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A SMALL AUTONOMOUS SYSTEM FOR STORING WIND ENERGY BY PUMPING WATER

BY

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Abstract. Wind energy presents an invariable character and needs storage systems in order to eliminate the problems which may occur at grid integration. A storage method suitable especially in high power application is pump storage. The purpose of this paper is the study of an autonomous system of wind energy pump storage for optimal efficiency.

Key words: wind energy; pump storage; efficiency.

1. Introduction

Due to the growing size of wind energy generation and its unpredictable character, wind energy grid integration is one of the concerns with very high interest because energy produced by wind power plants can create stability problems in the distribution networks (Mujaldi *et al.*, 2009; Vittal *et al.*, 2009; Papaefthimiou *et al.*, 2009). These may be solved using storage methods (Cristofari *et al.*, 2006; Kaldellis *et al.*, 2006).

A proven storage method, rediscovered after years and suitable solution in supporting grid integration, is pump storage. It is based on pumping water from an inferior basin into a superior one during the off-peak hours, using the surplus of wind energy, which otherwise will be lost. The water will be released

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in the peak periods by the hydro-electric plant, creating new energy (Cristofari *et al.*, 2006; Connoly, 2007; Gao *et al.*, 2006; Ning *et al.*, 2004; Peters *et al.*, 2008; Mansoor *et al.*, 1999).

Many locations on the earth have both facilitates provided by nature, wind and water, fact that makes possible wind energy storage by pumping water. Pumped storage is one of the most widespread way of storage with over 90 GW (Kaldellis *et al.*, 2006). It was applied in many countries like Japan – Okinawa Seawater Pump Storage Power Plant in Yanbaru, in UK – Dinorwig Plant in Wales, in Ireland, Denmark, Greece and others (Peters *et al.*, 2008). In Spain, the existing LaMuela pump storage plant of 635 MW will be extended with 852 MW and it is expected to start operation in 2012. This is presumed to be Europe's largest pumped hydro storage (Montero *et al.*, 2009).

Also Romania has a wind potential unexploited yet and a very high hydro potential, so pumped storage seems to be an eligible solution to implement. There has to be studied the locations which involves both wind and water and chosen the best ones.

2. Theoretical Aspects

In what follows a system for storing wind energy is studied, represented in Fig. 1. This is an autonomous system, unconnected to the grid and involves an electroenergetic chain with many variables, formed by the wind turbine, gearbox, synchronous generator, electric converter, asynchronous motor and finally the pump. Each element of this chain is studied with the purpose of increasing the total efficiency of the whole system.

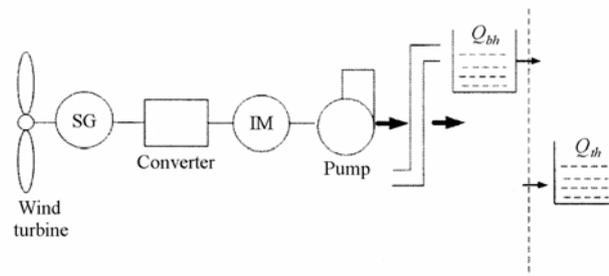


Fig. 1 – Model scheme.

The wind turbine chosen for verifying the model is a 2.2 kW wind turbine with three blades to see what happens in the case of low power and then the research will be made also for other levels of power. The behavior of the system is seen after simulation, using Matlab Simulink program. The mathematical model of the system is needed.

3. Mathematical Model

For the wind turbine eq.

$$P_W = \frac{\rho}{2} c_p (\lambda, \vartheta) A_R v_W^3, \quad (1)$$

is used, where: P_W is wind turbine power, [W]; $\rho = 1.225 \text{ kg/m}^3$ – air density; c_p – performance coefficient; A – area covered by the blades, [m^2]; v_W – wind speed, [m/s].

The c_p Betz's power coefficient is assumed to be 0.4, a real value for wind turbine with three blades (Hier, 2006).

The gearbox is implemented by eq.

$$k = \frac{n_1}{n_2} = \frac{T_2}{T_1}, \quad (2)$$

where: k is transformation ratio; n_1 – input speed, [rpm]; n_2 – output speed, [rpm]; T_1 – input torque, [N.m]; T_2 – output torque, [N.m].

It is considered that the gearbox have the efficiency of 98%.

The synchronous generator of 1 kW is simulated through eq.

$$P_m = T_m \omega_m, \quad (3)$$

where: P_m is the synchronous generator mechanical power, [W]; T_m – synchronous generator mechanical torque, [N.m]; ω_m – synchronous generator angular speed, [rad/s].

The efficiency at this rated power is of 85%.

