Optimal Control Framework and Scheme for Integrating Plug-in Hybrid Electric Vehicles into Grid

Shuang Gao [1], K. T. Chau [2], C. C. Chan [3], Chunhua Liu [4], and Diyun Wu [5]

[1] *Department of Electrical and Electronic Engineering, The University of Hong Kong, sgao@eee.hku.hk*
[2] *Department of Electrical and Electronic Engineering, The University of Hong Kong, ktchau@eee.hku.hk*
[3] *Department of Electrical and Electronic Engineering, The University of Hong Kong, ccchan@eee.hku.hk*
[4] *Department of Electrical and Electronic Engineering, The University of Hong Kong, chualiu@eee.hku.hk*
[5] *Department of Electrical and Electronic Engineering, The University of Hong Kong, dywu@eee.hku.hk*

Abstract
With the growing plug-in hybrid electric vehicles (PHEVs) integrated into the power grid, a large number of onboard batteries need to be charged via the infrastructure such as dedicated charging station and the parking lots. In this paper, a control framework is proposed to manage the charging and discharging by using vehicle-to-grid technology. In order to analyze the effect of the PHEV charging to the grid and the corresponding coordinated strategies, this paper describes a simulation model. Initially, the uncontrolled PHEV charging scenarios are performed. The load flow algorithm is applied to calculate the power distribution and power losses on a 33-bus test system. The results indicate the inadequacy of the current power system capacity for the growing electricity demand from PHEVs. Therefore, an optimal control algorithm is derived for PHEV charging and discharging to minimize the total real power loss. Compared to the uncontrolled PHEV charging results, the optimal control algorithm can achieve the maximum loss reduction. Moreover, the voltage drop at each node is limited within a tolerable range while the tightened branch current restrictions are satisfied.

Keywords
plug-in hybrid electric vehicle, charging infrastructure, vehicle-to-grid framework, charging strategy, power loss minimization

1. INTRODUCTION
Plug-in hybrid electric vehicle (PHEV) is considered as a promising approach to electric transportation. With the policy support from the government, massive investments have been put into the PHEV research and the commercial product development in the automotive manufacturers, which will increase the market share of PHEV remarkably [Zhang et al., 2008; Ipakchi and Albuyeh, 2010; Chau et al, 2008]. When a large number of PHEVs are integrated into the grid, the total charging demand constitutes a significant load. This extra load may have negative impact on the current power system operation. However, a proper control of PHEV charging load can allow the energy stored in the battery to assist in redistributing power demand from peak to off-peak, alleviating voltage collapse, and therefore enhance power system reliability and reduce supply side operating cost. To realize the PHEV charging control in the real situation, a framework must be built on the basis of the conventional supply-side power system control paradigm. The framework must combine the existing power grid with renewable distributed generation resources. Power electronics devices are extensively used in the controller of individual end-user load, which significantly improve the controllability of the active and reactive power of the individual devices. These controllable loads can be utilized via the proposed framework to achieve a power system level objective without the installation of new control facility. For the PHEV battery recharging system, the power electronics designed for PHEV battery charger were illustrated in [Evans et al., 2009] with the purpose to make the charging rate adjustable and bi-directional power transfers possible. PHEV battery charging load is considered as a desired control object in this framework since flexible power control is already available in battery charger [Anderman, 2004; Morcos et al., 2000; Guille and Gross, 2009].

Control architecture and communication infrastructure must be taken into account for incorporating each PHEV battery charging process. The coordinated control of PHEV battery charging requests the communication network. Ideally, it can achieve the two-way data communications between the high-level power system operator and the individual loads. There were some research in establishing the framework for vehicle-to-grid (V2G) operation [Quinn et al., 2010; Galus et al., 2010]. The importance of establishing the appropriate communication network is stressed in these papers. And the concept of aggregator for controlling a PHEV fleet is also introduced in the V2G framework. But the function of the aggregator is defined diversely for different conceptual description of the framework. In the above studies, very few optimal control algorithms are derived from the proposed framework. The conceptual framework and the implementation of the control scheme are not tightly integrated.

The existing power system structure is insufficiently considered for the forthcoming EV integration. Therefore, a framework for integrating PHEV is proposed. In this framework, the controllable end-user devices at the lowest level are deployed synthetically to achieve the overall objective at the transmission system level. In responding to the control target, the top level device can supervise the activity of a set of devices beneath it. The devices implement the order from the higher level and assign the tasks to the devices at the lower level. The management strategy for V2G operation is based on this hierarchical control network. The aggregation of a number of PHEVs in certain region is related to an additional power load located at a selected node of the residential distribution grid. A flexible two-way communication network is essential for the proposed framework to transfer the messages between the grid computation center and the controller of each individual PHEV. The PHEVs and other new components can fit in the existing grid topology in the framework which provides the guidance for the practical implementation of V2G infrastructure, like parking lots with the facility for recharging the battery in the residential and commercial buildings.

