

Impact of Distributed and Concentrated Winding Configurations on Flux Switching Generator

Buse Soydas¹, Tugberk Ozmen², Bati Eren Ergun¹, Nevzat Onat³ and Mehmet Onur Gulbahce¹

¹Electrical Engineering Department, Istanbul, Türkiye
soydas19@itu.edu.tr, ergunb16@itu.edu.tr, ogulbahce@itu.edu.tr

²Electric and Energy Department, Manisa, Türkiye
tugberk.ozmen@cbu.edu.tr

³Electrical Electronics Engineering Department, Manisa, Türkiye
nevzat.onat@cbu.edu.tr

Abstract

Owing to their mechanically robust rotor design and high power density, Flux Switching Permanent Magnet Generators (FSPMGs) have become a subject of increasing interest. In this paper, a 12-slot/10-pole FSPMG is analyzed to compare the performance effects of using concentrated versus distributed winding topologies. Key performance indicators, such as magnetic flux distribution, flux linkage, induced voltage, electromagnetic torque, and power output, were evaluated through a comparative analysis utilizing the Finite Element Method (FEM). The results indicate that the distributed winding configuration yields a 138.55% increase in peak induced voltage and a 43.7% increase in electromagnetic torque per current value compared to the concentrated winding. These improvements are primarily attributed to the enhanced winding factor and the more sinusoidal magnetomotive force (MMF) produced by the distributed topology. The findings suggest that the distributed winding configuration demonstrates enhanced electromagnetic performance, making it a promising candidate for high-performance FSPMG applications.

1. Introduction

FSPMGs stand out due to several key advantages, notably their high power density, effective cooling facilitated by the stator-mounted magnets, and enhanced mechanical robustness stemming from the rotor's magnet-free structure [1]. The back electromotive force (EMF) generated in these machines through magnetic field modulation provides a distinct advantage in control systems, especially owing to its near-sinusoidal waveform [2]. Furthermore, newly developed radial-axial flux-focusing topologies can simultaneously increase both the output power and the volumetric efficiency [3]. Despite these benefits, FSPMGs also present certain drawbacks; for instance, challenges like high cogging torque, manufacturing complexity, and rotor radial force in some topologies can significantly influence the design process [1]. These machines find extensive use in various fields, ranging from electric vehicles (EVs) and wind turbines to aerospace and mobile systems that necessitate compact power solutions [3].

FSPMGs gain further importance within the modern energy transition. Conventional centralized generation suffers from efficiency losses, environmental concerns, and transmission vulnerabilities, while microgrids and distributed renewable sources demand compact, efficient, and reliable machines [4]. Unlike many synchronous generator topologies where rotor-

mounted field windings require brushes (leading to efficiency loss and limited lifetime) or where surface-mounted permanent magnets face risks of damage, FSPMGs eliminate these drawbacks by placing all permanent magnets securely in the stator. This stator-active structure makes FSPMGs strong candidates for sustainable and decentralized energy systems such as wind-based microgrids.

One of the most critical design elements that directly impacts the electromagnetic performance of FSPMGs is the winding structure. Different configurations are typically utilized in these machines, including concentrated windings, distributed windings, overlapping windings, and multilayer windings [5, 6, 7]. While concentrated windings provide benefits like compact design, high power density, and reduced manufacturing costs, they are also associated with electromagnetic drawbacks, including significant harmonic content and torque ripple [8]. Distributed windings, in contrast, stand out due to their smoother flux distribution and lower harmonic content but come with drawbacks like manufacturing complexity and increased winding volume [9, 10]. In recent years, newly developed multilayer and overlapping winding structures have been proposed to enhance output performance [5, 7]. This diversity necessitates the selection of the most appropriate winding structure for FSPMG designs on an application-specific basis [6, 11].

In the context of FSPMGs, permanent magnets play a crucial role in providing excitation without requiring additional rotor windings, thereby improving efficiency through the elimination of copper losses. Among the various PM types, NdFeB and SmCo are most widely adopted due to their high remanence and coercivity, ensuring compact and high power-density designs [12]. Nevertheless, the dependence on rare-earth materials like Nd and Dy raises issues related to price volatility and supply chain risks, as international bodies have categorized these as critical resources. To mitigate such challenges, ferrite magnets—though offering lower magnetic capacity—are increasingly investigated as alternative options for stator-mounted excitation in FSPMGs, given their lower price and supply security [12].

