Modeling and Simulation of a Short-term Storage System for Renewable Energy Sources.

Conference Paper · January 2009

Source: DBLP

3 authors:

Juan Méndez
Universidad de Las Palmas de Gran Canaria

Antonio Falcon
Universidad de Las Palmas de Gran Canaria

Daniel Hernández-Sosa
Universidad de Las Palmas de Gran Canaria

Modeling and Simulation of a Short-term Storage System for Renewable Energy Sources

J. Mendez, A. Falcon and D. Hernandez
Institute of Intelligent Systems(SIANI), Univ. Las Palmas de Gran Canaria
35017 Las Palmas, Canary Islands, Spain, Email: jmendez@iusiani.ulpgc.es

Abstract— *The integration of renewable energy sources in grid systems has a significant impact on the stability of electric power distribution. High variable energies such as wind power have a lack of stability and, to avoid short-term variations in power supplied to the grid, a local storage subsystem can be used to provide higher quality in the fed energy. This paper contains a mathematical model and a simulator focused on energy management that may be useful to evaluate the service quality, the energy efficiency and the required storage capacity.*

Keywords: Modeling Power Systems; Energy Storage; Power Management; Renewable Resources; Systems Simulation; Grid Stability

1. Introduction

The use of renewable energy sources (RES) in electricity generation has many economical and environmental advantages, but has a downside in the instability and unpredictability introduced into the public electric systems. The more important renewable sources, wind and solar power, are mainly related to the weather in a local geographic area. However, the weather is a chaotic system with limited predictability. Many countries follow two trends in the development and planning of their public electric systems; the first is the increase in the generation power from RES and the second one is the transition to open electricity markets. These two trends have a common impact on the public grids, because they both increase the number of agents in the system and the level of uncertainty in the balance between generation and load.

The use of RES reduces the economic costs due to lesser fuel consumption, and also reduce the greenhouse gas emission. However, the access of more and bigger RES electricity producers can increase the risk of fail and decrease the service quality. That risk can be reduced by increasing the power reserve based on high response gradient systems. These, e.g. diesel or hydraulic, have a high speed of change in their generated power, that is suitable to balance the frequent sudden and unpredictable changes of RES-based electricity production. Therefore, the positive impact of the use of RES on the cost of fuel consumption would have a negative impact on the global cost of electricity systems.

The control and planning of public electric systems covers a widespread set of levels, ranging from the hundred millisecond domain associated to the frequency and voltage control[1], to the yearly planning domain. Precise regulations for these levels are the concern of the national Electricity Authorities of each country as well as to supranational agencies. The EC Project STORIES[2] provides an overview of existing regulations and the respective legislative framework related to RES implementation at a European level. In each national system, the Transmission System Operator(TSO) deals with the management of the electric system in the different control and planning levels. With the increasing penetration of RES systems, the TSO becomes concerned with the impact on system stability[3].

The forecasting of RES power production is a basic tool in the reduction of these high operative reserve, which must be ready to be used. According to the practical experiences of E.ON, the largest German electric company, wind power is only as reliable as the weather forecasting[4]. If the wind power forecast differs from the actual infeed, the TSO must cover the difference by using the reserves, which must amount to 50-60% of the installed wind power. According to E.ON, the expected maximum forecast deviation is more important that the mean forecast error. This is because even if the actual infeed deviates from the forecast level on only a few days of the year, the TSO must also be prepared for this improbable eventuality and have sufficient capacity available, *spinning reserve*, for a reliable supply to still guaranteed and the correct balance between generation and load to be restored.

The Electric Authorities of many different countries have included the power forecasting in its Regulatory Norms in order to preserve the quality of the electricity supply. The planning of an Electric System requires several levels related to different time scales and whether forecasting requires also different levels. Very close short-term forecasting, or nowcasting, is the immediate prediction in a time scale ranging from some minutes to several hours. Short-term forecasting address a time scale that ranges from one to three days, while medium-term forecasting covers from four days to several weeks.

