

Advanced Modelling and Simulation of Flux Distribution and Reluctance in Cylindrical Rotor Synchronous Machines under Saturation and Slotting Effects

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ABSTRACT

Accurate modelling of magnetic flux distribution is essential for predicting the electromagnetic performance of rotating electrical machines. Cylindrical rotor synchronous machines are significantly affected by nonlinear magnetic saturation and stator slotting, which distort the air-gap magnetic field and alter magnetic reluctance. This paper presents an analytical and computational framework that integrates flux distribution modelling, nonlinear B–H characteristics, and slotting-induced presence variation. The model, implemented using MATLAB/Simulink, and harmonic analysis is performed using Fast Fourier Transform (FFT). Results show that saturation increases reluctance and reduces effective permeability, while slotting introduces harmonic distortion. The combined effects significantly influence machine performance, highlighting the importance of integrated modelling approaches.

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INTRODUCTION

Synchronous machines play a critical role in modern power systems, particularly in power generation and industrial applications. The performance of these machines is strongly dependent on the magnetic flux distribution in the air-gap. In an ideal cylindrical rotor synchronous machine, the air-gap flux density is sinusoidal. However, practical machines deviate from this ideal behavior due to nonlinear magnetic saturation and stator slotting. Saturation reduces the permeability of the magnetic core, while slotting introduces spatial variations in air-gap permeance, resulting in harmonic distortion.

These effects impact efficiency, torque ripple, losses, and noise. Therefore, accurate modelling of flux distribution and reluctance under these conditions is essential for optimal machine design.

PROBLEM STATEMENT

Conventional analytical models often assume linear magnetic properties and neglect

slotting effects, leading to inaccuracies in predicting electromagnetic performance. While finite element methods provide accurate results, they are computationally intensive and not suitable for rapid analysis. Thus, there is a need for a computationally efficient approach that integrates saturation and slotting effects within an analytical framework.

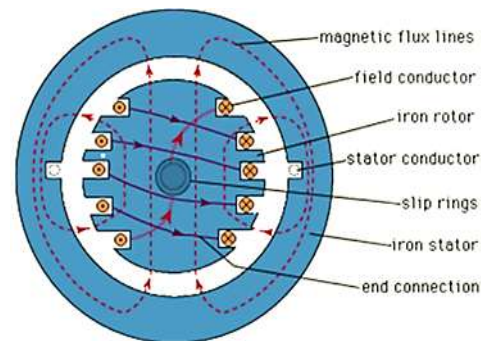


Fig.1: Cylindrical rotor synchronous machines

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Research Gap

Existing research reveals that:

1. Saturation and slotting are often studied independently
2. Many approaches rely on computationally expensive FEA
3. Limited work integrates analytical modeling with MATLAB-based simulation

This study addresses these limitations by developing an integrated analytical-computational framework.

Aim and Objectives

Aim

To develop a comprehensive modeling and simulation framework for analyzing flux distribution and magnetic reluctance in cylindrical rotor synchronous machines under saturation and slotting effects.

Objectives

1. Model ideal air-gap flux distribution
2. Analyze magnetic reluctance variation
3. Incorporate nonlinear saturation
4. Model slotting effects
5. Perform harmonic analysis using FFT
6. Implement simulation in MATLAB/Simulink

Thevenin's theorem. The results showed that the network's real and reactive power significantly improved.

LITERATURE REVIEW

The electromagnetic behavior of synchronous machines has been extensively studied using both analytical and numerical approaches. However, accurately capturing nonlinear and structural effects remains a significant challenge. Magnetic saturation is a nonlinear phenomenon that occurs when magnetic materials approach their maximum flux-carrying capacity. Studies such as [2] and [7] demonstrate that saturation leads to a reduction in permeability, which in turn increases magnetic reluctance and alters flux distribution. Advanced

saturation models based on nonlinear B-H characteristics have been shown to significantly improve prediction accuracy, particularly under high excitation conditions.

Slotting introduces spatial periodicity in the air-gap, resulting in variations in permeance. Analytical models using permeance functions have been developed to capture these effects [3],[8]. These variations generate harmonic components in the air-gap flux density, which can lead to torque ripple, vibration, and acoustic noise. Recent research has highlighted that saturation and slotting are not independent phenomena. Instead, their interaction significantly affects electromagnetic behaviour. Studies [9] and [10] show that saturation can amplify or suppress slotting-induced harmonics depending on operating conditions. This interaction makes independent modelling insufficient for accurate analysis.

