Electrical Power and Energy Systems 64 (2015) 275–284

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Joint operation of wind farm, photovoltaic, pump-storage and energy storage devices in energy and reserve markets

Moein Parastegari *, Rahmat-Allah Hooshmand, Amin Khodabakhshian, Amir-Hossein Zare

Department of Electrical Engineering, University of Isfahan, Isfahan, Iran

ARTICLE INFO

Article history:
Received 19 July 2013
Received in revised form 21 June 2014
Accepted 23 June 2014

Keywords:
Wind farm
Pump-storage power plant
Photovoltaic resources
Energy storage devices
Optimal bidding strategy
Energy and ancillary service markets

ABSTRACT

Renewable resources generation scheduling is one of the newest problems of the power markets. In this paper, joint operation (JO) of wind farms (WF), pump-storage units (PSU), photo-voltaic (PV) resources, and energy storage devices (ESD) is studied in the energy and ancillary service markets. There are uncertainties in wind power generation (WPG), photovoltaic power generation (PVPG) and the market prices. To model these uncertainties, the WPG is forecasted by using ARMA model and its scenarios are generated using Weibull distribution function. Moreover, other uncertain parameters are forecasted first, and their uncertainties are modeled by using scenario generation and scenario reduction method. The proposed JO method is used to determine the optimal bidding strategy of the PSU, PV, ESD and WF of IEEE 118-bus standard system. The results for these renewable energy resources confirm that the JO of these resources increases the profit and decreases the risk of the resources in comparison with their uncoordinated operation (UO).

Introduction

Before the deregulation of power systems, power system operators (ISOs) try to minimize the generation cost of the power system by solving unit commitment problem. After the deregulation, the ISOs try to maximize social welfare of both generation units and consumers. In this condition, generation companies (fossil and renewable power plants) use electricity price forecasting to determine their bidding strategy [1].

Nowadays, due to the increase in the fuel prices, and environmental emission, the use of renewable energy resources are increased [2–16]. Renewable energy resources include wind farms [2–4], pump-storage [6], photovoltaic units [8,10,17], waste biomass recovery resources and bio-based substances [18]. The amount of power generation of some of these renewable energy resources (especially WF and PV resources) depends on climatic conditions; therefore, by using these units the uncertainties of the power system are increased. It should be noted that today technologies are presented for sunlight conversion under not optimal weather conditions [19].

In order to reduce the effect of uncertainties, ISOs receive the imbalance penalty cost for any imbalance (the error between predicted and actual generation). In this situation, if a generation unit has surplus generation, it will receive surplus charge rate (less than spot market prices), else, if a generation unit has deficit generation, it should pay deficit charge rate (more than spot market prices) [3,5]. Since the power generation of WFs and PV resources are uncertain, their imbalance costs (risks) are high [2,3,14].

The IC of a unit will decrease if the unit forecasts its actual generation. In this regard, WF owners use autoregressive moving average (ARMA) model to forecast the generation [20,21]. In addition, adaptive neuro fuzzy inference system (ANFIS) method and the combination of the ANFIS and particle swarm optimization (PSO) techniques are two forecasting methods which are used in [22] and [23] respectively. On the other hand, the uncertainties of renewable generation units can be modeled by different scenarios [14,15]. After forecasting the WPG, Weibull distribution function is used to generate WPG scenarios to increase the expected profit and to decrease the risk of units [3,14,15,20]. In [15], the scenario generation method is accomplished for PV resources.

JO of the uncertain renewable energy resources and other units is another method which can be used to reduce the imbalance costs. This method increases the expected benefit and decreases the risk of joint units. Nowadays, many studies are performed on the joint operation of different units [3–8,12–16]. The JO of WF and ESD is studied in [3,13]. In [5], JO of WF and hydro units are evaluated. Also, the JO of WF and PSU in energy market is considered in [12,14,16,24]. In [8–10,13] the economic assessment of the

* Corresponding author.
E-mail addresses: Parastegari@eng.ui.ac.ir (M. Parastegari), Hooshmand_r@eng.ui.ac.ir (R.-A. Hooshmand), aminkh@eng.ui.ac.ir (A. Khodabakhshian), amir.zare66@gmail.com (A.-H. Zare).