The prediction in the time scale of nowcasting can be carried out by using the time series analysis approach. The short-term scale requires the cooperation between statistical and NWP tools, in regional and mesoscale weather models. In many countries the power forecasting for RES is related to hourly periods of planning of the electricity market. All the power supplies and demands of the energy agents must be related to these hourly periods. For example, the regulations for the short-term Spanish Electricity Market comprise two steps. In the step 1 in short-term time scale, the RES producers with power greater than 10 MW must provide the power forecasting for every hourly period of a full range of 24 hours 30 hours in advance. In step 2 in the nowcasting time scale, one hour ahead of each hourly period, corrections to the previous values can be sent to the Electricity Authority. This means that at the end of the hour h, the RES producer must send the corrections for the expected value of the average power, $\widehat{P}_{h+2}$, for hour $h+2$.

The prediction based on persistence is the simplest model and is based on the assumption of a high inertia in the subjacent physical model. If $y(t)$ is the value at time t of a time series, in persistence model the predicted value for k time ahead is: $\widehat{y}(t+k) = y(t)$. The simple persistence model can be overtaken by other. more advanced, models that involve persistence-like information. A reference model to compare different forecasting models has been proposed [5], [6]. It includes very short-term information, such as persistence, and long-term information. This proposed reference model is an extension of the pure persistence defined by the linear expression: $\widehat{y}(t+k) = b + ay(t)$.

In an Electricity Market applications we have two kinds of power values, the spot power $P(t)$ and its hourly average P_h. For the TSO, the spot power is very important to ensure the system stability at any time, but in the Electricity Market the hourly average is that required to RSE agents. The reference model for wind power forecasting proposed by Madsen [6] can be applied for hourly average power such as that required in the Spanish regulation as: $\widehat{P}_{h+2} = A_0 P_h + (1 - A_0)\overline{P}$, where A_0 and $\overline{P}$ are parameters computed from large-term training information. It is difficult to beat this reference model because is based on the shortest-term information, P_h, and in the longest-term information, $\overline{P}$.

Even if the forecasting techniques for RES power were perfect, the problems that its high penetration introduce in grids would not be avoided. Figure 1 shows a power series $P(t)$ in time steps of one minute, and their hourly average P_h. That last one is the best prediction that we can achieve. Even using this ideal case, the difference between the spot power $P(t)$ and the best estimated planed power $\widehat{P}_h = P_h$ is significant. The lack of quality in the electricity production based on RES, such as wind power, must require of higher power spinning reserves that entail additional costs. If the penetration of RES based power increases significantly, those costs will be billed to the RES producer by means of penalties. These are, or will be, imposed by the Electricity Authorities associated with the lack of quality in the fed energy.

The variance shown in every hourly period can be avoided by using short-term storage systems that reduce the impact of the chaotic behavior of the local weather in the public grids. Short-term storage systems can be implemented by using different technologies such as electric batteries, hydraulic reservoirs or inertial systems. Lazarewicz and Rojas [7] identify some of the basic problems involved in frequency regulation and their solution by using large batteries of inertial systems. Drouilhet [8] presents a wind power system with a diesel generator and a short-term energy storage using electric batteries. This system focuses on the power flow management, frequency and voltage control for high penetration of wind sources, mainly in isolated rural electrical systems. Its conclusion is that in conventional power generation systems, the short-term load variations are usually small and the main power source can supply the demand, but in the high penetration wind power systems the power feed to the system is stochastic in nature and highly variable. Edsinger[9] focuses on the evaluating of the economic feasibility as well as on the general performance of wind energy systems with energy storage options.

An application where the use of storage energy systems have been used extensively is in space applications where the supply of solar power changes along the orbit. The use of hybrid system of batteries and flywheels has been proposed and simulated [10]. To avoid the inertial problems, two or more counter-rotating wheels are used to produce null angular momenta. The design of such systems requires the definition of the battery and flywheel charging control schemes and the solar array regulation. The main advantages of inertial storage systems that have been proposed for satellite and space oriented applications is its reduce mass [11], [12]. The simulation of these systems was conducted using the power model for the Flywheel Attitude Control, Energy Transmission, and Storage (FACETS), which is constructed by using blocks provided in the Matlab and Simulink packages.

