Wind generation stabilization of fixed speed wind turbine farms with hydrogen buffer

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Abstract. The wind power generation, given the stochastic nature of its source, raises a number of disadvantages when it is integrated into the power system. To cope with these problems, a combination of wind power generation together with an energy storage system based on hydrogen is analysed in this work. The aim of the work is to study the presented issues and to analyse the symbiosis between the wind generation and a centralised energy storage system for a particular wind farm. To get this objective they will be modelled the wind park with an energy storage system based on hydrogen. The modelled energy storage is based only on hydrogen but it may carry also other storage systems that would improve the dynamic behaviour of the farm -response to disturbances, voltage dips, etc. The simulations carried out show that hydrogen buffer is a solution to the raised problem of the integration of wind farms in a market situation where compromises on the power to supply must be taken at least with 24 hours in advance.

Keywords: Wind energy, energy storage, distributed generation, grid integration, fuel cells

1. Introduction

The wind has become in recent decades one of the renewable sources of higher level of development and expansion. In the power generation plan published by the Spanish government, called **"Prospectiva de Generación Eléctrica 2030"**, it is expected that by 2030 the installed wind power will be 35% of the overall installed electrical generating power in Spain.

Apart from the benefits of a source of clean and sustainable energy, a high level of penetration of wind power in the overall electrical system also includes a series of new problems and challenges to be tackled.

The wind power generation, given the stochastic nature of its source, raises a number of disadvantages when it is integrated in the power system. To cope with these problems, a combination of wind power generation together with an energy storage system would improve considerably the security of supply to the grid [1] and, as a consequence, the overall operational efficiency of the utilities that now make the role of supporting (mainly thermal) will be improved.

The problem of electricity storage is an issue that is in force nowadays. In the field of wind power generation it has been investigated in depth as a means of regulating the active and reactive power injected to the grid. Different storage technologies with sufficient dynamic responses have been investigated. But, in general, these systems have low storage capacity and they accumulate energy in the range of seconds or minutes: hydraulic pumps [2], super capacitors [3], flywheels [4], electrochemical batteries [5], etc. There is also varied literature that has investigated the symbiosis between wind generation, photovoltaic generation and storage in autonomous systems and microgrids. In these cases the main objective is to guarantee electricity supply at all times. For these systems higher storage capacity systems are required such as diesel engine generators [6], [7], fuel cells [8], [9] as an emerging technology, or combinations of them [10].

However, in the case of wind farms that are integrated into the electric power system, a number of peculiarities that characterize such systems must be taken into account: (1) under the current legislation, the entire electricity production of this type is injected into the power system, (2) the electric system is operated by calculating the electric generation with a day in advance, in view of the planned consumption, randomness of the wind poses serious problems in regard to this anticipated prediction, (3) as a result of the previous wind farms can not be used as an slack bus, (4) there is no temporal correlation between wind generation and consumption, i.e. at times of peak generation demand can be minimal, (5) is necessary supply voltage drops of wind farms "instantly" (increasing the production of thermal power), otherwise could happen electrical blackouts of the system, and (6) the so-called voltage dip is one of the biggest drawbacks of wind turbines. When this phenomena occurs in the system, the wind turbines with Squirrel Cage Induction Machines (SCIM) are disconnected from the electrical grid to avoid being damaged and thus causing further disruptions in the system, in this case, lack of supply.

The research work proposed here, aims to study the presented problematic and analyse the symbiosis between the wind generation and a centralised energy storage system for a particular wind farm integrated in the power system. To get this objective they will be modelled the wind park with an energy storage system. The energy storage is based on hydrogen but it may carry also other storage devices that would improve the dynamic behaviour of the farm -disturbances, voltage dips, rapid response, etc.

2. Model

The main objective of the work is to study the behaviour of a wind park of medium power (20 MW) connected to a distribution network, and equipped with a storage system based on hydrogen power.

The first step of this study is the mathematical modelling of a wind farm with fixed speed asynchronous generators, an electrolysis based hydrogen generation system, a storage tank for that combustible and a solid oxide fuel cell (SOFC) for electrical power generation from hydrogen (Fig. 1). Simulation of the complete system has been addressed using MatLab© and Simulink©.

