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Robust scheduling of variable wind generation by coordination of bulk energy storages and demand response

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ABSTRACT

The intermittent nature of wind generation will lead to greater demands for operational flexibility. Traditionally, reserves came from conventional power plants provide the majority of additional required flexibility leading to higher efficiency losses due to technical restrictions of such units. Recently, demand response programs and emerging utility-scale energy storages gained much attention as other flexible options. Under this perspective, this paper proposes a robust optimization scheduling framework to derive an optimal unit commitment decision in systems with high penetration of wind power incorporating demand response programs as well as bulk energy storages in co-optimized energy and reserve markets. In this regard, an improved demand response model is presented using the economic model of responsive loads based on customer's behavior concept that gives choice right opportunity to customers in order to participate in their desired demand response strategy. Moreover, bulk energy storages are considered to be as active market participants. Computational results demonstrate how coordinated operation of different type of demand response programs and bulk energy storages can help accommodate wind power uncertainty from the economic and technical points of view.

1. Introduction

In recent years, wind energy penetration has increased remarkably due to government policies and support schemes to drive more renewable energy into the power market and the prospect for deployment of wind energy continue to grow in the future. This high share of variable wind generation may cause to flexibility gap in two ways. On one hand, the stochastic nature of wind generation increase supply side variability and hence increases the need for additional flexibility. On the other hand, wind generation displaces part of flexible conventional units according to their merit order in dispatch and consequently reduces the available flexible capacity of power grid [1]. In the light of the mentioned changes, not only the average operating efficiency decreased but also the system reliability put at risk [2]. Having these impacts in mind, there is an essential need for a greater operational flexibility through new emerging flexible technologies.

The flexibility options are classified into five basic categories including supply side fleet, demand side options, energy storages, network utilization, and improvement of the system operation principles in [1]. Moreover, Ref. [3] presents the same categorization with the exception that market mechanisms is also considered as an independent option. However, the focus of the current paper is on the potential of Demand Side Management (DSM) and emerging bulk Energy Storages (ESs) as flexible technologies alongside conventional supply side power plants.

Demand Response (DR) is known as a powerful measure that has potential to facilitate grid integration of wind power. In this regard, a comprehensive investigation on the role of DR for handling renewable energy resource intermittency is conducted in [4]. Moreover, a wide range of potential benefits of DR in power system operation, planning, and market efficiency in future smart power grid is presented in [5].

DR can motivate consumers to increase their consumption when there is an extra amount of wind generation and also DR programs can encourage consumers to decrease their load when

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Nomenclature

Indices

b, b'	index of system buses
i	index of generating unit
j	index of bulk energy storage units
l	index of transmission line
m	segment index for linearized fuel cost
$Tpeak$	index of peak hours
ω	index of worst case
t, t'	index of hours
NM	number of segments for the piecewise linearized emission and fuel cost curves of units
NG	number of generation units
NES	number of bulk energy storage units
NT	number of hours under study
NB	number of network buses

