

Modeling of Wind Generation Systems with Self-Excited Induction Generators Using the Finite Element Method

Ali Dilmi^{*1}, Ahcene Bouzida¹, Yassa Nacera¹

¹ Laboratoire des matériaux et développement durable (LMDD), Department of Electrical Engineering, Faculty of Applied Sciences, University of Akli Mohand Oulhadj, Bouira, Algeria

*Corresponding author; Email: ali.dilmi@univ-bouira.dz

Article Info

Article history:

Received , 01/05/2025

Revised , 01/06/2025

Accepted , 08/06/2025

Keywords:

Self-excited induction generator
wind energy

FEM

Power generation

Electrical generator

ABSTRACT

A self-excited induction generator (SEIG) represents a significant advancement in the realm of power generation, particularly through the utilization of renewable energy sources. This type of generator exhibits distinct advantages over alternative generator configurations and has garnered considerable attention in research and development endeavors in recent years. In this study, we focus on the modeling of both electrical and mechanical aspects of self-excited induction generators employing the finite element method. A model of a 1 MW self-excited induction generator was selected for detailed investigation, following the determination of the necessary magnetizing capacitors. The self-excitation process is initiated under no-load conditions, and subsequently, a balanced three-phase load is introduced once the stator voltage is established. The primary objective of this research is to deepen the understanding of SEIGs and their operational efficacy in renewable energy applications through comprehensive modeling and analytical techniques. By elucidating the operational principles and performance characteristics of SEIGs, this paper aims to contribute to the broader discourse on renewable energy technologies and their implementation.

I. Introduction

The growing concern for environmental issues and the pressing need to tackle climate change have elevated "renewable energy" to a central theme in discussions about development and employment. Among various forms of renewable energy, wind energy stands out as a clean and sustainable option with significant potential for growth. Addressing how to enhance the wind power sector and optimize the efficiency of wind energy development and utilization is a critical challenge that requires immediate attention. Currently, squirrel-cage induction generators are widely utilized in renewable energy systems, particularly in wind energy applications [1]. This widespread adoption can be attributed to several advantages of these generators, such as their low cost, straightforward design, ease of maintenance, and inherent protection against short circuits. In grid-connected energy systems, the reactive power needed by the induction generator is sourced from the grid. In contrast, for isolated energy systems, a three-phase capacitor bank is connected to the generator terminals to provide the necessary reactive power; this configuration is known as a Self-Excited Induction Generator (SEIG) [2,3]. The presence of residual magnetism in the rotor plays a vital role in this process. Similar to DC shunt generators, this residual magnetism generates a small voltage at the stator terminals, which enhances the rotor's magnetism due to the flow of capacitive current, thereby increasing the voltage. This voltage buildup continues until saturation occurs, which limits the maximum voltage that can be generated. This paper presents an analysis of a three-phase self-excited induction generator (SEIG) under both no-load and load conditions. A field circuit model based on the finite element method has been employed for this analysis.

II. Modelling Wind System

II.1. Modelling of wind energy

If we could fully capture the kinetic energy of a volume of air moving at a speed v using a device with a surface area S positioned perpendicular to the wind direction, The kinetic energy of the moving air can be harnessed, and the power output can be expressed by the formula:

$$P_v = \frac{1}{2} \rho s v^3 \quad (1)$$

- P : Air density (1.225 kg/m³ at sea level)
- S : The circular area swept by the turbine, where the radius of the circle is determined by the length of the blade RR and $S=\pi R^2$
- V : Wind speed

The aerodynamic power harnessed by a turbine, denoted as P_t , is influenced by the power coefficient C_p . This Relationship can be expressed as follows:

$$P_t = \frac{1}{2} C_p(\lambda, \beta) \rho s v^3 \quad (2)$$

A wind turbine is capable of converting only a specific percentage of the energy it captures from the wind. The power coefficient C_p serves as a measure of the turbine's aerodynamic efficiency, reflecting its design and operational characteristics. This coefficient can be defined using the following equation:

$$C_p(\lambda, \beta) = A_1 \left(\left(\frac{A_2}{\lambda_i} \right) - A_3 \times \beta - A_4 \right) \exp \left(\frac{A_5}{\lambda_i} \right) + A_6 \times \lambda \quad (3)$$

With:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3} \quad (4)$$

$A_1=0.5$; $A_2=166$; $A_3=0.4$; $A_4=5$; $A_5=-21$; $A_6=0.0068$

λ : The relative velocity representing the ratio of the linear velocity at the tip of the wind turbine blades to the wind speed.

β : The angle of the blade orientation.

The speed λ ratio on the other hand depends on the radius of the blade and its rotational speed:

Ωt : Rotation speed before multiplier.

