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Evaluating the Effect of Excitation on the Stability of Permanent Magnet Synchronous Generator (Pmsg) Performance

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ABSTRACT
The increasing demand for efficient and reliable renewable energy systems has highlighted the significance of Permanent Magnet Synchronous Generators (PMSGs) in modern power generation. This study focuses on evaluating the effect of excitation on the stability and overall performance of PMSGs, which are widely used in wind energy and other renewable applications. Stability in PMSGs is critical for maintaining consistent power output and minimizing system disturbances during dynamic operating conditions. A detailed modeling and simulation framework was developed to analyze the impact of varying excitation parameters, including the magnetic field strength and machine design characteristics. The study employed advanced computational tools to assess the steady-state and transient behaviors of the generator under different load conditions. Key performance metrics such as voltage stability, harmonic distortion, and torque ripple were monitored to evaluate the generator's stability margins. The findings reveal a strong correlation between excitation levels and system stability, with optimal excitation improving voltage regulation and reducing transient oscillations. However, over- or under-excitation introduces instability, leading to potential operational inefficiencies and system failures. The results also underscore the importance of precise control strategies for maintaining stability across varying load demands and environmental conditions. This research provides valuable insights for designing more robust PMSG systems and developing control strategies that optimize excitation for enhanced performance. These findings will benefit the renewable energy sector by ensuring reliable and efficient operation of PMSG-based systems.

KEYWORDS: Excitation, Stability, PMSG, Generator and Performance.

I. INTRODUCTION

The global transition toward renewable energy has increased the demand for efficient and reliable power generation systems. Permanent Magnet Synchronous Generators (PMSGs) are widely used in renewable energy applications, particularly wind energy, due to their high efficiency, compact size, and ability to operate at variable speeds [1]. Unlike conventional synchronous generators, PMSGs rely on permanent magnets for excitation, eliminating the need for external excitation systems. However, this fixed excitation presents challenges in stability under dynamic operating conditions [2].The stability of PMSGs is linked to excitation characteristics. In conventional synchronous machines, excitation control is essential for voltage regulation and stability [3]. However, PMSGs depend on the magnetic properties of the permanent magnets, limiting the flexibility to adapt to grid disturbances or load variations [4]. The integration of PMSGs into renewable energy systems further introduces complexities due to fluctuating mechanical inputs from wind speed variations [5]. This variability affects electrical output stability, necessitating advanced modeling and control strategies to ensure reliable performance [6].The primary challenge in PMSGs is the inability to adjust excitation in response to load changes, grid faults, and transient disturbances [7]. The excitation is governed by the permanent magnets’ properties, which can be affected by temperature variations and aging effects [8]. Consequently, PMSGs may experience voltage fluctuations, harmonic distortions, and transient instability during sudden load changes or grid disturbances [9].Stability in PMSGs is typically assessed by voltage regulation, transient response, and torque ripple [10]. Voltage regulation is influenced by rotor speed and permanent magnet strength, making it challenging to maintain under varying conditions [11]. Transient stability is critical during dynamic events such as sudden load increases or grid faults, as PMSGs lack an adjustable excitation system [12]. Additionally, torque ripple, caused by variations in the magnetic field, can result in mechanical vibrations, increased wear and tear, and overall system instability [13].Analytical modeling and simulations are essential for understanding PMSG behavior under different operating conditions [14]. These models incorporate electrical and mechanical equations governing the generator's operation, considering induced voltage, rotor dynamics, and electromagnetic interactions [15]. Computational tools like MATLAB/Simulink and PSCAD allow for dynamic simulations, enabling analysis of transient stability, harmonic distortions, and voltage regulation under varying loads [16].Simulations reveal that permanent magnet properties significantly influence stability and efficiency [17]. Design modifications and material advancements, such as high-temperature-resistant magnets, can mitigate performance issues due to temperature variations [18]. Additionally, incorporating real-time control strategies improves system response to dynamic grid and load conditions [19].

Given the fixed excitation limitations, advanced control strategies have been developed to enhance PMSG stability [20]. Field-Oriented Control (FOC) and Direct Torque Control (DTC) optimize real-time stator current and torque regulation, improving voltage stability and minimizing torque ripple [21]. Power electronic converters and voltage regulators also contribute to maintaining consistent output performance under varying conditions [22].The integration of energy storage systems, such as batteries and supercapacitors, further stabilizes power output by compensating for transient disturbances and load fluctuations [23]. Additionally, hybrid systems combining PMSGs with other generators, such as doubly fed induction generators (DFIGs), improve efficiency and grid adaptability [24].PMSGs are predominantly used in wind energy systems, particularly in direct-drive wind turbines, where they eliminate the need for mechanical gearboxes, reducing maintenance costs and increasing reliability [25]. They are also used in small hydroelectric and marine energy applications due to their compact and efficient design [26].PMSG deployment is expanding in rural electrification projects, particularly in Africa, where they provide off-grid renewable energy solutions [27]. However, the reliance on rare-earth materials for permanent magnets presents economic and environmental challenges, necessitating research into alternative materials and manufacturing processes [27-28].