http://dx.doi.org/10.1016/j.ijepes.2014.06.074

Nomenclature

NT, t total number of scheduling time and index of time
k, l, pv and w index of each generation unit, pump-storage power plant, photovoltaic resources and wind farms
s_p, s_w and s_{pv} index of scenarios of energy price, wind power generation, and photovoltaic generation
$\rho(s_p,\ s_{pv},\ s_w)$ probability of the s_p -th scenario of energy price, s_w -th scenario of wind farm generation, and s_{pv} -th scenario of photovoltaic generation
NS_P, NS_W and NS_{PV} total number of the energy price scenarios, wind generation scenarios, and photovoltaic generation scenarios, respectively
NW, NPS and NPV total number of the pump-storage power plants, photovoltaic resources and wind farms, respectively
$I_g(l, t)$ and $I_p(l, t)$ generating and pumping mode status indicator of l-th pump-storage unit at time t, where 1 means on and 0 means off state, respectively
$U_C(pv, t)$ and $U_d(pv, t)$ charging and discharging mode status indicator of the energy storage of the pv-th photovoltaic unit at time t, where 1 means active and 0 means inactive, respectively
$P_c(t)$ energy bid to the day-ahead market (for JO of wind farm, photovoltaic, energy storage device and pump-storage units)
$\tilde{P}_D(k,t)$ power production of k-th unit at period t in terms of MW
$P_{D,PS}(l, t)$, $\tilde{P}_{D,W}(w,t)$ and $\tilde{P}_{D,PV}(pv,t)$ power production of l-th pump-storage power plant, w-th wind farm, and pv-th photovoltaic resource at period t in terms of MW, respectively.
$R_{C,PS}(l, t)$ and $N_{C,PS}(l, t)$ spinning reserve and non-spinning reserve bidding strategy (offer) of l-th pump-storage unit at period t in terms of MW
$epr(s_p, t)$, $srpr(s_p, t)$ and $nsrpr(s_p, t)$ market price ($/MW) for energy, spinning and non-spinning reserve for s_p-th scenario of price at period t
S_{CR}, and D_{CR} surplus and deficit charge rate
β imbalance charge coefficient. (Ratio between imbalance price (surplus or deficit charge rate) and day-ahead market price)
a, b and c generation cost coefficients
$U(k, t)$ commitment status indicator of unit k at time t
$R_g(l, t)$ and $R_p(l, t)$ spinning reserve of generation and pumping mode of l-th pump-storage unit at period t in terms of MW
$N_u(l, t)$ and $N_d(l, t)$ available non spinning reserve of ON and OFF state of unit l at period t in terms of MW
$\tilde{P}_{D,W}(s_w, w, t)$ power generation of w-th wind farm in s_w-th scenario at period t
$Cost_{su}$, IRC, $Cost_{Batt}$ values of start-up cost of a unit, imbalanced revenue/cost, and the cost of a battery
$\upsilon^u(l,\ t)$, $\upsilon^u(l,\ ini)$ and $\upsilon^u(l,\ end)$ water content, initial and finial water content of the upper reservoir of the l-th pump-storage unit
$\upsilon^u_{\min}(l)$ and $\upsilon^u_{\max}(l)$ minimum and maximum limit of the water content of the upper reservoir of the l-th pump-storage unit
$\upsilon^L(l, t)$, $v^L(l, ini)$ and $\upsilon^L(l, end)$ water content, initial and finial water content of the lower reservoir of the l-th pump-storage unit
$\upsilon^L_{\min}(l)$ and $\upsilon^L_{\max}(l)$ minimum and maximum limit of the water content of the lower reservoir of the l-th pump-storage unit
$qg(l, t)$ and $qp(l, t)$ generation discharge water and pumping charge water of l-th pump-storage unit at period t
$qp_{min}(l)$ and $qp_{max}(l)$ minimum and maximum limit of the water charge of the l-th pump-storage unit.
$qg_{min}(l)$ and $qg_{max}(l)$ minimum and maximum limit of the water discharge of the l-th pump-storage unit
$P_{ChBatt}(bt, t)$ and $P^{\max}_{ChBatt}(bt)$ the amount of charging power of the bt-th energy storage device at time t and its maximum limit
$P_{DeBatt}(bt, t)$ and $P^{\max}_{DeBatt}(bt)$ the amount of power delivered while discharging of the bt-th battery at time t and its maximum limit.
$E(bt, t)$ amount of energy stored in the bt-th energy storage device at time t
$PF(k, t)$, $RV(k, t)$, $TC(k, t)$, $IRC(k, t)$ values of profit, revenue, total generation cost and imbalanced revenue/cost of k-th generation unit at time t

Parameters of scenario generation section
$Parameter(s, t)$ the value of the *Parameter* in the s-th scenario at tine t
$Parameter_{forecast}(t)$ the forecasted value of the *Parameter* at tine t
$\Delta\ Parameter(s)$ parameter forecast error at time t in the scenario s

JO of WF and PV resources is studied. In [11] it is shown that the JO of PV resources and WF affects the required operating reserve of the power system.

In the above-mentioned studies, the JO of WFs, PV resources, and PSUs in the energy and ancillary services markets is not considered. Furthermore, in some of these studies the statistical information of the wind generation is used without wind forecasting.

In this paper, the JO of WFs, PV resources, ESD and PSUs in the energy and ancillary services markets are studied. For this purpose, the optimal bidding strategy of units is determined by maximizing the expected profit of joint units. In this problem, the market prices, WPG and PV power generation (PVPG) uncertainties are modeled using the scenario tree method. Furthermore, in this paper, the Weibull distribution function with ARMA forecasting method is used to generate WPG scenarios. In order to evaluate the proposed method, its performance is tested on the renewable energy resources of the modified IEEE 118-bus standard system. Simulation results confirm the effectiveness of the proposed problem in increasing the expected profit and decreasing the imbalances of joint units.

Flowchart of the proposed structure for JO of units

The flowchart of the JO of renewable units in energy and ancillary service markets is shown in Fig. 1. The proposed structure consists of four main stages which are explained as follows:

Stage 1: In this stage, the amount of energy prices, WPG and PVPG are forecasted.
Stage 2: In this stage, by using the forecasted values (determined in the first stage), the scenarios of energy prices, WPG and PVPG are generated.
Stage 3: In this part, the proposed scheduling problem for the joint operation of PSU, PV, ESD and WF is presented. For this