Permanent and Dynamic Behaviours of Self-excited Induction Generator In balanced mode

M. L. Elhafyani, S. Zouggar
Université Mohammed 1er, Ecole Supérieure de Technologie LEEP BP. 473. 60000 Oujda Morocco.

M. Benkaddour
Université Mohammed 1er, Faculté des Sciences, Département de physique Oujda Morocco.

Y. Zidani
Université kadi Ayad, Faculté des Sciences et Techniques Marrakech Morocco.

Due to its various advantages over the synchronous generator, the induction machine (IM) can be used as a generator in remote and rural areas. It be haves as a generator when its rotor is driven above its asynchronous speed. The required reactive power is provided by a local capacitors bank connected to the stator of the IM. Both permanent and transient modes of the self excited induction generator (SEIG) are studied. In both cases (loaded and no-loaded), the evolution of the output voltage for different values of the excitation capacitor and speed is presented. We analyze also, the influence of the capacitors and speed values on start-up of the SEIG. A comparison between laboratory tests and simulation results is done, that demonstrate the effectiveness of the proposed model.

Key words: Renewable energy, Self-excited induction Generator, Variable speed, Transient analysis.

I. INTRODUCTION:

Taking into account its simplicity of use and its modest cost compared to a synchronous machine, the induction machine (IM) is as susceptible to function in generating in power stations of production of the electric energy [1,8].

In this case, the slip is negative and the rotor turns in the direction of the spinning field pattern at a slightly higher speed. The generator provides the active power to the utility, but the reactive power necessary to its supply is provided by the utility [1].
The majority of the wind energy converters installed today are equipped with an induction generator connected directly to the grid. Phase-compensating capacitors are connected at the wind turbines in order to compensate the reactive power consumed by the generator. An isolated operation of the induction generator is possible. The converter of wind energy is mainly equipped by both asynchronous generators and capacitors of self-excitation [1][9].

The condensers used are connected to the generator in order to compensate for the reactive power consumed by the generator. The frequency, the slip, the output voltage and the operating range of the system depend of the characteristics of the induction generator, the value of the capacitor and the wind speed of rotation [9].

The aim of this paper is to investigate the ability of some dynamic self-excited induction generator models to predict the output voltage depending of the variation of wind turbine speed (figure 1). We studied the following models: a first-order model based on the equivalent circuit and the Park model.

In the next section and section III, we present the description of the self-excited inductor generator and the equivalent circuit in the permanent mode.

Section IV deals with the transient mode of SEIG and the effect of the variation of magnetic inductance (Lm) on the machine operation. The effects of the wind speed variation, the load and the capacitor on the output voltage are illustrated. The simulation results are showed in section V.
The wind turbine acts like a primary strength to train the induction generator [11]. The power produced by the wind turbine part is given by the following formula:

$$P_{wt} = \frac{1}{2} \rho \, A \, C_p(\lambda) \, v_w^{\,3}$$

where :
ρ : the air density (kg/m^3)
A : the swept area (m^2)
Cp : the coefficient of wind turbine
v_w : the wind velocity (m/sec.)

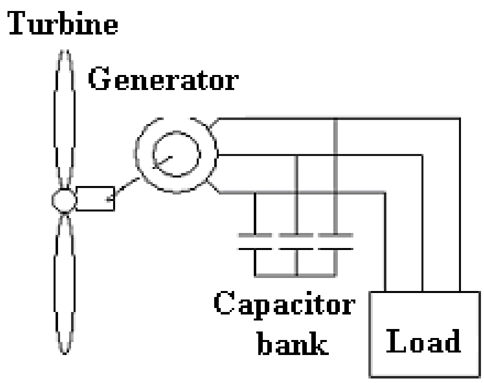
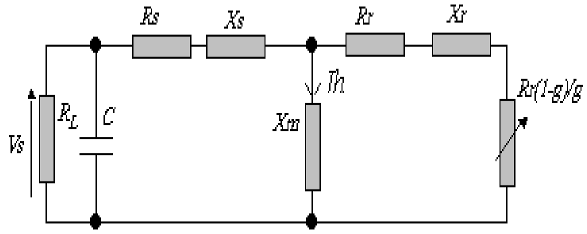


FIGURE. 1: Wind generator at variable speed based on the wound-rotor of induction generator

II. EQUIVALENT CIRCUIT OF SELF-EXCITED INDUCTION GENERATOR



Rs & *Rr:* Per phase resistances of stator and rotor.
Xs & *Xr* : Per phase reactance of stator and rotor .