Table 1.0: Different Methods used for Modeling of PMSG. [28].

Method	Description	Merits	Limitations
1. Analytical Modeling	Derivation of mathematical equations (d-q axis modeling) to represent the PMSG dynamics and stability.	- Provides precise theoretical insights. - Useful for initial design analysis and control design.	- Assumes linear system behavior, which may not capture nonlinearities in PMSG operations.
2. Simulation-Based Analysis	Simulation of PMSG in software tools like MATLAB/Simulink, PSCAD, or ANSYS to study dynamic response.	- Offers detailed analysis under various operating conditions. - Easy to modify parameters.	- Computationally expensive for large systems or long simulation periods.
3. Experimental Testing	Direct measurement and testing of PMSGs in a laboratory setup with varying excitation conditions.	- Provides real-world validation of theoretical and simulation results. - Highly accurate.	- Requires expensive hardware and time-consuming setup. - Limited to available test facilities.
4. Small-Signal Stability Analysis	Linearizing the PMSG model around an	- Effective for studying system behavior near	- Cannot analyze large disturbances or nonlinear

	operating point to assess stability via eigenvalue analysis.	steady-state. - Useful for controller design.	behavior.
5. Large-Signal Stability Analysis	Simulation or testing under large disturbances like faults or sudden load changes to assess stability.	- Suitable for analyzing transient and nonlinear system behavior.	- Requires significant computational or experimental resources.
6. Finite Element Analysis (FEA)	Use of FEA tools to model the magnetic field and evaluate its effects on PMSG stability and performance.	- High accuracy in modeling magnetic field and flux distribution.	- Computationally intensive. - Requires expertise in FEA tools.
7. Machine Learning Models	Training AI models (e.g., neural networks) to predict the impact of excitation on stability.	- Fast and effective for complex systems. - Can model nonlinear and multi-variable dependencies.	- Requires a large dataset for training. - Lack of interpretability in model results.
8. Frequency Response Analysis	Evaluates system stability by studying the frequency response (e.g., Nyquist, Bode plots).	- Effective for understanding stability margins (gain/phase margins).	- Limited to linear systems and small perturbations.
9. Field-Oriented Control (FOC)	Implementation of FOC to study the impact of excitation adjustments on stability and torque control.	- Widely used in industrial applications. - Enhances efficiency and dynamic performance.	- Requires precise tuning of parameters.
10. Direct Torque Control (DTC)	Evaluation of stability using DTC methods that control torque and flux directly without complex controllers.	- High dynamic performance and fast response.	- Higher torque ripple compared to FOC.
11. Power System Stability Studies	Assessing PMSG stability as part of a grid-connected system using power system simulators.	- Suitable for analyzing the impact of grid dynamics on PMSG stability.	- Complexity increases for large power systems.
12. Lyapunov Stability Theory	Application of Lyapunov functions to ensure system stability under varying excitation conditions.	- Rigorous mathematical framework for stability analysis.	- Challenging to construct suitable Lyapunov functions for complex systems.

II. MATERIALS AND METHOD

The methodology integrates theoretical analysis and simulation for a comprehensive evaluation.

1. Problem Definition and Scope

Objective:

- Investigate the impact of excitation variation on the dynamic and steady-state stability of PMSG performance.
- Analyze key parameters such as voltage regulation, frequency stability, power output, and rotor speed under varying excitation conditions.

Scope:

- Evaluate performance in both standalone and load-connected scenarios.
- Investigate transient and steady-state behaviors during excitation changes.

2. **Simulation Studies**

Modeling Environment:

- Use of Ansys Maxwell 2D software to simulate the PMSG system.
- System Components in the Simulation:
- PMSG Model: Include rotor dynamics, stator winding characteristics, and flux linkage.
- Excitation Source: Model a variable excitation control system.
- Load Model: Use resistive, inductive, and capacitive loads for testing.
- Fault Scenarios: Simulate load variations and transient disturbances.

Simulation Parameters:

- Rotor speed, excitation voltage, load type, and load magnitude.
- Output Analysis:
- Observe waveform stability, frequency response, and power output under varying excitation.

