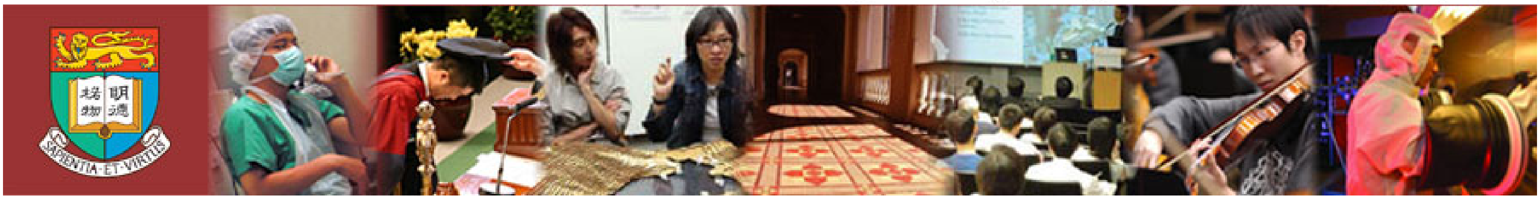

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Modeling and Coordinated Control for Integrating Electric Vehicles into the Power Grid

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Abstract — This paper introduces a framework for the integration of renewable energy generation units and electric vehicle into smart grid, which takes into account the setting up of the PHEV recharging infrastructure and modern power system. The impact of recharging a large amount of PHEVs on the existing power system is estimated considering the PHEV characteristics and the driving pattern of the vehicle owners. Three scenarios for uncontrolled and controlled charging are derived to investigate the impact in terms of power quality. The simulation results show the necessity to coordinate the PHEV recharging with the power network condition. Therefore an optimal algorithm is also designed to minimize the power losses based on the hierarchical structure of the proposed framework. The aggregation of PHEVs is expected to act as a controllable load or resource. Both of the battery charging and discharging are comprised in the optimal algorithm to achieve better performance in the V2G operation.

I. INTRODUCTION

With the growing number of plug-in hybrid electric vehicle (PHEV) in the auto market, the penetration of PHEV in the power grid is increasing to a considerable extent [1-4]. The recharging of the battery for a large number of PHEVs constitutes an additional power load for the current power system. Meanwhile the PHEV fleet can also act as a power resource. A flexible vehicle-to-grid (V2G) operation can be realized by charging and discharging of the PHEV aggregation. In order to implement energy conservation measures, the utilities are required to get energy from renewable resources [5-13]. But because those sources operate intermittently, they present a challenge for transmission and distribution systems. The V2G operation would help make it easier to integrate photovoltaic, wind, and other intermittent power sources. The control of this V2G operation request the communication network, ideally, the two-way data communications among all the elements. So the smart-grid managers can access all end users, and utilize all the controllable devices in the whole network to reach an overall objective.

In this paper, a simulation model for the test power network is initially established to analyze the optimal integration of these novel components. This simulation model combines the power grid optimization model and the PHEV recharging model. The existing power system structure is insufficiently considered for the forthcoming EV integration. Therefore, a framework for integrating PHEV is proposed. The management strategy for V2G operation is based on the proposed 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. The charging rate of individual PHEV is controlled by the battery charger [9] and expected to provide support to enhance the power supply reliability. Three charging scenarios are performed on this simulation model. The simulation results for the uncontrolled charging scenario indicates the undesirable effects that mass PHEV load could introduce to the grid. The charging of PHEVs is simply regulated in the off-peak control scenario, but a significant improvement in voltage level and line congestion can be made. Thus, the optimal control scheme is necessary to coordinate the recharging of PHEVs with the local load demand. With optimal control scheme, PHEV aggregations can exploit the battery storage energy to provide more flexible V2G services.

