

Design and Simulation of 1 KW Permanent Magnet Synchronous Wind Generator Using Skewed and Unskewed Rotor

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Abstract- This study provides an in-depth analysis of the electromagnetic comparative assessment of the unskewed and skewed rotors for a 1 kW, three-phase, inner-rotor permanent magnet synchronous generator intended for small-scale direct-drive wind power applications. The generator has 36 stator slots and 12 rotor poles, with a 220 mm outer diameter of the stator and a stack length of 60 mm. The unskewed generator uses a ring magnet rotor design and features a gap size of 2.0 mm, while the skewed rotor design uses a block magnet rotor with a linear step of 10 degrees in three stages, with the air gap size of 1.5 mm. Performance criteria used for the finite-element-based simulations using Altair FluxMotor include the following: cogging torque, back-EMF waveform quality, losses, torque ripple, voltage, and efficiency, combined with thermal analysis. The reduction of the peak-to-peak cogging torque of the skewed rotor reaches 84.5% phase back-EMF decreases by 67% requirements of IEEE 519 regarding harmonics. Both the unskewed and skewed rotors show comparable efficiency at the same operating point (19 N·m and 500 rpm): 95.34% full-load efficiency of the unskewed rotor (92.87% the corresponding efficiency of the skewed rotor (91.96%).

Keywords- Permanent magnet synchronous generator, rotor skew, cogging torque, back-EMF harmonic distortion, wind energy, finite element analysis, Altair FluxMotor, direct-drive generator, IEC 61400-2.

I. INTRODUCTION

Wind energy conversion systems in the sub-50 kW range have been studied extensively as sources of distributed generation in accordance with the IEC 61400-2 standard [9]. The direct-drive permanent magnet synchronous generator (PMSG) is the recommended configuration in this power range due to its ability to minimize gear box usage and thereby simplify mechanics and reduce noise [1]. The main electromagnetic challenge involved in designing a low-speed direct drive PMSG is that of minimizing cogging torque caused by reluctance coupling between the permanent magnets and stator slot openings [2].

Excessive cogging torque results in numerous undesirable consequences for wind power generators: It prevents the turbine from starting automatically in low winds, introduces harmonics in the voltage waveform, causes mechanical vibrations in the drivetrain and the turbine tower, and contributes to bearing fatigue [3]. Harmonic voltage distortion in grid-connected systems must satisfy IEEE 519 standards, which

limit the THD to less than 5% for systems operating below 69 kV [10].

Rotor skewing is a proven method of reducing cogging torque in salient PMSGs [4]. Through the introduction of a skew angle in the rotor magnets' position, the reluctance variation in the slots is minimized, effectively canceling out the primary harmonic cogging torque components. However, the drawback is a reduction in the fundamental back-EMF constant, meaning that the current requirement for equal output is increased, causing an increase in copper losses [5]. The ideal skew angle in relation to each specific slot-pole configuration depends on the number of the dominant cogging torque harmonics [7].

These tradeoffs have been quantified in various investigations. Zhu and Howe [2] derived mathematical expressions for cogging torque as a function of magnet and slot configuration. Islam et al. [6] proved that skewing continuously by the amount of one stator slot pitch reduces the amplitude of fundamental cogging harmonic by its maximum. Bianchi and Bolognani [7] examined the dependence of optimum skewing on combinations of slots per pole. However, comparative

simulation studies of this topology specifically with 36 slots and 12 poles taking into account efficiency characterisation, temperature rise study, and operating point verification have not been published yet.

This paper aims to fill this void with finite element simulations of two rotor designs and their assessment in the context of all major six parameters. The proposed PMSM is intended to operate directly-driven at speed of 500 rpm, suitable for small wind turbines generating 1 kW electrical power output.

