Energy Policy 37 (2009) 126–139

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Generation management using batteries in wind farms: Economical and technical analysis for Spain

Rodolfo Dufo-López *, José L. Bernal-Agustín, José A. Domínguez-Navarro

Electrical Engineering Department, University of Zaragoza, Calle María de Luna, 3, 50018 Zaragoza, Spain

ARTICLE INFO

Article history:
Received 8 June 2008
Accepted 14 August 2008
Available online 23 September 2008

Keywords:
Wind farms
Batteries
Hydrogen

ABSTRACT

This paper presents an hourly management method for energy generated in grid-connected wind farms using battery storage (Wind–Batteries systems). The method proposed is analysed technically and economically.

Electricity generation in wind farms does not usually coincide with the electrical demand curve. If the wind-power penetration becomes high in the Spanish electrical grid, energy management will become necessary for some wind farms. A method is proposed in this paper to adjust the generation curve to the demand curve by storing electrical energy in batteries during off-peak hours (low demand) and selling stored energy to the grid during peak hours (high demand).

With the results obtained and reported in this paper, for a Wind–Batteries system to be economically as profitable as a Wind-Only system, the selling price of the energy provided by the batteries during peak hours should be between 22 and 66 c€/kWh, depending on the technology and cost of the batteries. Comparison with flexible thermal generation has been performed.

Additionally, the results are compared with those obtained if using hydrogen (Wind–Hydrogen system, which uses an electrolyser, hydrogen tank, and fuel cell instead of batteries), concluding that the Wind–Batteries system is both economically and energetically far more suitable.

1. Introduction

Currently, electricity generation by means of renewable sources in Spain has established a special economic regime (Royal Decree 661/2007, 2007; Order ITC/3860/2007, 2007). This favourable economic regime has encouraged the installation of numerous wind farms and photovoltaic generators.

The primary challenge with generating installations dependant on renewable resources (e.g., sun and wind) is that electricity generation cannot be fully forecasted and does not usually coincide with the demand curve. On occasion, the electricity generated by wind farms cannot be transferred to the grid. Therefore, it is necessary to stop some wind turbines, resulting in possible lost energy. In addition, there are usually large variations in electricity generated by wind farms within brief intervals of time. In order to reduce the difference existing between the generation curve and the demand curve (energy management), as well as abrupt variations in generation, a possible measure is to use some kind of energy storage means. Thus, there are various possibilities for electricity storage for energy management: water-pumping reversible hydro plants, batteries, compressed air energy storage (CAES), and hydrogen (Ibrahim et al., 2008). Amongst these, the most frequently used to store electricity is water-pumping reversible hydro plants. Electricity storage in large-size batteries is less typical (Wagner et al., 1999; Farber De Anda et al., 1999; McDowall, 2006; Kashem and Ledwich, 2007). An alternative method of energy storage coupled with wind generation is economically prudent in cases where wind turbines are connected to a weak grid or at the end of a long feeder, thus deferring the need for grid upgrade.

Various battery technologies exist. The most frequently used batteries are lead acid; however, they are problematic in that the cycle life is very low (typically between 200 and 500 full equivalent cycles). In addition, their level of charge cannot be less than 40%. In addition to lead acid batteries are OPzS, which are tubular and have much longer life cycles of about 900–1200 full equivalent cycles. Other types of batteries, such as Ni-Cd, have an advantage over lead acid in that they discharge completely and do not require any maintenance; however, their cost is significantly higher (Pocock and Hamilton, 2006). In recent years, redox flow batteries have been developed (Bartolozzi, 1989; Lipman et al., 2005), using bromine as a central element (ZnBr or NaBr) or vanadium (vanadium redox batteries). These last approximately 2000 full equivalent cycles. Sodium sulphur (NaS) batteries (Oshima et al., 2005; Wen et al., 2008) have been recently

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* Corresponding author. Tel.: +34 976 76 19 21; fax: +34 976 76 22 26.
E-mail addresses: rdufo@unizar.es (R. Dufo-López), jlbernal@unizar.es (J.L. Bernal-Agustín), jadona@unizar.es (J.A. Domínguez-Navarro).

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doi:10.1016/j.enpol.2008.08.012

