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CONTINUOSLY VARIABLE TRANSMISSION IN MEDIUM-SIZED WIND GENERATORS

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Abstract. *Wind energy is renewable and is considered a source with very low environmental impact. To improve the wind energy available in an erratic wind speed regime, a wind generator equipped with continuously variable transmission (CVT) was modeled in Matlab. In this model a proportional and integral control (PI) adjust the system speed for operating at the highest efficiency point. It's able to control the energy converted by an induction squirrel cage generator connected to the power grid. The PI controller designed for controlling the transmission ratio was fast and stable under the simulated conditions despite the many nonlinear phenomena which govern the studied system. Similar behavior was observed when the system was studied with different induction generator models. Results indicate that the simulations need to consider complete models of the generator, particularly when the proposed study includes the stability of the electrical and mechanical system. When connecting the system to the power grid with the use of CVT, the simulations result in a 15% increment of the useful energy. This gain will be greater under conditions of wind distribution which are extremely different from the one used in the project. Considering the random behavior of the wind, this result indicates that for long periods, the use of CVT can justify the installation of wind generators for small and medium applications in places considered economically unviable at present.*

Keywords*: CVT, wind generator, induction machine*

1. INTRODUCTION

The total kinetic energy available in the airflow cannot be fully converted into mechanical power on the rotor shaft, according to Castro (2007). The relationship between the power extracted and that available in the air flow is given by the power coefficient, Cp. The theoretical maximum for this ratio is called the Betz limit.

$$C_p < C_{pBetz} = \frac{16}{27} = 0,59 \tag{1}$$

The Betz limit determines that a maximum of 59% of the kinetic energy of wind is converted into mechanical in the axis of the rotor. The power that can be effectively extracted by the rotor, P_u, is represented by:

$$P_u = \frac{1}{2} C_p(\lambda)\rho A V^3 \tag{2}$$

Where:

ρ: the air density;
A: area swept by the blades;
V: velocity of air flow.

Cp is a function of the rotor geometry and its aerodynamic, the wind speed and the rotational speed of turbine blades. Typically, the curves of Cp are shown as a function of the ratio λ between the peripheral speed of the blade tip speed and the air flow. Fig. 1 shows the typical features of Cp for different configurations of wind turbines. Observe that for each type of turbine there is a value that provides the maximum power coefficient λ_{opt}.

In the horizontal axis wind turbines typically used in wind generators, λ_{opt} has values ranging between 7 and 10 (Carlin *et al*. 2001). Thus, for greater turbine efficiency it is necessary that its speed varies depending on the wind speed in order to keep this λ_{opt}.

