Eduvest – Journal of Universal Studies
Volume 6 Number 5, April, 2026
p- ISSN 2775-3735- e-ISSN 2775-3727

Optimization Of Cogging Torque in 28-Pole 24-Slot Permanent Magnet Generator

Zacky Irfan Al Farisie[1], Tajuddin Nur[2]*, Marwan Rosyadi[3], Syamsir Abduh[4]
Institut Teknologi PLN, Indonesia[1,3,4]
Universitas Katolik Atma Jaya, Indonesia[2]
Email: zacky2310090@itpln@itpln.ac.id, tans@atmajaya.ac.id*, marwanrosyadi@itpln.ac.id, syamsir@itpln.ac.id

Keywords
PLTB, permanent magnet generator, cogging torque, optimization

Abstract
This study addresses the growing demand for efficient renewable energy conversion systems, particularly in low- to medium-wind-speed regions such as Indonesia, where wind resources typically range between 4–6 m/s. Permanent magnet generators (PMGs) are widely used in wind power plants due to their high efficiency and simple structure; however, their performance is often limited by cogging torque, which causes rotational resistance, vibration, and reduced energy conversion efficiency. This research aims to analyze and optimize the reduction of cogging torque in a 28-pole, 24-slot permanent magnet generator through geometric modification techniques. The study employs a quantitative simulation approach using FEMM 4.2 software and LUA 4.0 scripting to model magnetic flux distribution and torque characteristics. The optimization process includes variations in air gap widening, magnet edge shaping, slot opening adjustment, and the addition of dummy slots. The initial design produced a cogging torque of 0.00498 Nm. After the first optimization stage, the value decreased to 0.00028 Nm, while the second optimization achieved a significant reduction to 0.00005 Nm, corresponding to a 98.99% decrease. The results demonstrate that combining magnet edge shaping with dummy slots is highly effective in minimizing cogging torque and improving flux uniformity. In conclusion, the optimized design enhances generator performance, particularly in low-speed wind applications, making it a promising solution for sustainable energy development.

INTRODUCTION

(Prakht et al., 2020) In line with the national commitment to the development of clean and sustainable energy, the National Energy Council (DEN) targets to increase the portion of renewable energy in the national energy mix to reduce dependence on fossil energy and reduce greenhouse gas emissions (Ministry of Energy and Mineral Resources, 2021). One of the renewable energy sources that has great potential to be developed is wind energy, especially through the use of Wind Power Plants (PLTB) (Farrokh & Ghaheri, 2025).

Wind Power Plants (PLTB) are one of the renewable energy alternatives that continue to grow as the need for clean and environmentally friendly energy increases. Based on BMKG data, the average wind speed in Indonesia ranges from 4–6 m/s (Secretariat General of the National Energy Council, 2023). In Indonesia, the relatively low to medium wind speed characteristics demand the use of generators that are able to produce energy efficiently at low revs. Permanent Magnet Generators (GMP) are widely chosen in PLTB systems because of their high efficiency, simple construction, and ability to work without external excitation (Dong et al., 2025).

(Vaz et al., 2018) However, GMP faced technical obstacles in the form of Cogging Torque (CT). This condition is undesirable in permanent magnet generators because CT can cause initial resistance to rotor rotation due to the interaction of magnetic forces between the rotor magnet and the stator groove, thereby inhibiting the initial rotation condition of the rotor in low-speed PLTB applications (Sayed & Erturk, 2021). This fluctuating effect of torque also causes rotor rotation to become unsmooth, reduces energy conversion efficiency, and triggers vibration and noise that can accelerate the wear and tear of mechanical components (Bansal et al., 2023). In addition, non-uniform variations in magnetic force result in less stable voltage output, which lowers the overall performance of the system. Therefore, CT needs to be reduced so that the generator can work more efficiently, stably, and have a longer operational life.

