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# CONTROL AND OPERATING POINT OPTIMIZATION OF HYBRID EXCITATION SYNCHRONOUS GENERATOR APPLIED FOR WIND APPLICATION

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**Abstract** - The purpose of this paper is to evaluate the possibilities of hybrid excitation synchronous generator (HESG) for wind applications. In HESG, excitation flux is created by both permanent magnets and excitation coils, so the output voltage can be controlled by the DC excitation field. For isolated loads, it is then possible to use the simplest and the most reliable wind generator architecture composed only by a HESG, a rectifier and a DC/DC converter to control the excitation flux [3]. In this paper, the wind generator architecture is presented, modeled and simulated to demonstrate the interest of HESG for wind applications.

**Keywords** – HESG, wind generator modelling, turbine, DC/DC

## 1. INTRODUCTION

Wind power production of electricity depends primarily on the quality of the sites. Only a preliminary study of local weather data and a long period of field measurements allow appreciating the real value of a proposed site for the construction of wind turbines in terms of wind exposure, frequency and winds speed average. Wind turbines use two main types of power generators: synchronous and induction machine studied in [11].

The first large wind turbine implemented was based on the use of a cage induction machine directly coupled to the grid. This machine was driven by a multiplier. The advantages of transmissions multipliers are:

- A lower investment cost, in fact, the generator is much more expensive and the system goes through an AC-DC-AC,
- An easier installation,
- An increased efficiency when winds are strong.

Although a lower price has taken place in recent months, the rare earths market is changing and is highly volatile (Figure 1). All the signs of a bubble are present, and similarities with that of uranium are striking. A meltdown threat therefore occurs at any time, and investments are attractive but very risky.

For this reason, the studied machine in this paper uses ferrite permanent magnets. Figure 2 shows the stator (Figure 2a) and the rotor (Figure 2b) of the Hybrid Excitation Synchronous Machine (HESM) prototype studied in this paper (3 kW). The stator is characterized by distributed windings. Excitations coils are located at the top of the stator. The rotor uses the flux focusing principle. Comparing to a classical PM machine, additional massive parts are added to channel the flux created by the excitation coils.

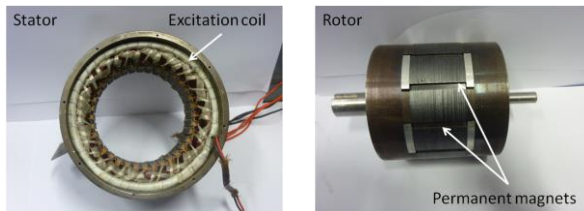
Several cases were studied for HESM; L. Vido et al. in [4] studied four prototypes machine, it also showed that bipolar hybrid excitation allows a better control than homopolar configuration. Y. Amara et al. also in [6] presented a study of control laws adapted to so-called "double excitation" or "hybrid" structures, and N. Naoe et al. studied HESM in [5] where it was analyzed by the finite element the no load characteristics of hybrid excitation generator (HE synchronous generator). F.Xinghe and Z.Jinbin in [14] show that it is practicable to either increase or decrease the flux in the generator within large range and to realize the steady-state control of output voltage through the adjustment of the excitation current. N.Yinhang, L. Chuang, J. Renhua, X. Jianchun, Z. Shushu in [15] have introduced a novel tangential radial hybrid excitation synchronous generator and they deeply analyse its

magnetic path model, complete the design and give some improved methods. In this paper, this original machine is studied for a wind turbine application showing how the excitation coils can be a degree of freedom to control the generator. Simulation results show a simple and robust control developed thanks to these excitation coils. The operating point maximizing the generator power as a function of the HESM speed, the turbine torque and the control voltage is therefore identified

The aim of the paper is to study the performances of HESM for wind applications. The wind generator architecture is presented, modeled, simulated and discussed.