Parameters

d_t^0	initial electricity demand at hour t (MW)
LD_b	demand contribution of bus b (MW)
C_{itm}^e	slope of segment m in linearized fuel cost curve of unit i at hour t ($/MW h)
MPC_i	minimum production cost of unit i ($)
ρ_t^0	initial electricity price at hour t ($/MW h)
ρ_t	electricity tariff in TBRDRPs at hour t ($/MW h)
C_{it}^{UC}	offered capacity cost of up-spinning reserve provision of unit i in hour t ($/MW)
C_{it}^{DC}	offered capacity cost of down-spinning reserve provision of unit i in hour t ($/MW)
C_{it}^{NSR}	offered capacity cost of non-spinning reserve provision of unit i in hour t ($/MW)
C_{it}^{UE}	offered energy cost of up-spinning reserve provision of unit i in hour t ($/MW h)
C_{it}^{DE}	offered energy cost of down-spinning reserve provision of unit i in hour t ($/MW h)
$C_{jt}^{ES,Energy}$	offered energy cost of bulk energy storage j at hour t ($/MW h)
$C_{jt}^{ES,U}$	offered capacity cost of up-spinning reserve provision of bulk ES j at hour t ($/MW)
$C_{jt}^{ES,D}$	offered capacity cost of down-spinning reserve provision of bulk ES j at hour t ($/MW)
$C_{jt}^{ES,NSR}$	offered capacity cost of non-spinning reserve provision of bulk ES j at hour t ($/MW)
C_{jt}^{UE}	offered energy cost of up-spinning reserve provision of bulk ES j at hour t ($/MW h)
C_{jt}^{DE}	offered energy cost of down-spinning reserve provision of bulk ES j at hour t ($/MW h)
C_b^{wind}	offered energy cost of wind power producer of bus b ($/MW h)
$C^{spillage}$	cost of wind power curtailment ($/MW h)
$VOLL_{bt}$	value of lost load in bus b at hour t ($/MW h)
A_t	incentive payment at hour t ($/MW h)
η_A	incentive's weighting coefficient
W_{bt}^*	forecasted value of wind generation in bus b at hour t ($/MW h)
η_{Ch}/η_{DeCh}	charge/discharge efficiency of bulk ES
$Elas_{tt'}$	price elasticity of demand
$P_i^{\min}/P_i^{\max}$	minimum/maximum output limit of generation unit i (MW)
RU_i/RD_i	ramp up/down of generation unit i (MW h^{-1})
SC_i	start-up cost of generation unit i ($)
MUT_i/MDT_i	minimum up/down time of generation unit i (h)
$P_j^{ChES,\max}/P_j^{DeES,\max}$	maximum charging/discharging power of bulk ES j (MW)
$E_j^{ES,\min}/E_j^{ES,\max}$	minimum/maximum energy limit of bulk ES j (MW h)
α_j	percent of initial energy level of bulk ES j
$E_{j,initial}^{ES}$	initial state of the charge of bulk ES j at the beginning of scheduling horizon
X_l	reactance of line l
$F_l^{\max}$	maximum capacity of transmission line l (MW)
τ	spinning reserve market lead time (h)

Variables

$\delta_{bt}^0/\delta_{bt\omega}$	voltage angle at bus b in hour t (rad)
$F_{lt}^0/F_{lt\omega}$	power flow through line l in hour t (MW)
U_{it}	binary status indicator of generation unit i in hour t
$I_{jt}^{DeBatt}/I_{jt}^{ChBatt}$	binary indicator of net discharge/charge status of bulk BES j
$LS_{bt\omega}$	involuntary load shedding in bus b at hour t of worst case (MW h)
$WS_{bt\omega}$	wind power spillage in bus b at hour t of worst case (MW h)
P_{itm}^e	generation of segment m in linearized fuel cost curve (MW)
d_t	modified demand of hour t after simultaneous IBDR and TBRDR programs (MW)
d_t^{TBRDRP}	modified demand of hour t after implementing only TBRDRPs (MW)
P_{it}	total scheduled power of unit i in hour t (MW)
SUC_{it}	start-up cost of generation unit i at hour t ($)
$P_{it}^{usr}/P_{it}^{dsr}$	scheduled up- and down-spinning reserve capacity of unit i in hour t (MW)
P_{it}^{nsr}	scheduled non-spinning reserve capacity of unit i in hour t (MW)
$P_{jt}^{ChES}/P_{jt}^{DeES}$	scheduled charge/discharge power of bulk ES j at hour t (MW)
$P_{jt}^{usr}/P_{jt}^{dsr}$	scheduled up- and down-spinning reserve capacity of bulk ES j in hour t (MW)
P_{jt}^{nsr}	scheduled non-spinning reserve capacity of bulk ES j in hour t (MW)
$sr_{it\omega}^U/sr_{it\omega}^D$	deployed up- and down spinning reserve of unit i at hour t of worst case (MW h)
$sr_{jt\omega}^{ES,U}/sr_{jt\omega}^{ES,D}$	deployed up- and down spinning reserve of bulk ES j at hour t of worst case (MW h)
E_{jt}^{ES}	energy stored in bulk ES j at hour t (MW h)

the wind power output is low. This rationale mechanism reshapes the load profile of the system and result in a flatter net load (load minus wind power) and potentially reduces the need for up and down ramping services. In this regard, Parvania and Fotuhi-Firuzabad [6] propose a load reduction DR program in order to achieve a smoother load profile and decrease the steep ramps of the net load caused by wind generation in a market-based environment. The drawback with this work is that the DR program used in this research only provides load reduction and the effects of load recovery is not studied. Yousefi et al. [7] has gone a step further by considering load reduction as well as load recovery using the self and cross price elasticity concept. However, the mentioned study used a deterministic approach while wind power has a stochastic nature.

The impacts of different types of DR programs on the operation of conventional units in the presence of variable wind generation is