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Toward mitigating wind-uncertainty costs in power system operation: A demand response exchange market framework

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ABSTRACT

The intermittent nature of the wind generation poses an obstacle to high penetration of wind energy in electric power systems. Demand response (DR) increases the flexibility of the power system by allowing very fast upward/downward changes in the demand. This potential can be interpreted as the ability to provide fast upward/downward reserves, facilitating the utilization of the wind power in the power system. Demand response exchange (DRX) market is a separate market in which DR is treated as a virtual resource to be exchanged between DR buyers and sellers. The major advantage of the DRX market in comparison to other DR proposals is that it allocates benefits and payments across all participants, fairly. However, there are still obstacles to its integration into the existing power markets. This paper proposes a short-term framework for DRX market that considers the interactions between the DRX market and energy/reserve markets. The proposed framework is aimed at reducing the operational costs incurred by the uncertainty of the wind power and providing a fair mechanism for valuation of the DR as a virtual resource. A stochastic programming model is used to clear the DRX market considering the wind power production scenarios. To illustrate the efficiency of the proposed DRX market framework, it is implemented on a simple and a realistic case study.

1. Introduction

Today, increasing price of the fossil fuels together with the environmental concerns has motivated governments to utilize renewable energy resources in the electrical energy sector. However, large-scale integration of the renewable energy resources (particularly wind power) in the electric energy systems has introduced two serious concerns which must be addressed in the operation of the power system [1–3]. First, the power system must be able to deal with the volatilities of the wind power generation. The effects of such volatilities are less profound in systems benefiting from sufficient flexible power resources, such as reversible hydro dams, energy storage technologies, and fast conventional generators. Second, high penetration of the intermittent resources into the power system may affect the operation of the conventional generators, leading to the deviation from economically-scheduled operating points.

Demand response (DR) may be considered as an efficient approach to cope with such effects in power systems with high level of wind power integration [4–7]. Basically, DR is considered as the consumers' ability to alter their normal consumption patterns in response to changes in electricity prices or because of incentive payments designed to resolve reliability issues [8]. Note that DR can be classified as either demand curtailment or demand increment.

The role of the DR in the operation and planning of the power systems with high level of wind power integration has been investigated by many researchers. These researches can be categorized into two groups based on the type of the investigated DR programs, including price-based DR and incentive-based DR. The effect of the price-based DR on the integration of the wind power has been investigated in [9–14]. Sioshansi and Short [9] used a unit commitment model to demonstrate the effect of real time-pricing (RTP) on the wind power integration. They showed that RTP can increase the amount of load served by the wind generation and the wind power generation actually utilized in real-time. The effects of DR in a future German power system have been investigated in [10]. It has been shown that using DR, the wind-uncertainty costs are reduced to less than € 2/MWh. The authors in [11] examined the use of RTP on a future UK power system with 15 GW wind penetration level. They showed that the RTP has the potential of removing the requirement of 8–11 GW of standby generation with a capital cost of £2.6–£3.6 billion. The impacts of demand shifting and peak shaving on wind integration are investigated in [12]. Finn et al. [13] investigated the effect of dynamic pricing and time-of-use tariffs in

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Notation

Indices

t	index of time periods, running from 1 to T
i	index of generating units, running from 1 to I
j	index of aggregators, running from 1 to J
q	index of wind power producers, running from 1 to Q
m	index of DR supply function blocks offered by aggregators, running from 1 to M
w	index of wind power scenarios, running from 1 to S

Variables

$d^U_{j,t,w}$, $d^D_{j,t,w}$	upward/downward DR deployed by aggregator j in period t and scenario w (MW)
$sd^U_{j,t}$, $sd^D_{j,t}$	upward/downward DR scheduled for aggregator j in period t (MW).
$dr^U_{i,t,w}$, $dr^D_{i,t,w}$	substituted upward/downward reserve of unit i deployed in period t and scenario w by DR (MW)
$dr^{NS}_{i,t,w}$	substituted non-spinning reserve of unit i deployed in period t and scenario w by DR (MW)
$dl_{j,t,w}$	substituted load shedding of consumer j in period t and scenario w by DR (MW)
$ds_{q,t,w}$	substituted wind power spillage of producer q in period t and scenario w by DR (MW)
$s^{RU}_{i,t}$, $s^{RD}_{i,t}$, $s^{RNS}_{i,t}$	auxiliary variables employed for computing the amount of scheduled up-, down-, and nonspinning reserves of unit i in period t replaced by DR, respectively (MW)
$p^D_{DR_{j,t}}(m)$, $p^U_{DR_{j,t}}(m)$	Upward/downward DR scheduled from the m-th block of supply function offered by aggregator j in period t (MW). Limited to $p^{U,\max}_{DR_{j,t}}(m)$ and $p^{D,\max}_{DR_{j,t}}(m)$

