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A Comparison between a Hydro-wind Plant and Wind Speed Forecasting using ARIMA Models

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Abstract. In this paper, we will present a comparison between two options for harnessing wind power. We will first analyze the behaviour of a wind farm that goes to the electricity market, having previously made a forecast of wind speed while accepting the deviation penalties that these may incur. Second, we will study the possibility of the wind farm not going to the market individually, but as part of a hydro-wind plant.

Keywords: Hydro-wind plant, Optimal control, Wind speed, Forecasting, ARIMA models
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INTRODUCTION

Spain has become the foremost country in the world in which wind power has become the leading electricity generating technology over an entire year (2013). This boom is mainly due to new regulations that allow wind farms to go to the market to sell the energy generated by their facilities. If wind farms offer in the pool, they will prepare their offers and schedule their power production. However, a major problem exists: the unpredictability of wind farm production. Forecasting errors lead to the wind farm incurring financial losses, known as deviation penalties.

In two previous papers, [1] and [2], the authors addressed the combined optimization of a pumped-storage hydro-plant and a wind farm. In both papers the authors considered a fixed-head model for the pumped-storage hydro-plant. This is the more suitable model when very large hydro-plants are considered, but is not the most suitable for the usual design size of a hydro-wind plant. Furthermore, weather forecasting was carried out in both papers with certain simplifications. In [2], we assumed that the deviations are a certain % of the wind power over the optimization interval, but did not carry out prior studies to calculate them; while in [1], Monte-Carlo simulations were performed considering the stochastic characteristics of the wind power.

This paper will make three substantial improvements with respect to these previous papers. First, we will consider variable-head hydro-plants, a much more realistic model for the case at hand. Second, we will consider a different plant hydro-wind configuration to those already presented in [1] and [2]. Third, in this paper we will assess the applicability of ARIMA models to the time series of hourly average wind speed. Moreover, we will review the main available functions for time series analysis and forecasting implemented in the R language for statistical computing [3].

SPANISH ELECTRICITY MARKET

A key aspect is that of knowing the time horizon for our forecasts. We accordingly need to know how the Spanish electricity market works. The Spanish electricity market [4] comprises a set of transactions organized in several sessions, with the *spot market* and *intraday market* fixing the forecast horizon. The day-ahead market in the Spanish wholesale electricity market is organized as a set of twenty-four simultaneous hourly auctions. The market operator performs the matching of offers, while the spot market closing time is 12 noon on day D-1. The aim of the intraday market, on the other hand, is to deal with adjustments to the *feasible spot schedule*. The intraday market is currently divided into six sessions. The horizons that our wind forecasts must cover range from $12-36$ hours, which should cover spot market offers $3-12$ hours after the last intraday session.

Furthermore, we also need to bear in mind that if wind farms offer in the pool, they will prepare their offers taking into account the unpredictability of wind farm production. Forecasting errors lead to the wind farm incurring financial losses, known as deviation penalties. Let us denote by $p^+(t)$ the price the market pays for the over-generation deviation. In the case of under-generation, we shall take into account the fact that we shall not be paid for the power we do not take to the market and that we shall also incur a penalty for not fulfilling what was agreed on. Let us denote by $p^-(t)$

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the price we must pay for the under-generation penalty. It is usual (and close to reality) to consider that:

$$p^{+}(t) = 0.6p(t); \;\; p^{-}(t) = 0.15p(t) \tag{1}$$

where $p(t)$ is the clearing market price.

FORECASTING WIND SPEED METHODS

Many methods have been developed to predict wind speed [5]. In recent years some new studies based on ARIMA models [6] have been carried out to forecast wind speed. Basically, in ARIMA models the forecasting of wind speed depends not only on the values of this speed in the more or less recent past according to the autoregressive component, but may also be a function of the residuals of past forecasts, which correspond to those hours prior to the one we aim to forecast. For a stationary time series, the ARIMA model (p,d,q) is represented as:

$$x_t = \sum_{i=1}^{p} \varphi_i x_{t-i} - \sum_{j=1}^{q} \theta_j a_{t-j} + a_t \tag{2}$$

where x is the time series of wind speed data and x_{t-i} is the $(t-i)$th data, a_t is a random time series of white noise (random uncorrelated variables with average value zero and variance σ_a^2), while φ_i and θ_j are the autoregressive and moving average parameters, respectively. In this paper, we have used the forecast package contained in R [7]. This package includes an automatic univariate forecasting method [8] by means of the function: *auto.arima {forecast},* which obtains the best fit of the ARIMA model to a univariate time series. To check the efficiency of the forecast, we will consider the mean absolute percentage error (MAPE), defined as:

$$MAPE = \frac{100}{n} \cdot \sum_{t=1}^{n} \left| \frac{A_t - F_t}{A_t} \right| \; [\%] \tag{3}$$

where n is the number of data, A_t is the actual value and F_t is the forecast value.

