Applied Energy 179 (2016) 338–349

Contents lists available at ScienceDirect

Applied Energy

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

Flexible interaction of plug-in electric vehicle parking lots for efficient wind integration

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HIGHLIGHTS

- Interactive incorporation of plug-in electric vehicle parking lots is investigated.
- Flexible energy and reserve services are provided by electric vehicle parking lots.
- Uncertain characterization of electric vehicle owners' behavior is taken into account.
- Coordinated operation of parking lots can facilitate wind power integration.

ARTICLE INFO

Article history:
Received 13 February 2016
Received in revised form 2 June 2016
Accepted 29 June 2016

Keywords:
Electricity market
Parking lot
Plug-in electric vehicles
Stochastic programming
Wind integration

ABSTRACT

The increasing share of uncertain wind generation has changed traditional operation scheduling of power systems. The challenges of this additional variability raise the need for an operational flexibility in providing both energy and reserve. One key solution is an effective incorporation of plug-in electric vehicles (PEVs) into the power system operation process. To this end, this paper proposes a two-stage stochastic programming market-clearing model considering the network constraints to achieve the optimal scheduling of conventional units as well as PEV parking lots (PLs) in providing both energy and reserve services. Different from existing works, the paper pays more attention to the uncertain characterization of PLs takes into account the arrival/departure time of PEVs to/from the PL, the initial state of charge (SOC) of PEVs, and their battery capacity through a set of scenarios in addition to wind generation scenarios. The results reveal that although the cost saving as a consequence of incorporating PL to the grid is below 1% of total system cost, however, flexible interactions of PL in the energy and reserve markets can promote the integration of wind power more than 13.5%.

1. Introduction

1.1. Motivation

The worldwide share of variable renewable energy sources especially wind power has achieved rapid promotion, so that based on the international energy agency (IEA) prediction, the annual wind-generated electricity of the world will reach 1282 TW h by 2020 which shows more than 370% rise in comparison with 2009 [1]. The emergence of such large-scale variable wind generation in near future presents new challenges for power system operators in two ways which result in a need for a greater flexibility. Firstly, wind generation increases the variability and uncertainty of the supply-side due to its stochastic nature and hence raises the need for flexibility. Secondly, wind generation displaces part of the conventional generation capacity due to its merit order in dispatch and consequently decreases the available flexibility of the system [2].

Traditionally, much of the required system flexibility has been obtained from conventional generation units. However, the flexibility characteristics of conventional units are restricted with their technical constraints including ramp rates, minimum stable outputs, minimum start, stop, up, and down times [3]. On this basis, the required flexibility will need to come either from conventional supply-side resources or from other flexible alternatives.

The plug-in electric vehicles (PEVs) have received remarkable attentions from policy makers' viewpoint and considered as a key element in future sustainable energy systems due to avoiding environmental pollutions and low oil dependency [4,5]. Moreover, PEVs are free from transportation for 96% time on average which makes it to a viable flexible option from power system operators' perspective [6]. Nowadays, there are many large-scale parking lots

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http://dx.doi.org/10.1016/j.apenergy.2016.06.145
0306-2619/

Nomenclature

Indices

B index of system buses $b = 1, \ldots, NB$
I index of generation units $i = 1, \ldots, NG$
J index of loads $j = 1, \ldots, NJ$
L index of transmission lines $l = 1, \ldots, L$
m index of segments of linearized fuel cost of generation units $m = 1, \ldots, NM$
n index of PEVs
pl index of parking lots $pl = 1, \ldots, NPL$
t index of time periods $t = 1, \ldots, NT$
$t_n^{arv/dep}$ index of arrival/departure time period of PEV n
wf index of wind farms $wf = 1, \ldots, NWF$
w index of scenarios $w = 1, \ldots, NW$