In the most published methods of optimal V2G operation, the PHEVs are simplified as a grid resource [White and Zhang, 2010a; Saber et al., 2010a]. The available generation capacity is estimated according to the total number of PHEVs that is predefined for a certain scale of power grid. The distribution of PHEVs in a grid network and the characteristics of PHEV charging/discharging power are neglected in formulating an optimal control scheme. Several recent studies develop the optimal control algorithm for V2G operation as a constrained load flow problem or a standard unit commitment problem. These control algorithms are performed by using the conventional optimization technologies such as linear programming, particle swarm optimization (PSO) and heuristic method. However, the alternating charging / discharging processes and changes of battery storage energy over the whole planning period are not reflected in the mathematical formulation.

To analyze the optimal integration of PHEVs, a simulation model for the power network should be initially established. In this model, the charging and discharging scenarios will be based on the estimation of the PHEV penetration degree [White and Zhang, 2010b; Saber et al., 2010b] and the battery recharging capability considering the general PHEV owner behaviors and the typical PHEV charging circuitry configuration. In the distribution grid, the PHEV battery charging model will be used for the power flow studies. The aggregation of a number of PHEVs in certain region will be related to an additional power load located at the selected node of the residential distribution grid. The charging rate of individual PHEV will be controlled by the battery charger and to enhance the power supply reliability. Because of the undesirable effects that mass PHEV load will introduce to the grid without coordination, an optimal algorithm will be developed to coordinate the large regulation capacity of the PHEV aggregation for power quality improvement.

2. LOAD FORMULATION FOR CHARGING PHEVS

2.1 Battery charging characteristics

Rechargeable Li-ion batteries are ubiquitous in the PHEV battery storage system. Compared to the other rechargeable batteries Li-ion battery has the specific energy, higher cell voltage and low self-discharge. For recharging PHEV on-board battery, the recommended way is constant current – constant voltage charging, namely to provide the constant current input to the battery until it is fully charged under the limited voltage condition. Figure 1 shows the state of charge (SOC) of the Li-ion battery when the aforementioned charging protocol is conducted. To increase the batter lifetime, the charging range in the whole capacity must be considered. In this simulation model, the partially depleted battery states to perform recharging and is charged up to approximately 90 % capacity. For instance, the SOC is above zero at the beginning and this PHEV charging ends when the SOC reaches 90 %. If it takes almost 6 hours to fully charge the battery

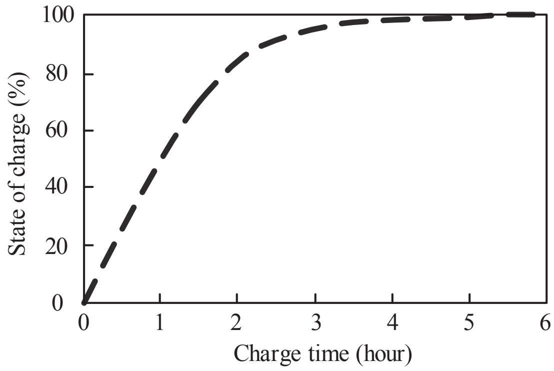

Fig.1 Typical Li-ion charge profile of SOC

from zero SOC to 100 % as shown in Figure 1, the charging period in the simulation model is set as 4 to 5 hours in each PHEV charging.

This charging characteristic of Li-ion battery is used to estimate the charging rate of each PHEV during the different section of the charging period and then the power demand of a PHEV aggregation. It can be seen from Figure 1 that the charging rate per hour at various initial SOC is remarkably different. Therefore the charging power of the PHEV at certain hour is set as follows:

$$P_{t1} = \frac{SOC_1 - SOC_0}{T} = 30\%E_{tot} \quad (1)$$

$$P_{t2} = \frac{SOC_2 - SOC_1}{T} = (70\% - 30\%)E_{tot} \quad (2)$$

$$P_{t3} = \frac{SOC_3 - SOC_2}{T} = (90\% - 70\%)E_{tot} \quad (3)$$

$$P_{t4} = \frac{SOC_4 - SOC_3}{T} = (100\% - 90\%)E_{tot} \quad (4)$$

where P_{t1} is the battery charging power in the first hour, T is the time interval representing 1 hour, and Etot denotes the total energy used in the entire charging period of 4 hours. The battery SOC changes from SOC_0 to SOC_4, indicating the increases of SOC per hour are 30 %, 40 %, 20 % and 10 % respectively.

2.2 PHEV charging scenario

The standard proportional typeface font is Times New Roman. Body text should be in 10 point. We consider the situation that a known number of PHEVs are deployed on the 33-bus radial distribution grid [Hosseini et al., 2009]. The PHEV loads are randomly distributed throughout the selected nodes in the network. The first vehicle charging scenario considered in this study is the uncontrolled charging. An overall penetration of 600 PHEVs is assumed, less than 10 % of total electricity consumption in the distribution system. The PHEVs are mainly charged at public charging stations and the charging points for vehicle owners in apartment complexes where the parking lots have recharging infrastructure installed. PHEV loads are more likely to be clustered in certain sites increasing the production for negative distribution system impacts. Thus, the PHEV load demand assembles at several nodes in the grid as shown in Figure 2. In this case, vehicle owners charge their vehicles at home when they come back from the work place [18]. The battery pack holds 9 kWh of energy and 90 % efficiency for on-board/off-board charger [Clement et al., 2009]. For urban driving, the PHEV efficiency is 0.14 kWh/km [CARB, 1995]. All PHEVs are plugged into a standard electricity outlet of 220V/13A, which is the power rating of Hong Kong residential electricity outlet. Thus, the PHEV charger operates at a maximum charging rate of 2.8 kW. Although this is the low charging mode for common household circuit, the PHEV can be fully charged within 4 hours. The PHEV begins charging as soon as it is plugged in the distribution grid at the fixed charging rate P_{1t}-P_{4t} as what mentioned before. These data are used to approximately estimate the PHEV battery charging demand and the driving range supported by each home charging, which are summarized as follows:

- Number of PHEVs = 600 vehicles
- Driving range per charging = 9/0.14 = 67 km
- Total EV energy requirement = 9/0.9*600 = 6000 kWh

The battery charging characteristics and daily driving requirements are considered to formulate the load profile of PHEV charging. The charging period is predefined based on the anticipation of general PHEV owner behavior. In the uncontrolled charging scenario, the charging start time for PHEVs is uniformly distributed over the range of 7pm and 11pm so that all the PHEVs charging can be completed by 3 am and

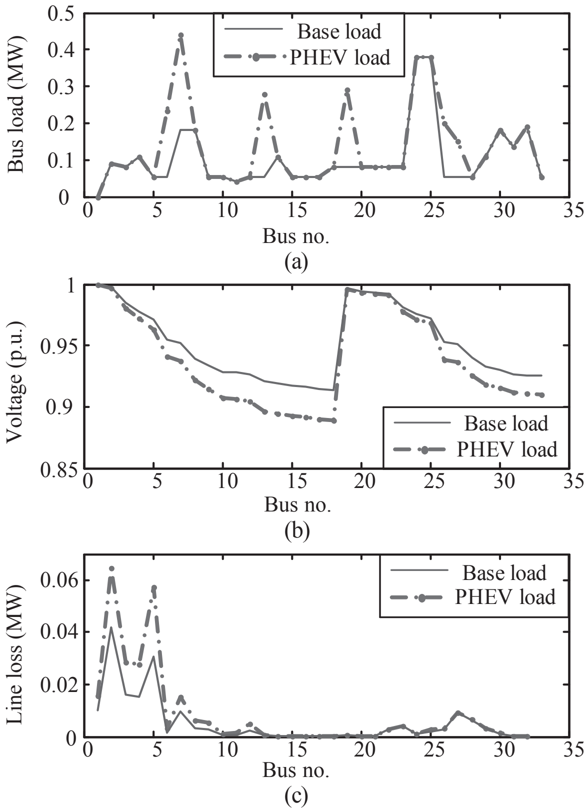

Fig. 2 PHEV charging load distribution in 33-bus system

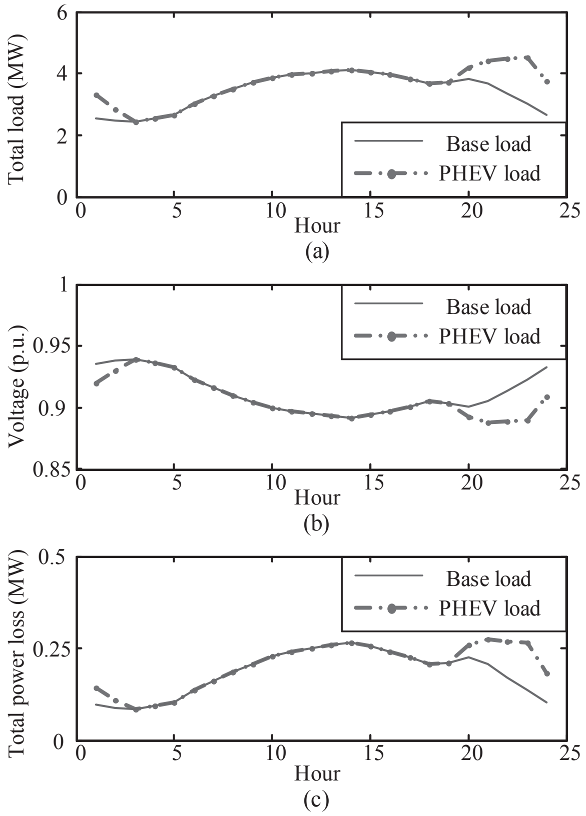

Fig. 3 Load, node voltage and total power loss profiles with and without PHEV charging

get ready for use in the morning. The energy required by each PHEV is uniformly distributed over 8 kWh to 11 kWh, and the charger power of each hour can be calculated accordingly. In Figure 3, the solid line represents the base load, a typical daily load profile of Hong Kong on workday. The dashed line is the load profile including the PHEVs integrated into the grid. The additional PHEV demand profile can be seen by the comparison between these two load profiles.

