An Online Optimization Approach for Plug-in Electric Vehicle Integration into the Electrical Grid

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Abstract— **The trend in sustainable transportation systems has led to an increase in the number of plug-in electric vehicles (PEVs). However, a major issue associated with widespread PEV deployment is the potential adverse impact of vehicle charging on the power grid. One way to address increase in demand from PEVs and avoid aggravated peak loads is through vehicle-to-grid (V2G) applications. This study develops an online optimization model for scheduling the centralized charging and discharging of a significant number of PEVs in a smart parking lot. The optimization problem is formulated using a rolling horizon method with objectives to meet the requirements of the electric vehicle owners while considering grid and aggregator needs. Finally, the model is used in a simulated problem to demonstrate the optimal solution**.

Keywords— ***Vehicle-to-grid, electric vehicles, optimization***

I. Introduction

Plug-in electric vehicles (PEVs) including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) are expected to revolutionize personal transportation as they become more affordable and as more consumers make the transition away from conventional vehicles that depend on fossil fuels. However, the connection of a large number of PEVs to the electrical grid presents both opportunities and challenges. The large increase in demand that will accompany the transition to electric transportation can cause the power infrastructure to become overburdened leading to issues of reliability. Modern power grids are large and complex systems that prove challenging to manage [1]. Therefore, widespread adoption of PEVs can add to complications in managing interdependencies of this critical infrastructure. For instance, charging significant numbers of PEVs concurrently poses risks of overburdening the power grid [2]. Furthermore, the successful deployment of electric vehicles depends, to a great extent, on the affordability, availability and quality of the associated services that a country's critical infrastructure can provide [3]. Grid modernization, including smart grids and microgrids [4], can better leverage the benefits of PEVs.

Through vehicle-to-grid (V2G), the increase in demand caused by PEVs can be controlled to avoid excessive peak loads [5]. In a V2G system, PEV batteries can be used for load management by storing excess electricity from the grid when needed and delivering electricity back to the grid when needed. A concern about V2G is the impact of frequent charging and discharging on the battery of participating PEVs [6]. Therefore, it is necessary to account for PEV battery wear in V2G optimization studies.

Strategies have been proposed for optimizing electric vehicle charging and discharging in vehicle-to-grid (V2G) systems [7-12]. Reference [11] presented a probabilistic unit commitment model for optimal scheduling of wind power, load forecasts and plug-in electric vehicles in a microgrid to enable power grid operators with optimal day ahead planning. Reference [12] modeled different aspects of PEVs using geographic information system and a mathematical algorithm based on genetic algorithms. The study minimized the cost of charging station installation and improved their geographic distribution.

Many of the existing studies on the optimization of electric vehicles in V2G systems focus on the technical and economic potential of V2G systems and/or on the benefits to the power grid. Uncertainties related to PEV owners have been mostly ignored. In this paper, an online model for optimal scheduling of the charging and discharging of PEVs in a centralized V2G system is developed. In this online problem, the state of PEVs and consumer preferences are unknown until the vehicles arrive at the V2G system. This model is based on the rolling horizon method and accounts for PEV driver needs and PEV battery life.

II. Methodology

This study considers a centralized V2G system connected to a smart grid where PEVs charge and discharge their batteries depending on the needs of the driver and the electrical grid. The system is managed by an aggregator, which acts as a central controller and middleman between the grid and the PEVs. The study is based on rolling horizon method [13, 14]. The rolling horizon method, decomposes scheduling problems with longer periods into simpler sub-problems with shorter periods [14]. As a result, the complexity

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of the original problem is reduced. This study employs a forward rolling horizon approach which begins the optimization process from the first period.

The optimization problem considers four main factors including a) minimizing the cost of charging PEV batteries b) maximizing the earnings from discharging PEVs c) ensuring that PEVs reach their desired state of charge (SOC) at departure time where possible and d) considering battery life in scheduling the charging and discharging of vehicles. This paper considers two scenarios, a non-V2G scenario and a V2G scenario.

III. Problem Formulation

In the non-V2G or business as usual scenario, vehicles begin charging once they enter the V2G system. They continue to charge until they reach their desired SOC. No discharging occurs in this scenario. In the V2G scenario, the charging and discharging schedule of PEVs are determined by the aggregator based on PEV driver needs as well as the electrical grid needs. In addition, the V2G scenario considers the age of the vehicle and incorporates a switching constraint similar to ref [8, 15].