Parameters

$C_{i,t,m}^{G\_Eng}$ slope of segments in linearized fuel cost curve (\$/MW h)
$C_{i,t}^{G\_DC}$ offered capacity cost of down-reserve of units (\$/MW)
$C_{i,t}^{G\_DE}$ offered cost of down-deployed reserve of units (\$/MW h)
$C_{i,t}^{G\_UC}$ offered capacity cost of up-reserve of units (\$/MW)
$C_{i,t}^{G\_UE}$ offered cost of up-deployed reserve of units (\$/MW h)
$C_{pl,t}^{PL\_DC}$ offered capacity cost of down-reserve of parking lots (\$/MW)
$C_{pl,t}^{PL\_DE}$ offered cost of down-deployed reserve of parking lot (\$/MW h)
$C_{pl,t}^{PL\_Eng}$ offered energy cost of parking lots (\$/MW h)
$C_{pl,t}^{PL\_UC}$ offered capacity cost of up-reserve of parking lot (\$/MW)
$C_{pl,t}^{PL\_UE}$ offered cost of up-deployed reserve of parking lots (\$/MW h)
$C_{wf}^{WP\_spill}$ cost of wind power spillage (\$/MW h)
$cap_{n,t_n^{arv},t_n^{dep}}^{PEV}$ capacity of PEV n that arrived at pl at t^{arv} and departed from pl at t^{dep} (kW h)
$Cap_{pl,t}^{PL}$ aggregated battery capacity of parking lot (MW h)
$F_l^{\max}$ maximum capacity of transmission line l (MW)
$L_{j,t}^{C}$ consumed power by loads (MW)
MPC_i minimum production cost (\$)
MUT_i/MDT_i minimum up/down time of generation units (h)
$N_{t^{arv},t^{dep}}^{PEV}$ aggregated number of PEVs that arrived to pl at t^{arv} and departed from pl at t^{dep}
$N^{PL,\max}$ maximum car space capacity of the PL
$N_{pl,t}^{PL}$ aggregated number of PEVs in the parking lots
$P_i^{\min}/P_i^{\max}$ minimum/maximum output of units (MW)
$P_{wf,w,t}^{W}$ actual wind generation of wind farms (MW h)
$P_{wf,t}^{WP,\max}$ forecasted wind generation of wind farms (MW)
RU_i/RD_i ramp up/down of generation units (MW/h)
SC_i start-up cost (\$)
$SOC_{pl}^{\min}/SOC_{pl}^{\max}$ minimum/maximum SOC level of parking lots
soc_n^{PEV} initial SOC of PEV n at arrival time
$soc_{n,t_n^{arv},t_n^{dep}}^{PEV}$ SOC of PEV n that arrived to pl at t^{arv} and departed from pl at t^{dep}
$soc_n^{PEV,\min/\max}$ truncation region for the initial SOC of PEV n
$SOE_{pl,t}^{PL}$ aggregated state of energy of parking lot (MW h)
SUR_i/SDR_i start-up/shutdown ramp limit of generation units (MW/h)
$t_n^{arv,\min}/t_n^{arv,\max}$ truncation region for the arrival time of PEVs
$t_n^{dep,\min}/t_n^{dep,\max}$ truncation region for the departure time of PEVs
$VOLL_{j,t}$ value of lost load (\$/MW h)
X_l reactance of line l
γ^{charge} charging rate of PEVs (kW/h)
$\gamma^{discharge}$ discharging rate of PEVs (kW/h)
η_{Ch}/η_{DeCh} charge/discharge efficiency of parking lots
$\mu_{arv/dep/soc}$ mean value of the random variables including arrival/departure time and SOC of PEVs
ρ_w probability of scenario w
$\sigma_{arv/dep/soc}^2$ variance of the random variables including arrival/departure time and SOC of PEVs
τ spinning reserve market lead time (h)
ψ_t contract of a PEV owner for desired SOC

Variables

$F_{l,t}^0/F_{l,t,w}$ power flow through line l (MW)
$LS_{j,w,t}$ load shedding of load j (MW h)
$P_{i,t}$ total scheduled power of units (MW)
$P_{i,t,m}^{e}$ generation of segment m in linearized fuel cost curve (MW)
$P_{pl,t}^{En,G2PL}$ injected power of grid to pl (MW)
$P_{pl,t}^{En,PL2G}$ injected power of pl to the grid (MW)
$R_{pl,t}^{PL\_DC}$ scheduled down-reserve capacity for pl (MW)
$R_{pl,t}^{PL\_UC}$ scheduled up-reserve capacity for pl (MW)
$P_{wf,t}^{WP,S}$ scheduled wind power of wind farms (MW)
$P_{wf,w,t}^{WP\_spill}$ wind power spillage of wind farms (MW h)
$r_{i,t,w}^{G\_dn}$ real-time deployed down-reserve of units (MW)
$r_{i,t,w}^{G\_up}$ real-time deployed up-reserve of units (MW)
$r_{pl,w,t}^{PL\_dn}$ real-time deployed down-reserve of pl (MW)
$r_{pl,w,t}^{PL\_up}$ real-time deployed up-reserve of pl (MW)
$R_{i,t}^{G\_DC}$ scheduled down-reserve capacity of units (MW)
$R_{i,t}^{G\_UC}$ scheduled up-reserve capacity of units (MW)
$SOE_{pl,w,t}^{PL}$ state of energy of pl (MW h)
$SUC_{i,t}$ start-up cost of generation units (\$)
$U_{i,t}$ binary status indicator of generation units
$U_{pl,t}^{PL2G}/U_{pl,t}^{G2PL}$ binary status indicator of PL2G/G2PL operation mode of pl
$\delta_{b,t}^0/\delta_{b,t,w}$ voltage angle at bus b (rad)

(PLs) worldwide up to 10,000 spaces. If some part of these PLs designated for PEVs, they would be large enough to participate directly in the electricity markets, without any need to load service entities or aggregators. For instance, it is planned that about 62% of the entire U.S. vehicle fleet would be PEVs by 2050 [7]. If this happens, it would impose a great load on the power system that may jeopardize the power system operation [8].

In such situation, coordinated scheduling of PLs in both operation modes consist of PL-to-grid (PL2G), i.e. injecting the power from the PL back to the grid, and grid-to-PL (G2PL), i.e. drawing