Electrical Power and Energy Systems 54 (2014) 341–351

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Optimum scheduling of micro grid connected wind-pumped storage hydro plant in a frequency based pricing environment

T. Malakar [a,*], S.K. Goswami [b,1], A.K. Sinha [a,1]

[a] Electrical Engineering Department, National Institute of Technology Silchar, Assam, India
[b] Electrical Engineering Department, Jadavpur University, Kolkata 700 032, India

ARTICLE INFO

Article history:
Received 27 January 2013
Received in revised form 12 July 2013
Accepted 13 July 2013

Keywords:
Optimum scheduling
Frequency based pricing
Availability based tariff
Pumped storage hydro
Micro grid

ABSTRACT

This paper presents a new formulation to maximize the operational profit of a micro grid connected hybrid system having wind farm and pumped storage unit for a day ahead electricity market in a frequency based pricing environment. Under frequency based pricing mechanism in India, the pricing for energy exchange is adaptive as per Availability Based Tariff (ABT) rate structure and the payment for deviation from schedule, i.e. Unscheduled Interchange (UI) charge is inversely proportional to the prevailing grid frequency. In this work, a small power system is considered as micro grid and it is expected that the hybrid system connected with the micro grid has a role to play to maintain the micro grid frequency. The pump storage hydro plant is operated to serve the dual role of minimizing the UI flow and maximizing the system economy by participating in frequency control based on energy price. The uncertainties in wind power prediction and loads are considered. The optimum operating schedule of PSH unit in coordination with wind farm is investigated. The optimization is performed by utilizing the water storage availability of pump storage hydro unit. An optimization algorithm is proposed and solved using Artificial Bee Colony algorithm. The solution of the proposed approach gives the strategies to be followed by the hybrid system to operate its pump storage unit. The effect of the initial storage water volume on the performance of the hybrid system has also been investigated. It reveals that the PSH units would not operate simply to compensate for the short fall or the surplus generation of the wind units in a frequency based pricing system. Rather, the pump storage units should take the advantage of the low price periods to maximize the profit of the hybrid system. The hourly energy management scenarios of the hybrid system with the micro grid are reported and the numerical case studies on PSH plant scheduling demonstrate the effectiveness of the proposed approach.

1. Introduction

With the increase in environmental awareness and strict regulation on environmental concerns, the clean, cheap energy generation and its utilization has attracted more attention than before over the last few years. There is continuous growth in the use of various types of Renewable Energy Sources (RES) in many countries around the world. The basic aim is to reduce the green house gas emissions caused by the conventional electric generators. To meet the emission cut target, attempts have been made to maximize the penetration of RES into electricity grids [1–3]. Wind power is the most widely used and acceptable source of renewable energy. The power generation largely depend on wind speed. Therefore, there are uncertainty and volatility associated with wind power generation.

To compensate for the uncertainty of wind generation system the uses of pumped storage hydro unit or battery storage in coordination with wind farm have been reported in the literature. The use of Pumped Storage Hydro (PSH) unit in coordination with wind farm has become an attractive solution. A number of research reports [4–6] analyze the operation of PSH unit to compensate the energy imbalance of smaller grid. The smaller grids with wind farm, face the difficulties to exploit fully the potentiality of wind power, mainly because of stochastic nature of wind and its seasonal variations. The PSH unit can play a significant role to recover the excess wind energy in the form of stored hydraulic energy during high wind periods and can participate in supplying energy to the grid during low wind periods by transforming the stored hydraulic energy into electricity. The basic optimization model for pumped storage hydro plant operation and coordinated operation of wind farm together with PSH unit has been discussed in [7,8] respectively. The problem has been

* Corresponding author. Tel.: +91 9435730108; fax: +91 3842 224797.
E-mail addresses: m_tanmoy1@rediffmail.com (T. Malakar), skgoswami_ju@yahoo.co.in (S.K. Goswami), ashokesinha2001@yahoo.co.in (A.K. Sinha).
[1] Fax: +91 3842 224797.

