Electromagnetic Performance Analysis of Novel Dual-Stator Electric Machine for Renewable Energy Conversion Applications

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Abstract— **Efficient electric generators are crucial for effectively integrating renewable energy sources like hydrokinetic energy. As renewable energy use grows, these generators must evolve to keep up with increasing demand. This study introduces a novel three-phase dual-stator permanent magnet synchronous generator (DSPMSG), a US-patented design aimed at boosting energy conversion efficiency from renewable sources. The design features three stator windings–one for each phase– wound on a bridge between the two stators to enhance magnetic flux linkage. The DSPMSG addresses common issues with single-stator and wound rotor machines, such as magnetic losses, torque ripple, harmonic distortion, and low efficiency. Results from simulating the DSPMSG using finite element analysis (FEA) in ANSYS® Maxwell® 3D show the DSPMSG is well-suited for renewable energy applications, demonstrating superior efficiency and performance, and supporting future development and deployment.**

Keywords: dual stator, synchronous generator, electrical machine, FEM, ANSYS

I. INTRODUCTION

The depletion of fossil fuel reserves and the adverse effects of global warming have made the utilization of renewable energy sources essential [1], in addition to extreme weather events, heightening the need for cooling and heating. This trend has led to a rise in renewable energy sources, such as hydrokinetic energy. Recent advancements aim to boost energy generation for both industrial and residential uses. The electric generator is vital to this integration [2]–[4]. Current efforts focus on creating efficient generators capable of effectively capturing hydrokinetic energy, whether via gear-driven or direct-drive systems. However, single-stator wound-rotor synchronous machines with distributed windings on the stator face limitations, notably second-order harmonic distortion and higher copper losses, which reduce efficiency in applications such as riverine hydrokinetic energy conversion systems [5]–[7]. This issue has spurred research into alternative designs, such as the dual-stator configuration.

Many dual-stator architectures have been proposed and studied for both high-speed and low-speed electric machines. The authors in [8] examine an axial flux switching permanent magnetic machine (FSPM) with 6 rotor and 4 stator poles capable of achieving a uniform flux distribution and reducing second-order harmonics. Several machine topologies are presented in the study. The first topology has the stator offset by 45° mechanical degrees, while the second topology shifts the stator by 45° mechanical degrees. The third topology is a hybrid of the previous two. However, a key disadvantage of the machine is the presence of high second and third-order harmonics. This harmonic distortion causes the back-emf-induced voltage to deviate from a sinusoidal waveform, resulting in phase voltage imbalance.

The design in [8] was modified in [9], replacing the axial rotor with a radial one. In this study, the magnetic rotor poles were offset by 45° mechanical degrees, corresponding to 180° electrical degrees. This design improved the magnetic flux distribution and effectively canceled even harmonic orders while reducing the third harmonic. The radial pole rotor has a natural rotational symmetry that cancels triplen harmonics in a three-phase system. Additionally, since the magnetic flux is more confined along the radial path, magnetic flux leakage is less than in the axial type.

Due to the architectural arrangement of a dual-stator topology, radial-type dual-stator PMSGs are prone to thermal issues stemming from the inner stator winding [10]. The inner stator of some of these designs is always enclosed by the rotor winding or permanent magnets, which can cause excess heat, preventing the machine from achieving its desired performance. As a result, heat removal was considered in [11], [12] by shaping the rotor to allow placing one of the stator windings inside a hollow-shaped cylinder to effectively utilize the unused space in the machine for heat dissipation, thereby yielding better efficiency.

In addition, it was revealed in [13] that using a single stator increases the second-order harmonics in a FSPM. This effect includes, but is not limited to, the performance and lifespan of the generator; it also results in voltage distortion, overheating, and other issues. The introduction of the second stator with windings helps to produce a corresponding flux linkage that cancels the even harmonic component made by the first stator winding to generate a close sinusoidal waveform with little harmonic distortion.

A multiphase dual-stator pseudo-pole permanent magnet synchronous generator was proposed in [14]. The recommended five-phase pseudo-pole configuration produces a

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strong and uniform magnetic flux density, resulting in high torque and greater flexibility under fault conditions compared to a traditional three-phase system. Thanks to its inherent fault-tolerant design, the machine can continue operating even when one or two phases fail. The study also introduces innovations to optimize the geometric configuration and employ non-overlapping concentrated windings, thereby improving efficiency while maintaining other key performance metrics. However, these advantages come at the cost of increased design complexity, which makes fabrication more challenging.