3. **Data Collection and Analysis**

Key Metrics:

- Voltage and current waveforms.
- Rotor speed and frequency fluctuations.
- Power output (real and reactive power).
- Transient and steady-state response.

Data Analysis Techniques:

- Time-domain analysis: Analyze voltage and current responses during transient and steady states.
- Frequency-domain analysis: Evaluate harmonic content and stability margins.
- Compare experimental results with simulated data to validate the model.

4. **Stability Evaluation**

- Perform stability analysis using:
- Transient Stability:
- Analyze the system's ability to recover from short-term disturbances.
- Steady-State Stability:
- Evaluate the system's behavior under constant operating conditions with varying excitation.
- Examine critical excitation levels for stable operation.

Model Equations

(1) Electrical Equations (in d-q reference frame)

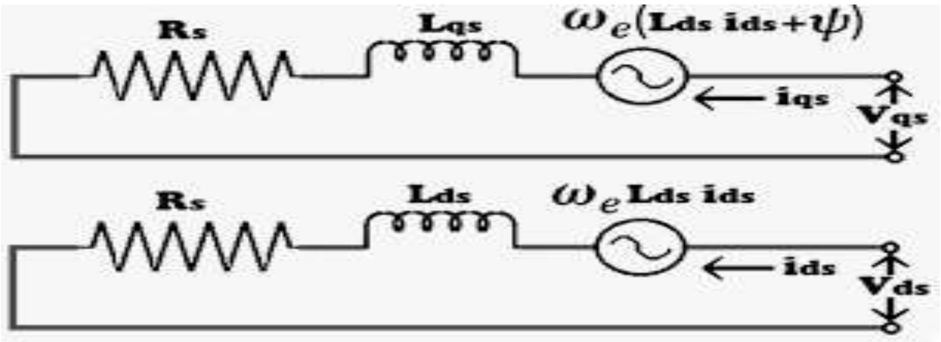


Figure 1: Equivalent Circuit of PMSG [29].

The stator voltage equations for the PMSG can be expressed as:

d-axis:

$$\mathrm{Vd} = \mathrm{Rs}_{\mathrm{id}} + \mathrm{L}_{\mathrm{d}}\frac{\mathrm{d}_{\mathrm{id}}}{\mathrm{dt}} - \omega_{\mathrm{e}}\mathrm{L}_{\mathrm{qiq}}\ (3.1)$$

q-axis:

$$\mathrm{Vd} = \mathrm{Rs}_{\mathrm{iq}} + \mathrm{L}_{\mathrm{q}}\frac{\mathrm{d}_{\mathrm{iq}}}{\mathrm{dt}} - \omega_{\mathrm{e}}\mathrm{L}_{\mathrm{diq}}\,\mathrm{d}\ (3.2)$$

Where:

vd,vq: d- and q-axis stator voltages (V), id,iq: d- and q-axis stator currents (A)

Rs: Stator resistance (Ω), Ld,Lq: d- and q-axis stator inductances (H)

ωe: Electrical angular velocity (rad/s), λf: Flux linkage due to permanent magnets (Wb)

(2) Mechanical Dynamics

The mechanical dynamics of the PMSG are described by the rotor's motion equation:

$$\mathrm{J}\frac{\mathrm{d}\omega\mathrm{r}}{\mathrm{dt}} + \mathrm{B}\omega\mathrm{r} = \mathrm{T}_{\mathrm{e}} - \mathrm{T}_{\mathrm{L}}\ (3.3)$$

Where:

J: Rotor moment of inertia (kg·m²), B: Damping coefficient (N·m·s), ωr: Rotor mechanical angular velocity (rad/s)

Te: Electromagnetic torque (N·m), TL: Load torque (N·m)

(3) Electromagnetic Torque

The electromagnetic torque is given by:

$Te = \frac{3}{2} \cdot p \cdot [\lambda_{fiq} + (Ld - L_q)idiq]$ (3.4)

Flux Linkage

The flux linkage (λ\lambdaλ) in the machine depends on excitation. For a PMSG, the excitation comes from the permanent magnets, but additional excitation methods (e.g., field weakening or external control) can influence stability. The flux linkage equations are:

$\lambda_d = L_{did} + \lambda_f$ (3.5)

$\lambda_q = L_{diq}$ (3.6)

Power Equations

The power balance in the system can be described as:

$P_{elec} = T_{e\omega r}$ (3.7)

$P_{mech} = TL_{\omega r}$ (3.8)