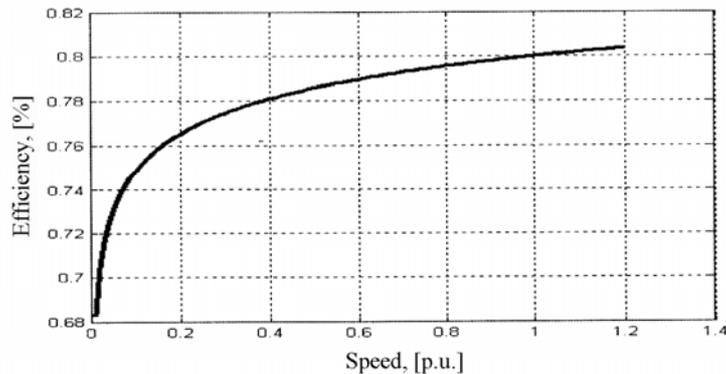


Fig. 2 – Pump efficiency.

The electronic converter is considered with scalar control, introduced in order to fit the power transfer to the pump by adjusting the motor mechanical curve and to exploit also the low speed energy given by the wind turbine at low wind speed. This is realized by increasing as much as possible the speed of the induction motor in order to avoid the low speed – low efficiency region of the pump (Fig. 2).

The converter is modeled using the ratio voltage/frequency constant, but for fitting with the pump power, which is a cubic one, it was deduced the law $U = kf^3 + U_0$, where $k = 0.0025$ and $U_0 = 14.43$ V, representing the voltage necessary to ensure the voltage drop on the stator reactance of the asynchronous motor, as can be seen in Fig. 3.

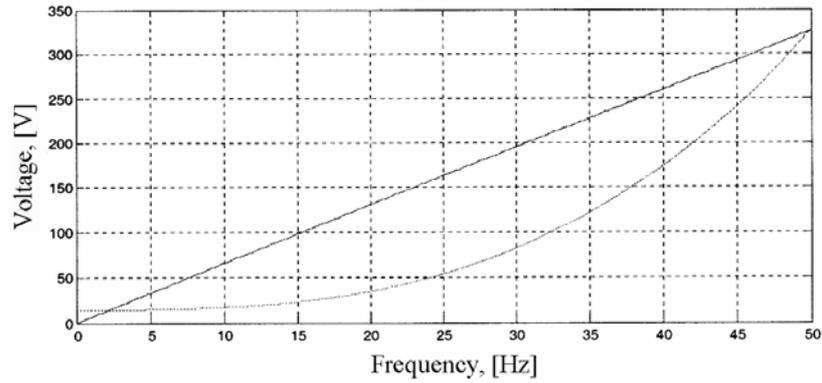


Fig. 3 – Variation law imposed for the electric converter.

Forward, in asynchronous motor model is introduced a law valid in the operation of the induction machine in motor regime, which is $T = k_1 s$, where $k_1 = T_n/s_n$. Under the frequency of 5 Hz there are problems regarding induction motor torque, because of high slip values, so the slip has to be compensated. In order to realize this at the stator frequency is added the rotor frequency and it is obtained the stator compensated frequency for maintaining the angular speed ω_{s1} operation point (Munoz *et al.*, 1998) (Fig. 4)

$$f_{s,c} = f_s + f_r, \quad (4)$$

where: $f_{s,c}$ is the compensated statoric frequency, [Hz]; f_s – statoric frequency, [Hz]; f_r – rotoric frequency, [Hz].

The centrifugal pump is modeled using eqs. (4),

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2} \right)^3 \quad (5)$$

and

$$\eta_2 = 1 - (1 - \eta_1) \left(\frac{n_1}{n_2} \right)^{1/10}, \quad (6)$$

where: P_1 is the pump power corresponding to n_1 , [W]; P_2 – pump power corresponding to n_2 , [W]; $n_{1,2}$ – pump speed, [rpm], $n_1 < n_2$; η_1 – efficiency corresponding to n_1 ; η_2 – efficiency corresponding to n_2 .

The pump efficiency characteristic is obtained using eq. (5), which is valid in variable speed case.