Despite significant improvements in dual-stator geometries, many existing designs still suffer from harmonic distortion, which limits their performance. To address this challenge, this paper investigates a novel dual-stator topology for low-speed renewable applications. The electromagnetic performance of the proposed topology is analyzed using finite element analysis (FEA) simulations under both no-load and load conditions to evaluate key performance metrics.

II. Proposed Dual-Stator 26/24 PMSG

The proposed US-patented dual-stator permanent magnet synchronous generator (DSPMSG) employs a common flux path to facilitate flux transfer between stators as shown in Figure 1. Both stators share an ordinary permanent magnet rotor that resembles a conventional 26-pole PMSG rotor, with the primary difference being the stator topology. Each stator contributes four poles per phase for a total of 24 stator poles, resulting in a dual-stator configuration with the rear stator offset by 180° electrical degrees relative to the front stator. This arrangement enhances harmonic cancellation, torque density, and output power, particularly at low speeds, while maintaining high efficiency.

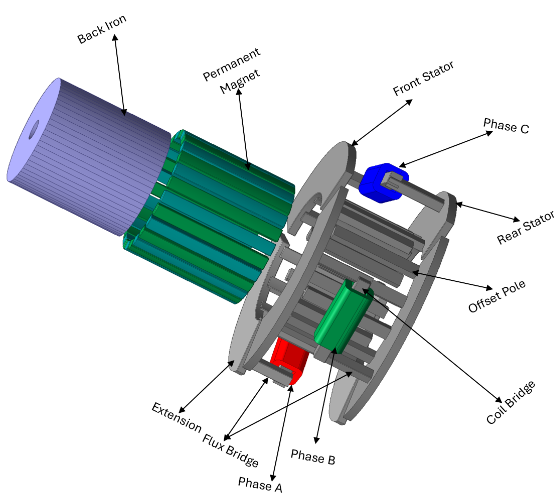

Fig. 1. Disassembled view of the 26/24 DSPMSG with a radial pole rotor structure.

The stator windings for each phase, also depicted in Figure 1, are wound on coil bridges that link the front and rear stators. The phase windings are arranged identically across both stators, which ensures that the resulting winding distribution achieves the required 120° electrical phase separation. This arrangement provides symmetrical magnetic coupling across the machine.

With 26 rotor poles, the first eight alternating poles (north and south) align with the stator poles associated with phase A. When the number of rotor and stator poles differ ($N_r \neq N_s$), a phase offset occurs among the flux peaks. In this configuration, Phase A reaches its magnetic peak at 0°, Phase B at 120°, and Phase C at 240°, thereby preserving a balanced three-phase system.

Additionally, a mechanical air gap is maintained between the poles of the dual stators. This separation prevents direct pole contact while ensuring that each stator interacts only with either a north or south rotor pole. Flux transfer between the dual stators occurs exclusively through the coil bridge, which enhances flux linkage uniformity and supports more stable electromagnetic performance within the proposed dual-stator architecture.

The design specifications for the 26/24 DSPMSG are detailed in Table 1. The generator is designed to produce an electrical output power of 2.7 kW at a synchronous speed of 277 RPM. The rotor back iron is made from magnetic steel with the M19-24G core material. Additionally, the iron magnetic poles are equipped with NdFeB magnetic material. NdFeB offers suitable magnetic properties, with a flux density ranging from 1.0 to 1.4 Tesla. The development of this novel generator follows the detailed methodology outlined in Fig. 2.

III. Analytical Design and Sizing of DSPMSG

First, the number of stator poles must be determined. Once the number of stator poles is known, the mechanical angle for each pole can be calculated. This angle is crucial for effectively distributing poles around the rotor's circumference. The following two fundamental equations guide the proper sizing of stator poles. Notably, the dual-stator has 24 magnetic poles.

$$N_r = N_s - k \quad \text{where } k = (1, 2, \ldots) \tag{1}$$

$$N_r = N_s + k \quad \text{where } k = (1, 2, \ldots) \tag{2}$$

N_r is the number of rotor poles, N_s is the number of stator poles, and k is the integer constant related to both rotor/stator poles combination. The inner diameter of the stator D_{si} can be determined using the outer diameter of the rotor D_{ro} and air gap length L_{AG} between the rotor and stator as follows.

$$D_{si} = D_{ro} + 2 \cdot L_{AG} \tag{3}$$

The stator pole pitch angle in mechanical degrees, can be determined as

$$pp_s = \frac{360^\circ}{p_s} \tag{4}$$

where p_s is the number of stator poles.

