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Research article

Effect of Magnet Thickness and Width Variation on Back EMF of 18-Slot 16-Pole Permanent Magnet Synchronous Generator

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Abstract: Permanent magnet synchronous generators (PMSG) converts mechanical energy into electrical energy through electromagnetic induction, with the excitation field generated by permanent magnets instead of coils. This paper investigates the effects of varying magnet thickness and width on the back electromotive force (back EMF) of an 18-slot 16-pole PMSG using finite element method (FEM) simulations. The aim is to understand how these geometric parameters influence the back EMF values, which are crucial for generator design and performance evaluation. The FEM modelling results show that a 5 mm magnet thickness yields the highest back EMF value of 130.47 V, while a 15 mm magnet width produces a back EMF of 100.65 V. Additionally, the back EMF constant (KE) is maximized at 0.79 V·s/rad for a 5 mm magnet thickness and 0.55 V·s/rad for a 15 mm magnet width. These findings provide insights into optimising magnet dimensions for improving the efficiency and output characteristics of PMSGs in various applications.

Keywords: PMSG, generator, 18s16p, FEM

1. Introduction

Permanent magnet synchronous generator (PMSG) have gained significant attention in recent years due to their numerous advantages over conventional wound-field synchronous generators [1], [2], [3]. These advantages include higher efficiency, higher power density, lower maintenance requirements, and improved reliability [4]. PMSG find widespread applications in various sectors, such as wind energy conversion systems, marine propulsion systems, and aerospace applications, among others [5], [6], [7], [8].

The operating principle of a PMSG is based on the interaction between the rotating permanent magnet field and the stator windings, which induces an electromotive force (EMF) in the stator coils. This induced EMF, also known as the back EMF, plays a crucial role in determining the generator's output voltage and power characteristics. The back EMF is influenced by several factors, including the magnetic flux density distribution, the number of stator slots and rotor poles, and the geometric dimensions of the permanent magnets [9].

One of the key geometric parameters that significantly impacts the back EMF and overall performance of a PMSG is the magnet thickness [10]. Thicker magnets typically result in higher magnetic flux density and, consequently, higher back-EMF values. However, increasing the magnet thickness beyond an optimal point can lead to diminishing returns due to factors such as magnetic saturation and increased manufacturing costs. Therefore, it is essential to strike a balance between magnet thickness and other design considerations to achieve the desired performance characteristics.

Another critical parameter that influences the back EMF and output characteristics of a PMSG is the magnet width. The magnet width determines the effective area of the magnetic flux interacting with the stator windings, thereby affecting the induced back EMF magnitude [11], [12]. Wider magnets generally result in higher back EMF values, but they also increase the overall size and weight of the generator, which may not be desirable in certain applications where compactness and lightweight design are crucial.

In this study, we investigate the effects of varying magnet thickness and width on the back EMF of an 18-slot 16-pole PMSG using finite element method (FEM) simulations. FEM is a powerful numerical technique widely used in electromagnetic analysis, as it allows for accurate modeling of complex geometries and material properties. By systematically varying the magnet thickness and width parameters, we aim to gain insights into their individual and combined effects on the back EMF values.

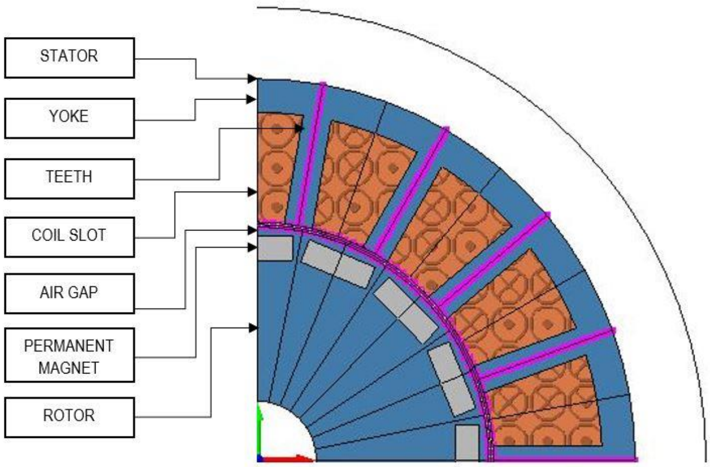
2. Literature Review

Generators are electrical machines that convert mechanical energy into electrical energy through the principle of electromagnetic induction. They are essential components in power plants and play a crucial role in generating electrical power. Generators typically produce three-phase voltage output, and their main components are the stator and rotor [13].