2.3 Impact of PHEV charging on grid

For evaluating the impact of PHEV charging on a daily basis, the electricity demand patterns in Hong Kong with and without PHEV charging, the corresponding voltage profiles of the node with a lower average voltage magnitude and the corresponding total power loss are illustrated in Figure 3. The solid line represents the normal load condition, and the dotted line represents the total load with the PHEV charging load integrated into the grid. The daily uncontrolled charging profile ramps up rapidly from 7 pm to 9 pm at the end of the normal workday and reaches the most charging capacity in the mid or late evening. The total power losses of the grid with and without PHEV charging are compared in the uncontrolled charging scenarios (shown in Figure 2 and Figure 3). There is clearly an increase of power losses and voltage drop during the charging period. It should be noted that the voltage drop during the charging period exceeds 10 % of the nominal value, which violates the lower bound of acceptable voltage magnitude stipulated in EN50160 [CENELEC European Committee, 1994]. It indicates that the ability of the grid to accommodate the extra PHEV charging demand may be insufficient. A coordinated control of battery charging is essential to diminish such negative effects on the power quality.

3. OPTIMAL CONTORL OF PHEV CHARGING

3.1 Framework for integrating PHEVs into grid

In the proposed framework for integrating PHEVs into the grid, power system managers monitor and utilize all the controllable devices in user-end to reach an overall objective for the entire grid. The V2G technology must be used in the updating of infrastructure to manage the battery charging and discharging. Figure 4 shows the hierarchical structure of the framework that is composed of power grid components and the control signal communication system. In responding to the control target, the top level device can supervise the activity of a set of devices beneath it. In this way, all the available devices are incorporated to achieve a single optimal objective. Furthermore, the communication infrastructure can be easily applied via this framework to fit the new components into the existing power system structure.

The control scheme differs from the centralized control structure in which the central controller has to interact with thousands of devices. By using this hierarchical structure, all the available power capacity of the controllable loads at various layers can be employed. The active and reactive power of the devices at the residential level is controllable by the wide utilization of power electronics in the loads. For instance, to minimize the total power loss or voltage drop in distribution grid, the input/output power of the connected PHEV battery packs, electric machines or other controllable end-users devices are regulated by their own converters. As shown in Figure 4, a central control system is at the top level of the communication network to manage the energy flow for a large power system. The control centre supervises the condition of the bulk transmission system and issues commands to dispatch the load or generation resource at each bus. The feeder relay, as the controller of the distribution system beneath the transmission system, receives the higher level command and interprets the control signal for the participating loads at distribution system buses. Particularly for the load of charging PHEVs, an aggregator takes charge of a group of PHEVs within a certain region, like dedicated charging stations or

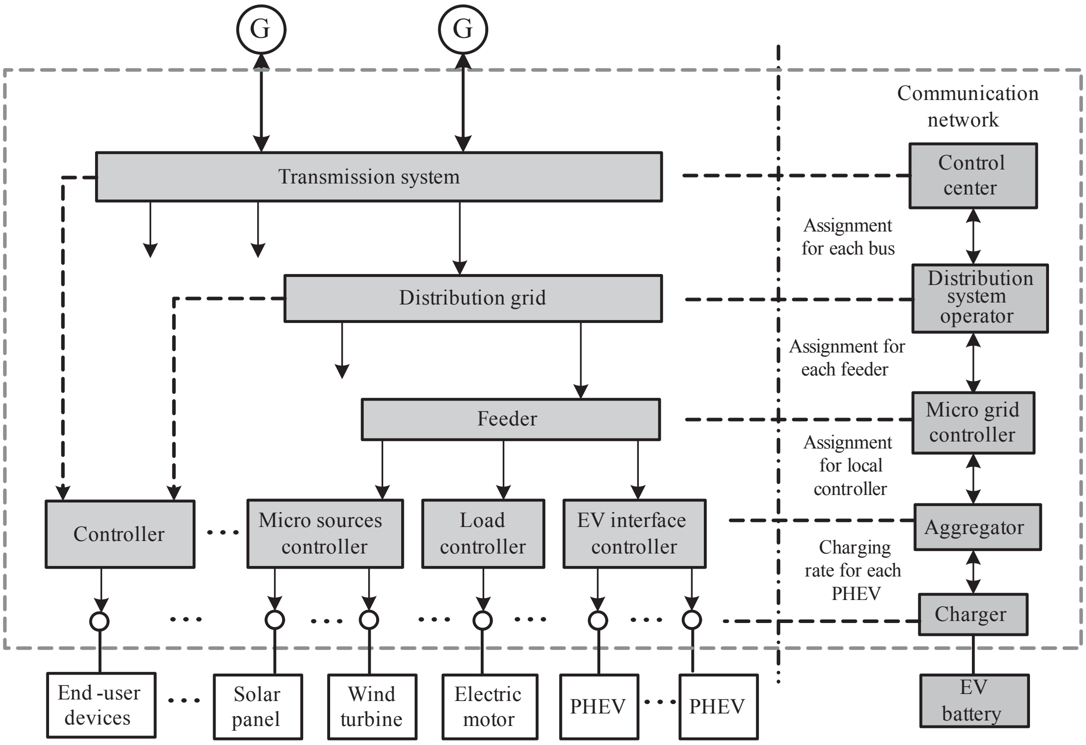

Fig.4 Hierarchical control framework for V2G operation

parking lots with charging facility. In the setting of the existing grid network, the aggregator engages the PHEVs under a certain bus in the distribution system. The aggregator in this hierarchical structure provides an interface between the group of PHEVs and the higher level control. The aggregator acquires the information of the PHEV aggregation and reports to the distribution system controller; meanwhile, it is also responsible for assigning the instructions to individual PHEVs. PHEVs at the lowest level in this framework follow the instruction to adjust the charging rate that is regulated by the battery charger. The aggregator can serve as the intermediary that exempts the higher level controller from the interaction with plenty of PHEVs, which is impractical for a large power system or a high PHEV penetration level.