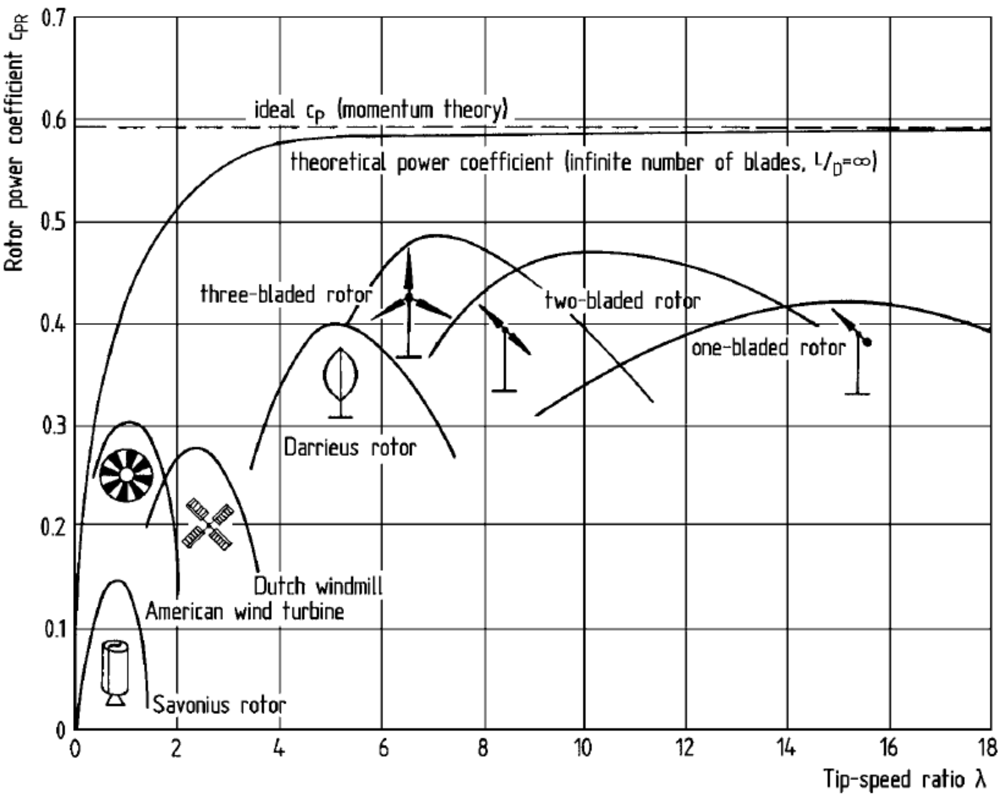

Figure 1.Typical features of C_p for different wind turbines configurations, (Hau, 2005)

However, the grid voltage has a fixed frequency of 60 Hz in Brazil. Wind generators must be able to match the variable frequency required to maximize the wind power with the fixed Brazilian network frequency. A classical solution to decouple both rotor and voltage frequency is a power electronic system. An alternative to decouple the frequency of the network and of the turbine is the use of a continuously variable transmission, CVT. Its application in wind turbines is primarily motivated by increasing the range of the turbine rotation, capacitating the rotor to operate at the best efficiency speeds.

The CVT generators applied to variable speed emerge as an economic alternative for power electronic systems in small and medium-sized wind generators. The possible incorporation of squirrel cage induction generators, known for their low cost and high reliability, increases the expectation of having a set of wind turbines economically viable for low power (Cotrell, 2004).

Another important characteristic of systems with CVT is a greater absorption of the dynamic nature of loads caused by gusts of wind, eliminating the need for absorbing elements with reduction of structural components, resulting in reduction of overall project costs (Rex and Johnson, 2008).

Some projects based on CVT are in current operation. A 2 MW wind turbine by Wikov incorporate a hydrodynamic transmission developed by Orbital Ltd (Wikov, 2011). A synchronous generator is responsible by the electromechanical conversion in this project. The DeWind D8.2 (DeWind, 2011) has used the same solution.

According to Mangialardi and Mantriota (1995) using the CVT is more efficient in areas with turbulent wind distribution.

This feature combined with the possible savings over systems using power electronics makes interesting use CVT in small and medium size configurations in many locations that have wind potential still underused.

Ribeiro (2010) present an evaluation of the energy gain of a CVT equipped medium-sized squirrel cage induction generator connects to a weak power system. In order to complete this work, the aim of this study was to evaluate the maximum energy gain of this controller.

2. PROPOSED MODEL

Figure 2 shows a simplified dynamic model of a turbine considering non-stationary wind conditions. It is composed of the wind turbine rotor, a transmission setting, and a CVT with an induction generator.

