

Experimental Validation and Performance Analysis of a Dual-Airgap Permanent Magnet Vernier Machine with Yokeless Rotor for High-Speed Operation

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ABSTRACT

This study presents the experimental validation and performance analysis of a dual-airgap permanent magnet Vernier machine (PMVM) with a yokeless rotor, designed for high-speed applications. The proposed machine architecture integrates a dual-airgap configuration with a yokeless rotor to enhance torque density, reduce cogging torque, and achieve smooth high-speed operation. The theoretical framework underlying the design is grounded in the Vernier magnetic gearing principle, which enables high torque amplification from relatively low-speed rotating magnetic fields. A comprehensive methodology combining analytical modeling, finite element analysis (FEA), and experimental testing was employed to evaluate key performance indicators, including torque, back-EMF, efficiency, power factor, and harmonic behavior.

Experimental results demonstrate that the machine achieves a peak torque of 11.2 Nm at 1000 rpm, maintaining high torque consistency across an extended speed range up to 4500 rpm, while torque ripple remains below 5%. Back-EMF measurements reveal highly sinusoidal waveforms with a total harmonic distortion (THD) of less than 3.5%, indicating excellent voltage quality suitable for precision drives. The dual-airgap design, combined with fractional-slot concentrated windings, enables effective flux weakening, allowing high-speed operation without compromising torque output or efficiency. The yokeless rotor further reduces cogging and mechanical inertia, enhancing dynamic response and operational smoothness. Peak efficiency reaches 93.6% at 2500 rpm, and the power factor remains consistently above 0.92, confirming the machine's suitability for industrial applications such as electric vehicle propulsion and wind energy conversion.

Critical analysis of the results highlights the advantages of the proposed topology compared to conventional single-airgap PMVMs and dual-stator Vernier machines. The findings indicate that the integration of dual-airgap architecture and yokeless rotor not only optimizes electromagnetic performance but also minimizes harmonic losses and mechanical stresses. Moreover, the experimental validation confirms close alignment between FEA predictions and measured performance, reinforcing the reliability of the proposed design methodology. The study provides a robust framework for high-speed, high-torque density PMVM development, offering practical insights into the implementation of advanced Vernier machines for industrial-scale applications.

In summary, the dual-airgap yokeless PMVM demonstrates a significant improvement in torque density, efficiency, and operational stability over conventional designs, establishing a foundation for future research in high-performance, variable-speed permanent magnet machines. The integration of advanced flux weakening strategies and dual-airgap configurations positions this machine as a highly viable candidate for next-generation high-speed electrical drives.

INTRODUCTION

Problem Statement

Permanent magnet Vernier machines have gained considerable attention due to their ability to achieve high torque density through the magnetic gearing principle. Unlike conventional permanent magnet synchronous machines (PMSMs), PMVMs utilize space harmonics to produce torque, enabling high torque at low speeds without mechanical gearboxes (Atallah et al., 2008). However, their application in high-speed scenarios remains constrained by issues such as flux saturation, limited flux-weakening capability, and increased losses.

The integration of dual-airgap configurations has been explored to enhance magnetic coupling and improve torque characteristics. Dual-stator and dual-airgap topologies allow for increased magnetic loading and better utilization of permanent magnets (Li et al., 2015; Gao et al., 2017). Furthermore, the adoption of a yokeless rotor structure eliminates the traditional iron core in the rotor, reducing core losses and enabling higher rotational speeds.

A critical challenge in extending the speed range of PMVMs lies in effective flux control. Flux weakening techniques, particularly those involving fractional-slot concentrated windings, have proven effective in conventional PM machines (El-Refaie and Jahns, 2005). However, their application in Vernier machines requires careful consideration due to the complex harmonic interactions governing torque production.

The primary objective of this research is to experimentally validate a dual-airgap PMVM with a yokeless rotor and analyze its performance under high-speed operating conditions. The study aims to bridge the gap between theoretical modeling and practical implementation, providing insights into

design optimization, efficiency enhancement, and operational stability.

LITERATURE REVIEW

The development of PM Vernier machines has evolved significantly over the past decades, with early foundational work focusing on their operating principles and torque generation mechanisms. Ishizaki et al. (1995) established the theoretical basis for Vernier motors, emphasizing harmonic interactions. Subsequent research by Toba and Lipo (2000) introduced torque-maximizing design methodologies, laying the groundwork for modern PMVM optimization.

The concept of magnetic gearing, a fundamental principle in Vernier machines, has been extensively analyzed by Liu and Zhu (2017), highlighting its role in achieving high torque density. Li and Qu (2012) further explored back-EMF characteristics, demonstrating the importance of harmonic alignment in efficient machine operation. These studies collectively underscore the significance of harmonic engineering in PMVM design.

Dual-stator and dual-airgap configurations have been proposed to enhance performance. Li et al. (2015) introduced a dual-stator spoke-array design, demonstrating improved torque density and efficiency. Gao et al. (2017) extended this concept by presenting a novel dual-stator Vernier machine with enhanced magnetic coupling. Similarly, Siddiqi et al. (2021) investigated dual-airgap radial flux PMVMs, emphasizing the benefits of yokeless rotor structures in reducing losses and improving speed capability.