Various studies have been carried out to reduce torque cogging through geometric approaches, such as magnetic shape modification, the application of the skewing method, noCThing, slot shape modification, to the addition of dummy slots (Correia et al., 2024; Nur & Herlina, 2019; Pranjić & Virtič, 2024; Pratama & Nur, 2025). Correia's research with a 40-pole/24-groove design, the results of the study showed that the use of a two-level coaxon at the rotor magnetic tip was able to significantly reduce the CT value. Meanwhile, several other studies have utilized variations in slot opening shape and magnetic flux distribution engineering to obtain finer torque characteristics, thereby lowering CT by 99.70% (Correia et al., 2024). In the Primary Research, the permanent magnet generator (24 slots/20 poles) was optimized using the magnet shaping method and dummy slot to reduce cogging torque. The results of the analysis showed that the magnetic shaping technique itself was able to reduce torque by 53%. However, the highest efficiency is achieved through the combination of magnet shaping with rectangular dummy slots which results in a significant reduction of 99.30% (Pratama & Nur, 2025).

(Pranjic & Virtic, 2024) Because of this problem, many researchers have proposed geometric approaches to suppress cogging torque. A recent review by Pranjić and Virtič summarized state-of-the-art reduction techniques in permanent magnet machines, including skewing, slot-opening modification, pole-arc optimization, magnet shaping, and dummy-slot configurations. Other studies have confirmed that cogging torque reduction remains a central design objective because it directly affects starting capability, torque smoothness, and electromagnetic performance. This means that generator geometry is not merely a structural detail, but a decisive factor in whether wind systems can operate efficiently in real applications.

Several previous studies are particularly relevant to the present research. Nur and Herlina showed that magnet edge shaping can improve cogging-torque reduction in inset permanent magnet generators, while (Abduh et al., 2025). reported that permanent magnet generator optimization for very low wind speed could achieve about 99.3% improvement relative to the original design. The uploaded manuscript also cites Pratama and Nur, who found that magnet shaping alone reduced torque by 53%, whereas combining magnet shaping with rectangular dummy slots produced a much larger reduction of 99.30%. Together, these studies indicate that combined geometric strategies generally outperform single-parameter modification (Jamali Arand & Ardebili, 2016).

Even so, an important research gap remains. Much of the existing literature examines different slot-pole combinations, different machine topologies, or isolated optimization techniques, so the evidence cannot simply be transferred to every permanent magnet generator configuration. The uploaded article makes clear that the 28-pole/24-slot generator still exhibited an initial peak cogging torque of 0.00498 Nm, meaning that this specific fractional-slot arrangement required further optimization (Öztürk et al., 2017). In other words, although the literature already offers several reduction methods, the best geometry sequence for a 28-pole/24-slot permanent magnet generator in low-speed wind applications has not yet been sufficiently established.

This gap creates strong research urgency. Wind turbines operating at low rotational speed are particularly sensitive to starting resistance, and even relatively small torque ripple can degrade start-up behavior and overall energy capture. The manuscript therefore frames cogging-torque suppression not only as a matter of electromagnetic refinement, but as a practical requirement for improving initial rotation capability, operating stability, and suitability for Indonesian wind characteristics. Given the rapid expansion of renewable deployment worldwide and Indonesia's continuing transition targets, optimizing generator performance at the machine-design level becomes both scientifically necessary and operationally important (Kana Padinharu et al., 2022).

The novelty of this research lies in the integrated optimization of a 28-pole/24-slot permanent magnet generator through the combined adjustment of air-gap widening, magnet edge shaping, slot opening, and dummy-slot addition. Rather than stopping at a single modification, the study evaluates a staged design pathway using FEMM 4.2 and LUA-based numerical modeling to identify which combination produces the most meaningful reduction in cogging torque. This is important because prior studies have shown the value of individual and combined strategies, yet this manuscript applies them specifically to a fractional-slot generator intended for low- and medium-wind-speed operation in the Indonesian context (Wang & Zhang, 2024).

