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GENERATION AND BATTERY MODELLING AND INTEGRATED CONTROL STRATEGIES FOR A BETTER ACCEPTANCE OF INTERMITTENT RENEWABLE ENERGY SOURCES IN THE ELECTRIC DISTRIBUTION SYSTEM

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ABSTRACT

The paper is aimed at describing the models of generation sources and storage systems for implementing integrated control strategies of a renewable generation park composed by wind turbines and batteries. The storage system is characterized from an electrochemical and thermal perspective, while the wind turbines have an electro-mechanical characterization. The purpose of the energy storage system is to be coupled to the wind generation system in order to realize different tasks: to have the generation output power smoothed and to grant no power transfer, for a certain period on Distribution System Operator (DSO) request, at the point of common coupling in any battery state-of-charge condition.

INTRODUCTION

The electric power system is facing an evolution from the traditional concept of energy generation by few localized power plants interconnected through a meshed system to distributed medium and small scale generators [1].
Moreover some typologies of these generators "embedded" into the distribution network are fed by renewable sources like wind and sunlight. Their main drawback is their unpredictable behaviour. This means to have for example maximum production during minimum demand or excess of generation in congested parts of the electric network, thus causing bottlenecks and overvoltage situations in some critical sections of the grid [2].
Hence the presence of energy storage systems may allow a better management of the electric system allowing the full exploitation of renewable energy sources. Of course, nowadays, the cost per stored Wh is quite high and so it might not be economically feasible to install huge amount of batteries. The size of the storage system can vary considerably and, depending on its size, different tasks can be performed: starting from short-term fluctuation leveling and power quality improvement, getting to primary frequency-power regulation and, in case of large storage sizing, granting day-ahead generation dispatching.
The main aim of the paper is to develop models of wind turbine and storage systems for implementing integrated control strategies of the whole resulting system thus describing the benefits that the storage system can provide.

STORAGE MODEL

The storage model proposed below is suited for electrical studies and it is a general model. For this paper it has been tuned on the specification of a NaNiCl battery. The proper dynamic regards the SOC (State of Charge) behavior, the electrochemical one and the thermal one. The last one is very crucial when high power stress is required and moreover for this typology is essential because its chemistry allows temperature ranges from 260 °C to 320 °C. The battery is hence equipped with auxiliary systems (fan and heater) to have the control system keeping temperature in this range.

SOC Dynamic

The first dynamic described is related to the behavior of the state of charge (SOC). This variable gives information about the quantity of energy still stored in the battery.
Its value is 1 when battery is fully charged and 0 when fully discharged. Because of the nature of NaNiCl it is not recommended to go under 0.2. The differential equation is shown further on: I_{dc} and I_{aux} are the currents flowing in the battery and used by the auxiliary system; C is the nominal charge (in Coulomb) of the battery.

$$\begin{cases} I_{dc} + I_{aux} = C * {dSOC}/{dt} \\ SOC(0) = SOC_0 \end{cases} \quad (1)$$

The NaNiCl battery hasn't auto-discharge, so no shunt elements are considered.

Electrical Dynamic

To evaluate the amount of energy that is stored or released by the battery the electrochemical dynamic has to be detailed. A first order model takes into account two voltage generators with a resistor in series as shown in Figure 1. The first one, V_{oc}, generates what is commonly known as open circuit voltage and its value is 2.58 Volt per cell. In other kind of storage the value is generally function of the SOC, but for the NaNiCl it is almost constant for the operating SOC range. The resistor takes into account the internal Joule losses and is assumed to be function of SOC and temperature.

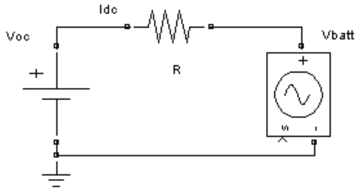

Figure 1. Electrochemical equivalent

The controlled generator, V_{batt}, models the behaviour of the dc/ac converter. Its task is to close the circuit and set, by the means of the control system, the current value to have the desired value of power flowing. The current is assumed positive if flows from V_{oc} to V_{batt} and that means a discharge action.

Thermal Dynamic

As foretold the thermal dynamic is quite crucial for this kind of battery and for hot temperature battery in general. A possible representation is reported in Figure 2. Using the electric components, the differential equations, reported subsequently, can be easily understood. If it is assumed that the temperature, T, behaves like voltage and the thermal power, Q, like current, then the capacitor and the resistor represents the thermal capacitance and resistance of the battery.

