Performance Improvement of Flux Switching Permanent Magnet Wind Generator Using Magnetic Flux Barrier Design

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Abstract: Flux-switching permanent magnet (FSPM) machines have attracted significant research attention in the field of wind power generation. In this study, the utilization of a magnetic flux barrier to improve the performance of the nine-phase FSPM generator designed for low-speed wind power applications is conducted. The proposed approach involves introducing magnetic flux barriers of different topologies to the conventional FSPM generator and analyzing their performance using 2D finite element simulations. Results suggested that |-shaped magnetic flux barriers exhibited the highest performance among other topologies, making them the appropriate choice for this generator. The geometry of the |-shaped flux barriers was further optimized using response surface methodology to maximize the generator’s performance. The proposed generator exhibits a significant decrease in cogging torque, achieving a remarkable reduction of up to 23.7%, while maintaining electromotive force. Moreover, it shows a significant decrease in permanent magnet eddy-current loss, with a noteworthy reduction of up to 51%. Additionally, significant improvements were demonstrated in terms of electromagnetic torque, torque ripple, output power, and efficiency. Details on the physical reasoning behind these improvements have been provided. Overall, the proposed FSPM generator with inserted flux barriers has the potential to meet the demands of low-speed wind power generation effectively.

Keywords: permanent magnet generator; flux switching; wind power generation; magnetic flux barrier

1. Introduction

Green technology and ecological sustainability have caught the attention of the international community as global environmental pollution and energy shortages become more severe [1–3]. Electricity production from renewable energy is quickly becoming an inevitable trend due to its exceptionally low greenhouse gas and carbon emissions [3–6]. Since wind power generation has gained much attention in the past ten years, improvements to wind turbine generators have been carried out continuously. Permanent magnet (PM) machines have become a competitive candidate for wind power generation due to their distinctive features, i.e., high torque density, high efficiency, and high reliability [5–7]. PM machines can be divided into two types, namely, stator-PM machines (SPM), in which PMs and armature winding are located in the stator part, and rotor-PM (RPM) machines, in which PMs are placed in the rotor part with the armature windings located in the stator [8]. Compared to the RPM machines, the SPM machines are found to have features more suitable as a wind power generator since it typically has low inertia, better thermal performance, higher robustness, and a simpler structure [9]. Three main categories of SPM machines are flux-reversal PM machines, doubly salient PM machines, and flux-switching PM (FSPM) machines [10–12]. Among these topologies, the FSPM machines have received the highest research attention for wind power generation due to their superior flux focusing effects, well-patterned sinusoidal
electromotive force (EMF), high torque density, and low voltage regulation [13,14]; they are therefore considered in this study.

The literature surveys on applications of FSPM machines for wind power generation are as follows. In 2017, L. Shao et al. introduced a 10 kW twelve-phase FSPM generator with different stator/rotor pole combinations, namely, 24/20, 24/22, 24/26, and 24/28. Among these combinations, the generator with the 24/22 stator/rotor pole configuration outperformed other combinations, making it an excellent choice for direct drive low-speed wind power [15]. In ref. [16], the nine-phase FSPM wind generator was proposed and investigated under two different stator-pole numbers. It indicated that the generator with 18/17 poles has the highest PM utilization, while that with 36/34 poles indicated a better cogging torque. Additionally, a comparative analysis was conducted between the twelve-phase FSPM generator presented in [15] and the nine-phase FSPM generator proposed in [17]. The research findings highlighted the exceptional capability of the twelve-phase FSPM generator to withstand overload conditions, owing to significantly enhanced voltage regulation. Furthermore, a performance evaluation was carried out to compare the twelve-phase generator with a surface-mounted PM generator in the context of low-speed wind power applications [18]. The study concluded that the twelve-phase surface-mounted PM generator exhibited superior characteristics, including lower voltage regulation, higher overload capability, and higher efficiency. On the other hand, the twelve-phase FSPM generator demonstrated improved cogging torque performance. In 2021, the outer rotor FSPM generator was proposed to improve the generator’s performance and was compared to the inner rotor (IR) FSPM generator [17]. It revealed that the IR-FSPM generator achieves higher-rated power, higher efficiency, higher magnetic flux, and lower cogging torque. In ref. [18], a design and comparative analysis of two types of FSPM generators for use in wind power generation were conducted: a counter-rotating dual-rotor FSPM generator and a co-rotating FSPM generator. The results indicated that a counter-rotating dual-rotor FSPM generator has significantly better torque capability than a co-rotating FSPMG. Subsequently, W. Ullah et al. proposed a new dual stator counter-rotation FSPMG for wind power generation [19] and compared it to its original structure with a single stator presented in [18]. It showed that the dual stator configuration exhibited significantly better torque capability and flux leakage than its conventional structure. In [20], a novel six-phase V-shaped FSPM generator specifically designed for low-speed wind power generation was introduced. The study conducted optimization of structural design parameters, including the number of rotor poles, stator inner radius, and rotor pole width, to enhance the generator’s overall performance. The results revealed that this particular generator exhibits high-power density and high efficiency, making it a highly recommended choice for the aforementioned application.

