



Enhancement of Stability and Power Quality in Salient-Pole Synchronous Generators via Rotor Flux Barriers for Quadrature-Axis Reactance Control

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ABSTRACT

Building upon our previous research (Kim et al. 2023), which conclusively established the rotor flux barrier as an effective method for selectively reducing quadrature-axis synchronous reactance (X_q), this study addresses a crucial question that arose from those findings. While Kim et al. (2023) successfully demonstrated the feasibility of reducing, it left a significant research gap: the systematic cause-and-effect relationship between this change and the resulting improvements in overall performance. This paper moves beyond merely modifying parameters to explore the cascading effects of reduction on the core operational characteristics of the generator. Our primary objective is to quantitatively trace the pathway from the implementation of the flux barrier to simultaneous enhancements in three interconnected performance metrics: steady-state stability (through load angle reduction), power quality (via improved voltage regulation), and operational efficiency (through reduced braking torque). To accomplish this, we employ a combined approach of theoretical analysis and experimental validation. Through rigorous finite-element analysis and testing on a 50 kVA prototype, we provide definitive evidence of the system-level benefits associated with controlled reduction. This work confirms that flux barriers serve not just as a technique for reactance suppression, but as a comprehensive structural enhancement strategy that addresses multiple performance objectives in a unified manner, particularly for salient-pole synchronous generators operating without damper windings.

1. INTRODUCTION

Salient-pole synchronous generators are essential power sources in isolated systems where grid support is unavailable, such as marine vessels, offshore platforms, and remote microgrids (Pyrhönen et al. 2008).

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In these applications, generators must maintain operational stability despite sudden load changes while delivering high-quality power to sensitive loads. Two critical performance metrics in this context are transient stability, which is characterized by the load angle (δ), and power quality, primarily determined by voltage regulation capability (Sumina et al., 1010). The load angle represents the angular difference between the rotor and stator magnetic fields, where a smaller angle under specific load conditions indicates a greater stability margin. Voltage regulation, defined as the percentage voltage drop from no-load to full-load conditions, directly affects the performance of connected equipment (Chau, 2015). Balancing small load angles and excellent voltage regulation is a fundamental challenge in generator design, as these objectives often involve competing design requirements.

The quadrature-axis synchronous reactance (X_q) is a key parameter influencing both stability and voltage characteristics in salient-pole machines. A reduction in X_q significantly increases this reluctance power component, shifting the entire power-angle curve upward and enabling greater power transmission at smaller load angles, thereby enhancing transient stability limits (Despalatovic et al., 2008). Additionally, from a voltage regulation standpoint, X_q is a major component of the machine's internal impedance as indicated by the simplified voltage phasor diagram. The voltage drop under load conditions ($\Delta U \approx I \cdot X_q$) is directly proportional to X_q , making its reduction crucial for improving voltage regulation performance. Despite this understanding, conventional design approaches have offered limited capability for selectively controlling X_q without compromising other performance aspects.

Building on our prior research (Kim et al. 2023), titled "Reduction of Quadrature Armature Reaction in Salient-Pole Synchronous Generator by Rotor Flux Barrier," this study addresses a critical follow-up question.

In our earlier work, we introduced a novel rotor design that incorporates strategically positioned flux barriers, comprehensively validated for efficacy through finite-element analysis and experimental testing on a 50 kVA prototype. This research conclusively demonstrated reductions in X_q of approximately 28~32% compared to conventional designs, without significantly affecting direct-axis characteristics. The flux barriers operated by selectively obstructing the quadrature-axis magnetic path, thereby reducing the corresponding armature reaction while maintaining optimal direct-axis flux distribution. However, while this proved the feasibility of the method for controlling reactance, it also led to a deeper investigation. The pivotal question remained: what is the comprehensive impact of this reduction in X_q on the overall operational performance of the generator?

While reducing a parameter is academically interesting, its practical relevance is validated only through demonstrable improvements in system-level performance. Therefore, systematically quantifying how the reduction in X_q translates into enhancements across key performance indicators—specifically, steady-state load angle, voltage regulation, and braking torque characteristics—became essential for continuing the research initiated in our earlier study (Kim et al. 2023).

It is important to note that while flux barriers have been explored in other machine types, including permanent magnet synchronous machines (Yamazaki et al. 2013; Salminen, 2006) and synchronous reluctance motors (Dziechciarz & Martis, 2017), their application and systematic performance analysis in conventional salient-pole synchronous generators represent a unique contribution from this research line, beginning with the earlier study and continuing here. Previous research on other machine types primarily focused on torque density improvement and field weakening capability, whereas stability and voltage regulation enhancements in conventional generators remained largely unexplored until our initial work. This paper is conceived as a direct and systematic sequel to our earlier study (Kim et al. 2023).

We present a comprehensive investigation that moves beyond mere parameter modification to a holistic performance evaluation. Our primary objective is to quantitatively trace the cause-and-effect relationship from the flux barrier-induced reduction in X_q , as established in our previous research, to the resulting changes in the most critical operational characteristics of the generator.

The research utilizes a rigorous methodology that combines advanced finite-element analysis (FEA) with comprehensive experimental validation on a 50 kVA, 4-pole, 60 Hz salient-pole synchronous generator prototype, using ANSYS Electromagnetics Suite 2021 R1. The FEA simulations incorporated the nonlinear BH characteristics of D24-50 and DW360-50 laminations, accurately modeling saturation effects under loaded conditions (Chan et al., 2009; Liang et al., 2016).

For experimental validation, a digital load angle measurement system was specifically designed and implemented to accurately capture variations in load angle. This system operated on the principle of direct measurement via precise phase comparison between the rotor position sensor signal and the generator's reference voltage. Voltage regulation tests were conducted at a 0.8 power factor to evaluate improvements in voltage stability under inductive load conditions. While a comprehensive analysis of braking torque was performed through detailed FEA simulations, the experimental validation of braking torque characteristics will be addressed in future research as part of our ongoing investigation into dynamic performance aspects.

The findings of this work contribute two key insights: first, they provide concrete quantitative evidence that links structural design changes to overall system-level performance improvements; second, they advance the understanding of the rotor flux barrier from a mere reactance reduction technique to a holistic design strategy aimed at enhancing both generator stability and power quality. The detailed dimensions and position of the flux barrier implemented in the 50 kVA prototype are illustrated in Fig. (1). This supports the full potential of the concept originally introduced in previous research, effectively connecting structural innovation to its operational benefits. Additionally, the established correlations between the reduction of X_q and performance improvements offer valuable design guidelines for developing next-generation generators intended for critical isolated power systems (Boldea, 2015a, 2015b). Table 1 shows the geometry of the flux barrier in the 50 kVA prototype.