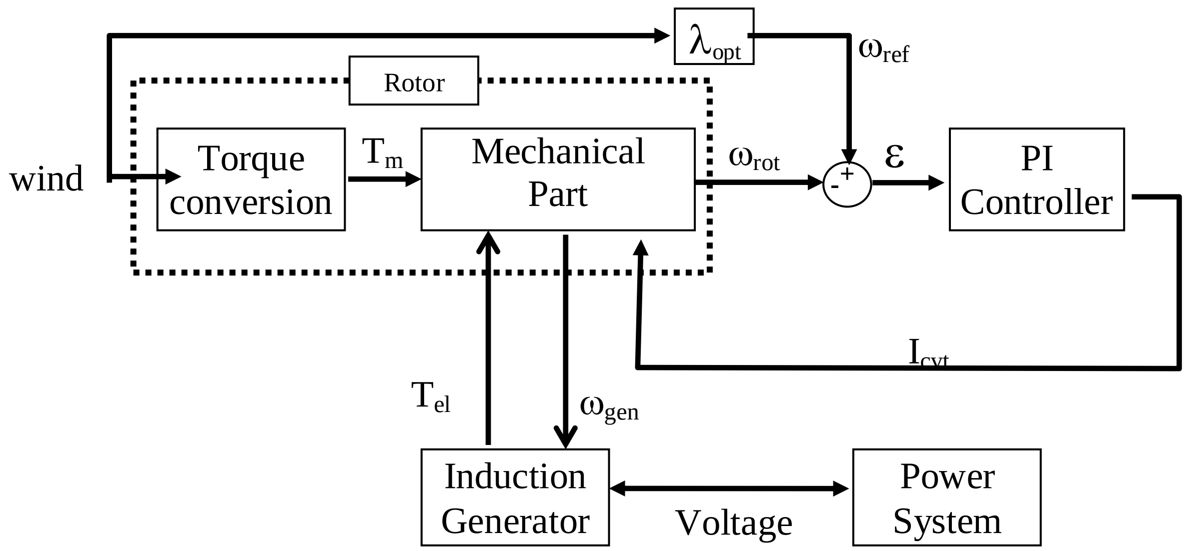

Figure 2. Block diagram of the model

In this model, the rotor is composed by two different parts: the torque conversion and the mechanical model. The wind produces a torque T_m that accelerates the generator rotor. A PI controller keeps the rotor angular speed at the reference speed regulating the CVT ratio. The electrical power converted in the induction generator is transferred to the distribution power system.

2.1. Rotor

The rotor in this model is the representation of the aerodynamic part of the system responsible for converting the power available in wind into speed on the shaft. A simplified model of a wind turbine presented in Matlab (2007) was used. The torque on the rotor shaft, T_{rotor}, is represented by Eq. (3).

$$T_{rotor} = \frac{\rho A V^3 C_p(\lambda)}{2\omega_{rotor}} \tag{3}$$

Where ρ is the air density and A the area swept by the blades; ω_{rotor} is the angular velocity and V is velocity of air flow; $C_p(\lambda)$ is the power coefficient. The $C_p(\lambda)$ model adopted is:

$$c_p(\lambda) = c_1\left(\frac{c_2}{\lambda_i} - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{4}$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda} - \frac{0.035}{1}} \tag{5}$$

$$\lambda = \frac{\omega_b r_b}{V} \tag{6}$$

Where λ is the ratio of the blade tip speed; ω_b the blade angular speed and r_b the blade radius. The coefficients c_1 to c_6 are estimated based on Cp versus λ curve characteristic of a 100°kW wind turbine, Fig. 3, as follows: $c_1 = 2000$, $c_2 = 200$, $c_4 = 1$, $c_5 = 180$ and $c_6 = 0.5$.

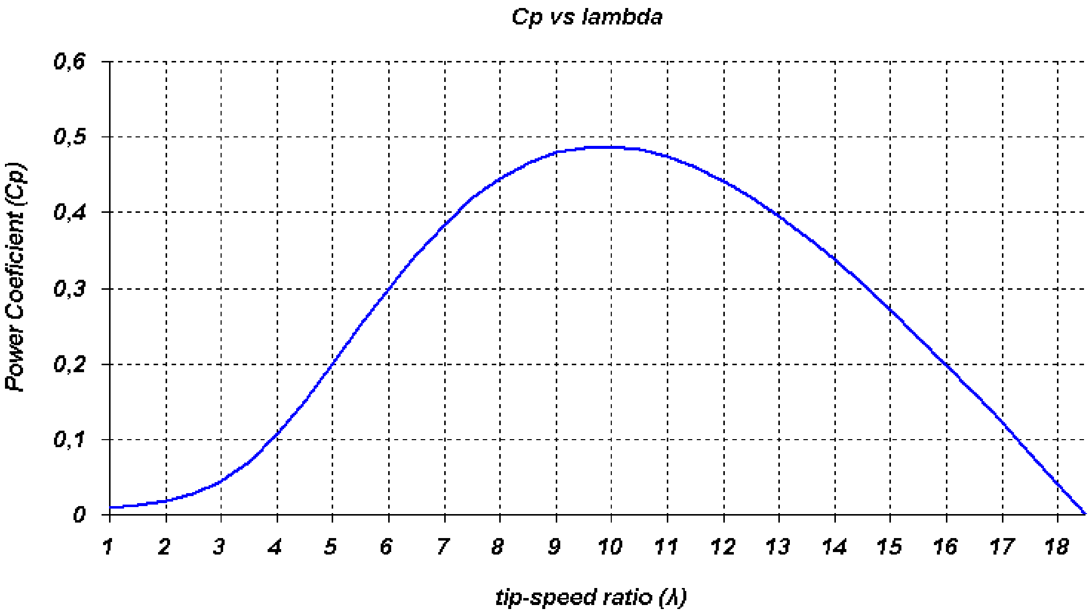

Figure 3. C_p vs lambda curve used in simulations

The mechanical system converts the torque T_{rotor} provided by Eq. (3) in speed on generator by using the model represented in Fig. 4. In this model, the turbine inertia is connected to the generator inertia by an axis represented by a torsional spring-damper. A simple gear and a CVT represent the transmission system. Initial conditions (IC) are introduced in order to avoid time consuming simulations. Some sensors are necessary to connect this model part to the other Simulink ones.