III. RESULTS AND DISCUSSIONS

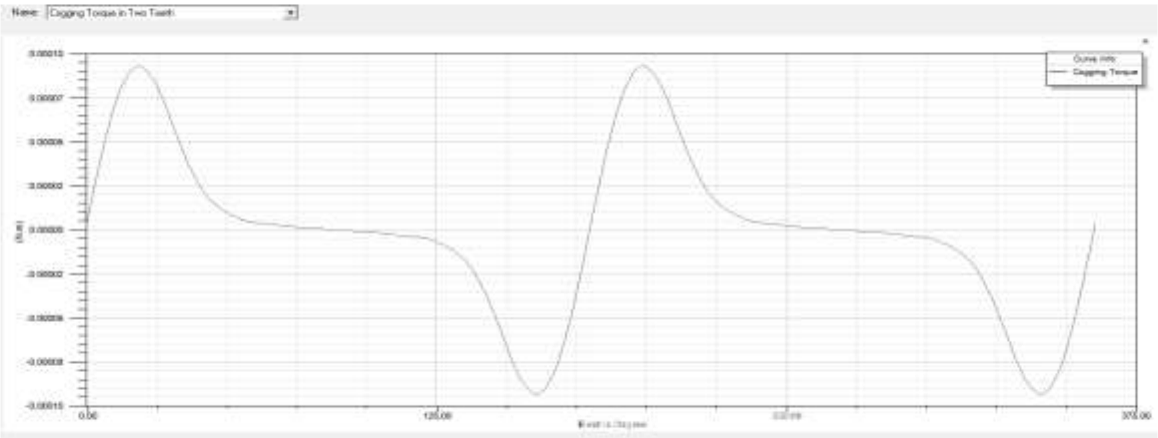


Figure 2: Torque in RMXPrt View

Figure 2 torque in RMXPrt view, this showed the behavior of the selected generator torque during operation. The generator had a high starting torque that later gain stability due to loading of the generator. When this generator in question was loaded gradually, the performance torque dropped sharply but in less than a 10sec, it bounces back and thereafter maintained stability throughout the operational period. The maximum torque experienced here was $0.0007*10^{3}$N-m. This was corresponding to the maximum electrical degree of 375^{0} electrically.

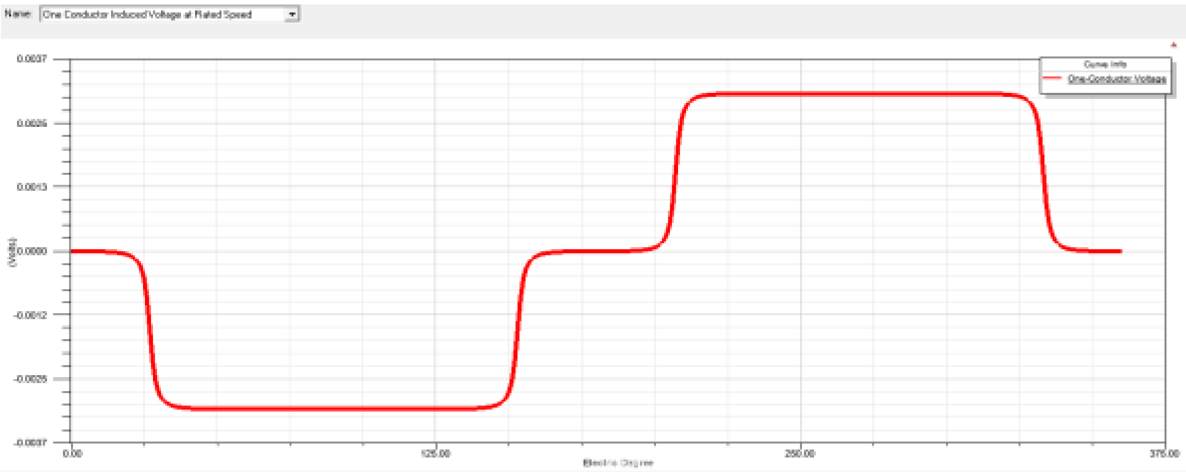


Figure 3: Single Conductor Voltage at rated speed

In figure 3 single conductor voltage at rated speed, it showed the rated voltage of the single line conductor while the generator was in operation. It is seen that once the generator was excited, voltage was generated and distributed within its windings. A single line conductor represents the winding conductors found in the generator. The voltage here was a function of its rotational speed. The higher the speed, the more the value of the voltage. For this type of generator to function maximally, the single conductor must be increasing as the speed of rotation also increases. It started from 0.00kV and progress to a maximum of 0.300kV. The reference maximum for this to occur was 375.00rpm.