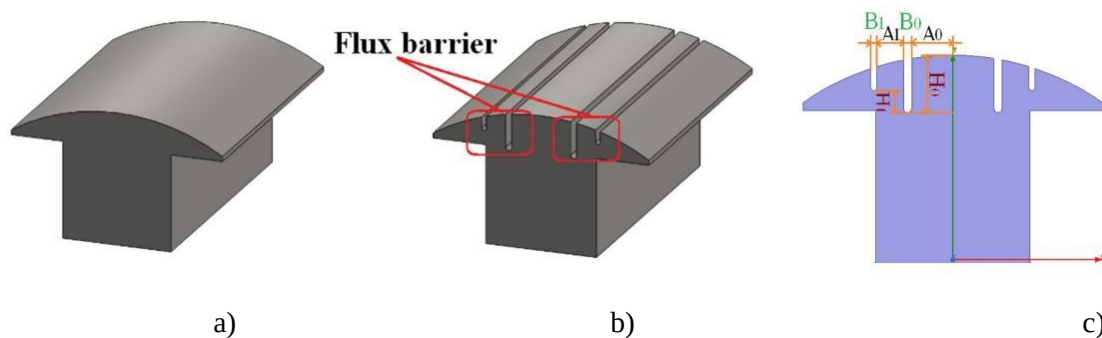


Fig 1. Rotor geometry of the 50 kVA, 4-pole salient-pole synchronous generator prototype: (a) conventional rotor without flux barriers, (b) proposed rotor with flux barriers, (c) detailed dimensions of the flux barrier.

Table 1. Main geometry data of the flux barrier

Parameters	B_0	B_1	A_0	A_1	H_0	H_1
(mm)	4	3	21	14	25	10

2. THEORETICAL AND NUMERICAL INVESTIGATION OF ELECTROMAGNETIC PERFORMANCE CHANGES

This section presents a theoretical framework for quantitatively analyzing how the reduction in X_q , achieved through the flux barriers introduced earlier, directly impacts three key operational characteristics: electromagnetic torque composition, load angle stability, and voltage regulation performance. The analysis integrates fundamental machine theory with numerical validation.

Generally, the electromagnetic power P_e is the active power component produced by the no-load electromotive force E_0 of a synchronous generator. Alternatively, the electromagnetic power can be described as the mechanical power absorbed by the electromagnetic torque generated by the load current flowing in the armature. From this, the power equation of a synchronous machine is expressed, taking into account the effects of the synchronous reactances.

$$P_e = \frac{mE_0U}{X_d} \sin\delta + \frac{mU^2}{2} \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \sin 2\delta \quad (1)$$

Here,

P_e : Electromagnetic power

m : Number of phases

E_0 : No-load electromotive force

δ : Load angle

U : Armature terminal voltage

These variations in synchronous reactance induce corresponding changes in specific electromechanical characteristics of synchronous machines.

As mentioned previously, the armature reaction field produced by the load current can be decomposed into direct-axis and quadrature-axis components for analysis. The flux barriers have a negligible influence on the direct-axis reaction field but significantly affect the quadrature-axis reaction field. Therefore, this section provides a comparative analysis of the roles played by the direct- and quadrature-axis armature reaction fields in synchronous machines, and the resulting changes in various electromagnetic characteristics caused by the reduction of X_q due to the flux barriers.

2.1 Influence of Flux Barriers on Electromagnetic Torque

2.1.1 Finite Element Analysis Setup

To quantitatively evaluate the electromagnetic performance, a two-dimensional finite element model of the 50 kVA, 4-pole, 60 Hz salient-pole synchronous generator was developed using ANSYS Electromagnetics Suite 2021 R1 (Transient Magnetic solver). The main ratings of the simulated generator are summarized in Table 2, and the key geometric parameters are listed in Table 3. The model geometry was constructed based on the exact dimensions of the manufactured prototype, including stator slots, rotor poles, field windings, and—for the proposed design—the flux barriers illustrated in Fig. (1).

Model dimension and symmetry: A 2D cross-sectional model was employed, assuming negligible end effects. To reduce computational cost, only one quarter of the machine (one pole pitch) was modeled using periodic boundary conditions (master–slave boundaries) at the lateral edges.

Table 2. Rating of the simulated generator

Rated quantity	Value	Unit
Apparent power	50	kVA
Power factor	0.8	-
Terminal voltage	380	V
Frequency	60	Hz
Number of poles	4	-
Excitation voltage	130	V
Excitation current	9.5	A

Table 3. Main geometry data of generator

Parameter	Value	Unit
Stator outer diameter	395	mm
Stator inner diameter	280	mm
Active length	170	mm
Air gap length (minimum at pole center)	1	mm
Stator slot opening	10.5	mm
Stator slot total height	17	mm
Number stator slots	48	-
Number of slots per phase and per pole	4	-
Number of conductors in a slot	12	-
Number of field winding turns per pole	320	-
Field winding pole width	75	mm
Field winding pole height	66	mm
Field winding conductor dimension	1.6	mm

Boundary conditions: A vector potential boundary ($A = 0$) was applied to the outer circumference of the stator and the inner circumference of the rotor shaft. The master–slave boundaries were assigned along the radial lines at the pole pitch boundaries with a phase shift corresponding to one pole pitch.

Mesh Refinement in Iron Bridges: The flux barriers create narrow iron bridges (approximately 1.5 mm thick) between the barrier and the rotor surface, where severe magnetic saturation occurs. To accurately capture the nonlinear permeability in these critical regions, local mesh refinement was applied. The maximum element size in the iron bridge areas was reduced to 0.3 mm, ensuring at least 5 layers of elements across the bridge thickness. This refinement allows the nonlinear B-H characteristics (Annexes A, B) to be resolved with high accuracy across the steep saturation gradient. The global mesh statistics in Table 4 represent the average element size in the core, while the refined regions have significantly finer mesh as described. The total number of elements, approximately 25,300 as listed in Table 4, includes this local refinement and reflects the actual mesh density used in the simulations.

Excitation and solution setup: Two types of magnetostatic solutions were performed:

- Field excitation only with pure d-axis armature current ($I_d=I_a$, $I_q=0$) to evaluate the d-axis armature reaction.
- Field excitation only with pure q-axis armature current ($I_q=I_a$, $I_d=0$) to evaluate the q-axis armature reaction and reluctance torque.

Post-processing: The electromagnetic torque was computed using Maxwell stress tensor method along the air-gap contour.

Table 4. Summary of the 2D finite element analysis parameters.

Parameter	Value	Unit
Model dimension	2D cross-section	–
Symmetry	1/4 model (one pole pitch)	–
Max. element size in air gap	0.2	mm
Max. element size in cores	2.0	mm
Total number of elements	~25 300	–
Material	Rotor core	D24-50 (Appendix A)
Material	Stator core	DW360-50 (Appendix B)

It should be noted that the FEA model employed a uniform air gap assumption with a constant length of 1 mm. This value corresponds to the minimum air gap at the pole center of the actual salient-pole machine, which has a non-uniform air gap characteristic due to its pole shape. The uniform gap assumption was adopted to maintain consistency with the analytical model and to isolate the effect of the flux barriers by keeping all other parameters identical between the conventional and proposed designs. Although this simplification does not fully represent the actual non-uniform geometry, the comparative analysis between the two designs remains valid as both models share the same assumption. Furthermore, the experimental validation on the actual prototype (with non-uniform air gap) confirms the predicted performance improvements, as shown in Figs. (13) and (14), demonstrating that the simplification does not compromise the core conclusions.