II. IMPACT OF PHEV CHARGING ON THE POWER GRID

A. *PHEV Charging Scenarios*

A typical 33-bus radial distribution grid [14] is used to estimate the effects of recharging PHEVs. PHEV interface devices may operate from a three-phase or single-phase supply points. Three-phase supply provides a larger power and hence faster charging mainly for the dedicated charging station. Currently the faster charging stations are quite limited, but the single-phase supply is widely available for recharging the battery at home or the parking lots. Thus, only slow charging at home and in public charging points located in residential areas is considered. We assume that the battery chargers have a power capacity of 3.75kW when connected to a standard 220V home circuit, and that the power efficiency of battery charger is 90% [15-16]. Table I summarizes the assumed characteristics of the PHEVs in respect of driving pattern and battery storage capacity [17-18]. We also assume an expected number of 1000 PHEVs which are deployed in the test system. The average distance traveled each vehicle is assumed to be 35 km and the hybrid runs roughly half of the distance in the electrical mode [15]. According to these assumptions, the charging energy and charging rate can be calculated. In this PHEV charging model, the slow charging from a standard electricity outlet takes about 4 hours to fully recharge the battery. The initial SOC (state of charge) of 10% and the target final SOC of 90% are defined to prolong the battery lifetime [19-20].

TABLE I
PARAMETERS FOR PHEV FLEET

Parameters	Value	Unit
Average battery capacity	9.4	kWh
Vehicle mass	1488	kg
All-electric range	60	km
Average energy use over drive cycle	59 and 23	Wh/km km/l
CD-mode energy use	0.183	kWh/km
Expected number of PHEV	600	vehicles

In this paper, it mainly considers three scenarios based on the behaviors of the vehicle owners, the characteristics of PHEV and power system operation conditions.

1) Uncontrolled charging scenario:
The uncontrolled charging scenario assumes that PHEV owners will plug-in and charging their vehicles whenever they return home, starting at approximately 6pm. The vehicle owners arrive home gradually so the starting time of PHEVs are uniformly distributed from 6pm to 10pm.

2) Off-peak charging scenario:
Charging a large fleet of PHEVs could pose problem to the power grid, especially if vehicle charging is coincident with peak hour of non-vehicle loads. But charging PHEVs during the night using excess generating capacity will result in minimal impacts on the power grid and lower charging costs [21]. Also, the delaying of PHEV charging could be done to prevent the potential increases in peak load and the coordination losses. So the off-peak charging scenario assumes that a simple timed controller is installed in the PHEV battery charging circuit which schedules charging three hours later than the uncontrolled scenario.

3) Optimal charging scenario:
An optimal control algorithm is applied in the optimal charging scenario to decide when PHEVs should be recharged and coordinate PHEV charging loads with the daily load profile. The start time of the optimal charging scenario is the same with the uncontrolled charging scenario which is defined by the empirical driving pattern of the commuters. The end point is the same with the off-peak charging scenario since each PHEV must be fully recharged in time for the first vehicle trip each morning.

B. *Impact of Uncontrolled Charging*

As mentioned previously, a massive deployment of EV connections into the electricity distribution grid may bring some grid operation problems, such as large voltage drops and branch congestions. In this section, the results of the impacts provoked by the PHEVs on a typical 33-bus distribution system [14] are presented. The specified voltage in the feeding point is 1.05 p.u. Fig. 1 shows the PHEV load distribution in the randomly selected nodes, and the ratio is attained through a random number generator.

Power flow studies are applied for the grid network with PHEV charging on a winter load profile [22]. The base load case with no PHEV plugged in and the PHEV charging scenario with the assumed number of PHEVs are compared, in order to evaluate the changes in the voltages and in the branches' congestion levels. To assess the daily losses, 24 power flows per scenario are performed. Fig.2 shows the hourly load with and without PHEV charging on a winter day [15]. In the uncontrolled charging scenario, the afternoon peak is increased due to the need of charging PHEVs from the commuters arriving home.

C. *Comparison with Off-peak Control Scheme*

The off-peak charging scenario is also shown in Fig. 2. Compared to the uncontrolled charging scenario, this control scheme would delay the start time for several hours so that the charging is conducted until the midnight and early morning. To establish a proper comparison between the two scenarios, the results regarding network impact assessment are depicted in the same setting of load profile and timeframe and shown in the same figures.

As shown in Fig. 2, the load peak hour in residential area coincides with the PHEV charging demand if there is no control actions applied. In the off-peak charging scenario, the PHEV charging requirement is simply postponed to avoid the peak period. In reality, the aggregator of PHEV fleet may implement this approach by recharging the PHEVs during the off-peak period under the dual tariff policy. The PHEV owners willing to participate in this control scheme may consume the battery charging energy at a cheaper electricity price. The effects of PHEV penetration in the voltage profiles of the 33 bus network during the peak hours is shown in the Fig. 3. Even though the charging is shifted in a rough way, the voltage drop and branches' congestion can be relieved significantly. The enhanced charging strategies should be developed to accommodate a larger amount of PHEVs in the power grid without the additional investments in grid reinforcement.

