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Wind generation applied to water desalination and H_2 production in remote areas with weak networks

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ABSTRACT

In this article are proposed the topology, the operation and the control strategy of a system for the provision of potable water and fuel production (H_2) in remote areas, which is powered by a wind turbine and it is based on the concept of Renewable Distributed Generation.

The system has a modular structure and comprises a Wind Generator, a Power Fluctuations Compensator, a Reverse Osmosis Desalination System and an Alkaline Electrolyser. All of these modules are interconnected through power electronic converters by an AC local bus, which in turn is linked to a pre-existing weak electrical grid. The complete system requires only an “assistance function” from the grid, using its voltage and frequency. Also, some reactive power is taken, as well as a small amount of active power to ensuring a minimum production of water and hydrogen when the wind resource is insufficient.

Both, the selected operation mode and the control strategy used, allow achieving a maximum level of generated power and smoothing its fluctuations. This is done to prevent worsening the quality of potable water and the hydrogen produced, and to minimize the introduction of disturbances to the weak electrical grid.

The work is completed with the computer simulation of the operation and control strategies. The obtained results are promising and fully validate the proposal.

1. Introduction

The lack of potable water and fuel in remote rural areas, as occurs in large parts of Argentina, motivates the application of new technologies for the production of these resources by mean of electric power. To do this, desalination plants using reverse osmosis and H_2 production plants by electrolysis, can be very appropriate.

Since the distribution networks that reach these rural areas are generally “weak” for the provision of the electrical power required in such plants, the use of local wind resource as a primary source allows complementary power generation implementation. In this sense, the Renewable Distributed Generation Systems (RDG) are particularly convenient, i.e., those that enable the production and supply of electric power in the vicinity of the consumption loads, and are linked to the pre-existing grid.

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In this article are proposed the topology, the operation mode and control strategy of an RDG system integrated with water desalination and H_2 production plants. The ensemble has a modular structure and is "assisted" by a pre-existing weak AC grid, using its voltage and frequency. A certain quantity of reactive power is taken from the grid, as well as a little amount of active power to ensuring minimum production of potable water and hydrogen when the wind resource is insufficient.

Both, the selected operation mode and the used control strategy, allow the maximization of the power taken from the wind resource and the smoothing of its fluctuations. This is done to prevent worsening the quality of potable water and the hydrogen produced, and to minimize the introduction of disturbances to the weak electrical grid [1].

Promissory simulation results are shown at the end of the article; they validate the proposal performed in this work in an integral way.

2. System configuration

The configuration of the proposed system is presented in Fig. 1. It is comprised of four functional modules linked together via a local AC bus, which in turn is connected to a weak grid by a 380 V/50 Hz three-phase link. The modules are: ***Wind Turbine*, *Power Fluctuation Compensator, Desalinator and Electrolyser***.

The horizontal-axis Wind Turbine, that can deliver 100 KW at nominal wind speed, is of classic design. It has three-blades with adjustable pitch, and drives a multipolar Permanent Magnet Synchronous Generator (PMSG) at variable speed. This type of electrical machine has the advantage of not requiring a gearbox, reducing mechanical losses, cost and maintenance. The output power of the generator is processed with an electronic conversion system. It consists of a three-phase diode bridge rectifier, a boost DC–DC converter and a three-phase voltage source inverter, linked to the AC bus by coupling inductors.

The ***Power Fluctuation Compensator*** is based on supercapacitors [2] and is connected to the AC bus via a bidirectional electronic conversion stage. It is composed of a two-quadrant boost DC–DC converter and a three-phase voltage source inverter coupled to the AC bus with a series inductor in each phase.

This type of storage system is highly competitive for its long life, high power density, small size and weight, low cost and can be constructed with less polluting materials.

The water ***Desalinator*** is based on the reverse osmosis process. A high pressure positive displacement pump provides saltwater to the desalination membranes. It is driven by a 50 KW AC squirrel cage induction motor. Power is supplied by a constant V/f drive.

The ***Electrolyser*** is alkaline, with a 50 KW nominal output power, and is connected by a controlled rectifier (AC/DC converter) to the AC bus.