This research employs FEM to examine how concentrated and distributed winding arrangements influence FSPMG performance. The analysis results for torque, flux linkage, induced voltage, and electrical and mechanical power values are compared in detail. The paper initially presents the fundamental characteristics and parameters of the reference generator under analysis. The second section describes the technical details and configurations pertaining to the concentrated and distributed winding structures. Finally, the results section presents the

numerical and graphical outcomes of the output parameters obtained for the different winding configurations.

2. Fundamentals of Flux Switching Permanent Magnet Machines

The fundamental operation of FSPMGs relies on altering the magnetic flux path and the associated magnetic reluctance, which varies according to the rotor's position. Variation in the magnetic flux path leads to time-variant flux linkage within the FSPMG armature windings, subsequently generating a sinusoidal voltage. Table 1 outlines the primary design parameters for the FSPMG analyzed in this work.

Constructed solely from laminated steel sheets, the FSPMG rotor examined here features a simple design. In contrast, the stator is built by winding concentric coils around axially magnetized permanent magnets positioned between U-shaped segments. The slot/pole combination of the FSPMG frequently employs the 12-slot/10-pole (12s/10p) topology [13], a popular choice for FSPMGs because of its reduced cogging torque.

Table 1. Design specifications of the FSPMG

Parameters	Values
Number of Phase	3
Slot Number of Stator	12
Number of Pole	10
Turns	70
Permanent Magnet	NdFeB35
Outer Radius of Stator (mm)	65.00
Outer Radius of Rotor (mm)	38.9
Air Gap (mm)	0.40
Magnet Thickness (mm)	3
Stack Length (mm)	90
Rated Speed (rpm)	1200
Torque (Nm)	-5.69
Phase Current (A)	3.7

3. Winding Topologies

A review of the literature on FSPMGs generally reveals a preference for the concentrated winding configuration. In a concentrated winding structure, the end-winding length is significantly shorter, which consequently leads to lower copper losses. Machines utilizing this winding topology exhibit higher power density and a greater slot fill factor. Furthermore, the windings are characterized by a more compact and simpler structure [14]. However, these benefits are countered by disadvantages, notably the excessive space harmonic content present in the air-gap MMF. Such unwanted harmonics lead to elevated core losses, greater torque ripple, and a diminished power factor for the machine [15].

To overcome these limitations, alternative topologies such as the multilayer (ML) or distributed winding have been proposed as a promising solution. This method provides two primary benefits compared to standard designs: the ability to produce a more sinusoidal stator MMF and the benefit of a shorter end-winding length [16].

These advantages directly contribute to measurable enhancements in overall system performance. The MMF's improved sinusoidal quality effectively reduces unwanted space harmonics, consequently producing a significantly smoother torque profile and lower torque ripple [13]. Moreover, the ML

winding topology leads to an improved fundamental winding factor. This improvement enables higher torque generation for equivalent stator copper losses, signifying better material utilization [16].

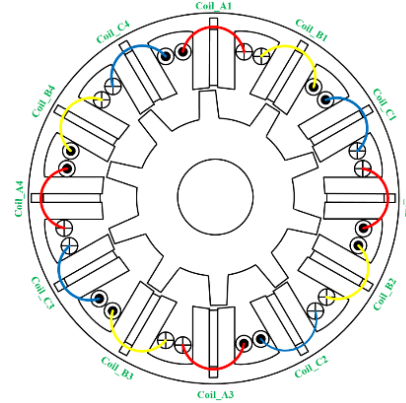


Fig. 1: Schematic of the concentrated winding configuration.

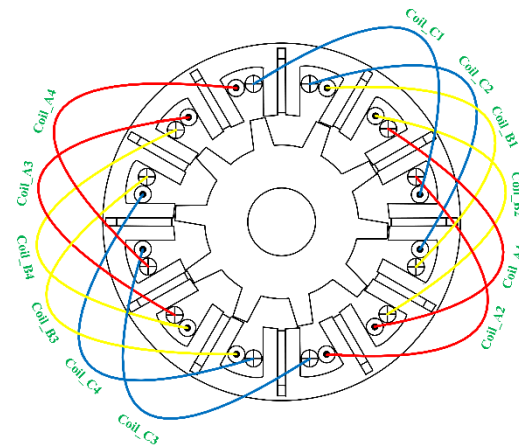


Fig. 2: Schematic of the distributed winding configuration.

