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H_2 production based on RDG and assisted by a weak grid. System topology, operation and control

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ABSTRACT

The Renewable Distributed Generation (RDG), such as production of electricity in the vicinity of the load, it is particularly beneficial when the distribution network is "weak" facing specific demands, as in hydrogen production systems connected to rural electrification networks. In these areas, the wind resource may be suitable for this type of generation. This work proposes the topology and the operation and control strategy for a hydrogen production station, "assisted" by a weak AC grid and "powered" by a variable speed wind turbine based on a three-phase double stator induction machine. The wind energy conversion is optimized through adequate control of the generator. The electrolyzer current is regulated for the maximum utilization of the generated power. The high-speed power fluctuations by turbulence are compensated through a controlled energy storage system based on a flywheel. In addition, the system configuration, its operation mode and control, and simulation results are presented.

1. Introduction

One of the distinctive features of Distributed Generation in AC is the production and supply of electrical energy in the vicinity of consumption. This is particularly beneficial when the distribution network is "weak" against the demand of punctual loads, as commonly happens with the hydrogen production systems connected to electrification networks in rural areas. Given that in many of these regions the wind resource often constitutes an important and competitive source of energy, its use is an alternative for the implementation of *Renewable Distributed Generation* in these areas [1,2].

For that purpose, in this paper is proposed the topology and the operation and control strategies for a hydrogen production station "*assisted*" by a weak AC grid, and "*powered*" by a variable speed *Wind Turbine*. A three-phase double stator induction machine (BDFIG) [3,4] is employed, with the principal stator winding directly connected to the grid, while the control stator winding is connected through a Static Kramer Drive. This scheme allows the system to maintain the wind generation with maximum power transfer at slow wind speed variations. This type of machine is an interesting alternative to the wound rotor induction generator, because it does not require slip rings and presents a greater number of poles reducing significantly the gearbox [5]. It also represents a valid alternative to the permanent magnet synchronous machine because it is cheaper and the converters, necessary for its control, only have to handle a fraction of the total power.

An additional equipment with *Flywheel* for *Energy Storage* is operated and controlled in order to smooth out the fast

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power fluctuations coming from the wind turbine, allowing a better operation and performance of the electrolyzer and a lower level of disturbances in the network connection point. This dynamic storage system is moved by an induction machine with an electronic drive connected to the AC side of the wind turbine. The Flywheel system is highly competitive for its durability, maintenance, power density and cost [6–9].

An alkaline *Electrolyzer* is fed by a controlled rectifier which regulates the power taken from the AC side. Its operation strategy leads to the complete utilization of the wind power.

The whole system only requires from the network an “assistance”, consisting of:

i) Provision of electrical parameters (V, f) for converters and BDFIG.
ii) Provision of reactive power to the BDFIG.
iii) Supply of a reduced active power to ensure minimum production of H_2 when wind resource is insufficient.

In the article are presented: the system configuration, the energy conversion and control strategy and the simulation results with conclusions.

2. System configuration

The configuration of the proposed conversion system is shown in Fig. 1. It is comprised of three functional modules linked together via an AC bus, connected in turn to a weak three-phase network of 380 V/50 Hz through a link. The modules are: *Wind Turbine, Storage System*, and *Hydrogen Production System*.

The *Wind Turbine* is a three-bladed horizontal axis turbine with adjustable pitch, which operates at variable speed. It drives through a gearbox a three-phase induction generator with double stator (BDFIG), whose principal stator winding is directly connected to the AC bus. A closed loop controls the electromagnetic torque of the BDFIG, tracking a reference T^*, which determines the operating point of the turbine under steady-state conditions. This control loop acts on the supply voltage of the auxiliary stator winding of the BDFIG by using a Static Kramer Drive [11]. A power control loop, acting on the pitch angle of turbine blades (β), limits the maximum generated power (P_{glimit}).

Wind Turbine data: Rated wind speed = 14 m/s; Ratio = 6 m; $C_{pmax} = 0.4$; $\lambda_{opt} = 6.7$.

