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Research article

Effect of Rotor Teeth Width Variations on Back EMF Constant of a 12-Slot 8-Pole Permanent Magnet Synchronous Generator: A Finite Element Analysis

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Abstract: Permanent Magnet Synchronous Generators (PMSGs) are widely used for converting mechanical energy into electrical energy through electromagnetic induction. Unlike conventional generators, PMSGs utilise permanent magnets to generate the excitation field, eliminating the need for external excitation coils. This study investigates the effects of rotor teeth width variations on the performance characteristics of a 12-slot, 8-pole PMSG using Finite Element Method (FEM) simulations. Specifically, the influence of rotor teeth width on flux density and back electromotive force (EMF) constant are explored. Three different rotor teeth widths, 5 mm, 7.5 mm, and 10 mm, are considered, and their impact on the generator's performance is evaluated. The FEM simulations reveal that increasing the rotor teeth width leads to a significant increase in the back-EMF constant values. The smallest back-EMF of 12.057 V and the lowest constant are observed for the 5 mm rotor teeth width, while the largest back-EMF of 20.774 V and the highest constant correspond to the 10 mm rotor teeth width. These findings highlight the importance of optimising rotor teeth geometry in PMSGs to achieve desired performance characteristics.

Keywords: PMSG, generator, 12s8p, back EMF, finite element method

1. Introduction

Electricity has become an indispensable source of energy for modern societies, playing a crucial role in commercial activities, industrial operations, and daily household life. The importance of electrical energy is reflected in the advancement of technology and economic growth in a country [1]. According to data from the Ministry of Energy and Mineral Resources (ESDM), the electrification ratio target for Indonesia is set at 95.35%, which represents the percentage of households with access to electricity compared to the total number of households nationwide. Currently, 62.5 million (93.03%) households receive electricity from PLN. In addition, 1.5 million (2.32%) households obtain electricity from non-PLN off-grid systems built by regional governments, private entities, the Directorate General of New Energy, Renewable and Energy Conservation (EBTKE) of the

Ministry of Energy and Mineral Resources, and households with electricity without a kWh meter [2].

However, approximately 3 million people (4.36%) remain without access to electricity, primarily in remote areas of the archipelago, due to inadequate infrastructure and the challenges faced by PLN in supplying these regions. To achieve the 100% electrification ratio target, ESDM plans to focus on New Renewable Energy (ETB) sources. This shift towards renewable electrical energy is driven by the dwindling availability of fossil fuels and the increasing demand for electricity in communities [3].

To address this challenge, various new renewable energy sources have been developed and researched. Given the growing demand for electrical energy in communities, there is an urgent need for power plants capable of providing sufficient electrical energy to meet these requirements. These power plants include hydroelectric (PLTA), coal power plants (PLTU), wind power plants (PLTB), diesel power plants (PLTD), gas power plants (PLTG), combined cycle gas turbine power plants (PLTGU), nuclear power plants (PLTN), and others. Every region, especially underdeveloped areas in Indonesia, requires access to electricity [4], [5], [6].

One promising development is the wind power plant (PLTB), which converts mechanical energy from rotating blades into electrical energy through a generator. Among the various generator types, the permanent magnet synchronous generator (PMSG) has gained significant attention. This generator consists of two main components: the rotor and the stator. The rotor houses the rotor core and magnets, while the stator comprises coils, teeth, yokes, and an umbrella component in some generator models [7].

The objective of this study is to investigate the effects of rotor teeth width variations on the performance characteristics of a 12-slot, 8-pole PMSG using Finite Element Method (FEM) simulations. Specifically, the study explores the influence of rotor teeth width on flux density and back electromotive force (EMF) constant. Three different rotor teeth widths, 5 mm, 7.5 mm, and 10 mm, are considered, and their impact on the generator's performance is evaluated.