(Bayor et al., 2018) Based on that novelty, the purpose of the study is to analyze and optimize magnet and slot-opening design so that cogging torque can be reduced to at least 98% from the initial condition (Husain et al., 2019). The manuscript states that the initial model serves as the reference case and that successive optimization steps are evaluated through magnetic-flux distribution and torque simulation. Accordingly, the main objective is not only to prove that geometric modification works, but also to determine the most effective configuration for improving starting performance and electromagnetic smoothness in a 28-pole/24-slot permanent magnet generator.

The expected contribution of this research is both theoretical and practical. Theoretically, it enriches the growing body of knowledge on cogging-torque minimization by testing a specific multi-parameter optimization sequence on a fractional-slot generator configuration. Practically, it offers a design reference for developing more efficient and stable generators for wind power plants in regions with modest wind speed, helping engineers improve start-up behavior, reduce mechanical stress, and support cleaner electricity generation. For that reason, the benefits of this study extend beyond one prototype, as the findings may guide future generator design, renewable-energy implementation, and follow-up research on electromagnetic optimization for wind systems.

METHOD

GMP Initial Design Structure

To determine the GMP design, it is necessary to pay attention to Slots per pole per phase (SPP) is the main parameter in the design of an electric machine that shows the ratio of the number of stator slots (s) to the number of poles (p) and the number of phases (a) where the output of the GMP voltage is 3 phasas, expressed in equation (1) (Jarso & Nallamothu, 2025).

$$SPP = \frac{s}{p\ x\ a} = \frac{24}{28\ x\ 3} = 0{,}28$$

Based on the calculations above, this study includes using a fractional design because the SPP value = 0.28. The fractional design is suitable for PLTB applications which are effective in lowering the cogging torque, but can cause sub-harmonics in the electromagnetic field (Jarso & Nallamothu, 2025).

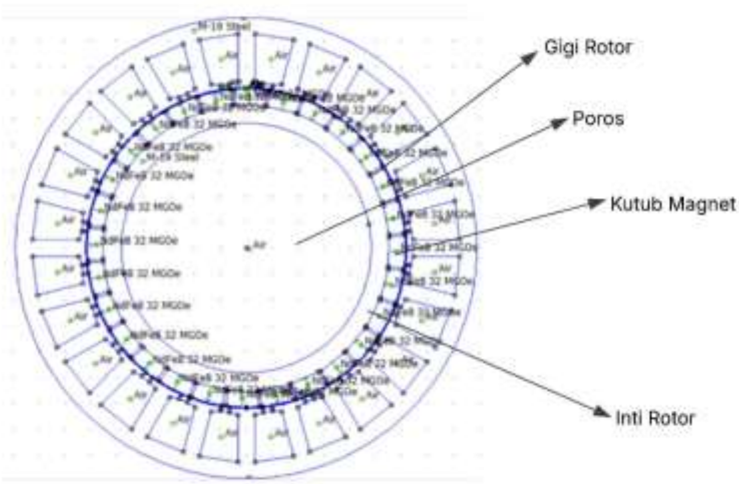

Figure 1. GMP Early Design

The initial design of the generator, in figure 1, has not applied artificial stator tooth grooves or magnetic tip trimming. The height of the stator teeth is set at 17.93 mm with a stator tooth width of 6.41 mm and the height of the stator shoe teeth 1.75 mm. The width of the air gap in this design is 0.60 mm. The permanent magnet has a magnetic tip height of 6.00 mm, a center magnet height of 6.30 mm, and a magnetic width of 11.44 mm.

