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A simple decentralized charging control scheme of plug-in electric vehicles for alleviating wind farm intermittency

Xiao Luo[a],*, Shiwei Xia[a], Ka-wing Chan[a]

[a]*Department of Electrical Engineering, The Hong Kong Polytechnique University, Hong Kong, China*

Abstract

Variable power output from large-scale wind farms present new challenge of balancing power system load with generation. To alleviate this problem, this paper proposes a decentralized charging control scheme for plug-in electric vehicles (PEVs) to neutralize wind power fluctuations. In the proposed scheme, each PEV autonomously adjusts its power in response to a real-time directing signal and based on its own urgency level of charging. No intelligent central control entity is needed. Simulation results demonstrate the effectiveness of the proposed charging control in directing PEV power to counteract wind power fluctuations. Also, proportionally fair distribution of counteracting duties among PEVs can be achieved so as to meet heterogeneous charging requirements of PEV users, and the total utility of the PEV fleet is proven to be maximized.

Keywords: Plug-in electric vehicle; decentralized charging control; heterogeneous charging requirements; wind power stabilization;

1. Introduction

Wind energy is currently incentivized in many countries. As the penetration level of wind power escalates, it would be increasingly difficult to keep the balance between system load and generation. Therefore, sufficient fast-reacting reserves are needed to accommodate large-scale wind farms. In the context of future smart grids, a multitude of plug-in electric vehicles (PEVs) are of great potential to provide massive fast reserve. In [1, 2], two PEV-integrated frequency control methods were proposed, all of which, however, adopt fully centralized approach to the PEV charging control. For a large and dispersedly located population of PEVs, a decentralized charging control scheme is generally more desired than a centralized one. This paper proposes a decentralized charging control scheme for numerous PEVs to counteract fluctuations in wind farm power output. The counteracting duties are distributed among PEVs in accordance with the heterogeneous charging requirements of PEV users. Because of the simplicity of the proposed scheme, it is fast enough for real-time application and is readily implementable.

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* Corresponding author. Tel.: +852 90643341; fax: +852 23301544.
E-mail address: luo.xiao.peter@connect.polyu.hk.

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2. The proposed decentralized PEV charging control scheme

2.1. PEV side: the urgency level of charging and the protocol of PEV power adjustment

Grid-connected PEVs are differentiated by their urgency level of charging. The urgency level of charging reflects how desirous a PEV is of grid-to-vehicle (G2V) charging power or oppositely how undesirous it is of vehicle-to-grid (V2G) discharging power, in order to satisfy the desired battery state-of-charge (SOC) upon the planned departure time. Therefore, the urgency level of charging μ is defined as a function of the battery capacity that can be fulfilled before the planned departure time and to be fulfilled from the current SOC to the desired SOC.

$$\mu_{i,t} = 1 \Big/ \left(P_{i,\max} \cdot \eta_p \cdot (T_i - t) / C_{\mathrm{batt},i} - (\mathrm{SOC}_{i,\mathrm{desired}} - \mathrm{SOC}_{i,t}) \right) \tag{1}$$

where $C_{\mathrm{batt},i}$ is the nominal battery capacity of PEV$_i$; $P_{i,\max}$ is the maximum charging power of PEV$_i$; η_p is the charger efficiency; T_i is the planned departure time of PEV$_i$; and t is the present time. The denominator of (1) is defined as the battery capacity margin (BCM) of PEV$_i$. Once BCM$_i$ drops below a preset threshold value (BCM$_\mathrm{threshold}$), PEV$_i$ will switch from responsive state to nonresponsive state. The nonresponsive PEV$_i$ will absorb its maximum charging power $P_{i,\max}$ and stop adjusting its power to counteract wind power fluctuations. This mechanism is to ensure that every PEV could satisfy its desired SOC before its planned departure time, i.e. the PEV user's charging requirement.

On the other hand, a responsive PEV would adjust its power in response to the grid-side directing signal, which will be defined in the next section. Individual PEV's contribution to the total counteracting power is proportional to the PEV's urgency level of charging when G2V counteracting power is on demand, and is inversely proportional to its urgency level of charging when V2G counteracting power is needed. The protocol of PEV power adjustment is summarized as follows:

$$P_{i,t} = \begin{cases} P_{i,\max}, & \mathrm{BCM}_i < \mathrm{BCM}_\mathrm{threshold} \\ sign(D_t) \cdot \min\left(P_{i,\max},\ \mu_{i,t}^{\,sign(D_t)} \big/ |D_t| \right), & \mathrm{BCM}_i \geq \mathrm{BCM}_\mathrm{threshold} \end{cases} \tag{2}$$

where D_t is the real-time directing signal at t; and $sign(D_t) = +1$ and -1 for $D_t > 0$ and $D_t < 0$, respectively.

