Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Coordinated control for EV aggregators and power plants in frequency regulation considering time-varying delays

Hongjie Jia [a], Xiaomeng Li [a], Yunfei Mu [a,*], Chen Xu [b], Yilang Jiang [a], Xiaodan Yu [a], Jianzhong Wu [c], Chaoyu Dong [a]

[a] Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China
[b] National Grid Energy Services Ltd, Beijing 100032, China
[c] School of Engineering, Cardiff University, Cardiff CF24 3AA, United Kingdom

HIGHLIGHTS

- A coordinated control strategy for EVs and power plants in frequency regulation is presented.
- A robust stability criterion to determine delay margin of frequency control system is proposed.
- The time-varying delays and uncertain inertia are considered in the stability criterion.
- The control strategy can decrease frequency deviations and output variations of power plants.

ARTICLE INFO

Article history:
Received 13 April 2017
Received in revised form 17 May 2017
Accepted 26 May 2017
Available online xxxx

Keywords:
Electric vehicles
Load frequency control
Time-varying delays
Inertia uncertainty
Robust stability criterion
Load demand response

ABSTRACT

Nowadays, large scale intermittent renewable energy is being integrated to power systems as a solution for the low-carbon development worldwide. With the increasing penetration of renewable power generation, system frequency stability is becoming more and more serious. To increase the utilization of renewable energy, electric vehicles (EVs) are suggested to participate in load frequency control (LFC) through aggregators due to their vehicle-to-grid (V2G) capability and quick response characteristic, which is denoted as EV-LFC controller in this paper. In order to fully take the advantages of EVs in the LFC, this paper presents a coordinated control strategy between EV-LFC controller and traditional power plants based LFC (PP-LFC) controller for frequency regulation. In this strategy, the EV-LFC has a priority in response than the PP-LFC when the system deviation violates its acceptable range. However, the LFC integrating EVs is with inevitable time delays due to the data and control signal transmission. Meanwhile, the system inertia uncertainty caused by renewable energy in power system may also cause instability problem. For this reason, an improved robust stability criterion is proposed to estimate the asymptotically stable for LFC system considering the inertia uncertainty and time-varying delays simultaneously. Additionally, a PI controller for EV-LFC controller is used to enhance the system frequency stability. Finally, the effect of increasing EVs number on the frequency stability is investigated, which may guide system operator to utilize EVs to the LFC properly. Case studies are carried out based on a simplified Great Britain (GB) power system. Simulation results show that the proposed coordination strategy can not only provide effective frequency regulation, but also reduce the output of traditional power plants, in which the inertia uncertainty and time delays are properly considered.

1. Introduction

In order to pursue the low-carbon development around the world, a great deal of large scale intermittent renewable energy is being integrated to power systems. For examples, the wind generation is about 30 GW within a total generation capacity of 100 GW by 2020 in the United Kingdom [1], while the cumulative installed capacity of wind power will be 210 GW by the end of 2020 in China [2]. As a result, the difficulty in frequency regulation is arisen due to the imbalance between the stochastic power output of intermittent renewable energy and load demand, which is a prevailing issue in power system stability research. On the other side, the frequency problem will in turn limit the utilization level of renewable energy in power system and retard the further development of low-carbon power system.

* Corresponding author.
E-mail address: yunfeimu@tju.edu.cn (Y. Mu).

http://dx.doi.org/10.1016/j.apenergy.2017.05.174
0306-2619/

Please cite this article in press as: Jia H et al. Coordinated control for EV aggregators and power plants in frequency regulation considering time-varying delays. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.05.174

Nomenclature

$\mathbf{\Omega_A}$	EV aggregators set
$\mathbf{A}_i$	the i-th EV aggregator
N	number of the EV aggregator
$E_{i,j}$	the j-th EV in $\mathbf{A}_i$
n_i	EVs number in $\mathbf{A}_i$
$\boldsymbol{s}_{i,j}$	the status set of $E_{i,j}$
$\boldsymbol{S}_i$	the status set of $\mathbf{A}_i$
$\boldsymbol{P}_{i,j}$	power controllability of $E_{i,j}$
$\Delta P^{+}{}_{i,j}$	output controllability of $E_{i,j}$
$\Delta P^{-}{}_{i,j}$	absorption controllability of $E_{i,j}$
$\boldsymbol{P}_{\mathbf{A}i}$	power controllability of $\mathbf{A}_i$
$P_{\mathbf{A}i}{}^{+}$	output controllability of $\mathbf{A}_i$
$P_{\mathbf{A}i}{}^{-}$	absorption controllability of $\mathbf{A}_i$
$\boldsymbol{P}_{EV}$	power controllability of the EV-LFC controller
$P_{EV}{}^{+}$	output controllability of the EV-LFC controller
$P_{EV}{}^{-}$	absorption controllability of the EV-LFC controller
ΔP_{EV}^{D}	demand signal for the EV-LFC controller
$\Delta \boldsymbol{P}_{\mathbf{A}}{}^{D}$	demand signal set for aggregators
$\Delta P_{\mathbf{A}i}{}^{D}$	demand signal for $\mathbf{A}_i$
$\Delta \boldsymbol{P}_{i,j}{}^{D}$	demand signal set for $E_{i,j}$
$\Delta P_{i,j}{}^{D}$	demand signal for $E_{i,j}$
$\Delta \boldsymbol{P}_{\mathbf{A}}{}^{R}$	response signal set of $\mathbf{A}_i$
$\Delta P_{\mathbf{A}i}{}^{R}$	response signal of $\mathbf{A}_i$
$\Delta \boldsymbol{P}_{EV}$	response signal of the EV-LFC controller
ΔP_T	total power mismatch
P_T^G	total generation
P_T^L	total load demand
Δf	system frequency deviation
f_n	nominal frequency
ΔP_R	power to keep system frequency in acceptable range
ΔP_T^U	power mismatch at Δf^U
ΔP_T^L	power mismatch at Δf^L
Δf^U	upper limit of Δf
Δf^L	lower limit of Δf
ΔP_{PP}^{D}	demand signal for the EV-LFC controller
$K_{EVi,j}{}^{\mathrm{dis}}$	discharging coefficient of $E_{i,j}$
$K_{EVi,j}{}^{\mathrm{ch}}$	charging coefficient of $E_{i,j}$
$K_{\mathbf{A}i}$	charging/discharging coefficient of $\mathbf{A}_i$
K_P	PROPORTIONAL gain
K_I	integral gain
$d_i(t)$	the i-th time-varying delay
τ_i	upper bound of $d_i(t)$
μ_i	changing rate of $d_i(t)$
k	uncertainty of inertia