2.1.2 Theoretical Analysis of Torque Components

In the general electromechanical analysis of synchronous machines, a prevailing view is that "without quadrature-axis reaction, there is no electromechanical energy conversion." This implies that changes in the quadrature-axis reaction can be a critical factor affecting the power output of synchronous machines, and thus, the alteration of quadrature-axis reaction by flux barriers can significantly influence the electromagnetic torque variation.

While numerous explanations exist regarding the roles of the armature reaction fields, the impact of flux barriers on electromagnetic torque is elucidated here using one of the most generalized methods. This method is explained using the principle of minimum reluctance, which states that magnetic flux always seeks the path of least resistance through a magnetic circuit.

Typically, a magnet is considered to have N and S poles. The direct-axis armature reaction field serves to weaken or strengthen the main field flux but cannot completely nullify it. Consequently, the resultant magnetic field fundamentally follows the path of the field flux. As shown in Fig. (2a), opposing polarities are established between the stator and rotor, resulting in a magnetic attraction force. However, this force is directed radially at each pole and does not have a tangential component. Fig. (2b) illustrates the corresponding configuration with flux barriers.

Since rotational torque acts in the tangential direction, these radial forces do not generate any rotational torque. Simply put, this state is analogous to a no-load condition where no current flows in the armature, or to conditions like a purely inductive load or a three-phase sustained short-circuit test used to evaluate generator characteristics. In both these cases, no electromagnetic power is produced, and thus, there is

no electromagnetic torque. The case with axial grooves in the poles results in a similar state and will not be discussed separately.

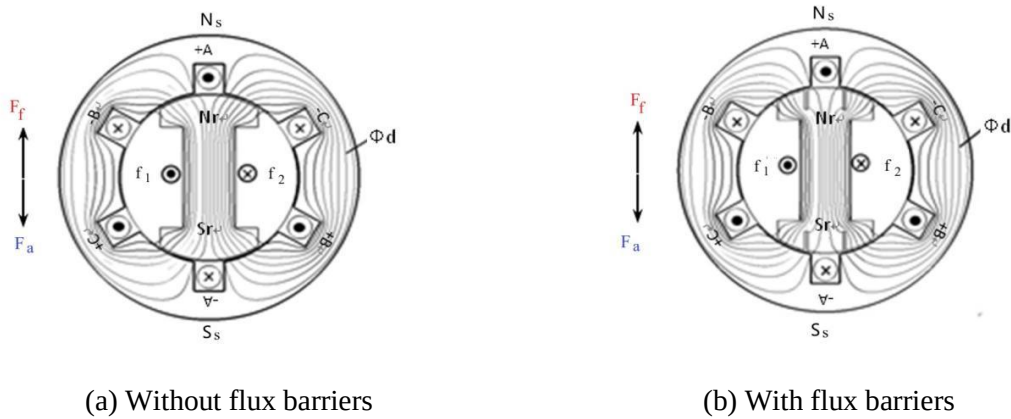


Fig 2. Conceptual diagram illustrating the force interaction between the direct-axis armature reaction field and the main field: (a) without flux barriers, (b) with flux barriers. The actual geometry and dimensions of the flux barriers implemented in the 50 kVA prototype are shown in Fig. (1).

However, in the case of the quadrature-axis armature reaction field, the direction of the rotor poles and the poles of the reaction field are oriented perpendicularly to each other, as shown in Figs. (3a) and (3b). Consequently, opposing polarities generate an attractive force, which creates a force couple acting in the tangential direction. Therefore, a rotational torque is produced, which constitutes the electromagnetic power output. Fig. (3b) shows the configuration with flux barriers, where the tangential force is reduced due to the increased reluctance in the quadrature-axis path. This attractive force can be calculated based on the principle of minimum reluctance, and its magnitude is related to the maximum and minimum permeance.

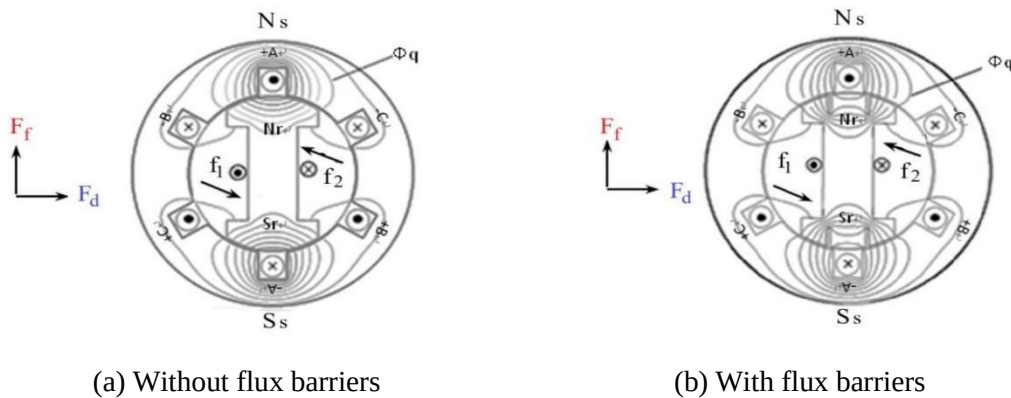


Fig 3. Conceptual diagram illustrating the force interaction between the quadrature-axis armature reaction field and the main field: (a) without flux barriers, (b) with flux barriers.

Since permeance is proportional to the magnitude of the magnetic flux, introducing grooves at the pole tips results in a lower permeance compared to the original structure. Consequently, the tangential force decreases, leading to a corresponding reduction in torque.

2.1.3. Numerical Validation of Torque Reduction

To provide numerical validation of the aforementioned theories, models with and without flux barriers were developed under identical structural and electromagnetic load conditions. The electromagnetic

torque acting on the rotor was then evaluated for cases involving only quadrature-axis and direct-axis armature reaction currents, respectively.

The equipotential magnetic line distributions for the conventional and proposed designs under d-axis armature reaction are shown in Fig. (4) and Fig. (5), respectively.

Fig. (6) and Fig. (7) present the corresponding distributions under q-axis armature reaction.