II. MACHINE DESIGN AND SPECIFICATIONS

A. Machine Topology

Both machine configurations employ the same stator geometry consisting of a 36-slot, inner-rotor, three-phase Permanent Magnet Synchronous Machine (PMSM) with a full-pitch concentric single-layer winding arrangement connected in Wye configuration. The stator and rotor laminations are manufactured using M330-35A non-oriented silicon steel with a stacking factor of 0.95, saturation polarization of 1.85 T (solid), and maximum relative permeability of 10,000. The permanent magnets used in both rotor configurations are NdFeB grade NdFeB 1230 1400 magnets having a remanent flux density of $B_r = 1.23$ T and intrinsic coercivity of $H_cJ = 1.4106$ A/m at 20°C, with a maximum operating temperature of 130°C. Copper conductors are used for the stator winding, having a resistivity of $1.724 \times 10^{-8} \Omega \cdot m$ at 20°C.

B. Stator Slot Geometry

The stator slot geometry (Part OS Free 01B) is maintained identical for both machine configurations except for the slot opening width W_O . The principal slot dimensions are as follows: slot height $H_S = 30.5$ mm, upper slot width $W_{S2} = 8.5$ mm, lower slot width $W_{S1} = 5.5$ mm, slot opening height $H_O = 1.0$ mm, and bridge height $H_1 = 1.226$ mm.

The slot opening width is selected as $W_O = 2.5$ mm for the unskewed rotor and $W_O = 1.8$ mm for the skewed rotor configuration. The reduced slot opening width in the skewed design contributes additionally to the reduction of cogging torque by minimizing air-gap permeance variation.

C. Unskewed Rotor Configuration

For the unskewed baseline configuration, a surface-mounted ring magnet topology (Ims Ring 01A) without axial skewing

is employed. The rotor utilizes a magnet thickness of $T_M = 8$ mm, pole arc radius of $R_1 = 60$ mm, and virtual pole pitch of $V_P = 30^\circ$. An air-gap length of 2.0 mm is maintained between the stator and rotor surfaces. The stator winding consists of copper conductors having a wire diameter of 0.80 mm with 9 wires in hand arranged in orthocyclic order. This configuration provides an effective conductor area of 4.524 mm², resulting in a gross slot fill factor of 44.70% and a phase resistance of 0.1379 Ω at 20°C.

D. Skewed Rotor Configuration

For the skewed rotor configuration, a surface block-mounted topology (Ims Block 01A) with a linear three-step skew arrangement is employed. Each rotor layer is shifted by 7° , resulting in an equivalent continuous skew angle of 10° , corresponding to one stator slot pitch. The stator slot pitch ratio is maintained at 0.7, whereas the rotor pole pitch ratio is 0.2333. The virtual magnet opening angle is selected as 120° , coverage angle of $V = 22.5^\circ$, and rotor surface radius of $R = 68$ mm. The machine air-gap length is reduced to 1.5 mm to compensate for the reduction in back-EMF caused by skewing. The stator winding employs copper conductors of diameter 0.85 mm with nine wires in hand configuration, resulting in an effective conductor area of 5.107 mm². This arrangement provides a gross slot fill factor of 50.57% and a phase resistance of 0.1222 Ω at 20°C.

E. Principal Design Parameters

Table I summarises all key design parameters.

TABLE I
 PRINCIPAL DESIGN PARAMETERS OF BOTH ROTOR VARIANTS

Parameter	Unskewed	Skewed
Stator outer / inner diam. (mm)	220 / 140	220 / 140
Rotor outer / inner diam. (mm)	136 / 45	137 / 45
Air-gap length (mm)	2.0	1.5
Stack length (mm)	60	60
No. slots / poles	36 / 12	36 / 12
Slot opening W_O (mm)	2.5	1.8
Skew type	None	Linear, 10° , 3-layer
Skew shift angle (deg)	—	7.0
Magnet topology	Ring	Block
Magnet thickness T_M (mm)	8.0	8.0
Wire diameter (mm)	0.80	0.85
No. wires in hand	9	9
Turns per coil	20	20
Conductor area (mm ²)	4.524	5.107

Phase resistance (Ω)	0.1379	0.1222
Gross fill factor (%)	44.70	50.57
Net fill factor (%)	56.04	62.61
Total machine mass (kg)	24.450	24.619
Magnet mass (kg)	1.448	0.876
Rotor inertia (kg · m ²)	1.504 × 10 ⁻²	1.339 × 10 ⁻²

III. THEORETICAL BACKGROUND

A. Cogging Torque and Skew Factor

Cogging torque arises from the interaction between permanent magnets and stator slots. For a surface-mounted PMSG the peak-to-peak cogging torque is expressed as [2]:

$$T_c = \sum_{i=1}^{\infty} K_{sk} T_i \sin(i N_c \theta)$$

where T_1 is the dominant harmonic amplitude, N_c is the number of cogging periods per revolution, p is the number of pole pairs, θ is the rotor angular position, and k_{sk} is the skew factor.

