DESIGNING A FINANCIAL-BASED ENERGY MANAGEMENT FRAMEWORK IN SMART PUBLIC PARKING LOT

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ABSTRACT

This paper develops an energy management framework for a large number of V2G-capable EVs parked at a parking lot, which its main objective is to maximize the parking lot operator's total profit from electricity sales. Meanwhile, besides completely fulfilling the energy requirements of EV owners, the proposed method considers the operational requirements of the power grid. In this regard, the authors first propose an electrical energy exchange model in which the parking lot operator purchases electrical energy directly from the wholesale market and stores it in the batteries of EVs and feeds part of this stored energy back into the grid through V2G capability during some specific time periods. After that, based on the presented energy exchange model, a linear optimization framework involving the necessary financial considerations is proposed for the energy management problem. Finally, numerical studies are carried out to show the efficiency of the proposed energy management method from the viewpoints of different players.

INTRODUCTION

Electric power systems have always suffered from lack of sufficient energy storage resources required to maintain the balance between demand and supply, which causes operators to continuously control the amount of power produced by generation units. One of the most promising solutions for this problem is to use the battery capacity of electric vehicles (EVs) that are rapidly growing in number and popularity all around the world. Studies have shown that personal vehicles are utilized only 4% of the time for transportation purposes, i.e. they are left completely useless the remaining 96% of the time [1]. Taking this point into account, the anticipated large number of EVs can provide power grids with a potential energy storage system in the near future. In this case, EVs can serve as active elements and feed the electrical energy stored in their batteries back into the grid. This capability, which is called vehicle-to-grid (V2G), enables EVs to flexibly treat as either loads or storage facilities.

Operating EVs as some dispersed energy storage devices can obviously introduce potential benefits to the power system. However, the limited and small battery capacity of each individual vehicle can only be as a "noise" to it. Therefore, there is the need to aggregate vehicles into large fleets to make their impacts tangible for the grid [2]. Considering an aggregator that is able to effectively organize and manage a huge number of EVs, the available batteries will be combined to create a large system with a considerable energy storage capacity. In this regard, public parking lots are appropriate candidates to act as aggregators [3] because they usually possess plenty of parking spaces and also allow vehicles to be parked for long time periods. In other words, due to the large number of EVs that can be parked and plugged-in at a public parking lot, a remarkable energy storage capacity can be obtained from the combination of existing vehicles' batteries [4]. But it should be noted that proper operation of a parking lot requires an efficient energy management system which is able to simultaneously consider the main concerns of different players of the problem, i.e. parking lot operator, EV owners, and grid operator. Without such an energy management system not only the potential benefits of V2G capability cannot be obtained, but also the huge charging power demand of EVs can adversely affect the normal operation of the power distribution system. Meanwhile, this uncontrolled situation may lead to dissatisfaction of EV owners by causing their vehicles not to be adequately charged at the time of departure. Therefore, the energy management of a large population of V2G-capable EVs parked at a public parking lot is of great importance from different viewpoints.

Over the last few years, a limited number of works have concentrated on designing energy management strategies for parking lots considering V2G capability. The authors in [5] propose a smart scheduling model that is able to intelligently control the charging and discharging plans of EVs at an urban parking lot with the objective function of maximizing each vehicle owner's profit from V2G capability. In this paper, some weighting factors are also defined to prioritize the charging and discharging processes of different EVs in the optimization procedure. An intelligent method to schedule the usage of electrical energy stored in the batteries of EVs parked at a parking lot has been presented in [6]. This method uses binary particle swarm optimization (BPSO) to determine the appropriate charging and discharging times that maximize EV owners' profits based on electricity price fluctuations. In this regard, EVs are charged during the low-price periods and discharged during the high-price periods. In [7] a large-scale parking lot with V2G capable EVs is managed in order to alleviate peak power demand and provide ancillary services to the power grid. The objective function considered in this paper is to maximize the overall profit on a vehicle fleet base. Meanwhile, the authors have utilized the estimation of distribution algorithm (EDA) to solve the optimization problem.

Considering the reviewed works in the literature, to the best of our knowledge, the previous studies have only focused on EV owners' preferences and grid operator's concerns without taking parking lot operator's priorities into account. Parking lot acts as an interface between EV fleet and power grid because it is equipped with some devices that are able to transfer electrical energy from a distribution transformer to the batteries of EVs. Therefore, it is obvious that without regarding the priorities of parking lot operator who is an important player of the problem, the energy management system will be seriously defective. Parking lots are usually operated by private investors who their major priority is to maximize the investment profitability. Based on this fact, it can be concluded that the main priority of parking lot operator is profit maximization. This vital factor is involved in the energy management strategy developed in this paper.

