behavior has been investigated, emphasizing the significance of material choice in improving motor efficiency [13]. The popularity of using permanent magnets in electric vehicles has soared owing to their knack for improving motor dynamic performance and high efficiency. Among the various permanent magnet (PM) configurations, the V-type PM has gained a most remarkable attention due to its advantages in reducing torque fluctuations and improving the overall vehicle performance. Basically, the V-type PM is appropriate for the type of interior permanent magnet (IPM) synchronous motors, including a rotor prepared with V-shaped poles [23], [27]. This advanced configuration produces a more reliable distribution of magnetic flux, which causes a decrease in torque variations and an increase in power output. It is important to note that, compared to other types of IPM motors, the V-type permanent magnet displays low cogging torque, extra enhancing the overall performance of EVs.

Wide studies in recent years have focused on the application of V-type PMs in EVs. Studies have shown that these magnets can significantly improve the stability of torque in EVs, resulting in a reliable and finer driving skills. Moreover, it is found an increase in the PM motor efficiency and power output is found, which results in a comprehensive enhancement in the acceleration and driving range of EVs [24], [25]. In general, the V-type PM is considered the preferred choice for EVs. It has the ability to mitigate fluctuations in developed torque, increase produced mechanical output power, and enhance efficiency. The wide research showed that the use of V-type PMs in EVs has generated favorable outcomes in terms of increasing overall vehicle performance [26], [27].

PMSM representation using the finite element method (FEM) is an electromagnetic analysis process in which the motor is divided into small parts called “elements”. Each element signifies a very small share of the motor construction, for example, a permanent magnet, stator, or air gap, and elementary behavior equations are applied to it to determine how magnetic fields and electrical currents interrelate through the PMSM. We can start with the equations, then the modeling steps, with each stage as the magnetic potential field equation ($J = \nabla \times (1/\mu)\nabla \times A$)). This equation is based on the magnetic potential theory, where the magnetic potential variable is used for easy identification of the magnetic flux inside the motor. This equation is solved at the level of each element of the model generating network. Where A: It represents the magnetic vector potential for each point inside the motor. μ: represents the magnetic permeability of the material (permeability) and can vary depending on the materials used, such as permanent magnets or iron parts. J represents current density, which is zero inside a permanent magnet. After calculating the magnetic flux density, A, it is used to calculate the magnetic flux density $B = \nabla \times A$, flow density B is the primary variable by which the strength of the magnetic field across the armature poles and magnets is analyzed and determined. Where Faraday’s law for induced voltage in the winding's induced voltage is based on this law, which describes how changing magnetic flux produces a voltage in the coil ($e = -\frac{dt}{d\Phi} = -N\frac{dt}{dB}$) where e: induced voltage, and depends on the rate of change in magnetic flux density. Φ: magnetic flux, which is calculated as the integral of the flux density across the surface of the coil. N: The number of turns, which directly affects the amount of induced voltage. The torque generated by the PMSM is calculated using the following relationship ($T = \frac{2}{3} \times p \times (\psi \times i)$ where T: represents the resulting torque. p: Number of polar pairs. ψ: binding flux for each phase. i: The current passing through the windings [26]-[28]. To determine the influence of rotor magnet dimensions on the loss field distribution of the PMSMs, the variation law of the electromagnetic field can be analyzed accurately. Based on Park-transformation, the supplied voltage and developed electromagnetic torque of the 3-phase PMSM in the d-q representation can be stated as (1) and (2) [29].

$$v_d = R_{id} + L_d \frac{d_{id}}{dt} - w_e L_q i_q \quad (1)$$

$$v_q = R_{iq} + L_q \frac{d_{iq}}{dt} + w_e (L_d i_d - \lambda_{PM}) \quad (2)$$

Where *vd*, *vq*, *id*, *iq*, *Ld*, *Lq* are the applied voltage, current, and inductance in *d-q*-frame, respectively, *R* is the armature resistance, ωe is the electrical angular speed of the rotated magnetic field, and λ_{PM} is the linkage flux produced by the PM. The FEM can be used to accurately investigate the electromagnetic relationship of the PMSM, where the transient field equation of the PMSM can be given by (3) and (4) [30], [31].