This paper focuses on the modeling and simulation of energy storage systems coupled to RES producers to increase the quality of the energy feed to the public grids. Our approach is to study the energy and power management rather than the modeling and simulation associated with any specific technology, device or technical solution. We agree that a first level of a simulation can be a general one based on the power and energy flows and transfer, while a more detailed simulation of a defined solution, which must use defined models for wind farms[13] and grid interaction[14], can be achieved after the analysis of the results obtained in the power and energy oriented simulation. For example, a general simulation can provide the total amount of energy storage needed for an RES system based on its logged power data. At this stage, it does not matter which kind of technology is used in a more detailed forward modeling. This paper includes a mathematical model of power and energy transfer between the RES source, the energy storage and the

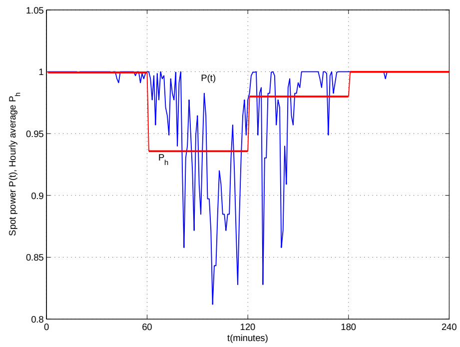


Fig. 1: Spot power and its hourly average for a wind power generator.

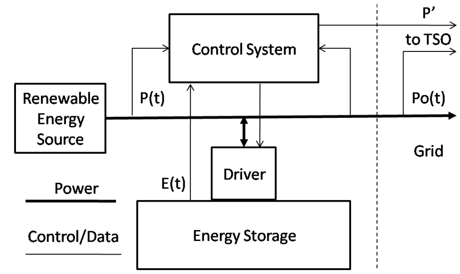


Fig. 2: The Storage and Energy Management System

public grid. A simulation based on Simulink is carried out and the results for different strategies and configurations are provided.

2. Mathematical Model

The outline of the generic model of a RES producer coupled to a energy storage and connected to a public grid is shown in Figure 2. The RES provides a power $P(t)$ that varies according the wind speed or sun radiation. The power planned to be sent to the grid in the hourly period is P', its value had been computed by means of some forecasting procedure before being sent to the TSO. The power that the system is effectively sending to the grid is $P_o(t)$. The difference $P_o(t)-P'$ is the deviation between the planned and the fed power; this difference is logged by the measurement systems of the TSO and the control system. These values will provide some quality parameters that will reduce the economic billing of the RES producer. This paper focuses only on the technical problem of the energy flows and on the measurement of the quality parameters and does not address the economic downside that is strongly dependent on the National Regulations of each country.

If no storage system is used, $P_o(t) = P(t)$, the penalties are related to the chaotic evolution of the local weather and some basic freedom degrees of the wind power system, eg. the pitch regulation of the blades. Precise forecasting procedures can reduce such impact but only partially, because most of the Electricity Markets are related to hourly periods, and one hour is too long a time period to have constant wind speed.

The National Regulations of some countries with high RES penetration have defined some quality constraints for the divergences and its economical downsides. In this paper, we adopt a simplified model: the energy sent to the grid must meet some quality constraints if penalties are to be avoided. It must be in an offset band such as $P' - \Delta \leq P_o(t) \leq P' + \Delta$. The Δ value is defined by the Grid Regulations and it can be defined as a fraction, δ, of the nominal power: $\Delta = \delta P_n$.

We define two logical conditions, the *into band* one when the output power is within the offset band, $P_o(t) \in P' \pm \Delta$, and the converse *out band* condition when the output power is outside this offset band $P_o(t) \notin P' \pm \Delta$. We can introduce some measures of energy amount and quality. The raw energy provided by the RES generator E_{res} and the energy feed in the grid E_{grid} are defined as follows:

$$E_{\text{res}} = \int P(t)dt \qquad E_{\text{grid}} = \int P_o(t)dt \tag{1}$$

If no storage system is used, both values are the same. The planned energy, E_{planne} and the energy fed into the grid outside of the quality band are expressed as:

$$E_{\text{planned}} = \int P'dt \qquad E_{\text{out}} = \int_{P_o(t)\notin P'\pm\Delta} P_o(t)dt \tag{2}$$

Moreover, we can introduce the excess or deficiency of energy feed when the system is out band as:

$$E_{\text{deviation}} = \int_{P_o(t)\notin P'\pm\Delta} |P_o(t) - P'|dt \tag{3}$$