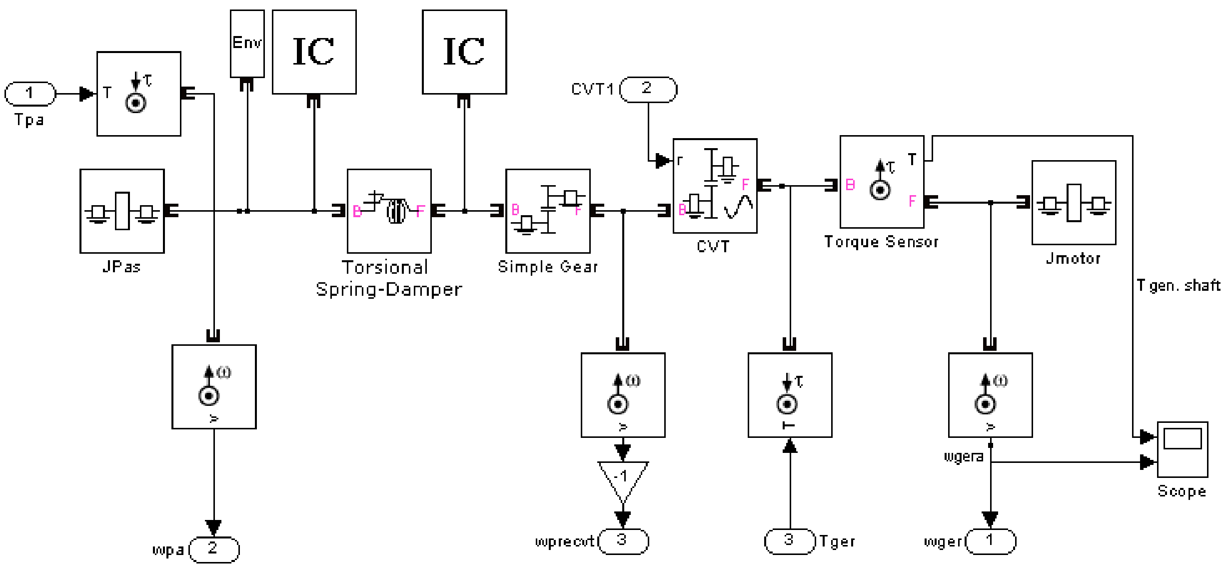

Figure 4. Mechanical part of the model using Matlab

2.2. Controller

To increase the use of wind resources, the turbine should always operate in the highest efficiency using Eq. (7). In the proposed controller ω_{opt} is the set point.

$$\omega_{opt} = \frac{\lambda_{opt} V}{r_{pa}} \tag{7}$$

The error e(t) is given by:

$$e(t) = \omega_{opt} - \omega_{rotor} \tag{8}$$

The model uses a proportional-integrative controller. The reference speed of the CVT system is given by Eq (9)

$$\omega_{ref} = k_P e(t) + k_I \int_0^t e(t)dt \tag{9}$$

Where k_P and k_I are respectively the proportional and the integrative gain.

2.3. Continuously variable transmission system

The Continuously Variable Transmission (CVT) is represented by a gain which is saturated (between 0.52 and 1.8) and has a limited rate of variation (the time to scan these extremes is 60 ms).

A fixed gearbox is positioned between the rotor and the CVT. The transmission ratio of 35.05 was chosen in order to adapt the blade speed and the generator nominal angular speed.

2.4. Electric generator

Two different models are used to represent the induction generator. The first is represented by Eq. (10). This simplified model presented in Fitzgerald (2006) has the advantage to accelerate simulations and is useful if the machine dynamic is much faster than the mechanical one.

$$T_{ger} = \frac{1}{\omega_s}\left[\frac{3V^2(R_r/s)}{(R_s + (R_r/s))^2 + (X_s + X_r)^2}\right] \tag{10}$$

