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Risk management and participation planning of electric vehicles in smart grids for demand response

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A B S T R A C T

Demand response (DR) can serve as an effective tool to better balance the electricity demand and supply in the smart grid. It is defined as "the changes in electricity usage by end-use customers from their normal consumption patterns" in response to pricing and incentive payments. This paper focuses on new opportunities for DR with electric vehicles (EVs). EVs are potential distributed energy resources that support both the grid-to-vehicle and vehicle-to-grid modes. Their participation in the time-based (e.g., time-of-use) and incentive-based (e.g., regulation services) DR programs helps improve the stability and reduce the potential risks to the grid. Smart scheduling of EV charging and discharging activities also supports high penetration of renewables with volatile energy generation. This paper proposes a novel stochastic model from the Independent System Operator's perspective for risk management and participation planning of EVs in the smart grid for DR. The risk factors considered in this paper involve those caused by uncertainties in renewables (wind and solar), load patterns, parking patterns, and transmission lines' reliability. The effectiveness of the model in response to various settings such as the area type (residential, commercial, and industrial), the EV penetration level, and the risk level has been investigated.

1. Introduction

The overall sales of electric vehicles (EVs) have been steadily rising [1]. The worldwide sales of modern EVs have recently passed the one-million milestone as shown in Fig. 1. Multiple reasons have contributed to such an increasing trend in recent years. One reason is that significant savings can be achieved by driving EVs in place of traditional internal combustion engine vehicles. One example of a Nissan Leaf vs. a Toyota Camry is shown in Fig. 2[2]. In addition, EVs release almost no carbon dioxide (CO_2) or air pollutants at the time of usage. As EV sales boom, the market share of EVs will also likely to increase in the future. However, the current power grids in many countries are not fully prepared for a high EV penetration. Therefore, unmanaged charging of EVs may cause problems such as system overload, power losses, and voltage fluctuations [3]. To deal with EVs' additional load and mitigate these potential issues, appropriate charging control is required. In literature, a wide variety of models were proposed for charging planning of EVs [4–7]. Controlled charging during the valley hours (midnight to early morning) can partially reduce such issues and increase the utilization rate of existing infrastructure [8]. The charging service is commonly referred to as the grid-to-vehicle (G2V) service. Given the high battery capacity of EVs, they are also considered suitable distributed energy resources to discharge and feed power back to the grid when needed [9–11]. The discharging service is usually referred to as the vehicle-to-grid (V2G) service.

The G2V and V2G services have the potential to enable the power grid to accommodate various EV penetration levels through the demand response (DR) programs [12,13], without significant system upgrades. The main idea of DR is to encourage electricity users to manage their demand during peak periods or when system's safety is at risk [14]. DR programs can be divided into two categories: time-based and incentive-based. Major time-based DR programs include time of use (TOU) [15], real time pricing [16], and critical peak pricing [17]. A common feature of such programs is the varying electricity price over time. The price will be higher during the on-peak periods and lower during the off-peak periods. The time-varying price intends to level the load, i.e., shift the load from the on-peak periods to the off-peak periods [18,19]. As a result, not only the generation costs of power grid decreases considerably, the

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Abbreviations

DR	Demand response
EV	Electric vehicle
G2V	Grid-to-vehicle
ISO	Independent system operator
RBC	Remaining battery capacity
SOC	State of charge
TOU	Time of use
V2G	Vehicle-to-grid

Indices and ranges

a	Aggregator index
g	Generator index
j	Wind power system index
k	Bus index
l	Line index
n	Solar power system index
s	Scenario index
t	Time index
A	Total number of aggregators
G	Total number of conventional generators
J	Total number of wind power systems
K	Total number of buses
L	Total number of lines
N	Total number of solar power systems
S	Total number of scenarios
T	Planning horizon

Decision variables

$b_{a,t,s}$	G2V reserve provided by aggregator a in time t of scenario s
$c_{k,t,s}$	Renewable energy curtailment in bus k in time t of scenario s
$d^{+}_{a,t,s}$	Energy charged to aggregator a in time t of scenario s
$d^{-}_{a,t,s}$	V2G reserve provided by aggregator a in time t of scenario s
$f_{l,t,s}$	Energy flow through line l in time t of scenario s
$p_{g,t,s}$	Energy dispatched from generator g in time t of scenario s
$x^{V2G}_{a,t}$	Required V2G reserve of aggregator a in time t
$x^{G2V}_{a,t}$	Required G2V reserve of aggregator a in time t
$z_{k,t,s}$	Unmet load of bus k in time t of scenario s
$\theta_{k,t,s}$	Voltage angle at bus k in time t of scenario s

