A HIERARCHICAL CONTROL METHOD OF MASSIVE PLUG-IN ELECTRIC VEHICLES FOR LOAD VALLEY FILLING

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ABSTRACT

In this paper a hierarchical control method of massive plug-in electric vehicles (PEVs) for load valley filling is proposed. The architecture consists of the main control center, sub-control centers and PEVs. The objective of the main control center is to flatten the total load curve by coordination of sub-control centers. It calculates the optimal load plans for each sub-control center using a two-stage optimization method. The objective of the sub-control center is to make the load follow the received load plan by coordinated charging control of PEVs. Sub-control centers can take different existing coordinated charging methods to control PEVs, no matter these methods are centralized or decentralized. By using the idea of hierarchical control and combining different coordinated charging methods together, the proposed flexible method can control massive PEVs spread in vast areas for load valley filling.

INTRODUCTION

Special attentions are paid to plug-in electric vehicles (PEVs) all around the world because of their advantages on easing the fossil fuel shortage and the environment pollution. It is expected that millions of PEVs will run on the road in the near future. Uncoordinated charging of so many PEVs may cause problems such as branch overload[1], voltage drop[2], and three-phase imbalance[3] to the grid. On the other hand, to the distribution system operators (DSOs), charging loads of controllable PEVs can be regarded as demand side management resources and dispatched directly or indirectly to improve the economics and security of the power grid. By adjusting the charging locations, charging periods and charging power of controlled PEVs, the power losses of distribution networks could be reduced[4]. By adjusting the charging power of PEVs when the frequency changes, PEVs could participate in frequency regulations[5]. By shifting the charging load of PEVs from peak load periods to valley load periods, PEVs can be used to flatten the load curve[6].

In most of proposed methods PEV coordinated charging problems are transformed into optimization problems and solved in a centralized way. The solving difficulty increases as the number of controlled PEVs increases. Considering millions of PEVs or more will be connected to the power grid in the future, it will be difficult to solve the optimization problem for the coordination of such massive PEVs directly. Some decentralized control methods[7] and hierarchical control methods have been proposed to solve this problem. In this paper a hierarchical control method for massive PEVs is proposed to achieve load valley filling. The architecture consists of three layers: the upper layer is the main control center; the middle layer is the sub-control centers and the lower layer is the controlled PEVs. The main control center calculates the optimal load plans for each sub-control center using a two-stage optimization method. The objective of the sub-control center is to make the actual load to follow the received load plan by coordinated charging control of PEVs. Sub-control centers can take different coordinated charging methods to control PEVs, no matter these methods are centralized or decentralized.

In following sections, the architecture and models of the proposed method are described in detail. Simulation results on a study case are presented and show that the proposed method can combine different coordinated charging methods together and is suitable for controlling massive PEVs in vast areas to achieve load valley filling.

ARCHITECTURE OF HIERARCHICAL CONTROL METHOD

The structure of the hierarchical control method for massive PEVs are shown in Fig. 1. This architecture consists of three layers. The upper layer is the main control center, which is responsible for the coordination of sub-control centers. It collects constraints reported by sub-control centers, calculates the optimal load plans using a two-stage optimization method for each sub-control center for the purpose of load shifting and sends them to corresponding sub-control centers. The middle layer is the sub-control centers, which is responsible for the coordination of controlled PEVs. They collect information of controlled PEVs, calculate constraints according to collected PEV information and report them to the main control center. Sub-control centers can take different coordinated charging methods to control charging load of PEVs to follow load plans, no matter these methods are centralized or decentralized. To sub-control centers that use decentralized control methods, they communicate and interact with the controlled PEVs to determine the charging schedules of PEVs. To sub-control centers that use centralized control methods, they calculate charging schedules of PEVs according to collected information and send them to each PEV respectively. The lower layer is the controlled PEVs.