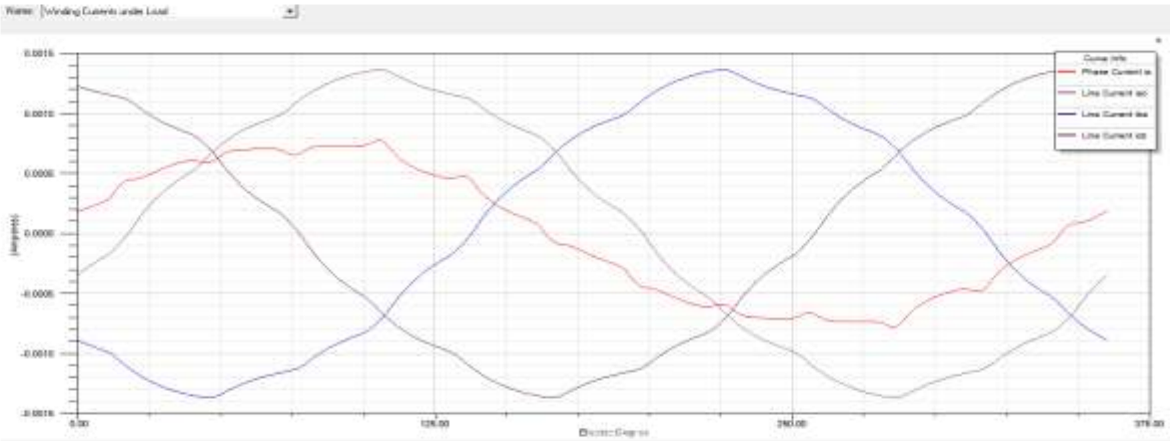


Figure 4: Winding Current under Load

In figure 4 winding current under load, it showed the behavior of the generator's winding current when it was loaded. At a transient level, the winding current appeared to be free from uneven harmonics. But immediately the generator was loaded, whether steady state load or variable loads, the winding current of the generator began to experience some harmonics. This harmonics helps to explain the transient response of the PMSG in real world practice and applications. The maximum current value displayed was 0.015*10A. The corresponding speed of the generator was 375.00rpm.

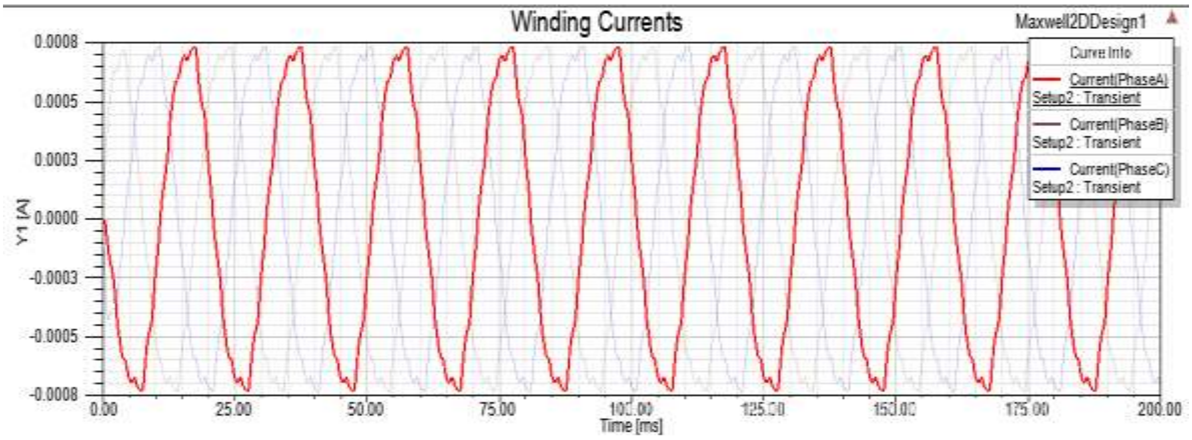


Figure 5: Phase A winding Current under Load

From figure 5 phase A winding current under load, this generator is a three phase type. But a single phase is being considered here. The outcome performance here reflects what happened to phase B & C respectively. From 0.000A, it performed maximally to 0.0006*10A. The corresponding time for this was 200.00sec. In real world practice, this is appropriate for industrial applications where constant variations in load is ebb.

