Modelling, Evaluation and Optimization of Vehicle-to-Grid Operation

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Abstract
This paper describes a simulation model of PHEV integration with the grid. This model provides primary PHEV charging and discharging scenarios based on the general PHEV owner behaviors and the typical PHEV charging circuitry configuration. Initially, the uncontrolled PHEV charging scenarios are performed to evaluate the impact of the PHEV loading on the distribution grid operation. The night charging scenario is chosen for detailed analysis and the load flow is used to calculate the power distribution and loss on the 33-bus test power network. The results indicate the inadequacy of current power capacity to meet the growing electricity demand from PHEVs. A simple control method of off-peak charging is performed to show the improvement in voltage levelling and line loading. Therefore, the appropriate control scheme should be derived for regulating the PHEV charging and discharging. An optimal algorithm is proposed for utilizing the PHEV charging and discharging power in a distribution system to minimize the total real power loss. During charging period, the power rate of individual battery charging is coordinated according to the optimal objective and constraints of charger, battery and power grid. Compared to the uncontrolled PHEV charging results, the optimal algorithm can achieve the maximum loss reduction for each charging scenario. Moreover, voltage drop at each node is limited in a tolerable range while the tightened branch current restrictions are satisfied.

Keywords: “PHEV”, “power loss minimization”, “optimal charging”, “distribution grid”

1 Introduction
The rise in fossil fuel prices, growing concern for environmental pollution and the demand for renewable energy [1-4] contribute to increasing interest in electric vehicles (EVs)
technology in recent years. Among them, the plug-in hybrid EV (PHEV) is considered as a promising solution for electrification of transportation sector and being introduced rapidly into the market by the mainstream automobile manufacturers [5-6]. The PHEV can be charged to store the energy by connection to electricity outlet, and have the capability to supply the energy storage to grid by discharging the battery [7-9]. The existing studies provide comprehensive topologies for bi-directional EV battery chargers [10]. The aggregation of PHEVs plugged in the distribution grid becomes an electric load in the short term. Numerous studies have examined the issue of PHEV penetration degree and electrical consumption over the next few years, which indicated that the penetration of PHEVs in 13 US regions would be up to 25% by 2020 [11]. Without controlled charging, large-scale PHEV deployment could challenge the accommodation ability of the current power supply adequacy, thus requiring the construction of new power plants. However, the integration of PHEV into power network also promises many advantages by providing ancillary grid support services or storage for renewable generation expansion. Given the potential for a controllable large-scale load or resource, it is important to understand the impact of growing PHEVs on the grid.

The aggregation of a sizable number of the PHEVs may constitute a significant load on the current power network. Additional PHEV loading increases the node voltage drop which contributes to the incremental power losses. This paper assesses the impact of PHEV charging on the grid operation in terms of power losses and voltage deviations by building the simulation model of the distribution grid with the PHEV penetration over certain degree. The results manifest the challenge of distribution system operation even though the PHEVs are charged in the off-peak time. It should cause a high risk of overload when the battery charging occurs near the daily peak; therefore, proper rescheduling of the grid operation is important for the grid with PHEV integration. In this paper, an optimal control method for PHEV charging is proposed to minimize the power losses and enhance power quality as well. The further deployment of V2G power for improving the system operation is also discussed.

2 Impact of Growing PHEV Loading

The purpose of the PHEV integration model is to estimate the impact of increasing PHEV charging load on the distribution grid. The proposed modeling method is described in detail and three PHEV charging scenarios are considered. The night charging is chosen to calculate the hour-by-hour loading profile and power loss.

2.1 Formulation of PHEV charging scenarios

A known number of PHEVs are deployed on the 33-bus radial distribution grid. The PHEV loads are randomly distributed throughout the selected nodes in the network. The first vehicle charging case in this study is the uncontrolled charging. The overall PHEV penetration is 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 who live in apartment complexes or higher density urban dwellings where the parking lots have recharging infrastructure installed. That is, PHEV loads are more likely to be clustered in certain sites increasing the production for negative distribution system impacts. Thus, we assume that the PHEV load demand assembles at several nodes in the grid as shown in Fig.1. In this case, vehicle owners charge their
vehicles at home when they come back from the workplace [12]. The PHEV begins charging as soon as it is plugged into the distribution grid at a constant power input until the battery is fully charged. The battery pack holds 9kWh of energy and 90% efficiency for on-board/off-board charger [13-15]. All PHEVs are plugged into a 220V/13A, the power rating of Hong Kong residential electricity outlet, operating at a maximum charging rate of 2.8kW. Although this is the low charging mode for common household circuit, the PHEV can be fully charged within 4 hours. The parameters set for formulating the PHEV charging load is listed in Table 1.