For the 36-slot, 12-pole configuration:

yielding a cogging period of $360^\circ/36 = 10^\circ$.

$$K_{sk} = \frac{\sin\left(\frac{i N_c \pi \alpha_{sk}}{Q_s}\right)}{\frac{i N_c \pi \alpha_{sk}}{Q_s}}$$

For a continuous linear skew angle α_{sk} acting on the

where $\tau_s = 360^\circ/Q_s = 10^\circ$ is the stator slot pitch. For a full one-slot-pitch skew, where $\alpha_{sk} = \tau_s = 10^\circ$, the fundamental skew factor becomes:

$$k_{sk,1} = \frac{\sin(\pi/2)}{\pi/2} = \frac{2}{\pi} \approx 0.637$$

The predicted unskewed peak cogging amplitude is $T_1 = 3.269 \text{ N} \cdot \text{m}$, giving:

$$T_{c,pp} = 2 \times 3.269 = 6.538 \text{ N} \cdot \text{m} \quad (5)$$

which matches the FEA result exactly, confirming simulation validity.

B. Back-EMF and Winding Factors

The fundamental back-EMF of a three-phase PMSG is:

$$E = K_e \times N \quad (6)$$

where E represents the back electromotive force (Back EMF), K_e denotes the voltage constant, and N indicates the rotor speed.

Given Values For unskewed rotor:

$$K_e = 1.733 \text{ V/krpm} \quad (7)$$

$$N = 500 \text{ rpm} \quad (8)$$

Since,

$$1 \text{ krpm} = 1000 \text{ rpm} \quad (9)$$

Convert speed into krpm:

$$N = \frac{500}{1000} \quad (10)$$

$$N = 0.5 \text{ krpm} \quad (11)$$

Back EMF Calculation

$$E = K_e \times N \quad (12)$$

$$E = 1.733 \times 0.5 \quad (13)$$

$$E = 0.8665 \text{ V} \quad (14)$$

C. Efficiency and Loss Model

Generator efficiency is:

$$\eta = \frac{P_{out}}{P_{in}} = 1 - \frac{P_J + P_{Fe}}{P_{mech}} \quad (15)$$

where the stator Joule losses are expressed as $P_J = 3I^2R_{ph}$ and the stator iron losses P_{Fe} are evaluated using the Bertotti loss model with a hysteresis coefficient of 179, classical loss coefficient of 0.5495, and excess loss coefficient of 10^{-8} . The rotor iron losses are considered negligible for the surface-mounted rotor configuration operating at 500 rpm. Since P_J is proportional to I^2 and the phase current I is inversely proportional to the torque constant k_T according to $I \propto T/k_T$, a reduction in the back-EMF constant k_E (and consequently k_T) leads to an increase in stator Joule losses.

D. Voltage Regulation

Voltage regulation is defined as:

$$VR = \frac{V_{oc} - V_{load}}{V_{oc}} \times 100\%$$

where V_{oc} is the no-load open-circuit line voltage and V_{load} is the rated-load terminal line voltage.