The second model is represented by the following equations:

$$V_{qs} = R_s.I_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_{se}\varphi_{qs} \tag{11}$$

$$V_{ds} = R_s.I_{ds} + \frac{d\varphi_{ds}}{dt} + \omega_{se}\varphi_{ds} \tag{12}$$

$$V_{qr} = R_r.I_{qr} + \frac{d\varphi_{qr}}{dt} + (\omega_{se} - p.\omega_{ger})\varphi_{dr} = 0 \tag{13}$$

$$V_{dr} = R_r.I_{dr} + \frac{d\varphi_{dr}}{dt} + (\omega_{se} - p.\omega_{ger})\varphi_{qr} = 0 \tag{14}$$

$$T_e = 1{,}5.p.(\varphi_{ds}.I_{qs} - \varphi_{qs}.I_{ds}) \tag{15}$$

$$\varphi_{qs} = L_s.I_{qs} + L_m.I_{qr} \tag{16}$$

$$\varphi_{ds} = L_s.I_{ds} + L_m.I_{dr} \tag{17}$$

$$\varphi_{qr} = L_r.I_{qr} + L_m.I_{qs} \tag{18}$$

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$$\varphi_{dr} = L_r.I_{dr} + L_m.I_{ds} \quad (19)$$

$$L_s. = L_{ls} + L_m \quad (20)$$

$$L_r = L_{lr} + L_m \quad (21)$$

And

$$s = \frac{(\omega_{se} - p.\omega_{ger})}{\omega_{se}} : \text{slip} \quad (22)$$

Where:

p: the number of pair of poles in the machine;
R: resistances of the stator (R_s) and the rotor (R_r);
I_q: the quadrature-axis current: stator (I_{qs}) and rotor (I_{qr});
I_d: the direct-axis current: stator (I_{ds}) and rotor (I_{dr});
V_q: the quadrature axis voltage: stator (V_{qs}) and rotor (V_{qr});
V_d: the direct-axis voltage: stator (V_{ds}) and Rotor (V_{dr});
L_m: the mutual inductance between stator and rotor;
L_l: the leakage inductance of the stator (L_{ls}) and the rotor (L_{lr});
ω_{se}: the synchronous electrical angular frequency ($2\pi f_s$);
ω_{ger}: the angular velocity of the generator;
f_s: the electrical frequency (60 Hz);p: machine pair of poles;

The simulated machine has the follow parameters:

Lls and Llr : 0,283 mH
Rs : 0,0302 Ω
Rr : 0,01721 Ω

In this complete model a machine magnetization curve is considered in Fig. 5. It is observed that in the region of the machine rated voltage, 460 V, the relationship between current and voltage is not linear.

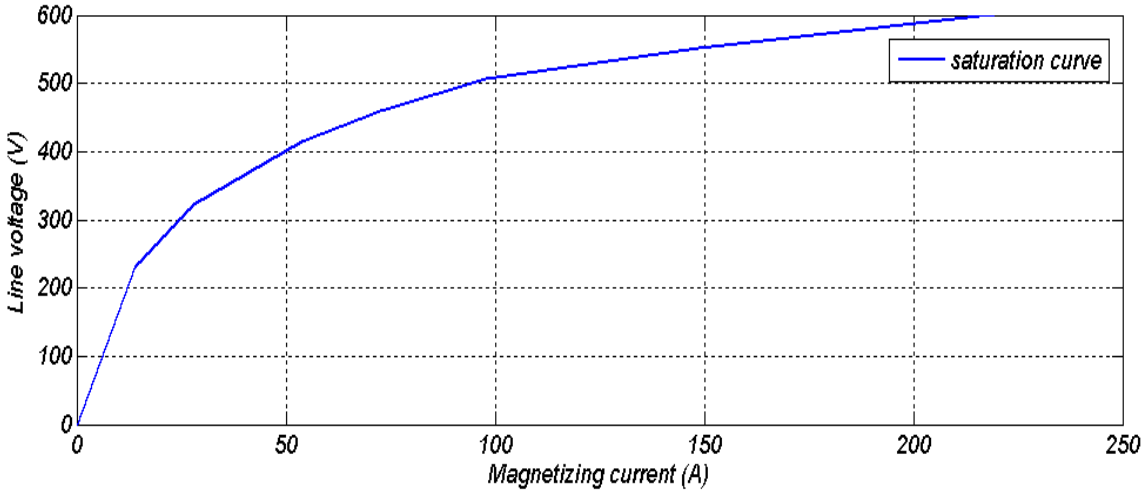

Figure 5. Generator saturation curve

Equation (10) was used considering that the voltage in the machine is not dependent on the electrical system. However, a small or medium power generator is normally connected to a distribution electrical system instead of a classical transmission one. In this case, the voltage is strongly loading-dependent and the wind variation can produce voltage variations. A control system needs to keep the voltage within an acceptable range in all load conditions.

Figure 6 shows the complete simulated electrical system.