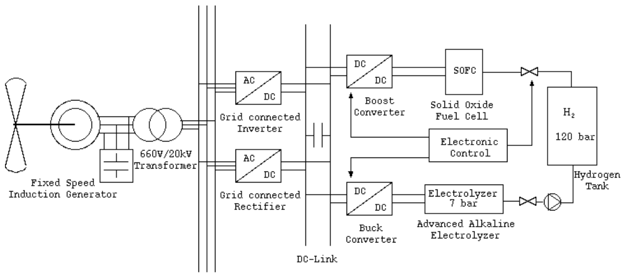

Fig. 1. Schematic of the modelled wind farm with hydrogen storage system.

The developed overall model allows the running of simulations that provide: (1) the farm's response to different situations in which the forecasts of wind have not been realistic and the hydrogen based system of storage-generation has to compensate the mismatches (quasi-stationary study), and (2) the dynamic response of the system to disruptions (transient study). In the latter case it would be necessary to consider storage systems with faster response such as flywheels or batteries.

A. Wind generation farm

For the modelling of the park the aggregated model [11] will be used. The aggregated approach represents a wind farm by one equivalent machine with re-scaled power capacity. This simplification is perfectly acceptable under normal operation of wind farms, given the constant speed characteristic of the SCIMs. This wind farm considered consists of 40 ABB G39-500 SCI generators of 500 kW and a nominal voltage of 690 V, with 125 kVAR capacitive compensation. After a step-up Ynyn transformer of 690/20000 V, each induction machine is connected through subterranean lines with the common bus at 20 kV. The developed electromagnetic transient simulation model of the wind farm allows to predict its behaviour under normal operating conditions and also under electrical disturbances.

Some of the machine inductances in the voltage equations that describe the performance of induction machines are function of the rotor speed, whereupon the coefficients of the differential equations (voltage equations) that describe the behaviour of these machines are time varying except when the rotor is stalled. A variable change is often used to reduce the complexity of these differential equations. This general transformation refers machine variables to a frame of reference that rotates at an arbitrary velocity ω_g [12]. The 3-phase variables associated with the natural reference frame *abc* are replaced with some equivalent variables refered to a *dq0* arbitrary reference frame (Fig. 2).

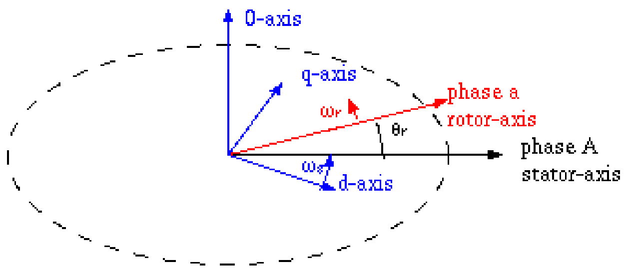

Fig. 2. Induction machine windings in the *dq0* arbitrary reference frame.

As a consequence, stator and rotor variables will be expressed in the *dq0* reference frame fixed in the rotor, so $\omega_g = \omega_r$. The electric model will be expressed through (1)–(6) with currents i_{sd}, i_{sq}, i_{s0} —for the stator side— and i_{rd}, i_{rq}, i_{r0} —for the rotor side—, as electrical state variables of the electromagnetic transient model.

$$\frac{di_{sd}}{dt} = \frac{L_m(R_r i_{rd} - u_{rd}) + L_r[\omega_r(L_s i_{sq} + L_m i_{rq}) + u_{sd} - R_s i_{sd}]}{L_s L_r - L_m^2} \quad (1)$$

$$\frac{di_{sq}}{dt} = \frac{L_m(R_r i_{rq} - u_{rq}) - L_r[\omega_r(L_s i_{sd} + L_m i_{rd}) - u_{sq} + R_s i_{sq}]}{L_s L_r - L_m^2} \quad (2)$$

$$\frac{di_{s0}}{dt} = \frac{u_{s0} - R_s i_{s0}}{L_{ls}} \quad (3)$$

$$\frac{di_{rd}}{dt} = \frac{L_s(u_{rd} - R_r i_{rd}) - L_m[\omega_r(L_s i_{sq} + L_m i_{rq}) + u_{sd} - R_s i_{sd}]}{L_s L_r - L_m^2} \quad (4)$$

$$\frac{di_{rq}}{dt} = \frac{L_s(u_{rq} - R_r i_{rq}) + L_m[\omega_r(L_s i_{sd} + L_m i_{rd}) - u_{sq} + R_s i_{sq}]}{L_s L_r - L_m^2} \quad (5)$$

$$\frac{di_{r0}}{dt} = \frac{u_{r0} - R_r i_{r0}}{L_{lr}} \quad (6)$$

where L_s and L_r are the stator and rotor side inductances, L_m is the magnetizing inductance, R_s and R_r are the stator and rotor resistances, and ω_r is the rotor electrical speed.

