중앙제어기반 전기자동차 충전시스템의 에너지관리 알고리즘에 관한 연구

논 문
60-3-15

A Study on the Power Management Algorithm of Centralized Electric Vehicle Charging System

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Abstract - As Plug-in Hybrid Vehicle and Electric Vehicle (PHEV/EV) take a greater share in the personal automobile market, their high penetration levels may bring potential challenges to electric utility especially at the distribution level. Thus, there is a need for the flexible charging management strategy to compromise the benefits of both PHEV/EV owners and power grid side. There are many different management methods that depend on the objective function and the constraints caused by the system. In this paper, the schema and dispatching schedule of centralized PHEV/EV charging spot network are analyzed. Also, we proposed and compared three power allocation strategies for centralized charging spot. The first strategy aims to maximize state of vehicles at plug-out time, the rest methods are equalized allocation and prioritized allocation based on vehicles SoC. The simulation results show that each run of the optimized algorithms can produce the satisfactory solutions to response properly the requirement from PHEV/EV customers.

Key Words : Plug-in Hybrid Electric Vehicle and Electric Vehicle (PHEV/EV), State of Charge (SoC), Charging spot system, Algorithm.

1. Introduction

Plug-in-Hybrid Electric Vehicle (PHEV) and Electric Vehicle (EV) has become a topical issue in recent years, because it has advantages, such as low energy consumption, less pollution and so on. So, it plays a pivotal role in solving environmental pollution and energy saving, especially in the paradigm of Smart Grid. Along with the drastic demand of PHEV/EV usage, the potential impacts of PHEV/EV load on power grid are deeply investigated in many previous researches [1]-[6]. Accordingly, the high penetration of PHEV/EV causes a burden for the power system both in terms of loading and power quality. Many findings for PHEV/EV charging management are also published that focused on minimizing peak load based on residential load profiles [6]-[7]. However, in practice besides the desire of power grid, there is also a variety of preferences from PHEV/EV owners such as minimize the total charging cost, maximize state of charge in a specific interval of time, etc.

Due to the characteristics of automobile the PHEV/EV owners can recharge their vehicles at taxi stands, parking lots, phone booths, as well as in driveways and garages at home. Thus, there are two types of PHEV/EV charging co-ordinations in general [4]:

- Distributed coordination.
- Centralized coordination.

Distributed coordination includes charging spot at home, office, or any independent charging spot in public locations. For charging management in this scenario Home Energy Control Box or Smart Charger should be integrated both for stand-alone home charging spot and a network of home charging spot [6]. In this paper, we investigate on the centralized coordination that is installed in parking lots as shown in figure 1. In this case, the system need to install a controller which gathers the necessary information such as battery capacity, state of charge (SoC), current and voltage ratings as well as other preferences of PHEV/EV from all vehicles owners. The chargers can be contained on vehicles (On-board charger) or on the charging spots (Off-board charger). The controller exchanges messages and data with charging spots via LAN links such as Ethernet, Power Line Communication (PLC), Wifi, etc.

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접수일자 : 2010년 10월 6일
최종완료 : 2011년 2월 21일

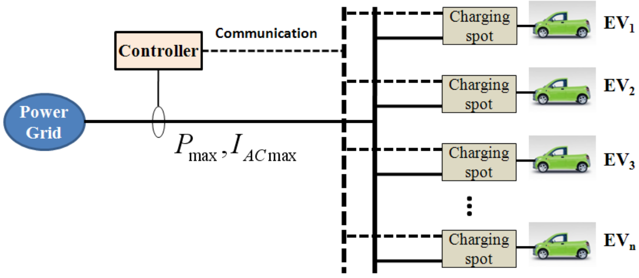


Fig. 1 Charging spot system architecture

There is a necessity for the system controller to compromise both the benefits of PHEV/EV customer and the desire from power utility. On one hand, the charging strategy must satisfy the preferences of PHEV/EV customer. For example, minimize the total charging cost based on real time pricing for the customers who are willing to pay when the electricity cost is below the expected threshold. For the customers who critically require maximum SoC of battery during charging time as possible, thus, the strategy needs to maximize the SoC of vehicles, etc. On the other hand, the controller also needs to satisfy the desire from utility, such as minimize the power consumption of charging spot system subject to allowed power from utility especially in peak hours, etc.

The vehicle charging process is continuous with a dynamically varying non-linear power consumption curve. The randomness of initial of states of charge, plug-in and out times and time-varying limited power from utility in large scale charging system, the various desires of vehicle owners lead to multi-objective and difficult mission of power allocation among charging spots. In the following parts, we propose the control algorithm for maximizing average state of charge of vehicle during charging time based on batteries and utility information.