2. Literature Review

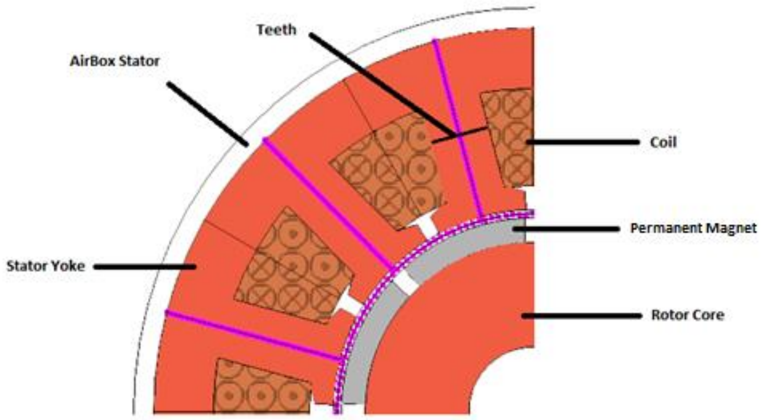
2.1. Generator

Generators, also known as alternators, are devices or machines that convert mechanical energy into electrical energy, typically through the process of electromagnetic induction. This process is referred to as power generation. Generators are capable of producing an electromotive force by electromagnetic induction, which is then converted into electric power. Generally, generators have a three-phase voltage output, making them the main component in power plants. The two main components of a generator are the stator and the rotor [8].

2.2. Permanent Magnet Synchronous Generator

Permanent Magnet Synchronous Generators (PMSG) are a type of generator in which the excitation field is generated by permanent magnets instead of coils, resulting in the magnetic flux being produced by a permanent magnetic field. These generators offer significant advantages and have garnered interest from researchers, particularly for their application in wind turbines. Permanent magnets in PMSGs can be mounted on the surface or embedded within the rotor [9], [10]. The construction of a PMSG is illustrated in Figure 1.

Figure 1. Generator parts.



2.3. Flux Linkage

Flux Linkage is the amount of magnetic flux that passes through a coil. It can be represented by the following equation [11].

$$\lambda = N \cdot \Phi \tag{1}$$

where λ is the flux linkage, N is the number of turns, and Φ is the magnetic flux. Both flux linkage and the flux itself are measured in Weber.

2.4. Back Electromotive Force

Back Electromotive Force (EMF) is the value of the voltage induced in a stationary coil. The back EMF value can be directly derived from the flux linkage function according to Faraday's law [12], as represented by the following equation.

$$\varepsilon = \frac{-N\Delta\phi}{\Delta T} \tag{2}$$

where Ɛ is the induced voltage, $\Delta\phi$ is the flux change, and Δt is the time change.

The back EMF constant (K_E) represents the construction of a PMSG. The K_E constant value can be calculated using the following equation.

$$K_E = \frac{\varepsilon}{\omega_e} \tag{3}$$

where K_E is the back EMF constant, Ɛ is peak value of back EMF and ω is angular rotor speed. The unit for K_E is volts-second per radian (V·s/rad).

2.5. Finite Element Method

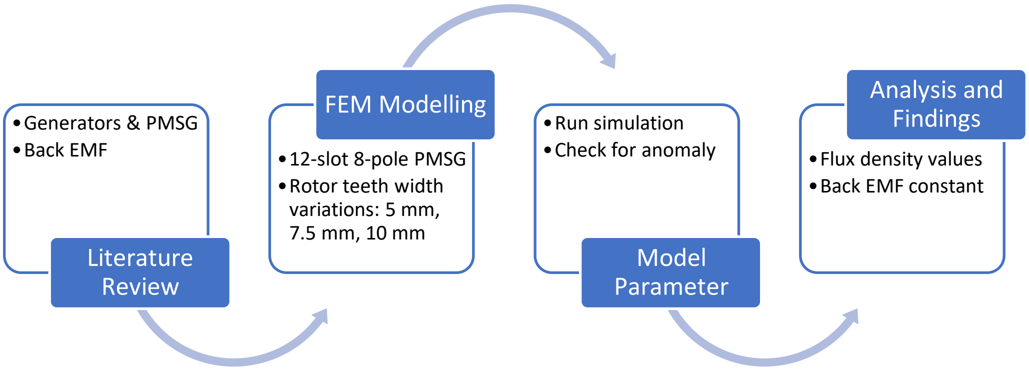
The Finite Element Method (FEM) is a systematic approach for converting a function in an infinite dimensional space into a function in a finite dimensional space, ultimately resulting in an ordinary vector (in an infinite dimensional space) that can be arranged by numerical methods. Objects analysed using FEM are divided into finite small parts. These small parts are then analysed, and the results are combined to obtain a solution for the entire area [13], [14].

FEM offers several advantages over other numerical methods, including the ability to calculate and evaluate a large number of options along with slight changes in the number of parameters, as well as perform detailed electromagnetic and mechanical analyses [15].

3. Methodology

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

Figure 2. Research workflow.



The initial stage involves conducting a comprehensive literature review. This process begins with understanding the fundamental concepts of generators, including their theoretical principles, specifications, operation, and functions. Subsequently, a reference study is carried out related to Permanent Magnet Synchronous Generators (PMSGs) to gain insights into their working principles. Additionally, calculations related to magnetic flux and back EMF constants are explored, and the appropriate method for analysing the generator object is identified.