2.1 Modeling the Storage Subsystem

A simplified model of the storage subsystem is composed of two parts: the energy storage itself and the driver or set of physical devices(electronic, electrical and mechanical) that allows the storage and recovery processes. The driver subsystem is an abstract wrapper of a complex system involving very different technologies. The energy storage can be implemented by electric batteries or hydraulic reservoir, while the driver can be a system of power electronics or water turbines and pumps. We will suppose that the energy amount is an observable variable by mean of some suitable sensors. Let $E(t)$ and $E_{\max}$ be the stored energy and the maximum energy capacity of the storage subsystem, verifying: $0 \leq E(t) \leq E_{\max}$. The main issue in the modeling is the energy conservation equation. However, a detailed model is required to take account of the efficiency in the storage/recovery processes. The changes in the stored energy are defined as:

$$\frac{dE}{dt} = \dot{E}_{\text{in}} - \dot{E}_{\text{out}} - \dot{E}_{\text{loss}} \quad (4)$$

where $\dot{E}_{\text{in}}$ is the input rate in the storage phase, $\dot{E}_{\text{out}}$ is the rate in the energy recovery phase and $\dot{E}_{\text{loss}}$ is the rate of energy lost in the storage itself. The increase in the stored energy is the following when $E < E_{\max}$:

$$\dot{E}_{\text{in}} = \begin{cases} \eta_s[P(t) - P'] & P(t) > P' + \delta_1 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

where η_s is the efficiency of the driver in the storage phase, and $\delta_1 \leq \Delta$. The decrease of energy in the recovery phase is the following when $E > 0$:

$$\dot{E}_{\text{out}} = \begin{cases} \frac{1}{\eta_r}[P' - P(t)] & P(t) < P' - \delta_2 \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

where η_r is the efficiency of the recovery phase and $\delta_2 \leq \Delta$. It is possible to model some losses as a ratio of the stored energy:

$$\dot{E}_{\text{loss}} = -\lambda E \quad (7)$$

where λ is a decay factor. The efficiency factors η_s and η_r in a hydraulic system are the efficiency of the pump in storage phase and the turbine in the recover one respectively. The output power that is sent to the grid, $P_o(t)$, is:

$$P_o(t) = \begin{cases} P' & P(t) > P' + \delta_1 \wedge E < E_{\max} \\ P' & P(t) < P' - \delta_2 \wedge E > 0 \\ P(t) & \text{otherwise} \end{cases} \quad (8)$$

One additional constraint can be introduced by defining an upper value for the maximum gradient for energy change, $|dE/dt| < D\text{max}$, which is the maximum power of the driver system.

3. Simulation

We have designed a basic object to simulate storage related problems with limited upper and lower capacities. This basic object is related to the following differential equation involving $x(t)$ as the data, which is the rate of change of the stored value, and $y(t)$ which is the stored value itself:

$$\frac{dy}{dt} + \lambda y = x(t) \qquad y(t) \in [0, y_{\max}] \qquad \left|\frac{dy}{dt}\right| \leq d_{\max} \quad (9)$$

where λ, $y_{\max}$ and $d_{\max}$ are constants. Positive values of $x(t)$ mean increasing the $y(t)$ value, which constitutes a storage phase while negative values of $x(t)$ mean decreasing the $y(t)$ value, which corresponds to recovery phase. Although it seems a linear system, it becomes nonlinear due to the constraints in the solution. This system has no solution for all values of $x(t)$. For example, if the storage is empty, $y = 0$, and we try to recover at the rate value $x(t)$, the value of $dy/dt = 0$ because it can not recover from an empty storage; the previous differential equation becomes: $0 + \lambda 0 = x(t)$, which means that only the value: $x(t) = 0$ is a consistent solution in this case. We will distinguish between the $x(t)$ value as a request and $x'(t)$, which verifies the Equation (9), as an effective value. Despite the similarities, it is verified that: $x'(t) \neq x(t)$ in the general case.

As in the FACETS system for space application[11], [12], we have used Simulink blocks to model the basic storage operations. To avoid some problems in the integration of the differential equation, we designed a block based on a simple implementation of the Backward Euler integration[15]. This block implements the following algorithm:

1) Compute a candidate value y_1 for $y(t)$ as in the ordinary linear system:

$$y_1 = \frac{x(t)\Delta t + y(t - \Delta t)}{1 + \lambda \Delta t} \quad (10)$$

2) Constrain the candidate value y_1 in the permitted range defined by the range $[y_{\text{lower}}, y_{\text{upper}}]$, where:

$$y_{\text{lower}} = \max(0, y(t - \Delta t) - d_{\max}\Delta t) \quad (11)$$
$$y_{\text{upper}} = \min(y_{\max}, y(t - \Delta t) + d_{\max}\Delta t) \quad (12)$$

Let y_2 be the resulting value which can be different from y_1. If the storage system is in the linear zone, in other words, it is neither full nor empty, the two values are the same.