NUMERICAL RESULTS OF FORECASTING WITH THE R PACKAGE

Let us now see a summary of the results obtained using the forecasting functions implemented in the R package. The analysis was performed using data collected on an off-shore station located in Cape Peñas, Asturias (Spain) [9]. A wind speed forecast was made for each of the 24 hours in day D, using the 24 hours of day D-1 as data. 30 days were analyzed from the months of May to June 2011. The MAPE of the tests was highly variable: 24.55, 5.57, 21.23, 17.74, 24.14, 51.3, 52.31, 31.6, 66.1, 10.44, 41.32, 31.7, 19.79, 34.51, 44.34, 18.55, 22.13, 45.74, 35.85, 18.56, 70.01, 28.21, 18.92, 39.27, 21.62, 67.97, 19.54, 16.24, 12.6 and 12.15, such that it is too high on some days to be considered satisfactory. However, we should also consider a very important fact: forecasts of wind power are derived from forecasts of wind speed. In traditional models, the power in the wind is proportional to the area of the wind rotor blades being swept by the wind, the cube of the wind speed, and the air density (which varies with altitude). The formula usually used is:

$$P = \frac{1}{2} \rho A V^3 \tag{4}$$

where, P is power in watts (W), ρ is the air density in kilograms per cubic metre (kg/m^3), A is the swept rotor area in square metres (m^2), and V is the wind speed in metres per second (m/s).

The fact that the power is proportional to the cube of the wind speed is very significant. For example, an acceptable MAPE of 20% in the forecast of wind speed becomes a poor 72.8% in the forecast of generated power. In the next section, therefore, we propose the comparison with a hydro-wind power plant.

OPTIMIZATION OF A HYDRO-WIND PLANT WITH A VARIABLE-HEAD MODEL

In two previous papers, [1] and [2], the authors considered a fixed-head model for the pumped-storage hydro-plant. This is the most suitable model when very large hydro-plants are considered, but is not so appropriate for medium-sized plants. In this paper we consider variable-head hydro-plants, in which the hydro-plant's hydraulic generation $P(t,z(t),\dot{z}(t))$ is a function of $z(t)$ in (m^3), the volume discharged up to the instant t, and $\dot{z}(t)$, the rate of water discharge at the instant t.

Furthermore, in [1] we only compensated for over-generation deviations in wind power. We used the surplus wind power generated on day D to pump water, but under-generation penalties were not compensated for. In [2] we proposed a configuration in which, in those cases in which the original schedule of the hydro-plant was to pump, it was impossible to take action via the wind farm.

To avoid the drawbacks of the configurations presented in [1] and [2], in this paper we will consider a new hydro-wind plant: the wind farm does not sell energy on the market, but uses the generated power to pump water to the upper reservoir of the pump-plant. Besides, the hydro-plant only pumps to harness wind power, never when it is operating optimally.

If we assume that b is the volume of water (pumped by the wind farm) that must be discharged during the entire optimization interval $[0,T]$, the following boundary conditions will have to be fulfilled: $z(0)=0$, $z(T)=b$. We also consider P to be bounded by technical restrictions: $P_{\min} \leq P(t,z(t),\dot{z}(t)) \leq P_{\max}$. The objective function the hydro-plant has to deal with is thus given by the revenue during the optimization interval $[0,T]$, where revenue is obtained by multiplying the hydraulic production, P, by the clearing market price, $\pi(t)$, at each hour t :

$$\max_z F(z) = \max_z \int_0^T L(t,z(t),\dot{z}(t))dt = \max_z \int_0^T \pi(t)P(t,z(t),\dot{z}(t))dt \tag{5}$$

To obtain the optimal solution, the problem is formulated in this paper within the framework of Optimal Control Theory [10]. We present the problem considering the control variable $u(t)=P(t,z(t),\dot{z}(t))$ and the state variable to be $z(t)$. Let us term the coordination function of $z \in \Omega$ the function in $[0,T]$, defined as follows:

$$\mathbb{Y}_z(t) = L_{\dot{z}}(t,z(t),\dot{z}(t)) \cdot e^{-\int_0^t \frac{P_z(s,z(s),\dot{z}(s))}{P_{\dot{z}}(s,z(s),\dot{z}(s))}ds} \tag{6}$$

Using Pontryagin's Maximum Principle [10], the following theorem is easily proved:

Theorem. *If z^* is a solution of our problem, then $\exists K \in \mathbb{R}^+$ such that:*

$$\mathbb{Y}_{z^*}(t) \;\; is \;\; \begin{cases} \leq K & if \;\; P(t,z^*(t),\dot{z}^*(t)) = P_{\min} \\ = K & if \;\; P_{\min} < P(t,z^*(t),\dot{z}^*(t)) < P_{\max} \\ \geq K & if \;\; P(t,z^*(t),\dot{z}^*(t)) = P_{\max} \end{cases} \tag{7}$$

On the basis of this theorem, the optimization algorithm that leads to the determination of the optimal solution for the hydro-plant is easy to construct. It should be stressed that the result obtained in this paper when modeling the hydro-plant as a variable-head load is completely different to that obtained in [1] and [2], in which a fixed-head model was used. Due to the control u being linear, the latter model leads to bang-bang type solutions and also to a different optimization algorithm.

COMPARISON AND CONCLUSIONS

With the aid of the algorithm presented here, a program was written using the Mathematica package. We are now in a position to analyze the combined optimization of a pumped-storage hydro-plant and a wind farm. In this section we will analyze whether it is in the interest of wind farms to go to the market. There are a number of factors that influence the final result, like for example: the efficiency of the hydro-plant, the volume of water available, deviation penalties and wind power production. The full results are very extensive and cannot be presented in this extended abstract. They can be summarized, however, by concluding that both configuration options appear interesting, although the choice of the hydro-wind plant offers more advantages under the most common working conditions. The system is highly sensitive to numerous factors and each company must carefully assess particular situations that may result in variations in the optimum configuration. Our study provides a useful, simple and efficient tool for taking such a decision.

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