Adoption of distributed windings to FSPM machines has been investigated as a key strategy to enhance the winding factor and, consequently, the overall machine performance [11]. Indeed, research conducted by Li et al. [11] has demonstrated that this alternative winding topology yields substantial gains, showing a significant improvement in torque and an increase of up to 90% in back-EMF for a given stack length. Improvements in performance extend beyond back-EMF, with torque production also showing significant gains. Figures 1 and 2 display the concentrated and distributed winding schematics for the FSPMG studied, respectively.

4. Results and Discussion

The electromagnetic performance of the FSPMG with both concentrated and distributed winding configurations was analyzed using FEM, and the comparative results are presented in this section.

As depicted in Fig. 3 and Fig. 4, the magnetic flux density distributions for both configurations at rated speed were examined. The distributed winding configuration (Fig. 3) leads to a more uniform and widespread flux distribution across the stator teeth compared to the concentrated winding (Fig. 4). The

concentrated winding results in higher localized flux density peaks, which can contribute to higher core losses and harmonic content.

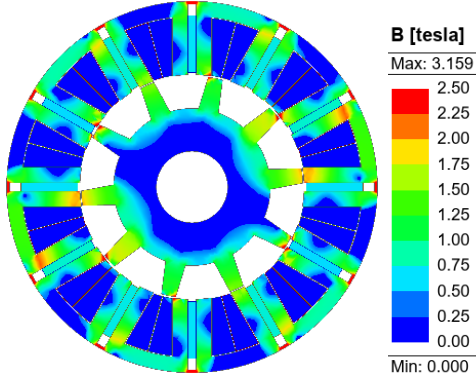


Fig. 3: Distribution of magnetic flux density for the distributed winding FSG.

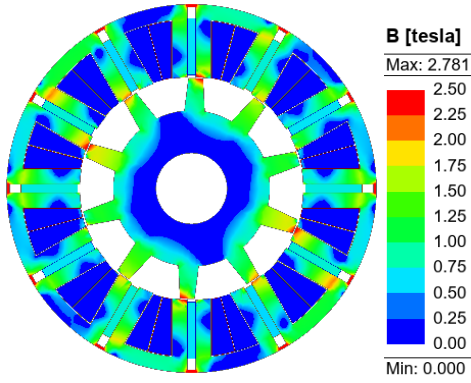


Fig. 4: Distribution of magnetic flux density for the concentrated winding FSG.

Figures 5 and 6 depict the flux linkage waveforms for the concentrated and distributed windings, respectively. A peak flux linkage of roughly 0.1385 Wb is attained by the distributed winding setup, surpassing the 0.0572 Wb peak of the concentrated winding.

As shown in Fig. 7, utilizing distributed winding boosts the fundamental component without significantly altering most harmonic orders of the radial air-gap flux density. The increase in the fundamental harmonic shown in Fig. 8 directly improves electromagnetic torque. Additionally, switching to the distributed winding leads to a marked reduction in the induced voltage waveform's total harmonic distortion (THD). These improvements are directly attributed to the stronger flux linkage provided by the distributed winding configuration.

Enhanced flux linkage directly translates into a much higher induced voltage. The distributed winding generates a peak induced voltage of approximately 361 V (Fig. 10), representing a remarkable 138.55% increase compared to the approximately 151 V peak voltage produced by the concentrated winding (Fig. 9). The improved winding factor of the distributed topology allows for a more effective interaction with the magnetic field, translating directly into a much higher induced voltage, which is a critical parameter for generator performance.

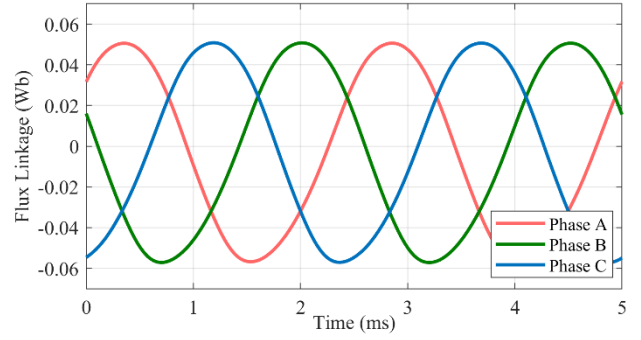


Fig. 5: Flux linkage in concentrated winding FSPMG.