Functions

$ls^B_{j,t,w}$	benefits obtained by reduction in load shedding imposed on consumer j in period t and scenario w due to DR (\$/h)
$sp^B_{q,t,w}$	benefits gained from DR for reducing wind power generation spillage of producer q in period t and scenario w (\$/h)
$su^B_{i,t,w}$	benefits obtained through replacement of start-up cost of unit i in period t and scenario w by DR (\$)

Constants

$C^{SU}_{i,t}$	start-up cost of unit i in period t (\$)
$C^{U,A}_{j,t}$, $C^{D,A}_{j,t}$	availability cost for upward/downward DR offered by aggregator j in period t (\$/MWh)
$C^{RU}_{i,t}$, $C^{RD}_{i,t}$	cost of upward/downward spinning reserve of unit i in period t (\$/MWh)
$C^{NS}_{i,t}$	cost of non-spinning reserve of unit i in period t (\$/MWh)
$L^{sh}_{j,t,w}$	load shedding of consumer j in period t and scenario w (MW)
$R^{U,d}_{i,t,w}$, $R^{D,d}_{i,t,w}$	deployed upward/downward spinning reserve by unit i in period t and scenario w (MW)
$R^{NS,d}_{i,t,w}$	deployed non-spinning reserve by unit i in period t and scenario w (MW)
$R^{U,s}_{i,t}$, $R^{D,s}_{i,t}$	scheduled upward/downward spinning reserve for unit i in period t (MW). Limited to $R^{U,\max}_i$, $R^{D,\max}_i$
$R^{NS,s}_{i,t}$	scheduled non-spinning reserve for unit i in period t (MW). Limited to $R^{NS,\max}_i$
$S_{q,t,w}$	wind power spillage of producer q in period t and scenario w (MW)
V^S_q	cost of wind power generation spillage of producer q (\$/MWh)
$T^U(j)$	time period that aggregator j offers for providing upward DR
$T^D(j)$	time period that aggregator j offers for providing downward DR
$VOLL_{j,t}$	value of lost load for consumer j in period t (\$/MWh).
$\lambda^E_{t,w}$	uniform price of energy in real time operation conditions at period t and scenario w (\$/MWh).
$\gamma^U_{j,t}(m)$	upward DR price of the m-th block of supply function offered by aggregator j in period t (\$/MWh).
$\gamma^D_{j,t}(m)$	downward DR price of the m-th block of supply function offered by aggregator j in period t (\$/MWh).
π_w	probability of wind power scenario w.
σ_j	load recovery coefficient offered by aggregator j

Ireland power grid, showing that by use of these programs Ireland's current generation portfolio could move from 11 to 40% renewable energy supply. However, the authors in [14] demonstrated that delays in the consumers' response to the price signals dramatically decrease the benefits of the DR in mitigating wind-uncertainty costs.

Some researchers have focused on incentive-based DR in the operation of the power systems [15–18]. The authors in [15] proposed an incentive-based DR program that facilitates the grid integration of wind power by reshaping the system load. Economic evaluation of the DR according to its potential for mitigating the wind power forecast error in the power system operation is proposed in [16]. Wu et al. [17] proposed a stochastic security-constrained unit commitment incorporating DR and storage program with the aim of managing renewable energy resources. Incorporating deferrable demand response resources and intermittent renewable resources in the stochastic unit commitment and economic dispatch models has been investigated in [18]. Falsafi et al. [19] proposed a stochastic model for scheduling energy and reserves provided by both the generating units and demand response providers (DRPs) with the aim of covering uncertainty of wind power.

Negnevitsky et al. [20] believe that as most existing approaches for DR scheduling consider only one or some participants' point of view, they may be unfair toward other participants. For example, all the above mentioned approaches deal with the DR scheduling from TSO's point of view without considering other DR beneficiaries (i.e. retailers and distributors). Maximizing an individual player's DR benefits may conflict with another individual's benefits [21]. Nguyen et al. [22] proposed a comprehensive approach for DR scheduling. They designed a separate market for trading DR, known as demand response exchange (DRX) market, in which DR is treated as a virtual resource to be exchanged between the DR buyers (TSO, retailers and distributors) and sellers (DRPs). Electricity consumers are the providers of the DR. They, via aggregators, can participate in the DRX market as DR sellers. The aggregators are independent agents that combine multiple consumers into a single unit to negotiate purchase from the retailers. The main advantage of using DRX market for DR scheduling is fair allocation of the incentive payments across all market participants [23]. A Walrasian [24] market clearing for the DRX market has been proposed in [25]. The