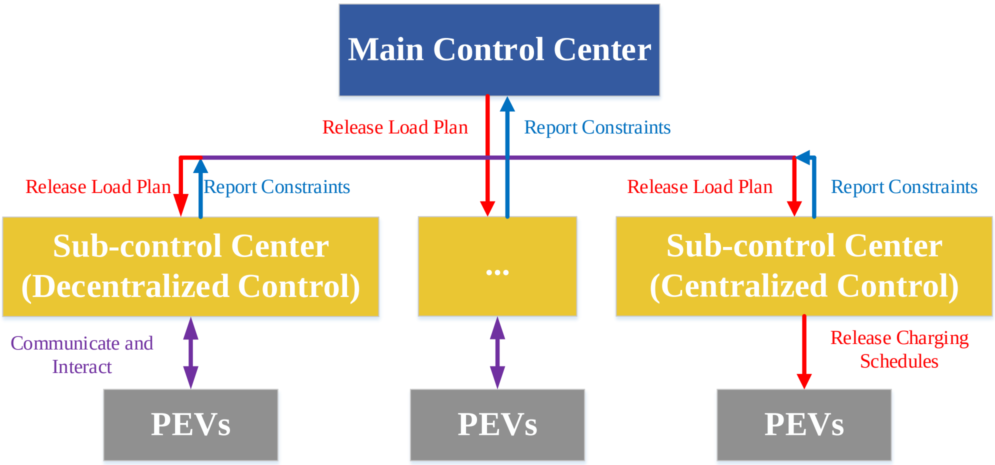


Fig. 1 Three-layer architecture of hierarchical control method

CONTROL MODEL OF MAIN CONTROL CENTER

In the main control center a two-stage optimization method is applied to calculate the load plans of each sub-control center. The first stage optimization ensures that the total charging load of PEVs can fill the load valley while the second stage optimization ensures that the load plans of sub-control centers are smooth and easy to follow. The objective function of the first stage optimization is as follows.

$$\min \sum_{t\in\tau} \Big(\sum_{i\in\Omega} G_{i,t} + D_t\Big)^2 \tag{1}$$

In (1) $G_{i,t}$ is the load plan of the sub-control center i at time t, D_t is the total normal load at time t, and Ω is the set of sub-control centers.

$$\underline{P}_{i,t} \le G_{i,t} \le \overline{P}_{i,t} \tag{2}$$

$$\underline{E}_{i,t} \le \sum_{t\ge n} G_{i,n}\Delta t \le \overline{E}_{i,t} \tag{3}$$

In (2) and (3), $\overline{P}_{i,t}$ and $\underline{P}_{i,t}$ are the upper and lower limits of the total PEV charging power of sub-control center i at time t; $\overline{E}_{i,t}$ and $\underline{E}_{i,t}$ are the upper and lower limits of the total PEV charging energy of sub-control center i at time t. $\overline{P}_{i,t}$, $\underline{P}_{i,t}$, $\overline{E}_{i,t}$ and $\underline{E}_{i,t}$ are reported by sub-control center i.

The first stage optimization problem has multiple optimal solutions. To avoid getting unsmoothed load plan curves, the objective of the second stage optimization problem is designed as follows.

$$\min \sum_{i\in\Omega} \Big(\sum_{t\in\tau} (G_{i,t} + D_{i,t})^2\Big) \tag{4}$$

In (4) $D_{i,t}$ is the normal load of sub-control center i at time t. Besides (2) and (3), the following constraint should be added to the second stage optimization model.

$$\sum_{t\in\tau} \Big(\sum_{i\in\Omega} G_{i,t} + D_t\Big)^2 \le \varphi D_l^* \tag{5}$$

In (5) φ is a weight equal or greater than one. D_l^* is the minimum value of the objective function (4). By solving the two-stage optimization model, the main control center can obtain the load plans of sub-control centers.

CONTROL MODEL OF SUB-CONTROL CENTER

In sub-control centers, $\overline{P}_{i,t}$, $\underline{P}_{i,t}$, $\overline{E}_{i,t}$ and $\underline{E}_{i,t}$ should be calculated and sent to the main control center. The following equations show how these variables are calculated.

$$\underline{P}_t = 0 \tag{6}$$

$$\overline{P}_t = \min\Big(\sum_{t\in\tau_i} R_i, P_{\text{limit}}\Big) \tag{7}$$

$$\underline{E}_t = \sum_{t\ge\tau_{end,i}} E_i^* \tag{8}$$

$$\overline{E}_t = \sum_{t\ge\tau_{begin,i}} E_i^* \tag{9}$$

In (7), $\tau_i = [\tau_{begin,i}, \tau_{end,i}]$ denotes the feasible charging period of PEV i. R_i denotes the maximum charging power of PEV i. P_{limit} denotes the load limit of the sub-control center. In (8) and (9), E_i^* denotes the total required energy of PEV i. Equation (8) means that the lower limit of the total PEV charging energy at time t, $\underline{E}_t$, equals to the total required energy of PEVs that have finished charging before time t. Equation (9) means that the upper limit of total PEV charging energy at time t, $\overline{E}_t$, equals to the total required energy of PEVs that have begun charging before time t.