The expression for the electromagnetic torque in terms of arbitrary reference-frame variables may be obtained in terms of currents as:

$$T_e = \frac{3}{2} P L_m (i_{sq} i_{rd} - i_{sd} i_{rq}) \quad (7)$$

The differential equations that describe the mechanical dynamics of the rotor are:

$$\frac{d\theta}{dt} = \omega_r \quad (8)$$

$$\frac{d\omega_r}{dt} = \frac{1}{J}[P(T_e + T_w) - D\omega_r] \quad (9)$$

where T_e is the electromagnetic torque, T_w is the torque due to the wind, J is the inertia of the rotor, D is the damping coefficient, and P is the number of pole pairs of the generator.

So, the overall electromechanical subtransient model of the wind generator is described as a system of eight differential non-linear Eqs. (1)–(6), (8) and (9), in the state-space, being $i_{sd}, i_{sq}, i_{s0}, i_{rd}, i_{rq}, i_{r0}$ electrical state-variables, and θ_r, ω_r mechanical state-variables.

B. Fuel Cell

Fuel cells are generally characterized by the type of electrolyte that they use. Solid Oxide Fuel Cells (SOFCs) have grown in recognition as a viable high-temperature fuel-cell technology. The most striking quality of SOFCs is that the electrolyte is in solid state and is not a liquid electrolyte. The operating temperature of the SOFC is in the range of 900–1000 ºC, the electrical efficiency is 55–60% [13], and its durability is of more than 40 000 h for stationary power applications [14]. They are very suitable for large-scale generation, rising to 50 MW of rated power.

The SOFC model developed in this work has been based on [15], [16]. The rated power is 4 MW (20% of the rated power of the park). This model focuses on the SOFC dynamic behaviour under a grid-connected condition. It is supposed a constant operation temperature of 1000 ºC. Model inputs are hydrogen flow, oxygen flow and current supplied to the load. The model output is the voltage (V) generated by the fuel cell.

C. Electrolyzer

The energy storage proposed in this paper needs of an electrolyzer to store surplus electricity. Alkaline technology is the most mature to date and the latest generation of such electrolyzers includes major improvements to the classical alkaline electrolyzers. The modelled electrolyzer type is a so-called advanced alkaline electrolyzer [17]. It operates at a pressure of 7 bar and at temperatures up to about 80 ºC. The cells are circular, bipolar, have a zero spacing geometry, and consist of NiO diaphragms and activated electrodes, which make them highly efficient. The electrolyte is a stationary 30 wt% KOH solution.

The model developed is suitable for transient simulations, therefore, it is compatible with these studies on wind energy storage that, given the wind fluctuation, has this stochastic character. The nominal power of the Electrolyzer is the same as the SOFC, 4 MW. Model inputs are T^a (constant, 80 ºC) and current (I). Outputs are voltage (V) and H_2 flow.

In addition to the electrolyzer, hydrogen storage has been also modelled. Hydrogen storage model assumes flow of hydrogen following the behaviour of ideal gases and storage at ambient temperature and standard industrial conditions; thereby, compressors will be needed in order to achieve this design pressure of storage. The input of the model is the hydrogen flow rate that is being produced by the electrolyzer.

D. Electronic control and Power Conditioning System

The electronic control performs the following tasks: (1) calculate the active electrical power to be generated by the SOFC, (2) from this, calculates flows of H_2 and O_2 that needs the SOFC, and (3) calculates the electric current to be injected into the electrolyzers.

Furthermore, given that both the SOFC and the electrolyzer work with DC, are required Power Conditioning Systems (PCS) to integrate these elements and the electrical network, which works with AC. In this paper it has been assumed that the PCSs are ideal, making the conversion AC/DC and DC/AC with a yield of 100% and unity power factor.