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TABLE I

PROPOSED DESIGN SPECIFICATION OF DSPMSG.

Properties	Value	Unit
Rated Power	2.7	kW
Rated Speed	277	RPM
Magnetic Type	NdFeB	
Rated Voltage	208	V
Load Resistance	15	Ω
Armature Current	8	A
Airgap	0.5	mm

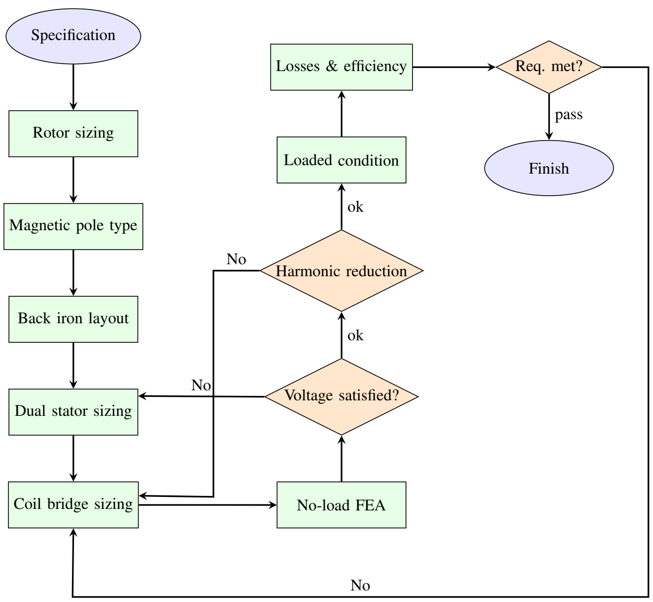

Fig. 2. Flowchart of the design procedure for the proposed dual-stator 26/24 PMSG.

The electrical distance between two north polarity stator poles, separated by a south pole, denoted as τ_S, is expressed as a multiple of the stator pole pitch as

$$\tau_s = 3 \cdot pp_s \tag{5}$$

The slot opening of the stator can be determined using N_s and the slot opening angle factor k_t. The stator slot opening width W_{so} can be found as

$$W_{\mathrm{so}} = \frac{360^\circ}{N_s} \cdot k_t \tag{6}$$

where

$$k_t = \frac{b_{so}}{\tau_s} = \frac{b_{so} N_S}{2\pi r_{si}} \tag{7}$$

where b_{so} is the slot opening width and r_{si} represents the inner radius of the stator.

The slot opening length L_{so} can be defined geometrically as

$$L_{so} = 2r_{si} \cdot \sin\left(\frac{\pi}{N_s} \cdot k_t\right) \tag{8}$$

A smaller slot opening angle factor k_t generally leads to a smoother air-gap flux density and reduced cogging torque. Therefore, optimizing k_t is crucial for achieving high-performance machine operation, particularly in applications where efficiency and low vibration are critical.

Since the generator air-gap length L_{AG} is constant, the effective cross-sectional area of the air gap A_G can be calculated as

$$A_G = D_{ro} \cdot L_{AG} \tag{9}$$

The height of each dual-stator pole h_{dsp} is determined by the height of the permanent magnet poles and the air gap, which is calculated as

$$h_{dsp} = h_{PM} \cdot L_{AG} \tag{10}$$

The arc shape width of the stator poles L_s is determined by using the arc shape width of the rotor poles. The stator pole arc width is calculated as

$$L_s = r \cdot \theta_s \tag{11}$$

with

$$\theta_s = \frac{L_s}{r_s} \tag{12}$$

where L_s is the arc width, r_s is the radius from the center of the circle to the arc, and θ_s is the central angle subtended by the arc.

The stator extension E_{ds} is implemented by increasing the radius by Δr, which enables more accurate coil sizing around the coil bridge. The stator extension is found to be

$$E_{ds} = r_s + \Delta r \tag{13}$$

Lastly, the stator outer diameter D_{so} is the same as the stator extension E_{ds}.

$$D_{so} = E_{ds} \tag{14}$$

The dual-stator dimensions and corresponding design parameters are summarized in Table 2.