Figure 1: Evolution of the price of NdFeB magnets since June 2001 (<http://www.metal-pages.com>)



(a) Stator (b) Rotor

Figure 2. Studied HESM topology [8]

## 2. WIND GENERATOR MODELING

### 2.1. WIND ARCHITECTURE

In this paper, the association of HESG, gearbox, inverter and load is investigated (Figure 3). Figure 4 shows the classical shaft output power versus wind speed. Four areas can be defined:

- Area I: Wind speed is not sufficient. The turbine is stopped.
- Area II: The power supplied to the shaft depends on the wind speed  $v_w$  (MPPT),

- Area III: The rotational speed is kept constant and the power  $P$  is provided remain equal to  $P_n$ ,
- Area IV: The safety system stops the operation of the energy transfer.

In the following subsections, each element of the system is modeled.

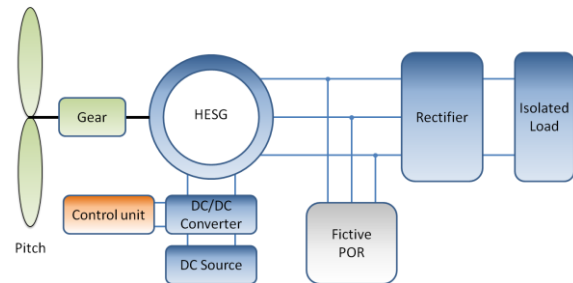


Figure 3 : Architecture of the wind generator

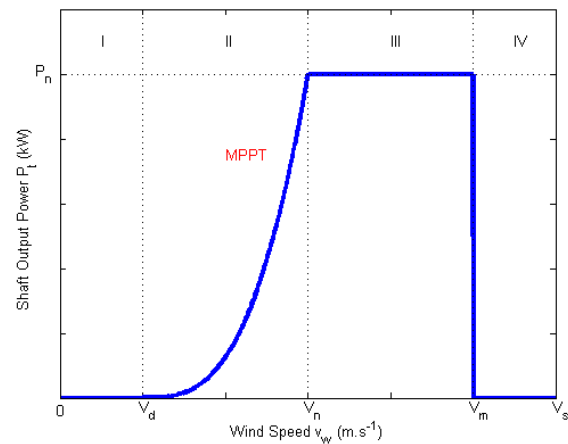


Figure 4 : Shaft output power versus wind speed

### 2.2. HYBRID EXCITATION SYNCHRONOUS MACHINE

Like all machines, HESM can operate in motor as well as in generator. The description of motor operating mode is obtained by using the voltages and currents usual equations. Taking into account some assumptions (unsaturated model, first harmonic hypothesis, iron and mechanics losses neglected); we can express the model of this machine based on the equations of HESM in the Park reference frame. These equations are divided into different sub-categories: voltages (1), fluxes (2) and torque equation (3), where  $v_d$ ,  $v_q$  and  $v_e$  are respectively the d and q-axis voltages and the DC field coils voltage.  $i_d$ ,  $i_q$  and  $i_e$  are respectively the d and q-axis currents and the DC field coils current.  $R_s$  and  $R_e$  are respectively the armature resistance and the DC field coils resistance.  $\psi_d$ ,  $\psi_q$  and  $\psi_e$  are respectively the d and q-axis fluxes and the DC field coils flux. Finally,  $\omega$  is the electrical speed.

$$\begin{cases} v_d = R_s i_d + \frac{d\psi_d}{dt} - \omega \psi_q \\ v_q = R_s i_q + \frac{d\psi_q}{dt} + \omega \psi_d \\ v_e = R_e i_e + \frac{d\psi_e}{dt} \end{cases} \quad (1)$$

$$\begin{cases} \psi_d = L_d i_d + M\sqrt{3}i_e + \psi_a \sqrt{3} \\ \psi_q = L_q i_q \\ \psi_e = M\sqrt{3}i_d + L_e i_e + \psi_{ae} \end{cases} \quad (2)$$

$L_d$ ,  $L_q$ ,  $M$  are respectively the d and q-axis inductance and mutual inductance (between d-axis stator armature and DC field coils).  $L_e$  is the DC field coils inductance.  $\psi_a$  is the flux created by the magnets in the armature coils and  $\psi_{ae}$  is the flux created by the magnets in the DC field excitation coils.