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right) = -(-J - \sigma\frac{dA}{dt}) \quad (3)$$

$$\frac{1}{\mu_1}\frac{\partial A}{\partial n} - \frac{1}{\mu_2}\frac{\partial A}{\partial n} = J_s \quad (4)$$

The simulated region, *A* the magnetic vector potential (Wb/m), *J* is the current density, μ is the permeability, σ is the conductivity, *Js* is the equivalent current density of the permanent magnet, S_1 is the boundary condition of the permanent magnet, $\mu 1$ and $\mu 2$ are the permeability of the two medium on the boundary of the permanent magnet. By merging the external electric circuit and computed model of PMSM electromagnetic field, the equation of the field circuit coupled model can be expressed as [22]-[32].

$$v_s = R_s i_s + L_e \frac{di_s}{dt} + \frac{l_{stk}}{S_{turn}} (\iint_{S+}^{i} \frac{\partial A}{\partial t} dS - \iint_{S-}^{i} \frac{\partial A}{\partial t} dS) \quad (5)$$

Where *v*s and *i*s are the phase voltage and phase current, respectively, *R*s is the total stator resistance, *L*e is the end winding inductance, *l*stk is the stack length of the core, S_{turn} is the cross-section area of one turn, S + and S − are the positively and negatively total areas of oriented coil. As stated in (1), the two variable torque components of PM machines are available.The first component is influenced by the rotor excitation PM flux ψ_{PM}, where its value is highly affected by the properties of the PM material, like size, maximum energy product of flux density B, and flux intensity H. While the second component, called reluctance torque, depends on the saliency ratio of the rotor reluctance, it is computed by two components L_q/L_d. The fixed term components are phase number m and pole pair number.

$$T_e = \frac{m}{2}\frac{p}{2}\left[\Psi_{PM} I_q + (L_q - L_d) I_d I_q\right] \quad (6)$$

The developed electromagnetic torque of internal PM machines may be approximately determined by varying (1) to comprise the d-q of the flux as stated in (2) [26]-[33].

$$T_{e\_IPM} = \frac{3}{2}\frac{p}{2}(L_d - L_q) I_d I_q \quad (7)$$

The study of the PMSM model is based on a V-type PM motor used in an electrical vehicle provided by the ANSYS software library. It has 4 poles and 24 slots with chorded windings located in the stator section. In the rotor core, a single-layer, V-type PM slices are introduced into the radial hole at each pole area. Due to the construction of the PM motor, a complete model, the dimension parameters of the motor is given in Table 1. The magnet width (*w* = 20-60 mm) and magnet depth (d = 2-6 mm). The flux barrier of the rotor magnet has varied in the range of (1-3 mm). The research objective of this study is to comprehensively investigate the influence of rotor magnet dimensions variation on the performance of permanent magnet synchronous machines (PMSMs). In detail, the work aims to clarify how variations in rotor magnet geometry, including width, depth, flux barrier width, and magnet bridge impact, on the electromagnetic performance, losses distribution, torque characteristics, and overall efficiency of PMSMs. By conducting a systematic analysis and comparison of different rotor dimensions [34], [35]. The study tries to provide valuable understanding into the optimal design parameters for maximizing motor efficiency and minimizing cogging torque while maintaining acceptable torque creation, minimal losses, and stable operation. Furthermore, the research aims comprises explore the tasks related to different magnet configurations, as well as recognizing chances for additional optimization improvement and enhancing the performance of PMSM. Figure 1 shows the steps involved in the process of representing the effect of V-shaped rotor magnet geometry on the dynamic performance of permanent magnet synchronous motors (PMSMs) using the finite element method (FEM). The process begins by defining the basic motor model, then the geometry of the V-shaped magnets is designed. Followed by forming the network (Meshing) and applying electromagnetic equations. After that, the current is fed into the stator coils so the equations are solved numerically using FEM, and the dynamic performance is analyzed to obtain the results. If performance improvement is needed, the process can be repeated with design modifications.

Through this research, the study objectives to add to the development of motor design and optimization schemes, with implications for several applications such as EVs renewable energy systems (RES), and industrial robotics. Rotor magnet structure of the PMSM was parametrically suggested, including the variations of magnet depth first, then magnet width and finally change of both width and depth. The effects of different depth-width dimensions on the cogging torque, d-q reluctances, and back EMF of the PMSMs were investigated using the FEA method and the ANSYS Electronics software using a voltage source and both of static and transient analysis option setting. Also, the optimal width/depth ratio and relation L_dq also determined. Also, flux barrier (FB) in V-type PMSMs offers a useful method to improve the motor performance [36], [37]. By carefully controlling the FB, it can increase developed torque, increase efficiency, and minimize the torque ripple, which leads to obtain efficient and reliable motor operation in several applications.