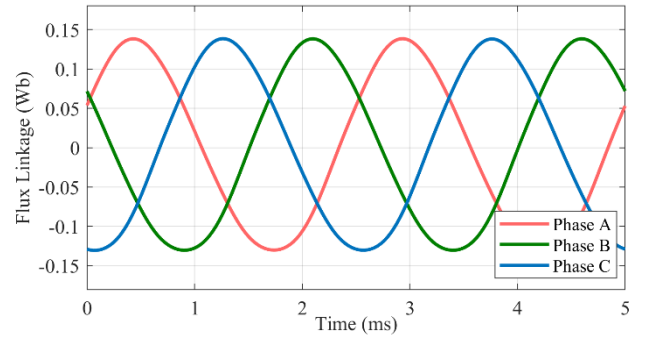


Fig. 6: Flux linkage in distributed winding FSPMG.

Fig. 11 demonstrate the electromagnetic torque characteristics for both winding types. Because the RMS phase current remains fixed at 3.7 A, evaluating torque per current offers a more suitable measure of performance. For the concentrated winding, the torque per current value is approximately 1.751 Nm/A, whereas the distributed winding achieves a significantly higher value of 2.516 Nm/A. This corresponds to a 43.7% improvement in electromagnetic torque per current with the transition to the distributed winding. The substantial enhancement highlights the superior electromagnetic energy conversion capability of the distributed winding, enabled by its stronger flux linkage and more effective MMF distribution.

The mechanical and electrical power characteristics, summarized in Table 2, provide a comprehensive comparison of the two winding configurations at a constant operating speed of 1200 rpm. In terms of per-unit values, the distributed winding reaches 1.437 p.u. mechanical power and 1.486 p.u. electrical power, compared to 1 p.u. for both metrics in the concentrated winding. However, this increase in mechanical power is meaningful primarily when considered together with the torque per current metric. At the same 3.7 A RMS phase current, the distributed winding reaches a torque per current of 1.437 p.u. compared to 1 p.u. for the concentrated winding, corresponding to a 43.7% improvement. This improvement clarifies the increased power output and corresponds with the observed rise in efficiency from 0.967 p.u. to 1 p.u. Furthermore, the distributed winding demonstrates a lower THD of the induced voltage (0.833 p.u.), highlighting its better waveform quality and lower harmonic distortion.

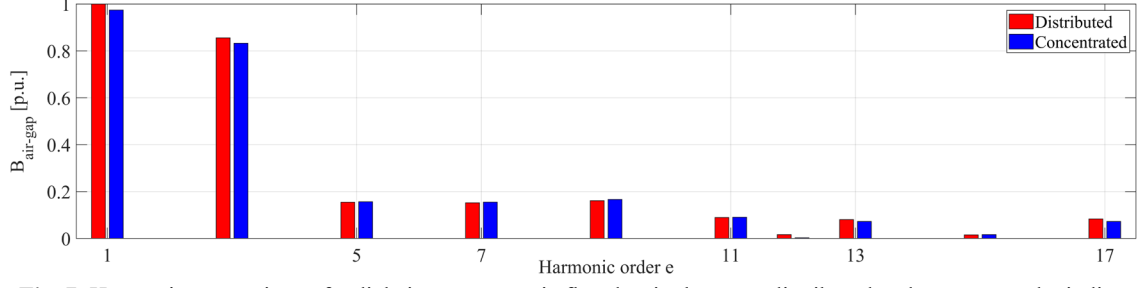


Fig. 7: Harmonic comparison of radial air-gap magnetic flux density between distributed and concentrated windings.