3. Operation and control of the system

An operating strategy for the whole system it is proposed with the intention to achieve the following objectives:

- Ensure a minimum production of potable water and hydrogen, even in the absence of wind resource. For this, the grid must provide only a small amount of active power necessary for the Desalinator and the Electrolyser ($P_{Dmin} + P_{Hmin}$).
- Prioritize potable water production. To do this, in a first step the wind resource is employed exclusively to increase the production of potable water above the minimum value provided by the grid, up to achieve the maximum flow of water.
- Dedicate the wind power excess to hydrogen production. This means, after reaching the maximum flow of potable water production, wind generation will be used to increase hydrogen production over the minimum value supported by the grid.
- Generate undisturbed electric power to prevent deterioration of the water and hydrogen quality, and also to minimize electrical disturbances introduced to the weak grid. For this a Power Fluctuations Compensator system is used, that is based on dynamic storage with supercapacitors. This allows smooth power generation with maximum use of the wind resource, using even the energy present in the rapid variations of the wind. In this way, the generated power it is not smoothed by limiting.

In order to achieve the objectives described above, a global operation strategy for the complete system is performed by individual control loops for each module, as presented in Fig. 1, whose operation is described below.

3.1. Wind turbine

The mechanical power provided by the wind turbine P_t is:

$$P_t = 0.5\rho A \upsilon^3 C_P(\lambda, \beta) \tag{1}$$

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

The turbine operating points at the maximum power describe a cubic parabola in the (P_t, ω_t) plane [3]:

$$P_{tmax}(\omega_t) = K_t \omega_t^3 \tag{2}$$

with P_{tmaxt} the P_t at maximum power and K_t a constructive constant.

Neglecting conversion losses, in the operation points of the wind turbine under steady state condition (ω = constant), it holds that:

$$P_t = P_g \tag{3}$$

with P_g the generator electric power.

To take full advantage of the power available in the wind, the P_{tmax} value must be imposed to the generator for each rotation velocity, in accordance with Eq. (3). In this form the steady state operating points of the turbine are forced to be located over the parabola described by Eq. (2). This action is achieved through the control structure presented in Fig. 1. A control loop, that varies the duty cycle of the boost DC–DC converter, fixes the rectified voltage, V_{rect}. The reference