$$c_{em} = p \cdot i_q \cdot \left[ (\psi_a + M i_e) \sqrt{3} + (L_d - L_q) i_d \right] \quad (3)$$

Where  $c_{em}$  is the HESM electromagnetic torque and  $p$  the number of pole pairs. The well-known relation between the HESM rotation speed  $\Omega$  and the armature voltages or current pulsation is given (4).

$$\omega = p \cdot \Omega \quad (4)$$

### 2.3. FICTIVE POINT OF REGULATION AND EQUIVALENT FIRST HARMONIC LOAD

In this paper, the rectifier commutations are not taken into account. The rectifier and the load are then assimilated to a three phases equivalent resistance  $R_c$ . In a generator operating mode, the armature voltages are seen as outputs while armature currents are the synchronous machine inputs. In this case, the defined problem is not a well-conditioned. To solve this, a regulation point defined by three phases fictives parallel resistances-capacitors (respectively named  $R_r$  and  $C_r$ ) is inserted between the HESM and the resistive load

$$\begin{cases} -R_{cr} C_r \omega v_q + R_{cr} C_r \frac{dv_d}{dt} + v_d = -R_{cr} i_d \\ R_{cr} C_r \omega v_d + R_{cr} C_r \frac{dv_q}{dt} + v_q = -R_{cr} i_q \end{cases} \quad (5)$$

$$\frac{1}{R_{cr}} = \frac{1}{R_r} + \frac{1}{R_c} \quad (6)$$

. These elements are calculated in order to minimize their impact regarding the energy consumption

[1],[2]. This system is defined by (5),  $R_{cr}$  is an equivalent resistance given by (6).

### 2.4. MULTIPLIER

Wind turbine is coupled to the generator through gearbox. The purpose of the gearbox is to convert the turbine rotational speed  $\Omega_t$  in a higher HESM rotational speed in order to downsize the HESM. The resistant torque  $c_{rt}$  represents the HESM electromagnetic torque  $c_{em}$  multiplied by minus the coefficient multiplier  $m_p$ . The minus is added because of the motor convention chosen to model the HESM (7).

$$\begin{cases} c_{rt} = -m_p c_{em} \\ \Omega = m_p \Omega_t \end{cases} \quad (7)$$

### 2.5. TURBINE

In this part, the turbine speed mechanical equation is defined (8), where  $J_t$  is the mobile parts moment of inertia and  $f_t$  the viscous friction coefficient.

$$J_t \frac{d\Omega_t}{dt} + f_t \Omega_t = c_t - c_{rt} \quad (8)$$

The turbine torque  $C_t$  is defined by (9) with MPPT hypothesis.  $S$  is the area swept (ie equals  $\pi R_p^2$ ) by the radius propeller  $R_p$  and  $\rho$  is the air density and  $P_n$  is the nominal power.

$$c_t = \begin{cases} 0 & \text{if } v_w \leq v_d, v_w > v_m \\ \frac{1}{2} \frac{C_p \rho S (v_w - v_d)^3}{\Omega_t} & \text{if } v_d \leq v_w < v_n \\ \frac{P_n}{\Omega_t} & \text{if } v_n \leq v_w < v_m \end{cases} \quad (9)$$

Where  $V_n$ ,  $V_m$  and  $V_w$  are respectively the minimal, maximal and wind speed

The turbine performance coefficient  $C_p = C_p(\lambda)$  is a function of the tip speed ratio  $\lambda$  defined by (10). The evolution of turbine performance coefficient versus tip speed ratio is represented in Figure 5.

