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A new self-scheduling strategy for integrated operation of wind and pumped-storage power plants in power markets

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ABSTRACT

Competitive structure of power markets causes various challenges for wind resources to participate in these markets. Indeed, production uncertainty is the main cause of their low income. Thus, they are usually supported by system operators, which is in contrast with the competitive paradigm of power markets. In this paper, a new strategy for increasing the profits of wind resources is proposed. In the suggested strategy, a Generation Company (GenCo), who owns both wind and pumped-storage plants, self-schedules the integrated operation of them regarding the uncertainty of wind power generation. For presenting an integrated self-schedule and obtaining a real added value of the strategy, participation of the GenCo in energy and ancillary service markets is modeled. The self-scheduling strategy is based on stochastic programming techniques. Outputs of the problem include generation offers in day-ahead energy market and ancillary service markets, including spinning and regulation reserve markets. A Neural Network (NN) based technique is used for modeling the uncertainty of wind power production. The proposed strategy is tested on a real wind farm in mainland, Spain. Moreover, added value of the strategy is presented in different conditions of the market.

1. Introduction

The liberalization of power markets is an ongoing process in various countries around the world. Although the degree of liberalization and rules of different markets differ broadly, participation of renewable resources especially wind farms is encouraged by the regulatory authorities of markets. Wind power generation requires high investment, while they have low operation cost. In spite of various advantages, operation of wind energy resources in the restructured power systems has a lot of problems [1–3]. GenCos, which participate in the market, are expected to present offers and deliver the agreed amount of energy in a given period. So, Due to the uncertain behavior of wind power generation, participation of wind power producers in the market without considering supportive strategies may decrease their profits.

Previous researches focus on the single participation of wind generation in electricity markets. In [4], an offering strategy for wind power producers under New Electricity Trading Arrangements (NETA) rules is proposed, allowing participants to offer only a few hours before the operation time. Ref. [5] presents a method for optimal offering strategy of wind producers based on minimization of their imbalance costs. This method utilizes stochastic programming to generate optimal wind power generation for a short-term power market. In [6], another strategy for minimization of imbalance costs of wind producers is developed that considers the probabilistic forecasting of wind generation and models the sensitivity of a wind power producer to the regulation costs. A new method for deriving the best offering strategy of a wind power producer in an electricity market including various trading floors is presented in [7]. A strategy for trading option of wind power in the emerging electricity market, based on the effect of wind generation on market clearing price (MCP), is discussed in [8]. It considers an award for wind producers if their participation in the market reduces the MCP. However, this strategy is only effective if there are large-scale wind power producers in the market. The proposed method in [9] models and evaluates the flexibility on switching tariffs as real compound options for wind producers to increase their profits and further reduce their operation risks. The aforementioned papers do not consider any support for participation of wind power producers in the market that can affect their revenues. In contrast, some research works investigate supportive strategies for participation of wind power producers in the market. Presented method in [10] deals with participation of wind resources in daily and hourly energy markets without taking into

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Nomenclature

A. Indexes

i	index of scenarios (probabilistic wind production scenarios)
t	index of hours in a day ($t = 1, \ldots, 24$)

B. Parameters and constants

C	operation cost rate of the pumped-storage plant (€/MW h)
e_i	corresponding error of the ith scenario in the distribution function
E_u^{max}, E_u^{min}	capacity limits of the upper reservoir (MW h)
E_u^0, E_u^{end}	initial and final levels in the upper reservoir in a day (MW h)
M	a large positive number that exceeds installed capacity of wind farm
MP_t	expected energy price in day-ahead market at hour t (€/kW h)
MP_t^{down}	expected negative imbalance price at hour t (€/kW h)
MP_t^{up}	positive imbalance price at hour t (€/kW h)
MP_t^s	expected price in spinning reserve market at hour t (€/kW h)
MP_t^r	expected price in regulation reserve market at hour t (€/kW h)
MP_t^{spot}	expected energy price in spot market at hour t (€/kW h)
N	number of identical pumped-storage units associated in the same pond
p_i	probability of the ith scenario
p_s	probability of spinning reserve delivery request
p_r^{up}	probability of regulation-up state
p_r^{down}	probability of regulation-down state
$P_{Wi,t}$	probable wind production in the ith scenario (kW)
$P_{W,t}$	real wind production at hour t (kW)
$\widehat{P}_{Wt}$	forecasted wind production at hour t (kW)
$P_{W\max}$	installed capacity of wind farm (kW)
$P_{gP}^{max}, P_{gP}^{min}$	generation power limits of each pumped-storage unit (MW)
$P_{pP}^{max}, P_{pP}^{min}$	pumping power limits of each pumped-storage unit (MW)
η	efficiency of the pump-turbine cycle