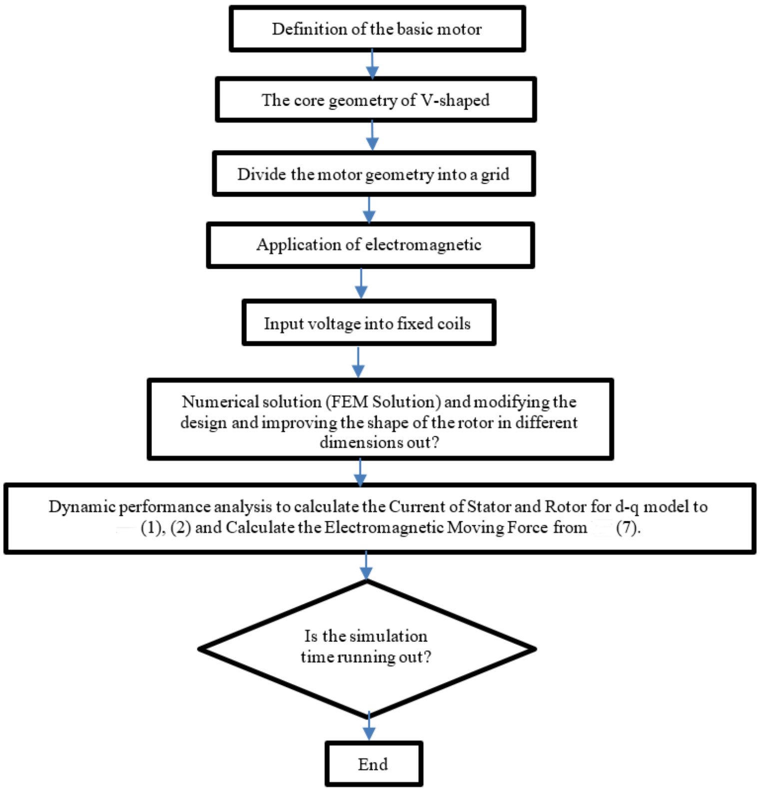

Figure 1. Flow chart of the steps involved in the process of representing the effect of V-shaped rotating magnet geometry

3. RESULTS ANALYSIS

In the current study, a 3-phase, 4-pole, 120-Hz, 3600 rpm, V-Type PMSM is used as the object of the article. Several investigations have been implemented to study the influence of the PM dimension change on the magnetic flux distribution. The motor parameters are included in Table 1. It is possible to get the magnetic flux distribution based on the transient finite element method [38], [39].

The parametric solution technique is applied in the current work, which is considered a suitable optimization method for electric motors to obtain fast and real results. In this technique, the parameters of the motor geometry are considered to have an adjustable value. By defining the maximum and minimum borders of the variable, the analysis is executed in the preferred solution periods. The solution limits the straight effects on the accuracy and time of the solution. As the sensitivity of the parameter step rises, the time analysis will be more accurate. The number of variable steps varies based on the sensitivity of the variables themselves. The parametric investigation conducted using ANSYS software provides an appreciation visions into the effects of width and thickness variations on the performance of V-type PMSM [40], [41].

The results high point on the significance of optimizing magnet dimensions to attain greater motor performance, with the best dimensions identified as 5-6 mm width and 35-40 mm thickness. These results contribute to the improvement of PMSM design and optimization for numerous engineering requests. FB is chosen in the same manner in 1-3 mm. The results of changing the PM width are shown in Figures 2(a)-2(d). Through a joint analysis of PM width and thickness, it was determined that the optimum width falls within the range of 5-6 mm, while the optimum thickness ranges from 35-40 mm. These lengths get the best out of developed torque, in addition to minimizing torque ripple, and enhancing the PMSM efficiency. The results of optimal variation of both depth and thickness of the change in the PM thickness are shown in Figures 3(a)-3(d). The results of optimal variation flux barrier of the PM geometry are shown in Figures 4(a)-4(d). The results shown in Figure 5 demonstrate the effect of parametric changes in magnet flux barriers on the parameters of permanent magnet synchronous motors (V-type PMSM).

