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An optimal dispatching strategy for V2G aggregator participating in supplementary frequency regulation considering EV driving demand and aggregator's benefits ☆

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HIGHLIGHTS

- A dispatching strategy for V2G aggregator participating in frequency regulation.
- Satisfying EV driving demand and maximizing benefits of aggregator simultaneously.
- A driving demand calculation module is used to obtain the required EV battery SOC.
- An optimal regulation power calculation model is designed to optimize aggregator profits.
- A regulation power allocation model is built to allocate regulation power to EVs.

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ABSTRACT

With the development of Vehicle-to-Grid (V2G) technology and increasing number of electric vehicles (EVs) integrating in power grid, supplementary frequency regulation service provided by V2G aggregator has been seen as the most promising grid ancillary service provided by the integrated EVs. In this paper, an optimal dispatching strategy of V2G aggregator is proposed to satisfy the driving demand of EV owners and maximize the economic benefits of aggregator simultaneously when it participates in supplementary frequency regulation. A judgment module is designed to determine EVs in aggregator whether participating in frequency regulation according to EV battery SOC for EVs' driving demand, which is calculated by EVs' daily driving distance. An optimal regulation power calculation model is built to optimize profits of aggregator and tracking performance of frequency load control signal from grid operator. A fair regulation power allocation module is designed to avoid over-discharging of EVs in aggregator. Finally, the proposed strategy is implemented in the simulation experiments to demonstrate its effectiveness.

1. Introduction

Since 90s of last century, the environment pollution problems caused by traditional vehicle exhaust have attracted extensive public attentions. Especially, in recent years, the continuous increasing of vehicle makes these problems more and more serious. With the rapid development of technology of electric vehicles (EV), using EV instead of traditional vehicle has been considered as one of the most effective solutions [1]. Meanwhile, the amount of global EVs has increase dramatically year by year.

With the rapid increasing of EVs, the integrating of such large scale of EVs would bring great challenges to power grid operation. To promote the coordinated development of power grid and EVs, the concept of vehicle-to-grid (V2G) was proposed in 1997 [2]. In the past near twenty years, V2G technology has been received extensive researches and has become mature. By using V2G technology, EV chargers could be operated in bidirectional mode, i.e., EV batteries can be charged when they are plugged in power grid, the energy stored in the EV batteries can also be delivered back to the power grid [3].

Now, the EVs integrating in grid not only are charging loads, but also could be used as power generation and energy storage units in power grid [4]. They could be utilized to participate in grid ancillary services to maintain power grid's stability and security, such as frequency regulation [5], voltage regulation [6], spinning reserve

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Nomenclature

$R_{opt}(t)$	optimal regulation power of aggregator at time t
$R^n_{opt}(t)$	optimal regulation power of nth EV at time t
$P_{reg}(t)$	frequency regulation price at time t
$P_{em}(t)$	market electricity price at time t
N	the total number of EVs managed by EV aggregator
$SOC^n(t)$	battery SOC of nth EV at time t
$SOC^n_{\exp}$	battery SOC of driving demand of nth EV owner
$C^n_{\max}$	rated capacity of nth EV battery
$R^i_{ch\_\max}$	battery maximum charging power limitation of nth EV
$R^i_{disch\_\max}$	battery maximum discharging power limitation of nth EV
$S(t)$	frequency regulation command signal at time t

[7], load peak shifting [8] and so on. However, the capacity of single EV is too little to participate in these grid ancillary services. Thus, a concept of V2G aggregator is proposed, which introduces a centralized control system to control a large scale of EVs to provide grid ancillary services [9]. Considering the communication delay between grid operator and V2G aggregator, communication delay between V2G aggregator and each EVs controlled by aggregator, V2G aggregator commonly is used to participate in the supplementary frequency regulation service, which requires V2G aggregator to follow a load frequency control (LFC) signal [10–12], which is within the achievable power capacity of V2G aggregator. The dispatching strategy is the key for aggregator, which regulates the charging and discharging power of each EV to participate in grid frequency regulation. The dispatching strategy determines the feasibility and economics of V2G aggregator participating in supplementary frequency regulation.