An analytical expression of this coefficient can be founded in [7].

$$\lambda = R_p \frac{\Omega_t}{v_w} \quad (10)$$

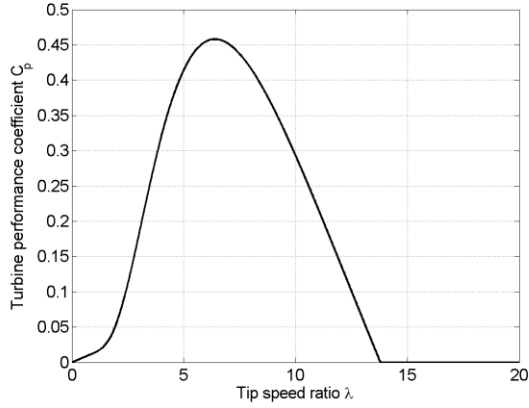


Figure 5: Aerodynamic turbine performance coefficient based on the ratio of speed of the turbine (with blades orientation angle equals zero).

### 2.6. DC-DC CONVERTER

The DC / DC converter is modeled by a constant gain  $G_0$ , so switching effects are not taken into account and  $v_{ec}$  is the DC-DC converter control voltage.

$$v_e = G_0 v_{ec} \quad (11)$$

### 2.7. SENSORS

The sensors are modeled as pure gains.

$$v_x = k_x x \quad (12)$$

The physical variable  $x$  can be a voltage (v), a current (i) or a speed ( $\Omega$ ). The sensor gain is noted  $k_x$ . The voltage  $v_x$  is the image of  $x$ .

### 2.8. PARAMETERS VALUES

The parameters values are given in Table I.

| Parameter                                  | Value     | Parameter          | Value |
|--|-----------|--------------------|-------|
| $\rho$ (Kg/m <sup>3</sup> )                | 1.2       | $C_r$ ( $\mu$ F)   | 10    |
| $f_i$ (kg.m <sup>2</sup> s <sup>-1</sup> ) | 0.001     | $R_c$ ( $\Omega$ ) | 100   |
| $J_t$ (Kg.m <sup>2</sup> )                 | 0.005     | $G_0$              | 10    |
| $k_i$ (S)                                  | 0.1       | $m_p$              | 5     |
| $k_v$                                      | $10^{-2}$ | $R_p$ (m)          | 3     |
| $k_\Omega$ (mV/rpm)                        | 20        | $P_n$ (kW)         | 3     |
| $L_d$ (mH)                                 | 69        | $\psi_{ae}$ (mWb)  | 66    |
| $L_q$ (mH)                                 | 89        | $\psi_a$ (mWb)     | 66    |
| $P$  | 6         | $M$ (mH)           | 73    |
| $R_r$ (k $\Omega$ )                        | 10        | $R_e$ ( $\Omega$ ) | 1.35  |
| $L_e$ (mH)                                 | 50        | $R_s$ ( $\Omega$ ) | 0.76  |

Table I. Parameters values

## 3. OPEN LOOP ANALYSIS

The open loop analysis objective is to find the variation of the controlled variables (excitation current  $i_e$  and rotation speed  $\Omega$ ) in function of the system inputs (DC-DC converter command voltage  $v_{ec}$  and turbine torque  $c_t$ ). So, the maximum values of controlled variables and control possibilities can be established. In fact, the turbine torque is controlled by the wind speed and the rotation speed, but in order to simplify the open loop study,  $c_t$  is firstly supposed to be an independent input,  $v_{ecm}$  is the DC-DC converter control voltage. The two inputs vary between two limits expressed as follow:

$$|v_{ec}| \leq V_{ecm} \text{ and } 0 \leq c_t \leq C_{tm} \quad (13)$$

Open loop study evaluates the output maximal values in steady state operation. An analytical solution was not found, so the maximum values are obtained thanks to the simulation of the open loop system. In order to justify the chosen value of the maximum turbine torque  $C_{tm}$ , it is necessary to find how this quantity varies with wind speed and rotation speed modification where:

$$0 \leq v_w \leq V_s \text{ and } 0 \leq \Omega_t \leq \Omega_{tm} \quad (14)$$

$\Omega_{tm}$  is the maximum turbine rotation speed.

The following figures give the optimal values of the turbine torque and the turbine rotation speed. It is then possible to find the optimal turbine torque and HESG rotation speed that maximize the turbine output power. In the open loop, each point of the optimal turbine torque and optimal turbine speed can be reached and insure that the performances can be reached in closed loop as well.