Permanent magnet synchronous generators (PMSG) are a specific type of generator where the excitation field is generated by permanent magnets instead of coils. This design eliminates the need for an external excitation source, resulting in higher efficiency, improved reliability, and reduced maintenance requirements [14], [15]. PMSG has gained significant attention in recent years, particularly in wind turbine applications, due to their inherent advantages over traditional generators.

In a PMSG, the permanent magnets can be either surface-mounted or embedded within the rotor structure. The construction of a typical PMSG is illustrated in Figure 1.

Figure 1. Parts of flux linkage generator.



The interaction between the rotating permanent magnet field and the stator windings induces an electromotive force (EMF) in the stator coils, which is known as the back EMF. The back EMF is a crucial parameter in generator design and performance evaluation [16], [17], [18]. Its value can be derived directly from the flux linkage function according to Faraday's law, as represented by the following equation:

$$\varepsilon = \frac{-N\Delta\phi}{\Delta T} \tag{1}$$

where Ɛ is the induction voltage, N is the number of turns, $\Delta\phi$ is flux change in Weber, and Δt is time change.

Another important parameter in PMSG design is the back-EMF constant (K_E), which represents the generator's construction and is calculated using the following equation:

$$K_E = \frac{\varepsilon}{\omega_e} \tag{2}$$

where K_E is the back EMF constant, Ɛ is peak value of back EMF and ω is angular rotor speed in rad/s.

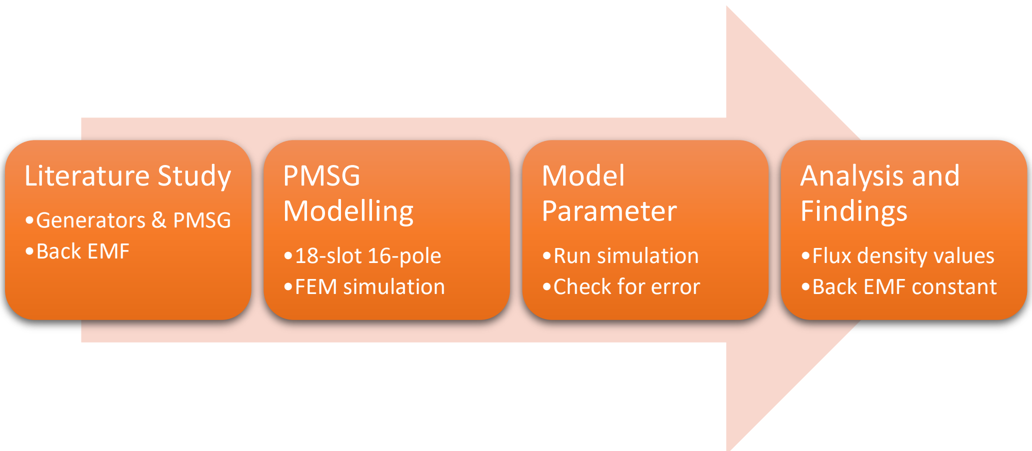
The finite element method (FEM) is a powerful numerical technique widely employed in electromagnetic analysis and design. It involves dividing the analysed object into finite small elements, analyzing these elements individually, and then recombining the results to obtain a solution for the entire domain. FEM offers several advantages over other numerical methods, including the ability to evaluate a large number of design options by varying parameters and perform detailed electromagnetic and mechanical analyses.

FEM has been extensively used in the modelling and analysis of PMSGs, allowing researchers to investigate the effects of various design parameters, such as magnet dimensions, on the generator's performance characteristics [19]. By systematically varying these parameters through FEM simulations, valuable insights can be gained into optimising the generator's design for specific applications and performance requirements.

3. Methodology

The research methodology consists of several stages, which are outlined in the flowchart presented in Figure 2.

Figure 2. Research workflow.