TABLE II

STATOR DESIGN SPECIFICATIONS FOR PROPOSED DUAL STATOR ELECTRIC GENERATOR

Properties	Value	Unit
Inner Diameter	132	mm
Outer Diameter	240	mm
Number of Stator Poles	24	
Stator Pole Type	1	
Poles Height	115	mm
Thickness	5	mm
Pole pitch	15	mm
Arc Length	7.3	mm
Extension Thickness	6	mm
Coil Bridge Width	15	mm
Linking Coil Bridge Length	80	mm
Front and Rear Coil Bridge pole height	76	mm
Embrace	0.6	
Steel Material	Iron	
Air-gap Length	0.5	mm

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IV. Back EMF And Harmonics of DSPMSG

The internally generated voltage peak value, E_{pk}, also known as the back EMF, can be determined using the expression below.

$$E_{\text{pk}} = \left| \frac{d\lambda_{\text{tot}}(t)}{dt} \right| = 2\pi^2 N B_{Ag,\text{pk}} K_m K_{\text{fund}} K_t \left(\frac{f_e}{N_s} \right) D_{is} L_e \quad (15)$$

where $\lambda_{\text{tot}}(t)$ represents the fundamental flux linkage as a function of time in Wb $\cdot$ turns, N is the number of turns per coil in the stator winding, and $B_{Ag,\text{pk}}$ is the peak value of the air-gap flux density in Teslas (T) or Wb/m^2. The coefficient K_m accounts for the magnet shape effect, K_{fund} is the fundamental winding factor, and K_t is the pitch factor that corrects for short-pitch windings. The variable f_e corresponds to the electrical frequency in Hz, and N_s is the number of stator slots. D_{is} denotes the inner stator diameter in mm, while L_e represents the effective axial length of the machine in mm.

The second-order harmonics in the back emf for a dual-stator configuration are expected to cancel out due to the flux flowing between the opposing stators. However, these harmonics will have a small magnitude relative to the fundamental frequency due to non-uniform air gaps and pole placement effects, as shown in Figure 4.

V. Performance Analysis of DSPMSG

This section outlines the performance of the DSPMSG under both open circuit and loaded conditions. Several critical performance metrics were assessed, including back-EMF voltage, total harmonic distortion, cogging torque, output power, and overall efficiency.

A. No-Load (Open-Circuit) Back EMF and Harmonics

The performance of the three-phase 26/24 DSPMSG was analyzed under no-load conditions. The no-load induced voltage of the DSPMSG is shown in Figure 3, and its FFT is shown in Figure 4. The results show that the second-order harmonic is significantly low in comparison to the fundamental.

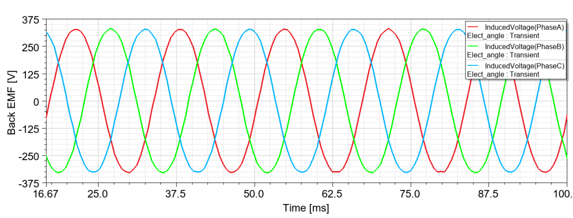

Fig. 3. No-load three-phase back-EMF waveform of three-phase dual-stator generator with 26 rotor poles and 24 stator poles.

B. Cogging Torque

The DSPMSG has a small amount of cogging torque, a significant source of noise and vibration in conventional single-stator machines. Figure 5 shows that the DSPMSG design significantly reduces cogging torque. This reduction occurs because the second stator is electrically offset by 180° from the first, causing its torque to cancel the first stator's torque partially. A small residual torque remains due to non-uniform air gaps and minor pole-placement differences.

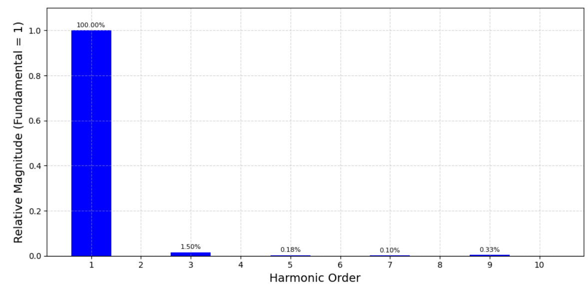

Fig. 4. FFT spectrum of the patented three-phase dual-stator machine as a generator with 26 rotor poles and 24 stator poles, illustrating the harmonic content of the induced voltage relative to the fundamental frequency.

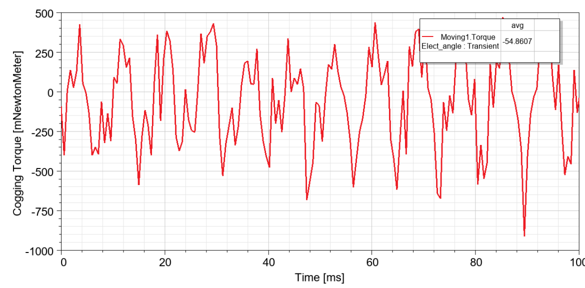

Fig. 5. Cogging torque of the dual-stator PMSG in mN·m.