2. Proposed methods

2.1 Power allocation strategy

In fact, there are a variety of requirements from both PHEV/EV owners and power grid aggregator. As mentioned early in part 2, PHEV/EV owners may require their car charged with maximum SoC in a specific interval of time. In that case, an algorithm to maximize the SoC of vehicles during charging time is needed. For customer whose attention is low paying regardless of charging time an algorithm for minimizing total charging cost based real time pricing of electricity should be deployed, etc. To power grid side the total of charging power during the peak hours is necessary to be under the value allowed by grid for peak shaving target. In a charging spot network where there're many different desires from different vehicle owners, the charging management responding properly those desires is such a difficult task.

In this research, we proposed the charging control strategy for centralized charging spot system. Also, we concentrated on power allocation methods. The first method considers the maximization of average SoC of vehicles during the charging time. The algorithm is applicable in case of customers expect to charge their vehicles as full as possible during plug-in time. The second power allocation way based on the SoC information of vehicles. The last method allocates gradually power to each vehicle. For both algorithms, we supposed that each vehicle is equipped a Battery Management System (BMS) to control the charging process of each vehicle, each charging spot also has an AC current limiter to implement the current allocation. Each charging spot also contains a control module for exchanging information with BMS system and the controller. The controller receives current state of each vehicle including $SoC_i(t)$, $V_{Bi}(t)$ from its charging spot via BMS system at every time step ΔT and then solving the management algorithm before issuing current allocation message to each charging spot.

According to [1]-[6], PHEV/EV may be considered as active loads that cause the increasing demand on the network during charging time. The impact is expected to be significant due to the high energy capacity and mass deployment of PHEV/EVs in the future. Hence, in order to lighten the burden on the power system, there is a need to limit the total power consumption of the charging

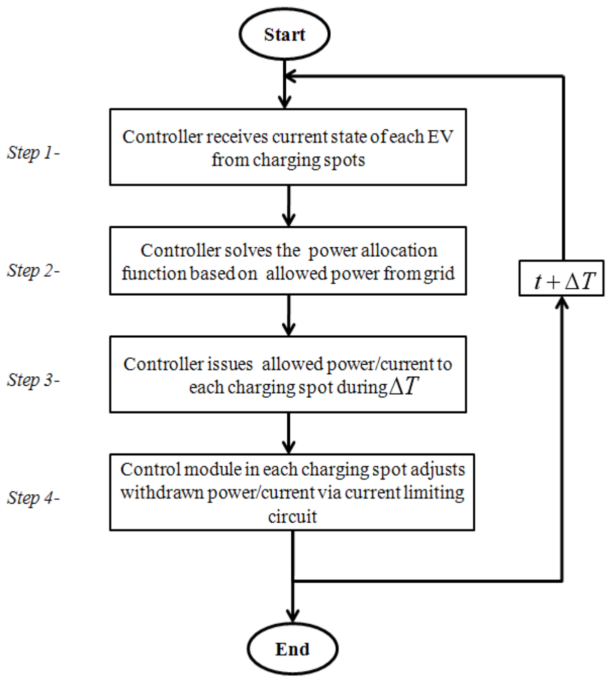


Fig. 2 Algorithm processing flow chart

spot network during peak hours of power system's load. To do that, the constraints from vehicle and utility should be taken into account. For proposed algorithms the constraints are the allowed power from grid at each time step $P_{\max}(\triangle T)$, initial and maximum state of charge of vehicles.. The following steps illustrate the solution:

2.2 Proposed power allocation methods

a. Maximize state of charge of vehicle

To achieve the goal of maximizing average SoC of vehicles during examined time the objective function should be:

$$Maximize\sum_{j}^{k}\sum_{i}^{n}SoC_{ij}(t+\triangle T) \tag{1}$$

Where n is the number of vehicle plug in charging system during examined time, k is the number of time step $\triangle T$ during examined time. The battery's parameters such as SoC, open circuit voltage, DC current drawn by batteries vary by time during charging and charging process of each battery pack is controlled by its BMS system. The controller receives information about batteries at every time step $\triangle T$ so the problem is solved by optimizing SoC of vehicles at every time step. Then, the objective function is simplified as:

$$Maximize\sum_{i}^{m}SoC_{i}(t+\triangle T) \tag{2}$$

Where m is the number of vehicles recharged during $\triangle T$. The SoC estimation task is one of the most important and difficult task. As presented in [7], there are several methods for SoC estimation:

- Based on SoC- battery open circuit voltage curve.
- Current integral method.
- Kalman filter method.
- RC model for Ni-MH battery.