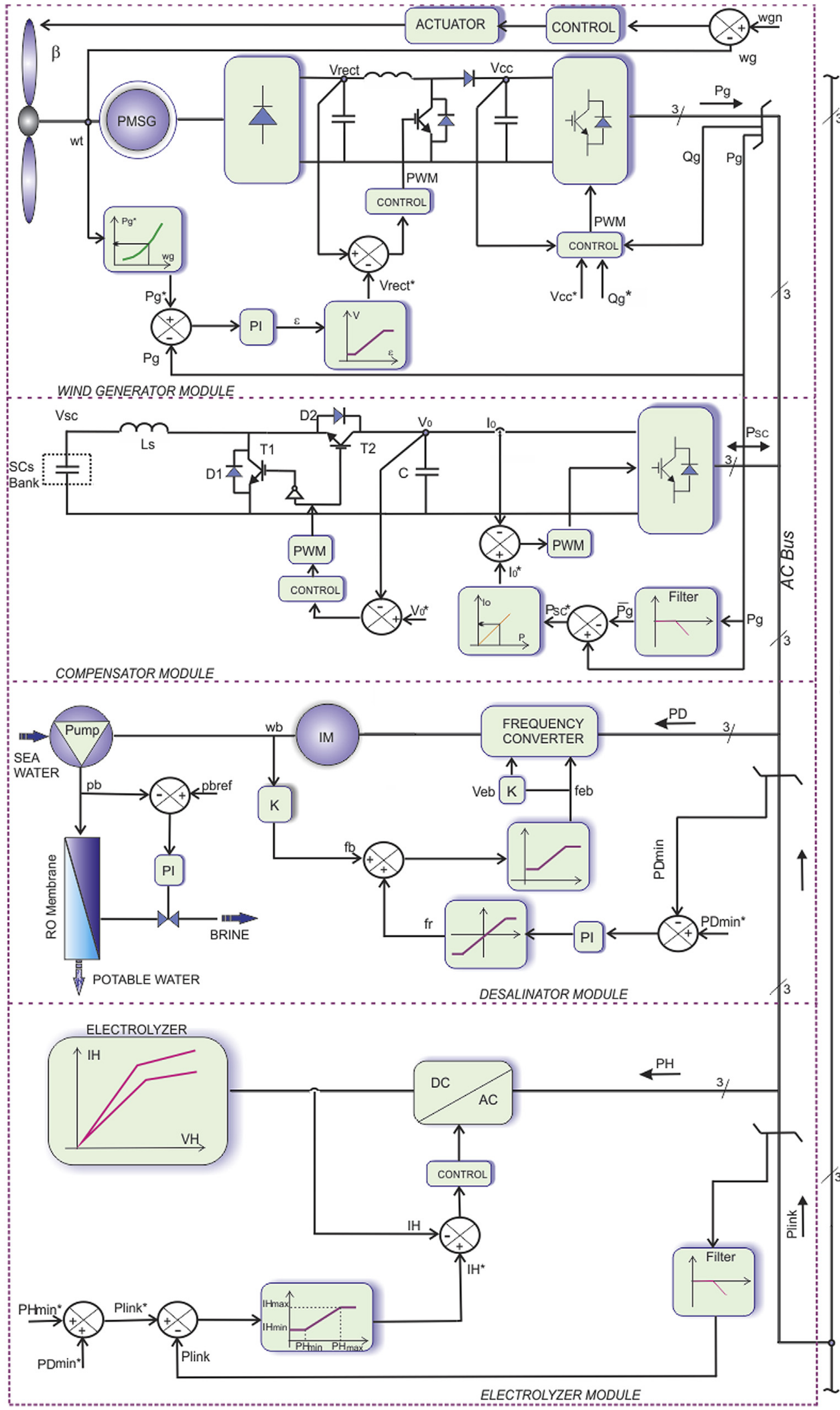

Fig. 1 – System configuration.

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voltage is provided by an outer loop. Saturations in the controller of this loop impose limits to the DC–DC converter input voltage, ensuring controllability.

The outer loop controls the generator power and its reference corresponds to a maximum wind power for each rotation speed. For this purpose, the reference for this loop P_g^* is determined by Eq. (2), and this requires the measurement of ω_t.

The inverter control loop has the objective of maintaining at a constant value the DC link voltage, V_{cc}. This is done to achieve an inverter proper operation, ensuring that the linear range of the PWM modulator is not exceeded. The inverter also supplies the reactive power required for a proper power factor in the AC bus.

Finally, the turbine has a control loop, acting on the blade pitch angle, that limits the maximum rotation speed and thereby the maximum mechanical power of the turbine [4], as shown in Fig. 2.

3.2. Fluctuations compensator module

A control strategy for this module has been developed, which allows the energy storage or supply during relatively fast variations in the wind velocity. The power compensator stores energy during positive variations (with respect to its mean value) of the generated power. On the contrary, the compensator supplies energy during negative power variations. Using this control strategy, jointly with the aforementioned wind turbine control loop, the total obtained power from the generator/compensator set is greater than in the case of the power smoothing by limiting. Therefore, as shown in Fig. 1, the instantaneous power that should flow by the compensator module, P_{SC}^* is:

$$P_{SC}^* = P_g - \overline{P}_g \quad (4)$$

with P_g the total electric generator power and $\overline{P}_g$ the average P_g value.

The power absorbed/delivered by the compensator module is controlled by the inverter. The power is varied adjusting the DC link current I_o, since it operates at a constant voltage. The current reference I_o^* for this loop is calculated as:

$$I_o^* = P_{SC}^* / V_o^* \quad (5)$$

with V_o^* the DC link voltage of the compensator module.

The value of P_{SC}^* in Eq. (5) is obtained by using Eq. (4), for which it is necessary to know $\overline{P}_g$, that is obtained through low-pass filtering of P_g.

The supercapacitor bank and the inverter are linked using a boost DC–DC converter, allowing variable voltage operation of the bank. The converter must be bidirectional because it should supply or absorb current from the supercapacitor bank to modify the stored energy. Remember that the supercapacitor bank voltage will vary depending on the stored energy level, according to the following relationship:

$$E_{SC} = \frac{1}{2} C_{SC} V_{SC}^2 \quad (6)$$

with C_{sc} the supercapacitor bank capacity.

3.3. Desalinator module

A control loop, acting on the brine outlet valve, is used to maintain a constant pressure in the RO desalination membranes, as presented in Fig. 1. It is well known that using an adequate pressure level ensures a good quality of potable water for the entire range of saltwater intrusion flow. A positive displacement pump provides the saline water flow to feed the membranes. The drive of the pump is carried by a squirrel cage type induction motor, fed by a frequency converter which operates at constant V/f with a slip control strategy [5].

Since the load presents a constant torque, due to the constant pressure operation of the RO membranes, the desalinator power (P_D) control is performed by varying the pump speed ω_p [6]. At the minimum speed, ω_{pmin}, the desalinator absorbs $P_D = P_{Dmin} = 10$ KW and when the allowable maximum speed ω_{pmax} is reached, the desalinator absorbs the maximum value of $P_D = P_{Dmax} = 50$ KW, as seen in Fig. 3.