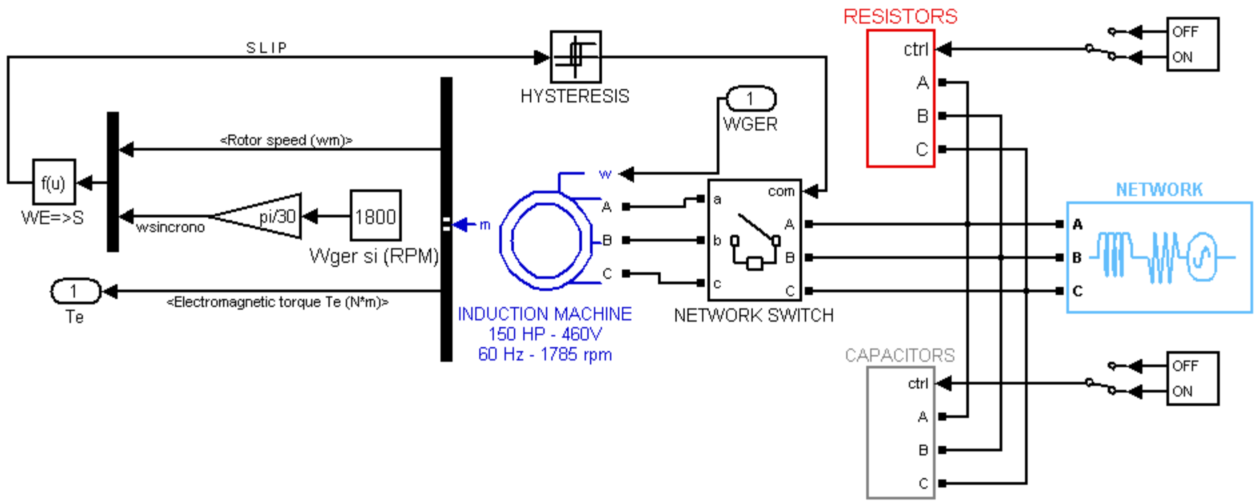

Figure 6. Electrical model including the network and the generator

An induction generator needs a reactive source to compensate the large amount of reactive power necessary to magnetize the machine. It was simulated by capacitors calculated to keep nominal voltage at no load conditions. The power load is simulated by a resistive load and an electrical system with distribution power system typical impedance.

To prevent the motorization of the generator during the starting or wind power reduction, a controller monitoring the slip was implemented. It shuts down the generator in a hysteresis way.

2.5 Wind model

The wind power is function of the wind speed and its representation needs to be carefully studied. Zhao *et al.* (2007) discuss that the wind speed can be represented by a statistic function with a power spectrum represented in Eq. (24).

$$v_y(t) = \bar{v} + \sqrt{2.S(i)}.\cos(2.\pi.nk(i).t + \alpha(i)) \tag{23}$$

$$S(i) = \frac{\dfrac{nk(i).z.\sigma^2}{\bar{v}}}{0.2.\sqrt[3]{(1+\dfrac{1.5}{2}.\dfrac{nk(i)}{\bar{v}})^5}} \tag{24}$$

Where v_y (t) is the instantaneous wind velocity; $\bar{\upsilon}$ the average wind speed adopted as 8 m/s; *i* the harmonic order between i=1 and i_{max}=100; $\alpha(i)$ the harmonic phase characterized by a random distribution. Equation (25) represents the wind frequency variation.

$$nk(i) = i.df + f_0 \tag{25}$$

With:

df : the interval between two consecutive frequencies 0,01 Hz;
f_0 : lower frequency used, 0;
σ : standard deviation of wind speed 1 m/s and
z: the reference tower height, 40 m.