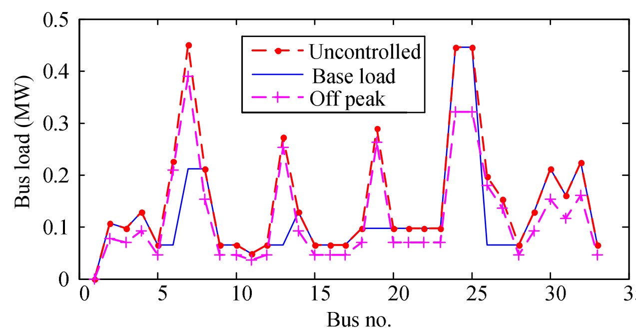

Fig. 1. Load pattern with and without PHEV

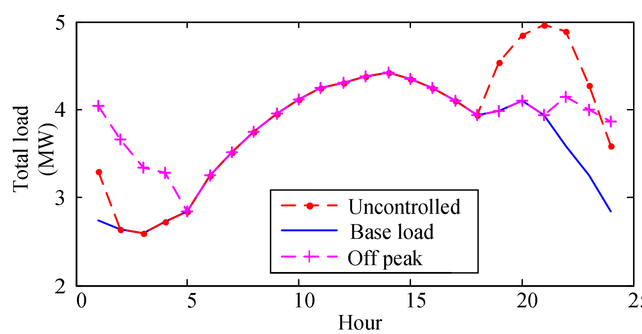

Fig. 2. Hourly load profile with and without PHEV charging

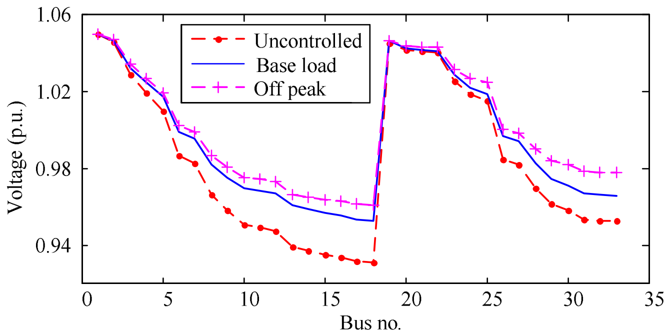

Fig. 3. Voltage magnitude at each node

III. Optimal Scheme for PHEV Integration

A. V2G Framework with the Renewable Energy Technologies

Fig. 4 shows the hierarchical structure of the framework which combines the power grid components and the communication network. 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. Also, the active and reactive power of the devices at residential level is controllable by utilizing power electronics in the system. For instance, a massive deployment of PHEV into the electricity distribution grid may bring some grid operation problems, such as branch congestions or large voltage drops. To minimize the total power loss or voltage drop, the input/output power of connected PHEV battery storage, electric machines or other controllable end-users devices [23-28] are regulated by their own converters according to coordinated operation scheme.

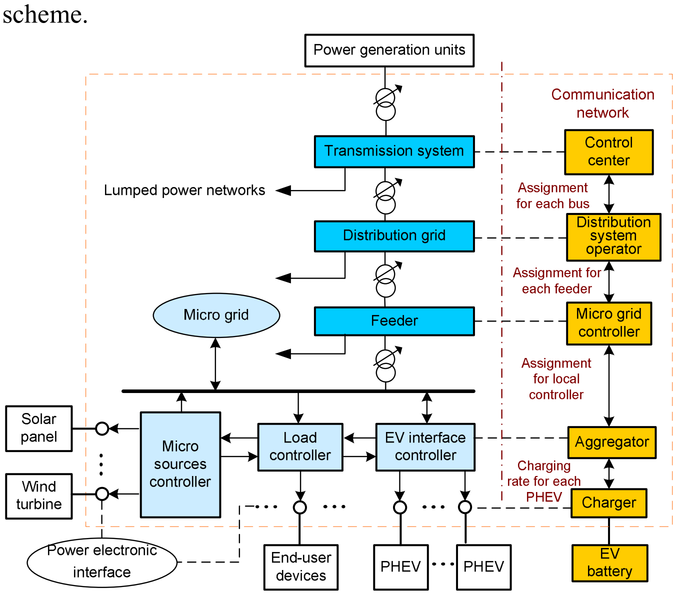

Fig. 4. Hierarchical control framework for V2G operation

B. Optimal Control Algorithm

In the uncontrolled scenarios, the vehicle model is used to determine the charging decisions made by the individual PHEV owners. The recharging power demand is formulated and embedded into the power system planning as an extraneous parameter. In the optimal charging scenario, the vehicle and power system models are integrated together. The grid operator coordinates the need of both power system and PHEV charging. The objective function is to minimize the sum of total power losses, subject to the constraints for both sides [29-30].