Table 1. Characteristics parameters of PMSM

Parameter	Unit	Value	Parameter	Unit	Value
Rated power	KW	5	Stator core length	mm	65
Rated voltage	V	220	Frequency	Hz	120
Rated current	A	8.2	Pole pairs		4
Rated torque	N.m	1.8	Stator resistance	Ω	2.23
Rated speed	r/min	3600	Stator inductance	H	0.00061
Stator outer diameter	mm	120	End leakage inductance	H	0.00022
Stator inner diameter	mm	76	Moment of inertia	$kg \cdot m^2$	1.68e-05

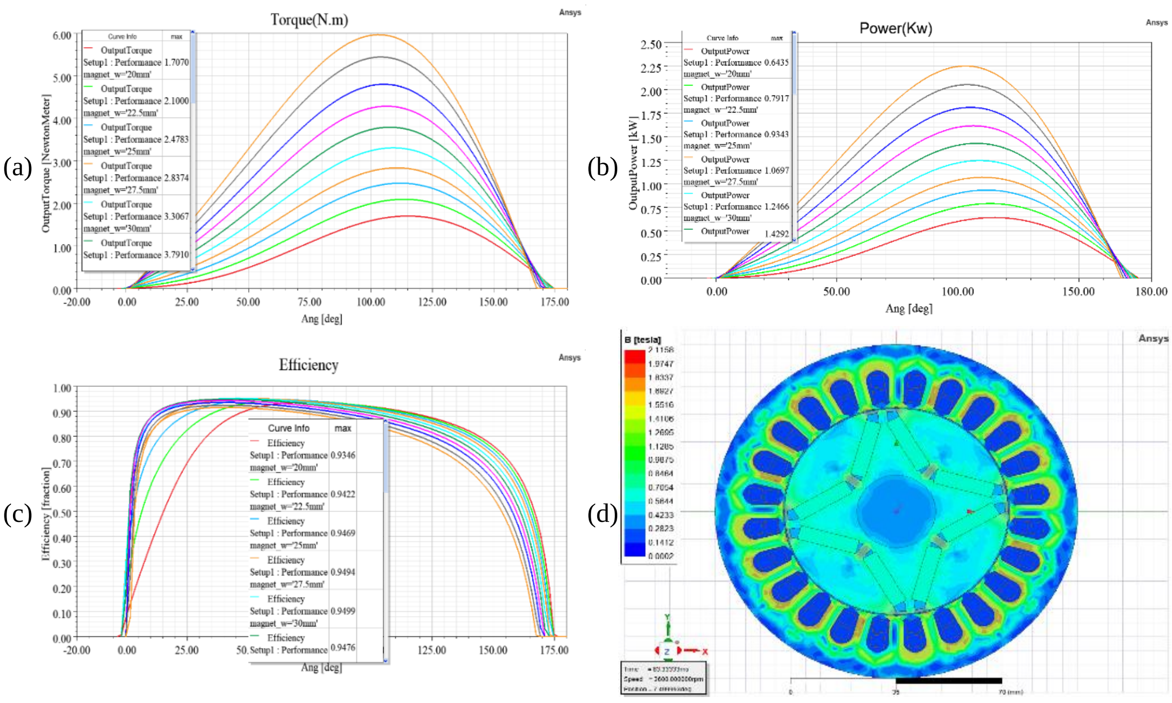

Figure 2. Show the effect of parametric variation of magnet width on the V-type PMSM parameters: (a) developed torque, (b) output power, (c) efficiency, and (d) magnetic flux density