This paper, as a complementary to the previous works, develops an energy management framework which its main objective is to maximize the parking lot operator's total profit from electricity sales. Meanwhile, besides completely fulfilling the energy requirements of EV owners, the proposed method considers proper operation of the power grid. In this regard, the authors first propose an electrical energy exchange model in which the parking lot operator purchases electrical energy directly from the wholesale market and stores it in the batteries of EVs and feeds part of this stored energy back into the grid through V2G capability during some specific time periods. After that, based on the presented energy exchange model, a linear optimization framework involving the necessary financial considerations is proposed for the energy management problem. This optimization framework is run by the parking lot operator to find EVs' optimal charging and discharging plans. Finally, using actual data and reasonable assumptions, some numerical studies are carried out to show the efficiency of the proposed energy management method from the viewpoints of different players.

GENERAL FRAMEWORK OF ENERGY MANAGEMENT STUDIES AT THE SMART PARKING LOT

In this section, first the energy exchange model proposed for the parking lot is described to clarify the financial transactions between different players of the problem. After that, the mathematical formulation of the energy management problem is presented.

Energy Exchange Model

As previously mentioned, the main objective of the energy management framework proposed in this paper is to maximize the parking lot operator's profit. Obviously, in order to obtain the parking lot operator's profit, it is essential to specify his total costs and income considering the financial transactions carried out by different players. In this regard, the authors have proposed the simple but very useful energy exchange model illustrated in Fig. 1. According to this model, the parking lot operator purchases electrical energy directly from the wholesale market and by paying for the "wires" activities of the power distribution company, i.e. delivery cost, receives the purchased energy and stores it in the batteries of EVs. A part of this stored electrical energy is sold to EV owners at time-of-use (TOU) tariff in order to satisfy their energy requirements. The other part of the stored energy is injected into the distribution grid through V2G capability at appropriate times of day. This V2G power, if provided during on-peak hours, not only reduces power losses in the system, but also helps mitigate distribution network congestion. These considerable advantages encourage the power distribution company to purchase V2G power provided by EVs parked at the parking lot. Based on this fact, it is here assumed that the parking lot operator sells the electrical energy obtained from V2G capability to the power distribution company at TOU tariff. Therefore, the parking lot operator's total costs are made up of energy cost and delivery cost, and his total income is generated from V2G capability and electricity sales to EV owners. Considering these factors, along with energy requirements of EV owners, the energy management system finds the optimal charging and discharging schedules in such a way that the parking lot operator's profit is maximized.

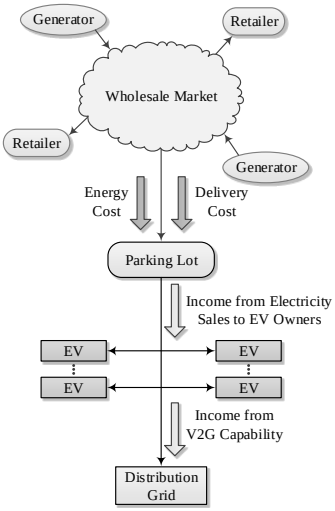

Fig. 1. Proposed model for the electrical energy exchange.

As previously mentioned, one of the most important issues that should be properly addressed is to determine the parking lot operator's and EV owners' shares in the V2G profit. In this regard, it is assumed that the profit earned from V2G capability of each individual vehicle is equally divided between its owner and the parking lot operator. This amount of profit can act as an incentive for EV owners because it can compensate a large portion of their charging costs.