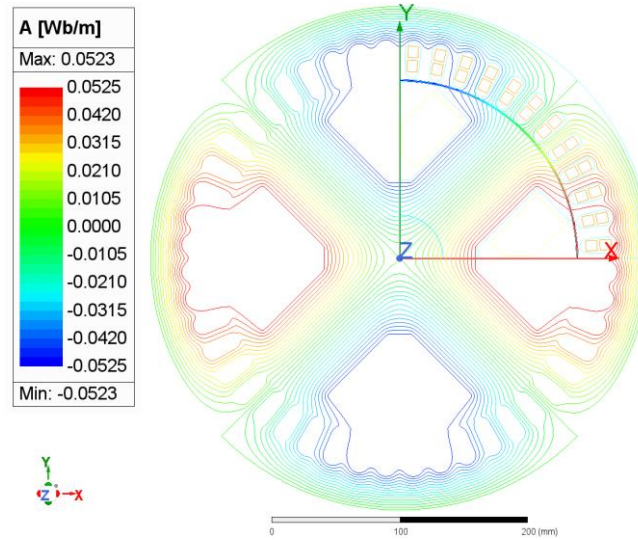


Fig 4. Equipotential magnetic line diagram of the 50 kVA, 4-pole, 60 Hz salient-pole synchronous generator prototype with only field current and direct-axis armature reaction current, without flux barriers.

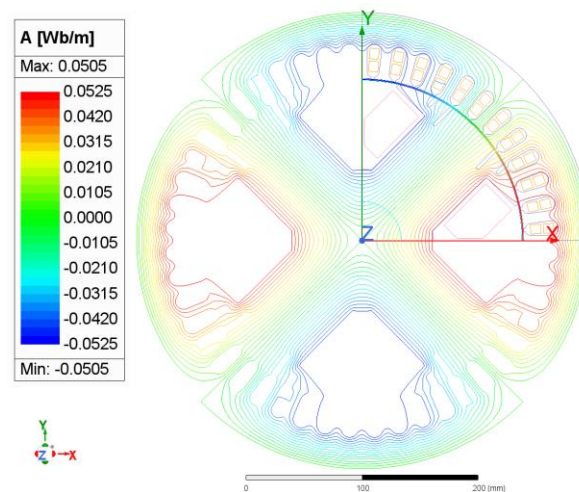


Fig 5. Equipotential magnetic line diagram of the 50 kVA, 4-pole, 60 Hz salient-pole synchronous generator prototype with only field current and direct-axis armature reaction current, with flux barriers.

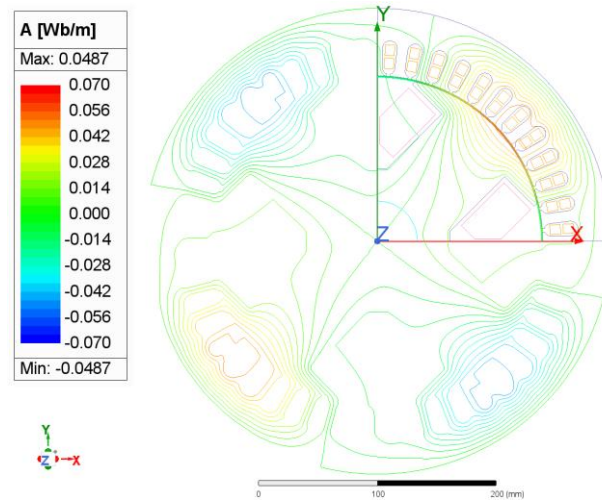


Fig 6. Equipotential magnetic line diagram of the 50 kVA, 4-pole, 60 Hz salient-pole synchronous generator prototype with only field current and quadrature-axis armature reaction current, without flux barriers.

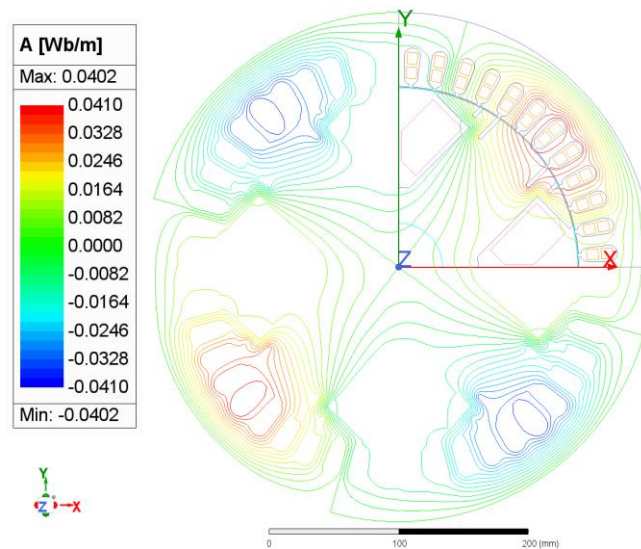


Fig 7. Equipotential magnetic line diagram of the 50 kVA, 4-pole, 60 Hz salient-pole synchronous generator prototype with only field current and quadrature-axis armature reaction current, with flux barriers.

Table 5 presents the electromagnetic torque components of the 50 kVA, 4-pole, 60 Hz salient-pole synchronous generator prototype under pure d-axis and pure q-axis armature reaction currents (FEA results, rated field current, rated armature current).

Table 5. Torque evaluation due to armature reaction.

Configuration	Torque with only direct-axis armature reaction current (Nm)	Torque with only quadrature-axis armature reaction current (Nm)	Reduction in braking torque (%)
SG	0.0316	-15.1246	-
SG with FB	0.014	-11.0167	27.2

The rated torque of the machine is 212.2 Nm at 40 kW, 1800 r/min. The q-axis torque under pure q-axis current excitation corresponds to 7.13% (conventional) and 5.19% (with FB) of rated torque, which is within the typical range (5–10%) for salient-pole synchronous generators without damper windings. The near-zero d-axis torque (<0.04 Nm) confirms the correct d-axis alignment and the numerical accuracy of the FEA model.

The electromagnetic braking torque of a salient-pole synchronous generator is clearly distinguished into two components: the fundamental braking torque essential for electromechanical power conversion, and the parasitic braking torque induced exclusively by the quadrature-axis (q-axis) armature reaction. The fundamental braking torque is the core torque component that converts the rotor's mechanical input power into electrical output power, and it remains unchanged for the same rated electrical output when the flux barrier is implemented. In contrast, the parasitic braking torque is an additional torque component that contributes no effective power transmission, but instead gives rise to q-axis related parasitic losses including stray load loss and harmonic core loss. The reduction in X_q by the rotor flux barriers exerts a selective effect on mitigating only this parasitic braking torque, without altering the fundamental power conversion characteristics of the generator.

At the rated operating point (40 kW, 1800 r/min) of the 50 kVA prototype, the q-axis parasitic braking torque is reduced by 4.1079 Nm, from 15.1246 Nm in the conventional salient-pole generator (SG) to 11.0167 Nm in the flux barrier-integrated design (SG with FB), corresponding to a 27.2% reduction in parasitic braking torque. This reduction translates to a decrease in unnecessary mechanical input power, which is calculated as:

$$\Delta P = \Delta T \times \omega = 774 \text{ (W)}$$

In this analysis, stator/rotor copper loss and mechanical loss (friction and windage) are assumed to remain constant, as the armature current, excitation current and rotational speed are identical for both the conventional and flux barrier designs. The 774 W reduction in mechanical input power can therefore be attributed primarily to the mitigation of q-axis related parasitic losses, with negligible impact on other loss components.