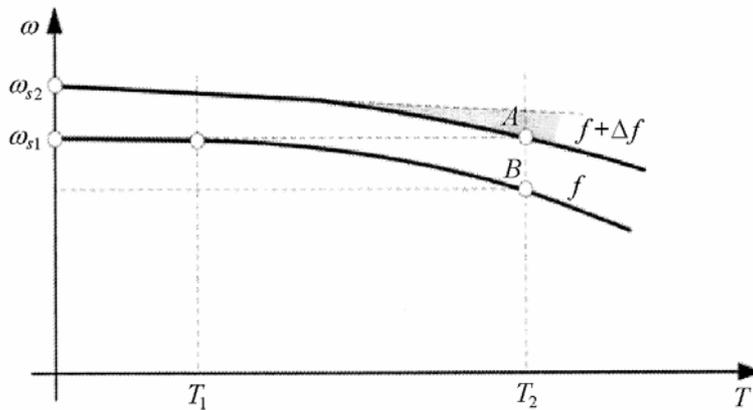


Fig. 4 – Slip compensation method [6].

4. Simulation Results

The simulation is realized using Matlab Simulink program. The block scheme with all the elements of the electroenergetic chain is represented in Fig. 5 and the results in Figs. 6,...,11. A more detailed view concerning the obtained results is given in Table 1.

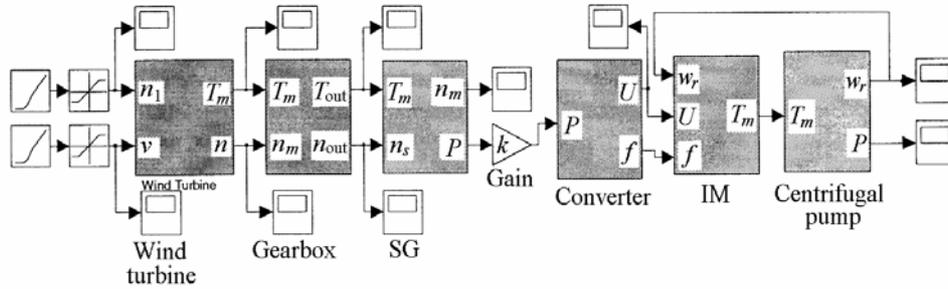


Fig. 5 – Block scheme of the model in Matlab Simulink.

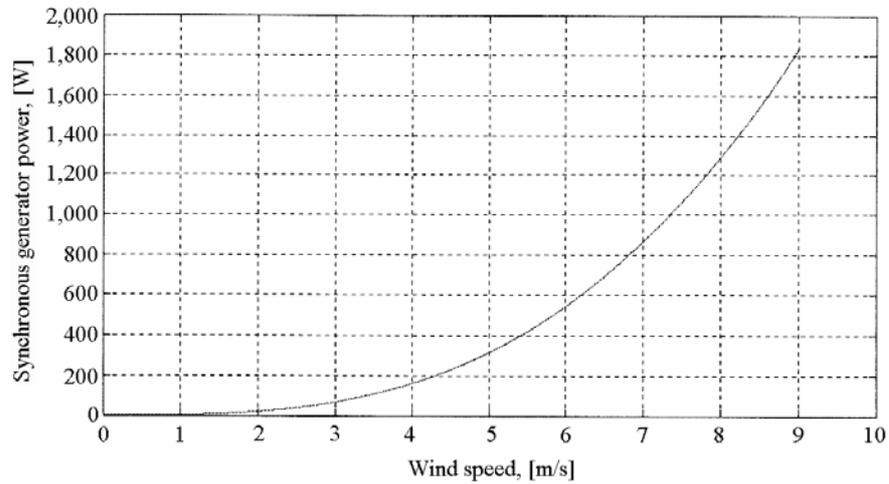


Fig. 6 – Synchronous generator power vs. the wind speed.

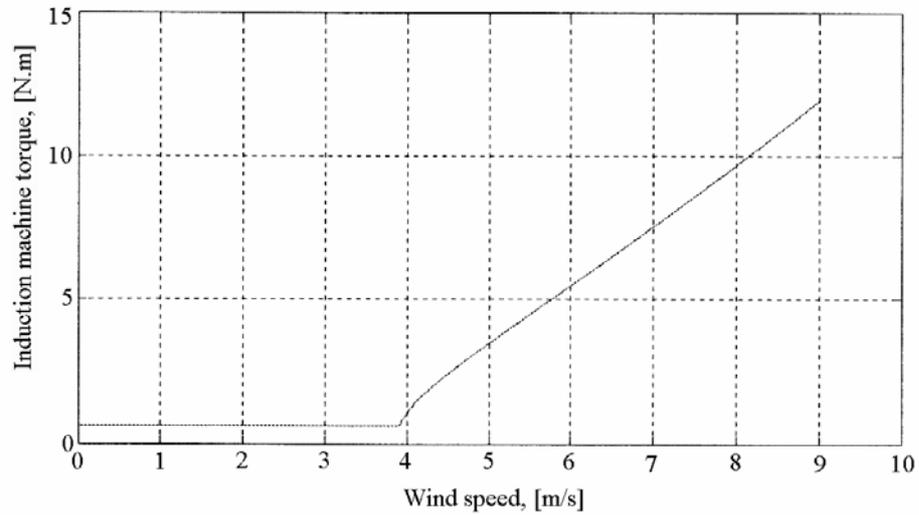


Fig. 7 – Induction motor torque vs. the wind speed.