The optimal charging model is formulated as minimizing total power losses [22]:

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

This function is subject to the following constraints including the power balance, PHEV recharging energy and capacity limits.

$$\sum_{i=1}^{N_G} P_{Gi}(t) = P_{load}(t) + \sum_{i=1}^{N_V} P_{Vi}(t) + P_{loss}(t) \tag{2}$$

$$P_i^{\min} \le P_{Gi}(t) \le P_i^{\max} \tag{3}$$

$$\left| I_{ij} \right| \le I_{ij}^{\max} \tag{4}$$

$$E_{Vi,\text{int}} = \sum_{k=1}^{n_{Vi}} SOC_{Vi,k} E_{Vi,k} = n_{Vi} E_{Vi,avg} \tag{5}$$

$$\sum_{t=1}^{t_{\max}} P_{Vi}(t) T = E_{Vi,\max} - E_{Vi,\text{int}} \tag{6}$$

$$P_{Vi}^{\min} \le P_{Vi} \le P_{Vi}^{\max} \tag{7}$$

$$0 \le E_{Vi,\text{int}} + \sum_{t=1}^{t_k} P_{Vi}(t) T \le E_{Vi,\max} \tag{8}$$

Notations:

t_{max} : whole planning period
l_{max} : number of the transmission lines
R_l : resistance of the l^{th} transmission line
I_l : line current
N_V : number of PHEVs connected to the grid at time t
N_G : total number of the generation units
$P_{Gi}(t)$: small-size distributed generation at the time step t
$P_{Vi}(t)$: charging rate of PHEV aggregation at the time step t
$P_{loss}(t)$: power losses at the time step t
P_i^{min} : lower output bound of the generation unit i
P_i^{max} : upper output bound of the generation unit i
$E_{Vi,int}$: initial battery energy of PHEV aggregation
n_{Vi} : number of PHEVs aggregated at each node
$SOC_{Vi,k}$: initial SOC of each PHEV battery pack
$E_{Vi,k}$: battery storage capacity of each PHEV
$E_{Vi,avg}$: mean value of the PHEV initial SOC
T : charging period
$E_{Vi,max}$: maximum amount of energy to recharge the PHEV aggregation i during the charging period
P_{Vi}^{min} : minimal recharging rate
P_{Vi}^{max} : continuous power rating of an electricity outlet
t_k : a time step within the charging period

IV. Results

A. Solutions of Optimal Charging Scheme

As mentioned before, PHEVs may work either as a load by recharging battery pack or as a generator feeding energy into the grid. The Charging rates of each PHEV fleet are shown in Fig. 5. In this optimal charging scenario, it can be seen that the PHEV charging actions are further improved. The V2G operation in the early evening helps to shave the peak load in the early evening, therefore curtail the voltage drop and line losses at maximum loading condition as shown in Fig. 6 and 7. The difference between the uncontrolled scenario and the optimal charging scenario is also presented in Fig. 7. The PHEV charging load and the discharging capacity are redistributed to minimize the objective function, which is the summation of power losses during the charging period. Moreover, the maximum value of power losses is reduced by a third in the peak hour, which indicates the remarkable decrease in line loading rate. The branch loading rate and voltage drop are both the limiting factors to accommodate larger PHEV load in the grid. With the optimal charging scheme, the voltage profile and line losses are improved so the higher level of PHEV integration is allowed.