### 3.1. INTERNAL CURRENT CLOSED LOOP

The model of closed current loop is implemented on Matlab Simulink. The transfer function of this system is a first order. As a matter of fact, a simple PI controller is needed to control it pole. A speed and armature currents compensation strategy is adopted. Consequently, a perturbation caused by the turbine torque (or by a load change) applied at  $t = 50$  ms has no effect on the internal current loop (Figure 10). It should be pointed that the voltage control necessary to obtain these results is compatible with common level of control voltages (less than 15 V).

### 3.2. EXTERNAL SPEED CLOSED LOOP

A closed speed loop can be investigated. A simple PI controller is not sufficient to control the speed dynamic. However, if the gain of the PI controller is adaptive (and depends on the armature currents), the control is possible. A compensation strategy is adopted, but because of classical assumptions (fast current loop and slow speed loop), it can be seen that the compensation strategy is not perfect (Figure) under turbine torque perturbation. Nevertheless, the adaptive gain PI controller allows the HESM rotation speed to reach its reference.

## 4. CONCLUSION

In this paper, a control strategy of a hybrid excitation synchronous machine in a wind generator system is investigated. Thanks to the degree of freedom provided by the DC field excitation coils, the generator architecture dedicated to isolated loads is very simple and then can be supposed very reliable. The control strategy is classical and consists in two imbricated loops: a fast internal current loop and a low external speed loop with an adaptive PI controller. It is shown that the dynamic performances of the wind generator are good under reasonable control voltage level. Finally, HESM seems to be a good candidate for wind applications. Influence of HESM harmonic and experimental study will be investigated and left for a future work.

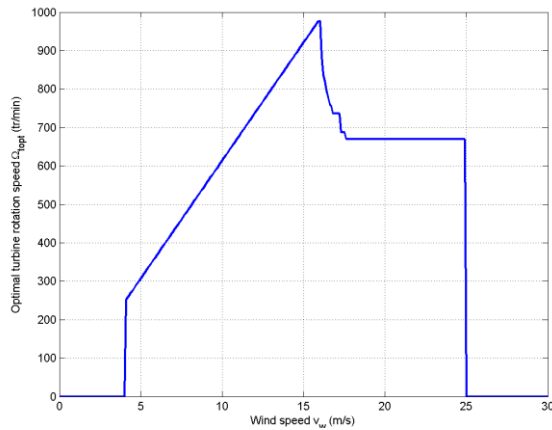


Figure 6: Optimal turbine rotation speed versus wind speed

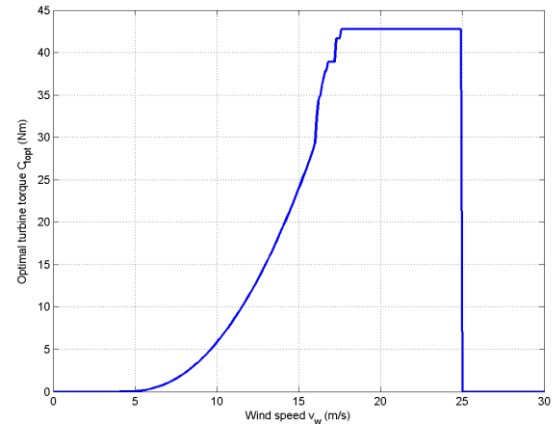


Figure7: Optimal turbine torque versus wind speed

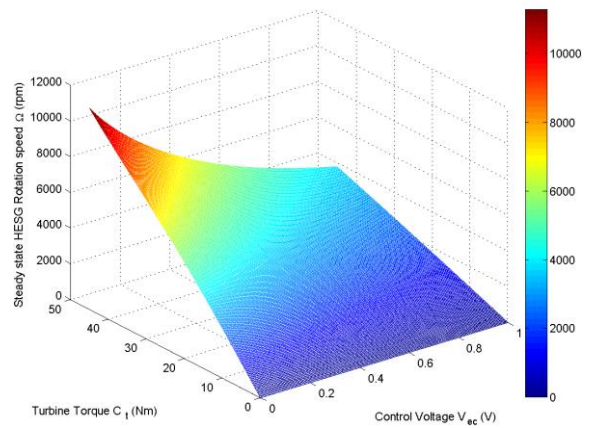


Figure 8. Steady state HESG rotation speed versus turbine torque and control voltage

