WIND GENERATION AND HYDROGEN STORAGE MANAGEMENT IN LIBERALIZED ELECTRICITY MARKET

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ABSTRACT

Intermittent renewable energy sources are promising to be the future of electricity generation. However their lack of sufficient predictability decreases their energy value considering current framework of electrical markets. The coupling of Wind Energy Conversion System (WECS) with a storage medium could improve the programmability of such generation plants in electrical markets.
In this paper an optimization algorithm, employing dynamic programming, has been implemented in order to find the optimal operation of such plants and to perform an economical analysis too. The developed optimization tool has been applied in a case study.
The presented approach can be very useful in order to foster the penetration of wind power as well as the hydrogen use as a storage medium in the deregulated market area

INTRODUCTION

Among renewable power sources wind represents the most attractive one considering the growth rate of world installed capacity during the last ten years (4.8 GW 1995 – 59 GW 2005) [1].
Today wind exploitation is assuming a relevant role in power systems, but due to its uncertainty TSOs have to develop grid as well as despatching methodologies. Moreover with the electrical deregulation their stochastic nature leads to a less competitiveness in the electrical market, especially where the imbalances are settled with penalties.
Therefore it can be interesting to assess the possibility of joining a WECS with a storage system, and in particular with hydrogen because it is envisaged as the future energy carrier for renewable sources.
Some publications are related to this topic. In particular Korpaas et al. focused their attention in studying the optimal operation of a storage system with an intermittent generation plant showing, in an energy market context, the added value to wind energy of this solution [2]. Castronuovo et al. proposed an optimization algorithm to assess the optimal daily strategy of a wind power plant joined with a pumped hydro and considering remuneration tariff instead of market hourly prices [3]. Bathurst e Strbac proposed a general algorithm to optimize a storage system joined with a wind farm considering imbalance penalties, hourly market fluctuation and market gate closure [4].
In these publications it is well examined the effect of storage in wind farm revenues, however it is not well considered the effect of plant components with respect to the cost-effectiveness of the global system, useful especially in operation planning.
In this paper a possible coupling of wind energy conversion system and hydrogen storage (WECS/H_2) has been studied in its effective operation. The plant model consists of a storage system, coupled with a WECS interconnected to the electrical grid, whose components (electrolyser, hydrogen tank and fuel cell) have been sized using a linear approach [5]. Some hypothesis have been taking into account for the system management and a dynamic programming algorithm has been implemented in order to maximize the market revenues with an optimal set of control variables.
This algorithm have been used considering the Italian Power Exchange (IPEX) and an existing wind farm in Sicily as a case study.

WECS/H_2 OPTIMIZATION TOOL

As it shown in Figure 1, the input data, historical market prices and measured wind energy, are pre-processed into a forecasting module before entering in the management tool.

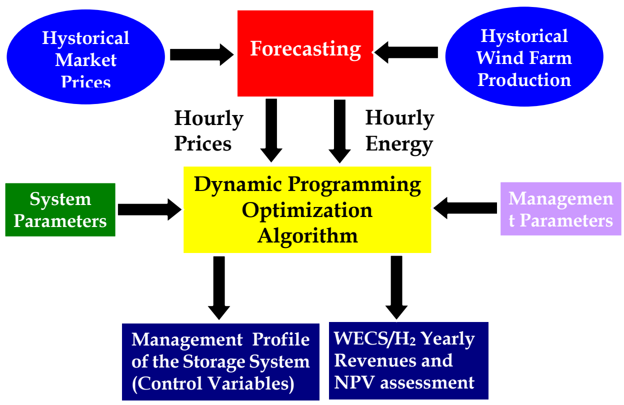

Figure 1. Outline of WECS/H_2 optimization tool

This module contains different forecasting methods such as the simple exponential smoothing (SES), the Markov chains approach and a combination of them [6]. They are used considering the electrical market gate closure as a parameter, therefore the historical data processing is adjustable depending on the chosen market. Besides these input data, the optimization module needs some parameters to be fixed. In particular the system parameters concern

with the components efficiencies, their maximum and minimum operating power and storage capacity as well. While the management parameters consists of economic indicators such as the overall plant cost, discount rate, initial investment, plant's life, economic opportunities (i.e. green certificates).
Once that simulations are performed with the same parameters of sizing step, it can be possible to verify the effectiveness of the previous assessment with a set of prices and wind energy that are nearer to the real.
The dynamic algorithm allows to include also not linear technical constraints in the system model and not to evaluate a priori the better time to store or to release energy.
The output of the optimization tool are the management profile, i.e. the control variables of the storage system, and the yearly additional revenues determined by the use of the storage plant.
The entire optimization tool has been developed in Matlab®.

