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A stochastic–probabilistic energy and reserve market clearing scheme for smart power systems with plug-in electrical vehicles

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ABSTRACT

In this paper, a novel stochastic–probabilistic energy and reserve market clearing scheme is proposed in the presence of plug-in vehicles (PEV) and wind power introducing a new model for PEV aggregators. The method is capable of managing the charging and discharging patterns of PEV aggregators. In this research, the total reserve for the day ahead market is detached into two different parts using the stochastic–probabilistic market clearing approach. The first part of the reserve is scheduled to overcome imbalances caused by uncertain generation and consumption. The second part of the reserve is procured in order to handle the probability of unit outages according to the reliability constraints. The approach is able to determine that how much of each types of reserves has to be provided by generation units or PEV aggregators. The PEV aggregators are modeled as large scale storage devices with stochastic capacities. The reliability formulations are linearized with the integration of the PEV aggregator models in order to form a mixed integer linear programming (MILP) problem. Finally, a multi-objective framework is formulated which considers the reliability metrics as an objective function instead of a constraint in addition to the total operation costs.

1. Introduction

In the recent years, concerns about environmental pollution and high fuel prices have gained interest for electrical vehicles as a promising alternative. The utilization of EVs in the future power grid will lead to many advantages including lower transportation costs and carbon emissions. According to these benefits, there is a high ambition for the transition of fossil fuel electric vehicles to plug-in electrical vehicles in many countries [1,2]. The unmanaged charging of EVs in the power system can cause many problems for the power system such as imposing additional operation costs and even jeopardizing the reliability of the system [3]. However if the charging and discharging of EVs is managed, these stochastic loads can contribute in providing the reliable and economic operation of power systems by the *V2G* procedure [4–6]. *V2G* is defined as utilizing electric vehicle fleets in order to provide energy and ancillary services such as spinning reserve for the power system [7–9].

Although PEVs are still in the development stage, different researches have been fulfilled to study the effects of PEVs on different economic, reliability, and environmental aspects of power systems [10–12]. For large scale power systems aggregators, can manage a number of PEVs parked in a certain area. Such PEV aggregators can act as a well-defined generation and storage system which is able to provide an additional generation capacity for handling the renewable power volatility and load forecasting error and also providing the reliability of the system due to the probability of unit generation outages. In the recent years, many papers have been conducted on modeling *V2G* (vehicle to grid) and the participation of PEV aggregators in energy and reserve markets. In [13], a framework is introduced for the optimal dispatch of electric vehicles for the economic dispatch problem. Refs. [14,15] present stochastic programming for solving the dispatch problem in the presence of PEV aggregators. In these researches the stochastic characteristics of PEV aggregators are modeled by probability distribution functions. A stochastic programming approach is introduced in [16] for the unit commitment problem. For PEV aggregators, different scenarios are generated. In [17–19], it is indicated that by the appropriate charging and discharging of electric vehicles economic benefits can be obtained. The capacity of electric vehicles is used in [20,21] to maximize the integration of renewable sources in the system. Also, [22] utilizes PEVs to manage distributed energy resources in a distribution system. Ref. [23] studies the effect of electric vehicles on the smart grid with the aim of decreasing operational costs. Smart parking lots

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Nomenclature

Indices

i	thermal generation unit
w	wind generating unit
pev	PEV aggregator
t	hour indices
s	scenario indices
j	generation unit outage