In this paper, for numerical calculation we used current integral for calculating battery SoC. During the charging process, SoC of battery pack increasing by the integration of DC current over time [7]. The relation between SoC at $t+\triangle T$ and current SoC is:

$$SoC(t+\triangle T)=SoC(t)+\frac{\int_{0}^{\triangle T}I_{DC}(t)dt}{Q_{\max}\times 3600} \tag{3}$$

For real time controlling, the battery SoC can be calculated in discrete time step with the sampling time is sufficiency small to assume that the battery current remains constant during the time step. Therefore:

$$SoC_{i}(t+\triangle T)=SoC_{i}(t)+\frac{I_{DCi}\times\triangle T}{Q_{imax}\times 3600} \tag{4}$$

Moreover, for PHEV/EV charger the AC input power and DC output power are related via the charger's efficiency:

$$I_{DCi}\times V_{Bi}(t)=\alpha\times I_{ACi}\times V_{AC} \tag{5}$$

Consequently:

$$SoC_{i}(t+\triangle T)=SoC_{i}(t)+\frac{\alpha\times I_{ACi}\times V_{AC}\times\triangle T}{V_{Bi}(t)\times Q_{imax}\times 3600} \tag{6}$$

Finally, the objective function is function of AC currents $I_{ACi}(t)$ allocated to each vehicles during $\triangle T$:

$$Maximize\sum_{i}^{m}[SoC_{i}(t)+\frac{\alpha\times I_{ACi}\times V_{AC}\times\triangle T}{V_{Bi}(t)\times Q_{imax}\times 3600}] \tag{7}$$

Subject to:

$$\begin{cases} SoC_{iInit}\le SoC_{i}(t+\triangle T)\le SoC_{imax} \\ \sum_{i}^{m}P_{i}\le P_{\max}\end{cases} \tag{8}$$

$$Or:\begin{cases} SoC_{iInit}\le SoC_{i}(t)+\frac{\alpha\times I_{ACi}\times V_{AC}\times\triangle T}{V_{Bi}(t)\times Q_{imax}\times 3600}\le SoC_{imax} \\ \sum_{i}^{m}I_{ACi}\le I_{ACmax}\end{cases} \tag{9}$$

b. Equalized allocation

For this method, after updating the allowed power from the grid, the controller will issue equalized currents that each vehicle can draw. To implement this method, controller updates bounded power from power system and then automatically issues the equal current that each vehicle can draw regardless of other vehicles information.

c. Prioritized allocation

The idea of this method is that the controller will adjust the power drawn by each vehicle in future time step by comparing current SoC of vehicles. Accordingly, the vehicle has the lower SoC has the higher priority to withdraw its requested power and vice versa.

3. Simulations and discussion

To evaluate the proposed algorithms, in this part we simulated and compared the performances of the system in two conditions non-managed and managed case. The simulations were implemented by coding in Visual Studio C++ software. The examined vehicle model is Electric Vehicle for charging trial in KERI with the battery capacity is 10Ah, lithium-ion battery pack's nominal voltage is 84VDC. The efficiency of on-board charger of each vehicle is $\alpha = 0.72$, the root mean square value of AC voltage supplied for each charger is 220V. Other input parameters also based on recorded information of EV charging test-bed in KERI. Appendix A shows the charging process of stand-alone charging station in KERI without management. Table 1 gives information of charging scenario includes five vehicles in five-charging spot network. The time step $\triangle T$ for implementing charging algorithms is 5 minutes. The allowed power curve from utility is assumed as on Fig. 4.

Table 1 Simulated parameters of EV system

Parameters	EV_1	EV_2	EV_3	EV_4	EV_5
SoC_{Init}	0.3	0.2	0.5	0.4	0.6
$V_{Init}(V)$	69.6	69.25	71.52	70.75	73.12
Plug-in time	18:00	18:15	18:30	18:40	18:50

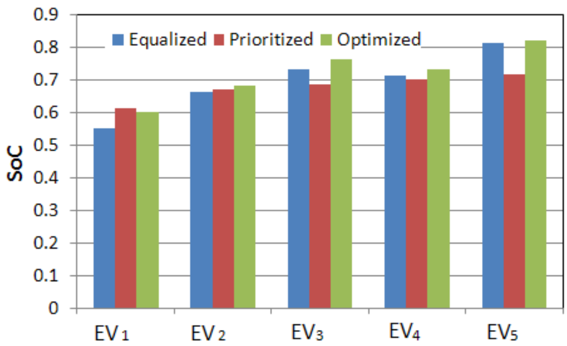


Fig. 3 SoC of vehicles at plug-out time

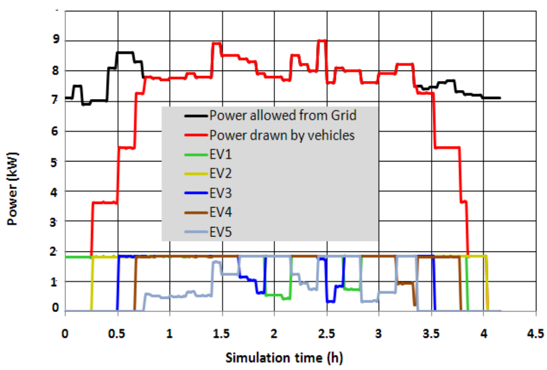


Fig. 4 Power allocation in optimized case

We compared the SoC of the vehicles at their plug-out time in non-managed and managed situations. The assumed plug-out time of vehicle EV1 to vehicle EV5 are 21:50, 22:00, 21:30, 21:45, and 21:20 respectively. The comparisons are shown in Fig. 3.