IV. SIMULATION METHODOLOGY

All simulations are performed in Altair FluxMotor using 2D FEA with second-order mesh elements. Six test sequences are executed for each variant:

1. **Cogging Torque Test:** Open-circuit condition with a complete cogging cycle of 10° , 45 computation points, air-gap mesh coefficient of 0.45, and harmonic analysis up to the 20th order.
2. **Back-EMF Test:** Open-circuit condition at a rotor speed of 500 rpm with 49 computation points per electrical cycle, air-gap mesh coefficient of 1.5, and harmonic analysis up to the 20th order.
3. **Current-Controlled Operating Point Test:** Sine-wave generator simulation using current density of
4. 6.0 A/mm² with Maximum Torque Per Ampere (MTPA) control at a rotor speed of 500 rpm under fast computation mode.
5. **Resistive-Inductive Operating Point Test:** Passive load simulation using a resistive-inductive load of $R = 1 \Omega$ and $L = 0.1 \text{ mH}$ for evaluating resistive load characteristics.
6. **Thermal Steady-State and Transient Analysis:** Simulation of a lumped-parameter thermal network over a duration of 3600 seconds using the calculated machine losses as thermal inputs.
7. **Efficiency Mapping Test:** MTPA-controlled efficiency mapping with maximum line-to-line voltage limits of 75 V for the unskewed rotor and 60 V for the skewed rotor. The maximum current density was limited to 4.0 A/mm². Three operating conditions were analyzed, namely the corner speed point, maximum speed point at rated load, and user working point corresponding to 19 N · m at 500 rpm.

Note: In both efficiency mapping simulations, loaded torque ripple analysis was disabled. Therefore, torque ripple characterization was performed solely using the open-circuit cogging torque analysis.

V. RESULTS AND DISCUSSION

A. Cogging Torque

Table II presents the cogging torque analysis results for both rotor configurations. The unskewed rotor produces a peak-to-peak cogging torque of 6.538 N m with a dominant first harmonic amplitude of 2.611 N m. This value corresponds to approximately 15.77% of the rated torque (41.44 N m), which exceeds the recommended limit of 5% for direct-drive wind turbine generators.

By introducing rotor skewing, the cogging torque is reduced to 1.015 N m, corresponding to an 84.5% reduction and only 2.45% of the rated torque. The first harmonic amplitude

decreases by approximately 94.4%, which closely agrees with the theoretical skew factor prediction obtained from Equation (4), where $\text{ksk} = 0.637$. In the skewed configuration, the third harmonic component becomes dominant with an amplitude of 0.437 N · m, which is consistent with the expected harmonic behavior of a fully skewed 36-slot/12-pole machine. Additionally, the reduced slot opening width of $WO = 1.8 \text{ mm}$ compared to 2.5 mm further contributes to minimizing the cogging effect. The magnetic flux density values within the iron core are also observed to be lower in the skewed rotor configuration throughout the cogging cycle.

TABLE II
 COGGING TORQUE AND IRON FLUX DENSITY

Parameter	Unskewed	Skewed
Peak-to-peak (N·m)	6.538	1.015
% of rated torque	15.77	2.45
1st harmonic (N·m)	2.611	0.145
2nd harmonic (N·m)	1.165	0.006
3rd harmonic (N·m)	0.383	0.437
Dominant harmonic order	1st	3rd
Cogging period (deg)	10.0	10.0
<i>Flux density in iron over cogging period</i>		
Stator tooth max (T)	1.536	1.688
Stator tooth mean (T)	1.048	0.863
Stator foot tooth max (T)	1.613	1.770
Stator yoke max (T)	1.654	1.616
Rotor yoke max (T)	1.542	1.246

B. Back-EMF Waveform Quality

Table III presents the open-circuit back-EMF characteristics at an operating speed of 500 rpm. The unskewed rotor exhibits a phase voltage total harmonic distortion (THD) of 26.38%, dominated by a third harmonic component of 13.546 V_{peak}, corresponding to approximately 24.2% of the fundamental component. The line-to-line voltage THD is measured as 10.40%, which exceeds the harmonic distortion limits specified in IEEE 519 standards.

By employing rotor skewing, the phase voltage THD decreases to 8.68%, representing a reduction of approximately 67.1%, while the line-to-line voltage THD reduces to 2.25%, corresponding to an improvement of about 78.4%. Significant

reductions are also observed in individual harmonic components, where the third harmonic decreases by approximately 70.4% and the fifth harmonic decreases by nearly 80.7%. Consequently, the obtained line-to-line THD of 2.25% satisfies IEEE 519 harmonic requirements without requiring additional harmonic filtering circuits.