The PHEVs are expected to be fully charged at their home location and drive to their workplaces in the morning. The number of the PHEVs charged at certain time is varied by a normal distribution function. The standard deviation $\sigma$ is determined in such a way that all the PHEVs are fully charged by the end of the charging period, namely 3:00 am. Since the starting point of uncontrolled PHEV charging is normally coincident with the high load demand in the early evening. The off-peak charging scenario is derived to delay the PHEV charging in order to shift it to the off-peak period.

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

2.2 Effects of PHEV charging

The load flow calculation is performed to evaluate the impact of this additional load. The hourly voltage profile and the total power loss are illustrated in Fig 2 (b) and (c). In both of the figure, the time step with the heaviest load demand is selected so that the maximum voltage drop and line losses can be manifested. Although the off-peak control scheme is simply designed to regulate the PHEV charging, the voltage drop and the line loading can be effectively reduced.
charging demand may be insufficient. Therefore, the appropriate control scheme is necessary to be applied onto the power grid with a high level penetration of PHEVs.

In Fig. 3 (a) the base load represents the daily electricity demand pattern in Hong Kong and the PHEV charging load is added. 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. There is a clear increase of daily peak demand due to the integration of PHEVs. The off-peak charging scheme can offset the peak load demand caused by PHEVs. Thus the voltage drop can be curtailed within the limited range. It could decrease supply adequacy and indicate the ability to accommodate the extra PHEV

3 Control Framework for V2G Operation

The integration of PHEV fleet into the power grid provides the opportunity to utilize the energy stored in the vehicle batteries as the power supply. The V2G is defined as the power that vehicle fleet feed back to the grid with appropriate connection. The upgrading the existing power grid to smart grid opens new opportunities for V2G implementation. The smart sensor and metering devices, the two-way communication network and the multi-layer control structure can be necessarily used for realizing V2G operation. The aggregator which supervises the charging and
discharging of PHEVs has to interact with power system operators at different levels. A V2G framework to effectively integrate the aggregated PHEVs into grid is proposed and depicted in Fig. 3. The construction of information layer is also described in the diagram to show the groups of data and signals for V2G control. Based on the conceptual framework derived for V2G implementation, a hierarchical structure with the controllable electric devices is constructed in the real power network.

4 Optimal Control Algorithm of Coordinated Charging

In order to reduce the negative effect of PHEV load, optimal charging method should be used to reduce the power loss and voltage drop [16-18].

4.1 Optimal algorithm for minimizing power losses

The objective of the coordinated charging scheme is to minimize power losses. Sequential quadratic programming method [19-20] 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:

$$\min P_{loss} = \min \sum_{l=1}^{N} \sum_{r=1}^{M} R_{l} \cdot I_{l}^{2}(t)$$

(1)

where $R_{l}$ and $I_{l}$ is the resistance and current on the transmission line, and the $P_{loss}$ represents the total power loss. This function is subject to the constraints of charging rate, battery state and power system operation limitations.

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:

$$\sum_{i=1}^{N_G} P_{Gi}(t) = P_{load}(t) + \sum_{i=1}^{N_S} P_{Si}(t) + P_{loss}(t)$$

(2)

where $N_G$ is the total number of the generators in the system including the small-size
distribution generators and limited capacity of discharging PHEVs, and \( N_V \) is the number of PHEVs connected to the grid at time \( t \).

2. Generation limits. Each generation resource in a certain bus has a generation range, which is defined as:

\[
P_{i \min} \leq P_{i}(t) \leq P_{i \max}
\]  

where \( P_{i \min} \) and \( P_{i \max} \) are the upper and lower boundaries of power output for each generator.

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

\[
|I_{ij}| \leq |I_{ij}^{\max}|
\]  

where \( I_{ij} \) is the current of the branch between bus "i" and "j".

4. The initial SOC of PHEV load. The state of charge (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.

\[
E_{V_i,\text{int}} = \sum_k SOC_{V_i,k} E_{V_i,k} = n_{V_i} E_{V_i,\text{avg}}
\]  

where \( E_{V_i,\text{int}} \) is the initial battery energy of PHEV aggregation, \( n_{V_i} \) is the number of PHEVs aggregated at each node, \( SOC_{V_i,k} \) is the initial SOC of each PHEV battery pack, \( E_{V_i,k} \) is the battery storage capacity of each PHEV, and \( E_{V_i,\text{avg}} \) is the mean value of the PHEV initial SOC predetermined in accordance with the characteristic of vehicle on-board battery pack.

5. Total energy for PHEV charging. It is expressed as:

\[
\sum_{i = 1}^{n_{V}} P_{i}(t) T = E_{V_i,\text{max}} - E_{V_i,\text{int}}
\]  

where \( T \) is the time interval and \( E_{V_i,\text{max}} \) is the maximal amount of energy to recharge the vehicles at the end of the charging period, indicating the battery energy storage capacity of each PHEV aggregation, because the vehicles must be fully charged before the departure from the parking lots.