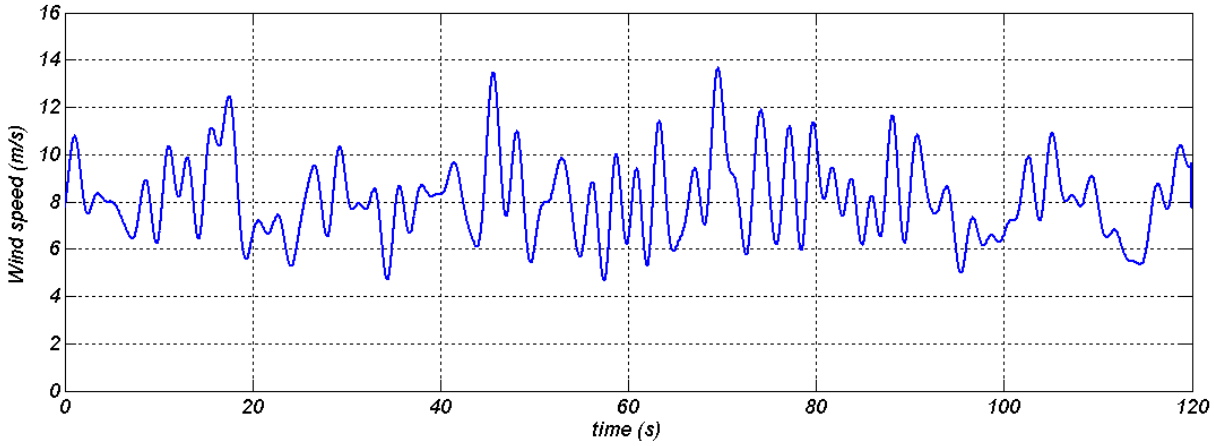

Figure 7. Simulated wind speed with 8 m/s of average wind speed.

The same distribution was adopted for different average speeds of 5, 6, 7, 8, 9, 10, 11 and 12 m/s.

3. RESULTS AND ANALYSES

Consecutive steps were applied in both induction generator models covering the complete wind speed range. The PI control response Fig. 8 shows the difference between models.

Results are similar only for central wind speeds. When a spread range of conditions needs to be simulated, the complete model is necessary. These results indicated that the complete model is necessary and it was used for all others simulations.

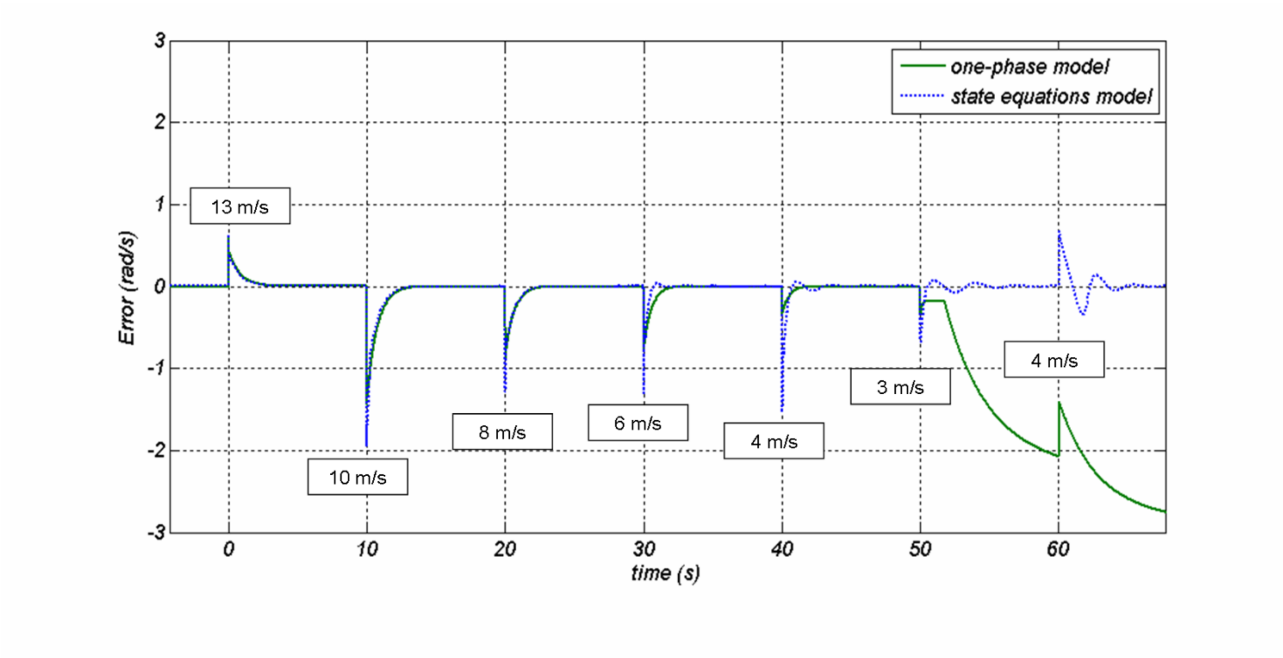

Figure 8. PI responses considering both induction generator models

In order to discuss the possible gain using CVT system G_{max} was defined by using Eq. (27). An induction generator in a wind generation system with no controller system will rotate approximately in a constant speed and so the turbine. In this case the converted power can be obtained as a function of wind speed, Eq. (1).