R_t : Radius of a blade [4].

II.2. Self -Excitation Phenomenon and Magnetization Curve

One type of wind turbine currently available in the case of stand-alone operation is the squirrel cage generators wind turbine, which uses a capacitor bank to provide the reactive power required for induction and are called self-excited induction generators (SEIGs). The capacitor bank connected at their terminals for self-excitation, the capacitor bank is calculated according to several approaches to provide the required reactive power. Wind turbines that use (SEIGs) consist of several parts, and these are the most important parts: wind turbines, gearbox, self-excited induction generators (SEIGs), capacitor bank, transformer [9], as shown in Fig. 1

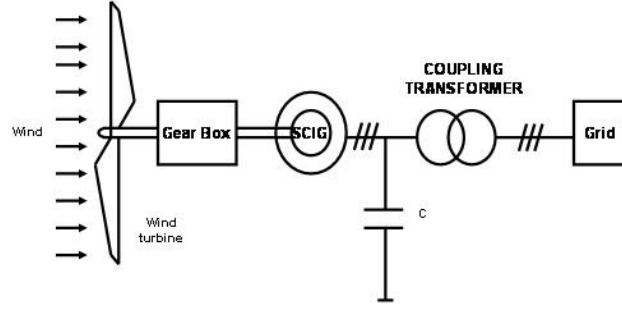


Figure 1. Basic wind generation system with self-excited induction generators (SEIGs).

If the induction motor rotor rotates faster than the synchronous speed, it can operate in generator mode and create energy. Equation (1) expresses the synchronous speed:

$$n_s = \frac{120f}{p} \quad (5)$$

f: is the frequency Hz.

P: is the number of poles.

The slip of a machine is the difference between the synchronous speed and the rotor speed, expressed by the following equation:

$$S = \frac{n_s - n}{n_s} \quad (6)$$

n: is the mechanical speed of the rotor.

Several analytical techniques have been proposed to calculate the minimum capacitance required for self-excitation of induction generators. According to, equation (7) is used to calculate the capacitance of the capacitor bank (in the delta link) to be connected in parallel with the induction generator

$$C_{\Delta} = \frac{Q_g}{3V^2 2\pi f} \quad (7)$$

Q_g is the reactive power absorbed as a generator.

V is the phase voltage.

To determine the value of the capacitance C_{Δ} , it is essential to quantify the reactive power absorbed by the induction generator. Several equations can be employed to calculate this parameter accurately:

$$p_n = S \cos \varphi_m \eta_m \quad (8)$$

$$Q_m = S \sin \varphi_m \quad (9)$$

$$S = \sqrt{3U_{line}I_{line}} \quad (10)$$

In generator mode, the electrical power generated by an induction machine can be expressed as:

$$P_{elg} = \frac{P_n \sin \varphi_g}{\eta_m \sin \varphi_m} \quad (11)$$

In the operation of induction machines, it is essential to maintain the condition of power equivalence between the motor and generator modes. This condition can be mathematically represented as: $S_{motor} = S_{generator}$ where S denotes the apparent power in each mode. This fundamental relationship ensures that the electrical power generated by the machine in generator mode is equal to the electrical power absorbed when operating as a motor. the electrical power in generator operation is equal to:

$$Q_m = \frac{P_n}{\eta_m} \tan \varphi_m \quad (12)$$

Once the reactive energy consumed by the induction machine while operating in motor mode has been established, we can proceed to evaluate the reactive power when the machine functions as a generator [5]. It is given by:

$$Q_g = \frac{\sin \varphi_g}{\sin \varphi_m} Q_m \quad (13)$$

P_n : is the rated mechanical power.

η_m : is the efficiency as a driving action.

φ_m : is the power factor angle as a motor.

When the rotor spins at a speed greater than the synchronous speed in the direction of the rotating magnetic field, and a capacitor bank is connected between the machine terminals, a small voltage develops at the stator terminals. This occurs because the rotor's magnetic field strengthens due to the flow of current from the capacitors, which further increases the voltage. This buildup of voltage continues until saturation is reached, the graph below shows the magnetization curve and the V-IC Characteristic [6]:

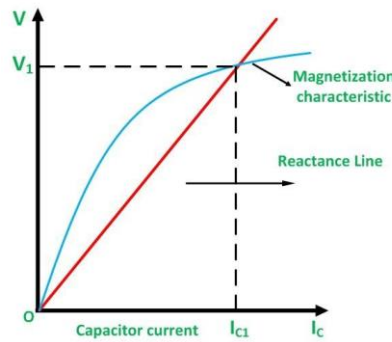


Figure 2. Induction generator magnetization curve.