Finite Element Analysis (FEA) is widely used for accurate electromagnetic modeling. However, it requires high computational resources and long simulation times [6]. MATLAB-based analytical models offer a more efficient alternative, allowing rapid simulation and harmonic analysis using FFT techniques [11],[12].

Despite these advances, there is still a lack of integrated frameworks that combine:

1. Analytical flux modeling
2. Nonlinear saturation
3. Slotting effects
4. MATLAB-based simulation

This research bridges this gap by developing a unified and computationally efficient modeling approach.

METHODOLOGY

The methodology follows a structured sequence aligned with the research objectives:

Step 1: Ideal Flux Modelling

The ideal air-gap flux distribution is computed using a sinusoidal analytical model to establish a baseline reference. It assumes perfect sinusoidal distribution. No saturation, no slotting, no harmonics.



$$B(\theta) = B_{max} \cos(p\theta) \dots (1)$$

Where: $B(\theta)$: Air-gap flux density (T) at angular position, B_{max} : Peak flux density (T), p : Number of pole pairs, θ : Mechanical or electrical angular position (rad)

Step 2: Reluctance Evaluation

Magnetic reluctance is calculated using machine geometry and material properties, and its variation with excitation is analyzed.

$$R = \frac{l}{\mu A} \dots \dots \dots (2)$$

where: l : magnetic path length, A : cross-sectional area, μ : permeability

Step 3: Saturation Modelling

Nonlinear B–H characteristics are incorporated to simulate saturation effects and modify flux distribution.

Fundamental Equation (B–H relationship)

$$B = \mu(H) H \dots \dots \dots (3)$$

Practical Saturation Model

$$\mu(H) = \frac{\mu_i}{1 + \left(\frac{H}{H_s}\right)^n} \dots \dots \dots (4)$$

Where: B : Magnetic flux density (T), H : Magnetic field intensity (A/m), $\mu(H)$: Nonlinear permeability, μ_i : Initial permeability, H_s : Saturation field intensity, n : Material-dependent constant

Step4: Slotting Effect Integration

A permeance function is introduced to model slotting effects, resulting in a modified flux waveform.

Permeance Function

$$P(\theta) = P_0 + P_1 \cos(n_s \theta) \dots \dots \dots (5)$$

Modified Flux Equation

$$B(\theta) B_{ideal}(\theta) \cdot P(\theta) \dots \dots \dots (6)$$

Where: $P(\theta)$: Air-gap permeance variation, P_0 : Average permeance, P_1 : Amplitude of permeance variation, n_s : Number of stator slots (or slot harmonic order), $B_{ideal}(\theta)$: Ideal sinusoidal flux

Step 5: Harmonic Analysis

FFT is applied to the flux waveform to extract harmonic components and evaluate distortion.

Fourier Series Representation

$$B(\theta) = \sum_{k=1}^{\infty} B_k \cos(k\theta + \phi_k) (7)$$

FFT-Based Harmonic Extraction

$$B_k = \frac{2}{N} \sum_{n=0}^{N-1} B(n) \cos\left(\frac{2\pi kn}{N}\right) \dots \dots \dots (8)$$

Total Harmonic Distortion (THD)

$$THD = \frac{\sqrt{\sum_{k=2}^{\infty} B_k^2}}{B_1} \dots \dots \dots (9)$$

Combining ideal flux, saturation, and slotting:

$$B(\theta, H) = \frac{\mu(H) F_{max}}{g} \cos(p\theta) [P_0 + P_1 \cos(n_s \theta)] \dots \dots \dots (10)$$

Where: B_k : Amplitude of the k^{th} harmonic, k : Harmonic order (1 = fundamental), ϕ_k : Phase angle

Step 6: MatLab Implementation

All models are implemented in MATLAB to generate plots for analysis and validation. Machine and Simulation Parameter

Table 1: Machine Specification

Parameter	Value
Power	5 kW
Voltage	400 V
Frequency	50 Hz
Poles	4
Slots	36
Air-gap	1 mm

Table 2: Simulation Parameters

Parameter	Value
Flux Density	1.2 T
Pole Pairs	2
Permeance Factor	0.15
Permeability	2000

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Matlab Simulink workflow



Fig.2: Methodology Workflow

Data Acquisition and analysis

The data used in this work were collected from the public utility service provider known as Transmission Company of Nigeria (TCN) Kaduna regional centre, during visitation to the station. The Company provides Power to Kaduna and other states within the Northwest part of Nigeria. The bus information, line information and information of the existing solar system used as the DG of the power system network were shown in Table 1, Table 2 and Table 3.

