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Coordinated sectional droop charging control for EV aggregator enhancing frequency stability of microgrid with high penetration of renewable energy sources

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HIGHLIGHTS

- A coordinated sectional droop charging control strategy is proposed.
- An EV aggregator enhancing frequency stability of a microgrid is achieved.
- All the EVs participating in the frequency regulation work in charging mode.
- A virtual inertial damping method is adopted to avoid the charging power vibration.
- Proposed strategy improves the frequency stability as penetration of EVs increases.

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ABSTRACT

For microgrids with high penetration of renewable energy sources (RESs) and electric vehicles (EVs), the stochastic charging/discharging of the EVs would result in a large impact on the secure and stable operation of the microgrids. Therefore, the coordinated control between EVs and RESs becomes an important challenge for keeping the microgrid stable. In this paper, a coordinated sectional droop charging control (CSDCC) strategy is proposed for an EV aggregator that participates in the frequency regulation of the microgrids with high penetration RESs. All EVs are controlled as grid-friendly loads, and the CSDCC strategy operates as a virtual synchronous generator by only controlling the charging power of the EVs. Because the discharging of an EV is not required, the CSDCC strategy has no detrimental effects on the EV battery life. The inertia damping characteristic of a synchronous generator is modelled as a virtual inertia factor, which can eliminate charging power vibration, and can improve the system inertia. Finally, the validity of the proposed strategy in enhancing frequency regulation is verified by demonstrating a set of comparative cases.

1. Introduction

Considering the advantages of the Electric Vehicles (EVs) and Renewable Energy Sources (RESs) on the energy security and environment, an accumulative number of countries consider the development of EVs and RESs to be a key solution against emission reduction and sustainable development [1–4]. Therefore, significant attention has been drawn to the synergistic use of EVs and RESs [5]. Moreover, numerous systems integrating the EV charging facilities and RESs such as microgrids, and EV charging stations are being developed fast. However, with the increasing popularity of EVs, and the high penetration of RESs, which are of inherent uncertainty and randomness, an adverse impact on the secure and stable operation of the distribution grid or a standalone microgrid is anticipated.

In order to make full use of the EVs and RESs, many research efforts have been undertaken on integrating the EVs and RESs into the distribution grid [6–14]. From a distribution grid point of view, an urban-scale photovoltaic charging station for EVs is presented in [6]. The results show that the percentage of energy transfer from the photovoltaic (PV) system to the EVs range from 1%–3% to 56%–72%. In [2,7], the vehicle greenhouse gas reduction potential is studied. The results show that the EVs have certain potentials for green house gas (GHG) emission reduction with smart charging. In [8], the optimal scheduling of a local distribution system containing RESs and EVs is investigated, wherein wind turbines (WTs) and PVs are included, and the EVs are regarded as vehicle to grid (V2G) sources. In order to

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Nomenclature

$P_{force\,t\,h}$	minimum charging power of aggregator h in time interval t
$P^{M}_{rate\,j}$	rated charging power of controlled charged EV j
$P^{\mathrm{Un}}_{rate\,k}$	rated charging power of uncontrolled charged EV k
$K_{t\,h}$	number of EVs charged in uncontrolled mode in aggregator h in time interval t
$M_{t\,h}$	number of EVs charged in controlled mode and needs full-power charging in aggregator h in time interval t
$P_{c\,max\,t\,h}$	maximum charging power of aggregator h in time interval t
$N_{t\,h}$	number of EVs in aggregator h in time interval t
$P_{rate\,i}$	rated charging power of EV i
$P_{c\,grant\,t\,h}$	granted charging power of aggregator h in time interval t
$P_{dispatch\,t\,h}$	the power to be dispatched for normally controlled EVs in aggregator h in time interval t under rated frequency
$P_{c\,l\,t}$	charging power distributed to normally controlled EV l in time interval t
$\Delta SOC_{l\,t}$	difference between expected departure SOC and current SOC of EV l
$SOC_{dep\,l}$	expected departure SOC of EV l
$SOC_{l\,t}$	current SOC of EV l
$P_{rate\,l}$	rated charging power of normally controlled EV l
$P_{agg\,t\,h}$	the charging power of aggregator h in time interval t considering frequency deviation
ΔP	the charging power deviation caused by frequency deviation
f_N	rated frequency
f_{dL}	the lower frequency limit of frequency regulation dead zone
f_{dH}	the upper frequency limit of frequency regulation dead zone
f_{min}	minimum frequency that the aggregator will stop frequency regulation
f_{max}	maximum frequency that the aggregator will stop frequency regulation
f_{RL}	the lower frequency boundary of sectional droop FR curve
f_{RH}	the upper frequency boundary of sectional droop FR curve
P_{RL}	charging power associated with f_{R_L}
P_{RH}	charging power associated with f_{R_H}
$K_{EV\,1H}$	primary droop coefficient of frequency regulation in higher frequency
$K_{EV\,1L}$	primary droop coefficient of frequency regulation in lower frequency
$K_{EV\,2H}$	secondary droop coefficient of frequency regulation in higher frequency
$K_{EV\,2L}$	secondary droop coefficient of frequency regulation in lower frequency
$P_{dispatch\,t\,h\,f}$	the power to be dispatched for normally controlled EVs in aggregator h under frequency f
$P_{c\,l\,t\,f}$	the charging power distributed to the normally controlled EV l under frequency f
$\Delta P_{c\,l\,t}$	change of charging power distributed to the normally controlled EV l under frequency f