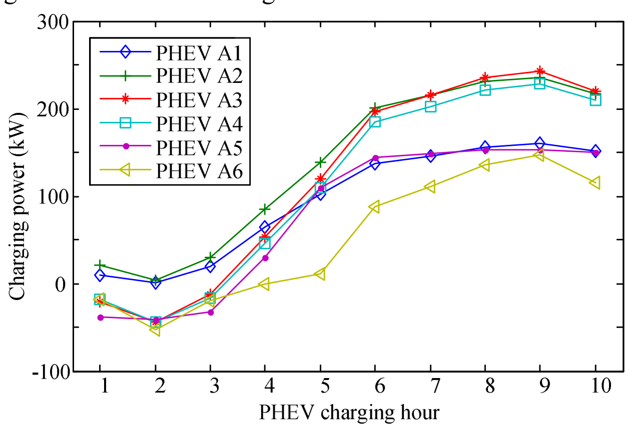

Fig. 5. Charging profiles for the six PHEV aggregations

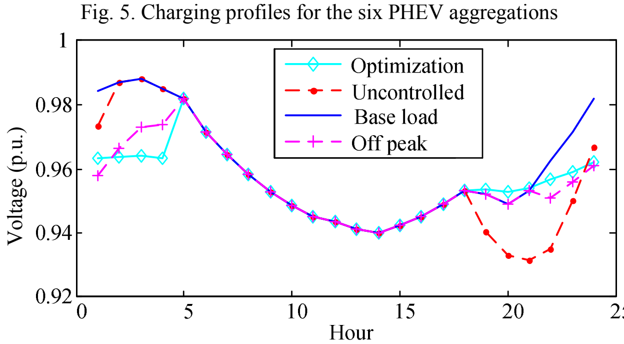

Fig. 6. Daily voltage profiles in the three scenarios

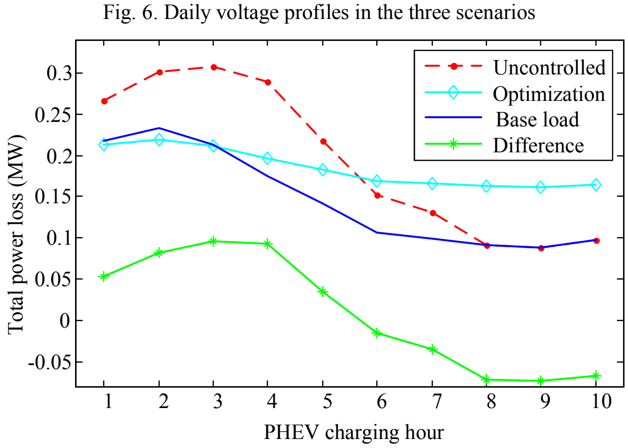

Fig. 7. Power losses for the uncontrolled and optimal charging scheme

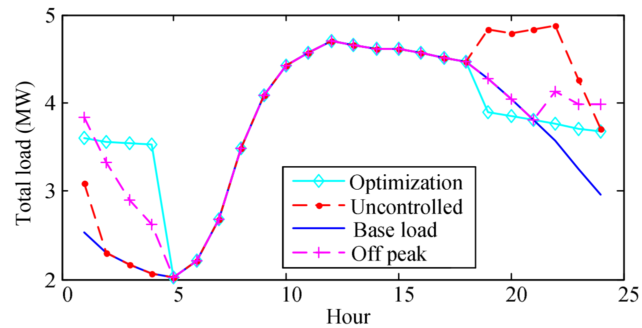

Fig. 8. Daily load profiles under the different base load condition

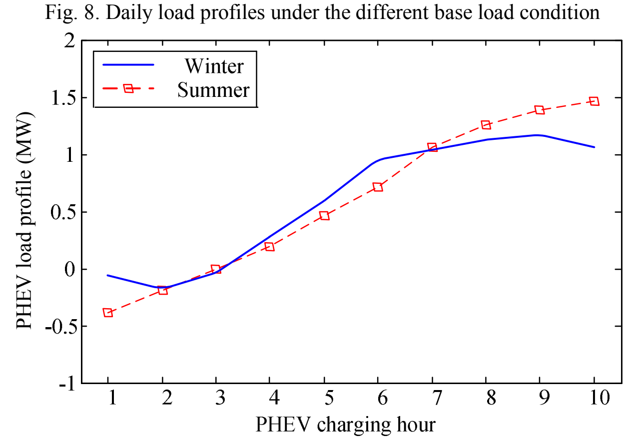

Fig. 9. Comparison of PHEV load based on different daily load pattern

B. *Different Load Profile of the Test Power Network*

A typical summer daily load profile is shown in Fig. 8 [15]. Three PHEV charging scenarios are performed on the summer load condition and the results for PHEV charging and discharging are added to the base load. Fig. 9 shows the total hourly charging of PHEVs, which highlights the effects of the differences in seasonal load profiles on PHEV charging. The driving and charging pattern are not changed in the uncontrolled scenario. With the optimal control method, the grid operator would opt for a fair amount of recharging between 12pm and 4am in the summer, so that the available capacity of the committed generators can be consumed. Moreover, in the winter, the grid operator would provide more power resource from discharging PHEV immediately after the commuters start to connect the vehicles to the power grid at home. The PHEVs act as a power supply due to the increasing demand in the early evening, whereas this is not done in the summer case.

C. *PHEV Penetration Level*

The highest voltage drop bus is selected to depict the daily voltage profile, which is shown in Fig. 6. The minimum voltage for the uncontrolled scenario occurs in the charging period and is already less than 0.94 at this penetration level. On the other hand, the minimum voltages for the off-peak and optimal charging scenarios are above the minimum value of no PHEV situation. The growth of PHEV penetration level may lead to more serious voltage drop and hence violating the lower voltage limit of the power grid. As