BDFIG data: Rated Power = 75 kW; Principal Stator: 440 V/ 50 Hz/12 poles; Control Stator: 700 V/8 poles.

The *Storage System* is based on a flywheel, driven by a three-phase induction motor (IM) with squirrel-cage rotor. A closed loop controls the motor torque tracking the reference T^*_{fw}, which allows to vary the flywheel speed and its stored energy. This loop varies the IM supply frequency beyond the rated value by a frequency converter. Meanwhile, the supply voltage is maintained at its rated value, to operate the IM in the field weakening region. In this way, it is possible to obtain a greater storage capacity by working with higher speeds.

The value of T^*_{fw} results from the compensation strategy of wind power fluctuations, which is presented in Section 3.

Induction Machine data: *Rated Power* = 15 kW; Stator: 380 V/ 50 Hz/4 poles.

The *H_2 Production System* consists of an alkaline electrolyzer powered by a controlled rectifier. A closed loop imposes the electrolyzer current by acting on the firing angle of the rectifier. A control loop determines the power that electrolyzer takes from the AC bus and the grid.

Electrolyzer data: Rated Power 60 kW; Minimum Power: 10 kW; Capacity: 12 m^3N/h. Pressure: 30 bar.

3. Operation and control of the system

An operation and control strategy is proposed for each module of the system.

3.1. *Wind turbine*

The torque T_t developed by the turbine is:

$$T_t = 0.5\rho A r v^2 C_p(\lambda,\beta)/\lambda, \tag{1}$$

with ρ the air density, $A = \pi\ r^2$ the swept area, r the blade radius, v the wind speed, $C_p(\lambda,\beta)$ the power coefficient, $\lambda = r\omega_t/v$: the tip speed ratio, β the pitch angle and ω_t the turbine shaft speed.

The turbine operating points for maximum power describe a parabolic curve in the (T_t, ω_t) plane [2]:

$$T_{topt}(\omega_t) = K_t\omega_t^2, \tag{2}$$

with T_{topt} the T_t for maximum power and K_t a constructive constant.

The operating point of the wind turbine under steady-state conditions ($\omega = constant$) is:

$$T_t' = T_g \tag{3}$$

with T_t' the T_t referred to the generator shaft side and T_g the generator torque.

The BDFIG, with the principal stator winding connected to the grid and the auxiliary stator winding fed by a Static Kramer Drive, has a torque-speed curve equivalent to that of the DFIG machine with Static Kramer Drive on the rotor [11]. This characteristic curve can be approximated by means a straight line (Fig. 2), such as:

$$T_g = K_g\left[\omega_g - \omega_0(V_C)\right], \tag{4}$$

with $\omega_o(V_C)$ the ω for $T_g = 0$, V_C the DC link voltage and K_g a constructive constant.

The speed ω_o coincides with the synchronous speed when V_C is zero. If V_C increases, ω_o increases proportionally. According to Eq. (3), to keep the turbine working at optimal torque points, the T'_{topt} value for each value of ω_g must be imposed on T_g. This is achieved through the control structure presented in Fig. 1, which acts on the amplitude of the auxiliary stator voltage through the Static Kramer Drive. The torque T_g is measured indirectly, dividing the total generated AC power by the generator shaft speed.

Fig. 2 shows the characteristic curves of the turbine (Eq. (1) with $\beta = 0$), and the characteristic curves of the BDFIG (Eq. (4) referred to the turbine shaft), for DC link voltages (V_C) that