promote the PV-self consumption in a PV-based battery switch station, a novel charging strategy is proposed considering the EV's battery swap demand in [9]. The coordination between the EV batteries and the PV system is studied thoroughly in this work. In [10], the real-time price-based demand response for a PV charging station is proposed. The automatic demand response based on the coordination control of the EV's charging behavior is demonstrated to be beneficial to the electricity bill, peak load mitigation, and PV self-consumption. In [11], an optimum location technique and a charging management method are introduced for the EVs that support the distribution grid voltage and frequency profile while considering the EV charging and discharging. The EV owners can save electricity bills, and the demand stress on the network can be shifted using the proposed charging management scheme. In [12], the optimal location of EV parking lots in a distribution network is investigated along with the distribution reliability constraints. In [13], a novel method for optimal allocation and sizing problem of RES and EV charging stations simultaneously and managing vehicle charging process is presented as a multi-objective optimization problem, which can reduce power loss, voltage fluctuation, charging and demand cost, and EV battery cost. In [14], a novel power routing algorithm for clusters of microgrids interconnected in a meshed network is presented, which can solve the optimal power flow problem while considering congestion and power loss, and is suitable for large scale optimal power routing application.

In addition to the investigations conducted on integrating the EVs and RESs into the distribution grid, there have been reports of research efforts on standalone microgrids with high penetration RESs and large-scale EVs [15–19]. A predominantly-standalone network with WTs is modeled based on the trend of EV adoption rates in Norway in [15], and the smart charging strategy is compared with the dumb charging strategy. The result indicates that the smart charging, along with energy storage system, has key advantages on preventing peak charging demand, increasing the use of WT power, and reducing the dependency on spot market. In [16], the control and operation of predominantly-standalone fast charging station (FCS) with decentralized control system are studied. The FCS is structured as a medium-voltage direct current microgrid, and is composed of a PV system and a battery storage system. In [17], the coordinated operation of an industrial microgrid with multi-energy carriers and EVs is studied, which aims to minimize the overall cost of providing electricity and heat based on an optimal power flow method. In order to solve the EV charging issues on a remote island, a real-time energy management scheme is proposed for an EV charging system located in a microgrid with a PV system and an energy storage system [18]. This reference also indicates that the energy supplied by the PV system reduces the burden on the microgrid significantly, which it is more economical than charging from a standalone generator. For a standalone microgrid composed of multi-energy resources, an energy management system is proposed in [19]. This system has a hierarchical structure aiming to minimize the operational cost and to guarantee real-time power balance while maintaining a safe range of diesel generation operation. The research in [20] demonstrates that the demand response resources are more profitable than the conventional fossil fuel generation. An economic evaluation is performed considering a standalone microgrid supplied by a biomass gasification plant.

All the investigations relating to standalone microgrids composed of RESs and EVs aforementioned focus mostly on the economic dispatch issues, but seldom on the issue of frequency enhancement by controlling the EV's charging behaviors. With regard to frequency enhancement, a V2G technique is studied in [21], where a V2G control scheme consisting of frequency droop control and scheduled charging is proposed. In [22], an autonomous energy management strategy is proposed for the EVs involved in frequency regulation. A rule-based decision-making method is studied considering the V2G and EV's charging demand. A coordinated control strategy for large-scale EVs and energy storage devices involved in frequency regulation is presented to improve the frequency stability, and to facilitate the integration of renewable energy [23]. In [24–26], variations of decentralized frequency control schemes to maintain the power grid frequency stability are proposed. The investigations presented in [21–26] concluded that the