3) Let $y(t) = y_2$
4) Computed the $x'(t)$ value as:

$$x'(t) = \lambda y(t) + \frac{y(t) - y(t - \Delta t)}{\Delta t} \quad (13)$$

If the system is in the linear zone, it is verified that $x'(t) = x(t)$. The value of $x(t)$ is the requested rate of storage and the value of $x'(t)$ the effective one. They are different if the system is constrained due to the dimensions of the storage or the limit in its maximum gradient. We have tried other implementations based on standard Simulink blocks, but they generated some glitches and errors in the simulation. The problem is that the Equation (13) involves the computation of a derivative and the Equation (10) involves the computation of an integral. Although in mathematics the derivative of the integral of a function is the same function, in discrete simulation it is not true at all. If the computation of the integral and derivative are accomplished in different blocks, some error will be generated. To avoid this, the best approach is to compute both, the derivative and the integral, in the same block. Based on this basic block we have constructed what solves the problem with the efficiency parameters:

$$\frac{dy}{dt} + \lambda y = \eta\, x(t) \quad (14)$$

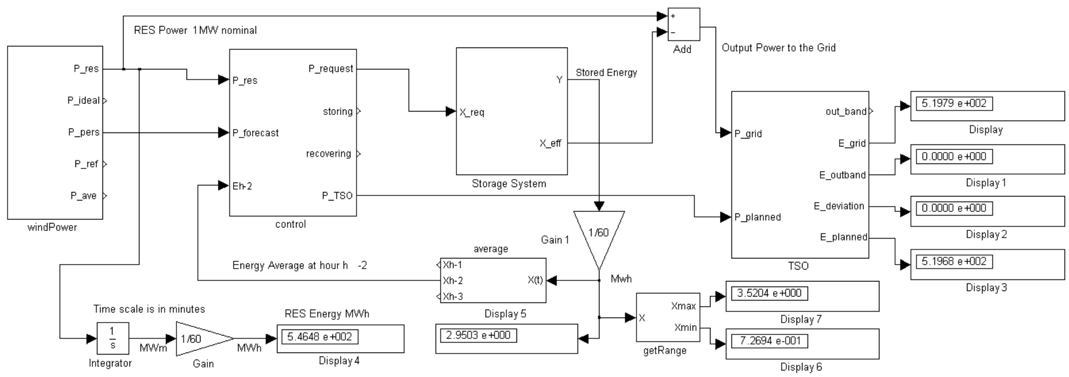


Fig. 3: Blocks in the modeling and simulation

where the efficiency depends on the direction of the storage/recovery process.

$$\eta = \begin{cases} \eta_s & x(t) \geq 0 \\ \frac{1}{\eta_r} & x(t) < 0 \end{cases} \tag{15}$$

Figure 3 shows the blocks of the modeling and simulation systems. The block Storage implements the defined model of a generic storage system focused on the power and energy management. The data source of the system is provided by the block windPower, which provides the spot power and some model of basic forecasting. It is implemented as a wrapper of a MATLAB file containing the power series in time steps of one minute and the whole series comprises 33 days. These data are obtained from wind speed series and a transfer function for a pitch regulated wind generator with values of 4 m/sec and 13 m/sec for cut-off and saturation respectively. The power is constant at the nominal value to the 25 m/sec limit, which is never reached in the series. The block windPower also provides some values of three basic forecasting models for hourly periods. The simplest model is the persistence model, which provides the predicted value: $\widehat{P}_{h+2} = P_h$. The second forecasting model is that suggested as the reference model [5], [6], which provides the predicted values: $\widehat{P}_{h+2} = a_2 P_h + (1 - a_2)\overline{P}$, where $\overline{P}$ is a long-term average of the available data of source power and a_2 is the correlation coefficient between P_h and P_{h+2}. These values in our case are: $a_2 = 0.82$ and $\overline{P} = 0.68$. The last forecasting model is not actually a forecasting, we called it the ideal forecasting because is the best, and unreal, prediction that can be achieved: $\widehat{P}_{h+2} = P_{h+2}$. It is included only for testing purposes, because this ideal and unreal forecasting does not solve the problems concerning the lack of quality in the power fed to the grid.

