Applied Energy 168 (2016) 724–738

Contents lists available at ScienceDirect

Applied Energy

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

Low carbon technologies as providers of operational flexibility in future power systems

Ivan Pavić *, Tomislav Capuder, Igor Kuzle

University of Zagreb Faculty of Electrical Engineering and Computing, Unska 3, Zagreb, Croatia

HIGHLIGHTS

- Mixed integer linear programming model for provision of multiple services from EV.
- EV energy and reserve services provision effects on power system operation.
- Impacts of conventional unit's decommission on system's operation and flexibility.
- Assessment of power system's flexibility under different wind generation polices.

ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form 29 January 2016
Accepted 30 January 2016
Available online 22 February 2016

Keywords:
Ancillary services
Electric vehicles
Flexibility
Power plant decommissioning
Reserve services
Wind curtailment

ABSTRACT

The paper presents a unit commitment model, based on mixed integer linear programming, capable of assessing the impact of electric vehicles (EV) on provision of ancillary services in power systems with high share of renewable energy sources (RES). The analyses show how role of different conventional units changes with integration of variable and uncertain RES and how introducing a flexible sources on the demand side, in this case EV, impact the traditional provision of spinning/contingency reserve services. In addition, technical constraints of conventional units, such as nuclear, gas or coal, limit the inherit flexibility of the system which results in curtailing clean renewable sources and inefficient operation. Following on that, sensitivity analyses of operational cost and wind curtailment shows which techno-economic constraints impact the flexibility of the high RES systems the most and how integration of more flexible units or decommission of conventional nuclear, coal and gas driven power plants would impact the system's operation. Finally, two different wind generation polices (wind penalization and wind turbines as reserve providers) have been analysed in terms of operational flexibility through different stages of conventional unit's decommission and compared with the same analyses when EV were used as reserve providers.

1. Introduction

Emerging integration of so called low carbon technologies (LCT), which are considered to be the essential link in creation of sustainable energy future, redefines operation and planning concepts of traditional energy systems. As the environmental goals of reducing CO_2 emissions drive the energy regulatory frameworks toward "all electric" systems by stimulating electrification of heat and transport, power system operators face the challenge of planning and operating increasingly variable and uncertain power systems [1]. While electric vehicles (EV) and, potentially, electrified heating (EH) act as sources of the variability and uncertainty from the demand side [2] integration of renewable energy sources additionally contributes to this from the supply side [3]. To alleviate the uncertain and variable nature of renewable energy sources (RES) new sources of flexibility become of critical value. Number of studies address the integration of different energy storage technologies (ES) [4–6] or demand response programs (DR) [7,8], but they rarely address the impact on power system operation planning and scheduling and how their integration impacts the existing generation units role in the system.

The capability of EV to participate in provision of energy arbitrage, ancillary services, as well as on their impact on distribution and transmission grid has gained much attention in recent literature. The authors in [9] proposed a multi-objective optimization model assessing the impact of EV on distribution grid, clearly showing how controlled charging in regards to uncontrolled brings benefits to daily distribution gird operation in multiple technical

* Corresponding author.
E-mail addresses: ivan.pavic@fer.hr (I. Pavić), tomislav.capuder@fer.hr (T. Capuder), igor.kuzle@fer.hr (I. Kuzle).

http://dx.doi.org/10.1016/j.apenergy.2016.01.123
0306-2619/

Nomenclature

Decision variables

$p_{t,i}^{g\_TP}$ thermal units generation
$p_{t,i}^{g\_HP}$ hydro units generation
$p_{t,i}^{g\_PS}$ pump storage generation/pumping
$p_{t,i}^{p\_PS}$ pump storage pumping
$p_t^{g\_WP}$ $p_t^{curt\_WP}$ wind power generation, wind power curtailment
$p_{t,i}^{c\_EV}$, $p_{t,i}^{d\_EV}$ electric vehicles slow charging/discharging
$p_{t,i}^{f\_EV}$ electric vehicles fast charging
$f_{t,i}^{up\_TP}$, $f_{t,i}^{dn\_TP}$, $r_{t,i}^{up\_TP}$, $r_{t,i}^{dn\_TP}$ thermal units primary(f)/secondary(r) up/down reserve provision
$f_{t,i}^{up\_HP}$, $f_{t,i}^{dn\_HP}$, $r_{t,i}^{up\_HP}$, $r_{t,i}^{dn\_HP}$ hydro units primary(f)/secondary(r) up/down reserve provision
$f_{t,i}^{up\_PS}$, $f_{t,i}^{dn\_PS}$, $r_{t,i}^{up\_PS}$, $r_{t,i}^{dn\_PS}$ pump storage primary(f)/secondary(r) up/down reserve provision
$f_{t,i}^{up\_EV}$, $f_{t,i}^{dn\_EV}$, $r_{t,i}^{up\_EV}$, $r_{t,i}^{dn\_EV}$ electric vehicles primary(f)/secondary (r) up/down reserve provision
$f_t^{up\_WP}$, $r_t^{up\_WP}$ wind turbines primary(f)/secondary(r) up reserve provision
$q_{t,i}^{up\_TP}$ thermal units tertiary up reserve provision
$c_{t,i}^{\_TP}$ total thermal power plant cost
$c_{t,i}^{\_HP}$ total hydro power plant cost
$c_t^{curt\_WP}$ wind power curtailment cost