C. Variables

$b_{i,t}$	binary variables used for definition of positive and negative energy imbalances (equals 1 to negative energy imbalance)
$E_{u,t}$	stored energy in the upper reservoir at hour t (MW h)
$E_{u,t}^{min}$	lower limit of stored energy in the upper reservoir at hour t (MW h)
$m_{g,t}$	binary variable equals 1 if pumped-storage plant works in generation mode
$n_{p,t}$	integer variable that indicates the number of units that are running in the pumping mode (0, 1, ..., N)
$P_{Pb,t}$	energy offer to the day-ahead market by pumped-storage plant at hour t (kW h)
$P_{Wb,t}$	energy offer to the day-ahead market by wind farm at hour t (kW h)
$P_{WPb,t}$	joint energy offer of the wind farm and pumped-storage plant at hour t (kW h)
$P_{gP,t}$	discharge power output of the pumped-storage plant at hour t (kW)
$P_{pP,t}$	pumping power input of the pumped-storage plant at hour t (kW)
$P_{gsP,t}$	power offer to spinning reserve market by pumped-storage plant at hour t in the generation mode (kW)
$P_{psP,t}$	power offer to spinning reserve market by pumped-storage plant at hour t in the pump mode (kW)
$P_{grP,t}$	power offer to regulation reserve market by pumped-storage plant at hour t in the generation mode (kW)
R_P	expected profit of pumped-storage plant in daily market (€)
R_W	expected profit of wind farm in daily market (€)
R_{WP}	joint expected profit of both wind farm and pumped-storage plant in daily market (€)

account the imbalance penalty. A new supportive method for pricing and utilizing wind resources in short-term power markets is suggested in [11]. This method derives the best level of contract for wind producers according to their expected power production. The above-mentioned methods increase the operation cost of system, while one of the most fundamental aims of restructuring power markets is eliminating the subsidies of producers to create perfectly competitive power markets. On the other hand, eliminating the subsidies from wind power producers not only reduces their revenues but also diminishes the development of wind energy resources because of their high investment requirements. Thus, some papers consider combinational operation of wind energy resources with other energy resources. Ref. [12] discusses a strategy for offering and operating a combination of wind and hydro-generation resources, which results in an increase in their joint revenues. In [13,14], joint operation of wind and pumped-storage power plants is studied. The studies include energy balance analysis and economic viability. In [15], the combined optimization of a wind farm and a pumped-storage facility from the viewpoint of the GenCo in a market environment is investigated. However, this research only considers participation of the resources in day-ahead energy markets, ignoring the fact that pumped-storage plants can also take part in ancillary service markets.

One of the most important strategies for increasing profits of the wind power producers is integrating wind resources with limited energy resources such as pumped-storage power plants. Coordinated operation of a wind farm and a pumped-storage plant can provide added value for the wind farm that takes part in the market in comparison with separate participation of them. Pumped-storage plants' capability of storing energy can significantly reduce the risk of self-scheduling for wind power producers in the market. In other words, as both resources in the integrated operation are owned by a GenCo, its flexibility in operation of them increases. Moreover, the GenCo can lower the uncertainty of its self-scheduling results [15,16]. At the same time, for presenting an integrated self-schedule, a GenCo needs to take part in all markets allowed to participate (i.e. energy market and ancillary service markets). So, self-scheduling the integrated operation of wind resources and pumped-storage plants necessitates participation of pumped-storage plants in energy and ancillary service markets. Otherwise, the obtained added value of the strategy is not exactly estimated and could be misleading.

Another important factor for an integrated self-scheduling is modeling the uncertainty of wind power generation. Without considering this uncertainty, the risk of wind producers for participating in the market increases [3,6].

As the main innovation, a new strategy for self-scheduling the integrated operation of wind generation and a pumped-storage plant is presented in this paper, which takes into account participation of the pumped-storage plant in energy and ancillary service