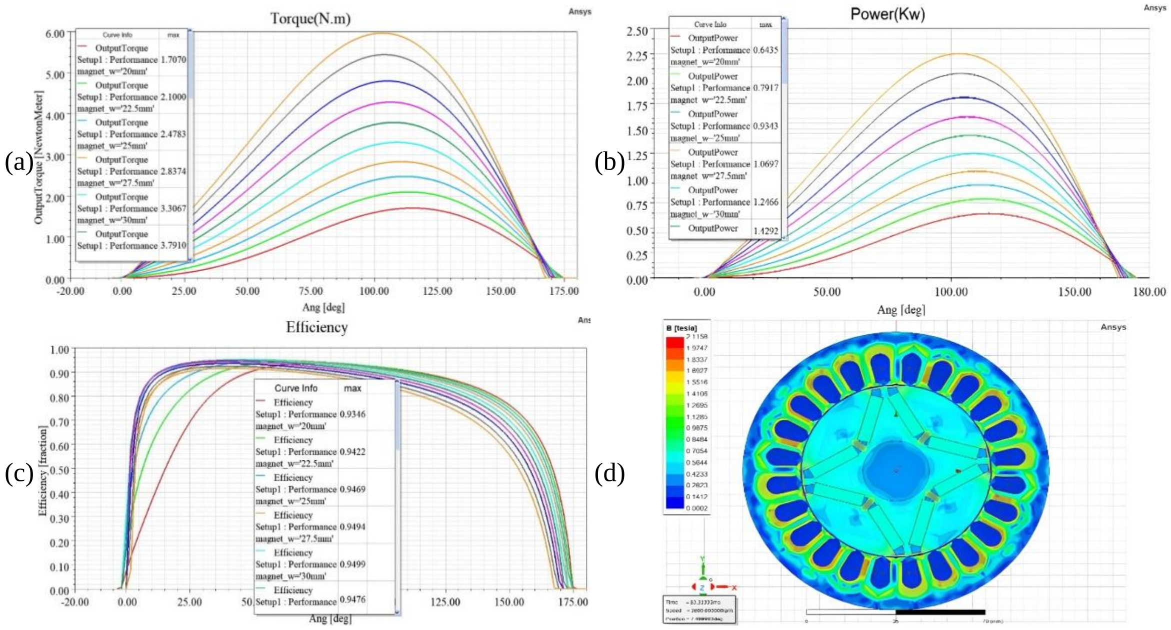

Figure 3. Show the effect of parametric variation of magnet thickness on the V-type PMSM parameters: (a) developed torque, (b) output power, (c) efficiency, and (d) magnetic flux density

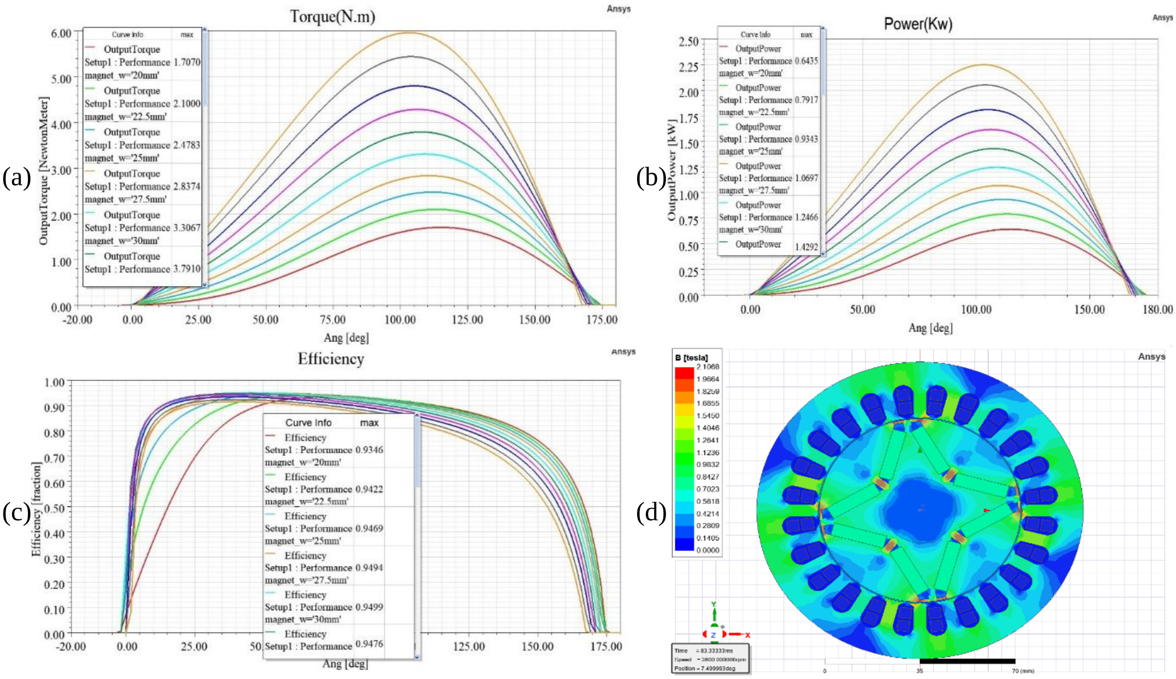

Figure 4. Show the effect of parametric variation of magnet depth-thickness on the V-type PMSM parameters: (a) developed torque (b) output power (c) efficiency (d) magnetic flux density