SYSTEM MODEL

In order to perform a time series simulation of the plant it is necessary to adopt some useful hypotheses. They are expressed by the following:

1. The storage system is added to an existing wind farm with its energy production data,
2. The optimization algorithm is referred to a year considering twelve typical monthly weeks,
3. The resolution time for energy and prices is one hour,
4. The storage system cannot simultaneously store energy from the wind farm and deliver it to the grid,
5. After the optimization period the storage level must be the same as the beginning one (storage balance).

For the economical issue the net revenues between the energy released from the storage (market peak-hours) and the missed gain for the energy stored (market off peak hours) are considered. The energetic balance of the system is represented in the following figures:

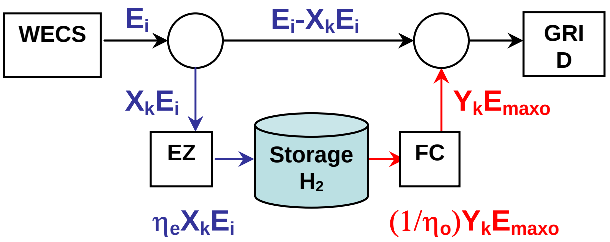

Fig. 2. Balance of the WECS+H_2 system

where:

- E_i is the hourly energy delivered by WECS,
- E_{maxo} is the maximum energy deliverable by the FC system,
- η_e is the efficiency of the EZ, Converter and Gas Compressor,
- η_o is the efficiency of the FC and Inverter,
- X_k is the fraction of the maximum input hourly energy for the electrolyser chosen by the algorithm,
- Y_k is the fraction of the maximum output hourly energy for the fuel cell system chosen by the algorithm.

It is important to notice that, in the proposed optimization problem the releasing time and storage time are not fixed, but it is the optimization algorithm that selects the storage systems operation
The objective function that maximizes the revenues along the year is developed in the next section.

OPTIMIZATION ALGORITHM

Instead of a simple linear approach [5], a dynamic programming algorithm is developed to assess the effectiveness of the previous approach and to include some improvements such as the lower limit in the input energy of the electrolyser.
With this approach the main problem is divided into stages, with a policy decision required at each stage. Moreover each stage has a number of states associated with the beginning of that stage. The effect of the policy decision at each stage is to transform the current state to a state associated with the beginning of the next stage. The solution procedure is designed to find an optimal policy for the overall problem [7].
With regard to the considered optimization problem each state is assumed to be equal to a certain storage level (S), included between maximum capacity and the empty storage condition, while the different stages model the hours that form the optimization time window. The transition from a generic state (h) of a stage (i) to a state (k) of the next stage (i+1) is reported in the following figure:

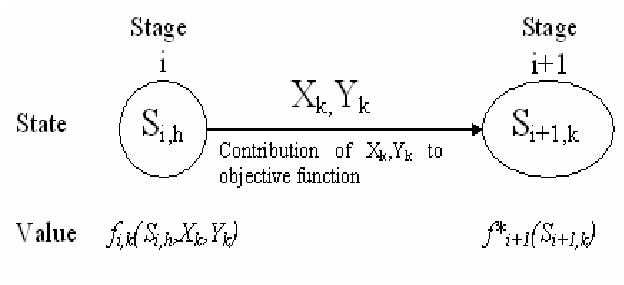

Fig 3. Basic structure of dynamic programming

The relation between one state and its previous is expressed by the following equation:

$$S_{i+1,k}=S_{i,h}+\eta_e X_k E_i-(1/\eta_o) Y_k E_{maxo}$$

$$\forall\ h,k=1,...,m;\ \forall\ i=1,\ldots,N;$$

The optimal policy decision for each transition from a stage to another is modelled by the following recursive relationship where is the revenues from the storage system:

$$f_i^*(S_{i,h})=\max_{X_k Y_k} f_{i,k}(S_{i,h},X_k,Y_k)=f_{i,k}(S_{i,h},X_k^*,Y_k^*)$$

where:

$$f_{i,k}(S_{i,h},X_k,Y_k)=\left(Y_k E_{mo}-X_k E_i\right)\pi_i+f_{i+1}^*(S_{i+1,k})$$

subject to the following constraints:

$$0\le X_k\le 1;\ \forall k=1,...,m$$

$$0\le Y_k\le 1;\ \forall k=1,...,m$$

$$E_{\min e}\le X_k E_i\le E_{\max e};\ \forall i=1,...,N;\ \forall k=1,...,m$$

where:

- m is the resolution level of the storage tank (the minimum discrete state of the storage tank capacity), N is equal to the number of hours that form the chosen optimization time window,
- π_{Hi} is the hourly day ahead market price,
- E_{mine} is the minimum energy input for EZ,
- E_{maxe} is the maximum energy input for EZ.