According to the load plan sent by the main control center, the sub-control center designs charging plans for each controlled PEVs and ensures that the aggregate load follows the load plan and meanwhile the demands of EV owners are satisfied. The objective function the sub-control center is as follows.

$$\min \sum_{t\in\tau} (P_t - G_t)^2 \tag{10}$$

In (10) P_t is the total charging load of PEVs at time t. G_t is the load plan at time t given by the main control center. Equation (10) means that the aggregate charging load of PEVs of this sub-control center should follow the load plan. The basic constraints are listed as below:

$$\underline{P}_t \le P_t \le \overline{P}_t,\ t \in \tau; \qquad (11)$$

$$\underline{E}_t \le E_t \le \overline{E}_t,\ t \in \tau; \qquad (12)$$

$$E_t = \sum_{i \le t} P_i \Delta t,\ t \in \tau; \qquad (13)$$

The basic load-following optimization problem consists of (10)-(13). Other constraints could be added into it if necessary. This load-following optimization problem can be solved by lots of proposed methods. In [4] a centralized control method is proposed to minimize the power losses of the distribution network. In [6] a decentralized control method is designed for valley filling, in which a probability transition matrix is calculated as the control signal and broadcast to PEVs for local charging schedule decisions. In this paper, their objectives are modified into load following and they are used for the coordinated charging control of PEVs in sub-control centers. Note that other coordinated charging methods of PEVs could also be used here as long as they can be used to solve the load-following optimization problem.

CASE STUDY

Simulation Settings

Assume that in the study case there are one main center and three sub-control centers, namely sub-control center A, sub-control center B and sub-control center C. The normal loads of areas A and C (controlled by sub-control centers A and C) are mainly the residential load, while the normal load of area B (controlled by sub-control center B) is mainly the commercial load. The curves of normal loads are shown in Fig. 2. It can be noticed that the load shapes are different. The peak loads are respectively 3715kW, 4000kW and 4500kW. The upper load limit are respectively 4000kW, 4500kW and 5000kW. Sub-control center A takes the centralized control method proposed in [4] to control PEVs while sub-control centers B and C take the decentralized control method proposed in [6] to control PEVs. The distribution network of area A is the same with the IEEE 33-bus network.

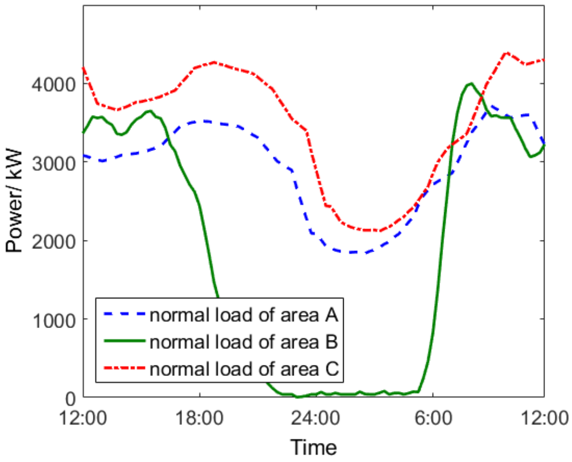


Fig. 2 Curves of normal loads of three areas

The charging power of PEVs is 7kW and the battery capacity is 32kWh. The numbers and distributions of arrival time, departure time and state of charge (SOC) of PEVs are listed in Tab. 1.

Tab.1 Basic Parameters of PEVs

Sub-control center	PEV number	Distribution of arrival time	Distribution of departure time	Distribution of SOC
A	240	$N(19{:}00,1^2)$	$N(07{:}00,1^2)$	$N(0.3,0.1^2)$
B	300	$N(08{:}00,1^2)$	$N(18{:}00,1^2)$	$N(0.7,0.1^2)$
C	360	$N(19{:}00,1^2)$	$N(07{:}00,1^2)$	$N(0.3,0.1^2)$

From Tab. 1 we can notice that in areas A and C PEVs are charged at home overnight while in area B PEVs are charged at the workplace in the daytime.

Simulation Results

Fig. 3 shows the load plans (expected load curves) of three sub-control centers calculated by the main control center. Owing to the second stage optimization, the load plans are smooth and easy to follow.