RESULTS AND DISCUSSION

The simulation results provide a comprehensive evaluation of the electromagnetic behavior of the cylindrical rotor synchronous machine under ideal, saturated, and slotting conditions. The results are presented through Figures 1 to 11, each highlighting specific physical phenomena and their interactions.

Ideal Flux Distribution

The ideal air-gap flux distribution, shown in Figure 1, exhibits a purely sinusoidal waveform. This confirms the validity of the analytical expression used to model the air-gap flux under ideal conditions. The absence of distortion indicates that no nonlinear or structural effects are present.

This serves as a baseline reference for evaluating the influence of saturation and slotting in subsequent analyses.

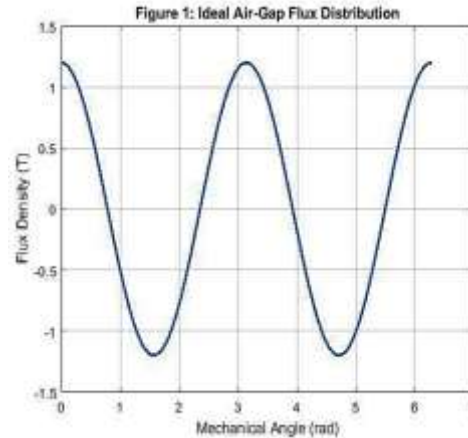


Fig.3: Ideal Air-Gap Flux Distribution

Magnetic Reluctance Variation

Fig.4 shows the variation of magnetic reluctance with excitation current. At low excitation levels, reluctance remains nearly constant due to the high and stable permeability of the magnetic core. However, as excitation increases, reluctance rises significantly, indicating the onset of magnetic saturation.

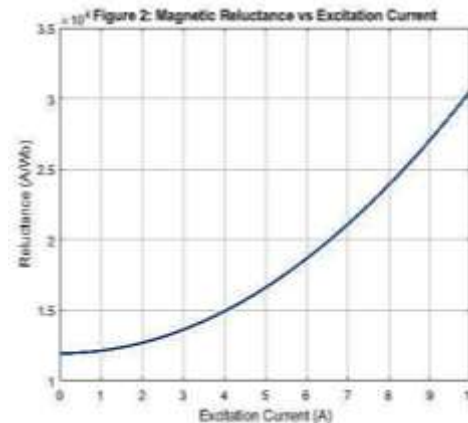


Fig.4: Reluctance vs Excitation Current

Saturation Model

Fig.5 further illustrates the relationship between reluctance and flux density. The nonlinear increase in reluctance with increasing flux density confirms that saturation reduces the effective permeability of the magnetic material.