Although the hierarchical framework is derived to coordinate the response of all the available loads for a common goal, the organization is flexible enough to handle the local problem instead of always the top level corrective control. For instance, if the decline of power quality is detected in the distribution grid, the controllable loads under the command of this distribution network can be deployed to provide active or reactive power support. In the above example, the voltage and power loss problem occur due to the uncoordinated PHEV battery recharging within the 33-bus distribution system. In order to mitigate the negative effect of PHEV load, optimal charging method should be applied via this framework to redistribute the PHEV charging loads at the selected nodes during the stipulated charging period.

3.2 Optimal control algorithm

During the charging period, the charging rate of individual battery is coordinated according to the optimal objective and constraints of the charger, battery and power grid. The objective of the optimal algorithm is to minimize the total power loss through the redistribution of PHEV charging load, thereby cutting the voltage drop within the distribution voltage deviation limit stipulated in EN50160 [CENELEC European Committee, 1994]. Sequential quadratic programming method [Haesen et al., 2007] is used to calculate the optimal active power for charging the PHEVs in the constrained parking lots. Therefore, the objective function for power loss optimization is given by:

$$\min P_{loss} = \min \sum_{t=1}^{t_{\max}} \sum_{l=1}^{l_{\max}} R_l \, I_l^2(t) \tag{5}$$

where t is the time step and t_{max} represents the whole planning period. l_{max} is the number of the transmission lines in the 33-bus power network. R_l is the resistance of the l^{th} transmission line, and I_l is the line current.

This function is subject to the constraints of charging rate, battery state and power system operation limitations.

3.2.1 System power balance

Power supplied from the generators must satisfy the load demand, the power of charging for PHEVs and the system losses as expressed by:

$$\sum_{i=1}^{N_G} P_{Gi}(t) = P_{load}(t) + \sum_{i=1}^{N_V} P_{Vi}(t) + P_{loss}(t) \tag{6}$$

where N_V is the number of PHEVs connected to the grid at time t, and N_G is the total number of the generation units in the system including the small-size distribution generators and limited capacity of discharging PHEVs. $P_{Gi}(t)$, $P_{load}(t)$, $P_{Vi}(t)$ and $P_{loss}(t)$ represent the power of the aforementioned system components at the time step t.

3.2.2 Generation limits

Each generation resource in a certain bus has a generation range, which is defined as:

$$P_i^{\min} \le P_{Gi}(t) \le P_i^{\max} \tag{7}$$

where P_i^{min} and P_i^{max} are the lower bound and upper bound of the output power of the generation unit i.

3.2.3 Transmission line limits:

In the power flow calculation, the branch power flow limit should be satisfied. It can be represented by setting current limits for each line:

$$|I_{ij}| \le |I_{ij}|^{\max} \tag{8}$$

where $|I_{ij}|^{\max}$ is the maximum amount of current that flows through the transmission line between bus i and bus j.

3.2.4 The initial SOC of PHEV load

The SOC of the batteries at the beginning of the charging period must be considered in the optimal algorithm as each PHEV parked in the recharging place has some energy stored in the battery [24-26]. It yields:

$$E_{Vi,\text{int}} = \sum_{k=1}^{n_{Vi}} SOC_{Vi,k} E_{Vi,k} = n_{Vi} E_{Vi,avg} \tag{9}$$

where $E_{Vi,int}$ is the initial battery energy of PHEV aggregation, n_{Vi} is the number of PHEVs aggregated at each node, $SOC_{Vi,k}$ is the initial SOC of each PHEV battery pack, $E_{Vi,k}$ is the battery storage capacity of each PHEV, and $E_{Vi,avg}$ is the mean value of the PHEV initial SOC predetermined in accordance with the characteristic of the battery pack.

3.2.5 Total energy for PHEVs charging

The total energy absorbed by PHEV is expressed as:

$$\sum_{t=1}^{t_{\max}} P_{Vi}(t)T = E_{Vi,\max} - E_{Vi,\text{int}} \tag{10}$$

where T is the time interval and $E_{Vi,max}$ is the maximal amount of energy to recharge the vehicles at the end of the charging period. It indicates the battery energy storage capacity of each PHEV aggregation, since the vehicles must be fully charged before the departure from the parking lots.

3.2.6 Limit of PHEV charging rate

The PHEV battery charging power regulated by the on-board/off-board charger should be limited in a proper range, taking into consideration of the recharging time and the availability of grid power:

$$P_{Vi}^{\min} \le P_{Vi} \le P_{Vi}^{\max} \tag{11}$$

where P_{Vi}^{min} is the minimal recharging rate, and P_{Vi}^{max} is the continuous power rating of an electricity outlet. The minimal recharging rate is a negative value during the discharging process.