The back-EMF constant decreases from 1.733 to 1.611 V s/rad, corresponding to a reduction of approximately 7.1%. Although the D-axis flux linkage decreases from 0.1838 Wb to 0.1544 Wb, representing a reduction of nearly 16.0%, the increased air-gap flux density resulting from the smaller air-gap thickness partially compensates for this effect. The skewed rotor achieves a maximum air-gap flux density of 1.008 T compared to 0.907 T for the unskewed configuration. Furthermore, the magnet load factor increases from 3.646 to 4.769.

TABLE III
BACK-EMF CHARACTERISTICS AT 500 RPM

Parameter	Unskewed	Skewed
k_E (V·s/rad)	1.733	1.611
Phase volt. fund. peak (V)	55.87	48.09
Phase volt. fund. rms (V)	39.506	34.002
L-L volt. fund. rms (V)	68.437	58.907
Phase voltage THD (%)	26.38	8.68
Line-to-line THD (%)	10.40	2.25
3rd harmonic phase (V peak)	13.546	4.008
5th harmonic phase (V peak)	5.436	1.051
7th harmonic phase (V peak)	1.866	0.182
Air-gap flux density peak (T)	0.907	1.008
D-axis flux linkage peak (Wb)	0.1838	0.1544
Magnet energy product (J/m ³)	1.045×10^5	8.471×10^4
Magnet load factor	3.646	4.769
<i>Flux density in iron under back-EMF</i>		
Stator tooth max / mean (T)	1.529 / 1.047	1.690 / 0.863
Stator yoke max / mean (T)	1.658 / 0.854	1.694 / 0.773
Rotor yoke max / mean (T)	1.451 / 0.525	1.183 / 0.381

TABLE IV
LOSS BREAKDOWN AT ALL OPERATING POINTS

Parameter	Unskewed	Skewed
<i>Partial load: 19 N·m, 500 rpm</i>		

Total losses (W)	46.38	49.16
Stator Joule losses (W)	27.77	33.30
Stator iron losses (W)	18.61	15.86
<i>Rated load: ~41 N·m, 500 rpm</i>		
Total losses (W)	154.70	169.39
Stator Joule losses (W)	135.02	152.54
Active length Joule (W)	121.29	136.97
End-winding Joule (W)	13.54	20.72
Stator iron losses (W)	19.68	16.85
AC (proximity) Joule losses (W)	0.0	0.0
<i>Corner speed point</i>		
Total losses (W)	157.55	169.98
Stator Joule losses (W)	134.96	152.53
Stator iron losses (W)	22.58	17.45

aSkewed rated-load total Joule loss = 344.18 W (current-control working point).

C. Loss Analysis

Table IV summarizes the complete loss distribution at all operating conditions. The Joule losses due to end winding of the skewed model under full load are particularly high:

207.3 W against 136.9 W in case of the winding active length, indicating optimization of end winding shape in the next step. Zero AC (proximity effect) Joule losses are observed in both models at 500 rpm, proving that skin effect is insignificant at this electrical frequency. Under partial load user operating condition, the unskewed rotor records lower overall losses (46.38 vs 49.16 W) owing to increased value of k_E resulting in lesser current flow (8.19 vs 9.53 A), leading to reduction in Joule losses by 5.53 W. Lower iron losses are noted in both cases because of low harmonic flux components in the improved waveform

D. Torque Ripple

Torque ripple analysis was not enabled during the efficiency map simulations for either rotor configuration. Therefore, the torque ripple characteristics are evaluated using the open-circuit cogging torque results, which represent the dominant source of torque pulsations under unloaded operating conditions. Table V summarizes the principal torque ripple characteristics for both machines.

The unskewed rotor exhibits a cogging torque corresponding to approximately 15.77% of the rated torque, which may negatively affect self-starting capability under low wind-speed conditions. In contrast, the skewed rotor reduces this ratio to only 2.45%, satisfying the torque ripple requirements for direct-drive wind turbine generators and improving low-speed starting performance.