C. Losses, Output Power, and Efficiency Under Load

The various power losses in the DSPMSG include copper, core, and mechanical losses, of which the stator copper losses (I^2R) and core losses (eddy current and hysteresis) are dominant. The DSPMSG has windings on each phase of the stator, and since the rotor is of the permanent magnet type, there are no rotor copper losses. To minimize losses, laminated M19 steel with a stacking factor of 0.95 is used. The input and output power, copper and core losses, and efficiency are listed in Table III.

TABLE III
Loss Analysis for the Proof-of-Concept Dual-Stator PMSG with 15-Ω Load Resistor

Parameter	**Value**
Load resistance, R_{load} [Ω]	15
Mechanical input power P_{in} [kW]	2.88
Electrical output power P_{out} [kW]	2.72
Hysteresis loss, P_{hys} [mW]	0.0360
Copper loss, P_{Cu} [W]	155.2
Core loss, P_{core} and Excess loss, P_{ex} [mW]	355
DC resistance loss, $P_{\text{DC,field}}$ [W]	8.2
Total loss, P_{loss} [W]	163.75
Efficiency, η [%]	94%

Using a voltage-source excitation slightly above the no-load induced voltage the load on the three-phase DSPMSG connected in a Y-configuration was varied from 15-Ω to 35-Ω in steps of 5-Ω as shown in Table IV. The optimal load

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TABLE IV
PERFORMANCE OF DUAL-STATOR PMSG VERSUS LOAD

Load (Ω)	Torque (N·m)	Power In (kW)	Power Out (kW)	Eff. (%)
15	99.00	2.88	2.72	94
20	74.00	2.16	1.95	90
25	60.00	1.73	1.49	86
30	50.00	1.44	1.14	79
35	42.56	1.23	0.89	72

Note: The electrical loading simulations for the dual-stator PMSG were conducted at the same synchronous speed.

angle δ is determined using the ANSYS® Maxwell® FEA optometric solver. A steady-state fast-reach auto-detection algorithm minimizes startup transients and voltage imbalance, improving simulation efficiency, ensuring stability, and balanced phase operation after the first cycle. These tests were conducted to evaluate the dual-stator machine's ability to maintain constant power output at synchronous speed. The induced torque is found in Table IV and its corresponding mechanical power in Fig 6. With a 15-Ω load, the generator delivers 2.72 kW at a fixed synchronous speed of 29 rad/sec.

The results in Table IV show how the DSPMSG performs efficiently under different load conditions. The results indicate that this design significantly lowers losses compared to traditional single-stator systems. This benefit arises from the balanced magnetic flux distribution between the two stators via the coil bridge, which creates an effective magnetic flux path that reduces flux leakage and boosts electromagnetic energy conversion. As a result, the dual-stator setup delivers higher efficiency and better performance across various load conditions.

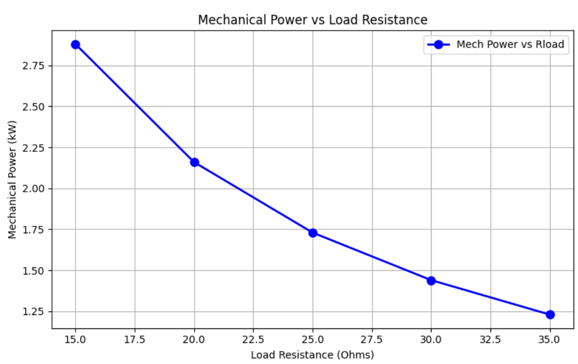

Fig. 6. Mechanical input power as a function of load resistance at synchronous speed.

VI. CONCLUSION

The proposed dual-stator permanent magnet synchronous generator exhibits better performance over conventional single-stator machines in terms of both harmonic levels and efficiency. The dual-stator topology effectively mitigates one of the main drawbacks of traditional synchronous machines—second-order harmonic distortion—by providing a more uniform airgap flux path that eliminates second-order harmonics and substantially reduces third-order components in the back-EMF. Even under rated-load conditions, where harmonic effects typically increase, the design exhibits minimal distortion, with only a minor third-order component from phase imbalance.

Furthermore, the dual-stator structure enhances overall machine efficiency by simplifying the magnetic circuit, reducing copper and core losses, and improving flux distribution. Collectively, these results confirm that the proposed dual-stator configuration delivers high efficiency and low distortion in electrical output, making it highly suitable for renewable energy applications.

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