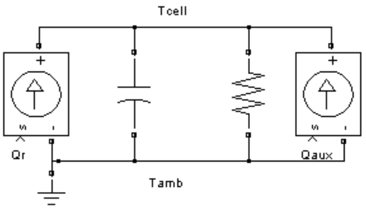

Figure 2. Thermal dynamic described by the mean of electric equivalent

The two current generators are used to model the thermal power generated by Joule effect and the thermal contribution of both cooling fan and heater device.

$$\begin{cases} Q_{\Pr} + Q_{Paux} + Q_R = Q_C \\ Q_R = {}^{\Delta T}\!/_{R_T} \\ Q_C = C_T * {}^{dT}\!/_{dt} \\ T(0) = T_0 \end{cases} \tag{2}$$

Protection and limitation

The battery control system has the task to stop the battery if the SOC level goes below 0.2 or above 1. It is also sensible to temperature and for example it has to turn off the cooling fan when temperature goes above a threshold, that is function of SOC, or turn on heater devices if the battery is cooling down.

WIND TURBINE MODEL

The wind turbine model is tuned for a 2 MW full converter direct drive equipped generator. This typology of wind turbine is characterized by the absence of gearbox and the presence of ac/dc/ac converter sized for the whole power.

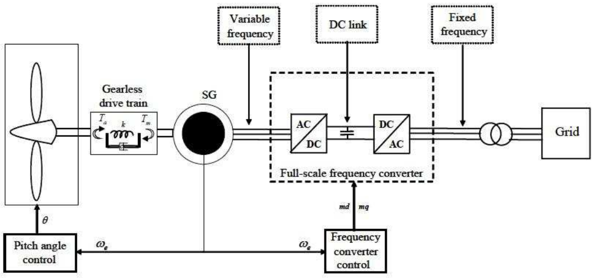

Figure 3. Full converter direct drive wind turbine concept

The dynamic analyzed regards the aerodynamic efficiency of blades, the maximum power tracking characteristic and the blade pitch control. Because there is no interest in power system stability studies, the generation/conversion system is modelled as a negative load.

Aerodynamic

The blade efficiency is represented by the power coefficient, c_p, that in terms of wind power quantify the percentage that the rotor extracts from the wind:

$$P_{rotor} = {}^{1}\!/_{2}\, c_p \cdot \rho \cdot A \cdot U^3 \tag{3}$$

This coefficient is function of the tip speed ratio, λ, and of the blade pitch angle, β. The value of λ depends on the ratio between blade peripheral speed and wind speed.

$$\lambda = \omega \cdot {}^{R}\!/_{U} \tag{4}$$

A possible analytic representation can be expressed by the following equation:

$$c_p = c_1 * \left\{ c_6 * \lambda + \frac{\left[-c_4 - c_3 * (2{,}5 + \beta) + c_2 * \frac{1}{\lambda + c_7 * (2{,}5 + \beta)} - \frac{c_8}{\lambda + (2{,}5 + \beta)^3} \right]}{\exp[c_5 * (\frac{1}{\lambda + c_7 * (2{,}5 + \beta)} - \frac{c_8}{\lambda + (2{,}5 + \beta)^3})]} \right\} + c_9 * \lambda$$

Maximum Power Tracking Characteristic

The maximum power is available only for a small range of values of λ, because when the wind changes, the task of the maximum power tracking (MPT) is to control generator rotational speed, ω, in order to have the desired output. Actually it is the curve, shown in Figure 4, that generates the reference power in function of the rotational speed of the turbine. In theory it would be better to express the reference power in function of the wind speed, which, unfortunately, cannot be measured with accuracy. So, instead of using wind speed, another control variable, the rotational speed of the turbine is used.

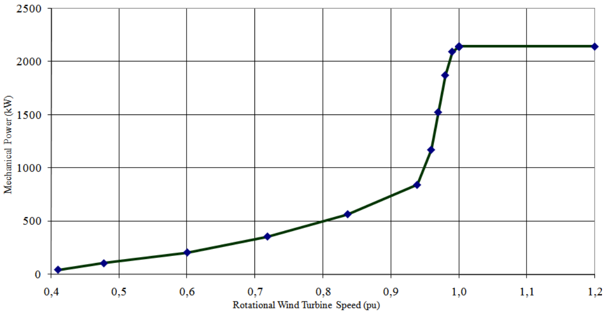

Figure 4. Maximum Power Tracking Curve

The logic behind this curve is quite simple: the control system sets a reference value of power to the generator that depends on the actual rotational speed, if the torque that the generator sets on the shaft is superior to the one captured by the rotor blades then the shaft slows. The reference power hence is reduced and if it is equal to the one produced by the turbine the system is steady otherwise the tracking action goes on.