3.2.7 Limit of PHEV battery capacity

The SOC of the battery must be between 0 % and 100 % during the charging period. So the energy stored in the PHEV aggregation regardless of charging and discharging at certain time step should satisfy the following inequality:

$$0 \le E_{Vi,\text{int}} + \sum_{t=1}^{t_k} P_{Vi}(t)T \le E_{Vi,\max} \tag{12}$$

where t_k is any time step within the charging period. Having known the initial energy stored in the battery, together with the energy obtained from the preceding charging and discharging processes, the current amount of energy storage can be calculated and restricted within the limit of $E_{Vi,max}$.

The flowchart of the proposed method is shown in Figure 5. The power flow analysis is implemented first using the input data of the 33-bus system with PHEV charging load. The results of the initial iterative calculation are used for the optimal scheduling of the generation resources and load demands. The primary feeder is the sole electrical resource in the 33-

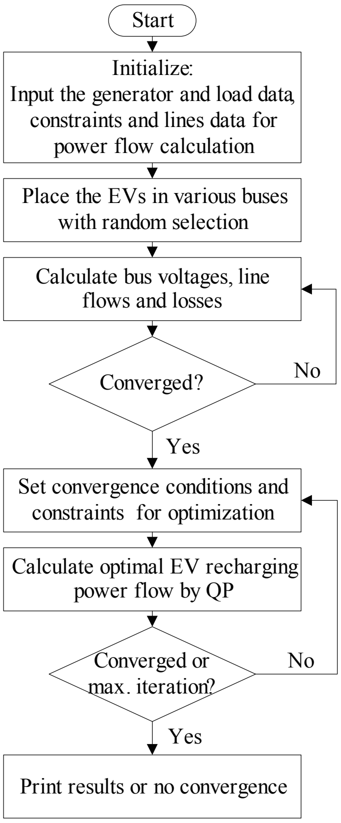

Fig. 5 Flowchart of optimal PHEV charging

bus distribution network. In reality, specific areas have a higher concentration of PHEVs. So in this case, all the PHEVs are assumed to be distributed at the six nodes chosen randomly, but the numbers of the PHEV aggregation at each node are not evenly distributed through the nodes. The ratio of size of PHEV aggregation at the six nodes is determined by the random number generator. In this case, six random numbers are uniformly generated so that the ratio is set as 11:16:14:13:9:6.

4. PERFORMANCE ANALYSIS

The charging period in the optimal charging scheme is the same as the time period in the uncontrolled charging scenario. The PHEVs are connected to the grid from 7 pm and must complete the charging process by 3am. The PHEV charging loads are controlled to match the periods of minimum demand. The PHEV charging powers at the six nodes, namely A1-A6, are depicted in Figure 6 based on the solution of optimal algorithm. In the first case, the initial SOC of the PHEV battery is zero, which means the battery is assumed to be empty before the start of charging. Under this condition, the discharging process never occurs for any of the six PHEV aggregations. Under normal circumstance, the PHEVs cannot deplete the battery storage capacity before recharging at home. In the following cases, the effect of initial battery storage energy to the PHEV charging profile is examined by varying the SOC in the constraints of the optimal control algorithm. As shown in Figure 7, there is still energy left in the batteries at the beginning of the charging period. This energy is determined stochastically based on a Gaussian function with an average of 10 % SOC and a standard deviation. The values of initial energy in the six PHEV aggregations are randomly gener-