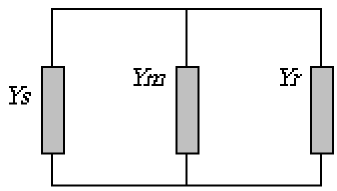


FIGURE. 2: Equivalent circuit of the self-excited induction generator

The generator starts turning as from as the wind speed overpasses a threshold that depends on the values of the capacities as well as on magnetic state of the machine (linear part of the magnetization curve) (figure 3). This threshold is defined by the following inequality:

$$\frac{1}{C\omega} < (L_m + l_{\sigma s})\,\omega$$

$L_m\omega = Xm$: magnetizing reactance (linear partThe induction machine used as the SEIG in this investigation is a three phase rotor induction motor with specifications: 1.5kW; 50 Hz; 220/380V; $I_s = 4.4$A; p=2;

The parameters given in the equivalent circuit shown in figure 2 are in this case:
R_s = 5.51Ω; R_r = 2.24Ω; *Xr=6.9Ω; Xs=6.9Ω; Xm= 38.81Ω*;

For SEIG application, the variation of *Xm* versus voltage should be taken into consideration.

III. STEADY-STATE MODEL

The asynchronous machine is modelled using the steady-state equivalent circuit shown in Figure 2. This circuit can be represented in terms of admittances [9]. Given the values of R-L load, the excitation capacitor *C*, the stator reactance *Xs* and of the stator resistance *Rs*, we deduce the stator admittance value.
The stator admittance can be expressed as:

$$Y_S = \mathrm{Re}(Y_S) + j\,\mathrm{Im}(Y_S) \quad (1)$$

The rotor circuit can be represented by:

$$Y_r = \frac{R_r/g}{\left(\frac{Rr}{g}\right)^2 + (X_r)^2} - j\frac{X_r}{\left(\frac{R_r}{g}\right)^2 + (X_r)^2} \quad (2)$$

The magnetic branch is represented by:

$$Ym = -j\frac{1}{Xm} \quad (3)$$

The equilibrium of the active and reactive power can be obtained by equalling the real parts of stator branch and the rotor branches; the results can then be calculated as follows:

$$R_e(Y_S) + Re(Yr) = 0$$

$$R_e(Y_S) + \frac{R_r/g}{\left(\frac{R_r}{g}\right)^2 + (X_r)^2} = 0 \quad (4)$$

With the equation (4), the slip *g* is determined.

The relationship between the imagining part of the rotor branch, the stator branch and the magnetizing branch is given by the equation (5).

$$I_m(Y_S) + \frac{X_r}{\left(\frac{R_S}{g}\right)^2 + (X_r)^2} + \frac{1}{X_m} = 0$$

This equation can be used to find *Xm*,

The relationship between magnetizing inductance *Lm* and the current *Ih* of *phase* is given by the equation (6) and is

$$L_m = \begin{cases} 0{,}25 & 0 \le Ih \le 0{,}9 \\ 0{,}13 + 0{,}126 \times exp^{(-2\times 0.04 \times (Ih-1)^2)} & 0{,}9 \le Ih \le 4{,}034 \\ \frac{2}{Ih^2} + \frac{1{,}27}{Ih} + 4{,}0310^{-3} & Ih > 4{,}034 \end{cases} \quad (6)$$

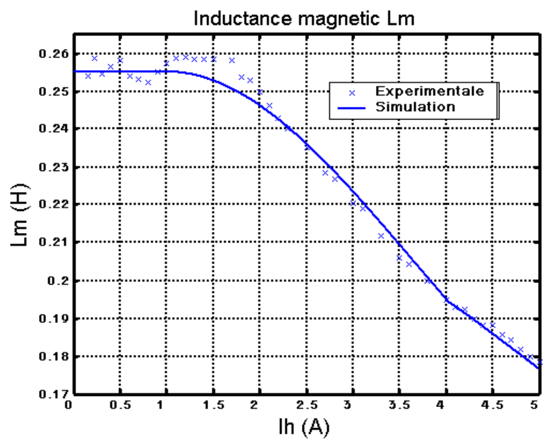
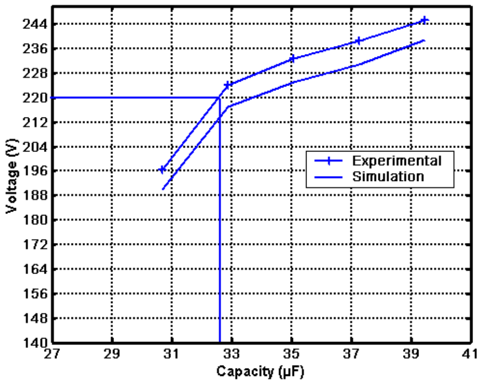