A controller able to keep the maximum convertible kinetic wind power energy attains the follow equation:

$$P_{\max} = \frac{\rho A V^3 C_{p\max}}{2} \qquad (26)$$

Comparing these both equations, the maximum gain that can be obtained using a CVT controller is

$$G_{\max} = \frac{P_{\max}}{P_u} = \frac{C_{p\max}}{C_p(\lambda)} \tag{27}$$

Figure 9 compares the system gain in two situations: the G_{max} and the simulated gain in some average wind speeds with random variation, as indicated in Fig. 7. It's shown that in a spread speed wind variation the system attains the maximum power conversion. Constant machine losses are the principal reason for the loss of gain at the low wind speed region. In this region the CVT had increased the system power in approximately 50%. In the region of high wind speed the gain is proportionally smaller (30%). The gain in this region is smaller than the maximum because of the induction generator rotor losses.

The energy gain by using a CVT is dependent of the wind speed distribution. For wind speeds varying near the designed one (i.e. 8 m/s), the use of CVT does not increase significantly the converted power by using an induction generator.

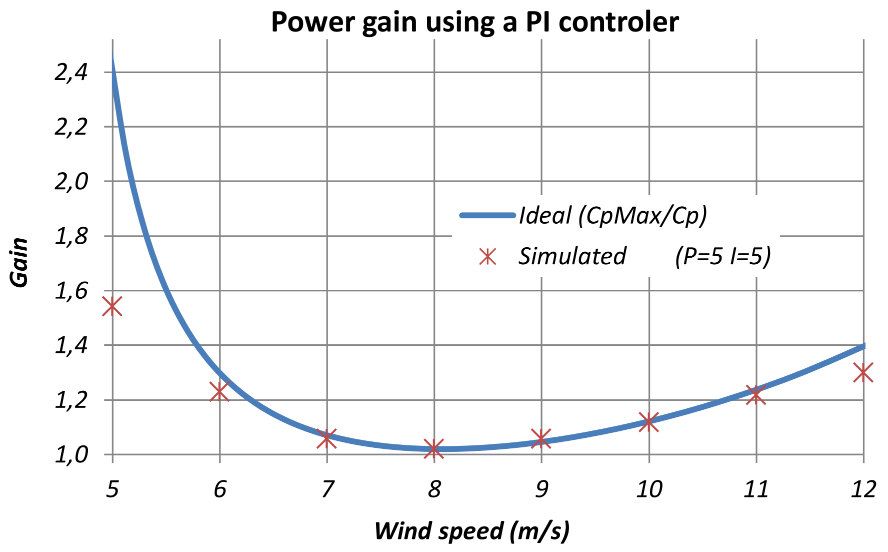

Figure 9. The system gain (the gain is 100% at 8 m/s)

The real wind speed cannot be considered constant. To calculate the possible gain for a range of speed it is necessary to integrate the power estimated by Eq. (1). Considering a uniform wind speed distribution between v_1 (m/s) and v_2 (m/s), the ideal gain is obtained in Eq. (28). For the simulated test in the range of 5 m/s to 12 m/s the ideal gain obtained was 17%.

$$Gain_{v1\ \max}^{v2} = \frac{v_2^4 - v_1^4}{4} \int_{v_1}^{v_2} \frac{C_p(\lambda)}{C_{p\max}} v^3 dv \tag{28}$$

Simulations were performed for a characteristic wind speed as showed in Fig. 7, with variable average wind speed in the entire range (5 to 12 m/s). The gain obtained in this particular simulation was 15%. Comparison with the ideal gain of 17% has demonstrated the proposed PI controller efficiency. This gain and the low cost induction generator with no power electronic use can justify the CVT cost effectiveness in low and medium power wind generators.

4. CONCLUSIONS

The PI controller designed for controlling the transmission ratio was fast and stable under the simulated conditions despite the many nonlinear phenomena which govern the studied system.

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Similar behavior was observed when the system was studied with different induction generator models. Results indicate that simulations need to consider complete models of the generator, particularly when the proposed study includes the stability of the electrical and mechanical system in a large wind speed range.

When connecting the system to the power grid with the use of CVT, the simulations result in a 15% increment of the useful energy. This gain will be greater under conditions of wind distribution that are extremely different from the one used in the project. Considering the random behavior of the wind, this result indicates that for long periods, the use of CVT can justify the installation of wind generators for small and medium applications in economically unviable places at present.

5. ACKNOWLEDGEMENTS

This work was partially supported by CNPq.

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