This research commenced with a comprehensive literature review encompassing the fundamentals of PMSG and the FEM software employed for analysis. Initially, a thorough understanding of generators, including their functions, operating principles, and component structures, was established. Subsequently, the study delved into the theory of PMSGs, highlighting their significant advantages and the growing interest among researchers, particularly in wind power plant applications.

Theoretical calculations were performed to determine the induced voltage and electrical constants, which served as crucial parameters for the subsequent simulations. Additionally, an in-depth study of the FEM method was conducted, emphasising its ability to evaluate a wide range of design options by varying multiple parameters while performing detailed electromagnetic analyses.

The next step involved modelling an 18-slot 16-pole PMSG using specialised magnetic software. All the necessary parameters derived from the previous calculations were incorporated into the model. In the event of encountering errors during the modelling process, the parameters were meticulously rechecked, and the simulation was repeated until no errors were present. Once a valid model was obtained, data processing and analysis were carried out, leading to the formulation of conclusions.

The modelling process involved systematically varying the magnet thickness and width to investigate their effects on the back EMF values. Multiple simulations were conducted with different magnet dimensions, and the resulting back EMF were recorded and analysed.

The FEM simulations provided a comprehensive understanding of the influence of magnet geometry on the generator's performance characteristics. By analysing the simulation results, valuable insights were gained regarding the effect of magnet thickness and width to back EMF, for further contributing to the design and development of high-performance PMSGs for various applications.

4. Results and Discussion

4.1. PMSG 18-slot 16-pole Modelling

The modeling of an 18-slot 16-pole (18s16p) permanent magnet synchronous generator (PMSG) system was carried out using finite element method (FEM) software with an adapted model. The specifications of the model used in this study are described in Table 1. Based on these specifications, the geometric modeling of the 18s16p PMSG is shown in Figure 3.

Figure 3. PMSG 18s16p model.

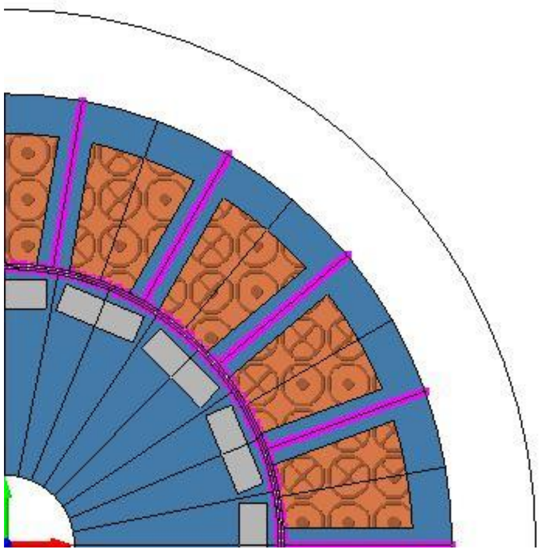


Table 1. Specifications of PMSG 18-slot, 16-pole.

Specifications	Model
Number of slots	18
Number of poles	16
Stator diameter (mm)	160
Rotor diameter (mm)	98
Shaft diameter (mm)	25
Core material length (mm)	20
Air gap width (mm)	1
Stator material	CR10: cold rolled 1010 steel
Rotor material	CR10: cold rolled 1010 steel
Coil material	Copper: 5.77e7 siemens/meter
Magnetic materials	Neodymium iron boron: 48/11

In the variation modeling, two models were set with 78 turns on the u, v, and w coils. This study investigated two variations in magnet dimensions: thickness and width as mentioned in Table 2. The variations were calculated and modeled Figure 4 and 5.

Table 2. Magnetic thickness and width variations.

