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Control of a variable speed asynchronous wind turbine dedicated to isolated site

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ABSTRACT

This paper focuses on the study of the asynchronous generator self-excited during operation in isolated mode. It concerns the analysis of a robust control of the asynchronous machine in order to improve the quality of the electrical energy produced in different environmental circumstances, and to promote the use of renewable energies in rural areas to improve education, the supply of drinking water, livestock and agriculture, access to information and communication. The present work concerns the description and modeling of the various mechanical parts of the wind turbine. It also tackles the steady-state and transient modeling of the asynchronous generator under self-excitation conditions. The practical results and the simulation ones have shown the influence of the self-excitation capacity on the output quantities of the wind system (voltage, current and torque) in vacuum and under charge (resistive and inductive). In the case where the asynchronous wind turbine is connected to a network, it imposes amplitude, waveform and frequency. But in the case of isolated sites, the asynchronous machine has a low power factor, what means it requires reactive energy. To correct this irregularity, we can improve the power factor by using variable capacitors. The excitation current (reactive power) must be permanently supplied according to the load connected. This requires an intelligent system that regulates the electrical energy produced.

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1. INTRODUCTION

Nowadays, electrical engineering research is oriented towards the exploitation of renewable energy, in order to offer the possibility to generate electricity cleanly and especially to a lesser dependence on natural resources, provided that their ordinary fluctuations and sometimes random fluctuations should be accepted. Among these sources of renewable energy, wind power represents a significant potential that will not to replace existing energy, but will mitigate a faster amortization of demand.

Thanks to these research activities, the latest generations of wind turbines operate at variable speed to extract the maximum electrical power depending on the wind speed [1-8]. The development of power electronics control techniques has introduced intelligent controls [9-14]. In the case of the use of wind turbines dedicated to isolated sites, various electrical machines are used such as the *DC* machine, synchronous machine and asynchronous machine. However, for reasons of reliability, robustness and cost, we opted in this work to the study of asynchronous motors as generators in isolated sites. Nevertheless, the major problem of this type of wind turbine is the amplitude of the voltage produced at the terminals of the asynchronous generator. Frequency and the power generated depend on the connected load, the wind speed and self-excitation capacities [15-33].

The objective of this work is divided into three parts: in the first part we present, the modeling of our proposed System: The wind turbine, self excited asynchronous generator (*SEIG*) and the Transient Model of *SEIG* in this parts, the relationship between magnetizing inductance (L_m) and phase voltage for induction machine was obtained experimentally. In the second part we are more interested, the simulation curve of variation speed and capacitance with the *SIEG* connected to load and no load in order to show the behavior of our machine. Finally the experimental results for our proposed System (Turbine, *SEIG,* with and without (Load and Rectifed)) are given to demonstrate the validity of our system.

2. MODELING OF THE WIND SYSTEM: WIND TURBINE – SELF EXCITED ASYNCHRONOUS GENERATOR (SEIG)

In this part of this work, we modelled a system consisting of a wind turbine with blades of length R, involving an asynchronous generator with gearbox of speed gain M.

2.1. Turbine model:

The model diagram of the mechanical equations of the wind turbine is given in Figure 1. For the turbine that used in this study, the power coefficient is approximated by the following formula. Figure 2 shows the variation of the coefficient Cp as a function of lambda.

$$Cp(\lambda)=\frac{G.\lambda.(\lambda_0-\lambda)}{A^2+(\lambda_0-\lambda)^2}\text{ ; With } G=0.19;\lambda_0=8.08;A=1.56$$