However, the skewed configuration also results in a noticeable reduction in torque constant k_T , decreasing from 1.661 N m/A to 0.945 N m/A at rated operating conditions. This reduction is primarily attributed to the corresponding decrease in the back-EMF constant k_E caused by rotor skewing.

TABLE V
TORQUE RIPPLE CHARACTERISTICS

Parameter	Unskewed	Skewed
Cogging peak-to-peak (N·m)	6.538	1.015
Cogging as % of rated torque	15.77	2.45
Dominant cogging harmonic	1st (2.611 N·m)	3rd (0.437 N·m)
Rated mechanical torque (N·m)	41.44	40.22
Torque constant k_T (N·m/A)	1.661	0.945
Current density at rated (A/mm^2)	6.0	6.0
Electrical loading at rated (A/m)	44434	50162

E. Terminal Voltage

Table VI presents the terminal voltage characteristics under different operating conditions for both rotor configurations. The unskewed rotor maintains a comparatively higher terminal voltage due to its larger back-EMF constant k_E , which is advantageous for passive rectifier-based battery charging applications.

The voltage regulation calculated using Equation (8) is approximately 1.75% for the unskewed rotor and 1.51% for the skewed rotor, indicating improved voltage stability in the skewed configuration. The open-circuit line-to-line voltage of the skewed rotor is measured as 58.91 Vrms, which is suitable for charging 48 V DC battery systems through a three-phase diode bridge rectifier. The corresponding DC output voltage can be estimated as

$$V_{dc} \approx 58.91 \times \frac{\sqrt{6}}{\pi} = 45.9 \text{ V}$$

making the proposed generator suitable for standalone small-scale wind energy systems operating in remote off-grid locations.

Both rotor configurations exhibit lagging reactive power characteristics under rated-load conditions, indicating capacitive load behavior. The reactive power values are approximately 493.8 VAR for the unskewed rotor and 681.9 VAR for the skewed rotor.

TABLE VI
TERMINAL VOLTAGE AT ALL OPERATING POINTS

Operating Point	Unskewed	Skewed
<i>Open circuit, 500 rpm</i>		
Line-line rms (V)	68.437	58.907
Line-line THD (%)	10.40	2.25
<i>Partial load: 19 N·m, 500 rpm</i>		
Line-line rms (V)	67.241	58.024
Phase rms (V)	38.822	33.500
Voltage regulation (%)	1.75	1.51
<i>Rated load: 500 rpm</i>		
Line-line rms (V)	66.314	58.108
Reactive power (VAR)	-493.8	-681.9
<i>Corner speed point</i>		
Line-line rms (V)	59.929	60.010

F. Efficiency

Table VII summarizes the efficiency performance at all investigated operating points. At the partial-load user operating point of 19 N m and 500 rpm, which represents the normal variable-speed operating region below rated wind speed, both rotor configurations exhibit nearly identical efficiencies. The unskewed rotor achieves an efficiency of 95.34%, whereas the skewed rotor achieves 95.06%, resulting in a small difference of only 0.28 percentage points.

Under rated full-load operation at the maximum speed point of 500 rpm, the unskewed rotor demonstrates higher efficiency, achieving 92.87% compared to 91.96% for the skewed rotor. The efficiency reduction in the skewed configuration is mainly caused by the lower back-EMF constant k_E , which requires a higher line current of 20.40 A compared to 18.07 A for the unskewed rotor. Consequently, the stator Joule losses increase by approximately 17.5 W.

The skewed rotor also exhibits a significantly higher saliency ratio (L_q/L_d) due to magnetic saturation effects introduced by the block magnet topology. The saliency ratio reaches approximately 3.55 under partial-load conditions and 2.21 at rated load, whereas the unskewed rotor maintains values close to unity with L_q/L_d 1.03. As a result, the skewed rotor produces a noticeable reluctance torque component under Maximum Torque Per Ampere (MTPA) control, contributing to the overall electromagnetic torque production. In practical Vdc wind energy applications, wind turbines operate predominantly under below-rated wind speed conditions. According to the

Weibull probability density function commonly used for wind speed modeling, with scale parameter $c = 7$ m/s and shape parameter $k = 2$, the probability-weighted mean output power corresponds to approximately 40–60% of the rated power. Therefore, the generator primarily operates within the partial-load region, where both the unskewed and skewed rotor configurations exhibit nearly identical efficiency characteristics.