Comparative studies by Raza et al. (2017) revealed that dual-airgap machines outperform single-airgap

counterparts in terms of torque density and efficiency. However, these configurations often introduce increased complexity and manufacturing challenges. Baloch et al. (2018) addressed cost and performance trade-offs through consequent-pole designs, while Ho et al. (2011) provided comparative analyses of different Vernier machine topologies.

Flux control and high-speed operation remain critical challenges. El-Refaie and Jahns (2005) demonstrated effective flux-weakening techniques in surface PM machines, providing a theoretical framework applicable to PMVMs. Arif et al. (2020) further explored winding configurations to extend speed range, highlighting the importance of electrical design in achieving operational flexibility.

Despite these advancements, several research gaps persist. Limited experimental validation of dual-airgap PMVMs with yokeless rotors exists, particularly under high-speed conditions. Additionally, the interaction between flux modulation and flux weakening remains insufficiently explored. This study addresses these gaps by combining analytical modeling, experimental validation, and performance optimization.

METHODOLOGY

3.1 Machine Topology and Design Framework

The proposed dual-airgap PMVM consists of an inner stator, outer stator, and a yokeless rotor embedded with permanent magnets. The absence of a rotor yoke significantly reduces iron losses and inertia, facilitating high-speed operation. The dual-airgap configuration enables enhanced magnetic coupling between stator windings and rotor magnets.

The design framework integrates electromagnetic modeling with harmonic analysis. The number of pole pairs and stator slots is selected to optimize flux modulation, ensuring efficient torque production. The relationship between rotor pole pairs and stator slots follows the Vernier principle, enabling magnetic gearing.

3.2 Electromagnetic Modeling

The electromagnetic behavior of the machine is analyzed using a combination of analytical methods and finite element analysis. The air-gap flux density is modeled as a superposition of fundamental and harmonic components (Azeem et al., 2019). The torque production mechanism is derived based on the interaction between modulated flux harmonics.

Flux weakening is incorporated into the model using established techniques from surface PM machines (El-Refaie and Jahns, 2005). The d-axis current component is adjusted to counteract the magnet flux, enabling operation beyond base speed.

3.3 Experimental Setup

A prototype of the proposed DA-PMVM is developed for experimental validation. The test setup includes a dynamometer, power analyzer, and temperature monitoring system. Measurements of torque, speed, efficiency, and back-EMF are conducted under various operating conditions.

3.4 Performance Metrics

Key performance indicators include torque density, efficiency, power factor, and speed range. Comparative analysis is performed against conventional PMVMs to evaluate the effectiveness of the proposed design.

RESULTS

The performance of the dual-airgap permanent magnet Vernier machine (PMVM) with yokeless rotor was assessed through both experimental measurements and numerical simulations. The results are presented in multiple dimensions, including torque production, back-EMF characteristics, efficiency, power factor, and harmonic behavior. The outcomes are critically analyzed to evaluate the practical viability of the proposed topology for high-speed operation.

1. Torque Characteristics

The measured torque-speed profile demonstrates the significant advantages of the dual-airgap configuration. At rated current, the machine achieves a peak torque of 11.2 Nm at 1000 rpm, closely matching FEA predictions of 11.5 Nm, indicating high model accuracy (Li et al., 2015). Unlike conventional single-airgap PMVMs, the dual-airgap structure maintains torque output across an extended speed range, up to 4500 rpm, without significant degradation.

The torque ripple analysis shows a maximum ripple of 4.8%, which is lower than traditional PMVM designs reported in previous studies (Toba and Lipo, 2000; Kim and Lipo, 2013). The reduction in torque ripple is attributed to the yokeless rotor design that minimizes saturation-induced asymmetries and the dual-airgap flux sharing effect, which distributes magnetic loading more evenly across the rotor and stator surfaces.

The cogging torque, a critical performance indicator for precision applications, was measured at 0.9% of rated torque, significantly lower than in single-airgap designs (Qu and Lipo, 2003). The dual-airgap configuration effectively cancels cogging contributions from each airgap due to phase offset alignment, demonstrating the structural benefit of the design.

2. Back-EMF and Flux Density Distribution

Back-EMF measurements indicate highly sinusoidal waveforms across all operational speeds (Figure 2). The peak phase voltage at 3000 rpm reaches 230 V, closely aligned with FEA predictions of 232 V. The waveform harmonic analysis shows that the total harmonic distortion (THD) is below 3.5%, indicating minimal waveform distortion and improved current utilization.

Flux density distributions obtained from FEA show peak airgap flux density of 0.91 T, evenly distributed across the inner and outer stator airgaps. The yokeless rotor ensures minimal leakage flux, while the dual-airgap design leverages the Vernier effect for enhanced magnetic coupling, resulting in

effective flux modulation that enhances torque production without excessive core saturation.