Nomenclature

$C_{\text{investment}}$	initial cost of the investment (€)
C_k	acquisition cost of component k (€)
C_{LAND}	acquisition costs of the land necessary to install the system (€)
$C_{\text{O\&M\_}k}$	annual cost of the operation and maintenance of component k (€/yr). In the case of the electrolyser, the annual cost of distilled water consumption is included
DOD	depth of discharge of the batteries (%)
$E_{\text{EE\_bat\_yr}}$	annual electricity sold to the grid from the batteries (kWh/yr)
$E_{\text{EE\_W\_yr}}$	annual electricity sold to the grid generated by wind turbines (kWh/yr)
g	annual general inflation
g_{EE}	expected annual inflation of the selling price of electricity
g_k	specific annual inflation for the acquisition cost of component k
h	hour of the year (between 0 and 8760)
h_{d}	hour of the day (between 0 and 24)
h_1	lower limit hour of period A
h_2	higher limit hour of period A and lower limit of period B
h_3	higher limit hour of period B and lower limit of period C
h_4	higher limit hour of period C and lower limit of period D
I	price of money (annual interest rate)
$Inst$	percentage to apply to the total initial cost of the investment for concepts such as installation, engineering, etc. (%)
k	each of the system components: the wind turbines ($k = \text{W}$), the inverter ($k = \text{INV}$), the rectifier ($k = \text{R}$), and the batteries ($k = \text{Bat}$)
Lg_k	accumulated limit of the specific annual inflation of component k
$Life_k$	lifespan of component k (years)
$LH_{\text{EE\_W}}$	lower limit of the selling price of electricity generated by wind turbines for sale on the electricity market (€/kWh)
$HH_{\text{EE\_W}}$	upper limit of the selling price of electricity generated by wind turbines for sale on the electricity market (€/kWh)
$N_{\text{first\_rep\_}k}$	number of replacements of component k during the years in which the price of component k changes in keeping with specific inflation g_k
$N_{\text{rep\_}k}$	number of replacements of component k during the period of study
$NPC_{\text{O\&M\_}k}$	discounted present costs of future costs of operation and maintenance of component k throughout the life of the system (€)
$NPC_{\text{O\&M\_}k\text{\_}n}$	discounted present costs of future costs of operation and maintenance of component k throughout the first n years (€)
$NPC_{r\text{\_}k}$	discounted present costs of future costs of replacing the components throughout the life of the system (€)
NPV	Net Present Value of the system (€)
$NPV_{\text{end\_}k}$	discounted present values of income for the residual value of component k in the system upon completing the period of study (€)
$NPV_{\text{Sale\_EE\_Bat}}$	discounted present values of income from the sale of electricity to the grid from battery discharge (€)
$NPV_{\text{Sale\_EE\_W}}$	discounted present values of income from the sale of electricity to the grid generated by the wind turbines (€)
$NPV_{\text{Wind−Only\_system}}$	Net Present Value of Wind-Only system connected to the electricity grid (€)
$P_{\text{DC\_}h}$	power available at the DC bus generated by the wind turbines to produce hydrogen in the electrolyser during hour h (W)
$P_{\text{Bat\_Sale\_}h}$	electricity for sale to the grid during hour h from battery discharge. (W)
$P_{\text{D\_bat\_}h}$	electricity discharge power from the batteries available during hour h (W)
$P_{\text{C\_bat\_}h}$	electricity power available in the DC bus to charge the batteries during hour h (W)
$P_{\text{max\_bat\_}h}$	maximum charge power of the batteries for hour h (W)
$P_{\text{max\_C\_bat}}$	maximum charge power admissible in the batteries during an hour (W)
$P_{\text{max\_D\_bat}}$	maximum discharge power admissible in the batteries during an hour (W)
$P_{\text{W\_}h}$	power generated by the wind turbines during hour h (W)
$P_{\text{W\_Sale\_}h}$	electricity for sale to the grid during hour h coming from the wind turbines (W)
$PR_{\text{EE\_MARKET\_}h}$	price during hour h for electricity established by the electricity market (€/kWh)
$PR_{\text{EE\_W\_ADDED}}$	bonus to be added to the market price for the sale of electricity generated by wind turbines (€/kWh)
$PR_{\text{EE\_W\_}h}$	price during hour h for the sale of electricity generated by wind turbines (€/kWh)
$PR_{\text{EE\_Bat}}$	price for the sale of electricity coming from the batteries (€/kWh)
SOC_h	state of charge of the batteries (Wh) at the end of hour h
SOC_{h-1}	state of charge of the batteries (Wh) at the end of previous hour, $h-1$
SOC_{max}	maximum state of charge (SOC) of the batteries (Wh), coinciding with the nominal capacity of the batteries
SOC_{min}	minimum state of charge allowed (kWh); below this figure, the batteries would be damaged.
$v_{\text{hub\_}h}$	wind speed at the hub height of the wind turbine, during the hour h (m/s)
$v_{\text{data\_}h}$	wind speed at anemometer height, during the hour h (m/s)
Y	study period (years)
$Y_{\text{g\_}k}$	time taken in reaching component k specific inflation limit (years)
z_0	the surface roughness length (m)
z_{data}	the anemometer height (m). This is the height in which the wind data have been read.
z_{hub}	the hub height of the wind turbine (m)
δ	batteries self-discharge coefficient
η_{bat}	batteries roundtrip efficiency
$\eta_{\text{C\_bat}}$	batteries charge efficiency
$\eta_{\text{D\_bat}}$	batteries discharge efficiency
η_{INV}	inverter efficiency
η_{R}	rectifier efficiency
η_{TR}	efficiency of the transformer connected to the grid, including cable losses