A magnetic flux barrier is a well-known technique used in PM machine design to improve the performance of such machines [21]. The principle of this approach is to enhance the magnetic flux utilization of machine structure; as a result, an enhanced power-speed profile, in addition to torque capability and lower losses, can be achieved [22–24]. In [25], the implementation of magnetic flux barriers within the rotor component of a five-phase FSPM machine was conducted. The primary objective of this study revolved around mitigating the detrimental impact of eddy-current losses. The findings demonstrated the effectiveness of the proposed configuration of magnetic flux barriers in reducing eddy-current losses by up to 55.2%, resulting from a decreased non-working harmonic air gap flux density. M. Sanada et al. performed the magnetic flux barrier for the enhancement of torque and power capabilities of PM-assisted synchronous reluctance motors (SynRMs) [26]. By optimizing the barrier shape using the symmetrical PM arrangement method, the machine’s torque and output power were shown to be improved. Katsumi Yamazaki et al. performed the differential evolution algorithm to optimize the shape of the magnetic flux barrier for PM eddy-current loss reduction in PM-assisted SynRM, showing that the optimized barrier shape worked well for the improvement of such a loss [25]. An installation of magnetic flux barriers in other synchronous PM machines for loss reduction purposes
has been widely demonstrated [23,26,27]. M. Naseh et al. [28] utilized the magnetic flux barriers with shape optimization using the Taguchi method to improve the torque, torque ripple, and total harmonic distortion (THD) of PM-assisted SynRM [29]. Utilization of magnetic flux barriers with the optimization of its configuration through the response surface (RS) method to achieve the torque enhancement in the rotor FSPM machine was demonstrated in [30]. The results showed that an optimized shape of barriers could yield significant enhancement of electromagnetic torque. In addition, applications of magnetic flux barriers to improve the torque capability of interior PM machines were demonstrated. In [31], a study proposed four different types of flux barriers aimed at enhancing the torque performance of interior PM machines. The research findings revealed that the triangular barrier shape, positioned at the ends of the magnets, exhibited the lowest torque ripple and reduced cogging torque. K. Ishikawa et al. [32] introduced an optimization method for designing the shape of magnetic flux barriers, with a focus on improving torque performance. The results demonstrated that the implementation of magnetic flux barriers using this optimization approach resulted in a significant enhancement in torque and cogging torque [33]. In 2019, E. Sayed et al. conducted a comprehensive review of the utilization of magnetic flux barriers in interior PM machines. The review aimed to ascertain the potential benefits of implementing magnetic flux barriers, including improvements in electromagnetic torque, torque ripple, cogging torque, efficiency, and manufacturing cost [34]. It was demonstrated in [35] that optimizing the placement of magnetic flux barriers in PM machines can lead to improvements in torque ripple, cogging torque, and torque waveform. Furthermore, Y. Li et al. demonstrated that the utilization of magnetic flux barriers not only increases the torque magnitude of consequent-pole FSPM machines but also improves their overall efficiency [36]. Subsequently, the implementation of airspace flux barriers was shown to enhance the torque. While there is an abundance of literature on the implementation of magnetic flux barriers to enhance the performance of PM machines, their utilization for PM generator purposes has not been reported yet.