The described algorithm concerns with the optimization of the WECS/H_2. The remaining part of the WECS/H_2 economical evaluation is based on the well-known Net Present Value approach. In particular considering the economic indicators of the employed technology it is possible to assess the effectiveness of the investment.

APPLICATIONS AND RESULTS

The case study, used to employ the developed tool, involves Sicily where today several wind farms are installed yet and others have been authorized. Moreover, owing to the local network asset with respect to the generation available, the day ahead market prices are greater than the weighted average of the prices of all Italian market zones.

In order to assess the optimal operation of the formerly designed storage system the dynamic algorithm has been employed. This is performed using the same period of the sizing stage and processing the historical data with the forecasting module that uses different forecasting methods. The historical data consist of one year of hourly energy, that belongs to a big wind farm in the centre of Sicily near 50 MW, and the corresponding day ahead market prices of the Sicilian zone.

The storage system is formed by the following component that comprise the balance of plant elements. The main characteristics are report in the table 1.

Table 1 Main components of the storage system [8]

ELECTROLYZER	
Type	Norsk hydro Type 5040
Hourly Production of H_2	300-485 Nm^3/h
Energy Consumption	~4.30 kWh/ Nm^3h
Rated Power	2 MW
Energetic System Efficiency	74 %
FUEL CELL	
Type	MCFC
Rated	1 MW
Energetic System Efficiency	45%
STORAGE TANK	
Energetic Density	~ 0.5 MWh/m^3
Pressure	~20 MPa

Employing the procedure developed in [6] the remaining system parameters have been obtained. In particular the required size of subsystems is reached by joining the necessary modules of the previous components. In the following table there are also the management parameters, among which the initial investment and the investment life are assessed considering the projected costs to 2020 and the possibility to receive the Green Certificate for the energy released from the plant.

Table 2 Optimization Tool Parameters

System Parameters	**Size of Electrolyzer System**	9 MW
	Storage Tank Capacity	90 MWh
	Size of Fuel Cell System	3 MW
Management Parameters	**Discount Rate**	5 %
	Inflation Rate	2.2 %
	Investment Life (2020)	20 years
	Initial Investment for the Storage System (2020)	~ 6 M€
	Period of Green Certificate Availability (Current Italian Rules)	12 years
	Variable O&M cost	~ 60 k€

Running a simulation, considering the processed data with the forecasting module, it is possible to see the following results of the optimization tool. For example using the SES/Markov approach the resulting storage level and the control variables are reported respectively in the figure 4 and 5:

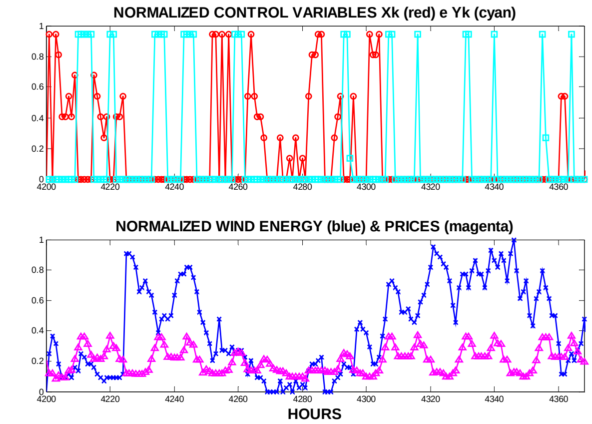

Fig 4. Control Variables (X_k o, Y_k □), Wind Energy (x) and Market Prices (Δ) for a week