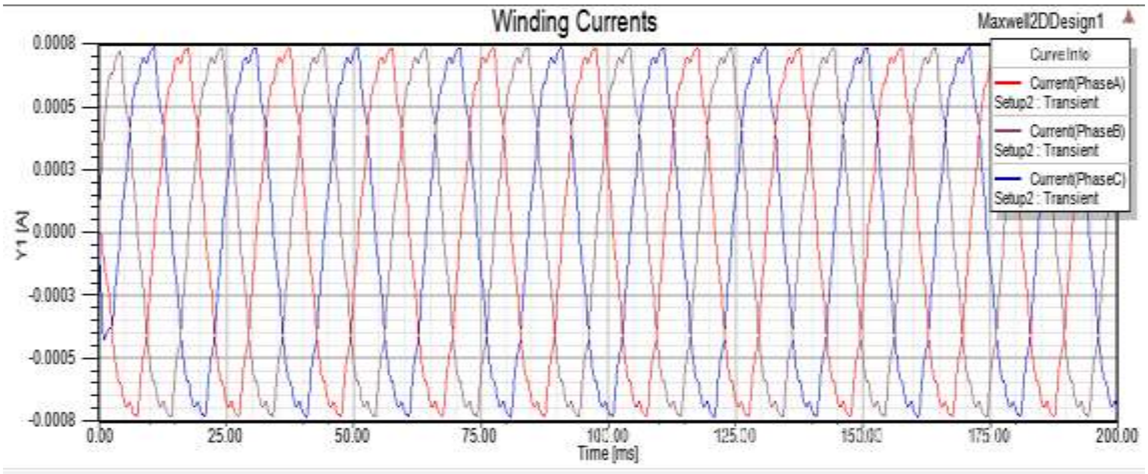


Figure 6: Winding Current in 2D Excitation

From figure 6 winding current in 2D excitation, the two dimensional representation of the winding currents for the selected generator with respect to its phases A, B & C. A bessellic response showed that for the generator to give out its maximum power and torque, the transient current yielding flux within the windings of the stator and stator during excitation, helps to keep the generator running synchronously, thereby reducing the effect of eddy current while increasing the induced voltage and currents, that would then lead to saturation within the ambers of the former. Though, the 2D model interface helps to give a more interpretations of what took place in the generator but it lacks the credibility to produce a more robust and holistic view of the interplay within the generator's windings. To this end, a 3D model interface would do better.

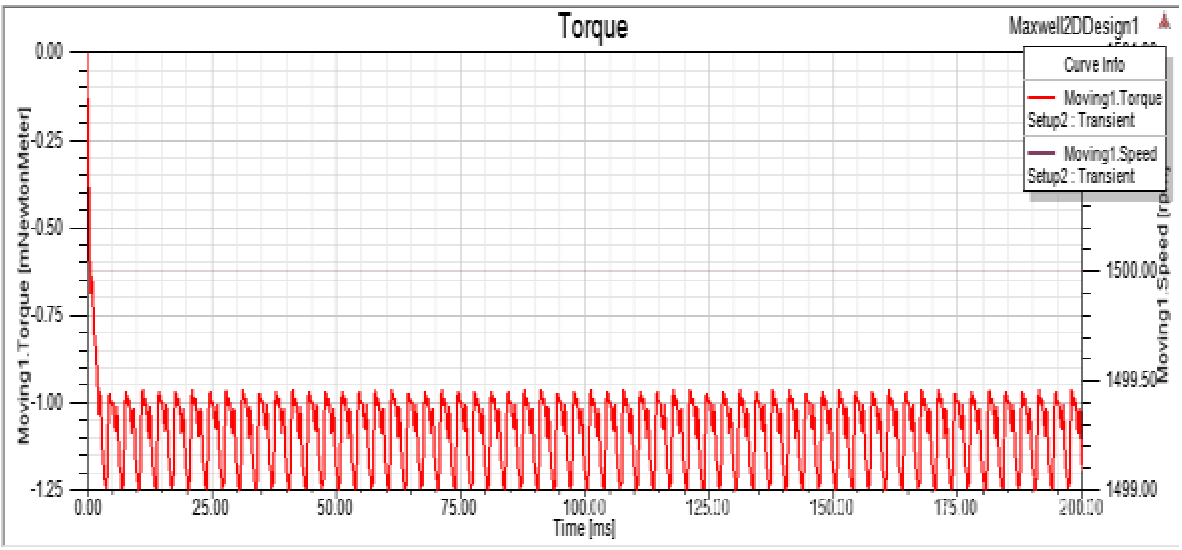


Figure 7: Generator Torque in 2D Excitation

In figure 7 generator torque in 2D excitation, it showed the simulated generator's torque in a 2D model. The torque started at 0.00N-m and then progressed over a certain range before settling down between -1.00N-m and -1.25N-m. This was the maximum operational range throughout the period of excitation. This negative sign in the torque showed that it was a generator. Recall; in voltage equations of motors and generators, the motor receives power, hence its sign is positive, while the generator sends out power, hence the sign is negative which indicates loosing flux. In real life, the torque here clearly represents the behavior of the generator under excitation. This characteristic of the PMSG is clearer when carried out in the 2D interface as it allows for a two dimensional view of the generator's performance. The total time taken for this to occur was 200.00sec.