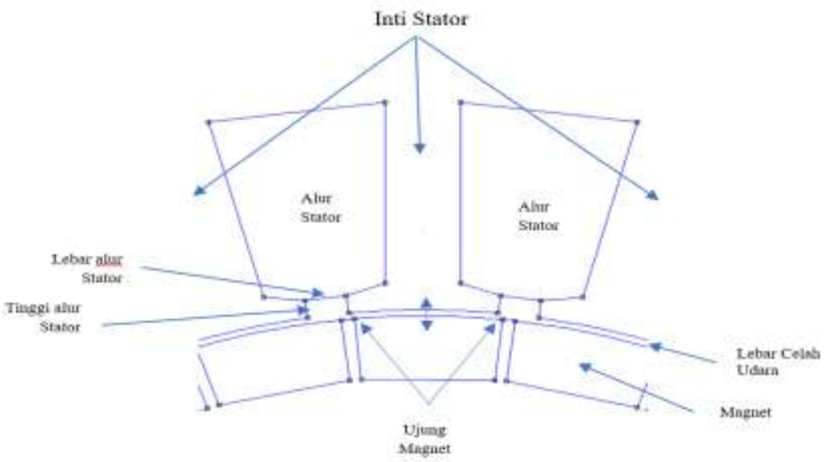

Figure 2. Stator and Rotor on GMP

In Figure 2 above, the stator-rotor image shows the configuration of the stator core, the stator groove, the permanent magnet, and the air gap as the main path of magnetic flux distribution. The geometric parameters analyzed include the width and height of the stator grooves, the width of the air gap, as well as the shape of the magnetic tip that interacts directly with the stator teeth. These interactions cause variations in the reductance of the air gap that trigger the occurrence of CT in the permanent magnet generator, so this design is used as a prerequisite before the geometry optimization process is carried out.

RESULT AND DISCUSSION

Initial Design

In Figure 6. The initial design of the 28-pole, 24-slot permanent magnet generator is demonstrated through the magnetic flux density distribution of the FEMM simulation. The flux distribution is still uneven, particularly in the air gaps and the tips of the stator teeth, which are characterized by high flux concentrations in certain areas. The maximum flux density value reached about 1.52 T, while some other areas were still at low flux levels. The result of the CT value in the initial design was quite high in the range of 0.00498 Nm, This condition shows a significant variation in reluctance between the rotor and the stator, so that it has the potential to produce a relatively large cogging torque in the initial design. Therefore, this design is used as a basic reference before the optimization process to improve the uniformity of the flux distribution and lower CT.

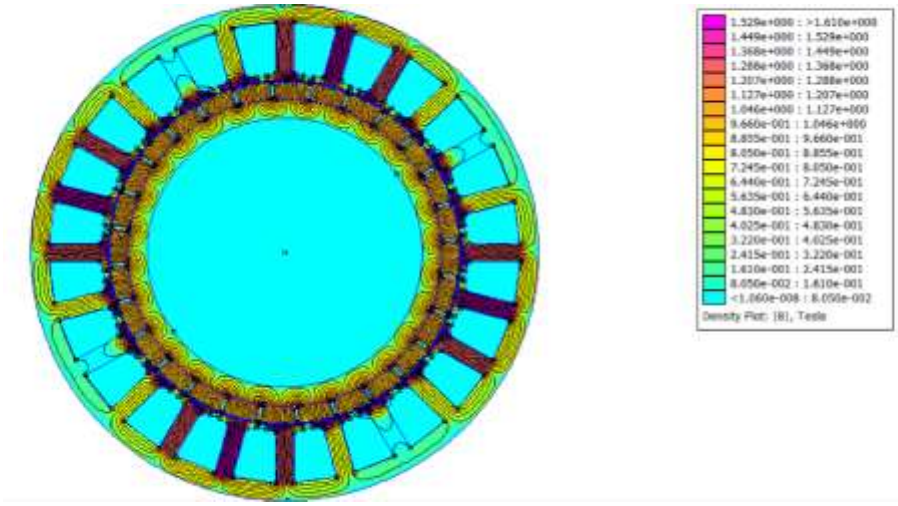

Figure 3 Initial Design Flux Distribution

Effect of Air Gap Widening Magnet Edge Shaping, and Slot Opening on GMP

In figure 4. optimization design 1, which applies air gap widening and magnetic edge shaping, and adjustment of the opening slot from 3.5 mm to 2.0 mm wide, the advantage is that the CT value results are smaller than the initial design, the range of 0.00028 Nm and the distribution of magnetic flux in the air gap becomes more even, so that the flux concentration at the tip of the stator teeth and the magnetic edge is reduced, the maximum flux density value decreases compared to the initial design and is in the range of 0.88 T, which has an impact on reducing local saturation as well as reducing cogging torque compared to the initial design. In addition, the variation in reluctance between the rotor and the stator can be suppressed so that the initial rotation performance of the generator is better.