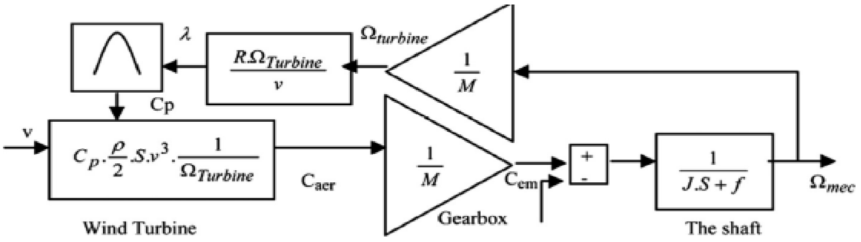


Figure 1. Block diagram of the turbine model

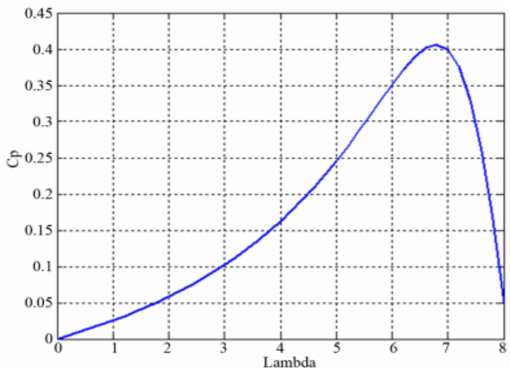


Figure 2. Evolution of the function Cp

2.2. Steady-state model of SEIG

The Self-excited Induction Generator SEIG is modelled in the steady-state by using the equivalent diagram shown in the Figure 3. The linear model of *SEIG* considers that the magnet-izing inductance is constant, which is not true, as it’s seen in the Figure 4, because the magnetic material used for manufacturing is not linear. It is very essential to take into account the saturation effect of the magnetic circuit and of the variation of mag- netizing inductance.

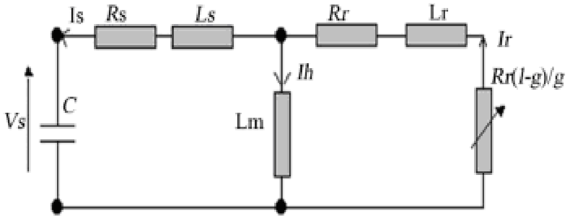


Figure 3.The phase equivalent circuit of the SEIG

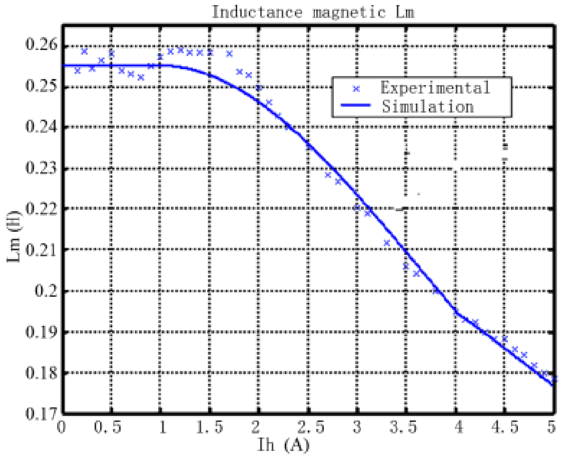


Figure 4. Magnetizing inductance of the induction machine

To approach the characteristics of the induction machine (All the experimental points *Lm*) by a mathematical function, we used an approximation method.

The experimental curve of the magnetic inductance is divided into three parts:

$$\begin{cases} L_m = 0.25H \qquad for: 0 \le I_h \le 0.9 \\ L_m = 0.13 + 0.126.\exp(-0.08.(I_h - 1)^2) \qquad for: 0.9 \le I_h \le 4.034 \\ L_m = -\dfrac{2}{I_h^2} + \dfrac{1.27}{I_h} + 4.0310^{-3} \qquad for: I_h \succ 4.034 \end{cases}$$

2.3. Transient model of SEIG

By taking into account the initial conditions for the process of self excitation, the transient state of (*SEIG*) is represented in the model of Park by the matrix according to:

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + sL_s + \dfrac{1}{sC} & 0 & sL_m & 0 \\ 0 & R_s + sL_s + \dfrac{1}{sC} & 0 & sL_m \\ sL_m & -\omega_r L_m & R_r + sL_r & -\omega_r L_r \\ \omega_r L_m & sL_m & \omega_r L_r & R_r + sL_r \end{bmatrix} . \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} + \begin{bmatrix} V_{cod} \\ V_{coq} \\ K_d \\ K_q \end{bmatrix}$$

K_q and K_d are constant, they re present resp ectively the initial induced voltages of the d-axis and q-axis axes *(d,q)*. V_{cqo} and V_{cdo} are initial voltages of the capacitor bank on the two axes d and q. From this matrix we have developed a mathematical model of the asynchronous generator that we use in the simulation of the wind system.

Table 1. Parameters of the proposed wind system

SEIG	R_s=5.51 Ω ; R_r = 2.24 Ω ; L_s = L_r =0.022 H ; L_m =0.123 H ; *P*=2)
Turbine	$J_{turbine}$= 0.436 kg.m²; J_g =0.0063 kg.m²; *M*=3.9; ρ =1.225; *f*=0.0063N.m. S^{-1} ; *R (length of the blade)*=1.8 m

3. SIMULATION RESULTS AND DISCUSSIONS

3.1. The influence of the inductive load on the output voltage of the proposed wind system

To see the influence of inductive load on our wind system, we conducted simulation tests by introducing an inductor in series with the resistance so as to have a cos (φ) diverse as shown in Figure 5.