In this study, the electricity available for charging and discharging are defined in terms of electricity units. An electricity unit is defined as the maximum amount of power that is available for charging a vehicle during a given time slot or the maximum amount that can be discharged back to the grid by a vehicle during each period. The objective function for the V2G scenario is given in (1) below. The schedule for the PEVs is achieved by minimizing the sum of the cost of charging and the penalty assigned to unfulfilled electricity units minus the earning from discharging. The goal is to meet PEV driver needs where possible while taking into account electrical grid needs.

$$obj = Min \frac{\left(\sum_t \sum_i x_{it} * c_t + \sum_i pz * z_i - \sum_t \sum_i y_{it} * p_t\right)}{\# PEVs} \quad (1)$$

Where i and t represent the indexes for PEV and time respectively. y_{it} represents a binary variable which indicates whether a PEV is being discharged or not at time t. Therefore, y_{it} = 1 signifies that a vehicle is discharging and y_{it} = 0 indicates that a vehicle is idle. Similarly, x_{it} is a binary variable that indicates if a PEV is being charged in time t. p_t and c_t are price of discharging at time t and the cost of charging at time t, respectively. pz is a cost incurred as a penalty due to unfulfilled electricity units and z_i refers to the number of unfulfilled electricity units, which is the number of electricity units below the desired SOC at time of departure. Since no discharging occurs in the non-V2G or business as usual scenario, the term $\sum_t \sum_i y_{it} * p_t$ is zero.

Some key constraints for the model include the following:

$$\sum_i x_{it} \leq cp_t \qquad \forall t \quad (2)$$

A key energy constraint in this study is capacity of the smart parking lot cp_{t}, which is the power available to the parking lot from the electric utility. Another energy constraint is the battery capacity (mc_i) of each vehicle expressed in electricity units. Equation (2) specifies that the electricity available for charging PEVs in the system at any given point in time cannot exceed the maximum electricity allocated to the parking lot cp_t during that time. Equation (2) ensures that the load of all the PEVs in the system at any given time slot does not exceed the maximum capacity of the parking lot cp_t during that time.

The constraint in (3) imposes a limit on the number of times a vehicle battery can be switched. Here, a switch is considered a change from one state to another. Three states including charging discharging and neutral are considered. A change from charging to neutral or discharging to neutral in either direction is counted as one switch.

$$\sum_i s_{it} \leq ms_i \qquad \forall t \quad (3)$$

Where S_{it} is the number of switching as described above and ms_i is the maximum switching which is assigned based on the age of the battery. There are three categories of battery age inluding new, intermediate, and old. The older the battery the less switching is permitted.

In addition, a constraint is introduced to specify that at any given time t for each PEV i, the sum of electricity units due to charging and discharging as well as unfulfilled units during a PEV's presence in the system equals the difference between the desired state of charge u_i and the initial state of charge $isoc_i$ of that PEV.

IV. Results and Discussion

A. Simulation Considerations

This study considers a V2G parking lot with 750 PEVs. Five 24-hour periods are considered and then the results of simulation over 5 days are averaged. Each 24-hour day is divided into 30-minute periods resulting in a total of 48 periods per day.

A level 2 charging rate of 3.3 kW/hour resulting in fixed electricity units of 1.65 kWh per 30-minute period is considered. The cost of charging and discharging vary throughout the day and are highest during peak periods and lowest during off-peak periods or periods of lower demand.

Fig. 1 shows the arrival time of PEVs in the parking lot averaged over a five-day period. As Fig. 1 shows, vehicles begin to arrive at the 5:30 am time slot or the 11th period and continue to arrive till the 48th period which is the final period of the day. Once a PEV arrives in the V2G system, the aggregator determines the optimal schedule for charging and discharging the vehicle. All vehicles must depart the smart parking lot by the end of the 48th period

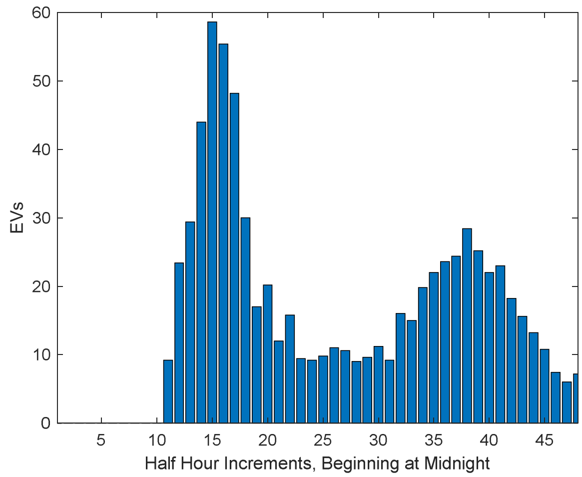

Fig. 1. Average arrival distribution of PEVs

B. Simulation Results

The results in Fig. 2 show the charging and discharging pattern of the non-V2G and V2G scenarios averaged over 5 days in comparison to the capacity of the parking lot (i.e., the electricity available to the parking lot). The business-as-usual or non-V2G scenario follows the arrival distribution pattern more closely than the V2G scenario because the PEVs in the non-V2G scenario begin charging once they arrive in the system and continue to charge where possible until they reach the desired SOC. As Fig. 2 illustrates, the total electricity units used for charging at any point cannot exceed the electricity capacity of the parking. It can also be observed that the electricity units used for charging reduces and eventually drops to zero during periods where the capacity is low. This period of low capacity corresponds to the period of peak electricity demand where electricity cost is highest. In the non-V2G scenario, the cost of charging is not considered in determining vehicles' charging schedule due to the previously mentioned requirement to begin charging vehicles once they arrive in the system till their desired SOC is met if there is available capacity.