Effect of Air Gap Widening Magnet Edge Shaping, and Slot Opening on GMP

In figure 4. optimization design 1, which applies air gap widening and magnetic edge shaping, and adjustment of the opening slot from 3.5 mm to 2.0 mm wide, the advantage is that the CT value results are smaller than the initial design, the range of 0.00028 Nm and the distribution of magnetic flux in the air gap becomes more even, so that the flux concentration at the tip of the stator teeth and the magnetic edge is reduced, the maximum flux density value decreases compared to the initial design and is in the range of 0.88 T, which has an impact on reducing local saturation as well as reducing cogging torque compared to the initial design. In addition, the variation in reluctance between the rotor and the stator can be suppressed so that the initial rotation performance of the generator is better.

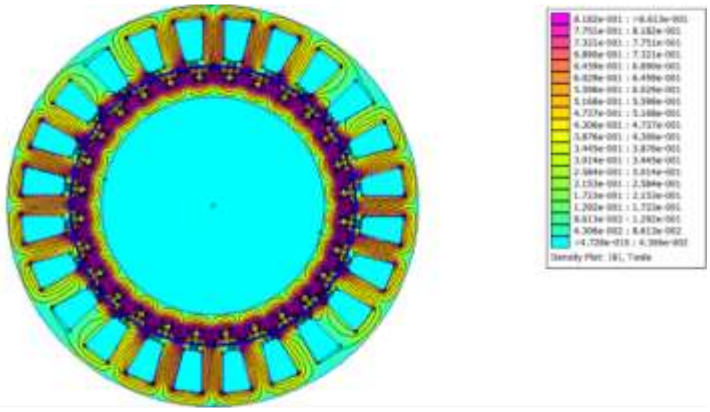

Figure 4. Flux Distribution Design Optimization 1

However, the disadvantage of this optimization is that the maximum flux density value tends to decrease due to the widening of the air gap, so that it has the potential to reduce the total electromagnetic torque if it is not compensated with a suitable magnetic or current design, and the periodic reductance fluctuations are still not fully reduced due to the absence of the addition of dummy slots to the stator.

Effect of Air Gap Widening Magnet Edge Shaping, Slot Opening and Dummy Slot on GMP

In Figure 8. The application of air gap widening (air gap), magnetic edge shading (Magnet Edge Shaping), slot opening adjustment, and the addition of dummy slots to the stator teeth provide a significant improvement in the uniformity of the magnetic flux distribution in permanent magnet generators.

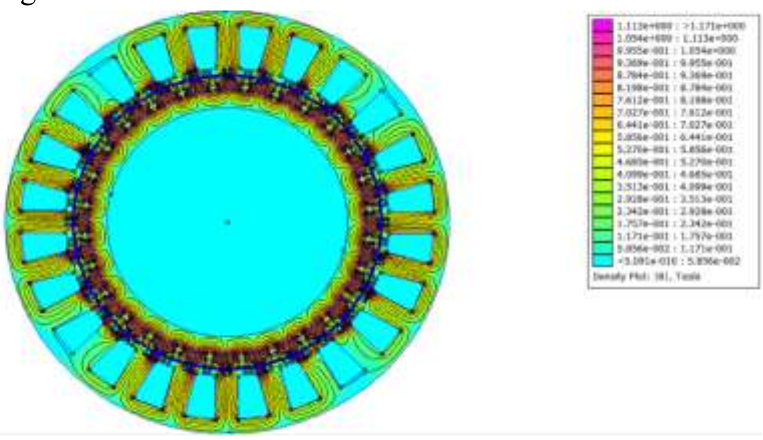

Figure 5 Flux Distribution Design Optimization 2

The simulation results show that the magnetic flux in the air gap becomes more homogeneous with a decrease in the concentration of flux at the tip of the stator tooth and the magnet–stator meeting area. The result of the CT value in the optimization design 2 is in the range of 0.00005 Nm, which is quite optimal and the maximum flux density value is in the range of 1.11 T, which is still within the safe limit of the core material and shows reduced local saturation. The addition of dummy slots plays a role in reducing periodic variations in reluctance, so that the fluctuations of the magnetic force between the rotor and the stator are smaller. This condition directly contributes to a more optimal reduction in torque cogging compared to the initial design and optimization 1.