Generator efficiency is calculated as $\eta = P_{\text{out}}/(P_{\text{out}}+P_{\text{loss}}) \times 100\%$. Based on the estimated total loss reduction of 774 W, the flux barrier design achieves a net efficiency improvement of approximately 1.6 percentage points at the rated operating point. This efficiency gain is a theoretical estimate derived from 2D finite element analysis (FEA); a slight deviation from experimental values is expected due to unmodeled 3D effects (e.g., end-winding leakage flux) and manufacturing tolerances.

The efficiency improvement resulting from the selective reduction of q-axis parasitic braking torque yields fuel consumption savings during long-term operation of diesel generator sets in isolated power systems such as marine vessels and remote microgrids, further validating the practical engineering and economic value of the rotor flux barrier design for salient-pole synchronous generators.

2.2 Variation of Load Angle and Voltage Regulation

As derived from the phasor diagram of a synchronous generator, a change in the X_q affects the current components and the load angle.

The analytical model in Section 2.2 uses the synchronous reactances (X_d , X_q) as input parameters. These values were obtained from detailed FEA simulations using the approach established in our previous work (Kim et al. 2023) (slip test simulation method), but updated for the specific flux barrier dimensions shown in Fig. (1) and Table 1 of the present study. Therefore, the effect of the flux barrier

is implicitly included in the reduced X_q value used in equations (3)-(5). The iterative algorithm in Fig. (9) then solves for the load angle and voltage regulation based on these machine-specific parameters.

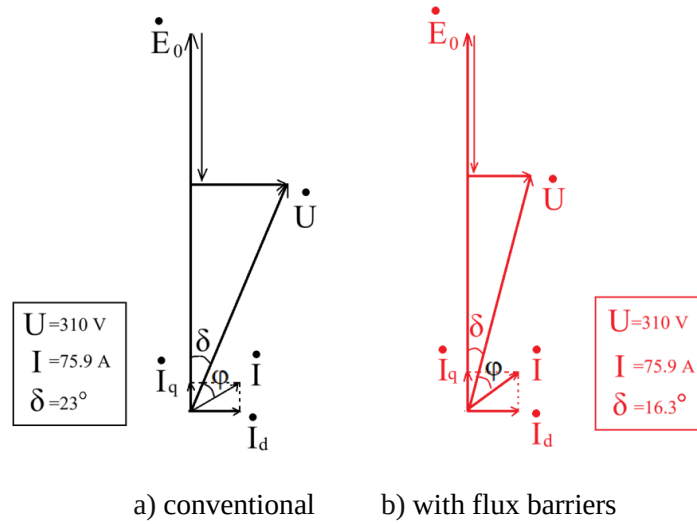


Fig 8. Reduction of load angle due to decreased armature Synchronous Reactance. The diagram is based on the ratings of the 50 kVA, 4-pole, 60 Hz salient-pole synchronous generator prototype.

As shown in Fig. (8), when the output power, terminal voltage, and field current are held constant, a decrease in X_q alters the geometric configuration of the phasor diagram, leading to a reduction in the load angle (δ) at the new equilibrium point. The decrease in X_q reduces the $I_q X_q$ voltage drop, which, for a given power, inherently tends to decrease the load angle δ .

This decrease in the load angle (δ), under constant terminal voltage and power, causes an increase in the quadrature-axis current component I_q and a decrease in the direct-axis current component I_d . Consequently, as X_q decreases, I_q tends to increase, thereby acting to limit the extent of the load angle reduction. However, since I_q increases only by the cosine component relative to the load angle, its magnitude remains consistently smaller than the decrease in X_q . Thus, overall, the load angle decreases.

Furthermore, the reduction in load angle results in an increase in the reactive current component I_q and a decrease in the active current component I_d . According to the phasor diagram (Fig. 8), both the $I_d X_d$ and $I_q X_q$ voltage drops decrease. Under constant excitation conditions (i.e., no change in the internal electromotive force), this leads to a rise in the terminal voltage. Under normal operating conditions, this manifests as a reduction in the voltage regulation.

The relationship between the changes in load angle and voltage regulation due to the reduction in armature Synchronous Reactance under standalone operation can be analyzed with respect to the load ratio using the following method.

$$\begin{cases} U = E - jI_d X_d - jI_q X_q \\ E = U \cdot \cos \delta + I_d X_d \\ X_d = f(I_d) \\ X_q = f(I_q) \end{cases} \quad (2)$$

Per-unit values are assumed for voltage and current under constant power conditions:

$U^* = 1.0$ and $I^* = \text{const}$. Under these conditions, where $X_d = f(I_d)$ and $X_q = f(I_q)$, the unknown variables are E (internal voltage) and δ (load angle).

Given the multiple unknown variables and the interdependent nature of these parameters, a computational numerical method is required to solve the system. The following algorithm is used to calculate the load angle and voltage regulation:

- Under the condition where the generator's terminal voltage and load current are expressed in per-unit values, set the voltage as the reference value and increment the current from no-load conditions at fixed intervals.
- Initialize the values for X_d and X_q , and calculate the corresponding load angle (δ) and power factor angle (φ).

$$\psi = \arctan\left(\frac{I \cdot X_q^* + U^* \sin \varphi}{U^* \cos \varphi + I \cdot r_1^*}\right) \quad (3)$$

$$\delta = \psi - \varphi \quad (4)$$

Here, r_1 : Stator resistance

- Based on the power factor angle, calculate I_d and I_q . Then, determine the corresponding X_d and X_q values from numerical analysis data, based on the calculated I_d and I_q .

$$\begin{cases} I_d = I \cdot \cos(\delta + \varphi) \\ I_q = I \cdot \sin(\delta + \varphi) \end{cases} \quad (5)$$

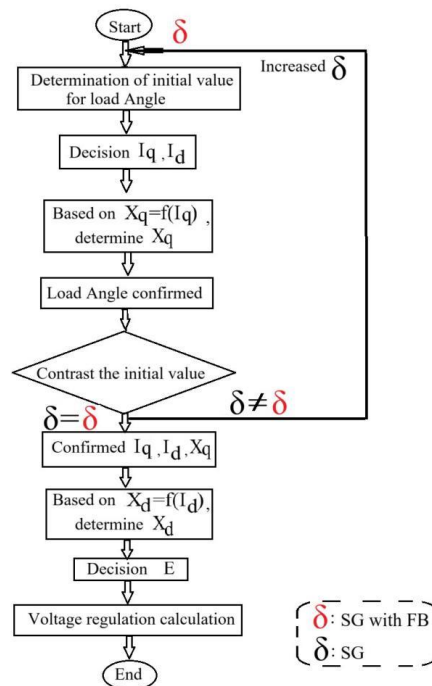


Fig 9. Algorithm for calculating load angle and voltage regulation under constant output power, applied to the 50 kVA, 4-pole, 60 Hz salient-pole synchronous generator prototype.

The calculation process iterates continuously, replacing the initial values with the calculated values, until the difference between them falls within the allowable error tolerance. This iterative process determines the final values of the load angle (δ), X_d and X_q .