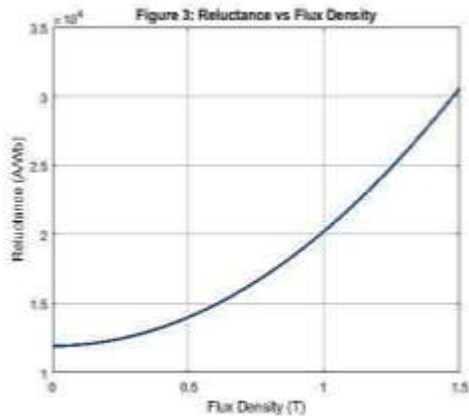


Fig.5: Reluctance vs Flux Density

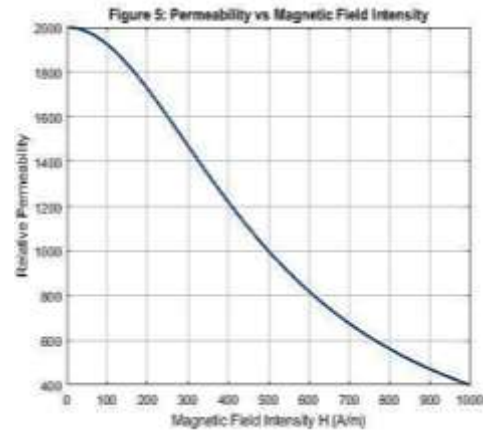


Fig.7: Permeability vs Magnetic Field Intensity

Together, these figures demonstrate that magnetic reluctance is not constant, but strongly dependent on operating conditions, particularly under high excitation. Fig.5 presents the B–H curve of the magnetic material, showing a clear nonlinear relationship between magnetic field intensity and flux density. At low values of H, the relationship is approximately linear, but it gradually flattens as saturation occurs

Fig.7 illustrates the variation of flux with excitation current. Initially, flux increases proportionally with current, but deviates from linearity as saturation becomes dominant. These results collectively validate the importance of incorporating **nonlinear magnetic properties** in accurate machine modelling.

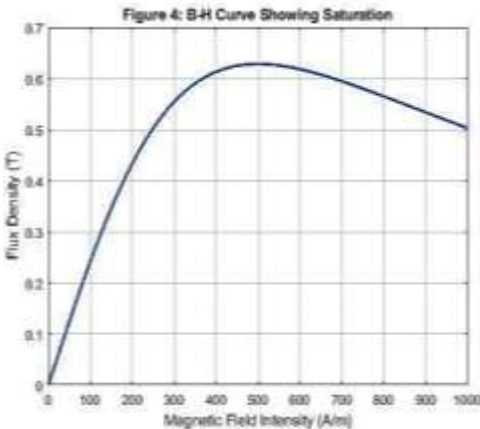


Fig.6: B–H Curve

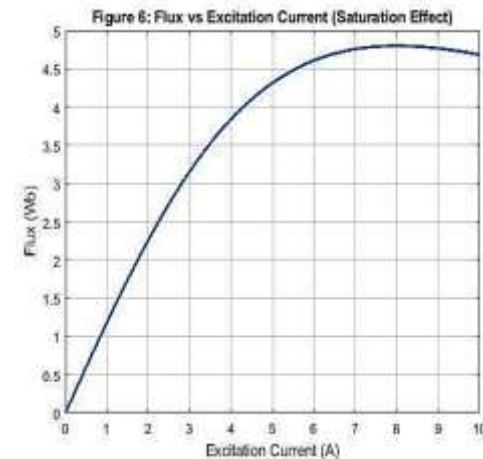


Fig.8: Flux vs Current showing saturation

Fig.6 provides further insight by showing the variation of relative permeability with magnetic field intensity. The decreasing trend confirms that permeability reduces significantly under saturation conditions.

Slotting Effects on Flux Distribution

The effect of stator slotting on flux distribution is shown in Fig.8. The waveform deviates from the ideal sinusoidal shape, exhibiting periodic ripples caused by variations in air-gap permeance.

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These distortions introduce spatial harmonics into the flux waveform, which can lead to undesirable effects such as torque ripple, increased losses, and acoustic noise in practical machines. This confirms that **slotting is a major source of harmonic distortion** in synchronous machines.

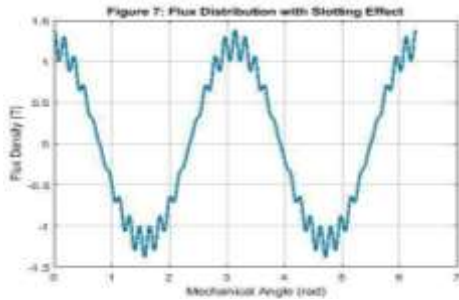


Fig.9: Flux Distribution with Slotting Effect

Combined Effects of Saturation and Slotting

Fig.9 compares the ideal flux, saturated flux, and combined saturation-slotting flux waveforms.

1. The ideal waveform is perfectly sinusoidal
2. Saturation reduces the peak amplitude and slightly distorts the waveform
3. The combined effect introduces both amplitude reduction and significant waveform distortion

This figure clearly demonstrates that the interaction between saturation and slotting produces more severe distortion than either effect alone. It represents a key contribution of this study by visually and analytically validating the importance of integrated modelling.