In this context, the main contributions of this work are, firstly, modeling and optimal design of the magnetic flux barriers to improve the performance of the nine-phase FSPM generator. To the best of our knowledge, a study on the optimization of magnetic flux barriers to achieve enhanced performance specifically for PM generators has not been reported to date and is thoroughly investigated for the first time in this work. Secondly, the electromagnetic performance indicators of the optimized structure are analyzed and compared to those of a conventional structure. Thirdly, a comparison of the performance of the optimized structure to existing PM generators is made.

2. Topology Selection

The conventional structure employed in this study is the nine-phase C-core 18-stator/37-rotor pole FSPM generator, which is well suited for low-speed wind power generation, as shown in Figure 1a. The conventional generator comprises PMs sandwiched between a C-shaped lamination stator core, with each pole being wound by an armature winding. When analyzing the field distribution of this structure, it is observed that the magnetic field circulation extends excessively into the rotor’s inner diameter. This aspect is impeding the utilization of the magnetic field and requires improvement. To enhance the performance of the generator, an improved version of the conventional FSPM generator was developed by the insertion of magnetic flux barriers in its rotor with three different topologies, namely, \( |- \)-shaped, T-shaped, and \( \perp \)-shaped, as depicted in Figure 1b–d, respectively. These barrier topologies were designed and expected to improve magnetic flux utilization, which further leads to an improvement in the power-generating capability. The \( |- \)-shaped barriers are installed at the inner rotor section aligned with the rotor pole, and as a result, the number of \( |- \)-shaped barriers was equal to the rotor pole number. Meanwhile, the T-shaped and \( \perp \)-shaped barriers are inserted at the inner rotor, and the number of these barrier topologies was set to 18 by taking the number of magnetic field circulation loops into account. Despite the installation of flux barriers, all machines are operated based on the flux-switching principle.
Meanwhile, the T-shaped and ⊥-shaped barriers are inserted at the inner rotor, and the number of these barrier topologies was set to 18 by taking the number of magnetic field circulation loops into account. Despite the installation of flux barriers, all machines are operated based on the flux-switching principle. To select the highest-performing geometry of flux barriers in this study, the preliminary results of the proposed FSPM generators with 1 mm thickness flux barriers are compared. This investigation considers the magnitude of EMF and cogging torque, as they have significant implications for the power generation capacity and quality of wind generators. The EMF is closely associated with the efficiency and effectiveness of power generation, while the cogging torque plays a crucial role in the starting performance of PM generators. Table 1 compares the EMF and cogging torque of four machines, i.e., conventional, |-shaped, T-shaped, and ⊥-shaped barriers FSPM generators. It clearly shows that the FSPM generators with the insertion of |-shape barriers have the smallest cogging torque with a high EMF value. This structure is therefore the most capable for low-speed wind power generation and is chosen for further optimization of flux barrier geometry. The main machine specifications of the conventional and the proposed |-shaped barrier FSPM generators are listed in Table 2.

Figure 1. Topologies of the nine-phase C-core 18-stator/37-rotor pole FSPM generators. (a) Conventional structure. (b) |-shaped barrier FSPM generator. (c) T-shaped barrier FSPM generator. (d) ⊥-shaped barrier FSPM generator.
### Table 1. Comparison EMF and coggging of the FSPM generators with different topologies of flux barriers.

<table>
<thead>
<tr>
<th>Indicators (Unit)</th>
<th>Conventional</th>
<th>1-Shaped</th>
<th>T-Shaped</th>
<th>⊥-Shaped</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMF (V&lt;sub&gt;rms&lt;/sub&gt;)</td>
<td>228.41</td>
<td>228.38</td>
<td>227.68</td>
<td>226.98</td>
</tr>
<tr>
<td>Cogging torque (N·m&lt;sub&gt;p-p&lt;/sub&gt;)</td>
<td>0.16</td>
<td>0.128</td>
<td>0.179</td>
<td>0.129</td>
</tr>
</tbody>
</table>