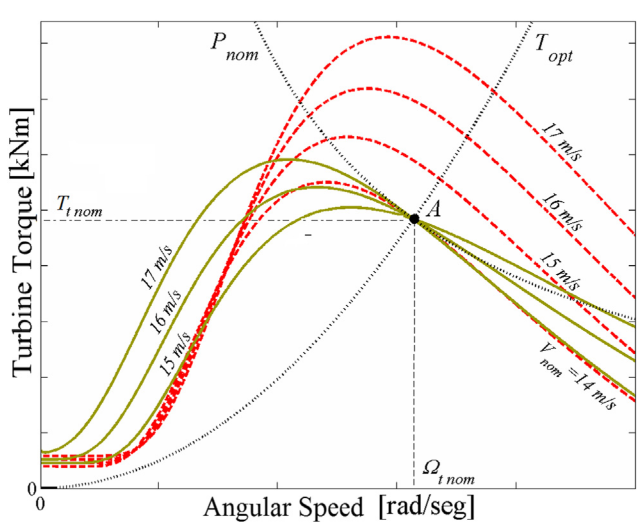

Fig. 2 – Wind turbine power limitation.

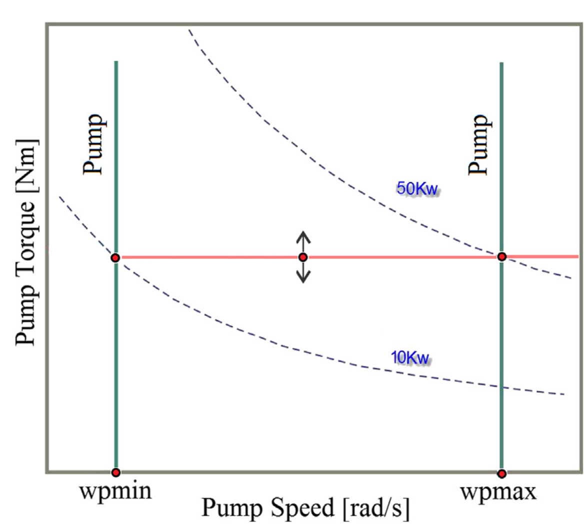

Fig. 3 – Operating points of the pump.

The power of the desalinator module (P_D) is determined by a closed loop whose aim is to maintain constant the power drawn from the grid, at the P_{Dmin} value. To achieve this goal P_D will vary depending on the average generated power ($\overline{P}_g$), in the following way:

$$\begin{aligned} &P_D = P_{Dmin} + \overline{P}_g \quad \text{if} \quad \overline{P}_g \le (P_{Dmax} - P_{Dmin}) \\ &P_D = P_{Dmax} \quad \text{if} \quad \overline{P}_g > (P_{Dmax} - P_{Dmin}) \end{aligned} \tag{7}$$

3.4. Electrolyser module

In this module, as shown in Fig. 1, a control loop regulates the electrolyser current (I_H) varying the firing angle of the controlled rectifier. The current reference (I_H^*) comes from an outer loop that controls the power that the entire system takes from the grid (P_{link}). The control objective of this loop is to keep this power at a constant value. The reference of this loop is obtained as:

$$P_{link}^* = P_{Hmin} + P_{Dmin} \tag{8}$$

where P_{Hmin} is the electrolyser power for minimum H_2 production, and P_{Dmin} is the minimal power of the desalinator.

The controller of the power loop includes saturations that define a safe operating range for the electrolyser, I_{Hmin} and I_{Hmax}, resulting:

$$\begin{aligned} &P_H = P_{Hmin} \quad \text{if} \quad \overline{P}_g \le (P_{Dmax} - P_{Dmin}) \\ &P_H = P_{Hmin} + \left[\overline{P}_g - (P_{Dmax} - P_{Dmin})\right] \quad \text{if} \quad \overline{P}_g > (P_{Dmax} - P_{Dmin}) \end{aligned} \tag{9}$$

In accordance with the power values given by Eqs. (7)–(9), the power exchanged with the network, (P_{link}), is given by:

$$\begin{aligned} &P_{link} = P_{Dmin} + P_{Hmin} = P_{link\_max} \\ &\text{if} \ \overline{P}_g \le (P_{Dmax} + P_{Hmax}) - (P_{Dmin} + P_{Hmin}) \\ &P_{link} = (P_{Dmax} + P_{Hmax}) - \overline{P}_g < P_{link\_max} \\ &\text{if} \ \overline{P}_g > (P_{Dmax} + P_{Hmax}) - (P_{Dmin} + P_{Hmin}) \end{aligned} \tag{10}$$

A low-pass filter is used in the measurement of P_{link} to avoid rapid changes in I_H, which may impair the operation of the electrolyser [7].