Parameters

NT	total number of hours
NG	total number of generation units
$Npev$	total number of PEV aggregators
NW	total number of wind generation units
ruw	up reserve deployed by element for load and generation imbalances (MW)
rdw	down reserve deployed by element for load and generation imbalances (MW)
$\gamma_{pev}^{V2G(G2V)}$	discharging (charging) cost of PEV aggregator ($/MW h)
γ_i^{ruw}	price of imbalance reserve up deployment by generation units for load and generation imbalances ($/MW h)
γ_i^{rdw}	price of imbalance reserve down deployment by generation units for load and generation imbalances ($/MW h)
γ_{pev}^{ruw}	price of imbalance reserve up deployment by PEV aggregators for load and generation imbalances ($/MW h)
γ_{pev}^{rdw}	price of imbalance reserve down deployment by PEV aggregators for load and generation imbalances ($/MW h)
ruc	reliability reserve procured by element for unit outages (MW)
γ_i^{rudc}	price of reliability reserve deployment by generation units for unit outages ($/MW h)
$V2G(G2V)$	discharging (charging) mode of PEV aggregators
SOC_{pev}	state of charge of the PEV aggregator (MW h)
γ_{pev}^{rudc}	price of reliability reserve deployment by PEV aggregators for unit outages ($/MW h)
$P_{i,max(min)}$	maximum(minimum) generation limit of generation unit (MW)
$LS_l(t,s)$	amount of load curtailed (MW)
π_s	probability of each scenario
$Load$	mean value of forecasting errors
σ	standard deviation of forecasting errors
$SOCs_{pev}^{max}$	available capacity of PEV aggregator for each scenario (MW h)
Ps_w	generation of wind units for each scenario (MW)
NS	total number of scenarios
b_i, c_i	cost coefficients of generators ($/MW h), ($/h)
P_i	generation of thermal units (MW)
u_i	commitment status of thermal generation units
$PEVA_{pev}$	amount of power provided by arrived vehicles (MW)
$RU(RD)$	ramp up (down) limit (MW)
$v_{pev}^{V2G(G2V)}$	binary variable specifying discharging (charging) mode for PEV aggregators
$vs_{pev}^{V2G(G2V)}$	binary variable specifying discharging (charging) mode for PEV aggregators for each scenario
$P_{pev}^{V2G(G2V)}$	discharged (charged) power by PEV aggregators (MW)
Δt	charging/discharging time interval (h)
SOC_{pev}^{max}	available capacity of PEV aggregator (MW h)
$SOCR_{pev}$	required power for PEV aggregator (MW)
$P_{pev,max}^{G2V(V2G)}$	maximum charging (discharging) limit of PEV aggregator (MW)
WS_w	amount of wind power curtailed (MW)
D	total load (MW)
U_i	unavailability probability of generation unit
v_r	rated speed (m/s)
v	wind speed (m/s)
v_{ci}	cut in speed (m/s)
v	wind speed (m/s)
c	scaling factor
$VOLL$	value of loss of load ($/MW h)
WSC_w	price of wind curtailment ($/MW h)
P_w	generation of wind units (MW)
Ds	total load for each scenario (MW)
v_{co}	cut of speed (m/s)
P_{rated}	rated power of the wind farm (MW)
Ds	total load for each scenario (MW)
$SOCs_{pev}$	state of charge of the PEV aggregator for each hour (MW h)

are used in [24] to decrease the system power loss and improve the voltage profile. Ref. [25] formulates a robust optimization framework for the dispatch of large scale V2G in the power system. All of these researches provide different models for the integration of electric vehicles or PEV aggregators, however reliability metrics are not considered in these researches.

Few literatures have studied the PEV capacity management for power system reliability improvement. In [26], although the impact of electric vehicles are investigated on the power system, the capacity of EVs are not managed to improve the reliability of the system. In [27], electric vehicles are used to increase the reliability of islanded distribution networks. In [28], the expected energy not supplied (*EENS*) parameter is used to assess the impacts of electric vehicles on power systems. In [29], the LOLP metric is used to assess the impact of PEVs on the reliability of the system. The results show that if the charging and discharging of electrical vehicles are managed properly the power system reliability can be enhanced. In [30], it is simulated that how can sufficient charging affect the generation system adequacy.

As mentioned in the main manuscript, electric vehicles will be one of the main components of smart power systems in the future. With the high penetration of these vehicles in the system without proper programming, additional costs can be imposed to the system while exacerbating the system reliability. However, by using the *V2G* procedure and considering the empty capacity of electric vehicle batteries a virtual storage system with a changing capacity can be added to the system. Hence, aggregating the available capacity of these electric vehicles by the PEV aggregator a large scale storage system can be integrated in the system. By the appropriate scheduling of the PEV aggregators, the operational costs can decrease. Also, the reliability of the system can be enhanced or a certain level of reliability can be obtained with a lower cost by the integration of the PEV aggregators in the system.

This paper presents a novel method for managing the participation of PEV aggregators in energy and reserve markets. A new formulation is presented which models PEV aggregators as storage devices with a stochastic capacity. The simultaneous energy and reserve market is presented as a stochastic–probabilistic MILP formulation. Two types of reserves are defined in this research. *Imbalance reserve* which is provided for overcoming the uncertainty caused by wind generation and load forecasting errors is the first type of reserve. The second type of reserve is defined as *reliability reserve* which is procured to overcome the probability of unit outages. This research determines that what portion of each type has to be provided by generation units and what portion has to be procured by PEV aggregators in order to satisfy a certain