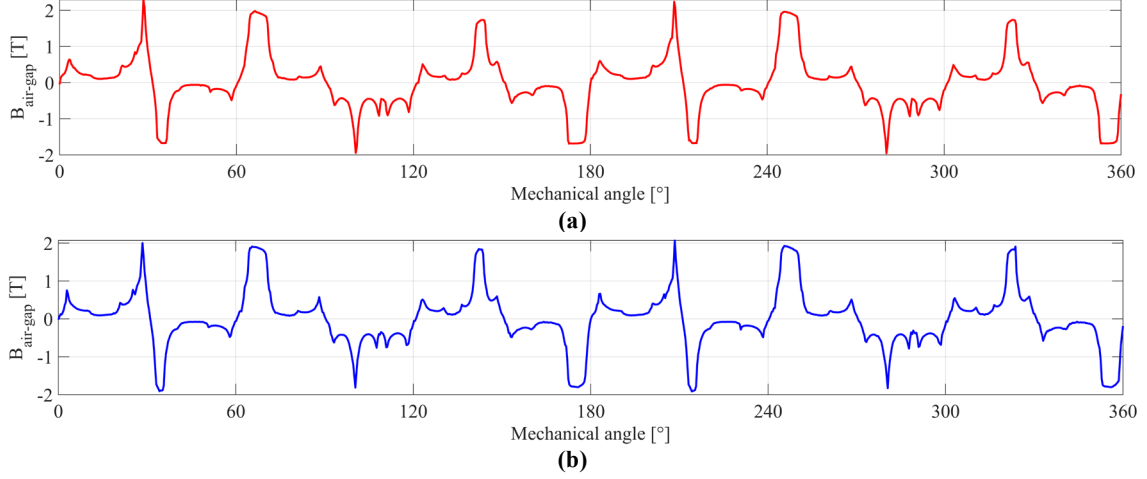


Fig. 8: Air-gap flux density waveform's radial component for (a) the distributed winding setup and (b) the concentrated winding setup.

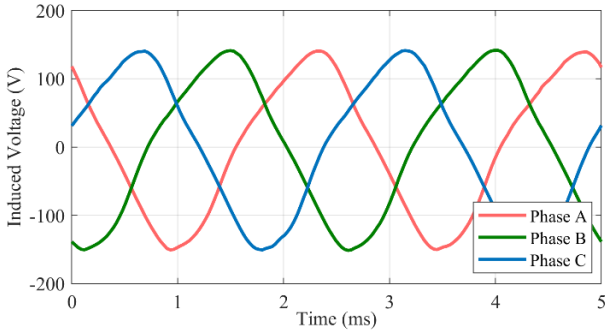


Fig. 9: Induced voltage in concentrated winding FSPMG.

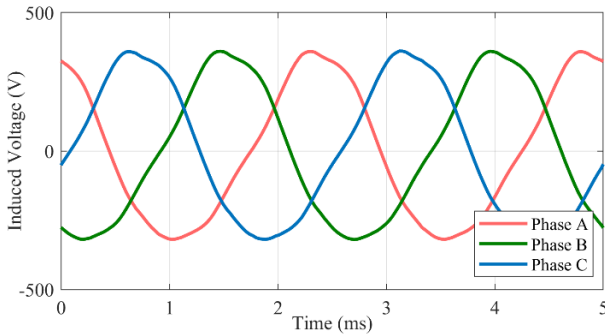


Fig. 10: Induced voltage in distributed winding FSPMG.

Table 2. Operational quantities for concentrated vs. distributed windings

Performance Metric	Concentrated Winding	Distributed Winding	Difference (%)
Mechanical Power	1 p.u.	1.437 p.u.	+43.7%
Electrical Power	1 p.u.	1.486 p.u.	+48.6%
Efficiency	0.967 p.u.	1 p.u.	+3.412%
Electromagnetic Torque per Current	1 p.u.	1.437 p.u.	+43.7%
THD of Induced Voltage	1 p.u.	0.833 p.u.	-16.7%

These results unequivocally establish the superiority of the distributed winding configuration for achieving high power density in FSPMG designs.

5. Conclusion

In this paper, a comparative FEM analysis was performed on a 12-slot/10-pole FSPMG utilizing both concentrated and distributed winding configurations. The objective was to measure how the winding topology affects the generator's primary electromagnetic performance metrics.

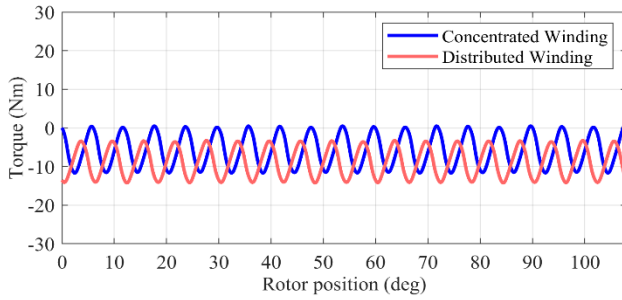


Fig. 11: Torques for different winding configurations.

The results conclusively demonstrate the significant superiority of the distributed winding configuration. Key findings indicate that the distributed winding yields a 138.55% increase in peak induced voltage and a 43.7% increase in electromagnetic torque per current value compared to the conventional concentrated winding. These improvements are attributed to the enhanced winding factor and more sinusoidal MMF distribution of the distributed topology, which leads to a more effective flux linkage. Based on these findings, it is concluded that for high-performance applications where output power density and torque are critical, the distributed winding configuration is a significantly more effective and suitable choice for FSPMG design. Future work could involve the manufacturing of a prototype for experimental validation of these simulation results and a more detailed analysis including thermal performance and cogging torque minimization techniques.

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6. References

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