4. Simulation results

The simulations were performed in the MATLAB®/*Simulink* environment. An averaged model for the complete system was developed using elements of the *SimPowerSystems* library, allowing an analysis during a time lapse of several seconds.

Fig. 4 shows the power variation in each module of the system as function of the time. In (a) is shown the wind profile employed: no wind for $t < 2.5$ s, a constant wind of 6 m/s for $2.5 \text{ s} < t < 5$ s and a constant wind of 12 m/s for $5 \text{ s} < t < 7.5$ s. A sinusoidal variation, with an amplitude of 1 m/s and a frequency of 0.5 Hz, is superimposed from $t = 7.5$ s.

Initially, the fluctuations compensator module is inactive, and then active for $t > 13$ s. In (b) is shown the turbine power (P_t), whereas (c) shows the power exchanged by the inertia of the turbine-generator set (P_J). In (d) can be seen the generator power (P_g) and in (e) the power flow of the compensator module (P_{SC}). The power consumed by the desalinator (P_D) and the electrolyser (P_H) are presented in (f) and (g) respectively. Finally, in (h) can be seen the power provided by the weak grid (P_{link}).

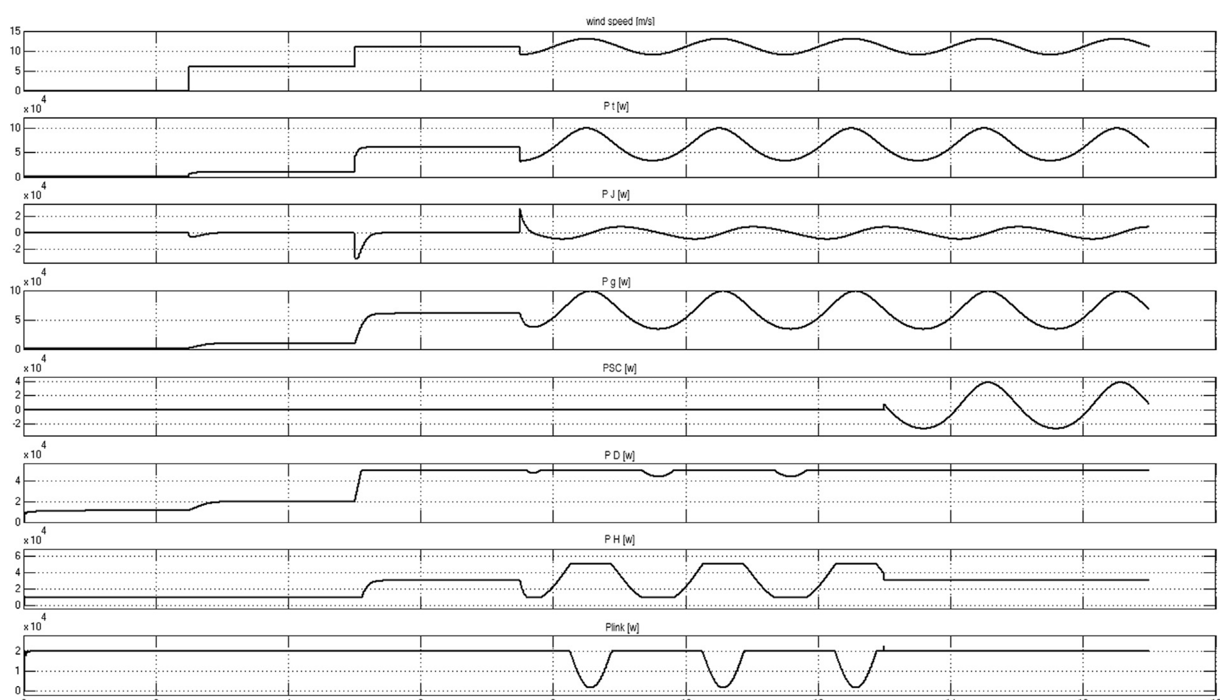

Fig. 4 – a) Wind profile b) Turbine power, c) Inertia power, d) Generator power, e) Compensator power, f) Desalinator power, g) Electrolyser power, h) Grid power.

5. Conclusions

- The modularity of the proposed system makes it highly flexible and reconfigurable, both in its topology as in their control.
- The constituent parts have low costs of investment and maintenance.
- The simulation results have validated the operation mode and control strategy for an efficient use of the wind resource and good performance of the desalinator and the electrolyser, minimizing perturbations in the weak electrical grid.
- The use of PMSG in wind energy conversion systems and supercapacitors to compensate its fluctuations, constitute a very promising alternative for RDG with good power quality.

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