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Grid frequency regulation strategy considering individual driving demand of electric vehicle

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ABSTRACT

The precondition for electric vehicles (EVs) to be involved in the system frequency regulation (FR) is that the owner's driving demand can be satisfied, which is the key factor in promoting vehicle owners to participate in system FR service. At present, many studies have proposed FR control strategy, but most of them are confined to the fleet level of EVs and ignore the individual level. And the individual demand of EV in FR process includes both satisfying the energy demand and reducing the harm to storage battery caused by the conversion between charge and discharge state. Accordingly, this paper firstly expounds the demand declaration strategy of EVs. Based on the declared information, the grouping strategy of EVs connected to the grid is proposed. Then the FR control strategy at the level of individual EV is elaborated. At last, the load frequency control (LFC) model considering the driving demand of EV is established. The simulation results show that the proposed control strategy can effectively satisfy the energy demand of individual EVs participating in FR, control the number of conversions between charging and discharging state, and achieve the aim of stabilizing system frequency fluctuation.

1. Introduction

As the energy crisis intensifies, as a representative of new energy vehicles, EVs have been recognized as the main direction of the automobile industry development in the 21st century. Countries around the world attach great importance to the development and promotion of electric vehicles [1,2]. The promotion of "One Thousand Vehicles in Ten Cities" pilot project and the private purchase of energy vehicle subsidy programs in China have provided a powerful impetus to the start-up and accelerated development of the domestic electric vehicle market [3].

The rapid development of EVs will have a tremendous impact on the power grid, thereby promoting the study of Vehicle-to-Grid (V2G) technology [4]. Meanwhile, FR ancillary service provided by EVs to the grid has gradually become one of the research hot spots [5,6]. The existing research elaborates the characteristics of EV's participation in grid FR service from the aspects of both feasibility and economy [7,8]. According to the fast response characteristics of EVs, the feasibility of EVs to provide FR service is showed in Ref. [8]. Ref. [7] elaborated on the economic feasibility of EVs to participate in system FR and used the data from NYISO to obtain the economic benefits brought by participating in FR.

With the increase of quantity of EVs, the individual participation of EV in grid FR service is getting more difficult to manage. Therefore, EVs are involved in FR in the form of EV fleet in most researches. Ref. [9] established the CPN controller by using the colored petri net (CPN) mathematical model to control the charging and discharging behaviors of EV fleet to participate in FR. Ref. [10] proposed a multi-objective decision-making methodology for the daily scheduling of EV fleet involved in FR. Ref. [11] takes the EVs in the parking lot as model objects. And through calculating and adding up the charging and discharging benefits of EV individuals during the FR process, the FR ancillary service income of the EV fleet is obtained.

Participating in FR in the form of EV fleet is relatively easy to manage, but the FR instructions are usually given only at the level of EV fleet, ignoring the FR strategy of individual EV. The method proposed in Ref. [12] combined the inertial emulation and droop control for EV fleet to be involved in primary frequency regulation, but ignored the control of single EV. Ref. [13] put forward a coordinated control strategy for FR in a grid with large-scale EV fleet and energy storage, in which the constraint of the state-of-charge of single EV was considered. However, this strategy ignored the damage resulted from frequent charge and discharge of the battery during FR process and the EV battery energy requirements after participating in FR service. In the control strategy of EV's participation in grid FR proposed by Ref. [14], queuing theory and fuzzy multi-criteria method are used to meet the

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Nomenclature

Acronyms

EV	Electric vehicle
FR	Frequency regulation
LFC	Load frequency control
V2G	Vehicle-to-grid
SOC	State-of-charge
EVA	Electric vehicle aggregator
TBC	Tie-line bias control
TBC-TBC	The combined tie-line bias control
ACE	Area control error