6. The limit of PHEV charging rate. The PHEV battery charging power regulated by the on-board/off-board charger should be restricted in a reasonable range [21], taking into consideration of the recharging time and the availability of grid power.

\[
P_{V_i,\min} \leq P_{V_i} \leq P_{V_i,\max}
\]  

where \( P_{V_i,\min} \) is the minimal recharging rate, and \( P_{V_i,\max} \) is the continuous power rating on name plate of an electricity outlet.

In the algorithm, the power flow analysis is firstly implemented 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. While the potential use for PHEVs is as distributed electrical sources, the first case only considers the loading characteristics. The ratio of the PHEV charging demand at the six nodes is defined from the random number generator. The charging rate of each PHEV aggregation is decided by optimal control algorithm and varying over the time. Two of them are depicted in the Fig. 5, which are the nearest and farthest points from the main generation unit.

4.2 Simulation results for optimal charging scenario

The PHEV charging is dispatched in the period that is the same with the uncontrolled charging. As shown in Fig. 3, the daily load demand stays the same pattern. Fig. 6 shows the
additional PHEV charging load that is appended onto the base load. Under the optimal control scheme, the PHEV charging loads are shifted to match the periods of minimum demand. The power losses are reduced by the regulation of PHEV charging load as shown in Fig. 7.

Figure 6: PHEV charging load with and without the optimal regulation

Figure 7: Total losses of the different scenarios during the charging period

Figure 8: Minimum voltage profile on a daily basis

The comparison of the voltage profile in optimal charging and the uncontrolled charging scenarios is illustrated in Fig. 8, where the minimum bus voltage at each time step is selected. The proposed optimal charging scheme reduces the voltage deviation below 10% of the distribution nominal voltage (the standard limit set in EN50160 [22]). This extra load can be accommodated by the current power system without serious augment in the power losses and voltage drop.

5 Improved Algorithmic Model for V2G Operation

The management of charging PHEVs is the mere concern in the above algorithm while the PHEV aggregation can act as both controllable load and resource for participating in the power system planning. The ability of PHEV discharging into grid can also be evaluated by using this simulation model and algorithm. It should be noted that even a small size of PHEV discharging aggregation can provide peaking and peak reserve capacity, especially during the peak demands. A V2G ratio is introduced to assess the battery capacity that can be used for power supply compared to the demand for battery charging. The V2G ratio is expressed by:

\[ r_{V2G} = \frac{E_{V2G}}{E_{EV}r_{V2G}} \]  

where \( r_{V2G} \) is the ratio of energy for power supply to the energy required for charging PHEVs.

In the 33-bus system simulation with V2G capability, 20% of PHEV charging amount in previous scenarios is assumed to provide discharge capacity while the PHEV fleets are placed in the same nodes as the above case. The algorithm can also be adopted to schedule a very limit PHEV discharging capacity to shave the peak demand in the daytime. The new boundary must be set in the constraints to manifest the actual V2G capacity.

Although the available discharging energy is small, the results in Fig. 9 show a substantial reduction of power loss and the improvement of voltage stability. The V2G energy is supplied to make sure the voltage drop is
within 10%, which can meet the voltage standard defined in EN50160 [16], and improve the grid-buffering capability of the PHEV aggregation.

![Graph](image)

Figure 9: 24-hour simulation results for the improved V2G operation scheme: (a) daily load profile with and without PHEVs; (b) minimum voltage profile; (c) total power losses

6 Conclusion

In this paper, a combined model of PHEV and power network is built to assess the impact of increasing PHEVs on the existing distribution grid. The simulation results indicate that the deployment of PHEVs in a distribution network will have diverse effects on power loss and node voltage drop, which indicating the necessity of power regulation method. A hierarchical structure of the V2G framework is thereby derived to perform the optimal control scheme. Both the characteristics of PHEV and power system model are included in the optimal control algorithm to demonstrate the realistic situation for V2G operation. By the comparison to the uncontrollable charging case, the optimal method can efficiently minimize the total real power loss, and maintain the bus voltage. This PHEV model and optimal charging scheme paves the way to a practical vehicle-to-grid operation, and proves the V2G operation can allow the high level penetration of PHEVs in the existing grid and may be able to support the system operation.

Acknowledgements

This work was supported by a grant (Project no. 201007176031) from the HKU SPACE Research Fund and the Committee on Research and Conference Grants of University of Hong Kong.

References


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Prof. C. C. Chan is currently an honorary professor in the Department of Electrical & Electronic Engineering, University of Hong Kong. He has authored 4 books, published over 120 technical papers, and held 7 patents. Prof. Chan is also a Fellow of the Royal Academy of Engineering, U.K., an Academician of the Chinese Academy of Engineering, a Fellow of the Ukraine Academy of Engineering Science and a Fellow of both IEEE and IET.