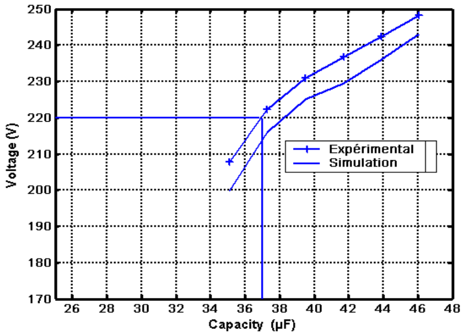
FIGURE 3.Magnetizing inductance of the induction *machine.*

In order to reach the steady-state equilibrium point of the induction machine, the output voltage *Vs* is expressed as a function of the values of both the slip $\bar{g}$ (Equation (4)) and *Xm* (Equation (5)), and for the different values of the excitation capacitor.

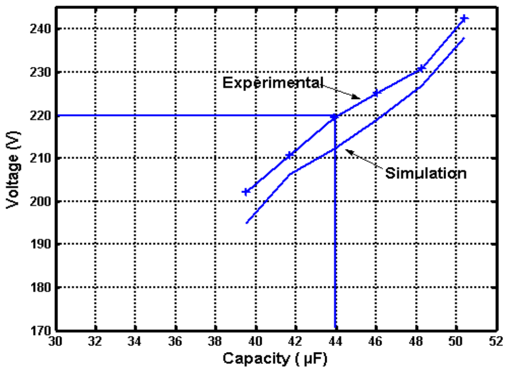
The figures 4a, 4b and 4c show the simulation and the experimental results of the output voltage Vs as a function of the excitation capacitor C for three different values of the : ω_r= 1500, 1417 and 1333rpm.



a) ω_r □1□rpm



b) ω_r =1417 rpm



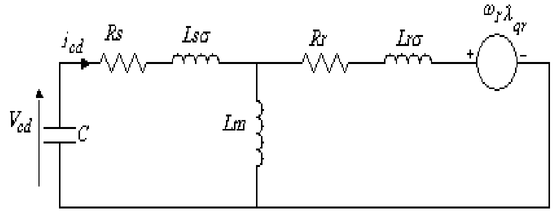
c) ω_r = 1333 rpm

FIGURE 4: Evolution of the voltage versus *C* .

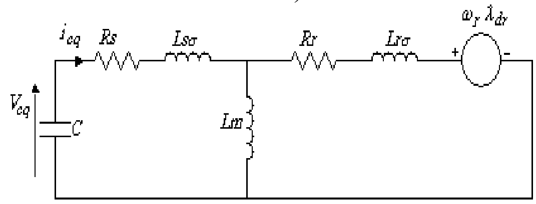
Figure 4 demonstrates that the difference between the experimental and simulation results is weak. This is due to the fact that one neglected the influence of the following parameters: the temperature, the resistance of iron and the perturbations on the operation system.

IV. TRANSIENT MODEL OF SEIG

The transient model of *the SEIG* is shown in Figure 5 [10].



a)



b)

FIGURE 5. D-Q mode of the SEIG at no-load
a) Axe D b) axe Q

Where:
$L_{s\sigma}$ & $L_{r\sigma}$ leakage inductances of stator and rotor.