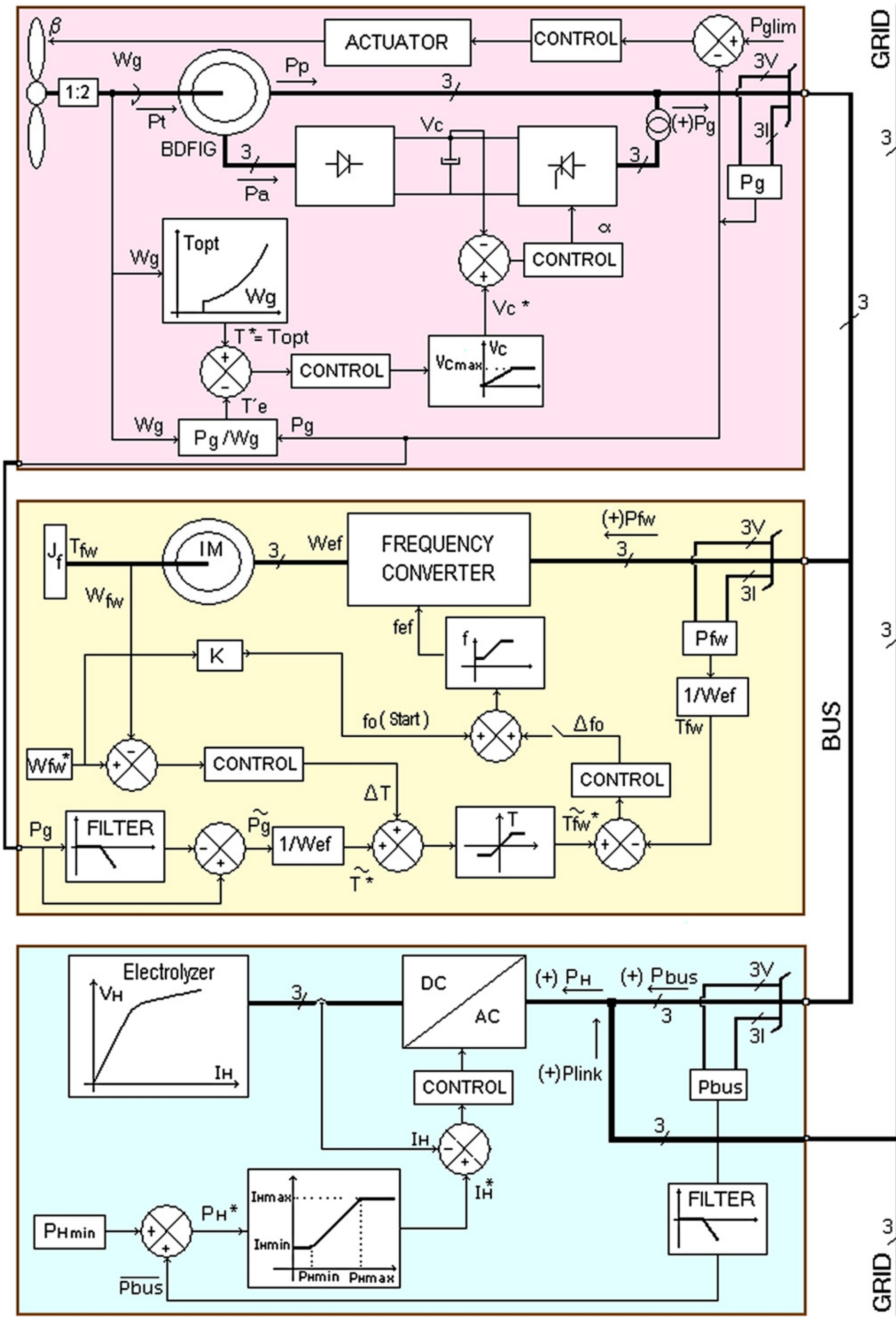

Fig. 1 – Modular System Structure.

make the subsystem to operate on the optimal torque points for different wind speeds (Eq. (2)). When the wind speed is very high, the generated power can exceed the rated value of the generator. To avoid this, limits on the rotation speed and the power output are set. The maximum speed is determined by the V_{Cmax} value in the torque control loop. The maximum power is regulated by a control loop acting on the blade angle pitch (β) [12]. For powers lower than the rated power, the $\beta = 0$ condition is maintained and the power will be the maximum attainable according to the parabola described by Eq. (1). The Fig. 3-(a) shows the action of the pitch control loop and the Fig. 3-(b) shows the operating regions of the wind turbine resulting from the action of the two control loops.

