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Dispatching strategies of electric vehicles participating in frequency regulation on power grid: A review

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ABSTRACT

Recently, with the rapid growth of electric vehicle (EV) and development of Vehicle-to-Grid (V2G) technology, EVs participating in frequency regulation service to support power grid operation has been seen as one of the most promising power grid ancillary services provided by EVs integrated in grid. The dispatching strategy of EVs determines the feasibility and efficiency of EVs participating in frequency regulation, which have been received extensive researches. This paper will review the current dispatching strategies of EVs participating in frequency regulation. At first, the system structure of EVs participating frequency regulation is introduced. The stability and economy of EVs participating frequency in grid are analyzed. Secondly, the existing dispatching strategies are categorized into strategies for stability problem and strategies for economy problem, which are discussed in detailed. Finally, the existing problems and the future researches in EVs participating in frequency regulation on power grid are summarized.

$SOC^n_{\min}$, $SOC^n_{\max}$ Minimum/Maximum SOC of EV n in %.

1. Introduction

Since the 90's of last century, with the rapid increase of number of vehicles, traditional vehicle exhaust emission has become one of the largest sources of air pollution. Meanwhile, global climate change and fossil energy shortage make EVs instead of the traditional vehicles receiving long-term attention all around the world. In recent years, the developments of motor and battery technology have accelerated this trend. The global number of EVs on road has exceeded 1,000,000 in 2015, according to International Energy Agency (IEA)'s 2016 Global EV Outlook [1]. Vehicles proportion would continue to grow rapidly in the coming decades in many countries. For example, according to data from [2], the number of EVs in 2020, 2030 and 2050 will account for 35%, 51% and 62% in American.

Large number of EVs integrated in power grid would bring great challenges for the power grid operation, the large charging load and its changes could bring great impacts on power grid. To solve these problem, Kempton and Letendre proposed the concept of V2G in 1997 [3]. The main idea of V2G is EV battery charge operates in bidirectional mode, i.e., EV batteries could obtain energy from power grid and the energy stored in them could be delivered back to power grid. Thus, the batteries of EVs could be used as energy storage devices or power resources to participate in the grid services. EVs integration could not only be charging loads in grid, but also can be used as energy storage units and generating units, to provide spinning reserve [4], frequency regulation [5], voltage regulation [6] and other ancillary services.

To promote the common development of power grid and EVs, utilizing EVs to provide power grid ancillary services has become an inevitable trend. In general, EVs are averagely parked for 22 h every day [7], capacity of their batteries could not be ignored. The EVs battery's characteristics of large capacity and fast response make EVs very suitable to participate in grid frequency regulation. Therefore, Participating in frequency regulation has become one of the most promising and practical ancillary service provided by EVs.

At present, EVs participating in frequency regulation has become a hot research topic. Dispatching strategies determines the feasibility and effectiveness of EVs participating in frequency regulation. Thus, in recent years, many scholars focus on the dispatching strategies to improve the grid frequency stability and make full use of EVs. The two main problems faced by EVs participating frequency regulation are grid frequency stability and economy when EVs participating in frequency regulation. To optimize the operation stability and economy of grid and EVs, many dispatching strategies are proposed. However, there strategies have different optimization objectives and background. Thus, this paper will comprehensively review and categorize the existing dispatching strategies of EVs participating in frequency regulation on power grid.

In this paper, the system structure and two ways of EVs participat-

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Nomenclature

Symbols	The meaning of the symbols
$R_{reg}(t)$	Power capacity of regulation at time t in kWh
$E(t)$	Charging energy of EV at time t in kWh
$P_{reg}(t)$	Frequency regulation price at time t in $/kWh
$P_r(t)$	Unit price of power from grid at time t in $/kWh
$P_{regUp}(t)$, $P_{regDown}(t)$	Price of regulation up/down at time t in $/kWh
$R_{regUp}(t)$, $R_{regDown}(t)$	Power of regulation up/down at time t in kWh
$SOC^n(t)$	State of charge (SOC) of EV n at time t in %

ing in frequency regulation are introduced. The stability and economy of EVs participating in frequency regulation are analyzed. The overviews of the existing dispatching strategies of EVs participating in frequency regulation are discussed in detail. Finally, the existing scheduling problem and the future research direction are summarized.

2. System structure of EVs participating in frequency regulation

There are two mode of system structure of EVs participating in frequency regulation, i.e., distributed dispatch system and centralized dispatch system [8].