A) Operating without load

The equation (7) can be found from the equivalent circuit given by Figure 5.

$$\begin{bmatrix}0\\0\\0\\0\end{bmatrix}=\begin{bmatrix}R_S+pL_s+\frac{1}{pC} & 0 & pL_m & 0\\ 0 & R_S+pL_s+\frac{1}{pC} & 0 & pL_m\\ pL_m & -\omega L_m & R_r+pL_r & -\omega L_r\\ \omega L_r & pL_r & \omega L_r & R_r+pL_r\end{bmatrix}\begin{bmatrix}i_{qs}\\i_{ds}\\i_{qr}\\i_{dr}\end{bmatrix}+\begin{bmatrix}V_{cqo}\\V_{cdo}\\k_q\\k_d\end{bmatrix}$$

Equation (7)

Where :

Ls=Ls□ + *Lm*
Lr=Lr□ + *Lm*

Equation (7) is derived from the equivalent circuit given in Figure 7. This equation represents all dynamics of the induction generator taking into account the initial conditions for the self-excitation process. *Kq* and *Kd* are constant, they represent respectively the initial induced voltages along the d-axis and q-axis due to the remanant magnetic flow in the core of IM. V_{cqo} and V_{cdo} are initial voltages of the capacitor bank on the two axes d and q [10].

The equation (7) does not take into account R-L load because that is not an element of the generator model.

B) Operating with load

In this case, the output voltage can be described by following equation

$$\frac{dV_{sd}}{dt} = -\frac{1}{C}.i_{sd} - \frac{1}{R_L C}.V_{sd} \qquad (8a)$$

$$\frac{dV_{sq}}{dt} = -\frac{1}{C}.i_{sq} - \frac{1}{R_L C}.V_{sq} \qquad (8b)$$

The generated torque can be expressed according to the relation (9):

$$C_u = N_p \frac{L_m}{L_r}(\Phi_{rd}.i_{sq} - \Phi_{rq}.i_{sd}) \qquad (9)$$

where :

N_p : Number of poles ($N_p = p = 2$)

$$\Phi_{rd} = L_r\, i_{rd} + L_m\, i_{sq}$$

$$\Phi_{rq} = L_r\, i_{rq} + L_m\, i_{sd}$$

V. SIMULATION RESULTS IN TRANSIENT MODE OF THE SEIG

Using the Matlab/Simulik tool, we simulate the equations 7, 8 and 9. The transient state of the IM is studied [12].

V.1. Start-up with no load

Figure 6 illustrates the output voltage of the empty (no-load) SEIG versus time. The start-up time is about 0,8

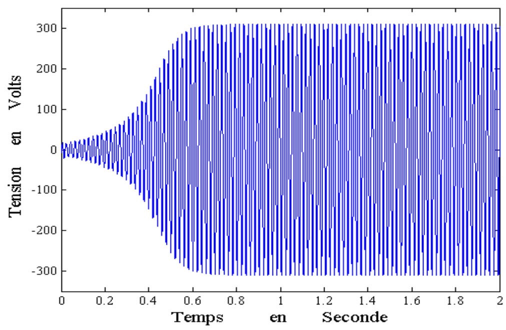


FIGURE 6. The output voltage waveform Vs at ω_r= 1500rpm and C=73.5µ

Figure 7 illustrates the stator voltage evolution during the loadless starting when the excitation capacity is decreased by 16%. It is noted that the voltage also decreases by 18%.

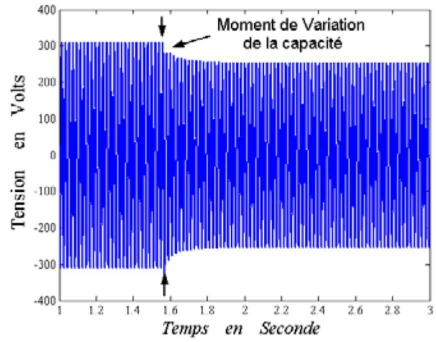


FIGURE 7. The voltage evolution Vs when the capacity decreases by 16 %.

Figure 8 shows the effect of varying the drive speed of the output voltage *Vs*. When the drive speed decreases by 10%, it is recorded that the output voltage decreases by 20%.

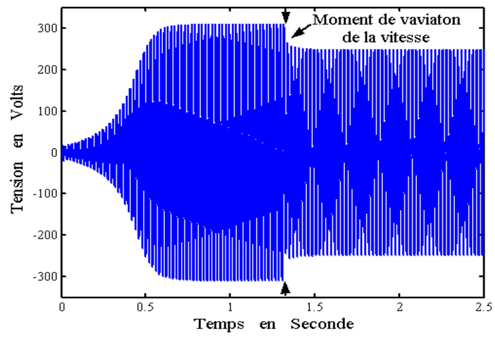


FIGURE 8. Voltage waveform when the speed decreases by 10%.