3.2. *Storage system*

Is proposed a control strategy for the Storage System that allows the Flywheel to store energy during increasing wind

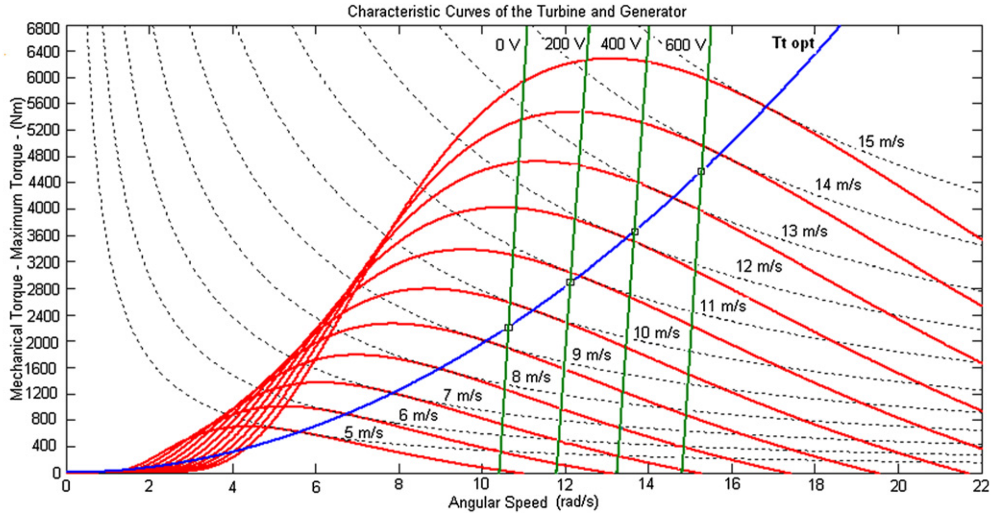

Fig. 2 – Wind turbine operating points.

power variations and provide energy for decreasing variations. The instantaneous power that must flow through the Storage System module, P_{fw}, is:

$$P_{fw} = \tilde{P}_g = P_g - \overline{P}_g, \tag{5}$$

where P_g is the total electrical power of the wind turbine, $\tilde{P}_g$ is the fast variation, and $\overline{P}_g$ is the mean value.

For the correct operation of the flywheel, its speed (ω_{fw}) should be within a given range. Therefore a minimum speed is established; below this value the stored energy is small and not useful. On the other hand, mechanical limitations determine the maximum speed. The relationship between $\omega_{fw\max}$ and $\omega_{fw\min}$ is usually set in 2:1 or 3:1, giving a useful variation of kinetic energy ΔE of 75% or 89% of $E_{\max}$, because:

$$\Delta E = E_{\max} - E_{\min} = \frac{1}{2} J_{fw} \left(\omega_{fw\max}^2 - \omega_{fw\min}^2 \right), \tag{6}$$

with J_{fw} the inertia moment and $E_{\min}$ and $E_{\max}$ the energy for $\omega_{fw\min}$ and $\omega_{fw\max}$.

In order to smooth out P_g, the flywheel must be able to store or deliver energy at any time. It is therefore necessary that when the flywheel is in repose mode it operates at an intermediate speed value, given by:

$$\overline{E} = \frac{E_{\min} + E_{\max}}{2} \rightarrow \omega_{fw}^* = \sqrt{\frac{\omega_{fw\min}^2 + \omega_{fw\max}^2}{2}}, \tag{7}$$

To fulfill the objectives defined by the Eq. (5) and Eq. (7) a torque control loop is used on the flywheel. The reference for this loop, T_{fw}^*, consists of two components:

$$T_{fw}^* = \tilde{T}_{fw} + \Delta T = \tilde{P}_g / \omega_{efw} + \Delta T \tag{8}$$

The first one, $\tilde{T}_{fw}$, corresponds to the smoothing of P_g, and is obtained from $\tilde{P}_g$, calculated by Eq. (5). This in turn requires knowing the value of $\overline{P}_g$, which is obtained through a low-pass filter since its variation is *slow*.