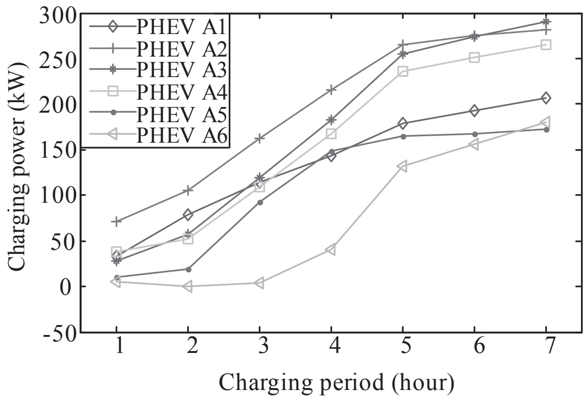

Fig. 6 Optimal PHEV charging profiles with 0 % initial SOC

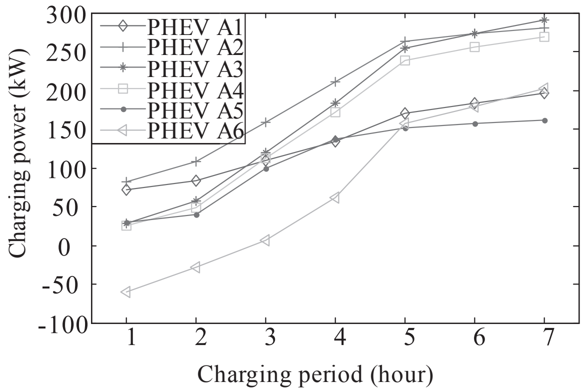

Fig. 7 Optimal PHEV charging profiles with 10 % initial SOC

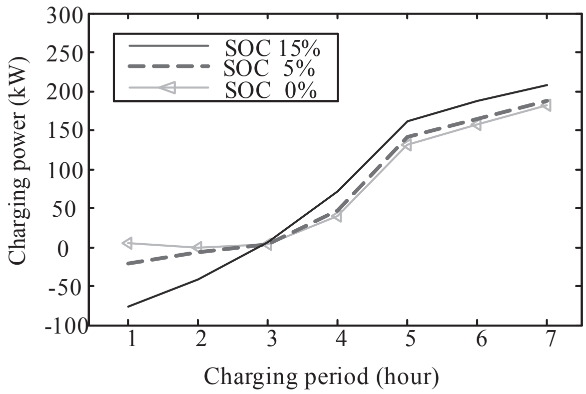

Fig. 8 Optimal PHEV charging profiles under different initial SOCs

ated and the mean of generation function is set as 10 % of the total energy storage capacity. Compared to the case of zero storage energy, the charging profiles of the aggregations are changed to better achieve the optimization objective. The discharging processes happen at the early stage of the PHEV charging period because the remaining capacity can be dispatched as the generation resource. The A6 PHEV aggregation is selected to demonstrate the optimal charging scheme under the condition of different initial battery SOCs, namely, 0 %, 5 % and 15 %. Figure 8 shows the corresponding charging profiles. It can be seen that PHEV aggregator under 15 % initial SOC has higher degree of flexibility to select charging or discharging and to operate in a wide range of charging/discharging rate.

Each line loss of the distribution grid is also automatically computed by the optimal algorithm as shown in Figure 9. As indicated in the objective function, the summation of all the line loss constitutes the total power loss, which is depicted in the Figure 10. The simulation results in Figure 10 can be compared with the same items in uncontrolled charging scenario. It shows a curtailment in power loss and voltage drop. This extra load can be accommodated by the current power system without serious augment in the power losses and voltage drop.

The total power losses at each time step under uncontrolled scenario and optimal charging scheme are shown in Figure 11. Furthermore, the difference is calculated by subtracting the power loss in the optimal scheme from that in the uncontrolled scenario. Based on the results, the proposed optimal charging scheme can reduce the voltage deviation below 10 % of the distribution nominal voltage and minimize the power loss as well. The optimal charging strategy is coordinated to match the off-peak electrical demand by timing and diversifying the PHEV load, and thereby mitigate the impact of the additional PHEV load on the distribution network.

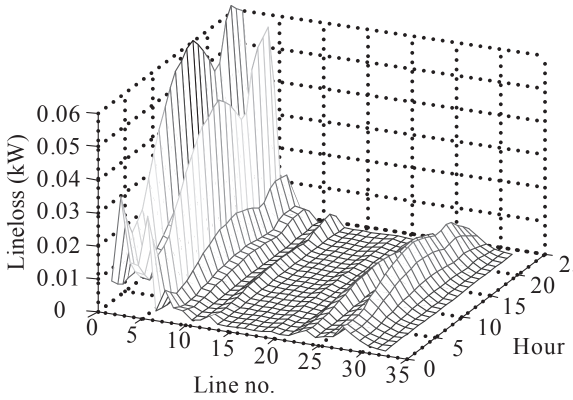

Fig. 9 Line losses in grid

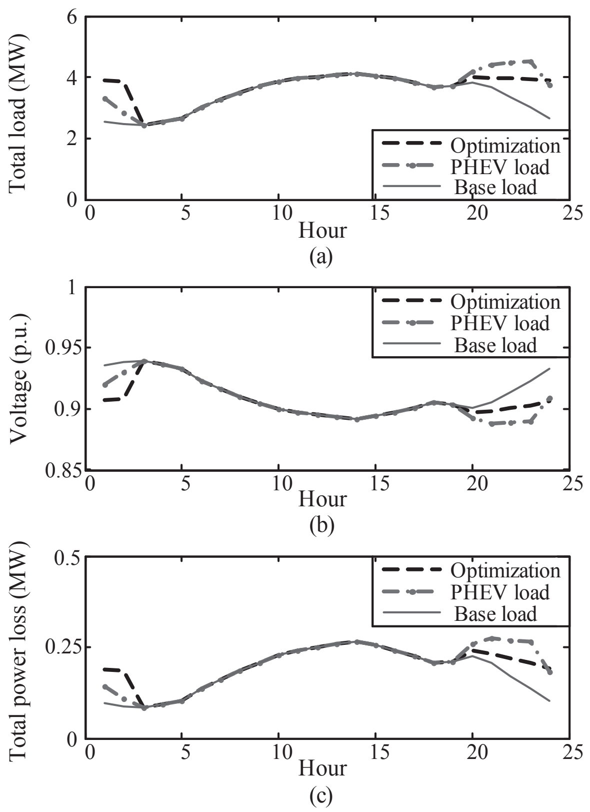

Fig. 10 Load, node voltage and total power loss profiles with and without optimization