- Using the determined values of I_d , I_q , X_d , X_q , and the load angle (δ), the no-load electromotive force (E_0) is calculated.
- The voltage regulation ($\Delta U\%$) is then determined from the per-unit difference between this no-load electromotive force (E_0) and the rated terminal voltage.

Based on the algorithm shown in Fig. (9), a program was developed to analyze the variations in voltage regulation and load angle with respect to the load ratio, under the same load conditions, both with and without flux barriers. The results of this analysis are presented in Fig. (10) and (11).

Through this study, it has been numerically verified that installing flux barriers in a standalone salient-pole synchronous generator reduces its armature reaction, thereby improving its load angle and voltage regulation characteristics.

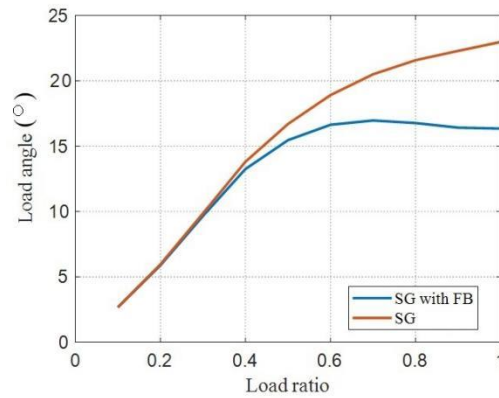


Fig 10. Variation of load angle with load ratio.

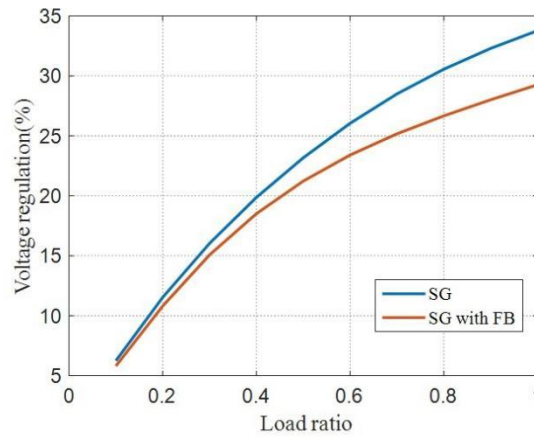


Fig 11. Variation of voltage regulation with load ratio.

2.3 Air Gap Flux Distribution and Harmonic Characteristics

The influence of flux barriers on the air gap magnetic field and its harmonic content was analyzed using the same FEA methodology established in our previous work (Kim et al. 2023). Fig. (12) and (13) show the air gap flux density distributions for the conventional and proposed designs, respectively. The corresponding harmonic components extracted from these waveforms are summarized in Table 6.

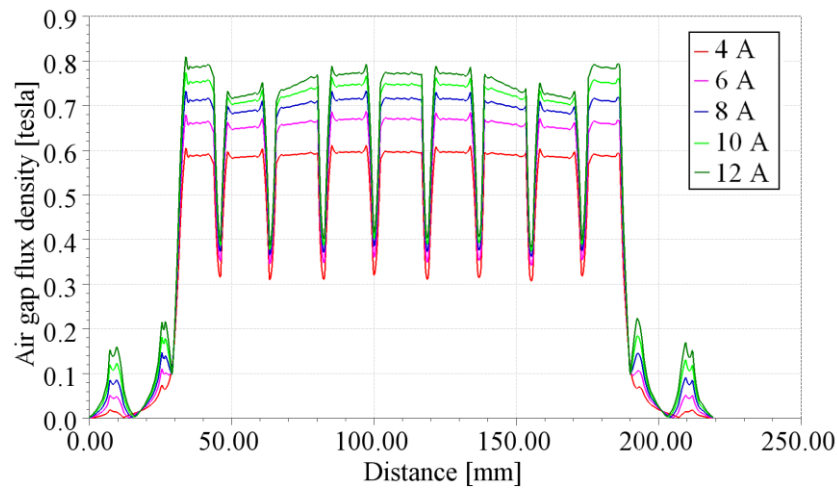


Fig 12. Air gap flux density distributions with excitation current in a single pole region.

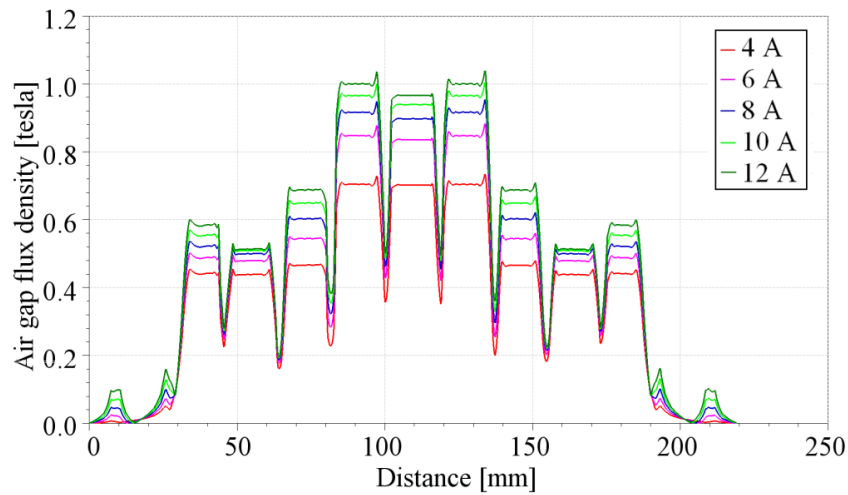


Fig 13. Air gap flux density distributions with excitation current in a single pole region with flux barrier.

Table 6 presents the harmonic analysis of the air gap magnetic field under varying excitation currents. The total harmonic distortion (THD) of the air gap flux density ranges from 24% to 27% for both designs, which is typical for salient-pole synchronous machines without damper windings.

Table 6. Harmonic analysis of air gap magnetic field with excitation current

Excitation current (A)	THD (%)		Fundamental flux density (T)		Third harmonic flux density (T)		5th harmonic flux density (T)		7th harmonic flux density (T)	
	SG	SG with FB	SG	SG with FB	SG	SG with FB	SG	SG with FB	SG	SG with FB
4	26.984	25.159	0.4879	0.4525	0.0520	0.0071	0.0403	0.0424	0.0297	0.0071
6	26.417	25.563	0.5473	0.5275	0.0542	0.0141	0.0441	0.0509	0.0339	0.0071
8	26.082	25.056	0.5827	0.5699	0.0523	0.0170	0.0468	0.0566	0.0396	0.0113
10	25.90	24.723	0.6081	0.6010	0.0484	0.0198	0.0492	0.0622	0.0438	0.0170
12	25.758	24.413	0.6279	0.6237	0.0437	0.0226	0.0516	0.0665	0.0467	0.0226

The flux barriers primarily affect the low-order harmonics:

- The 3rd harmonic is significantly reduced across all excitation levels (e.g., from 0.0520 T to 0.0071 T at 4 A).
- The 7th harmonic is also consistently reduced (e.g., from 0.0297 T to 0.0071 T at 4 A).
- The 5th harmonic shows a slight increase in the proposed design, but its magnitude remains small (below 0.07 T) and does not significantly affect the overall waveform quality.