The second component, ΔT, obtained from the reference ω_{fw}^*, corresponds to the correction introduced by a *slow*

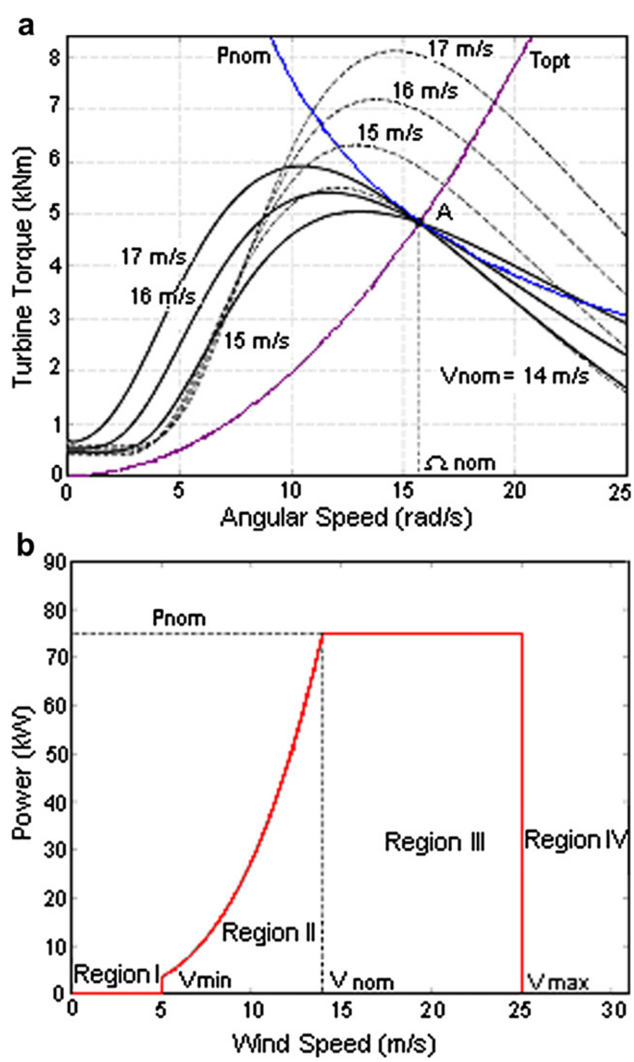

Fig. 3 – (a) Pitch Control, (b) Operating Regions of the Wind Turbine.

response speed regulation loop of the flywheel. Due to its response time, this loop does not interfere with the power smoothing loop.

3.3. H_2 production system

It is desired that the electrical power to supply the electrolyzer (P_H) comes predominantly from the Wind Generator-Flywheel assembly (P_{bus}). For this purpose a control loop determines P_H by regulating the current of the electrolyzer (I_H), through a current control loop acting on the firing angle of the controlled rectifier. The reference of the current loop (I_H^*) is derived from the desired value ofP_H^*, calculated as:

$$P_H^* = P_{H\min} + P_{bus}, \tag{9}$$

with $P_{H\min}$ the electrolyzer power for minimum H_2 production.

The controller of the power control loop has saturations that define a range of safe operation for the electrolyzer, $I_{H\min}$ and $I_{H\max}$. In this way, the power taken from the grid (P_{link}) is:

$$P_{link} = \begin{cases} P_{H\min} & if \quad P_H^* < P_{H\max} \\ P_{H\min} - (P_H^* - P_{H\max}) & if \quad P_H^* \geq P_{H\max} \end{cases} \tag{10}$$

To avoid quick changes in I_H, which can impair the operation of the electrolyzer [10], a low-pass filter is used in the measurement of P_{bus}.

4. Simulation results

The system was simulated in the MATLAB®/*Simulink* environment. A system model was developed using available elements in the library of the *SimpowerSystems* toolbox and the model of the BDFIG presented in [13] and [14].