shown in Fig. 10, if the PHEV charging load is increased by 60%, the minimum voltage for the off-peak charging scenario will reach 0.94. If the PHEV charging load is further increase by 100%, even the optimal charging scheme fail to keep the minimum voltage above the minimum value in the case without PHEVs. In this situation, new generating capacity may be necessary to satisfy higher peak load on the grid and the existing transmission.

The light and high penetration levels are defined based on the minimum voltage magnitude of the three charging scenarios. At light PHEV penetration level, only the minimum voltage of the uncontrolled scenario reaches the base load minimum value. On the contrary, at high PHEV penetration level, even the optimal charging scenario approaches to the minimum voltage in the base load case. The results of the preceding section are presented as the moderate case only for comparison. The total power losses during the charging period are also compared for the three PHEV penetration levels in Fig. 11. As expected, the optimal charging provides better results since both PHEV charging and discharging are flexibly deployed for the optimal objective.

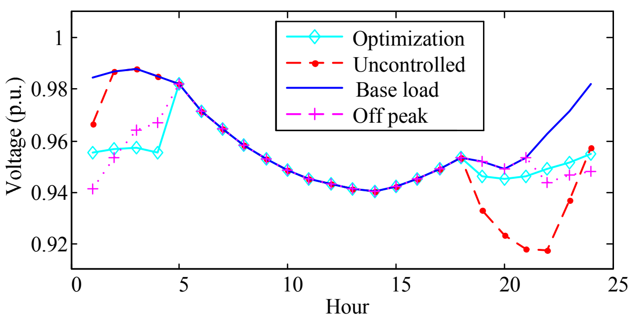

Fig. 10. Voltage profile for the PHEV charging demand increased by 60%

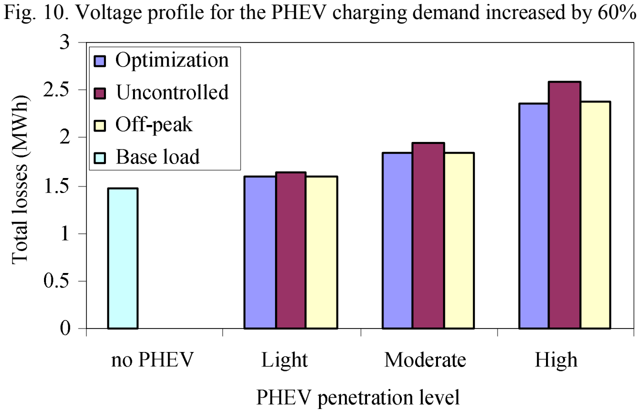

Fig. 11. Total losses in the three charging scenarios for the selected day

D. V2G Operation in Daytime

The PHEV commuters go to work in the morning, park the vehicles around the working place, and go back home in the late afternoon. So the PHEVs can also be plugged into the grid during the daytime when they are in the parking lots with PHEV recharging infrastructure installed. Also, the grid operator can control the recharging of PHEV between two trips during the day to perform the V2G operation. We assume most of the PHEVs are fully charged during the night and still have sufficient energy stored in the battery. Once plugged into the grid, PHEV batteries may act as a supply-side resource to release the energy for the V2G services.