The torque generated shows an increase with improved design of magnetic flux barriers, reflecting improved dynamic performance of the motor. Output energy also increases with modifications in baffle design, indicating the effectiveness of improvements in enhancing mechanical energy. The overall efficiency of the motor improves as the magnet flux increases, which indicates reduced losses. Magnetic flux density is directly affected by the design of the barriers; the improved design results in increased flux density, which enhances the overall performance. These results indicate the importance of careful design of magnetic flux barriers in improving the performance of synchronous motors. Figure 6 presents the finite element analysis of the effect of changing the magnet width on the parameters of the V-type synchronous motor. The results indicate that the magnet width increases with an increase in the furnace temperature, which means that the motor needs more power for driving force. The direction of the front light is also clearly visible, resulting in the highest accuracy of performance.

After presenting and discussing the results, it can be stated that the modeling process using the finite element method (FEM) provides high accuracy in the performance analysis of permanent magnet synchronous motors (PMSMs), reducing the need for expensive and complex practical tests. This method provides accurate simulation of electromagnetic properties, torque, and current flow, and can therefore be relied upon to evaluate designs and test improvements without the need to manufacture prototypes [42], [43].

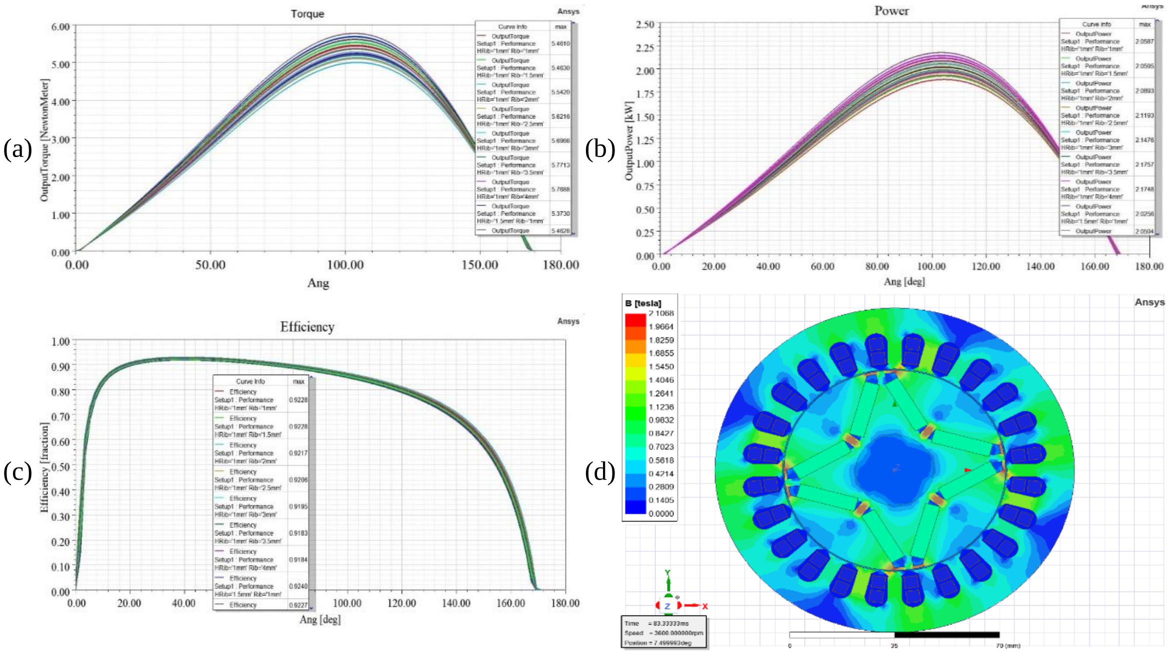

Figure 5. Show the effect of parametric variation of magnet flux barriers on the V-type PMSM parameters: (a) developed torque (b) output power (c) efficiency (d) magnetic flux density