3. Simulation results

With the developed models, simulations were performed to analyse the behaviour of the wind farm when working in a market situation, where the compromise of power to supply must be taken at least with 24 hours in advance. Usually, the prediction error for one day wind forecast is about 10%-15% [18]. Faced with a setpoint of active power imposed by the previous forecast, the aim is to see what is the response of the modelled farm. The power generated by wind has been modelled as the sum of a constant value (average power) and a frequency variable sinusoidal wave (Fig. 3). It has been modelled in this way because so can be observed the dynamic response of the system better than with an entry based on actual values of wind speed. The reference simulation time is one hour, keeping the setpoint constant throughout it. Three different cases were considered: (1) the active power required by the power system exceeds the power of wind, (2) the power required is less than the power from wind, and (3) the power required is equal to the average power of wind.

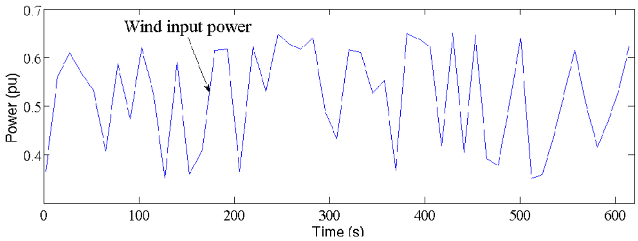

Fig. 3. Input power supplied by wind in p.u.

A. Required setpoint power greater than actual wind input power

In this case the fuel cell will have to make a net contribution of power to the system, while the electrolyzer will only be operational at moments where the instantaneous power of wind exceeds the target power. This case determines the rated capacity that must have the fuel cell. In Fig. 4 is shown the system response obtained for an input wind power of 0.5 p.u. average value and a power requirement of 0.6 p.u. for one hour. Fig. 5 shows the power supplied by the fuel cell.

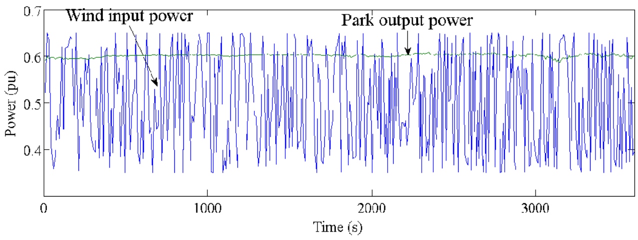

Fig. 4. Response of the wind farm when required setpoint power is greater than actual wind input power.

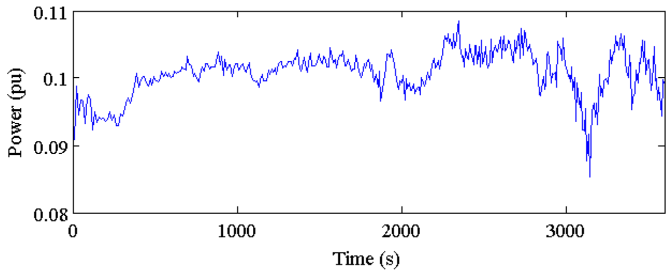

Fig. 5. Power supplied by the fuel cell.

The volume of hydrogen required by the fuel cell was 1110 Nm^3 (at 0 ºC and 1 atm), the volume generated by electrolyzer 51 Nm^3, therefore, the net volume employed to generate the electricity required by the system in this case was 1059 Nm^3.

B. Required setpoint power lower than actual wind input power

In this case there is a net surplus power that may be stored in the form of hydrogen through the electrolyzer. The fuel cell will work in the moments when the instantaneous input power is lower than that imposed. The average input power is 0.7 p.u., and the required target power 0.6 p.u.

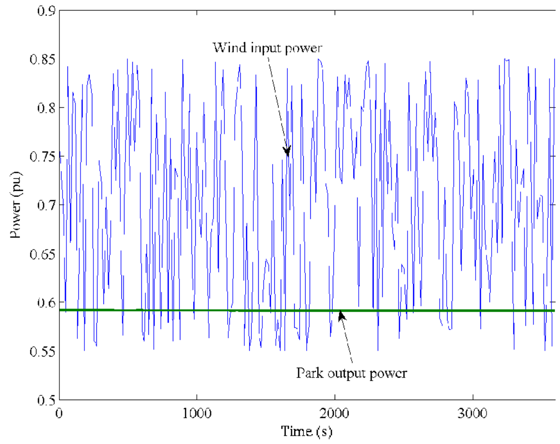

Fig. 6. Response of the wind farm when required setpoint power is lower than actual wind input power.