III. Numerical Solution of SEIG Using Finite Element Method

In this research endeavor, we have opted to investigate a squirrel-cage asynchronous machine, the specifications of which are detailed in the table below. This choice allows us to explore the fundamental principles and operational characteristics inherent to this type of machine.

Table 1. SEIG parameters

Parametters	Value
Rated pawer	1 MW
Rated Voltage	3000 V
Coupling	Delta
Poles Number	2
Motoring Rated Speed	3135
Rated Frequency	51.83
Working temperature	75(°)

Following the completion of essential calculations to ascertain the self-excitation capacity, we proceeded to model the induction generator and its self-excitation behavior utilizing the time-stepped finite element method (TSFEM). The accompanying figure below depicts the model of the induction generator along with its corresponding field distribution.

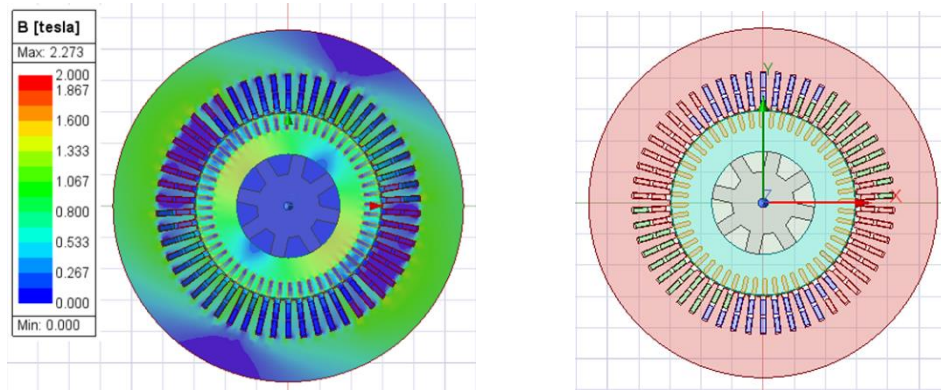


Figure 3. FE model of the generator and its field distribution.

The output voltage of a self-excited induction generator is subject to the interplay of various parameters, including the rotor speed, the connected load, and the capacitance value. In this section, we delve into the intricate relationships between these factors and their impact on the output characteristics of the self-excited induction generator at no load state

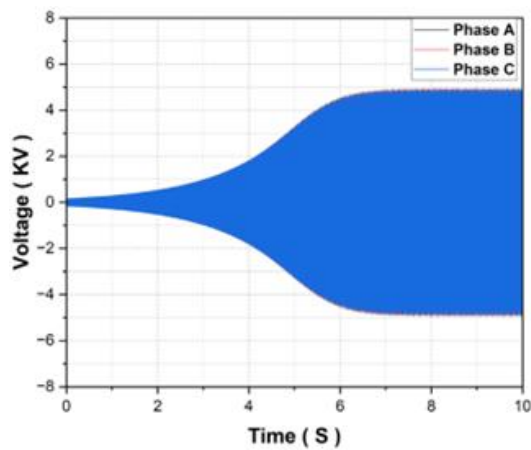


Figure 4. SEIG buildup voltage during self-excitation Process at no load state

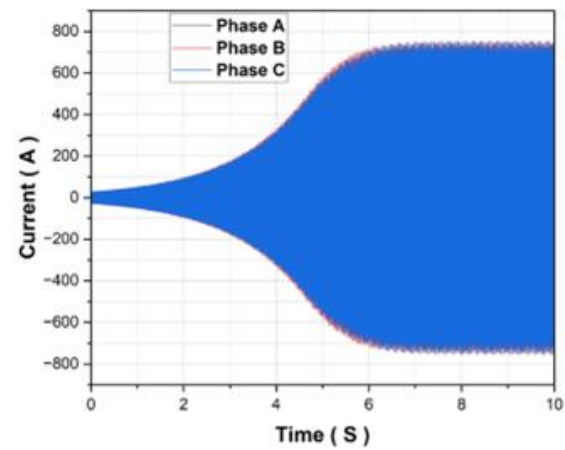


Figure 5. SEIG line current during self-excitation Process at no load state

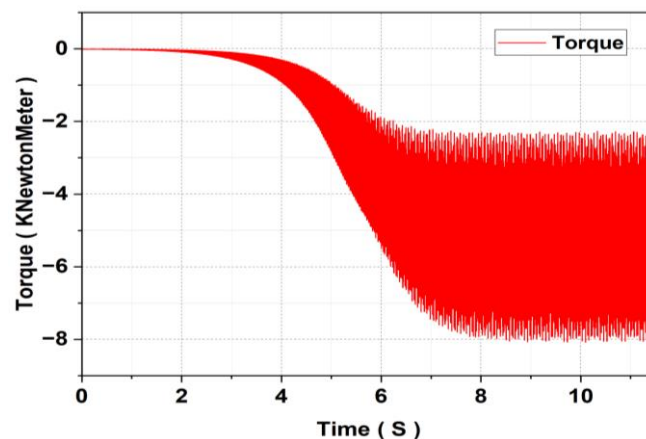


Figure 6. SEIG electromagnetic torque during self-excitation process at no load state