V.2.Start-up on the resistive load

Figure 9 represents the voltage waveform *Vs* of a stator phase during the starting period. We note that the output voltage reached the value of stabilization 220V at 1,14 seconds after the start-up.

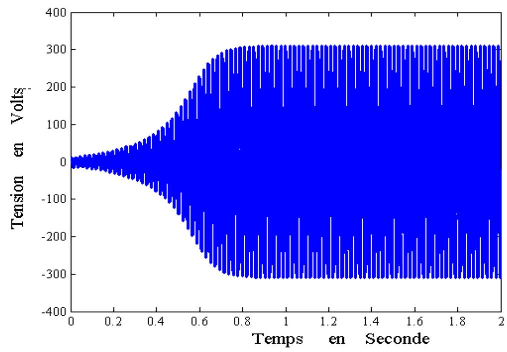


FIGURE 9. Stator voltage waveform Vs at ωr= 1500rpm (C=107µF and RL=90Ω)

VI. CONCLUSION

In this paper, we studied the dynamic and permanent behaviours of a self-excited induction generator (SEIG).We also presented the effects of varying the resistive load, the excitation's capacitors and the drive speed on the stator output voltage. The excitation capacities must be well calculated in order to assure a successful starting of the induction generator. We have obtained the experimental results and done simulations of the induction generator.

The simulation results obtained by using the Matlab/simulik tool show the effectiveness of the studied model.

As a future work, we plan to use these results to regulate the output voltage of the induction generator.

[1] Y. Zidani and M. Naciri "A Numerical Analytical Approach for the optimal Capacitor used for the Self Excited Induction Generator " 32nd *IEEE PESC* Power Electronics Specialists Conference , pp 216-220, June 17-22 2001, Vancouver, Canada..

[2] Y. Zidani; " Contribution à l' Etude de la Génératrice Asynchrone auto-excitée", Master Thesis, 1999, Ecole Mohammadia d'Ingénieurs, Rabat, Maroc.

[3]. S.P.Singh, Bhim Singh and M.P Jain, "Performance characteristics and optimum utilization of a cage machine as capacitor excited induction generator", IEEE Transactions on Energy Conversion, Vol.5, No.4, pp 679- 685 December 1990.

[4] S. El-Aimani, F.Bruno, R.Benoit " Modélisation de Générateurs Eoliens à Vitesse Variable Connectes à un Bus Continu Commun", FIER, Tome II, pp356-362, Tetouan, 8-10 mai 2002.

[5] Techniques de l'Ingénieur, traité Génie électrique, « Machine asynchrone : régime permanent », D 3 480

[6] H. Aît Bouh, "Contribution à la régulation de la tension et de la fréquence à une génératrice asynchrone", Master Thesis. 2000, Ecole Mohammadia d'Ingénieur, Rabat, Maroc

[7]. Y. Zidani and M. Naciri «A Steady State Analysis of the Self Excited Induction Generator Controlled by an Electronic Load Governor." 4th IEEE PEDS Power Electronics and Drive Systems, pp. 903-907 Octobre 22-25 2001, Bali, Indonésie.

[8]N.Janssens (ELIA&UCL) «La problématique des productions à caractère intermittent et aléatoire, en particulier les parcs d'éoliennes. » journée d'étude de la SRBE-KBVE, Février 24 2005, Mons.

[9] Eduard Mujadi, Jesus Sallan , Mariano Sanz, charles P. Butterfield "*Investigation of Self Excited Induction Generators for wind turbine application*", IEEE Industry Application Conference 34 IAS Annual Meeting, 3-7 October 1999 Arizona USA..

[10] D. Seyoum, C. Grantham and F. Rahman, *"Analysis of an Isolated Self Excited Induction Generator Driven by a Variabe Speed Prime Mover",* AUPEC 2001, Curtin University of Technology Perth 23-26 Sep 2001 Australia.

[11] Eduard Mujadi, Brian Gregory, Diane Bord "*Self Excited Induction Generators for Variable-Speed Wind Turbine Generation*", IEEE Industry Application Conference 34 IAS Annual Meeting, pp 343-352, 3-7 October 1999 Arizona USA.

[12] M.L.Elhafyani, S.Zouggar, Y.Zidani, M.Benkaddour " *Modélisation et Simulation d'une Machine Asynchrone à Bague à l'aide du logiciel Simulink*", 2ème journées Annuelles d'informatique JAI'05, Mai 25-26 2005, Oujda, Maroc.