0142-0615/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2013.07.021

Nomenclature

B_{ij}	line susceptance between bus i and j
c^t	hourly market price for schedule interchange in Rs/MW h
C_{PS}^t	cost of extra power sold to the micro grid in Rupees
C_{PPL}^t	cost of extra power purchased from micro grid for supplying load in Rupees
C_{PPP}^t	cost of power purchased from micro grid for pumping in Rupees
C_{SI}^t	cost of schedule interchange in Rupees
D_{LU}^t	uncertainty in load demand at hour t
$D_{LU}^{\max}$	maximum load demand uncertainty
E^t	hourly reservoir energy level in MW h
E^U	maximum energy level of the reservoir in MW h
E^L	minimum reservoir energy level to maintain in MW h
f^t	frequency at hour t in Hz.
G_{ij}	line conductance between bus i and j
i, j	index of buses
P_{HS}^t	hourly active power delivered by hybrid system to the micro grid in MW
P_W^t	hourly available wind power generation in MW
P_H^t	hydro generation from pumped storage hydro unit in MW
P_{CG}^t	hourly real power from central generators in MW
$P_{CG}^{\min}$	minimum real power of central generators in MW
$P_{CG}^{\max}$	maximum real power of central generators in MW
P_P^t	power consumption during pumping hours in MW
P_D^t	hourly real power demand in MW
P_H^L	minimum hydro generation in MW
P_H^U	maximum hydro generation in MW
P_P^L	minimum pump load in MW
P_P^U	maximum pump load in MW
P_{WU}^t	uncertainty in wind power at hour t
$P_{WU}^{\max}$	maximum wind power uncertainty
Q_{CG}^t	hourly reactive power generation from central generators in MVAR
Q_D^t	hourly reactive power demand in MVAR
Q_{HS}^t	hourly reactive power (if any) from hybrid system in MVAR
$Rate^{\mathrm{UI}}$	rate of unscheduled interchange in Rs./MW h
S_{ij}^t	line flow between bus i and bus j in MVA at hour t
S_{ij}^U	maximum line loading limit of line between bus i and bus j in MVA
t	index of interval or hour
UI_{PS}^t	hourly extra power sold to the grid as unscheduled interchange in MW
UI_{PPL}^t	hourly extra power purchased from grid for load balance in MW
UI_{PPP}^t	hourly extra power purchased from grid for pumping in MW
UI^t	hourly unscheduled interchange in MW
UI^U	maximum unscheduled interchange
$\lvert V_i^t \rvert$	voltage magnitude at ith bus at hour t
$\lvert V_i^{\min} \rvert$	minimum voltage magnitude of bus i
$\lvert V_i^{\max} \rvert$	maximum voltage magnitude of bus i
η_H	efficiency of PSH unit during hydro generation
η_P	efficiency of PSH unit during pumping
θ_i, θ_j	voltage phase angle of ith bus and bus j

formulated as an Optimal Power Flow (OPF) which finds the working strategies of an Independent Power Producer (IPP) to minimize their operating cost. The improvement of operational economics of a wind farm for daily basis has been discussed in [9] by optimal utilization of its pumped storage hydro plant. The problem has been formulated as hourly discretized optimization problem for finding a daily operating strategy of both wind farm and pump storage plant. In this type of profit maximization problem, it is intended by the utility to operate its PSH unit to store water during low pricing periods or during high wind speed hours and to operate its PSH unit to discharge water during high pricing period or during inadequate wind speed hours. A hybrid practical power system consisting of wind farm with pumped storage hydro plant has been demonstrated in [10] and the suitability of its operating strategy has been discussed. A formulation has been made to improve the energy dispatch share from renewable energy sources by proper utilization of PSH unit. A joint optimization model under market environment has been addressed in [11] for both wind farm and PSH unit in two different mode of operation. The profit maximization is analyzed first by operating wind farm and PSH unit independently to exchange energy with the market and second, by operating the PSH unit in coordination with the wind farm. In Ref. [12], an optimum daily operational strategy has been discussed for an IPP having wind farm and PSH unit for a day ahead electricity market. The formulation has been tested on an Indian test system.

An accurate wind power prediction is necessary by the utility for finding such operational strategy. Inaccuracy in prediction has an impact on various issues of power system operation, such as; day ahead scheduling, optimal power flows, system stabilities, transmission congestions, and operational economics. The impact on market price due to inaccuracy in wind power prediction has been addressed in [13] when a large scale wind farm is integrated into an electric power system. The operating strategy of a wind power producer in a short term electricity market under uncertainty has been investigated in [14].

Power system restructuring and deregulation has changed the power system operation in respect to frequency regulation, generation redispatch, etc. The frequency regulation is the mechanism of controlling frequency by minimizing supply demand gap. Because of random variations in wind power generation, frequency fluctuation in grid has become a major concern in recent times. For random wind power penetration into the grid, the system stabilizes to a new steady operating point with a frequency different than the nominal. This frequency deviation from nominal would result unscheduled power flow through the lines if no control action is initiated. This Unscheduled Interchange (UI) flow would thus try to improve the grid prevailing frequency. The cost of UI flow is made frequency dependent in Indian power system operation [15]. The power system operations in Indian context under frequency based pricing have been reported in the literatures [16–18]. The Generation Scheduling (GS) problem as a day ahead