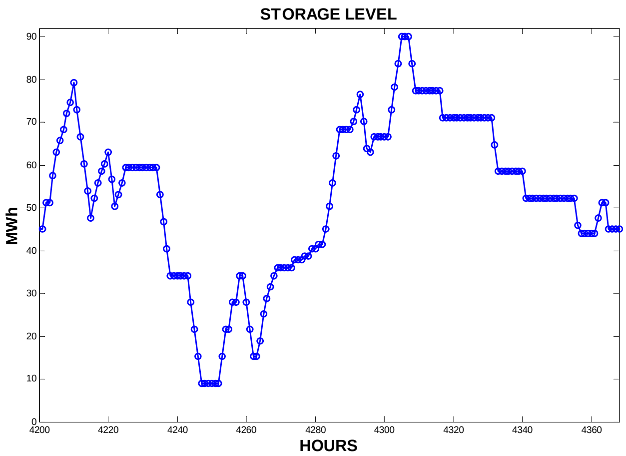

Fig 5. Energetic storage level of the WECS/H_2 system for a week

In the previous figure it is showed the exploitation of the storage capacity and in figure 4 it is possible to notice the effect of the interaction between prices and wind power on the storage behaviour.
Another interesting result concerns with the NPV analysis. The optimization tool could be used to assess the possible breakeven point of a subsystem technology. In figure 6, considering the energetic efficiency of the FC system as a parameter, it is possible to know the value that yields the NPV equal to zero.

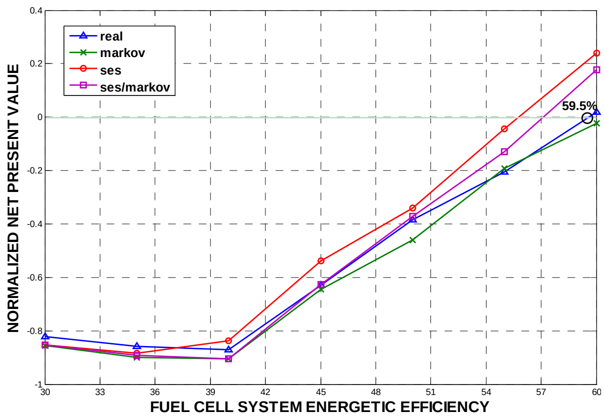

Fig 5. Energetic storage level of the WECS/H_2 system for a week

The various forecasting technique range from an efficiency of 55.5 % to 60.5 %, comprising the effective power delivered from the plant. Today this target is achievable only with combined cycle generation plant, and fuel cell system are not ready.

CONCLUSION

In this paper the problem of optimal sizing of a storage plant based on hydrogen technology coupled with a wind farm plant has been analyzed. The main aim is to evaluate, using a proper optimization tool, the optimal operational strategy considering different forecasting methods. Moreover it is possible to lead an economical analysis with the NPV method that is quite flexible and allows to make different sensitivity studies considering technical and economical parameters.
A case study in Sicily has been analyzed taking into account the day ahead market prices in Italian Power Exchange (IPEX) and a big wind farm. The results shows the good performances of the dynamic algorithm in the management of the storage system and the possibility to perform a complete economical analysis of the entire plant varying the model parameters.

REFERENCES

[1]. GWEC, 2005, Global Wind 2005 Report, 10
[2]. M. Korpaas, A.T. Holena, R. Hildrumb, 2003, *Operation and Sizing of an energy storage for wind power plants in a market system,* Electrical Power and Energy Systems, Vol. 25, 599-606
[3]. E.D. Castronuovo, J. A. Peças Lopes, 2004, *On the Optimization of the Daily Operation of a Wind-Hydro Power Plant* , IEEE Transactions on Power Systems, vol. 19, 1599-1606.
[4]. G.N. Bathurst and G. Strbac, 2003, *Value of Combining Energy Storage and Wind in Short-Term Energy and Balancing Markets*, Electric Power System Research 67, 1-8.
[5]. G. Tina, C. Brunetto, A Moschetto, M. Ferraro and V. Antonucci, 2006, *Analysis of hydrogen storage opportunities for wind energy generation in the Italian electricity market*, Proc 2006 of the European Wind Energy Council
[6]. G. Tina, C. Brunetto, C. Manuli, 2007, *Forecasting Methods for Wind Power Management in Liberalized Electricity Market,* Abstract accepted for CIRED
[7]. S. Hillier, Lieberman G.J, 2001, *Introduction to Operations Research*, McGrawHill, New York,
[8]. T. Noro, 2003, *Celle a Combustibile, Tecnologia e Possibilità Applicative*, Dario Flaccovio Editore