Next, a 12-slot, 8-pole PMSG model is created with varying magnet thicknesses or rotor teeth widths of 5mm, 7.5mm, and 10mm using specialised magnet software. Once the model is constructed, simulations are performed. If any anomalies or discrepancies arise in the simulation data, the model parameters are thoroughly checked and verified within the simulation software. If no anomalies are detected, the process proceeds to data processing and analysis.

The obtained data includes flux density values and back EMF constant values from the simulation results, which are influenced by parameters such as the number of slots, number of poles, stator outer diameter, air gap, rotor outer diameter, rotor inner diameter, rotor teeth width, and number of windings. After conducting a comprehensive analysis of the data, conclusions can be drawn from the research findings.

4. Results and Discussion

4.1. Modelling of PMSG 12-slot, 8-pole

The modelling of the PMSG 12-slot, 8-pole system was carried out using FEM software with an adapted model. The specifications used in this model are described in Table 1, while the materials for the three PMSG models were selected as per Table 2.

Table 1. Specifications of PMSG 12-slot, 8-pole.

Specifications	Model Variation 1	Model Variation 2	Model Variation 3
Number of slots	12	12	12
Number of poles	8	8	8
Outer stator diameter (mm)	95	95	95
Inner stator diameter (mm)	50	50	50
Air gap	1	1	1
Outer rotor diameter (mm)	49	49	49
Inner rotor diameter (mm)	8	8	8
Teeth width (mm)	5	7.5	10
Number of turns	100	100	100

Table 2. PMSG materials.

Component	Material
Iron Core	M19: USS Transformer 72 -- 29 Gage
Magnet	NdFeB: 50MgOe
Coil	Copper: 5.77e7 Siemens/meter

Based on Table 1 and 2, the geometric modelling of the resulting PMSG 12s8p is shown in Figure 3.

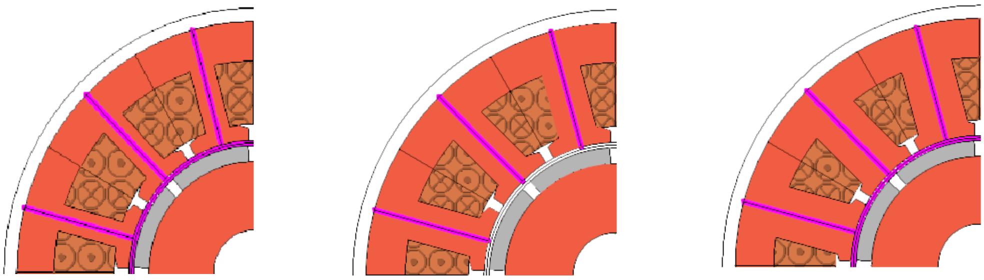

(a) (b) (c)

Figure 3. PMSG models with teeth width variation: **(a)** 5 mm; **(b)** 7.5 mm; **(c)** 10 mm.

In the variation modelling, the two models were set at 100 turns on the u, v, and w coils. This paper investigates two variations (in mm) in magnet thickness, which are calculated and presented in tabular and model forms.

4.2. Simulation Results

Upon completion of the simulations, flux density images and flux density values were obtained. The flux density images are shown in Figure 4. The back EMF value referred to in this paper is the average DC voltage obtained from the absolute maximum value of the voltage between phases. The back EMF values for each variation, in correspond with the flux density values are shown in Table 3.