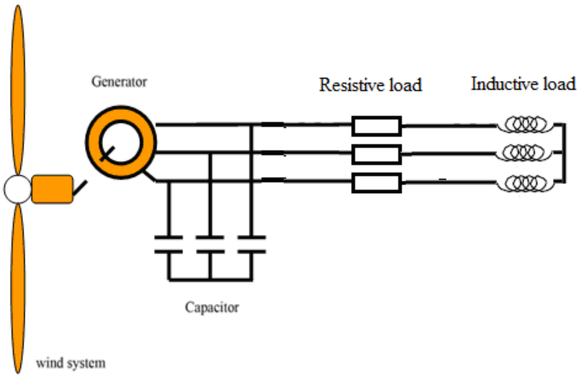
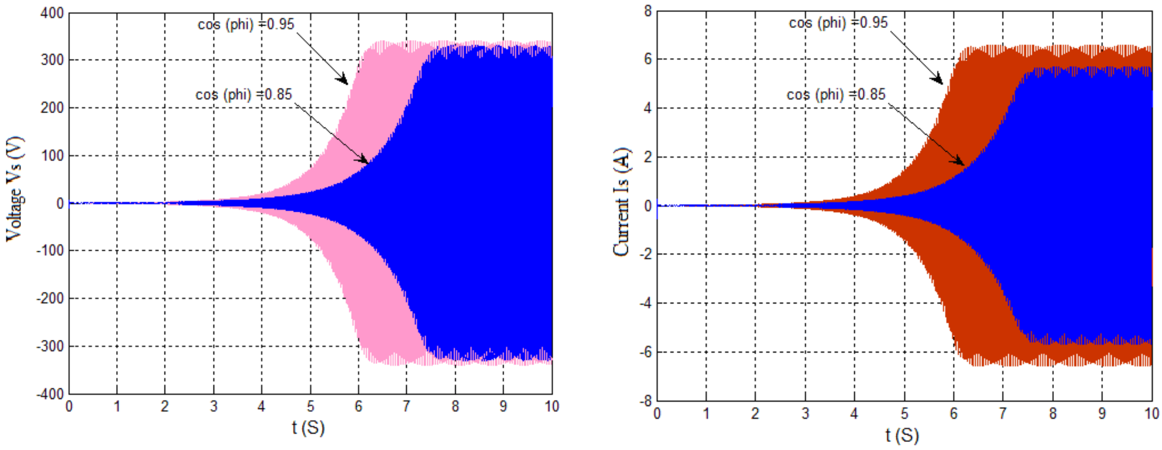


Figure 5. Diagram of the system to be simulated

Figure 6 (a) illustrates the evolution of voltage V_S for a different power factor (for R=100Ω; L=190mH; $\cos\varphi = 0.85$) and (for R=100Ω; L=100mH; $\cos\varphi = 0.95$)



(a) *Evolution of the voltage Vs time for (*V = 9m/s, C = 65 μ F and R = 100Ω*).*

(b) Evolution of the current I_s for (V = 9m / s, C = 65 F and R = 100Ω).

Figure 6. Evolution of the voltage V_s and the current I_s for (*V = 9m/s, C = 65 μ F and R = 100Ω*).

We notice that the start time for a power factor of 0.95 is higher than the start time for a power factor of 0.85. We also note that the amplitude of the voltage delivered for the two power factor values undergoes a small variation. Figure 6(b) illustrates the variation of the current I_S as a function of time for a different power factor ($\cos\varphi = 0.85$ and $\cos\varphi = 0.95$).

We note that the amplitude of the current I_S delivered by our wind system experiences a slight variation for a change of 0.95 power factor to 0.85. We note that the introduction of an inductive load causes a consumption of reactive power supplied by the capacitor banks, and therefore automatically deducted from the energy of the machine magnetization.

3.2. The influence of the excitation capacitance on the output voltage of the proposed wind system

Figure 7 shows the block diagram of our proposed wind system, which is based on a self-excited (1.5KW) asynchronous machine, connected to an AC / DC energy converter (rectifier) with an LC filter, and which powers a resistive load (R). To supply a load of 100ohm in an environment of 9m / s, a capacitance of $C_0 = 81\mu F$ is the optimum value for the *SEIG* priming.Thus a good choice of LC filter values ($L = 9mH$, $C = 2200\mu F$) gives us a well filtered voltage is of the order of *311V*, which is our desired value and imposed by our specifications as shown in Figure 8 (a). The curve of Figure 8 (b) shows the simulation results of output voltage when the capacitor C excitation of induction generator varies sharply.