2.2. Grid side: the real-time directing signal

In the proposed charging control scheme, a real-time signal is used to direct the responsive PEVs to adjust their power such that the aggregate PEV power can follow the varying wind power. Measurement on wind farm power output and data of charging power of responsive PEVs would be transmitted to an information hub, where the directing signal is updated as follows:

$$D_t = sign(P_{\mathrm{wn},t}) \cdot \left| D_{t-1} + \beta\left(\textstyle\sum_{i=1}^{n} P_{i,t-1} - P_{\mathrm{wn},t}\right) \right| \tag{3}$$

where β is a parameter affecting the rate of change of the directing signal; $P_{i,t-1}$ is the power of responsive PEV$_i$ in time slot $t-1$; n is the number of responsive PEV; and $P_{wn,t}$, the difference between the actual and forecasted wind farm power output, represents the wind power fluctuation to be counteracted at t. The directing signal would be broadcasted to all PEVs under control. Upon receiving D_t, if PEV$_i$ is in responsive state, its smart charger would adjust its charging power according to the second equation in (2), and then transmit the new charging power data back to the information hub. The sign of D_t follows that of the wind power to be counteracted, which indicates whether G2V or V2G counteracting power is needed. To avoid numerical difficulty, PEVs will not respond to D_t when D_t is 0.

2.3. Proof of the counteracting power distribution efficiency

The efficiency of the counteracting power distribution among responsive PEVs can be evaluated by considering the total utility of the responsive PEVs. Each PEV$_i$ is associated with a logarithmic utility function which satisfies the law of diminishing returns [3]: $u_{i,t} = sign(D_t)\cdot \mu_{i,t}{}^{sign(Dt)} \log\left|P_{i,t}\right|$. Thus, the problem of maximizing the total utility of the responsive PEVs is formulated as follows:

$$\max_{\boldsymbol{P}}\ U_t(\boldsymbol{P}) = sign(D_t)\cdot \sum\nolimits_{i=1}^{n}\left(\mu_{i,t}{}^{sign(D_t)}\log\left|P_{i,t}\right|\right),\qquad \text{subject to}\quad \sum\nolimits_{i=1}^{n} P_{i,t} = P_{\mathrm{wn},t} \tag{4}$$

where $P_{i,t} \in \boldsymbol{P},\ \forall i = 1,2,...,n$. The G2V case ($D_t$>0) is analyzed here as an example. Applying Lagrange multipliers to Problem (4): $\nabla U_t(\boldsymbol{P}) = \lambda\nabla(\sum\nolimits_{i=1}^{n} P_{i,t} - P_{\mathrm{wn},t})$, from which $P_{i,t}$ can be expressed in terms of λ: $P_{i,t} = \mu_{i,t}/\lambda_{\mathrm{G2V}}$. Together with the constraint in Problem (4), it can be found: $\lambda_{\mathrm{G2V}} = \sum \mu_{i,t} / P_{\mathrm{wn},t}$. Thus, the solution to Problem (4) is $P_{i,t} = P_{\mathrm{wn},t}\cdot \mu_{i,t}/\sum \mu_{i,t}$ when G2V counteracting power is needed.

In the proposed charging control scheme, given a positive amount of wind power fluctuation to be counteracted (P_{wn}>0), when the PEV power adjustment converges to an equilibrium, $P_{i,t} = \mu_{i,t}/D_{t,\mathrm{eq}}$, where $D_{t,\mathrm{eq}}$ is the directing signal at equilibrium characterized by $dD_{t,\mathrm{eq}}/dt = 0$. According to (3), the zero rate of change of D_t indicates that $\sum P_{i,t} = \sum P_{i,t-1} = P_{\mathrm{wn},t}$. Thus, $\sum P_{i,t} = \sum \mu_{i,t} / D_{t,\mathrm{eq}} = P_{\mathrm{wn},t}$. Then $D_{t,\mathrm{eq}}$ can be obtained as $D_{t,\mathrm{eq}} = \sum \mu_{i,t} / P_{\mathrm{wn},t}$, and for responsive PEV$_i$: $P_{i,t} = \mu_{i,t}/D_{t,\mathrm{eq}} = P_{\mathrm{wn},t}\cdot \mu_{i,t}/\sum \mu_{i,t}$. This solution is exactly the same as the solution to Problem (4) for the G2V case. The V2G case can be proven in the similar way. Therefore, the charging power profile formed under the proposed charging control can maximize the total utility of the responsive PEVs. The distribution of counteracting duties among responsive PEVs is therefore proven to be efficient where proportional fairness is achieved.

3. Simulation results

In the simulation, a 70 MW wind farm and a fleet of 2400 PEVs are considered. The charging period spans 5 hours. The initial SOC is between 30-50% and the desired SOC is 95%. The planned departure time is between the 3rd and the 5th hour. The 24 kWh PEV battery model [4] is adopted and the maximum charging power is 5 kW. The wind farm power is measured once every 30s. The value of β in (3) depends on the size of wind farm and the number of PEV. In the simulation of wind power compensation $\beta = 0.04$.