### Table 2. Dimension of the conventional and the optimal 1-shaped barrier FSPM generators.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Conventional</th>
<th>1-Shaped</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phases</td>
<td>phase</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Number of stator pole</td>
<td>pole</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Number of rotor pole</td>
<td>pole</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Lamination length</td>
<td>mm</td>
<td>148</td>
<td></td>
</tr>
<tr>
<td>Stator outer radius</td>
<td>mm</td>
<td>130.8</td>
<td></td>
</tr>
<tr>
<td>Rotor outer radius</td>
<td>mm</td>
<td>110.38</td>
<td></td>
</tr>
<tr>
<td>Rotor inner radius</td>
<td>mm</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Stator pole arc</td>
<td>degree</td>
<td>2.625</td>
<td></td>
</tr>
<tr>
<td>Air gap length</td>
<td>mm</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>PM type</td>
<td>-</td>
<td>NdFeB</td>
<td></td>
</tr>
<tr>
<td>Remanence of PM</td>
<td>T</td>
<td>1.2</td>
<td></td>
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<tr>
<td>PM arc</td>
<td>degree</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>PM length</td>
<td>mm</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>Rotor pole arc</td>
<td>degree</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>Rotor yoke arc</td>
<td>degree</td>
<td>6.825</td>
<td></td>
</tr>
<tr>
<td>Rotor pole height</td>
<td>mm</td>
<td>15.41</td>
<td></td>
</tr>
<tr>
<td>Cut delta length</td>
<td>mm</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Stator yoke</td>
<td>mm</td>
<td>4.57</td>
<td></td>
</tr>
<tr>
<td>Number of turns per phase</td>
<td>turn</td>
<td>168</td>
<td></td>
</tr>
<tr>
<td>Shaft material</td>
<td>-</td>
<td>Non-magnetic</td>
<td></td>
</tr>
<tr>
<td>Rated speed</td>
<td>mm</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Flux barrier height, h&lt;sub&gt;fb&lt;/sub&gt;</td>
<td>mm</td>
<td>-</td>
<td>15.86</td>
</tr>
<tr>
<td>Flux barrier thickness, t&lt;sub&gt;fb&lt;/sub&gt;</td>
<td>mm</td>
<td>-</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### 3. Flux Barrier Design and Optimization

#### 3.1. Design of Flux Barrier

The proposed rotor topology, with magnetic flux barriers inserted, is shown in Figure 2. 1-shaped flux barriers were installed at the inner rotor section aligned with the rotor pole. The number of flux barriers is determined based on the flux circulation loop of the conventional structure, which is 37. This rotor topology is specifically designed to improve the utilization of the magnetic field and mitigate flux leakage by improving the pattern of the magnetic field circulation loop. Improved utilization of the magnetic field can lead to enhanced output power and reduced cogging torque, both of which are critical factors for wind power generation. To achieve the highest machine performance, the geometry of the flux barrier parameters is designed by adjusting their design, including the barrier height, h<sub>fb</sub>, and thickness, t<sub>fb</sub>, as defined in Figure 2. The optimization procedure is detailed in Section 3.2.

#### 3.2. Optimization of 1-Shaped Flux Barrier Using Response Surface Methodology

In this context, two design parameters of magnetic flux barriers, h<sub>fb</sub> and t<sub>fb</sub>, were optimized using the RS methodology. This method was chosen because it is particularly effective in solving problems that involve only a few design parameters. This is due to the clear relationship that exists between the decision variables [37]. As for a wind generator, the objective functions should be set to maximize the generated EMF while minimizing cogging torque. Increasing the EMF leads to a higher power-generating capability, while cogging torque plays an important role in starting performance, especially in low-speed wind power generation.
The RS method is a statistically based and efficient approach capable of examining the parameters that impact a response or objective function. Its primary objective is to obtain the optimal combination of input parameters to achieve the best value of the response variable. In addition, it can reduce the number of experiments required while exploring the interaction between the effective design parameters [38]. Therefore, the second-order regression model of RS is used to find the optimal values of $h_{fb}$ and $t_{fb}$, as given by Equation (1).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} X_i X_j$$ \hspace{1cm} (1)$$

where $Y$ is the corresponding response variable; $\beta_0$, $\beta_i$, and $\beta_{ij}$ are the regression coefficients; $\beta_{ii}$ is coefficients of terms, which is the square of the variable itself; $\beta_{ij}$ is the coefficients of product term of two different variables; and $X_i$ and $X_j$ are the design variables. Figure 3 illustrates the flowchart that outlines the design process utilizing the RS methodology.