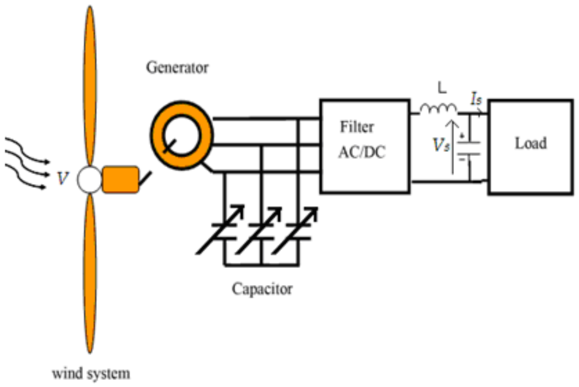
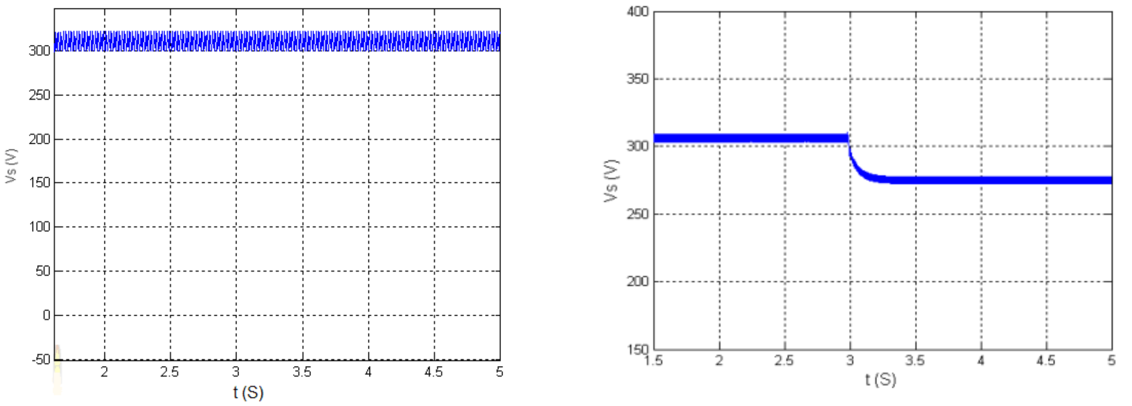


Figure 7. Synoptic diagram of a wind system with a load-related rectifier



(a) The output voltage Evolution of the under load wind system

(b) Evolution of the output voltage with a sharp decrease of 10% capacity of excitement from 81µF

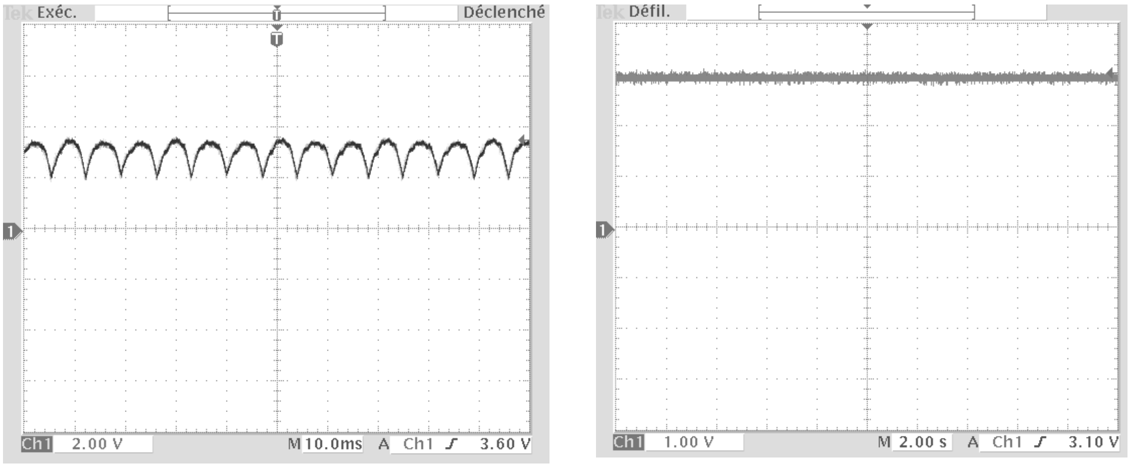
Figure 8. The output voltage Evolution of the proposed wind system

4. PRACTICAL RESULTS AND DISCUSSIONS

Figure 9 represents a photo of the experimental test bench which contains the asynchronous machine to be studied; this machine is driven mechanically by a continuous-current machine which plays the role of the wind speed.

Figure 9. The experimental test bench

A first series of experimental tests consists in validating our model proposed in Figure 7. Figure 10 (a) represents the voltage at the output of the rectifier PD3, Figure 10 (b) represents the output signal of the wind system after LC filtering. The generator used is modeled and implemented on Matlab/Simulnk whose internal parameters are determined beforehand.