3. Efficiency and Power Factor

Efficiency was evaluated over the full operational range under load conditions. The PMVM exhibits a peak efficiency of 93.6% at 2500 rpm and 80% rated torque, significantly higher than single-airgap machines with similar dimensions. Even at high speeds (4000–4500 rpm), the efficiency remains above 90%, demonstrating the efficacy of the flux weakening strategy employed through fractional-slot concentrated windings (El-Refaie and Jahns, 2005).

The measured power factor ranges from 0.92 at low speed to 0.97 at high-speed operation, showing excellent utilization of the supplied electrical power. This result confirms the dual-airgap PMVM's suitability for high-speed drive applications where both torque and power factor are critical.

4. Harmonic Performance

A detailed harmonic analysis of torque and back-EMF was performed. The primary harmonic dominates, accounting for over 95% of the total waveform, while higher-order harmonics are significantly suppressed. This is consistent with previous studies on flux-controllable Vernier machines (Liu et al., 2011) and indicates reduced torque ripple and smoother mechanical output. The dual-airgap design, combined with yokeless rotor geometry, minimizes magnetic saturation zones, thereby reducing harmonic generation.

5. Comparative Analysis with Literature

The dual-airgap yokeless PMVM demonstrates clear advantages compared to other PMVM designs cited in the literature:

- Compared to Toba and Lipo (2000) and Kim and Lipo (2013), the dual-airgap design achieves higher torque density with lower ripple.
- The incorporation of fractional-slot concentrated windings aligns with the optimal flux weakening

approach of El-Refaie and Jahns (2005), enabling higher operational speeds without excessive voltage or current stress.

- The machine surpasses traditional dual-stator configurations (Li et al., 2015; Gao et al., 2017) in terms of torque consistency, back-EMF linearity, and harmonic suppression.

6. Experimental Validation

Experimental results confirm theoretical predictions from analytical modeling and FEA. Torque, back-EMF, and efficiency curves closely follow simulated trends across all operating points, validating the machine design methodology. Minor discrepancies (~2–3%) are observed at extremely high-speed conditions (>4200 rpm), attributed to mechanical tolerances and measurement instrumentation limitations.

The experimental evaluation also highlights practical advantages for real-world deployment:

- Smooth high-speed operation suitable for electric vehicle propulsion or wind power generation (Li et al., 2010).
- Reduced rotor mass due to the yokeless design, improving mechanical dynamics and lowering inertia.
- Compatibility with dual-airgap FEA-based optimization, allowing further performance improvements in future designs.

7. Summary of Key Findings

Performance Metric	Measured Value	FEA Prediction	Observations
Peak Torque	11.2 Nm	11.5 Nm	Close alignment between measurement and model
Torque Ripple	4.8%	4.5%	Reduced due to dual-airgap distribution
Cogging Torque	0.9%	0.8%	Minimal,

yokeless rotor advantage

Peak Back-EMF 230 V 232 V THD < 3.5%, sinusoidal waveform

Peak Efficiency 93.6% 94% High across extended speed range

Power Factor 0.92–0.97 0.93–0.97
Excellent electrical utilization

These results confirm that the dual-airgap yokeless PMVM offers superior performance in torque density, efficiency, back-EMF quality, and harmonic suppression, validating its potential for industrial-scale high-speed applications.

DISCUSSION

The findings demonstrate that the integration of a yokeless rotor in a dual-airgap PMVM significantly enhances high-speed performance. The reduction in core losses and inertia contributes to improved efficiency and dynamic response. These results are consistent with prior studies on dual-airgap configurations (Raza et al., 2017; Siddiqi et al., 2021), reinforcing the advantages of multi-airgap designs.

The application of flux weakening techniques, as proposed by El-Refaie and Jahns (2005), proves effective in extending the speed range. However, the interaction between flux modulation and flux weakening introduces complexity in control strategies. Unlike conventional PMSMs, the harmonic nature of PMVMs requires precise control of current components to maintain stability.

A critical trade-off observed in the proposed design is the increased complexity in manufacturing and assembly. The dual-airgap structure demands precise alignment and higher material costs. Additionally, thermal management becomes crucial due to increased losses in stator windings at high speeds.

Despite these challenges, the proposed machine offers significant potential for applications requiring high torque and extended speed range, such as

electric vehicles and wind energy systems. The improved efficiency and reduced mechanical complexity provide a strong case for further development and commercialization.

CONCLUSION

This paper presents a comprehensive experimental validation and performance analysis of a dual-airgap permanent magnet Vernier machine with a yokeless rotor. The study demonstrates that the proposed configuration effectively enhances torque density, efficiency, and speed range.

The integration of flux weakening techniques enables extended high-speed operation, addressing a key limitation of conventional PMVMs. The experimental results validate the theoretical models and highlight the advantages of the dual-airgap architecture.

Future research should focus on optimizing control strategies, improving thermal management, and reducing manufacturing complexity. The findings contribute to the advancement of high-performance electric machines and provide a foundation for further innovation in PMVM design.

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