To find out the CT% value with a reduction target of at least 98%, a comparative analysis of the cogging torque value between optimization design 1 to the initial design, and optimization design 2 to the initial design was conducted. The calculation of CT% is carried out using a predetermined equation, by comparing the maximum cogging torque value produced by each design. Torque cogging data is obtained through simulations with variations in rotor angles in the range of 0° to 25°, where at each angle a torque value is generated that can have a positive or negative value due to the direction of the opposite magnetic force. In the evaluation process, the value of cogging torque is treated as an absolute value, so positive and negative signs are ignored and only the amount of torque is the focus of the analysis.

Furthermore, from all the data in the angle range, the largest torque cogging value was selected as a representation of the torque cogging characteristics of each design. The CT% value obtained reflects the success rate of the optimization method in lowering the cogging torque, where the closer it is to 100%, the greater the cogging torque reduction achieved. Thus, the high CT% value indicates that the generator design has better performance, especially in improving the initial rotation capability and operating performance at low speeds.

Initial Design, Optimization Design 1 and Optimization

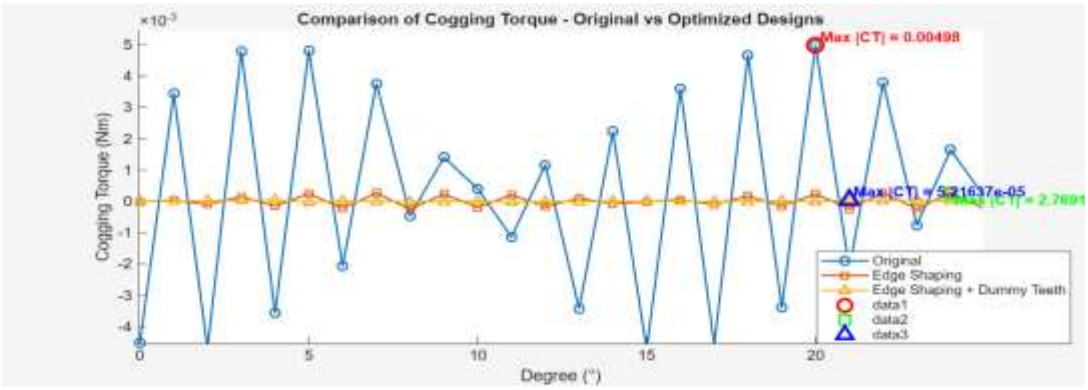

Figure 6. CT Comparison Graph on Initial Design, Optimization Design 1, and Optimization Design 2

In Figure 6. Based on the results of the simulation of torque cogging in the angle range of 0°–25°, the initial design showed large torque fluctuations with an absolute maximum value of 0.00498 Nm. After the application of optimization 1 (edge shaping), the amplitude of cogging torque decreased significantly with an absolute maximum value of 0.00028 Nm, which showed an improvement in magnetic flux distribution and a decrease in reductance variation. Furthermore, in optimization 2 (edge shaping + dummy slot) the best results were obtained, with the maximum absolute cogging torque value of only 0.00005 Nm. The addition of dummy slots proved to be effective in reducing periodic reluctant fluctuations between rotors and stators, resulting in the most optimal cogging torque reduction and improving the performance of the generator's initial rotation.