As rapid development of load demand response [3,4], electric vehicle (EV) can be used as a suitable source for the load frequency control (LFC) due to its vehicle-to-grid (V2G) capability. Based on the existing literatures, the motivations of deploying EVs as a promising type of demand side resource are listed as follows:

(1) The dispatch of EVs can be achieved through EV dispatch module, including mobile phone apps, charger, logic computer and database. The EV manufactures, owners, and power system operators can communicate and respond to different system operating states [5].
(2) The EVs customer acceptance of the participation in the demand response can be encouraged by the owners' behavior and rewards [6,7], which artificially motivate EVs to participate in the LFC.
(3) The charging and discharging of EVs are electromagnetic and chemical processes rather than mechanical processes. Therefore, the EVs have a much quicker response time than the traditional power plants to provide frequency response to the power system [8].
(4) The construction of EVs infrastructure is currently ongoing, where the charging/discharging modes and EVs' parking lots allocation can be optimized together with smart power distribution networks [9,10].

In view of above motivations, EVs have a great potential to be one of the most important participants in the demand side response. The EVs with V2G capability have the ability to provide spinning reserve [11], and act as an efficient power plant to decrease the frequent power variation of the traditional generator [12]. Many control strategies based on V2G were proposed to satisfy vehicle user convenience and provide frequency regulation simultaneously [13-15]. Coordination with heat pumps [16] or battery energy storage [8] can make the best use of EVs in assisting system frequency stability. Various LFC controllers based on different control theories, such as the fixed structure mixed H_2/H_∞ [17], output feedback H_∞ [18] and fuzzy control [19] were designed to enhance the robust performance against the system uncertainties. However, the time delays and parameter uncertainties in the LFC control loops are not fully considered in the LFC.

Time delays exist widely in the LFC control loops [20,21] especially when some low-cost and heterogeneous communication techniques are utilized to collect EVs' states or send control signals from control center to the individual EVs. The communication delay of EV dispatch module in the demand-side response is affected by the network signal intensity, download and upload speed, CPU speed and RAM size [5]. And the total operation time for a single optimization is 0.5–0.6 s. On the other hand, the large-scale of EVs with spatial distribution are controlled by different aggregators to participate in the LFC, which also leads to time delays in the control process. It is well known that the time delays usually result in control deterioration and system instability, or changing the system dynamic characteristics, such as the oscillation mode and system critical eigenvalues [22]. Consequently, the determination of delay margin that the system can sustain without losing its stability, is a key issue in the LFC controller designing. Some methods have already been proposed to determine the delay margin [20,23,24] in which the free-weighting method was widely used [25,26], due to its universality, simple usage and less conservatism. However, the method has low computational efficiency since a vast number of unknown variables are introduced which need to be calculated. And an analytical method to determine delay margin in [20] is invalid to cope with the time-varying delays. For this reason, a novel method to determine delay margin, which is used to treat the time-varying delays in the LFC controller will be proposed in this paper based on the method with high efficiency in [27].

Another issue discussed in this paper is the uncertainty of system inertial, which is affected by the intermittence of renewable power generation [28,29]. For example, the wind and photovoltaic generators are usually unable to provide inertia support during frequency event, and the resultant low inertia should be considered during frequency response process [30]. To cope with these problems, a roust stability criterion will be introduced into the EV based LFC (abbr. EV-LFC) controller designing to consider the uncertain inertia and time-varying delays simultaneously.

The main contribution of this paper is based on a proposed coordinated control strategy between the EV-LFC and traditional power plants based LFC (abbr. PP-LFC) controller in order to make the best use of EVs to decrease the system frequency deviations,