(a) Evolution of the rectified voltage by the PD3 converter

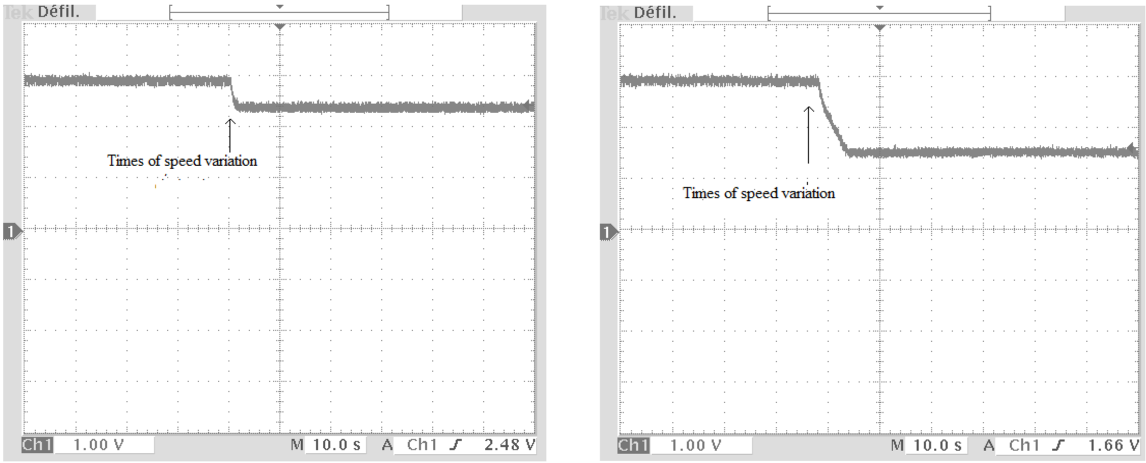
(b) The output voltage after LC filtering (*L = 6mH, C = 2200µF*)

Figure 10. Recovery and filtering of the wind turbine system output voltage, with a resistive load of 100 Ω and an excitation capacity of 81 Mf

For a 9m / s (1500 rpm) wind speed, and an excitation capacity of 81µF, a load of the order of 100Ω, the output voltage is of the order of 310V.We note that for the same conditions, the voltage value in simulation and in experimentation is nearly the same, therefore the validity of the proposed model.

4.1. Influence of the wind speed variation on the output voltage of the proposed wind system

Figure 11(a) illustrates the variation of the output voltage during a sudden change in wind speed from 9m/s to 8m/s with an excitation capacitance of 81µF, by charging on a resistive load of 100 Ω, and Figure 11(b) illustrates the variation of the voltage upon a change of 9m/s to 7 m/s.

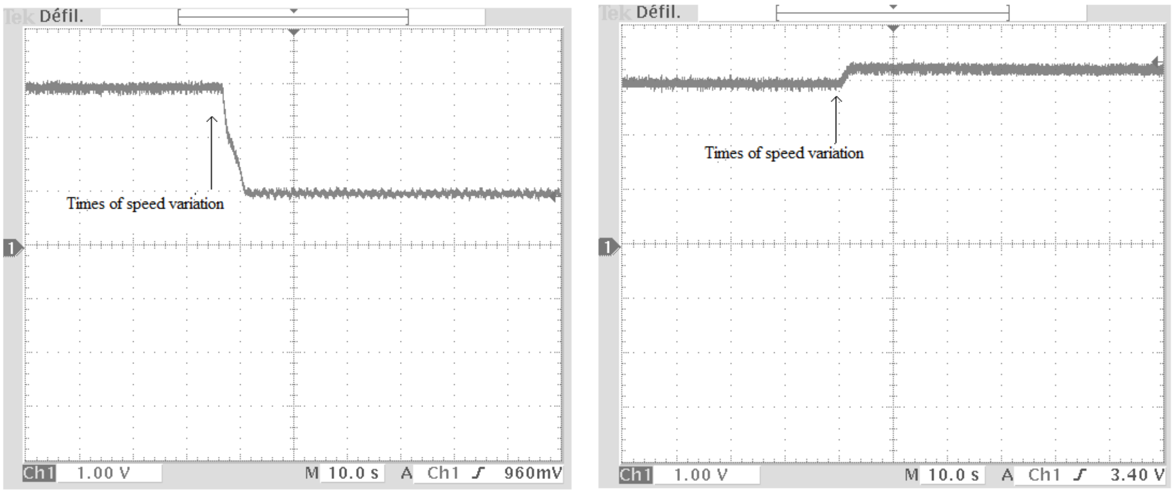


(a) Evolution of the output voltage with a severe decrease in wind speed from 9 m/s to 8 m/s.