By simulating the systems we have experienced that the storage system becomes systematically empty or full depending on the configuration parameters. In those states the system can neither store nor recover energy to regulate the output power, because it runs into its non-linear zones. To avoid that the energy storage systematically becoming full or empty, a factor of innovation can be introduced in the planned power k hours ahead as:

$$\widehat{P}^{(inv)}_{h+k} = \widehat{P}_{h+k} + k_1(E_h - E_{\mathrm{obj}}) \tag{16}$$

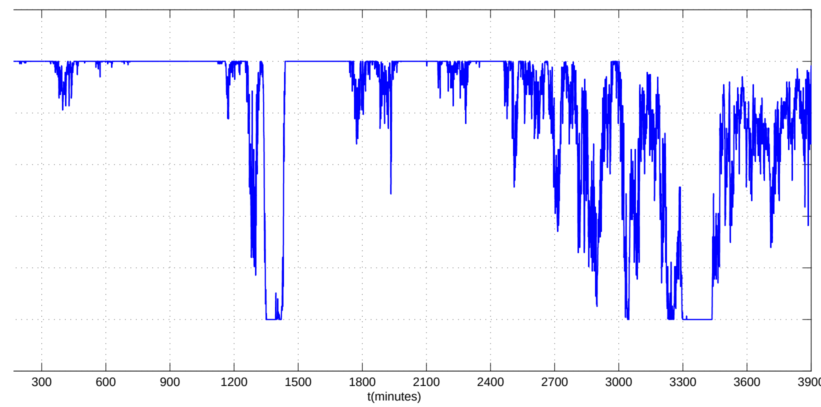
where E_h is the average stored energy in the h hour, k_1 is a small constant parameter and E_{obj} is some objective level of storage. This strategy corrects the systematically biases and non linear states.

The Control block implements the storage strategy. An additional parameter has been added to avoid feeding power to the grid at power lower than a defined minimum value. This $P_{\min}$ value and the lower threshold δ_2 in Equation (8) mean that no power is fed to the grid lower than the $P_{\min} - \delta_2$ value. It computes the planned power for each two hours ahead period and sends it to the TSO block. At every simulation step it computes the power balance and sends the requested power to the storage system to be stored or recovered. It uses the data provided by the Average block that implements the feedback innovation term to correct the states of bias.

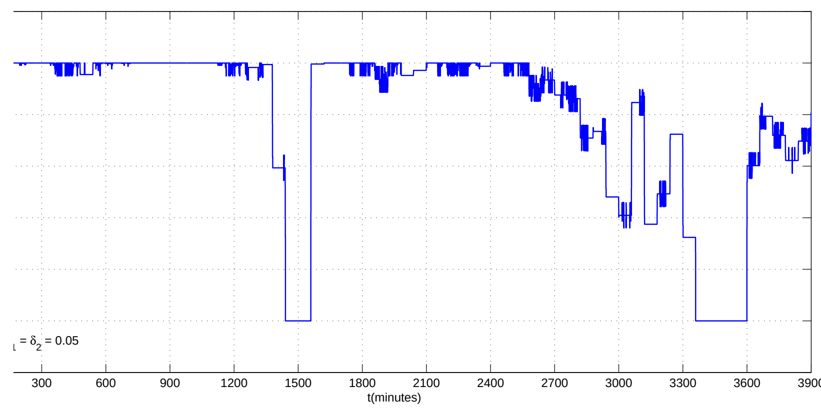
The TSO block is mainly a logger of the power feed to the grid. It detects the *in band* and *out band* states according to the Δ parameter, which is defined in the Regulatory Norms of the Electricity Authority, and the planned power for each Market period. The energy feed in the different states is computed by integrating the power.