Binary dummy variables

$w_{t,s}$, $w'_{t,s}$, $w''_{t,s}$, $q_{a,t,s}$ Binary dummy variables

Dependent variables

$RBC^{Agr}_{a,t,s}$	RBC of aggregator a in time t of scenario s
$SOC^{Agr}_{a,t,s}$	SOC of aggregator a in time t of scenario s

Parameters

B_l	Susceptance of line l
C^{+Agr}_a	Cost of V2G reserve provided by aggregator a
C^{-Agr}_a	Cost of G2V reserve capacity for aggregator a
C^{Cur}_k	Cost of renewable energy curtailment at bus k
C^{UL}_k	Penalty cost for one unit of unmet load at bus k
C^{Gen}_g	Generation cost of generator g
C^{Ch}_t	Electricity price for charging EVs in time t
C^{Dch}_t	Discharged energy cost of EVs in time t
C^{Dis}_t	Discount for providing G2V service at time t
F^{max}_l	Maximum capacity of line l
$H_{l,k}$	Incidence matrix coefficient (-1, 0, or 1) at bus k of line l
M	A very large number (big-M)
P^{max}_g	Upper limit for power generation of generator g
P^{min}_g	Lower limit for power generation of generator g
P_s	Probability of occurrence of scenario s
R^{dn}_g	Ramp down limit of generator g
R^{up}_g	Ramp up limit of generator g
$SOC^{Agr}_{a,0}$	Initial SOC of aggregator a
$\alpha(l)$	Bus that line l starts
$\beta(l)$	Bus that line l ends
γ	User defined risk factor
η^{+Agr}_a	Charge efficiency of EVs for aggregator a
η^{-Agr}_a	Discharge efficiency of EVs for aggregator a

Random parameters

SOC^{-}_a	Desired leaving state of charge in percentage for aggregator a
SOC^{+}_a	Expected joining state of charge in percentage for aggregator a
$\delta_{l,t,s}$	Whether or not line l fails in time t of scenario s
$\lambda_{k,t,s}$	Load at bus k in time t in scenario s
$\pi^{+}_{a,t,s}$	Joining EVs' capacity of aggregator a in time t of scenario s
$\pi^{-}_{a,t,s}$	Leaving EVs' capacity of aggregator a in time t of scenario s
$\varphi_{j,t,s}$	Generation of wind system j in time t of scenario s
$\psi_{n,t,s}$	Generation of solar system n in time t of scenario s

EV owners pay less for their charging expenses. The EVs will be utilized only in the G2V mode when participating in the time-based DR programs. The TOU is recognized as the most efficient time-based tariff in reducing EVs' charging costs and emissions [20].

Incentive-based DR programs for EVs include frequency regulation and spinning reserve [21–24]. Such applications have not been widely implemented yet, but they have great foreseeable potentials [25,26]. Both programs are a part of ancillary services, which are designed to support the power grid's reliability and continuous flow of electricity so that supply will continually meet demand. The regulation service is a real-time service to balance load and power generation so that the frequency will be maintained within a specific range of the nominal frequency (e.g., 60 Hz). The frequency deviates from its nominal value when there is a mismatch between load and electricity supply. EVs can be utilized in both the G2V and the V2G modes when participating in the incentive-based DR programs. The regulation down service is implemented in the G2V mode when power generation exceeds the load, and the regulation up service is implemented in the V2G mode when the power generation is insufficient for the load [27,28].

Several studies examined the strengths, weaknesses, opportunities, and threats of using EVs for frequency regulation. The participation of EV owners is motivated by the additional revenue for the bidirectional energy flow [29]. Various techniques were proposed for cost benefit analysis of applying EVs in the V2G mode [30–32]. It was shown that the benefits justify the battery degradation and replacement expenses [33]. Han et al. [34] investigated