For the calculation of optimization design 1 with the initial design below:

$$CT1\ (\%) = 100\% - \left(\frac{CT_2}{CT_1}\ x\ 100\%\right)$$

$$CT_1\ (\%) = 100\% - \left(\frac{0{,}00028}{0{,}00498}\ x\ 100\%\right) = 94.37\%$$

The CT% value obtained is still below the minimum limit of the study, so further optimization is needed. Therefore, the analysis was focused on the comparison between the optimization design 2 and the initial design to increase the CT value.

$$CT2\ (\%) = 100\% - \left(\frac{CT_2}{CT_1}\ x\ 100\%\right)$$

$CT_2\ (\%) = 100\% - \left(\frac{0.00005}{0,00498}\ x\ 100\%\right)$ = 98.99%

The CT% value obtained has exceeded 98%, which is in the range of 98.99%, indicating that the optimization process carried out has been significantly successful in reducing torque cogging. The comparison between the optimization design 2 and the initial design confirms that the geometric modifications applied are able to improve the performance of the generator, especially in improving the ability of initial rotation and operation at low speeds.

CONCLUSION

Based on the results of numerical modeling and simulation using FEMM 4.2 on the GMP design of 28 poles and 24 slots, several conclusions were obtained as follows:

GMP with a 28-pole and 24-slot configuration in the initial design resulted in an absolute maximum cogging torque value of 0.00498 Nm, which is still relatively high for low-speed Wind Power Plant (PLTB) applications. The application of optimization 1, which includes air gap widening and Magnet Edge Shaping, and slot opening adjustment, is able to reduce the maximum cogging torque to 0.00028 Nm with a reduction value of 94.37%. However, these results have not met the minimum research target of 98% (Venkatesh et al., 2025).

Optimization 2, which combines air gap widening and Magnet Edge Shaping, slot opening, and addition of dummy slots, provides the most optimal results with a maximum cogging torque value of 0.00005 Nm. The CT% value produced in optimization 2 reached 98.99%, thus exceeding the research target and showing the success of the optimization method in significantly reducing cogging torque. The addition of dummy slots has been shown to be effective in reducing periodic variations in reluctance between rotors and stators and smoothing out the distribution of magnetic flux in air gaps.

Overall, the optimization design 2 is able to improve the initial rotation capability and stability of generator operation, so it is considered feasible to be applied to PLTB systems with low to medium wind speed characteristics.

REFERENCES

Abduh, S., Karunanithi, S., & Nur, T. (2025). Analysis of the Cogging Torque Reduction in Permanent Magnet Generators for a Very Low Wind Speed. *Energies*, *18*(11), 1–22. https://doi.org/10.3390/en18112802

Bansal, R., Marwaha, S., & Verma, C. (2023). Cogging Torque Minimization of PMBLDC Motor for Application in Battery Electric Vehicle. *Journal of Electrical Engineering and Technology*, *18*(3), 1733–1743. https://doi.org/10.1007/s42835-022-01322-w

Bayor, S. W., Kodjo, M. K., Salami, A. A., & Kpogli, K. A. (2018). Simulation of the Magnetic Field in Electric Machines by the Finite Element Method under FEMM 4.2: Case of a Definition of Short Circuit Defect between Spiers. *International Journal of Engineering Research and Applications*, *7*(11), 30–39.

Correia, L. A., Nur, T., Pandjaitan, L., & Herlina, H. (2024). Analisis Pengaruh Teknik Coakan Dua Langkah terhadap Penurunan Torka Cogging terhadap Pergeseran Poros pada Mesin Magnet Permanen. *ELKOMIKA: Jurnal Teknik Energi Elektrik, Teknik Telekomunikasi, & Teknik Elektronika*, *12*(4), 1007. https://doi.org/10.26760/elkomika.v12i4.1007

Dong, W., Sun, H., Hua, C., & Yang, H. (2025). Wind Power Generation System and Its Wind Alignment Regulation Based on Feedforward Control. *Energy Reports*, *13*, 2555–2564. https://doi.org/10.1016/j.egyr.2025.01.061

Farrokh, F., & Ghaheri, A. (2025). Robust Hybrid Optimization Design for Axial Flux-Switching Transverse-Flux Permanent Magnet Wind Generator. *Results in Engineering*. https://doi.org/10.1016/j.rineng.2025.107124