The fundamental component of the air gap flux density is slightly reduced at low excitation (e.g., from 0.4879 T to 0.4525 T at 4 A), but the difference diminishes as the excitation increases, converging at rated excitation (0.6279 T vs. 0.6237 T at 12 A). This confirms that the no-load voltage characteristic is practically maintained under rated conditions.

Overall, the flux barriers achieve the desired reduction in X_q without compromising the sinusoidal nature of the air gap flux distribution, thereby preserving the generator's power quality.

2.4 Summary of Theoretical Predictions

The theoretical framework presents three key hypotheses for experimental validation:

- The implementation of a flux barrier consistently reduces the steady-state load angle throughout the operational range, thereby enhancing transient stability.
- There is a significant improvement in voltage regulation, characterized by a reduced percentage voltage drop from no-load to full-load conditions.
- A substantial decrease in electromagnetic braking torque is anticipated, resulting from the reduced reluctance torque component due to the higher quadrature-axis reluctance.

These predictions, based on fundamental machine theory and numerical analysis, will be verified through experimental results in the subsequent sections. This will confirm the comprehensive impact of reducing the quadrature-axis reluctance on generator performance characteristics.

3. EXPERIMENTAL VALIDATION

This section presents the experimental validation of performance improvements resulting from the reduction of X_q . This follows our previous findings (Kim et al. 2023), which conclusively demonstrated the effectiveness of flux barriers in reducing X_q . The focus here is on quantifying how the verified reduction of X_q translates into measurable enhancements in the operational characteristics of the generator.

Fig. (14) shows the fabricated rotor with flux barriers used in the experimental prototype.

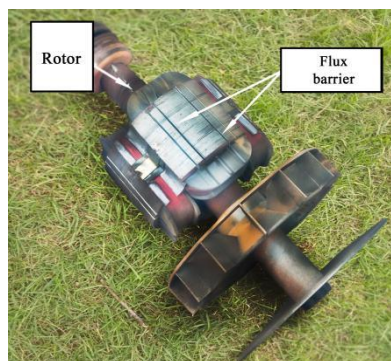


Fig 14. Rotor with FB (50 kVA, 4-pole salient-pole synchronous generator prototypes).

The experimental setup was consistent with (Kim et al. 2023), utilizing the same 50 kVA, 4-pole salient-pole synchronous generator prototypes, both with and without flux barriers.

A digital load angle measurement system was implemented, based on a phase comparison between the rotor position and reference voltage signals. The load angle of the generator is measured according to the following procedure:

- First, a permanent magnet of a specific width is mounted on the side of the generator's rotating shaft.
- Then, a flux sensor (Hall effect sensor) is fixed to the machine frame or ground, maintaining a constant distance from the magnet. As the shaft rotates, the permanent magnet periodically passes the sensor, generating a square wave pulse signal. The frequency of this signal is identical to the mechanical rotational speed of the generator.
- The generator is initially operated under no-load conditions to simultaneously measure two signals. Using the rising edge (or falling edge) of the pulse signal from the flux sensor as a reference point, the instantaneous value of one phase of the generator's terminal voltage is sampled. Both signals are converted via an analog-to-digital converter (ADC) and transmitted to an embedded computer. Subsequently, a host computer analyzes the phase difference between the two signals. This phase difference measured under no-load conditions is established as the zero point for the load angle, incorporating any inherent system offset.
- Finally, load is applied to the generator, and the same measurement process is repeated. The pure load angle for that specific load condition is determined by subtracting the pre-defined zero point value from the real-time measured phase difference.

The experimental results provide conclusive validation of two key performance relationships:

- First, load angle measurements showed a consistent reduction across the operational range when compared to the conventional design, as illustrated in Fig. (15). This reduction of 10~23% in load angle across the tested range validates the improved transient stability margin predicted by our theoretical analysis.

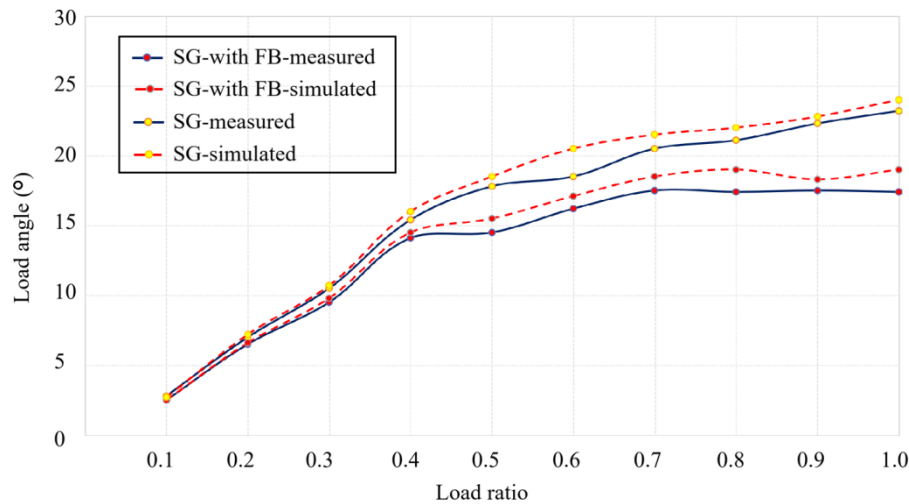


Fig 15. Variation of load angle.

The average error between simulation and experiment at rated load is within 3.4% for the conventional design and 9.1% for the design with flux barriers.

- Second, voltage regulation tests conducted at a 0.8 power factor confirmed substantial improvement, as shown in Fig. (16). The voltage regulation improved by approximately 22% at full load, decreasing from 34.9% in the conventional design to 27% with flux barriers.

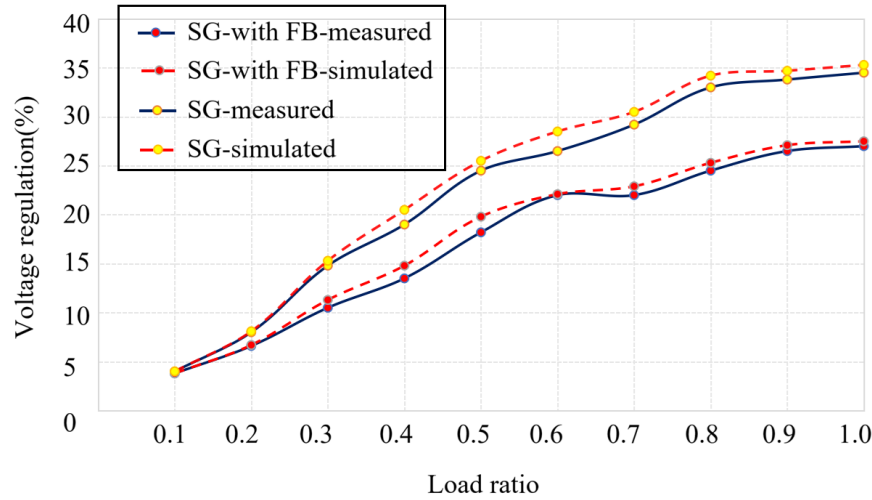


Fig 16. Variation of voltage regulation.