During the optimization process, the range of design variables is specified to cover the region that would enable the highest generator performance as detailed in Table 3. Figure 4 displays the contour and surface plots of the EMF and cogging torque, $T_{cogging}$, as functions of $h_{fb}$ and $t_{fb}$. The results show that the magnitude of EMF is mainly dependent on $h_{fb}$, with only slight variations in $t_{fb}$. Additionally, it is found that changing the flux barrier geometry has only a small impact on EMF. On the other hand, cogging torque is primarily dependent on the thickness of the flux barriers, rather than their height. The analysis demonstrates that increasing $h_{fb}$ beyond 30 mm leads to a reduction in EMF, while increasing $t_{fb}$ beyond 1.25 mm results in a rapid worsening of cogging torque. However, by appropriately setting $t_{fb}$, cogging torque can be significantly reduced. Findings clearly indicate that the optimal values for $h_{fb}$ and $t_{fb}$ in our wind generator are 15.86 mm and 1 mm, respectively, as they most effectively achieve the objective functions for the wind generator considered in this study.

![Figure 2](image-url)  
**Figure 2.** Topology and design parameters of |-shaped flux barrier.

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of flux barrier, $h_{fb}$ (mm)</td>
<td>15–40</td>
</tr>
<tr>
<td>Thickness of flux barrier, $t_{fb}$ (mm)</td>
<td>0.5–1.5</td>
</tr>
</tbody>
</table>
Figure 3. A flowchart illustrating the design sequence using RS methodology.

Figure 4. (a) Surface plots and (b) contour plots of the EMF and cogging torque as a function of $h_{fb}$ and $t_{fb}$.
mm, respectively, as they most effectively achieve the objective functions for the wind generator considered in this study.

Table 3. Range of design parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of flux barrier, ( h_{fb} ) (mm)</td>
<td>15 – 40</td>
</tr>
<tr>
<td>Thickness of flux barrier, ( t_{fb} ) (mm)</td>
<td>0.5 – 1.5</td>
</tr>
</tbody>
</table>

Figure 4. (a,b) Surface plots and (c,d) contour plots of the EMF and cogging torque as a function of \( h_{fb} \) and \( t_{fb} \).  

4. Electromagnetic Performance Comparison

This section analyzes the electromagnetic performance of the proposed FSPM generator, which has been optimized with the insertion of a flux barrier. The analysis was conducted using 2D finite element (FE) analysis under both no-load and on-load conditions and compared to the performance of the conventional structure. A comparison was made at a rated speed of 500 rpm, with identical copper loss. The no-load performance indicators examined include PM flux-linkage, EMF, and cogging torque. Meanwhile, on-load indicators including electromagnetic torque, output power, loss, and efficiency were also analyzed.

4.1. No-Load Performance

4.1.1. PM Flux Line Distribution

The magnetic field distribution in a PM machine’s structure is a critical factor that affects its performance. Figure 5a–d display the \( d \)-axis no-load flux distribution profile of the conventional and proposed structures. It is worth noting that the color bar scale of Figure 5c,d has been specifically adjusted to enhance the distinction between them. The figures reveal that the installation of a barrier pushes the PM flux circulation in the rotor to a region closer to the air gap, indicating that the utilization of PMs is improved. This shift in the magnetic field circulation pattern is a direct consequence of the increased reluctance of the rotor yoke caused by the presence of the barriers. Furthermore, the magnetic flux concentration at the air gap decreases after installing the flux barriers, leading to a reduction in cogging torque. The above observation suggests the superior performance of the proposed FSPM generator.