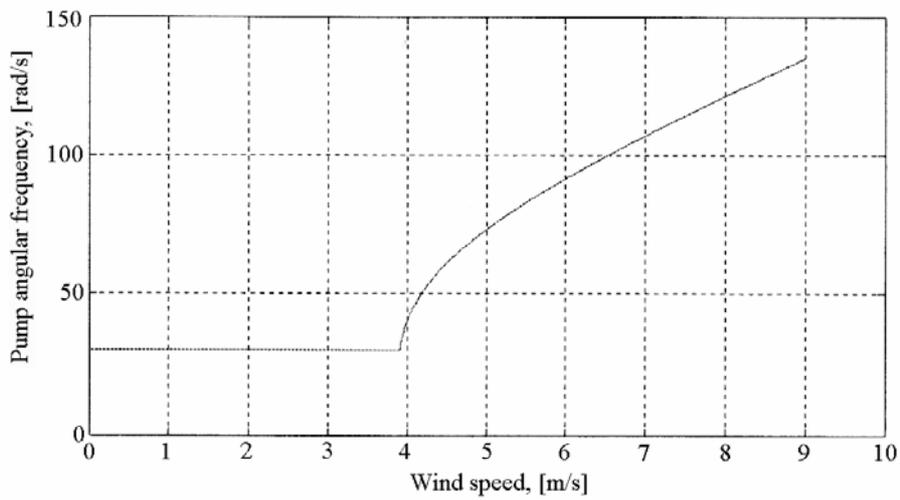


Fig. 8 – Pump angular frequency vs. the wind speed.

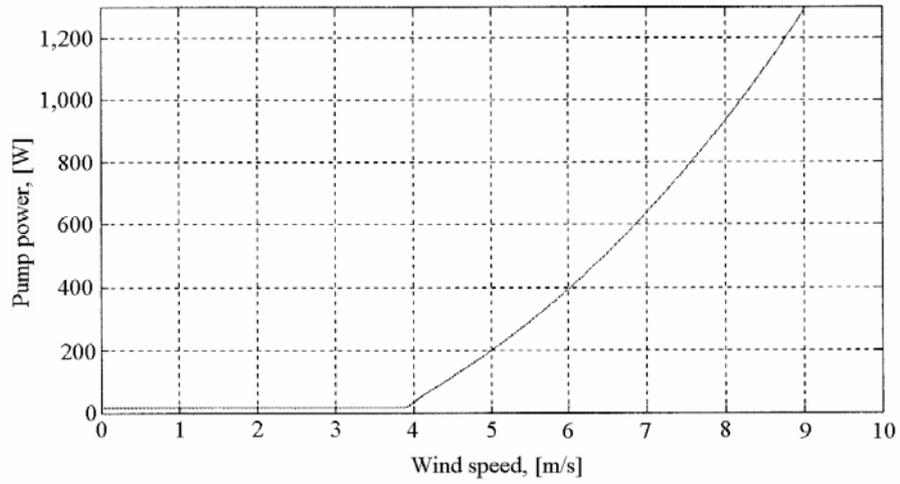


Fig. 9 – Pump power vs. the wind speed.

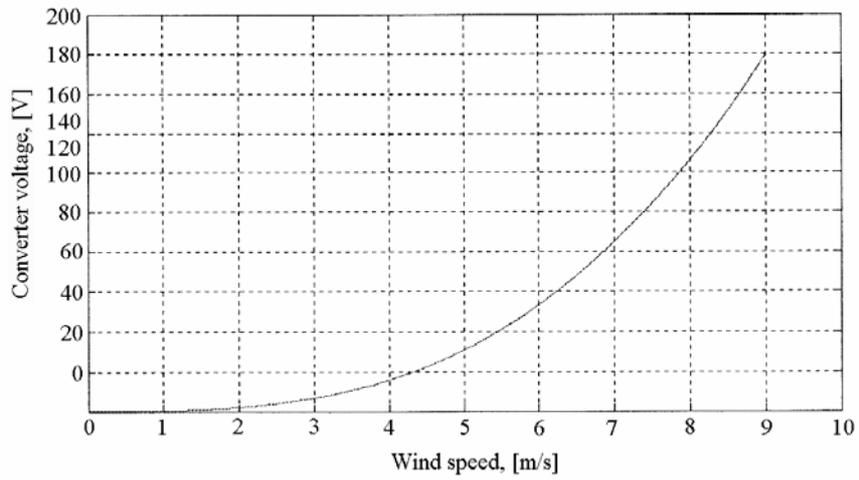


Fig. 10 – Converter voltage vs. the wind speed.