Indexes

T_i	The residence time in the gird
ρ_i	The credibility of EV
DC	The discharging group
C	The charging group
$SOC_{i,j}$	The SOC of the i-th EV at time j
T^*	The threshold of the residence time in the grid
SOC_{max}	The upper limit of EV battery SOC
SOC_{min}	The lower limit of EV battery SOC
Re	The energy demand group
d_i	The time when the i-th EV leaves the grid
T_i^D	The charging duration of the i-th EV to meet the driving demand
$P_{i,j}^r$	The charging power of the the i-th EV at time j in the energy demand group
m_i	The charging and discharging power limit of the i-th EV
Se	The frequency regulation service group
$\|DC_j^k\|$	The number of elements in the k-th discharging group at time j
$\|C_j^k\|$	The number of elements in the k-th charging group at time j
N_j^{dc}	The total quantity of EVs in the discharging group at time j
N_j^c	The total quantity of EVs in the charging group at time j
$TIME_{i,j}$	The number of charge–discharge conversion times of the i-th EV in frequency regulation service group at time j
P_{task}	The system frequency regulation demand power
$\overline{T}_i^a$	The i-th EV's historical average actual FR participating time
$\overline{T}_i^d$	The i-th EV's historical average declared FR participating time
ρ_{up}	The upper threshold of credibility
ρ_{down}	The lower threshold of credibility
R_{j+1}	The real-time predictive controllable capacity of all EVs for frequency regulation at time $j+1$
R_{j+1}^{up}	The real-time predictive controllable capacity of all EVs for up-regulation at time $j+1$
R_{j+1}^{down}	The predictive controllable capacity of all EVs for down-regulation at time $j+1$
Δf	The system frequency deviation
$\Gamma_{j+1}^{dc}(i)$	The unit participation time contribution of the i-th EV in the discharging group at time $j+1$
E_{ev}	The total battery energy storage of a single EV
η_c	The charging efficiency of EV
η_{dc}	The discharging efficiency of EV
T_{j+1}^{dc}	The set consisting of the unit participation time contribution of EVs in the discharging group sorted in descending order at time $j+1$
Q_{j+1}^{dc}	The set consisting of the EVs which are selected to discharge for FR at time $j+1$
P_{j+1}^{dc}	The up-regulation power output of the discharging group of EVA at time $j+1$
$\Gamma_{j+1}^{c}(i)$	The unit participation time contribution of the i-th EV in the charging group at time $j+1$
T_{j+1}^{c}	The set consisting of the unit participation time contribution of EVs in the charging group sorted in descending order at time $j+1$
Q_{j+1}^{c}	The set consisting of the EVs which are selected to charge for FR at time $j+1$
P_{j+1}^{c}	The down-regulation power output of the charging group of EVA at time $j+1$
P_{j+1}	The frequency regulation power output of EVA at time $j+1$
Ω_i	The frequency regulation participation rate of the i-th EV
Ψ_i	The frequency regulation utilization rate of the i-th EV
T_i^P	The time duration in which the i-th EV has continuous power input/output during the FR process
M	The inertia constant
D	The load damping coefficient
T_{delay}	The system delay time constant
$P_{unit,j+1}$	The FR demand power allocated to the traditional unit at time $j+1$
R	The governor speed regulation factor
T_g	The governor time constant
T_{ch}	The turbine time constant
B	The frequency deviation factor
T_{ACE}	ACE calculation time constant
AR_i	The arrival time of the i-th EV
DP_i	The departure time of the i-th EV on weekday
DS_i	The driving distance of the i-th EV on weekday
$Speed$	The driving speed of EV

personalized requirements of vehicle users for time and capacity, but the frequent charging and discharging behaviors of EV's battery during FR process were ignored. Ref. [15] puts up with a frequency management system which combines both droop response and inertial response to determine the frequency control command of EVs, but it ignores the limitation of charging–discharging conversion times of single EV.

Although a few studies have considered the FR control strategy at the individual level of EV, most of the researches neglected the restriction on frequent charging and discharging of EV batteries during FR process. Therefore, this paper proposes a load frequency control strategy applied to the individual level of EV. Through real-time prediction of EV's controllable capacity, EVs participate in the system FR under the premise of meeting the individual demand. In the FR process, the EV fleet is divided into the discharging group and the charging group. By limiting the frequency of EVs switching between the charging and discharging groups during the FR process, the purpose of controlling the frequent charging and discharging behaviors of EV battery is achieved.

The organization of the paper is as follows. Section 2 elaborates the structure of the demand declaration strategy. Section 3 describes the grouping strategy of EVs. The content of EV's FR power allocation strategy is outlined in Section 4. The FR model considering the driving demand of EVs is given in Section 5. And Section 6 presents the simulation results. Finally, some conclusions are summarized in Section 7.

2. EV demand declaration strategy

In the process of EVs accessing the grid to participate in system FR ancillary service, the demand declaration strategy framework is shown in Fig. 1. The electric vehicle aggregator (EVA) collects the declared demand information of EVs which are accessing the grid in real time,