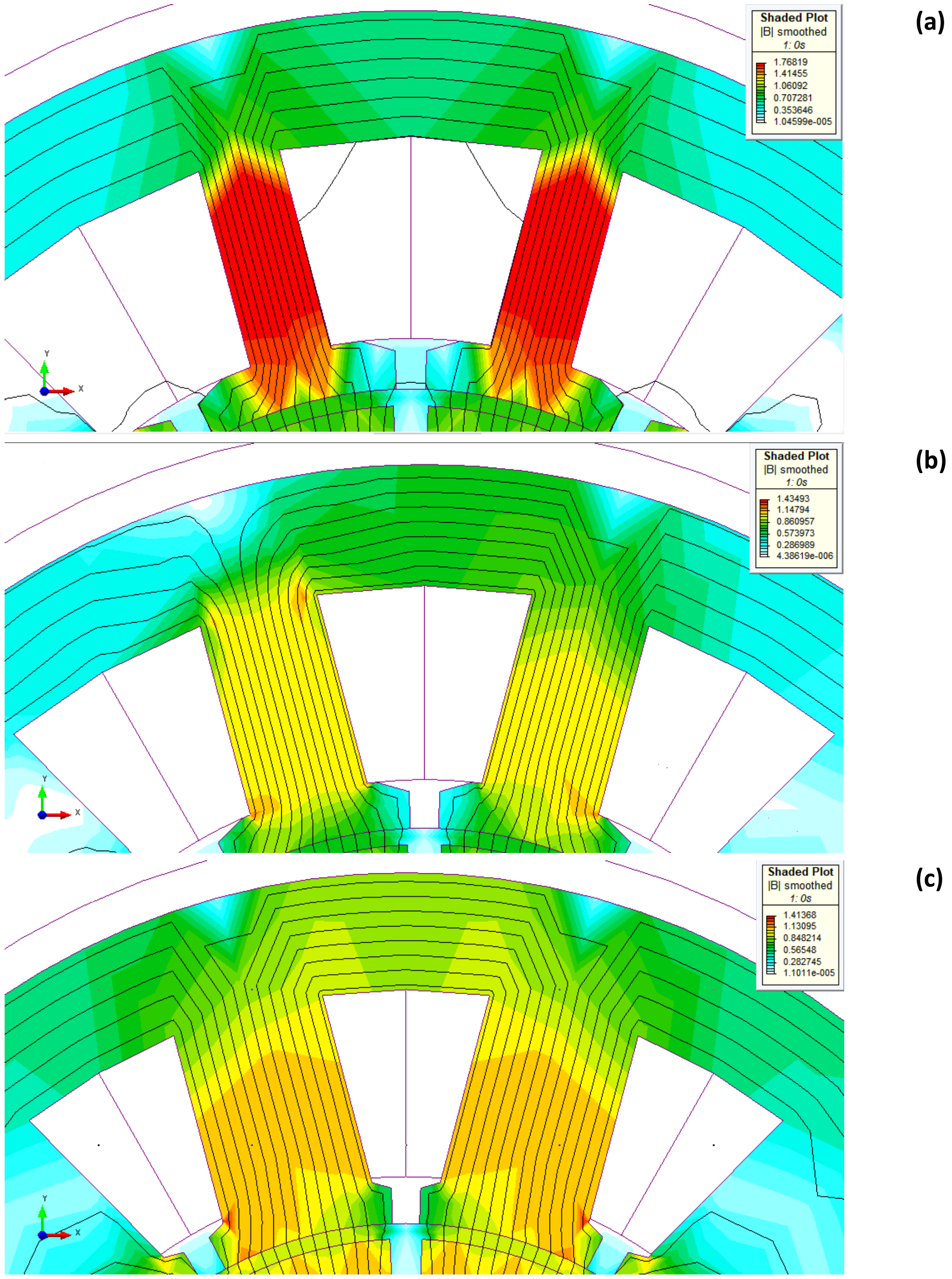


Figure 4. Flux density with teeth width variation: **(a)** 5 mm; **(b)** 7.5 mm; **(c)** 10 mm.

Table 3. Flux density, average V_{DC} and back EMF value for each width variation.

Teeth Width (mm)	Flux Density (T)	Average V_{DC} (V)	K_E (Vs/rad)
5 mm	1.76	16.853	0.161
7.5 mm	1.42	18.057	0.172
10 mm	1.13	20.774	0.198

The simulation results revealed that the flux values for rotor teeth widths of 5 mm, 7.5 mm, and 10 mm are 1.76 T, 1.42 T, and 1.13 T, respectively. The corresponding back EMF values, expressed as the average DC voltage, are 16.853 V, 18.057 V, and 20.774 V, respectively. Additionally, the calculated electrical constant (KE) values for each model are 0.161 Vs/rad, 0.172 Vs/rad, and 0.198 Vs/rad.

5. Conclusions

Based on the results of the analysis, several conclusions can be drawn. Firstly, it is observed that the largest flux density of 1.76 T occurs with the 5mm Teeth variation, suggesting that smaller teeth widths result in greater flux density. Secondly, the addition of teeth width to the PMSG, while keeping other parameters constant, increases the resulting back EMF value. Thirdly, the increase in teeth width, alongside other constant parameters, leads to a higher value of the KE constant generated.

To further improve and develop upon the findings of this research, several next steps are recommended. Firstly, it is advisable to explore variations in other parameters within the 12s8p PMSG model to better understand their impact on performance characteristics. Additionally, further research should be conducted to analyse the characteristics of cogging in PMSGs, providing deeper insights into generator behaviour and potential optimisation strategies.

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

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