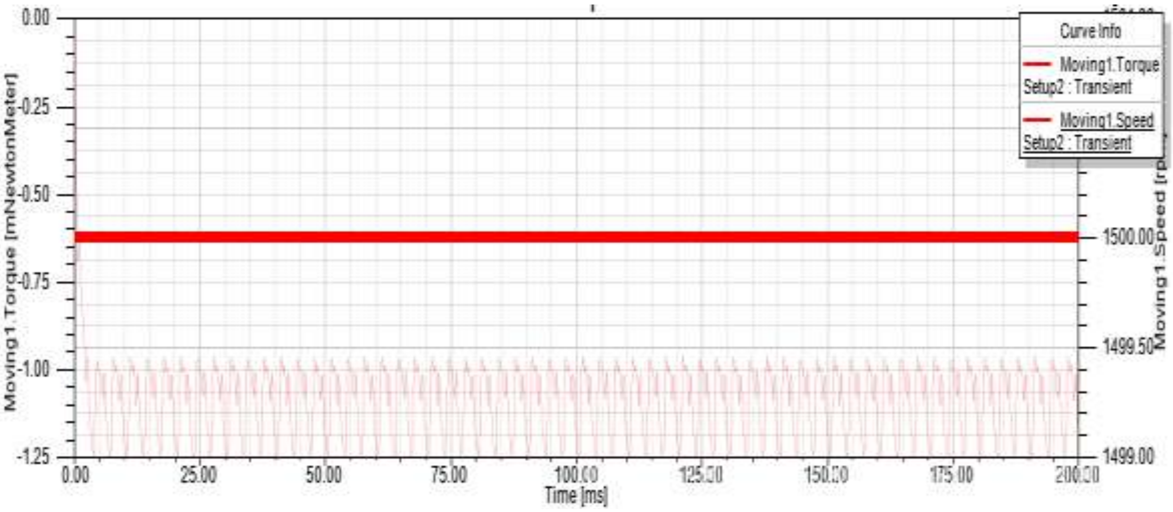


Figure 8: Generator Speed in 2D Excitation

In figure 8 generator speed in 2D excitation, it showed the simulated speed for the PMSG. The generator speed was constant throughout the period of excitation. The speed was constant because, in real world applications, if the speed of the generator is not constant, it would lead to fluctuations in the generated voltage and currents which in turn would affect the connected loads inform of flicker-effect. The speed started at 1500rpm and progressed throughout with the same constant value despite the loading effect on the generator. The time taken for this to be accomplished was 200.00sec.