Currently, the dispatching strategy for V2G aggregator participating in supplementary frequency regulation has become a research hotspot. Some dispatching strategies are proposed considering on the problem of satisfying EV's charging demand or driving demand when EV aggregator participating in supplementary frequency regulation [13–17]. To satisfy charging demand of EVs in aggregator, a dispatching strategy considering charging demands is proposed in [14]. To reduce the EV owner's cost and obtain the desired EV battery SOC when EV departs, a model predictive control based dispatching strategy is proposed in [15]. A dispatching strategy considering the operational status and mobility needs is proposed in [16]. In [17], a dispatching strategy is proposed to maximize the profit for the EV owner and satisfy EV charging demand during the whole parking time.

Meanwhile, many dispatching strategies are proposed to optimize the aggregator's profit when it participating in supplementary frequency regulation [17–22]. A dispatching strategy is proposed to maximize the revenue obtained from aggregator participating in the supplementary frequency regulation in [18]. To optimize aggregator's profit under electricity price uncertainty, the dispatching strategies considering the electricity price is proposed in [19,20]. In [21], a dispatching strategy is proposed to minimize the operating cost of aggregator when it participating in frequency regulation. In [22], a real-time welfare-maximizing regulation allocation based dispatching strategy is proposed to fairly allocate the regulation power capacity among the EVs. In [23], a dispatching strategy is proposed to optimize the aggregator's profit considering the fair allocation of charging or discharging power of EVs. A stochastic dynamic programming based dispatching strategy is proposed to optimize the charging and frequency regulation capacity bids of EVs in [24]. In [25], a robust frequency regulation scheduling algorithm is proposed to maximize the revenue of aggregator under the frequency regulation performance-based compensation scheme.

According to the mentioned above, the satisfying driving demand of EV and optimization of benefits of aggregator are the two main problems faced by EV aggregator dispatching strategy participating in supplementary frequency regulation. The first problem refers to the satisfaction of EV owners, the second problem refers to the attraction for V2G aggregator participating in frequency regulation. The above existing dispatching strategies have not considered on both of them comprehensively.

The contribution of this paper is the development of a novel optimal dispatching strategy for V2G aggregator participating in supplementary frequency regulation, to (I) optimizes the tracking performance of load frequency control signal, (II) satisfy EV owner's driving demand and maximize the economic benefits of V2G aggregator as much as possible in same time. The SOC for EV owner's driving demand is calculated by the daily driving distance information. A judge module is designed to determine which EVs in aggregator participating in frequency regulation. An optimal regulation power participating in frequency regulation calculation module is built for aggregator to optimize the profits of aggregator and tracking performance of frequency regulation command signal. A regulation power allocation module is designed to fairly allocate the charging or discharging power of each EV participating in frequency regulation based on their capacity.

The rest of this paper is organized as follows. In Section 2, the structure of V2G aggregator participating in supplementary frequency regulation is described. In Section 3, the principle and design objective of the proposed dispatching strategy are proposed. The detailed design of the proposed strategy is presented in Section 4. The results of simulation experiments are discussed in Section 5. Finally, the conclusion is presented in Section 6.

2. V2G aggregator participating in supplementary frequency regulation

V2G aggregator is a control center of EVs, which manages the charging and discharging behavior of each EV in aggregator. The system structure of V2G aggregator participating in supplementary frequency regulation is shown in Fig. 1.

As seen in Fig. 1, when aggregator participates in supplementary frequency regulation, aggregator receives load frequency control signal from grid operator and sends its participating power capacity information back to grid operator. Meanwhile, aggregator dispatches the charging or discharging power command to each EV according to the load frequency control signal, information of EV owner's requirements and state information of each EV. The aggregator plays a connector role between EVs and power grid.

3. The proposed dispatching strategy

3.1. Principle

The proposed dispatching strategy consists of driving demand calculation module, EVs participating frequency regulation judge module, optimal regulation power participating in frequency