4. Results

The first test performed on the system was the computation of the results of the TSO block without any storage system. This test provided the raw quality factors corresponding to the RES generator. The test was based on a time series of 791 hours. The first three columns on Table 1, with the label no storage(NS), contain the energy values for the three forecasting strategies, P(Persistence), R(Reference Model) and I(Ideal). An unexpected conclusion that can be obtained is that the Reference Model introduced by Nielsen[5] and Madsen[6] has the worst quality values. It has been claimed



(a) RES Power



(b) Power sent to grid

Fig. 4: Simulation results, in each hourly period the power fed to the grid can change at most $\pm 5\%$ of the nominal power.

Table 1: Quality Parameters

Energy(MWh)	P(NS)	R(NS)	I(NS)	P	R	I	P(In)	R(In)	I(In)
E_{grid}	546.48	546.48	546.48	526.89	521.56	540.14	519.76	519.73	536.46
E_{out}	270.05	471.36	174.41	7.88	1.25	4.37	0.00	0.00	0.00
$E_{\text{deviation}}$	110.90	132.80	41.84	14.20	5.00	1.58	0.00	0.00	0.00
E_{planned}	546.51	546.63	546.48	540.93	525.81	540.90	519.68	518.67	534.78
E_{init}	-	-	-	3.00	3.00	3.00	3.00	3.00	3.00
E_{end}	-	-	-	0.43	2.11	0.01	2.95	3.32	2.86
E_{max}	-	-	-	3.00	5.00	3.42	3.52	3.59	3.48
E_{min}	-	-	-	0.00	0.00	0.00	0.73	0.92	2.45

P: Persistence, R: Reference Model, I: Ideal Forecasting, NS: No Storage, In: Innovation

that it has less error in wind power forecasting than the Persistence Model but it performs worse in terms of the quality of the energy supplied to the grid.

When the storage system is used, the energy provided by the RES generator is managed by the control system. It is stored and recovered according to the defined strategy. It means that some energy amount will be lost due to the efficiency of the storage driver. The use of the storage system provides more quality in the power fed to the grid, at the cost of lower amount of feed energy. The more quality, the less energy is an approach that will be economically feasible depending on the structure of prices, penalties and subsidies of each country.

Figure 4 shows the power for a simulation. Subfigure 4a shows 3900 minutes of the power provided by the RES generator. Subfigure 4b shows the power fed to the grid with a storage system. The parameters for the control block are: $\delta_1 = \delta_2 = 0.05$, $k_1 = 0.1$, $E_{obj} = 3\,\mathrm{MWh}$ and $P_{\min} = 0.25\,\mathrm{MW}$. The last of those means that no energy is fed with a power lower than $P_{\min} - \delta_2 = 0.2\,\mathrm{MW}$. The parameters of the storage system are $E_{\text{int}} = 3\,\mathrm{MWh}$, $E_{\max} = 5\,\mathrm{MWh}$, $\lambda = 0$ $\eta_r = \eta_s = 0.9$ and no constraint is imposed in the maximum allowable gradient. Figure 4 shows how the power holes of the RES generator are time-delayed in relation to the fed power. This allows the TSO to have the planned power two hours in advance, thus avoiding uncertainty in the planning od the public electricity system.

Table 1 contains the results for a large simulation, the same parameter previously considered with a lower efficiency: $\eta_r = \eta_s = 0.8$, which means a global efficiency of $\eta_s \eta_r = 0.64$. The columns without the label innovation(in) do not use the innovation factor, which means: $k_1 = 0.0$. Other included data are the values of the initial and final energy, as well as the maximum and minimum energy values.

In the columns without the innovation term, the Reference Model performs better than the other forecasting. It has the lowest values in out band and deviation energy. However, it was the more unstable because the storage became full and empty in the simulation. The last three columns have the best performance in quality. The storage was neither full nor empty, and also the final storage capacity was also close to the initial one. This means that the storage was always in the linear zone and the out band and deviation energies were null. However, the energy amount fed to the grid was lower in the three cases than in the same strategies in the previously considered groups.

In the performed experiment, which concern to 1 MW of power, the storage of 5 MWh in capacity was sufficient except in the case of the Reference Model without innovation, where there is an overflows. These results are consistent with the analysis by Butler[16] that evaluated the storage needed for several tasks in the electric system. For spinning reserves between 10-100 MW that author estimated about one half hour; for local frequency regulation related to 1 MW one hour and for a renewable application of 1 MW, 1-4 hours, equivalent to 1-4 MWh in line with the simulated results.