Pitch angle control

The pitch control system has to reduce the aerodynamic efficiency by increasing the blade angle attack. Its control is sensible to rotational speed: if this values goes above 1 per unit, the PI (proportional-integral) control system commands the increase of the pitch angle.

Prime mover: Wind data

Because of the interest in studying the fluctuation induced in the turbine power output it is necessary to have appropriated wind speed data. Figure 5 shows the four wind profiles, used to feed the four wind turbines that compose the park. These data are from a real wind park and have a sample time of 5 seconds.

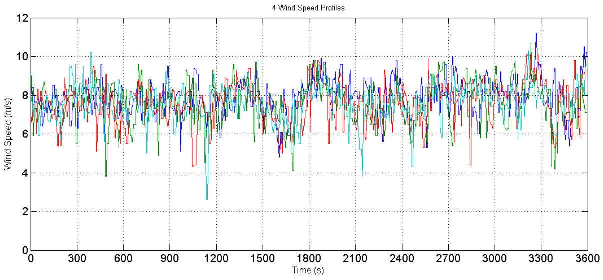

Figure 5. 4 Turbulent wind speed profiles

It can be noted how much wind speed is changeable. In this 3600 seconds range it varies quite often between 6 to 10 m/s.

WIND PARK AND BATTERY CONTROLLER

The system studied is composed by 4 wind turbines 2 MW nominal power coupled with a storage system of 2 MWh – 2.5 MW. Figure 6 shows the layout of the park: the storage system is connected before the point of common coupling (PCC) of the park. The whole system is then connected through a 132/20 kV transformer to the main grid.

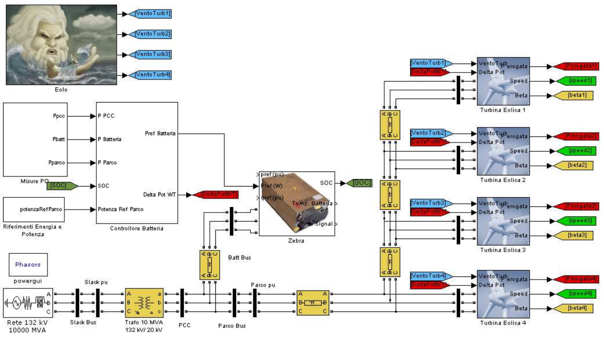

Figure 6. Layout of the wind park and storage system

The idea is to control the battery charging and discharging in order to control the whole plant output. The park controller sets the reference power that the storage system has to accomplish. This controller is equipped with a PI regulator and is sensible to the error between the power produced by the all wind turbines and the expected reference power. Moreover it is present in the control loop another contribution sensible to the SOC level of the battery. This control reduces or increases the battery reference power with the purpose to keep the SOC in an adequate range so that storage is always available.

SIMULATION RESULTS

Two scenarios are studied: the first one is related to smooth the wind power output, the second is to grant no power transit at the PCC for a certain time because of DSO request. The hypothesis is that the wind forecast is correct, that means that each ten minutes a reference power, that depends on the mean wind speed, is sent to the plants. It is clear that at each time step the wind turbines will not produce the forecasted power because of the turbulence. The main task is hence to smooth the fast fluctuation induced in the wind by the local terrain. Figure 7 reports the mean ten minutes wind speed.

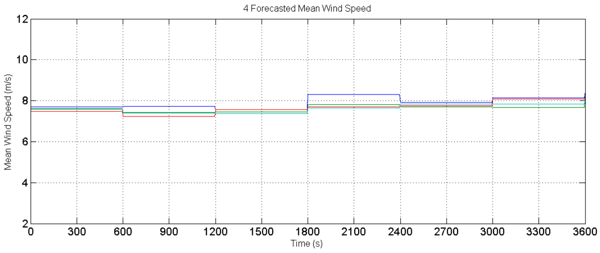

Figure 7. 4 Forecasted Mean Wind Speed

Smoothing wind park Output

Figure 8 reports the output of wind park. The benefits in the power that transits at the PCC because of the battery smoothing action can be appreciated in the first diagram.