(b) Evolution of the output voltage with a strident decrease in wind speed from 9 m/s to 7 m/s

Figure 11. Experimental evolution of the output voltage by charging on a load of 100 Ω and a capacitance of 81µF, with a sudden decrease in the wind speed

Figure 12 (a) illustrates the output voltage variation during a change in the wind speed of 9m/s to 6m/s, and Figure 12 (b) illustrates the variation of the voltage during an increase in wind speed from 9m/s to 10m/s. Formerly, we observe that the oscillation of the rotational speed of the generator caused during a decrease or a gust of wind induces significant variations in the voltage, and it has a direct impact on this generated voltage.



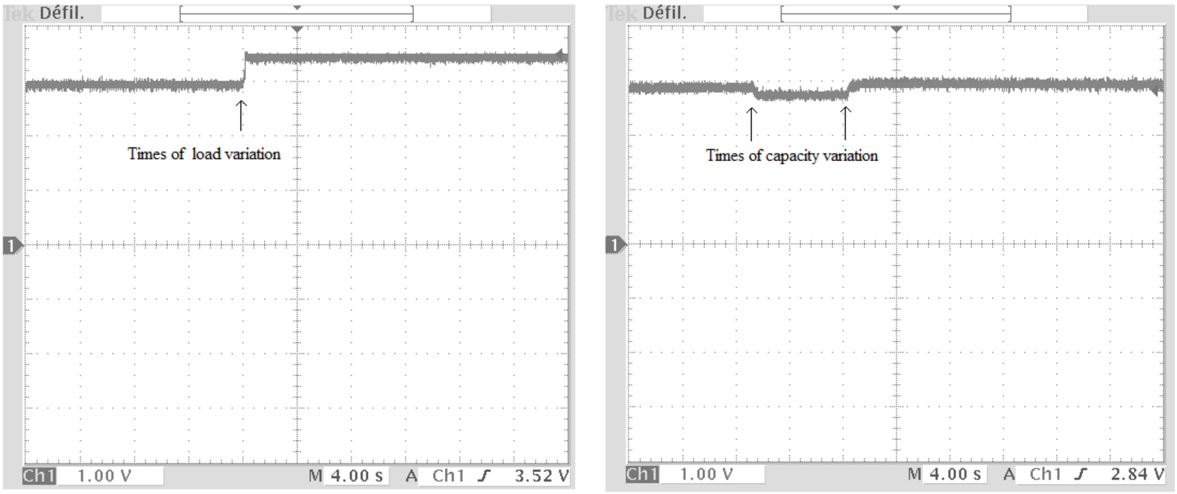
(a) The output voltage Evolution with a sudden decrease of the wind speed from 9 m/s to 6 m/s.

(b) Evolution of the output voltage with a sharp decrease in wind speed from 9 m/s to 10 m/s

Figure 12. Experimental evolution of the output voltage by charging on a load of 100Ω and a capacity of 81μF, with a decrease and a sudden increase of the wind speed

4.2. Effect of load variation and excitation capacity on the voltage

In the first time, our objective is to study the influence of a 50% variation of the resistive load fed by our wind system on the evolution of the amplitude of the voltage. In second time, the system is driven at 9m/s (1500tr/min) in still debiting on a resistive load of 100Ω.



(a) Evolution of the output voltage with a sudden decrease in the excitation capacity from 81μF to 60μF and then an increase to 120μF

(b) Evolution of the output voltage with a sudden variation of the load of 50% from *100ohm* and an excitation capacity of *81μF* and for a speed of *9m/s*

Figure 13. Evolution of the output voltage with a variation of the load and an excitation capacity

After a variation of the load, we notice that the tension undergoes a slight variation; the figure below illustrates this variation of the voltage Figure 13(a). Figure 13(b) illustrates the variation in the voltage during a sudden attenuation followed by an increase in the excitation capacity. From previous studies, we find that wind speed, load, and capacity have direct influences on the magnitude of the voltage delivered. Such a voltage control strategy must take into consideration these three factors.

5. EXPERIMENTAL CONTROL OF THE OUTPUT VOLTAGE OF ASYNCHRONOUS WIND TURBINE

In this experimental study, we work on the operation of the wind energy system with two banks of capacitors connected in parallel, a bank with fixed capacitors that provides the *SEIG* (75µF), and the other bank with variable capacities. We have performed a number of practical tests whose purpose is to adjust the voltage across the load to a reference value *311V* in a manual way by adjusting on the variable capacitance bench for each fluctuation in: the speed of the wind, the load or the *SEIG* excitation capacity.