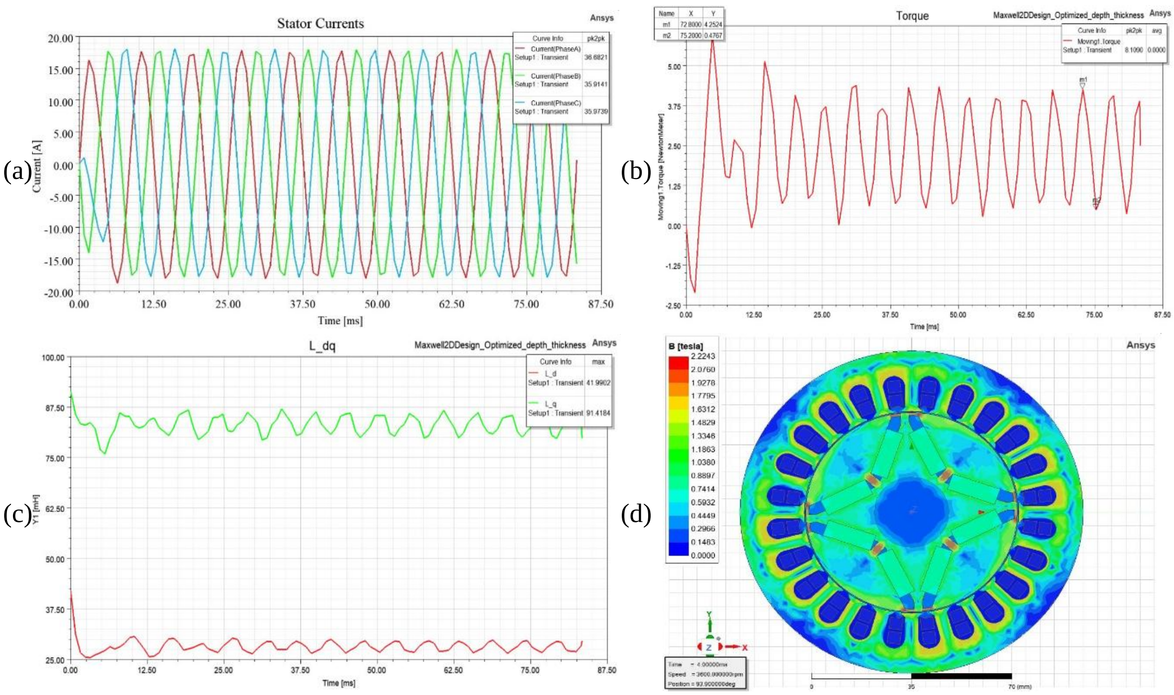

Figure 6. Show the finite element analysis due to variation of magnet width on the V-type PMSM parameters: (a) stator current, (b) output torque, (c) d-q inductances, and (d) d-q stator currents

4. CONCLUSION

In this research, it is confirmed that the width of the rotating magnet has a prominent effect on improving the performance of permanent magnet synchronous motors (PMSMs), as it enhances the motor efficiency and reduces the cogging torque. This is because the wider magnet effectively changes the magnetic flux distribution, which increases the strength of the magnetic field and enhances torque generation. In contrast, increasing the depth of the magnet may cause additional losses such as eddy currents and core losses, which impair the overall efficiency. The research demonstrates the importance of the optimal balance between magnet width and depth for motor development and improving the overall performance of the electric propulsion system. In addition to the above, the research also shows the importance of studying the effects of rotating magnet design with parametric analytical methods, as these studies help determine the optimal dimensions that increase the efficiency of motors and improve performance. These results confirm that focusing on the precise geometry of magnet dimensions, such as width over depth, can enhance the stability and overall efficiency of the motor while reducing unwanted losses. This research is clearly reflected in the development of renewable energy solutions and modern electric propulsion systems, which contribute to improving sustainability and performance. This paper presents future ideas for researchers by using artificial intelligence methods to update the best design of the motor for future industrial applications.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Ahmed Jadaan Ali	✓	✓	✓		✓			✓	✓		✓	✓	✓	
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Basil Mohammed Saied	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	

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

We have no known conflicting financial interests or personal relationships that could influence the work reported in this paper.

DATA AVAILABILITY

We confirm that the data supporting the findings of this study are available within the article.

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