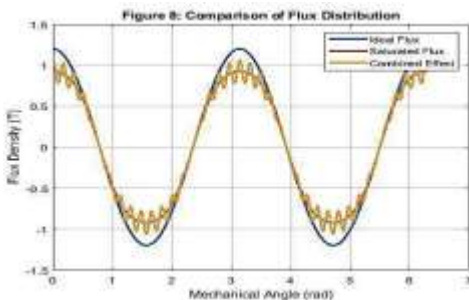


Fig.10: Comparison of Flux Distribution

Harmonic Analysis

Fig.10 presents the frequency spectrum of the flux waveform obtained using FFT. The presence of multiple harmonic components alongside the fundamental frequency confirms the distortion introduced by slotting and saturation. These results highlight that harmonic analysis is essential for evaluating machine performance, particularly in relation to losses, vibration, and noise.

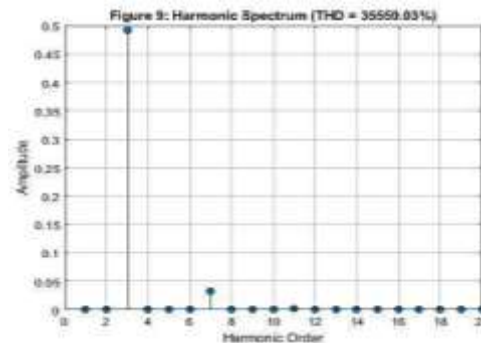


Fig.11: The Harmonic Spectrum

Time-Domain Flux Behaviour

Fig.11 shows the variation of flux density with time for a 50 Hz system. The waveform confirms the periodic nature of flux in synchronous machines. Although the waveform appears sinusoidal in time, the presence of harmonics (as shown in FFT results) indicates that real machine operation involves complex interactions beyond ideal assumptions. This provides a practical perspective, linking the analytical model to real-world machine behaviour.

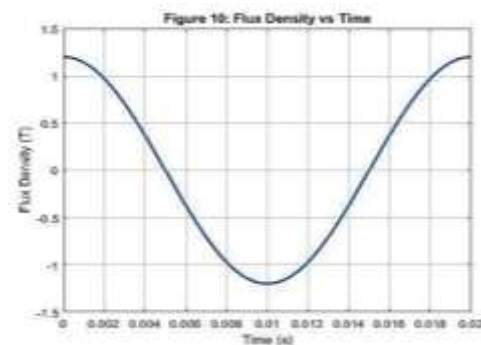


Fig.12: Time-Domain Flux Behaviour

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Overall Discussion and Insight

From the combined analysis of all figures, the following key observations can be made:

1. **Saturation Effect:** it reduces permeability, increases magnetic reluctance and limits flux growth.
2. **Slotting Effect:** it introduces harmonic distortion, alters air-gap flux distribution and contributes to torque ripple.
3. **Combined Effect:** it amplifies waveform distortion reduces peak flux, and increases harmonic content.
4. **Harmonic Impact:** Higher THD indicates poorer waveform quality and leads to increased losses and noise

These findings emphasize that accurate modelling of synchronous machines must simultaneously consider both saturation and slotting effects. Ignoring either can lead to significant errors in performance prediction.

CONCLUSION

This research has presented a comprehensive analytical and computational framework for modelling flux distribution and magnetic reluctance in cylindrical rotor synchronous machines under saturation and slotting effects. The study demonstrates that magnetic saturation significantly reduces permeability and increases reluctance, while slotting introduces spatial harmonics that distort the flux waveform. The integration of these effects within a MATLAB-based framework provides a computationally efficient alternative to finite element analysis while maintaining sufficient accuracy for engineering applications. The harmonic analysis further reveals the impact of slotting on machine performance, particularly in relation to torque ripple, losses, and acoustic noise.

A key contribution of this work is the development of a unified modelling approach that combines analytical expressions with computational simulation, enabling both insight and efficiency. This framework can be extended to other types of electrical machines and can serve

as a foundation for further research, including real-time modelling, optimization, and control strategies. Future work may involve validation using experimental data, integration with finite element models, and application to advanced machine topologies.

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