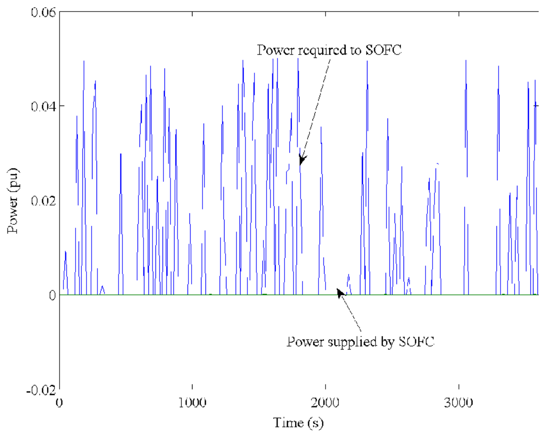

Fig. 7. Power required and supplied by the fuel cell.

Fig 6 shows in this case an offset regarding the target power. The system, instead of providing an output of 0.6 p.u., brings 0.59 p.u. approximately. This is because when requesting the fuel cell to provide power, it does not respond quickly enough (see Fig. 7) and, therefore, the output power obtained is basically that provided by wind power minus the power processed by the electrolyzer. An energy storage buffer with better dynamic response (e.g. electric battery, flywheel or ultra-capacitor) would improve the outcome, providing the missing energy.

The net volume of hydrogen generated in this case was 607.4 Nm^3. The fuel cell has employed only 0.5 Nm^3.

C. Required setpoint power equals to actual wind input power

Paradoxically, the case in which the forecasts match the power required by the system operator will be the most demanding for the storage system because electrolyzer and fuel cell will have to work continuously.

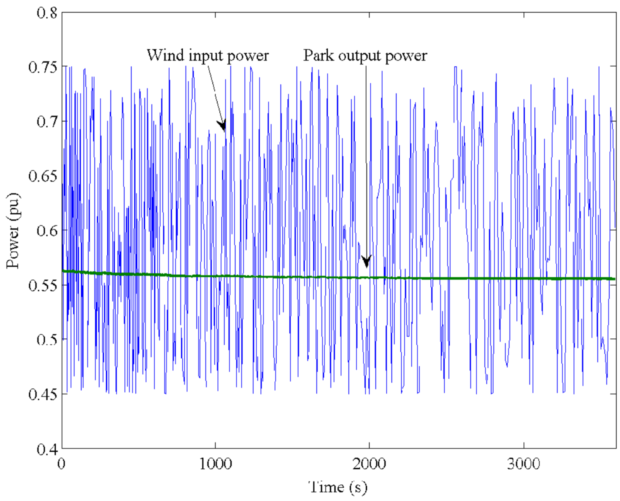

Fig. 8 Response of the wind farm when required setpoint power equals to actual wind input power.

Fig 8 shows in this case, as in the previous one, a pronounced offset regarding the setpoint power. The reason is again the inability of the fuel cell to reach the demanded dynamic.

4. Conclusions

The proposed approach allows wind farms, as standard power plants, to provide previously offered power improving the efficiency of the overall electric system. Moreover, through the electrolyzer, the remaining wind power is stored as hydrogen, improving also the performance of the wind farm.

The simulations performed with the developed model show that the wind farm equipped with a buffer system based on hydrogen gets an uniform active power output in all studied cases. Furthermore, when the actual wind power and the target output power for the farm are compatible with the dynamics of the SOFC, there is a good tracking response of the overall system. The steady state error that appears otherwise is a consequence of the slow response of the SOFC with regard to a general control scheme for the power curve of the wind farm. To cope with this problem there is a need for additional energy buffers with extra response dynamics.

It can be concluded that hydrogen buffer is a solution to the raised problem of the integration of wind farms in a market situation where compromises on the power to supply must be taken at least with 24 hours in advance.

5. References

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