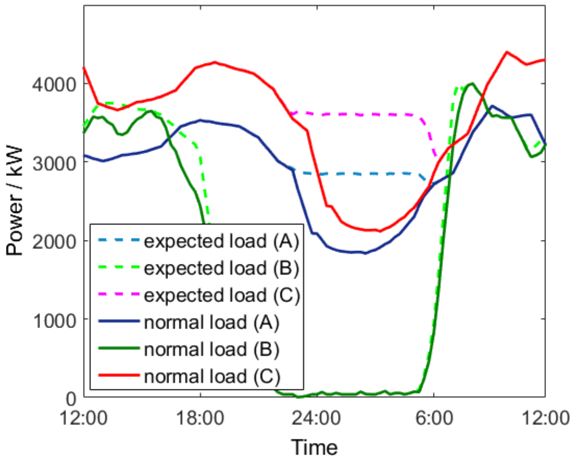
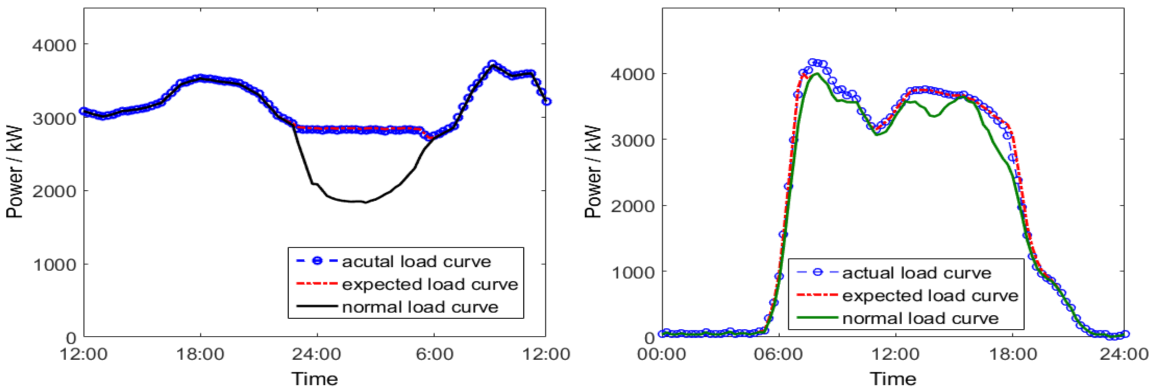


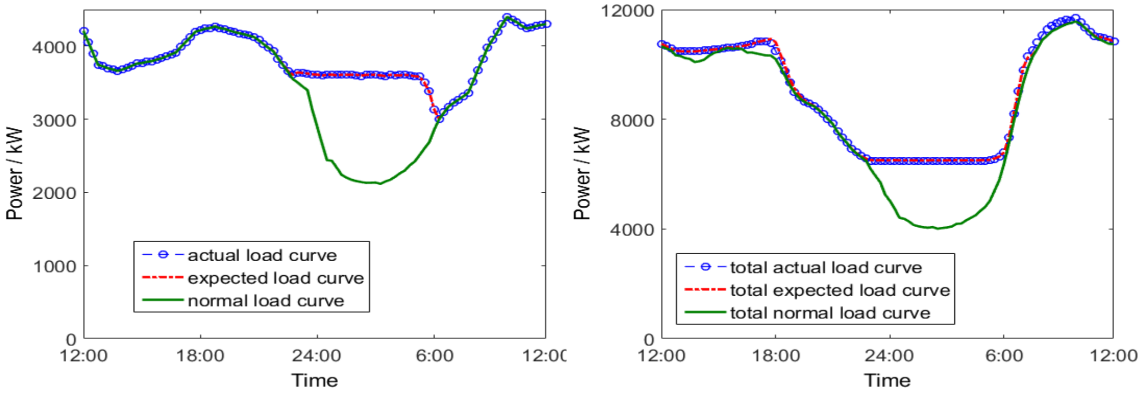
Fig. 3 Expected load curves (load plans) of three areas

Fig. 4 shows comparison between the actual load curves and expected load curves. From Fig. 4 (a)-(c) we can know that the actual load curves of three sub-control centers successfully follow the received load plans (the expected load curves), no matter the coordinated charging methods are centralized or decentralized. Fig. 4 (d) shows that the total expected load curve fills the overnight load valley owing to the first stage optimization. The total actual load curve follows the expected load curve well and fills the load valley, indicating that the proposed method can be used to control massive PEVs in vast areas for load valley filling.



(a) Sub-control Center A

(b) Sub-control Center B



(c) Sub-control Center C

(d) Total Load of Three Sub-control Centers

Fig. 4 Comparison between actual load curves and expected load curves (load plans)

CONCLUSION

In this paper a hierarchical control method of massive PEVs for load valley filling is proposed. The three-layer architecture of the method and control models of the main control center and sub-control centers are presented. By using a two-stage optimization method the optimal load plans are calculated in the main control center. Different existing coordinated charging methods can be used to control PEVs in sub-control centers, making the proposed method flexible. The method is applied to a study case in which exists three sub-control centers and one main control center. The simulation results show that the actual loads of sub-control centers can successfully follow the load plans released by the main control center, and the aggregate charging load of three sub-control centers can fill the load valley, which indicates that the proposed method is suitable for controlling massive PEVs spread in vast areas for load valley filling.

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