These experimental results demonstrate a strong correlation with the theoretical predictions, successfully validating the proposed cause-and-effect relationship. Specifically, the reduction in X_q directly facilitates simultaneous improvements in both stability (as indicated by the reduced load angle) and power quality (as indicated by improved voltage regulation).

Although the experimental results validate the theoretical predictions, consistent discrepancies between the FEA and measured values are observed in Figs. (15) and (16). These discrepancies can be attributed to the following factors.

- First, due to the limitations of two-dimensional modeling, the 2D FEA model does not account for three-dimensional phenomena such as end-winding leakage and axial fringing fluxes. This leads to an underestimation of the effective q-axis reactance, resulting in a slight overestimation of the performance improvement. This effect is more pronounced under heavy load conditions.
- Second, there is the issue of idealized material properties. The BH curves used in the simulation (Appendix A, B) are derived from standard Epstein test data. However, these may differ from the local magnetic properties of the components after actual stamping and stacking processes. Specifically, the local saturation behavior at the pole shoe corners may deviate from the modeled characteristics.
- Third, manufacturing tolerances play a role. The actual air gap length and flux barrier dimensions may deviate by up to ± 0.05 mm from the nominal values shown in Fig. (1) and Table 1. Such geometric variations affect the permeance of the quadrature-axis magnetic circuit.
- Fourth, measurement uncertainty is a factor. The load angle measurement system has a phase detection resolution of $\pm 0.1^\circ$, which introduces a systematic error of approximately $\pm 2\%$ in the load angle reading under light load conditions.

This combined effect is visible in Fig. (15), where the discrepancy between FEA and measurement is slightly larger under light load conditions (attributable to measurement uncertainty) and also shows a consistent offset under heavy load conditions (attributable to 2D modeling simplifications).

Despite these limitations, the overall trend and the relative improvement (22–27%) are consistently reproduced, confirming the validity of the proposed approach. Furthermore, this experimental validation completes the investigation initiated in (Kim et al. 2023), confirming that flux barriers serve as a comprehensive design strategy that translates reactance modification into tangible operational benefits for salient-pole synchronous generators.

4. CONCLUSION

This study systematically demonstrates that the reduction in quadrature-axis synchronous reactance (X_q), achieved through the implementation of rotor flux barriers—established in our previous work (Kim et al. 2023)—leads to significant performance improvements in salient-pole synchronous generators. By integrating theoretical analysis with experimental validation, this research provides solid evidence of the system-level benefits resulting from controlled X_q reduction.

The key findings reveal a clear cause-and-effect relationship: the strategic use of flux barriers directly reduces X_q , which simultaneously enhances three critical performance metrics.

- First, the decreased X_q allows for a significant reduction in load angle, thereby improving the steady-state stability margins of the generator.
- Second, the altered reactance characteristics result in substantial improvements in voltage regulation, enhancing power quality in isolated power systems.
- Third, theoretical and numerical analysis (Finite Element Analysis, FEA) confirms a notable reduction in electromagnetic braking torque; however, comprehensive experimental validation remains for future work, contributing to improved operational efficiency.

These findings validate the core hypothesis presented in both the abstract and introduction: that flux barriers serve as more than a mere technique for reactance suppression; they are a comprehensive strategy for structural enhancement. By establishing quantitative relationships between X_q reduction and multiple performance improvements, this work offers both theoretical insights and practical design guidelines for developing next-generation generators, especially for applications that require enhanced stability and power quality without the use of damper windings.

The outcomes of this research thus complete the investigation initiated in (Kim et al. 2023), confirming that rotor flux barriers provide a viable and effective approach for holistic generator performance enhancement. Future work will focus on extending this research to dynamic stability analysis and optimizing barrier geometry for maximum performance benefits across different generator configurations.

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Appendix A. B–H Characteristic of D24-50 Electrical Steel

Fig. (17) shows the nonlinear B–H curve of the D24-50 non-oriented electrical steel used in the rotor cores of the prototype. The data were obtained from the manufacturer's datasheet and implemented in the FEA model to account for saturation effects under loaded conditions.

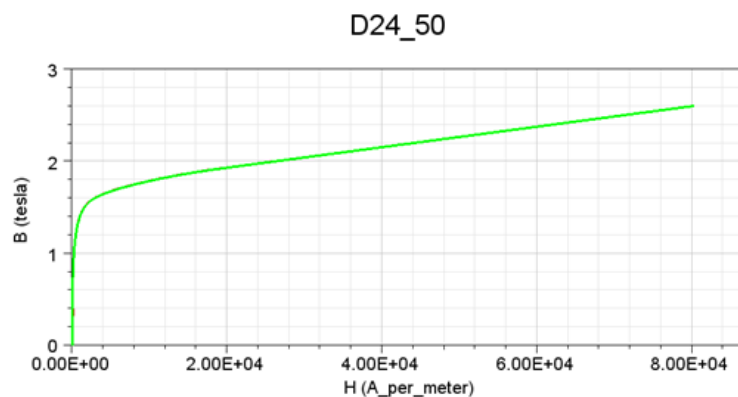


Fig 17. B–H curve of D24-50 lamination steel.

Appendix B. B–H Characteristic of DW360-50 Electrical Steel

Fig. (18) shows the nonlinear B–H curve of the DW360-50 non-oriented electrical steel used in the stator cores of the prototype. The data were obtained from the manufacturer's datasheet and implemented in the FEA model to account for saturation effects under loaded conditions.

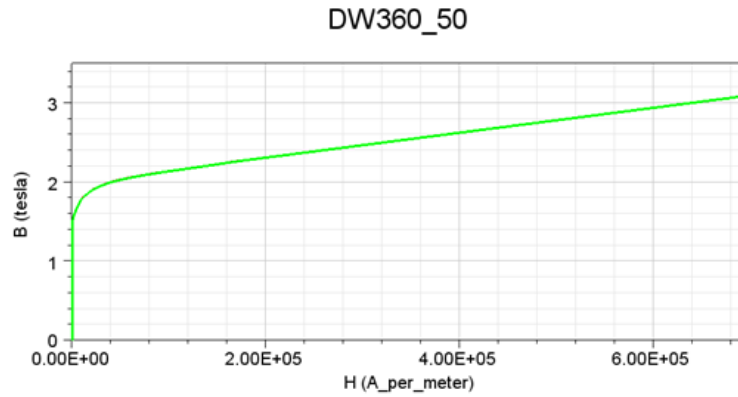


Fig 18. B–H curve of DW360-50 lamination steel.