Fig. 4-(a) shows the temporal evolution of the power generated by the Turbine-BDFIG assembly (P_g), while (b) shows the power flow in the Flywheel (P_H). In Fig. 4-(c) can be seen the power consumed by the electrolyzer (P_H), and finally in (d) the power taken from the grid (P_{link}). The wind profile employed is

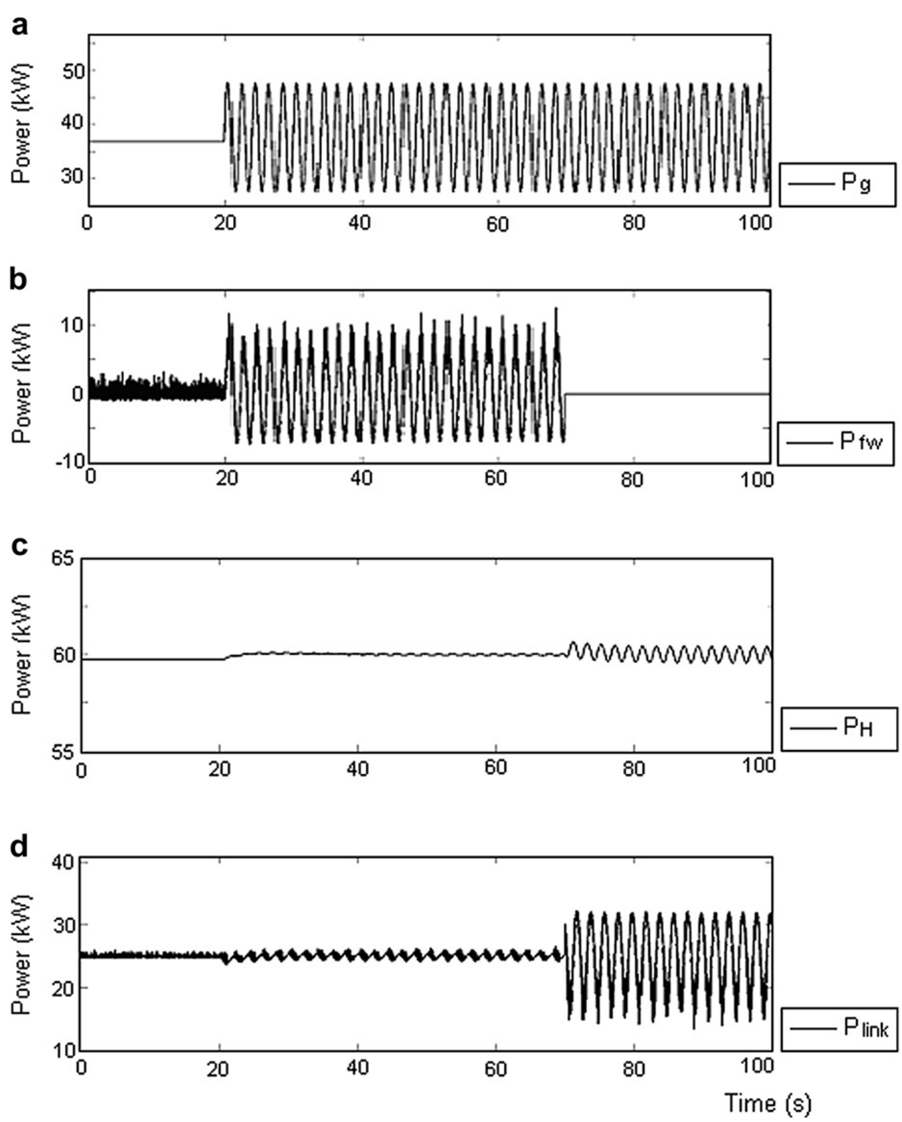

Fig. 4 – Power of: a) turbine-BDFIG assembly, b) flywheel, c) electrolyzer, d) grid.