4.1.2. Open-Circuit PM Flux-Linkage and Electromotive Force

The waveforms of open-circuit PM flux-linkage of the conventional and proposed generators are depicted in Figure 6. It is seen that the insertion of magnetic flux barriers slightly enhances the PM flux-linkage scale. Analysis of the EMF profile of both structures is shown in Figure 7, demonstrating that the proposed structure has a slightly higher EMF magnitude than the conventional structure. In addition, the spectrum corresponding to the EMF profile is shown in Figure 7b. It demonstrates that the proposed structure contains slightly lower THD than the conventional one, which implies its better quality of generating waveforms.
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Figure 5. Open-circuit field flux distribution of (a,c) the conventional and (b,d) proposed FSPM generators.

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Figure 6. PM flux linkage waveforms of the conventional and proposed FSPM generators.

4.1.3. Cogging Torque

The cogging torque profile, which typically plays an important role in starting performance and low-speed operation of wind turbines, is analyzed, as shown in Figure 8. The pattern of the cogging torque of the proposed structure remains the same as the conventional structure since they have a similar pole topology. In particular, the magnitude of the proposed structure's cogging torque is 0.122 N·m, which is 23.7% lower than 0.16 N·m of the conventional value. This indicates that the insertion of flux barriers has a strong impact on the cogging torque profile of this machine. The significant reduction in cogging torque in the proposed generator is due to a reduced magnetic field concentration at the air gap, as previously observed in Section 4.1.1. As a result, the small cogging of the proposed generator implies its superior performance for low-speed wind power generation.

Figure 8. The Cogging torque waveforms of the conventional and proposed FSPM generators.
Figure 6. PM flux linkage waveforms of the conventional and proposed FSPM generators.

Figure 8. The Cogging torque waveforms of the conventional and proposed FSPM generators.

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Figure 8. The Cogging torque waveforms of the conventional and proposed FSPM generators.

4.2. On-Load Performance

To assess the performance of the proposed generator under on-load conditions, the external rated resistive loads were connected to the generators while analyzing their performance. The proposed generator’s performance was compared to those of the conventional structure at the same rated speed of 500 rpm. A constraint was imposed to ensure that the copper loss of both structures is identical, with the value carefully selected to avoid any overheating problems.

4.2.1. Electromagnetic Torque

The electromagnetic torque waveforms of the conventional and proposed FSPM generators are shown in Figure 9. The proposed generator is found to exhibit a higher average torque than the conventional structure. Furthermore, a lower torque ripple is observed in the proposed generator. The significantly lower fringing fluxes near the rotor pole due to the barrier of the proposed structure were found to be the main reason for its low cogging torque.
10th harmonic orders played a significant role in generating PM eddy-current losses, both with |-shaped flux barriers having better overall performance than the conventional generator. Comparison electromagnetic performance at 500 rpm.

Table 4. Parameters (Unit) Conventional Proposed
EMF (Vrms) 228.41 228.41
Cogging torque (N·mpeak) 0.160 0.122
Rated current (A) 3.5
Output voltage (Vrms) 170.61 171.40
Average torque (N·m) 110.46 110.96
Torque ripple (%) 0.18 0.13
Output power (W) 5374.06 5399.23
Core loss (W) 129.74 129.05
Copper loss (W) 155.95
Eddy-current loss (W) 17.17 8.37
Efficiency (%) 94.51 94.70

4.2.2. Losses and Efficiency

The overall performance indicators for both the conventional and proposed FSPM generators are listed in Table 4. It was found that the FSPM generator with |-shaped flux barriers produced higher output power than the conventional generator, with a maximum of 5399.23 W. The proposed FSPM generator had slightly lower core loss than the conventional structure due to its lower weight of lamination core. Furthermore, a significant decrease in PM eddy-current loss after inserting flux barriers was observed. To explain this decrease, the on-load air gap flux density including its spectral profile was analyzed, as shown in Figure 10. It shows that the generator's harmonic spectrum is altered after the installation of flux barriers. Based on the waveform of the air gap flux density, it is possible to identify the working harmonics by considering the quantity of stator slots and rotor teeth [28]. For the machine structures investigated in this work, it reveals that the 8th and 10th harmonic orders played a significant role in generating PM eddy-current losses, both of which were lowered after the installation of flux barriers. Additionally, the proposed generator has slightly higher efficiency than the conventional one. In summary, our results demonstrate that the proposed nine-phase C-core 18-stator/37-rotor pole FSPM generator with |-shaped flux barriers has better overall performance than the conventional generator and can be considered a superior choice as a generator for low-speed wind power generation.