Input parameters

P_t^d power demand
F_t^{up} primary up reserve requirements
F_t^{dn} primary down reserve requirements
R_t^{up} secondary up reserve requirements
R_t^{dn} secondary down reserve requirements
Q_t^{up} tertiary up reserve requirements
$P_t^{\_WP}$ potential wind power generation
PF^{curt_WP} penalty factor for wind power curtailment
$R_t^{EV\_0.5h}$, $R_t^{EV\_4h}$ secondary and tertiary reserve requirements increase caused by uncontrolled EVs charging
$\sigma_t^{sl(0.5h)\_EV}$, $\sigma_t^{sl(4h)\_EV}$ EVs uncontrolled charging standard deviation for secondary and tertiary reserve
$\sigma_t^{(0.5h)\_WP}$, $\sigma_t^{(4h)\_WP}$ wind power standard deviation for secondary and tertiary reserve

Input parameters

Ni_TP number of thermal technology types
Ni_HP number of hydro technology types
Ni_PS number of pump storage technology types
Ni_EV number of electric vehicles types
σ^d power demand standard deviation
P^{gmax} the largest online unit in power system
Δt time period (0.5 h) for energy calculation
$S_i^{0\_EV}$ energy conserved in (all) EVs in time step zero

Abbreviations

CCGT combined cycle gas turbine
HPP hydro power plant
EPS electric power system
ES energy storage
EV electric vehicle
G2V grid-to-vehicle
HP hydro power
LCT low carbon technologies
MILP mixed integer linear programing
NPP nuclear power plants
OCGT open cycle gas turbine
PS pump storage
RES renewable energy sources
TP thermal power
TSC total system cost
TSE total system emissions
UC unit commitment
V2G vehicle-to-grid
WPP wind power plant

and economic aspects. Similar to [9], the authors in [10] provides detail analyses of EV grid impacts and suggest DSO grid investment to support EV integration in order to better manage daily grid operations. Stochasticity of EV connection to the grid has been studied in [11] by optimization model updating if unexpected EV disconnections occur. Aggregating multiple EV units in a single market participant, so called virtual power plant, and coordinating their operation with different renewable and conventional generation units for future energy scheduling is proposed in [12]. Combined effects of high RES and EV integration is also analysed in [13] with different EV types and charging strategies emphasizing mutual benefits in scenarios with higher wind penetration. Improved utilization of wind and solar power, through flexible coordinated charging of EV has been discussed in [14] along with sensitivity analyses of different input parameters. Using EV as frequency controllers is proposed in [15] where it has been shown that EV can help utilize more variable RES by provision of frequency control. Automatic generation control (AGC) requirements are rapidly increasing with the uptake of RES, therefore, paper [16] proposes coordinated EV and battery storage frequency regulation supporting todays conventional frequency regulation providers. A novel stochastic–probabilistic energy and reserve market clearing scheme is proposed in [17], modelling plug-in vehicles (PEV) though a new market subject, a PEV aggregators. A bi-level optimization algorithm based on multiagent systems and dynamic game theory was developed in [18], modelling the oligopoly energy and reserve market. Authors in [19] use both EV and EH to improve efficiency of system and to allow higher integration of RES. Benefits of inteligent control of EV is researched in [20], where focus is put on analysing if EV can be used to substitute cross border capacities. Interesting review of EV technology's benefits and impediments can be found in [21–23]. As it can be seen from the above the topic of EV has been in focus in recent years, analysing its pros and cons from different perspectives, jointly concluding capability of EV to act as a provider of new flexibility will be one of key factors in determining the share of variable renewable sources in future power systems. However, it needs to be mentioned that none of the papers above elaborates how behaviour of conventional units changes taking into account both energy and reserve unit commitment plans. This paper provides a comprehensive analysis of EV as provider of spinning reserve services in future low carbon systems.