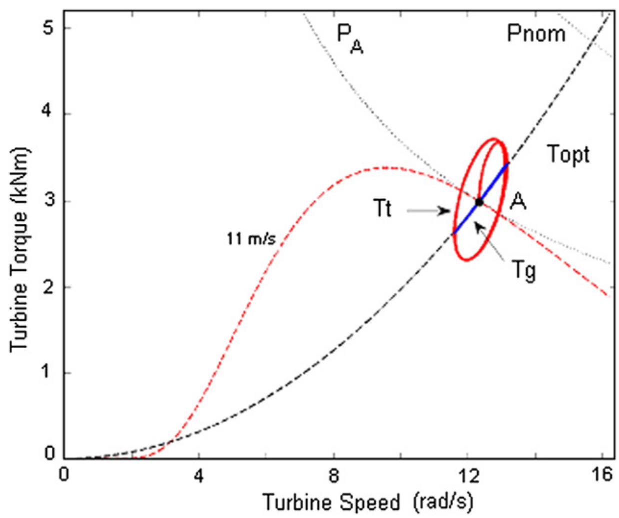

Fig. 5 – Trajectories in the Torque-Speed plane: T_t (solid red) and T_g (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a constant wind (*11 m/s*) to which is superimposed, from *t = 20 s*, a sinusoidal variation of amplitude *1 m/s* and frequency *0.5 Hz*. The Flywheel is initially enabled, and disabled at $t > 70$ s Fig. 5 shows the trajectories of the Turbine and the BDFIG variables in the torque-speed plane; point *A* corresponds to the steady-state operation achieved during the firsts *20 s* of simulation. The difference between red and blue trajectories is due to the mechanical inertia of the Turbine-BDFIG assembly.

5. Conclusions

- The modularity of the proposed system makes it highly flexible and reconfigurable, both in topology and in its control.
- The constituent parts have a low cost of investment and maintenance.
- The simulation results have validated the operation and the control strategy of the proposed system for an efficient use of the wind resource and a good operation of the electrolyzer.
- The use of BDFIG in wind energy conversion systems and the flywheel in energy storage systems to compensate the power fluctuations constitute a very promising option for RDG with good power quality.

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REFERENCES

[1] Burton Tony, Sharpe David, Jenkins Nick, Bossanyi Ervin. Wind energy handbook. Wiley and Sons; Dec 2001. 642 pages.
[2] Bianchi F, De Battista H, Mantz R. Wind turbine control systems. London: Springer; Jun 2006. 228 págs.
[3] Williamson S, Ferreira AC, Wallace AK. Generalised theory of the brushless doubly-fed machine. Part 1: analysis. IEE Proc - EPA 1997;144(2):111–22.
[4] Williamson S, Ferreira AC. Generalised theory of the brushless doubly-fed machine. part 2: model verification and performance. IEE Proc - EPA 1997;144(2):123–9.
[5] Carlson R, Voltolini H, Runcos F, Kuo-Peng P. A performance comparison between brush and brushless doubly fed asynchronous generators for wind power systems. ICREPQ'06, Palma de Mallorca 7 April, 2006;5(6). Paper 405.
[6] Cárdenas R, Peña R, Asher GM, Clare J, Blasco-Giménez R. Control strategies for power smoothing using a flywheel driven by a sensorless vector-controlled induction machine operating in a widespeed range. IEEE TIE 2004;51(3):603–14.
[7] Ghedamsi K, Aouzellag D, Berkouk EM. Control of wind generator associated to a flywheel energy storage system. RE 2008;33:2145–56.
[8] Hardan F, Bleijs JAM, Jones R, Bromley P, Ruddell AJ. Application of a power-controlled flywheel drive for wind power conditioning in a wind/diesel power system. EMD'99, Canterbury, UK. pp. 65–70; 1999.
[9] Takahashi I, Okita Y, Andoh I. PEDES_96, New Delhi. In: Development of long life three phase uninterruptible power supply using flywheel energy storage unit, vol. 1; 1996. p. 559–64.
[10] Bergen A, Pitt L, Rowe A, Wild P, Djilali N. Transient electrolyser response in a renewable-regenerative energy system. IJHE 2009;34(1):64–70.
[11] Bose BK. Power electronics and AC drives. Prentice-Hall; 1986.
[12] Camocardi P, Battaiotto P, Mantz R. Autonomous BDFIG-wind generator with torque and pitch control for maximum efficiency in a water pumping system. IJHE 2010;35:5778–85.
[13] Roberts P. A study of brushless doubly-fed (induction) machines: contributions in machine analysis, design and control. University of Cambridge; 2004.
[14] Rüncos F. Modelagem, projeto e análise de máquinas assíncronas trifásicas duplamente alimentadas sem escovas. Brasil: UFSC; 2006.