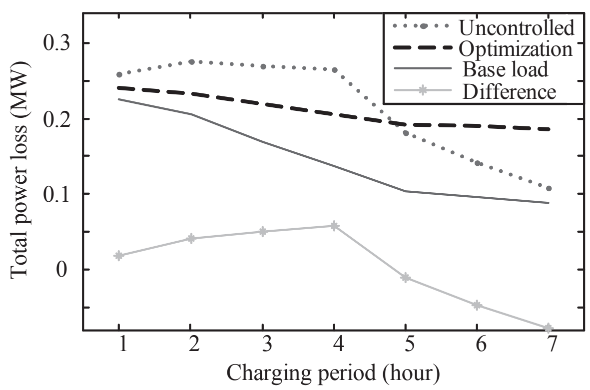

Fig. 11 Total power losses with and without optimization

5. CONCLUSION

This paper has explored the coordinated control of the PHEV charging load to mitigate the negative impact due to a large number of PHEVs plugged into the power grid. A hierarchical framework for managing the controllable load in the large power system is proposed to build a multilayer control structure. This hierarchical network allows all the available use-end devices to participate in the load control for a common goal, mainly for supporting the power system stability and reliability. In this framework, the user-end devices at the lowest level are grouped together and supervised by the higher level controller. The optimal control strategy is designed and implemented in a 33-bus distribution grid under this framework. The aggregator is responsible for the PHEV charging regulation at each node according to the solution of the optimal algorithm. The load flow analysis for the integration of PHEVs has already shown the negative impacts in terms of voltage drop and total power loss. The objective of optimal algorithm is set to minimize the total power loss, which is achieved by redistributing of the PHEV charging or discharging power at different time steps. The simulation results of optimal charging scenario are compared with the uncontrolled PHEV charging which validates the effectiveness of the proposed optimal control method.

Acknowledgements

This work was supported by a grant (Project code: 201007176031) from the HKU SPACE Research Fund and the Committee on Research and Conference Grants of the University of Hong Kong.

References

Anderman, M., The challenge to fulfill electrical power requirements of advanced vehicles, *Journal of Power Sources*, Vol. 127, No. 1, 2-7, 2004.

CARB staff, *California Air Resources Board Staff Report*, CARB, 1995.

Chau, K. T., C. C. Chan, and C. Liu, Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles, *IEEE Transactions on Industrial Electronics*, Vol. 55, No. 6, 2246-2257, 2008.

Clement, K., E. Haesen, and J Driesen, Stochastic analysis of the impact of plug-in hybrid electric vehicles on the distribution grid, *International Conference and Exhibition on Electricity Distribution*, 1-4, 2009.

Evans, P., S. Kuloor, and B. Kroposki, Impacts of plug-in vehicles and distributed storage on electric power delivery networks, *National Renewable Energy Laboratory*, Golden, CO, 2009.

Galus, M. D., M. Zima, and G. Andersson, On integration of plug-in hybrid electric vehicles into existing power system structures, *Energy Policy*, Vol. 38, 6736-6745, 2010.

Guille, C., and G. Gross, A conceptual frame work for the vehicle-to-grid (V2G) implementation, *Energy Policy*, Vol. 37, No. 11, 4379-4390, 2009.

Haesen, E., J Driesen, and R. Belmans, Robust planning methodology for integration of stochastic generators in distribution grids, *IET Renewable Power Generation*, Vol. 1, No. 1, 25-32, 2007.

Hosseini, M., H. A., Shayanfar, and M. F. Firuzabad, Reliability improvement of distribution system using SSVR, *ISA Transactions*, Vol. 48, No. 1, 98-106, 2009.

Ipakchi, A., and F. Albuyeh, Grid of the future, *IEEE Power and Energy Magazine*, Vol. 7, No. 2, 52-62, 2010.

Morcos, M. M., N. G. Dillman, and C. R. Mersman, Battery chargers for electric vehicles, *IEEE, Power Engineering Review*, Vol. 20, No. 11, 8-11, 2000.

Quinn, C., D. Zimmerle, and T. H. Bradley, The effect of communication architecture on the availability, reliability, and economics of plug-in hybrid electric vehicle-to-grid ancillary services, *Journal of Power Sources*, Vol. 195, 1500-1509, 2010.

Saber, A. Y., and G. K. Venayagamoorthy, Intelligent unit commitment with vehicle-to-grid -A cost-emission optimization, *Journal of Power Sources*, Vol. 195, 898-911, 2010.

Std. EN50160, *Voltage Characteristics of electricity supplied by public distribution systems*, CENELEC European Committee for Electrotechical Standardisation, 1994.

White, C. D., and K. M. Zhang, Using vehicle-to-grid technology for frequency regulation and peak-load reduction, *Journal of Power Sources*, Vol. 196, 3972-3980, 2011.

Zhang, X., K. T. Chau, and C. C. Chan, Overview of thermoelectric generation for hybrid vehicles, *Journal of Asian Electric Vehicles*, Vol. 6, No. 2, 1119-1124, 2008.

(Received April 13, 2011; accepted May 16, 2011)