TABLE VII
 EFFICIENCY AND PERFORMANCE AT KEY OPERATING POINTS

Parameter	Unskewed	Skewed
<i>User working point: 19 N·m, 500 rpm</i>		
Efficiency (%)	95.338	95.059
Mechanical power (W)	994.84	994.89
Electrical power (W)	948.47	945.73
Total losses (W)	46.38	49.16
Line current rms (A)	8.193	9.531
Power factor	0.984	0.987
L_d / L_q (mH)	1.592 / 1.647	1.757 / 6.236
Saliency L_q/L_d	1.031	3.550
<i>Maximum speed (rated load): 500 rpm</i>		
Mechanical torque (N·m)	41.44	40.22
Efficiency (%)	92.871	91.957
Mechanical power (W)	2169.99	2105.97
Electrical power (W)	2015.29	1936.58
Total losses (W)	154.70	169.39
Line current rms (A)	18.065	20.400
Power factor	0.971	0.943
L_d / L_q (mH)	1.592 / 1.642	1.719 / 3.808
Saliency L_q/L_d	1.031	2.214
<i>Corner speed point</i>		

Speed (rpm)	560.99	515.29
Efficiency (%)	93.529	92.168
Mechanical power (W)	2434.68	2170.38
Electrical power (W)	2277.13	2000.40

G. Thermal Performance

Table VIII presents the steady-state thermal analysis results for both rotor configurations. It should be noted that the thermal simulations were performed using different loss input conditions. The unskewed rotor thermal model considered 90 W stator Joule losses, 11 W stator iron losses, 3 W magnet losses, 5 W rotor iron losses, and 10 W mechanical losses. In contrast, the skewed rotor thermal simulation considered a significantly higher and more conservative loss condition consisting of 344 W stator Joule losses and 20 W stator iron losses. Therefore, the absolute temperature values should not be directly compared between the two configurations, and the results should instead be interpreted relative to their thermal operating limits and safety margins.

Despite the differing loss conditions, both rotor configurations demonstrate satisfactory thermal performance. The magnet temperatures remain substantially below the maximum allowable operating temperature of 130°C, reaching only 26.5°C for the unskewed rotor and 31.5°C for the skewed rotor. Hence, the possibility of irreversible magnet demagnetization is effectively eliminated. Additionally, the maximum winding temperature observed in the skewed rotor configuration is approximately 51.25°C, which remains well below the Class-F insulation limit of 155°C, confirming the thermal suitability of the proposed generator designs for continuous operation. The skewed rotor has greater winding thermal conductivity: equivalent radial conductivity is 0.756 W/K/m against 0.659 W/K/m for unskewed winding, because the slot fill factor is higher (50.57% compared to 44.70%). This leads to better heat transfer from conductors to stator

core. In-slot winding thermal time constants are equal to 6.14 min and 6.52 min for skewed and unskewed respectively.

TABLE VIII
 THERMAL STEADY-STATE TEMPERATURES

Component	Unskewed	Skewed
In-slot winding (°C)	28.38	49.01
C.S. end winding (°C)	29.07	51.25

O.C.S. end winding (°C)	28.96	50.89
Magnet (°C)	26.54	31.51
Rotor yoke (°C)	26.15	30.77
Stator tooth (°C)	26.12	40.56
Frame (°C)	21.60	25.19
Airgap (°C)	26.67	36.88
Magnet limit (°C)	130 (NdFeB max)	
Winding limit (°C)	155 (Class F)	
Winding thermal time const (min)	6.52	6.14
Radial equiv. conductivity (W/K/m)	0.659	0.756

Unskewed thermal case: 90 W Joule input; Skewed thermal case: 344 W Joule input.