Husain, T., Hasan, I., & Sozer, Y. (2019). Cogging torque minimization in transverse flux machines. *IEEE Transactions on Industry Applications*, *55*(1), 385–397. https://doi.org/10.1109/TIA.2018.2868541

Jamali Arand, S., & Ardebili, M. (2016). Cogging Torque Reduction in Axial-Flux Permanent Magnet Wind Generators with Yokeless and Segmented Armature by Radially Segmented and Peripherally Shifted Magnet Pieces. *Renewable Energy*, *99*, 95–106. https://doi.org/10.1016/j.renene.2016.06.054

Jarso, G. C., & Nallamothu, R. B. (2025). Strategic slot-pole optimization in electromagnetic coupling with random forest regressor model. *Results in Engineering*, *27*, 105640. https://doi.org/10.1016/j.rineng.2025.105640

Kana Padinharu, D. K., Li, G. J., Zhu, Z., Azar, Z., Clark, R., & Thomas, A. (2022). Effect of Airgap Length on Electromagnetic Performance of Permanent Magnet Vernier Machines with Different Power Ratings. *IEEE Transactions on Industry Applications*, *58*(2), 1920–1930. https://doi.org/10.1109/TIA.2021.3135256

Nur, T., & Herlina. (2019). Enhancement of Cogging Torque Reduction. *ICECOS Conference*. https://doi.org/10.1109/ICECOS.2018.8605247

Öztürk, N., Dalcalı, A., Çelik, E., & Sakar, S. (2017). Cogging Torque Reduction by Optimal Design of PM Synchronous Generator for Wind Turbines. *International Journal of Hydrogen Energy*, *42*(28), 17593–17600. https://doi.org/10.1016/j.ijhydene.2017.02.093

Prakht, V., Dmitrievskii, V., Kazakbaev, V., & Ibrahim, M. N. (2020). Comparison between Rare-Earth and Ferrite Permanent Magnet Flux-Switching Generators for Gearless Wind Turbines. *Energy Reports*, *6*, 1365–1369. https://doi.org/10.1016/j.egyr.2020.11.020

Pranjić, F., & Virtič, P. (2024). Cogging Torque Reduction Techniques in Axial Flux Permanent Magnet Machines: A Review. *Energies*, *17*(5). https://doi.org/10.3390/en17051089

Pranjic, F., & Virtic, P. (2024). Cogging Torque Reduction Techniques in Axial Flux PM Machines. *Energies*, *17*(5). https://doi.org/10.3390/en17051089

Pratama, Y. N., & Nur, T. (2025). Optimization of Cogging Torque in a Permanent Magnet Generator Using Magnet Shaping and Stator Dummy Slot Methods for a 10 KWP Wind Power Plant. *Syntax Literate: Jurnal Ilmiah Indonesia*, *10*(12), 12659–12676.

Sayed, A. El, & Erturk, E. (2021). Minimizing Cogging Torque in Permanent Magnet Synchronous Generators for Small Wind Turbine Applications. *International Journal of Renewable Energy Research*, *11*(2).

Vaz, J. R. P., Wood, D. H., Bhattacharjee, D., & Lins, E. F. (2018). Drivetrain Resistance and Starting Performance of a Small Wind Turbine. *Renewable Energy*, *117*, 509–519. https://doi.org/10.1016/j.renene.2017.10.071

Venkatesh, G., Vijaya Chandrakala, K. R. M., Kumari, P., Saravanan, S., Balamurugan, S., & Ratheesh, P. (2025). Enhanced Power Density and Energy-Efficient High-Speed Permanent Magnet Starter-Generator Using Multi-Physics Optimization Strategies for Future Electric Aircraft. *Results in Engineering*. https://doi.org/10.1016/j.rineng.2025.107216

Wang, Y., & Zhang, G. (2024). Investigation of Cogging Torque in Permanent Magnet Homopolar Inductor Machines Based on Air-Gap Field Modulation Principle. *IEEJ Transactions on Electrical and Electronic Engineering*, *19*(1), 130–139. https://doi.org/10.1002/tee.23954