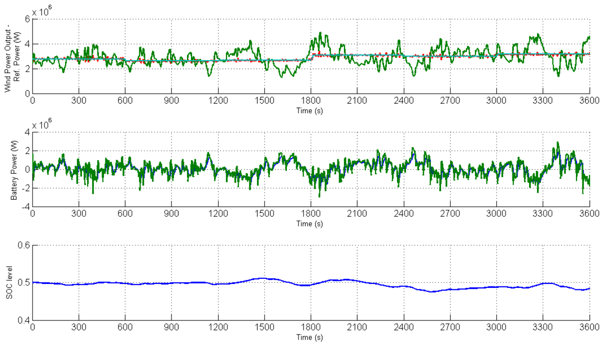

Figure 8. First diagram: Wind turbine output (green), Ref. Power Park (light blue), PCC power (red); Second diagram: Battery Output; third diagram: SOC level

No power transit at PCC

In this scenario it is supposed that at the fifth minutes the DSO commands the wind park to reduce its output to zero and to have it null for 30 minutes. It can be seen in Figure 9 how, by mean of the storage, the power at the PCC is kept to zero until the SOC level of battery reaches 0.8.

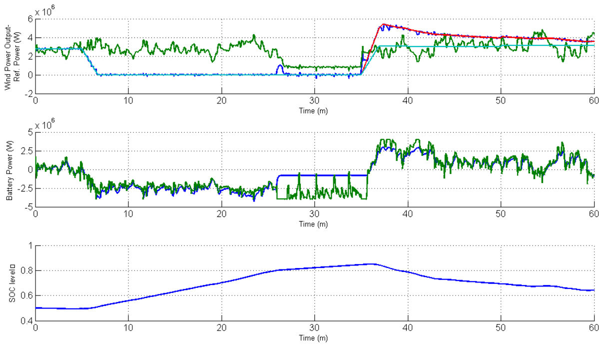

Figure 9. First diagram: Wind Turbine Power Output (green), Ref. Wind Power (blue), PCC power (red); Second diagram: Battery Output; third diagram: SOC level

At this point the battery controller has to reduce the reference output because a so intensive charge cannot be tolerated. The park controller hence sends a signal to each wind turbine that overrides the MPT controller. This signal forces the reference power to a value that causes an acceleration in the wind turbine because of the unbalance between the accelerating wind torque and the generator one. Figure 10 shows how this increase in rotational speed causes the action of the pitch control system that has to pitch the blades in order to reduce wind output.

When the DSO allows again power transit, this signal is shut down and the turbines produce again the maximum power. Moreover the battery control system forces a deep discharge of the battery in order to take the SOC far from the maximum level. As foretold this SOC feedback is needed to keep the battery in a reasonable range of values.

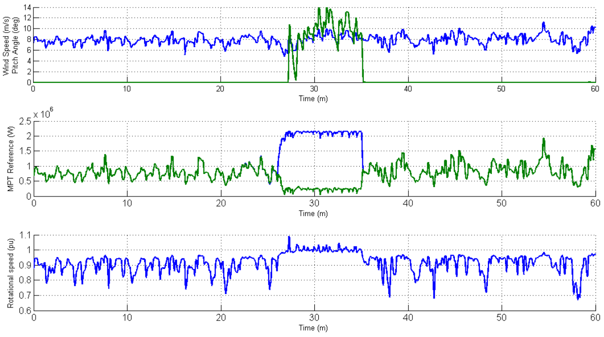

Figure 10. First diagram: Wind speed (blue), Pitch angle (green), Second diagram: MPT Ref. Power (blue), derated MPT Ref. Power (green); third diagram: Wind turbine Rotational Speed (blue)

CONCLUSIONS

The paper addressed the issues related to wind power turbulent output and to the medium voltage electric network overloading. The coupling with a storage system can grant some benefits in term of controllability of wind park output. If controlled in the right way the storage system can in fact smooth the turbulent output of wind turbines and allows to store wind power in case of orders by the DSO to reduce or to have zero power output at PCC. A detailed model of storage as well as a model of a wind turbine have been proposed. Moreover a new feature of wind turbine control, that allows to reduce their output instead of being disconnected, has also been shown.

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