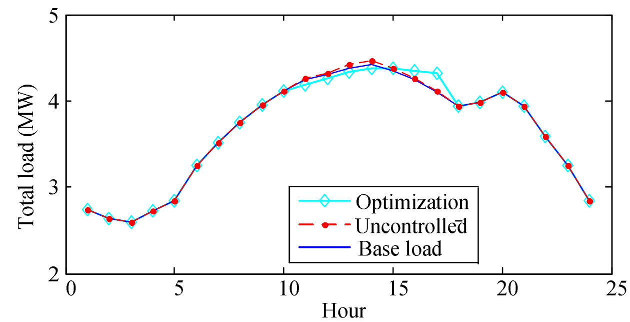

Fig. 12. Daily load profiles in the daytime PHEV charging scenarios

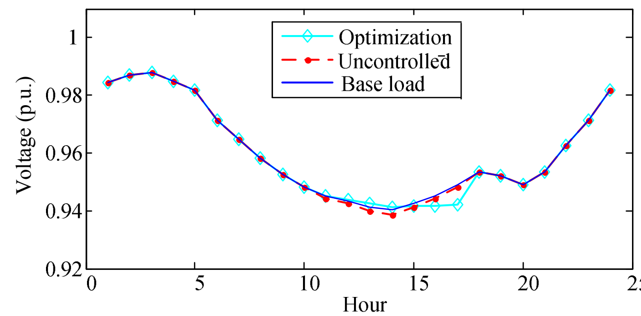

Fig. 13. Daily voltage profiles in the daytime charging scenarios

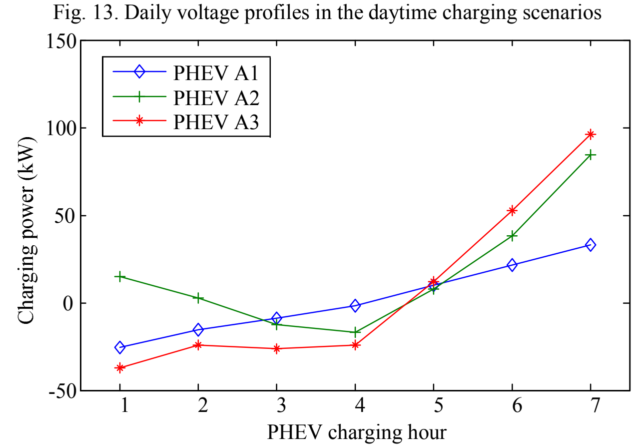

Fig. 14. Charging profiles for the three PHEV aggregations in the daytime

In order to estimate the V2G operation in the daytime, The following assumptions are made: firstly the average value of the initial SOC is stipulated as 60%, and secondly the number of PHEVs integrated into the grid is set to merely 40% of PHEVs in the previous scenario. Among these PHEVs, 50% of them must be recharged to the target SOC of 90%, and others only require to maintain the initial SOC of 60% in average by the end of the V2G operation period. Three buses are selected randomly for the PHEV aggregation, and the distribution of the PHEVs through these three buses is uncertainty. Thus the ratio for the sizes of PHEV aggregations is given by a random number generator and set as 6:34:19 in this case. The PHEV charging and discharging pattern based on the same daily load profile is shown in Fig. 12. The corresponding voltage profile presenting the highest voltage drop bus is shown in Fig. 13. In the uncontrolled scenario, only PHEV charging happens in the whole operating period from 10am to 6pm. With the optimal charging scheme, on the other hand, the discharging of PHEV aggregation is performed during the peak hours to provide resources for the grid. The charging rates of each PHEV aggregation are shown in Fig. 14. Each individual PHEV aggregation performs the charging and discharging according to the solutions of the optimal control algorithm.

V. Conclusion

This paper examines the impacts of increasing integration of PHEVs into the distribution grid, and proposes the controlled charging scheme to coordinate the V2G operation of PHEVs and the power system. In the optimal charging scenario, the grid operator has a great deal of flexibility in coordinating charging decisions given the needs and restrictions of both sides. With an uncontrolled strategy, PHEV charging will increase peak load. This increase could necessitate more generating capacity in the system. This problem with uncontrolled charging could be overcome if the optimal control scheme is used to coordinates the V2G operation of PHEVs with the electric network. The voltage drop and line loading can be reduced to prevent the violation of the system limits with the higher PHEV penetration level.

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