Fig. 1 shows a basic simulation where 10 responsive PEVs with urgency level of charging μ from 1 (PEV 1) to 10 (PEV 10) take 30 kW G2V power first and then supply -20 kW V2G power. At t = 240s, the values of μ_1, μ_2, and μ_3 are changed from 1, 2, and 3 to 16, 22, and 28, respectively. $\beta = 0.005$. From Fig. 1, it can be seen that when being charged each PEV converges to a positive power proportional to their value of μ. When being discharged, a PEV with larger μ supplies less V2G power. After t = 240s, the V2G power distribution autonomously converges to a new equilibrium profile consistent with the increased μ_1, μ_2, and μ_3.

Fig. 2 shows the results of wind power fluctuation counteraction. It can be observed from Fig. 2(a) that under the proposed decentralized charging control, the aggregate power of responsive PEVs can accurately track the variation of the wind power. The resultant stabilized wind power profile shown in Fig. 2(b) is much less fluctuating. Fig. 2(c) displays the SOC of 3 PEVs with the same initial and desired SOC but different planned departure time. It can be seen that the PEV with earlier departure time receives more charging power and all three PEVs obtain desired SOC upon their planned departure times. This example confirms the ability of the proposed charging control scheme to fulfill PEV users' heterogeneous charging requirements by discriminative charging.

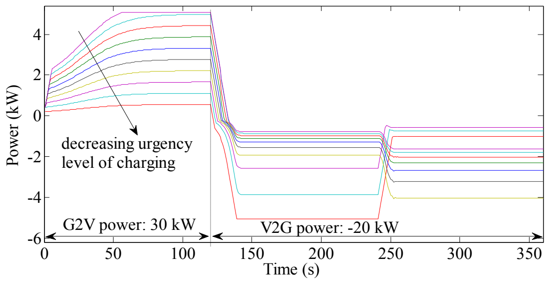

Fig. 1. G2V/V2G power distribution among PEVs with different urgency level of charging

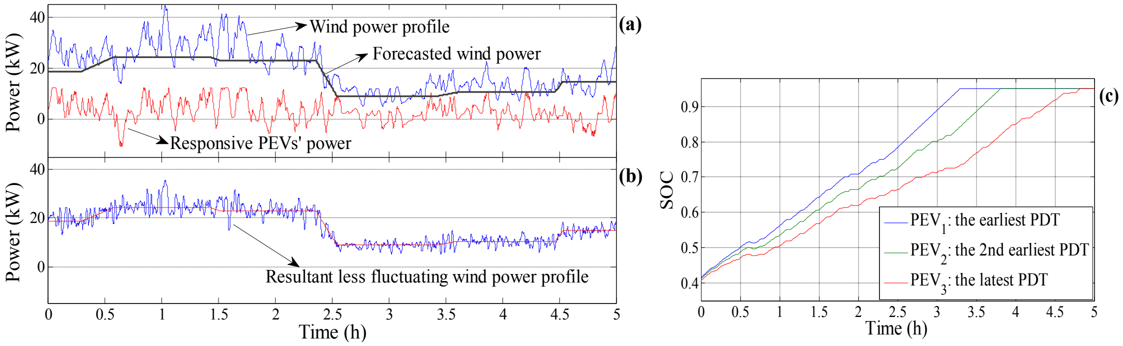

Fig. 2. (a) Wind power profile and the aggregate power of responsive PEVs; (b) fluctuation-counteracted wind power profile; (c) SOC of 3 PEVs with different planned departure time (PDT)

4. Conclusion

In this paper, a simple decentralized charging control scheme is proposed for PEVs to counteract wind power fluctuations. Each responsive PEV reacts to a real-time directing signal and autonomously adjusts its power in accordance with its own urgency level of charging. The counteracting duties are distributed among PEVs in a proportionally fair way such that the total utility of the responsive PEVs is maximized. Simulation results verified that the proposed PEV charging control scheme is effective in directing PEV power to alleviate wind power intermittency. Moreover, in the proposed control scheme, heterogeneous charging requirements can be satisfied without causing any inconveniences to PEV users.

References

[1] YF Mu, JZ Wu, J Ekanayake, N Jenkins, HJ Jia. Primary frequency response from electric vehicles in the Great Britain power system. *IEEE Trans Smart Grid* 2013;**4(2)**:1142–1150.

[2] T Masuta, A Yokoyama. Supplementary load frequency control by use of a number of both electric vehicles and heat pump water heaters. *IEEE Trans Smart Grid* 2012;**3(3)**:1253–1262.

[3] F Kelly, Charging and rate control for elastic traffic, *European Trans Telecom* 1997;**8**:33–37.

[4] Y Ota, H Taniguchi, T Nakajima, KM Liyanage, J Baba, A Yokoyama. Autonomous distributed V2G (vehicle-to-grid) satisfying scheduled charging, *IEEE Trans Smart Grid* 2012;**3(1)**:559–564.

Biography

Shiwei Xia received the MSc degrees in Electrical Engineering and Automation from Harbin Institute of Technology. He is currently pursuing the Ph.D. degree in Hong Kong Polytechnic University. His research area is smart grid with renewable energy.