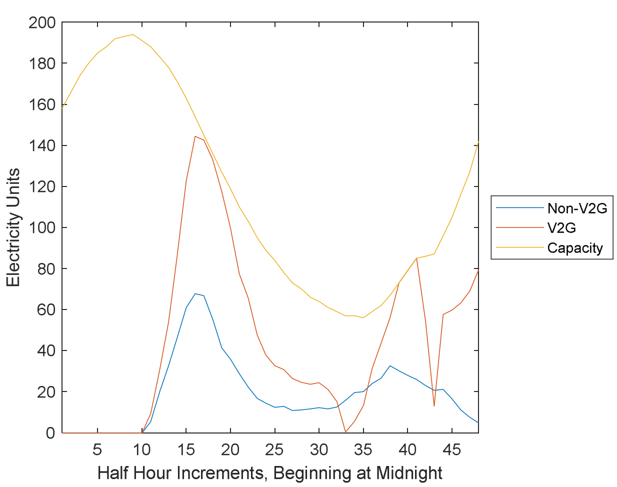

Fig. 2. Charging distribution for V2G and non-V2G scenarios

Fig. 3 illustrates a major distinction between the V2G and the non-V2G model variations, which is the fact that while discharging occurs in the V2G scenario, this is not the case in the non-V2G scenarios. As a result, the electricity units due to discharging for the non-V2G scenario is zero for the entire study period. In contrast to the charging behavior depicted in Fig. 2, it can be observed in Fig. 3 that the discharging for the V2G scenario peaks during periods of low capacity, which occur during peak electricity demand and when the price for discharging is highest. This behavior can be attributed to the objective function which aims to maximize earnings from discharging.

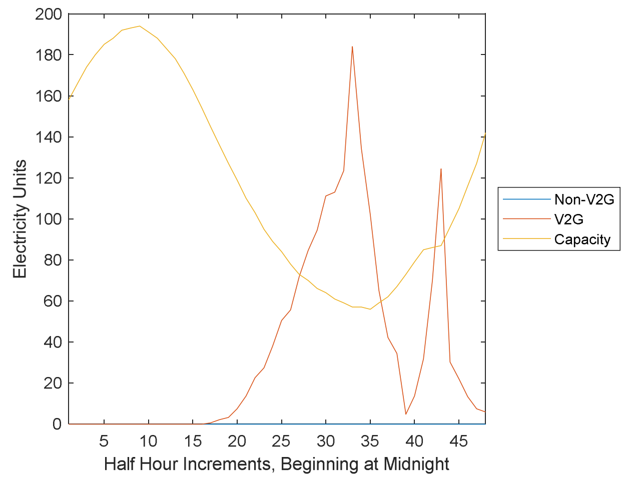

Fig. 3. Discharging distribution for V2G and non-V2G scenarios.

Fig. 4 shows the objective function averaged over five days. This objective function is based on (1) and aims to minimize the cost of V2G participation, which is the sum of the cost of charging and the penalty cost for unfulfilled electricity units minus the earnings from discharging vehicles.

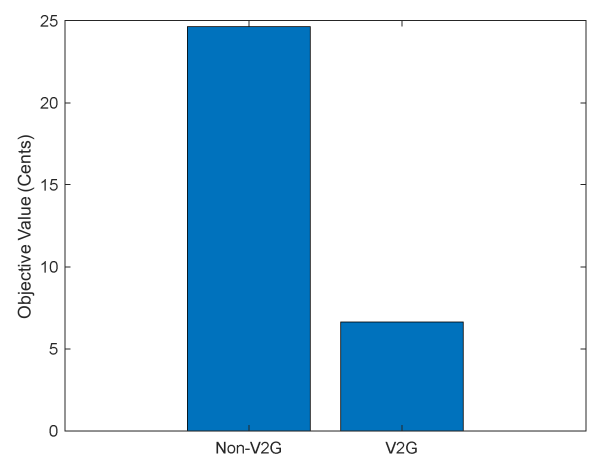

Fig. 4. Average objective function values for V2G and non-V2G scenarios

As can be seen in Fig. 4, the scenario that does not involve V2G has a significantly higher objective function value compared to the V2G model variation. Since the non-V2G model variation does not involve V2G, there is no way to offset the cost of charging the PEVs. In addition, the vehicles in the non-V2G scenario are charged if the vehicles have unfulfilled electricity units and there is available capacity in the V2G parking lot. However, in the V2G scenario, the cost of charging is reduced by the payment the customer receives from discharging their vehicles. Therefore, the V2G scenario results in a significantly lower objective function value. Furthermore, the V2G model variation considers battery age and degradation by reducing the participation of vehicles with older batteries in V2G activities.

V. Conclusions

This paper describes an online optimization model for scheduling the charging and discharging of PEVs in a centralized V2G system. The model aims to meet PEV drivers' needs where possible while considering grid needs and constraints as well as PEV battery age. The results of the study show that the cost associated with participation in the V2G scenario is significantly less than in the non-V2G scenario due to the ability to offset the cost of charging with earnings from discharging.

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