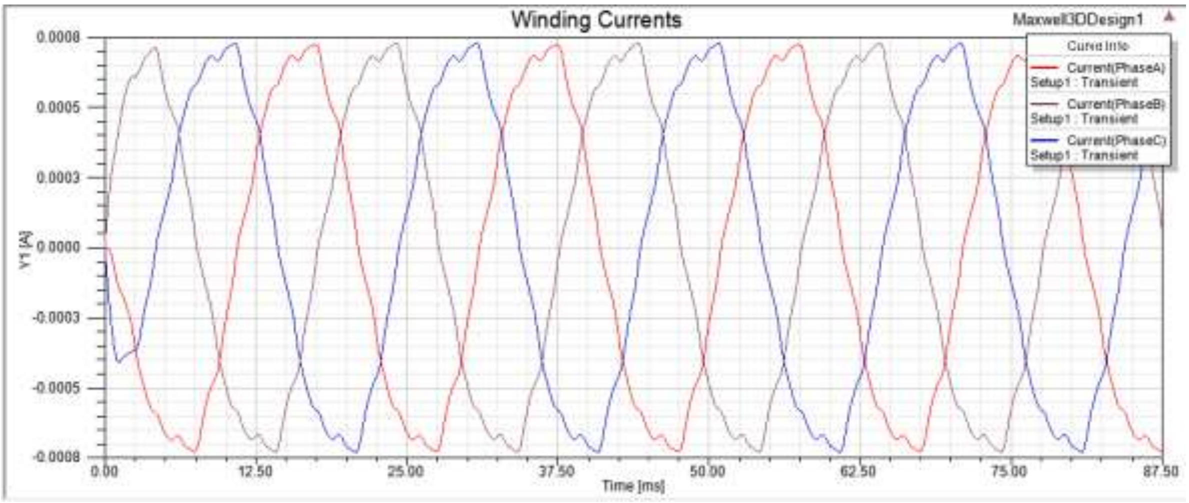
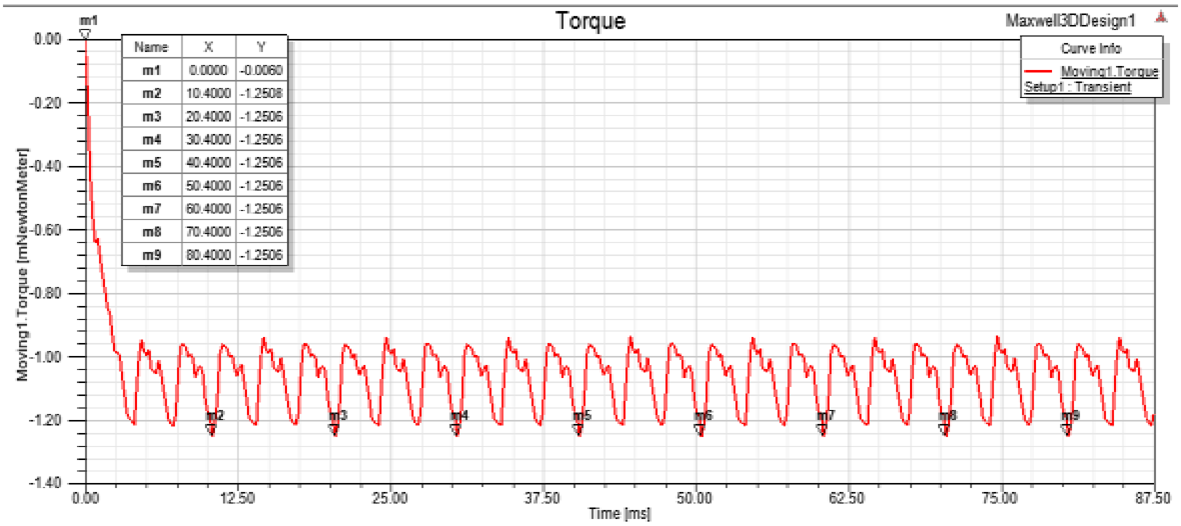


Figure 9: Generator Winding Current in 3D Excitation

From figure 9 generator winding current in 3D excitation, the three dimensional representation of the winding currents for the selected generator with respect to its phases A, B & C is shown. A semi-bessellic response showed that for the generator to give out its maximum power and torque, the transient current yielding flux within the windings of the stator and stator during excitation, helps to keep the generator running synchronously, thereby reducing the effect of eddy current and hall effect while increasing the induced voltage and currents, that would then lead to saturation within the ambers of the windings. The 3D model interface gave a better view of the current windings within the generator core. It allows for clearer views than the 2D and RMXPrt interfaces.



Name	X	Y
m1	0.0000	-0.0060
m2	10.4000	-1.2508
m3	20.4000	-1.2506
m4	30.4000	-1.2506
m5	40.4000	-1.2506
m6	50.4000	-1.2506
m7	60.4000	-1.2506
m8	70.4000	-1.2506
m9	80.4000	-1.2506

Figure 10: Generator Torque in 3D Excitation

In figure 10 generator torque in 3D excitation, it showed the simulated generator’s torque in a 3D model. The torque started at 0.00N-m and then progressed over a certain range before settling down between -0.87N-m and -1.20N-m. This was the maximum operational range throughout the period of excitation. This negative sign in the torque showed that it was a generator. Recall; in voltage equations of motors and generators, the motor receives power, hence its sign is positive, while the generator sends out power, hence the sign is negative which indicates loosing flux. In real life, the torque here clearly represents the behavior of the generator under excitation. This characteristic of the PMSG is clearest when carried out in the 3D interface as it allows for a three dimensional view of the generator’s performance. The maximum progressive points were denoted as M1, M2, M3, M4, M5, M6, M7, M8, & M9. Each of these maximum point had a corresponding time interval of 0.00sc, 11.00sec, up to 80.00sc respectively. This detailed stage by stage rendering of the generator’s parameters makes 3D modeling interface more reliable than 2D model. The total time taken for this to occur was 87.50sec.

IV. CONCLUSION

This paper concludes that excitation has a significant impact on the stability and performance of PMSGs. Proper excitation control and optimization are essential for maintaining stable operation, especially under transient conditions, load variations, and grid disturbances. The research found that excitation influences not only the efficiency of PMSGs but also their fault tolerance and long-term durability. However, more research is needed to fully understand the interaction between excitation and other physical phenomena such as thermal and mechanical stresses, particularly in renewable energy systems where grid variability is common.

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