In distributed dispatch system, the integration points of EVs locate in the public or private areas, which distribute widely. The grid operator controls each individual EV to participate in frequency regulation, as shown in Fig. 1. In centralized dispatch mode, the integration points of EVs locate in a charging station, a parking lot or a community, which are centralized distribution. An aggregator was used to control and manage each individual EV to participate in frequency regulation. The grid operator only manages the aggregators and it does not need to manage each individual EV, as shown in Fig. 2..

3. Stability and economy problem faced by EVs participating in frequency regulation

The problems faced by EV participating in frequency regulation mainly are in two aspects, stability problem and economy problem. The stability problem refers how to maintain the stability of grid frequency and provide frequency regulation services by control or management of the large scale EVs integrated in grid. The economy problem refers to how to increase EV owners or aggregator's benefits and encourage more owners and aggregators to participate in frequency regulation ancillary service. With the rapid increasing of EVs integrated into the grid, more and more researchers pay attention to the stability and economy analysis of EVs participating in frequency regulation.

3.1. Stability of EVs participating in frequency regulation

The stability criterion of grid frequency is the power generation must match the load consumption. A mismatch will cause the deviation of the grid frequency from the criterion operating point (50 Hz in China, 60 Hz in USA) [9]. There is a strict criterion of grid frequency fluctuation range.

The existing researches on stability of EVs participating in frequency regulation mostly focus on its effects on grid frequency stability and feasibility analysis. The feasibility and practicality of EVs participating in frequency regulation is evaluated in [3]. The impact of EVs integration and the technical potential of frequency response from EVs integrated in grid are analyzed in [9]. A project that EVs participate in frequency regulation service is demonstrated in [10]. The effects of autonomous distributed vehicle-to-grid on power system frequency control are evaluated in [11]. The role of EVs contributes to frequency response in the Great Britain power system is investigated in [12], the simulation results demonstrates that utilizing EVs to stabilize the grid frequency can significantly reduce frequency deviations. In [13], a quasi-Monte Carlo (QMC) based probabilistic small signal stability analysis (PSSSA) method is proposed to assess the power grid frequency stability when EVs participating frequency regulation.

3.2. Economy of EV participating in frequency regulation

The economy is the important factor to attract EVs participating in frequency regulation. The economy factors mainly are benefits of EV owners, aggregators and power grid operators. Most researches about economy focus on revenue evaluation, economic analysis of EV owners or the power grid operators, the fair allocation of regulation capacity and other economic problems.

3.2.1. Economy evaluation of EVs participating in frequency regulation

Currently, there still not exists a strict and standard analysis tool for the revenue evaluation of EVs participating in frequency regulation. However, it has shown its promising economic value for the grid and EV owners, which would be shown in following:

1) Reduce peak load through the reasonably charging and discharging behaviors. Thereby, reduce the cost of start of generation units to regulate peak and frequency deviation in power grid.
2) Compensate the grid fluctuation caused by intermittent renewable energy, increase the economy of the grid operation and reduce the cost of investment in the grid.
3) Improve the reliability of power supply. Thereby, reduce the cost of power grid maintenance.
4) Reduce charging cost of EV owners or EV aggregator, who also could obtain additional benefits through participating in frequency regulation.

3.2.2. Economy analysis

Now, how to increase EV owners' or aggregator's benefits became a research hotspot. It has been received more and more attention [14–19]. By using Swedish and German actual energy market data, the conditions EVs participating in frequency regulation which can generate revenues are analyzed in [15]. The opportunities for EVs to obtain revenues from participating in frequency regulation are evaluated in [16]. According to the simulation, its results demonstrate that under the reasonable dispatching strategy, EVs can not only reduce charging cost, but also can get additional revenue from the grid, which would inspire the EV owners participate in frequency regulation. The economic feasibility of V2G frequency regulation considering the EV battery wear is studied in [17]. An economic evaluation of revenues from primary frequency regulation for an EV aggregator managing EV fleet is discussed in [18]. The economic and environmental benefits obtained from electric delivery trucks participating in frequency regulation are analyzed in [19].

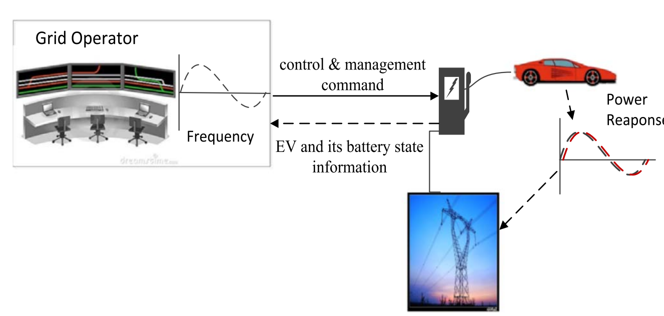

Fig. 1. The structure of distributed dispatch system.