Synoptic diagram of the test bench made in the LGEM lab as shown in Figure 14. Figure 15 illustrates the variation of the voltage across a load of 75Ω, with and without manual adaptation of the reactive energy. The sufficient modification capacity to adjust the voltage to *310V* for a sudden decrease in wind speed from *9m/s to 8m/s* is of the order of *54µF*, as much as for a simulation test we find that the regulation for these same conditions, the value of the sufficient modifying capacity is of the order of *24µF*. So, we note that this difference in capacitance between the experiment and the simulation is mainly due to the speed – slowing - down phenomenon on the generator shaft when increasing the reactive energy supplied to the *SEIG*.

In order to validate this observation, we carried out a test to regulate the tension under the same conditions of Figure 15 (speed variation from *9 m/s to 8 m/s*, fixed excitation capacity of the order of *75µF, 75Ω* load) but for a *25µF* change capacitance value as shown in Figure 16. Figure 17 illustrates the voltage variation for a sharp decrease in the SEIG excitation capacity. Figure 18 illustrates the variation of the voltage without and with manual regulation during a sudden change in the connected load.

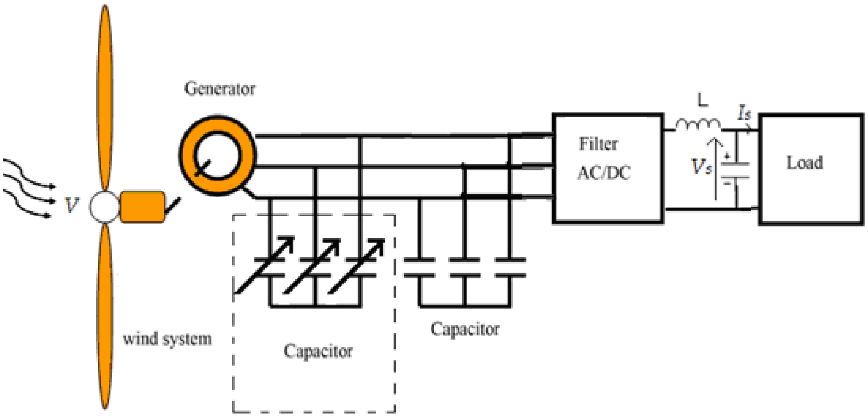
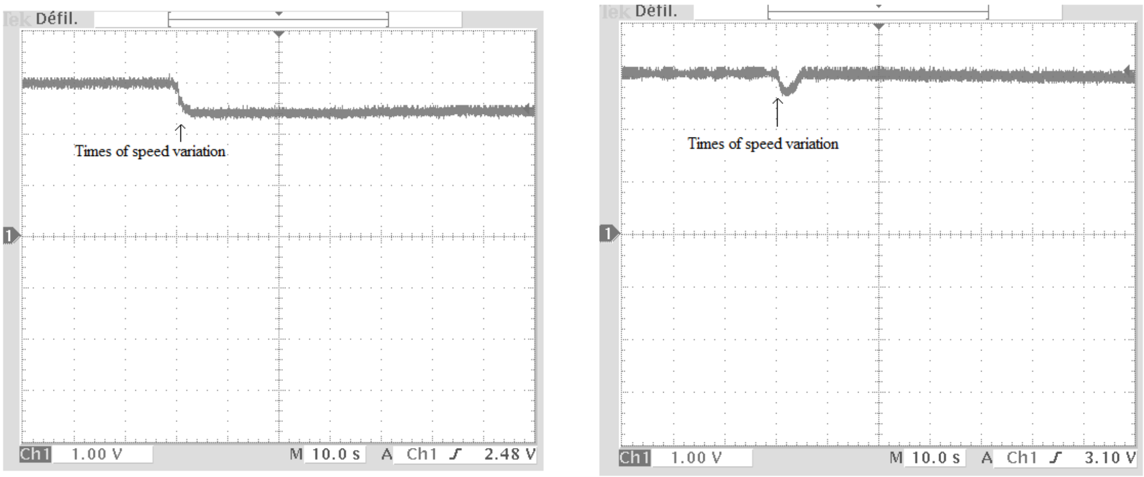


Figure 14. Synoptic diagram of the test bench made in the LGEM lab



(a) (b)

Figure 15 Evolution of the output voltage with and without reactive energy regulation with a severe decrease in wind speed from 9m / s to 8m / s