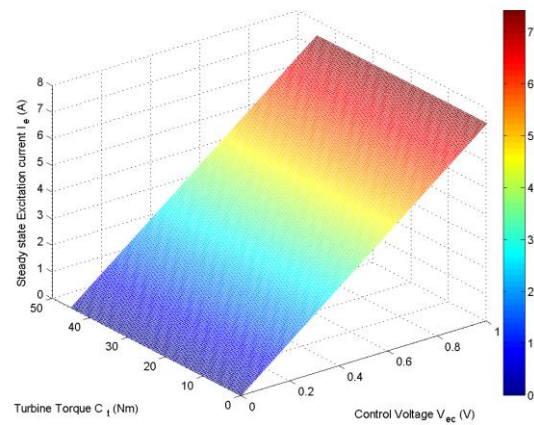


Figure 9. Steady state HESG excitation current versus turbine torque and control voltage

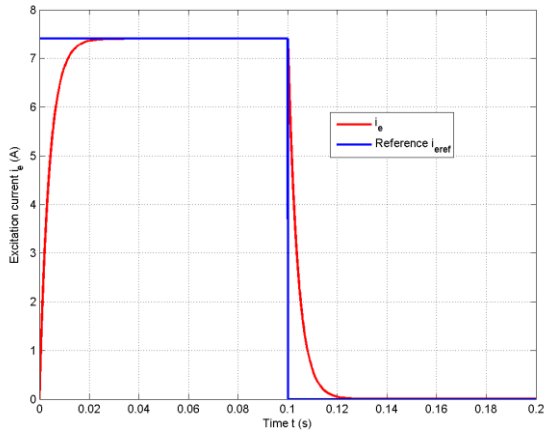


Figure 10. Shape of the excitation currents, a resistant torque step is applied at 50 ms.

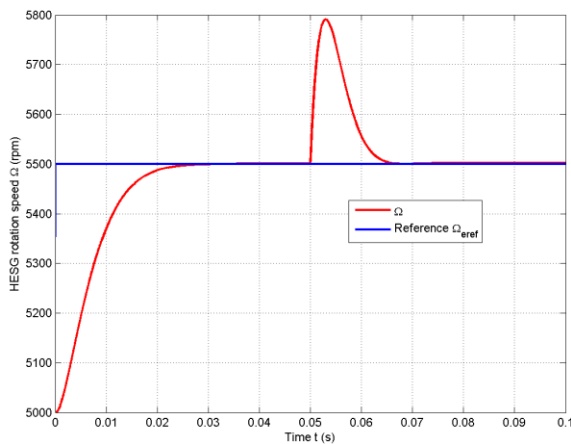


Figure 11. Shape of the HESM rotation speed, a resistant torque step is applied at 50 ms.

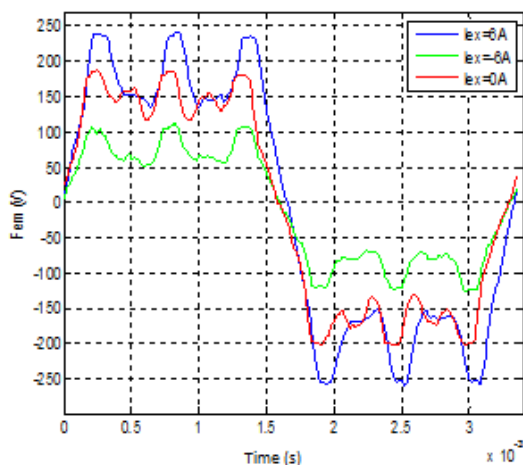


Figure 12: Back-EMF waveforms for  $I_{ex}=-6A$ ,  $i_{ex}=0A$  et  $I_{ex}=6A$

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