It is observed in given simulation that optimized schedule performs much better than other ones. However, in order to compare and test the proposed algorithms under all possible situations, the algorithms were implemented in different condition with stochastic input parameters. The varying of input information each as follows:

- Plug-in time: gradually changed every 5 minutes.
- State of charge at plug-in time: gradually changed from 0.1 to 0.6.

While the examined is fixed at 4 hours. We simulated 100 runs for each allocation method with 20 states of each vehicle. Fig. 5 shows the comparison among three proposed schemes.

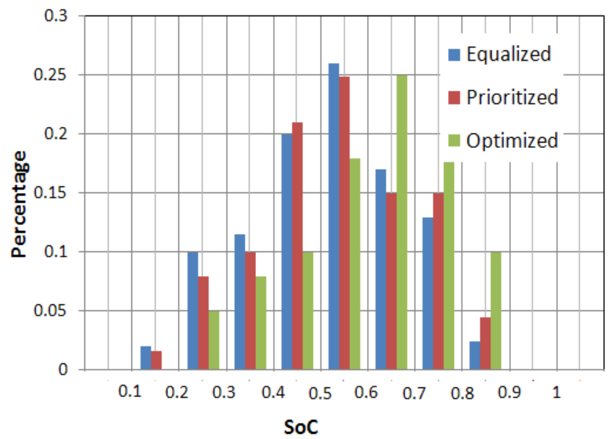


Fig. 5 Distribution of SoC of vehicles

In optimized scheme, most of the vehicles leave at high value of SoC, there is 58% cases the vehicles plug-out with SoC over 0.6. While for the cases of equalized and prioritized are 34% and 35.5% respectively. Also, the percentage of vehicles plug-out in low SoC in optimized scheme is much smaller than two other schemes.

4. Conclusion

As a result of the fast development in PHEV/EV technology and its application, the impacts of vehicle load on power system are predicted to be unavoidable in the coming years. The state-of-art of battery, BMS system and Multi-agent Energy Management System are also the promising factors supporting the development of smart charging spot system.

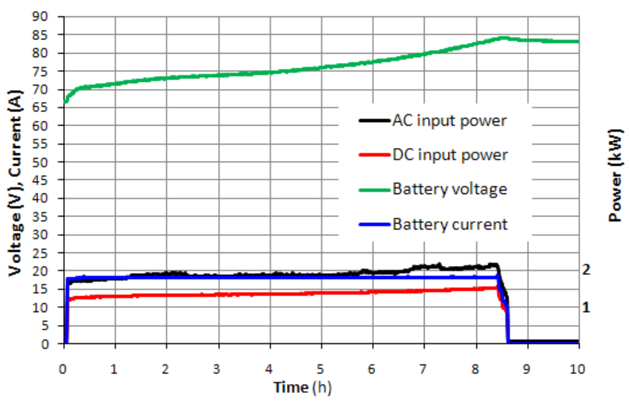
In this paper, the real-time dispatching schedule for centralized charging spot system is analyzed, the proposed method offer a good performance with some premises. However, to be more adaptable in Smart Grid paradigm and more beneficial to vehicle owners, a charging strategy based on electricity real time pricing should be also developed in future work.

Acknowledgement

This work was supported by the Korea Electrotechnology Research Institute(KERI) grant funded by the Korean government and University of Science and Technology (UST).

Appendix A

Recorded information of EV charging test-bed in KERI (Stand-alone Charging Spot)



Nomenclature

$SoC_i(t)$	State of charge of vehicle ith at time point t ($SoC_i \in [0,1]$)
$SoC_{iInit}(t)$	Initial state of charge of vehicle ith at plug in time.
SoC_{imax}	Maximum state of charge of vehicle ith.
I_{DCi}	DC current supplied for vehicle battery ith (A).
I_{ACi}	AC current supplied for vehicle battery ith(A).
I_{ACmax}	Maximum AC current allowed from utility (A).
$V_{Bi}(t)$	Open circuit voltage of vehicle battery ith (V)
V_{AC}	R.M.S of AC voltage supplied for chargers
Q_{imax}	Rated capacity of vehicle battery ith (A.h).
P_i	Active power supplied for vehicle ith (W).
P_{max}	Maximum power allowed by grid at time step $\triangle T$
$\triangle T$	Time step (s).
α	Charging circuit system efficiency.

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