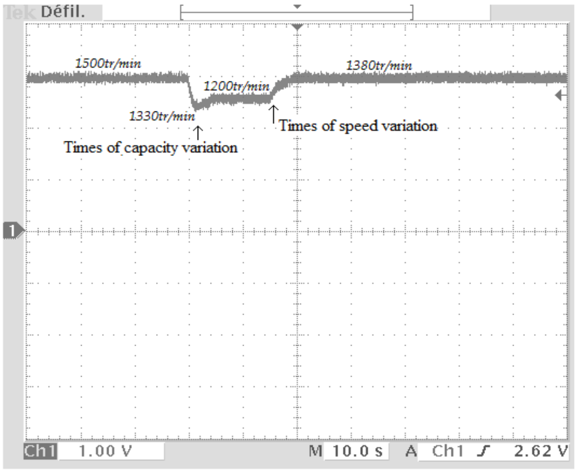
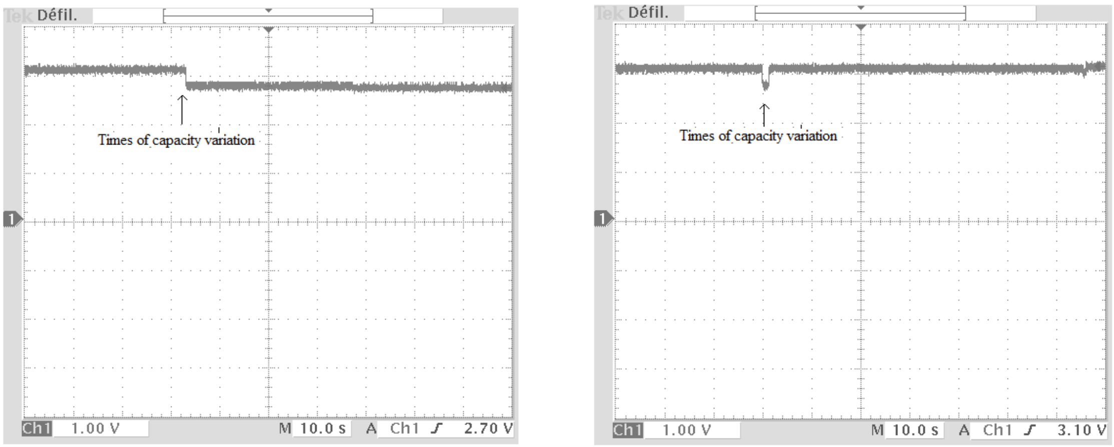
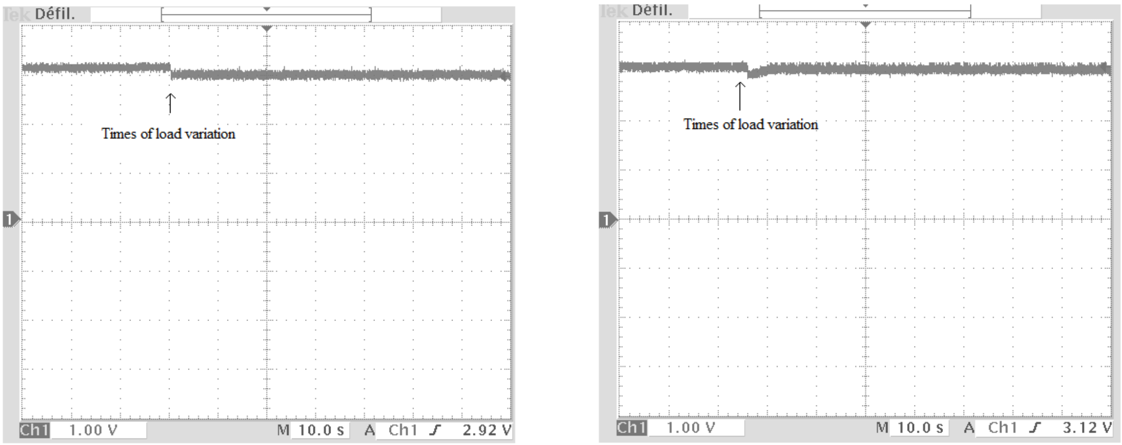


Figure 16. Evolution of the output voltage with manual reactive energy control and speed control on the *SEIG* shaft



(a) (b)

Figure 17. Evolution of the output voltage without and with adaptation of the excitation reactive energy with a sudden decrease in the excitation capacity



(a) (b)

Figure 18. Evolution of the output voltage without and with adaptation of the excitation reactive energy with a sudden decrease of the load of 25% from 75ohm

6. CONCLUSION

In an increasingly important ecological context, this work contributes to the field of renewable energies, especially the small wind turbine used in isolated sites. Particularly, it concerns the development of a variable speed asynchronous wind turbine control strategy. The approach we have undertaken to develop a control strategy is to progress a model of the wind turbine and a model of the asynchronous generator transient in terms of self-excitement.

The coupling of these two models, allows us not only to study the influence of the self-excitation capacity on the output quantities of the wind system (voltage, current and torque), but also to study the constraints related to the operation of the chain wind turbine. On the basis of these types of modeling, we solved the problem of the variation of the tension at the exit of the wind system, in spite of the speed variation of the wind or the load. For this, a control of the reactive energy excitation of the asynchronous generator has been developed. Experiments are presented to validate the proposed models.

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