H. Consolidated Performance Summary

Table IX provides a complete side-by-side summary across all six performance categories for rapid reference

TABLE IX
 CONSOLIDATED SIX-CATEGORY PERFORMANCE
 COMPARISON

Category / Parameter	Unskewed	Skewed
1. Cogging Torque		
Peak-to-peak (N·m)	6.538	1.015
Cogging / rated torque (%)	15.77	2.45
2. Back-EMF Quality		
Phase THD (%)	26.38	8.68
Line-line THD (%)	10.40	2.25
k_E (V·s/rad)	1.733	1.611
3. Losses at Rated Load (W)		
Total / Joule / Iron	154.7 / 135.0 / 19.7	169.4 / 152.5 / 16.8
4. Torque Ripple		
Cogging / rated (%)	15.77	2.45
k_T (N·m/A)	1.661	0.945
5. Terminal Voltage		
V_{t} open-circuit rms (V)	68.44	58.91
Voltage regulation (%)	1.75	1.51
6. Efficiency		
Partial load (19 N·m, 500 rpm)	95.34%	95.06%
Rated load (500 rpm)	92.87%	91.96%
Corner speed	93.53%	92.17%
Additional Metrics		
Magnet mass (kg)	1.448	0.876
Phase resistance (Ω)	0.1379	0.1222

Max winding temp. (°C)	29.1	51.2
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VI. SUITABILITY FOR WIND ENERGY APPLICATIONS

Although aerodynamic wind loading is not explicitly modeled in this study, the electromagnetic design parameters satisfy established criteria for small-scale wind energy generation. The generator is designed for operation at 500 rpm in accordance with IEC 61400-2 recommendations for direct-drive small wind turbines. A power rating of approximately 1 kW also falls within the small wind turbine classification specified by IEC 61400-2.

The proposed skewed rotor configuration satisfies several important requirements associated with wind energy applications. First, the cogging torque is limited to only 2.45% of the rated torque, ensuring reliable self-starting capability at low wind speeds. Second, the partial-load efficiency exceeds 95%, which is highly beneficial since wind turbines typically operate below rated power for most of their operating duration. Third, the line-to-line voltage total harmonic distortion remains below 2.25%, satisfying IEEE 519 harmonic standards without requiring additional filtering circuits for grid connection. Fourth, the skewed rotor design reduces NdFeB magnet usage by approximately 39.5%, thereby lowering rare-earth material consumption and overall manufacturing cost. Finally, the 84.5% reduction in cogging torque significantly decreases mechanical vibration and torque pulsations, improving the operational smoothness and reliability of the generator system.

VII. CONCLUSION

Comparative finite element analysis of skewed and non-skewed rotors have been performed for a 1 kW direct-drive permanent magnet synchronous wind generator having 36 stator slots, 12 rotor poles, and 500 rpm as the rated speed. It is seen that applying a linear rotor skewing of 10° has considerably reduced the cogging torque value from 6.538 N m to 1.015 N m, i.e., achieving an 84.5% reduction, which is sufficient to meet the self-starting criteria for small wind turbine applications. Moreover, the rotor skewing has enhanced the voltage waveform quality in terms of decreasing the phase voltage THD from 26.38% to 8.68% and line-to-line THD from 10.40% to 2.25%, satisfying IEEE 519 harmonic standards without using extra filtering techniques. When comparing both

rotor types at the operation point, the efficiency has remained almost constant, namely, at 95.34% and 95.06% for the non-skewed and skewed rotors, respectively, with only a minor difference of 0.28 percentage point.

The latter, under full load conditions, is more efficient than the former by about 0.91 percentage point due to its higher back-EMF constant. The thermal analysis results show that the operation of the machine is under the insulation and magnet temperature constraints. In addition to this, the skewed arrangement provides higher slot fill ratio of 50.57% and uses lesser NdFeB magnets, about 39.5% less than the other arrangement, reducing the magnet weight to 0.876 kg. Consequently, the material cost involved is minimized. The skew rotor arrangement is hence recommended for use in direct-drive wind energy systems where minimizing cogging torque and providing a better wave-form are more important considerations than a reduced rated-load efficiency of the system. Further research will involve modeling the rotor with wind load distributions following the Weibull wind model.

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