Figure 9. Electromagnetic torque waveforms of the conventional and proposed FSPM generators.
The FSPM generator with optimized flux barriers exhibits a 23.7% reduction in cogging torque. Therefore, it clearly indicates that the proposed optimal FSPM generator with |⊥-shaped flux barriers is a structure with superior characteristics beneficial for use in low-speed wind power generation. It was discovered that the insertion of |⊥-shaped magnetic flux barriers in such a generator provided better generator performance than the other two barrier types, T-shaped and V-shaped flux barriers inserted are compared to the other existing radial-flux PM wind generators, as shown in Table 5. It reveals that the V-shaped FSPM generator being proposed has the capability to generate a power density of 678 kW/m³, which is moderate when compared to existing radial-flux PM wind generators, but it is still a significant accomplishment. Furthermore, the cogging torque of the V-shaped FSPM generator is ranked as the second smallest when compared to other wind generators currently available. Therefore, it clearly indicates that the proposed optimal FSPM generator with |⊥-shaped flux barriers is a structure with superior characteristics beneficial for use in low-speed wind power generation. This technology also has great potential for practical application in the renewable energy industry.

Table 5. A comparison of power density and cogging torque with other radial-flux PM wind generators.

<table>
<thead>
<tr>
<th>References</th>
<th>Output Power per Machine Volume (kW/m³)</th>
<th>Cogging Torque per Machine Volume (N·m_p/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed structure</td>
<td>683.0</td>
<td>15.43</td>
</tr>
<tr>
<td>[20]</td>
<td>1004.3</td>
<td>7.85</td>
</tr>
<tr>
<td>[15]</td>
<td>1004.1</td>
<td>51.49</td>
</tr>
<tr>
<td>[36]</td>
<td>939.7</td>
<td>50.20</td>
</tr>
<tr>
<td>[16]</td>
<td>768.2</td>
<td>1229.14</td>
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<tr>
<td>[39]</td>
<td>692.6</td>
<td>74.66</td>
</tr>
<tr>
<td>[40]</td>
<td>636.2</td>
<td>159.06</td>
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<td>[18]</td>
<td>606.1</td>
<td>446.56</td>
</tr>
<tr>
<td>[41]</td>
<td>432.9</td>
<td>816.11</td>
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<tr>
<td>[42]</td>
<td>217.9</td>
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</table>

5. Conclusions

This study demonstrated the implementation of magnetic flux barriers in improving the performance of a nine-phase FSPM wind generator designed for low-speed wind power generation. It was discovered that the insertion of |⊥-shaped magnetic flux barriers in such a generator provided better generator performance than the other two barrier types, T-shaped and V-shaped. The geometry of the |⊥-shaped flux barrier was further optimized using response surface methodology to maximize the generator’s performance. The FSPM generator with optimized flux barriers exhibits a 23.7% reduction in cogging torque compared to the conventional structure while maintaining flux linkage and EMF scale. An analysis of the magnetic field distribution provided physical reasoning for this cogging torque reduction as well as improved magnetic flux utilization. Furthermore, on-load analysis of the electromagnetic torque and ripple of the proposed generator showed improvement from the conventional structure. The study also demonstrated a substantial improvement from the conventional structure. The study also demonstrated a substantial
reduction in PM eddy-current loss, reaching up to 51%. This reduction was attributed to the lower non-working harmonic of the air gap flux density. The proposed generator was capable of producing an output power of up to 5399.23 W, achieving an efficiency of 94.7%. In comparison to other existing PM wind generators, this design not only exhibits a high power density but also has the second smallest cogging torque. Therefore, the proposed generator has the potential to effectively meet the demands of low-speed wind power generation.

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References


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