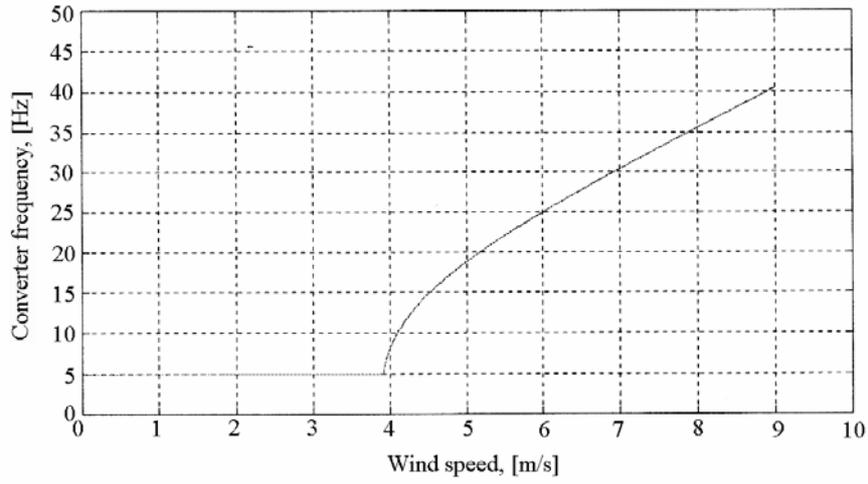


Fig. 11 – Converter frequency vs. the wind speed.

Table 1
Obtained Results in the Simulation

Wind speed m/s	Power SG, P_{SG} W	Voltage U V	Frequency f Hz	Torque IM, T_{IM} N.m	Angular speed IM Ω_{IM} rad/s	Power P_{pump} W	Angular speed Ω_{pump} rad/s	Efficiency	Global efficiency
0	0	0	0	0	0	0	0	0	0
1	0	0.1	5	0.61	15.71	0	0	0	0
2	2.51	0.25	5	0.61	15.71	0	0	0	0
3	20.1	2	5	0.61	15.71	14.42	30.63	0.71	0.29
4	67.85	6.8	5	0.61	15.71	14.42	30.63	0.21	0.085
5	160.83	15.75	8.14	1.06	25.48	33	40.28	0.21	0.082
6	314.13	30.8	18.8	3.46	58.76	200	72.7	0.64	0.25
7	542.83	54	24.25	5.5	79	393.5	91.24	0.72	0.29
8	861.97	84.48	30.5	7.65	95.44	636.3	106.97	0.73	0.29
9	1,268.8	126	35.5	10	111.47	932.5	121.37	0.74	0.294
10	1,832	179.6	40.42	11.95	126.98	1,288	135.04	0.7	0.28
11	1,832.6	179.6	40.42	11.94	127	1,284.8	134.93	0	0.28
12	1,832.6	179.6	40.42	11.94	127	1,284.8	134.93	0.7	0.28

5. Conclusions

Including slip compensation the induction motor torque is reduced at start and it contributes at raising the efficiency of the system up to 25%. But being involved an electroenergetic chain with many variables and with elements of small efficiency, a low power level, still the global efficiency is small, this can be obviously improved in the case of large power wind turbine case, which involves electroenergetic chain elements with higher efficiency. For example, if wind turbines with rated power higher than 1 MW are considered, the generator efficiency is over 97%, the asynchronous motor is over 96%, thus results a global efficiency of 33%. Furthermore, a conversion efficiency of the system of 66% results, if it is not taken into consideration the wind turbine power factor, c_p , which is different depending on the wind turbine type and the location of the system.

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UN SISTEM AUTONOM DE MICĂ PUTERE PENTRU STOCAREA ENERGIEI EOLIENE PRIN POMPAREA APEI

(Rezumat)

Se prezintă un sistem autonom de 2.2 kW de stocare a energiei eoliene prin pomparea apei. Acesta este format din turbină eoliană, cutie de viteză, generator sincron, convertor, motor asincron și pompă. Este prezentat modelul matematic al fiecărui element în parte, model necesar pentru realizarea simulărilor, fiind incluse o metodă de control a convertorului și o metodă de compensare a alunecării motorului asincron, cu scopul obținerii unui randament cât mai bun.