Part	Size (mm)	
	Variation 1	Variation 2
Magnet thickness	3	5
Magnet width	9	12

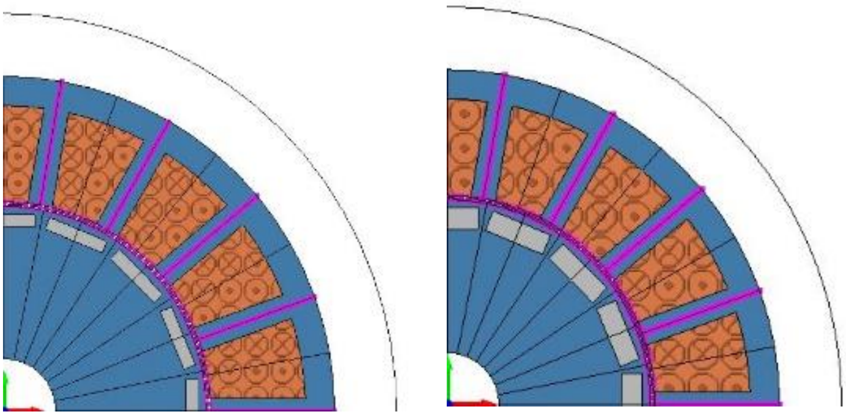

(a) (b)

Figure 4. PMSG models magnet thickness variation: **(a)** 3 mm; **(b)** 5 mm.

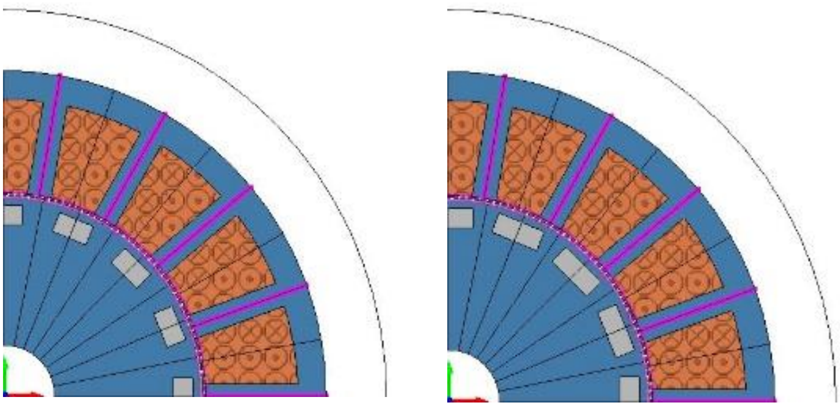
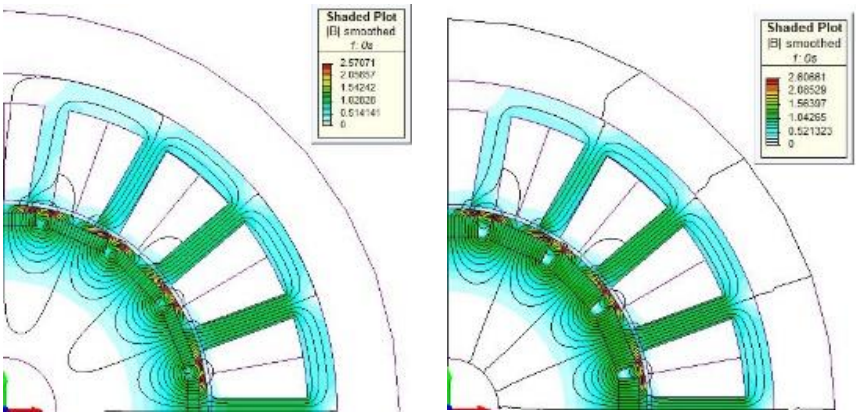

(a) (b)

Figure 5. PMSG models magnet width variation: **(a)** 9 mm; **(b)** 12 mm.