5. Conclusion

The higher penetration of the RES in the future will introduce high disturbance into the electric systems by increasing the risk of instability. This risk can be avoided by increasing the spinning reserves; that is, by increasing the cost of the public electricity systems. The Electricity Regulations would move toward increasing the effects of the quality parameters in the system of prices and penalties. In addressing those problems, we have defined a mathematical model for energy storage based on general parameterized systems and also constructed a simulator focused on the management of the power and energy. This model can be used as a first level approach to simulate storage systems. With this approach, we avoid the device dependent details to obtain general conclusions about strategies, storage capacity, quality and efficiency. The simulator provides precise data about the increase in quality parameters and the corresponding decreasing in the amount of energy fed to the grid.

Acknowledgment

This research was partially supported by the Autonomous Government of Canary Islands, grant PI2007/039. The authors would like to thank to the Instituto Tecnológico de Canarias(ITC) for the use of the wind speed series acquired from its facilities in Pozo Izquierdo, Gran Canaria Island.

References

[1] I. Erlich, W. Winter, and A. Dittrich, “Advanced grid requirements for the integration of wind turbines into the German transmission system,” in *IEEE Power Engineering Society General Meeting*, 2006, pp. 7–13.

[2] E. Panteri, “EC Project STORIES. Set of the existing regulations and legislative framework related to RES implementation,” http://wwww.storieproject.eu, 2008.

[3] P. B. Eriksen, T. Ackermann, H. H. Abildgaard, P.Smith, W. Wintera, and J. M. R. Garcia, “System operation with high wind penetration,” *IEEE Power and Energy Magazine*, vol. 3, no. 6, pp. 65–74, 2005.

[4] E.ON-Netz, “Wind Report 2004,” http://www.eon-netz.com, EON, Tech. Rep., 2004.

[5] T. S. Nielsen, A. Joensen, H. Madsen, L. Landberg, and G. Giebel, “A new reference model for wind power forecasting,” *Wind Energy*, vol. 1, pp. 29–34, 1998.

[6] H. Madsen, “EC Project ANEMOS: A protocol for standardizing the performance evaluation of short-term wind power prediction models,” Technical University of Denmark, Tech. Rep., 2004.

[7] M. L. Lazarewicz and A. Rojas, “Grid frecuency regulation by recycling electrical energy in flywheels,” in *IEEE Power Engineering Society General Meeting*, vol. 2, 2004, pp. 2038–2042.

[8] S. Drouilhet, “Power flow management in a high penetration wind-diesel hybrid power system with short-term energy storage,” NREL, Tech. Rep. CP-500-26827, July 1999.

[9] A. W. Edsinger, A. W. Warren, L. H. Gordon, and G. C.Chang, “SIMWEST - a simulation model for wind energy storage systems,” in *Proceedings 13th Intersociety Energy Conversion Engineering Conference*, 1978, pp. 2108 – 2114.

[10] B. G. Beaman and G. M. Rao, “Hybrid battery and flywheel energy storage system for leospacecraft,” in *The Thirteenth Annual Battery Conference on Applications and Advances*, 1998, pp. 113 – 116.

[11] J. L. Fausz and D. J. Richie, “Flywheel simultaneous attitude control and energy storage using a VSCMG configuration,” in *Proceedings IEEE International Conference on Control Applications*, 2000, pp. 991 – 995.

[12] B. C. Wilson, B. Babuska, C. Potter, and J. L. Fausz, “Power system design for a spacecraft simulator using energy storage flywheels,” in *3rd International Energy Conversion Engineering Conference*, 2005.

[13] J. O. G. Tande, E. Muljadi, O. Carlson, J. Pierik, A. Estanqueiro, P. Sørensen, M. OŠMalley, A. Mullane, O. Anaya-Lara, and B. Lemstrom, “Dynamic models of wind farms for power system studies. IEA wind annex XXI,” IEA, Tech. Rep., 2007.

[14] A. D. Hansen, P. Sørensen, F. Blaabjerg, and J. Becho, “Dynamic modelling of wind farm grid interaction,” *Wind Engineering*, vol. 26, no. 4, pp. 191–208, 2002.

[15] *Simulink 7 Reference*, The MathWorks Inc., 2008.

[16] P. C. Butler, “Battery storage for utility applications: Phase I - oportunities analysis,” Sandia National Laboratories, Tech. Rep. SAND94-2605, October 1994.