The process of no-load self-excitation for the generator is initiated from 0 to 3 seconds, subsequently followed by the abrupt introduction of a balanced three-phase load to the stator. Leveraging the data acquired from the validated finite element method (FEM) model, Figures 7 and 8 present the graphical representations of the

developed stator voltage waveform, line current during the self-starting phase, with the rotor operating at a constant speed n . This analysis elucidates the generator's dynamic response during the transition from no-load to loaded conditions.

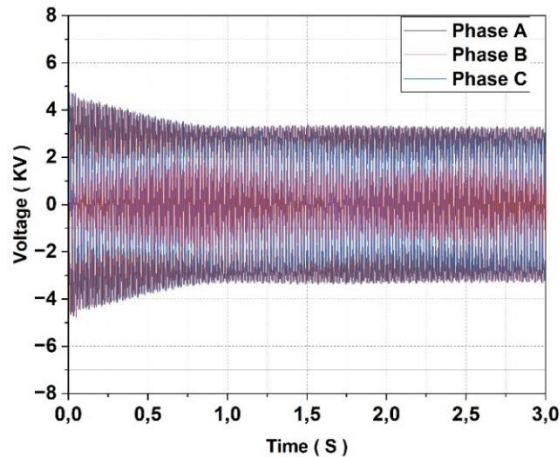


Figure 7. SEIG buildup voltage during self-excitation Process at load state

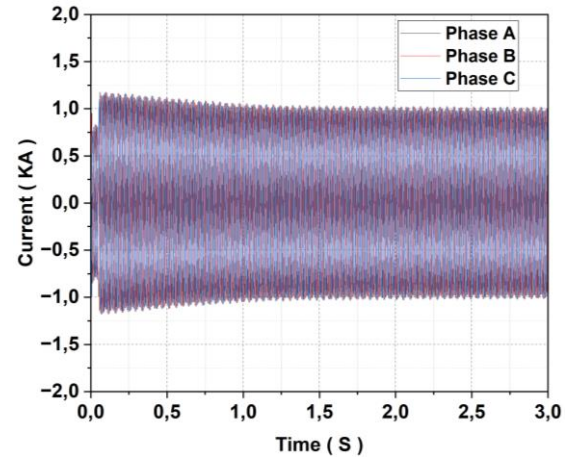


Figure 8. SEIG buildup current during self-excitation Process at load state

IV. CONCLUSION

In conclusion, self-excited induction generators (SEIGs) represent a pivotal technology in the realm of renewable energy, particularly for decentralized power generation. Their ability to operate autonomously, coupled with the integration of renewable sources such as wind and hydro, positions them as a sustainable solution for rural electrification and off-grid applications. The unique characteristics of SEIGs, including their self-regulating capabilities and adaptability to varying loads, enhance their viability in diverse energy landscapes. As the global demand for clean energy solutions continues to rise, the advancement of SEIG technology will play a crucial role in facilitating the transition towards a more sustainable and resilient energy future.

References

- [1] Yao, J.; Yao, F. Status Quo, Development and Utilization Efficiencies of Wind Power in China. *Processes* 2021, 9, 2133. J. Clerk Maxwell, *A Treatise on Electricity and Magnetism*, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.
- [2] Rani, A., Shankar, G. (2016, March). Standalone operation of wind turbine operated self excited induction generator. In *IEEE 2016 3rd International Conference on Recent Advances in Information Technology (RAIT)*, pp. 321-325, 2016.
- [3] Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, "Electron spectroscopy studies on magneto-optical media and plastic substrate interface," *IEEE Transl. J. Magn. Japan*, vol. 2, pp. 740–741, 1987.
- [4] Kendouli, F., Nabti, K., Labed, K., Benalla, H., " Modélisation, simulation et contrôle d'une turbine éolienne à vitesse variable basée sur la génératrice asynchrone à double alimentation, " *Journal of Renewable Energies*, vol. 14, pp.109-120, 2011.
- [5] J.M Chapallaz, J. Dos Ghali, P Eichenberger, G. Fischer, "Manuel on induction motors used as generator", GATA, vol 10, 1992
- [6] Kumari, A., Thosar, A. G., Mopari, S. S. Determination of excitation capacitance of a three phase self excited induction generator. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, 2015, 4(5), 4069-4074.