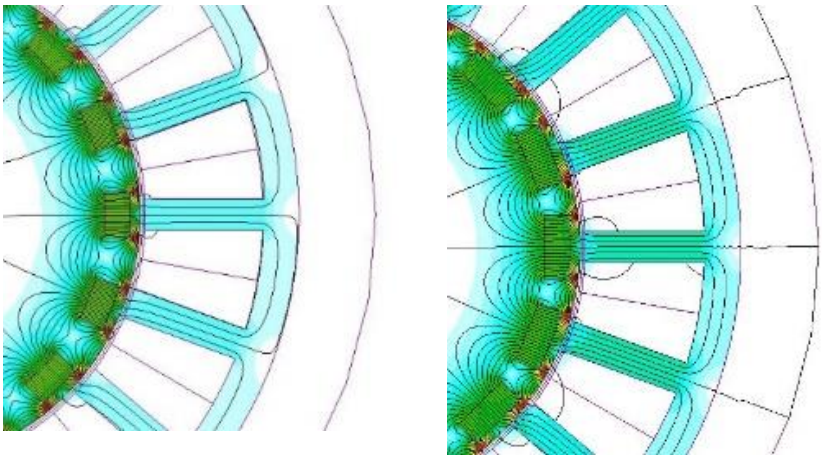
4.2. Back EMF

Before discussing the back EMF constants, the magnetic flux flow in the modelling was analyzed. Figures 6 and 7 illustrate the flux flow in the magnetic modeling with magnet thicknesses of 3 mm and 5 mm, and magnet widths of 9 mm and 12 mm, respectively.



(a) (b)

Figure 6. Flux flow on magnet thickness variation: **(a)** 3 mm; **(b)** 5 mm.



(a) (b)

Figure 7. Flux flow on magnet width variation: **(a)** 9 mm; **(b)** 12 mm.

To quantify the flux density, measurements were taken at the densest part of the teeth in the simulations. The simulation results for the 18s16p generator with a magnet thickness of 3 mm yielded a flux density value of 1.07 Tesla, while for a thickness of 5 mm, the flux density value was 1.16 Tesla. In the simulations for magnet width variations, the flux density value was 0.42 Tesla for a width of 9 mm and 0.79 Tesla for a width of 12 mm. The modeling results were further processed to obtain the DC-Voltage value, average voltage, and KE value of the generator at a speed of 1000 rpm. The results showed in Table 3.

Table 3. Simulation results.

Part	Magnet thickness (mm)		Magnet width (mm)	
	Variation 1	Variation 2	Variation 1	Variation 2
Flux density (Tesla)	1.07	1.16	0.42	0.79
DC voltage (Volt)	118.97	130.47	23.20	58.52
K_E (V.s/rad)	0.72	0.79	0.18	0.33

From Table 4, it can be observed that the peak DC voltage value was obtained for the 5 mm magnet thickness variation at 130.47 V, followed by the 3 mm magnet thickness variation at 118.97 V. For the magnet width variations, the 12 mm width yielded a DC Voltage of 58.52 V, while the 9 mm width resulted in a DC Voltage of 23.20 V.

The back EMF values were also obtained from the data. For the magnet thickness variations, a KE value of 0.79 V·s/rad was obtained for a thickness of 5 mm, and 0.72 V·s/rad for a thickness of 3 mm. As for the magnet width variations, the KE value was 0.33 V·s/rad for a width of 12 mm and 0.18 V·s/rad for a width of 9 mm.

These results clearly demonstrate the significant impact of magnet dimensions on the performance characteristics of the PMSG. Increasing the magnet thickness and width generally led to higher flux density and back EMF values, which are desirable for improved generator efficiency and output. However, it is crucial to consider other design factors, such as weight, cost, and manufacturing constraints, when optimizing magnet dimensions for specific applications.

5. Conclusions

Through the comprehensive analysis and simulations conducted in this study, several significant conclusions can be drawn. Firstly, it is evident that increasing the thickness and width of the permanent magnets leads to a tighter flux concentration on the teeth of the generator. This phenomenon directly impacts the back electromotive force (back EMF) values, as thicker and wider magnets result in higher back EMF values being produced. Specifically, the simulations demonstrated that a magnet thickness of 5 mm yielded the highest DC voltage value of 130.47 V and a KE value of 0.79 V·s/rad, while a magnet width of 12 mm produced a DC voltage of 58.52 V and a KE value of 0.33 V·s/rad. These findings highlight the significant influence of magnet dimensions on the performance characteristics of PMSG.

Based on the insights gained from this research, several suggestions can be made for further refinement and development. Firstly, it would be valuable to explore variations in other parameters of the 18-slot 16-pole PMSG model, such as stator and rotor geometries or winding configurations, to understand their impact on generator performance. Additionally, conducting further analysis regarding the PMSG output value when the permanent magnets are placed on the rotor using a surface-mounted method could provide valuable insights into alternative magnet configurations and their respective advantages and trade-offs.

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Conflicts of Interest: The authors declare no conflicts of interest.

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