Problem Formulation

In this paper, the main objective of the energy

management system is to maximize the parking lot operator's profit from electricity sales while satisfying the energy requirements of EV owners. In this regard, the authors have proposed the following optimization framework to determine the optimal charging and discharging powers of EVs at different time slots:

$$\max \sum_{i=1}^{M}\sum_{k=1}^{T}\left[\left(-P_{i,k}^{disch.}\cdot\Delta t\cdot p_k^{ToU}\right)-\left(P_{i,k}^{ch.}\cdot\Delta t\cdot(p_k^{RT}+p_k^{Del.})\right)\right] \quad (1)$$

s.t.

$$\begin{cases} P_{i,k}^{ch.}=0 & if \quad P_{i,k}^{disch.}\neq 0 \\ P_{i,k}^{disch.}=0 & if \quad P_{i,k}^{ch.}\neq 0 \end{cases}$$

(2)

$$\begin{cases} 0\le P_{i,k}^{ch.}\le P_i^{\max} \\ -P_i^{\max}\le P_{i,k}^{disch.}\le 0 \end{cases} \quad (3)$$

$$SOC_i^{ini.}+\frac{1}{Cap_i}\sum_{j=k_i^{arr.}}^{k_i^{dep.}}\left[P_{i,j}^{ch.}+P_{i,j}^{disch.}\right]\cdot\Delta t=SOC_i^{des.} \quad (4)$$

$$\begin{cases} P_{i,k}^{ch.}=0 & if \quad k<k_i^{arr.} \ \& \ k>k_i^{dep.} \\ P_{i,k}^{disch.}=0 & if \quad k<k_i^{arr.} \ \& \ k>k_i^{dep.} \end{cases} \quad (5)$$

where, the following nomenclature is used:

$P_{i,k}^{ch}$	Charging power of the ith EV at k^{th} time slot.
$P_{i,k}^{disch.}$	Discharging power of the ith EV at k^{th} time slot.
Δt	Time slot of the studies.
p_k^{ToU}	Time-of-use tariff at k^{th} time slot
$p_k^{Del.}$	Delivery cost at k^{th} time slot.
p_k^{RT}	Wholesale electricity price at k^{th} time slot.
$P_i^{\max}$	Maximum allowable charging or discharging power associated with the ith EV.
$SOC_i^{ini.}$	Initial state-of-charge associated with the ith EV.
$SOC_i^{des.}$	Desired state-of-charge associated with the ith EV.
Cap_i	Battery capacity of the ith EV.
$k_i^{arr.}$	Arrival time of the ith EV.
$k_i^{dep.}$	Departure time of the ith EV.
M	Total number of EVs.
T	Number of time slots in the period of studies.

The outstanding feature of the proposed optimization framework is that it is modeled as a linear programming (LP) problem, which guarantees the optimality of the achieved solutions. In this formulation, $P_{i,k}^{ch.}$ and $P_{i,k}^{disch.}$ are the decision variables and solving the optimization problem should determine their optimal values. The objective function represents the parking lot operator's profit that is obtained by subtracting total costs from total income. The first constraint ensures that $P_{i,k}^{ch.}$ and $P_{i,k}^{disch.}$, which respectively represent the charging and discharging powers of EVs, will never have non-zero values at the same time. This is obviously due to the fact that it is impossible for an EV to be simultaneously charged and discharged. The second constraint causes the charging and discharging powers of EVs to always be within the allowable range. The third constraint fulfills the energy requirements of EV owners because it ensures that once an EV leaves the parking lot, its battery is certainly charged up to the desired level of state-of-charge (SOC). Finally, the fourth constraint specifies the time period in which an EV is allowed to be charged or discharged. In other words, this constraint causes the charging and discharging powers of an EV to be equal to zero out of the period between its arrival and departure times.

By solving the proposed optimization problem, the optimal charging and discharging schedules of EVs parked at the parking lot would be found as follows:

$$\boldsymbol{P_i^{ch.}}=[P_{i,k_i^{arr.}},\ldots,P_{i,k_i^{arr.}+n},\ldots,P_{i,k_i^{dep.}}] \qquad \forall\ i\in \boldsymbol{M}$$

$$\boldsymbol{P_i^{disch.}}=[P_{i,k_i^{arr.}}^{disch.},\ldots,P_{i,k_i^{arr.}+n}^{disch.},\ldots,P_{i,k_i^{dep.}}^{disch.}] \qquad \forall\ i\in \boldsymbol{M}$$

where, $\boldsymbol{P_i^{ch.}}$ and $\boldsymbol{P_i^{disch.}}$ are respectively the vectors containing the charging and discharging schedules of the ith EV, and $\boldsymbol{M}$ is the vector of EVs that enter the parking lot all day long.

NUMERICAL STUDIES AND ANALYSIS

In this section, the proposed energy management framework is applied to an urban parking lot and some numerical studies are conducted to analyze its efficiency from technical and financial point of views. In this regard, first a summary of the assumptions and input data required to carry out the simulations is provided. After that, the impacts of V2G capability on the main concerns of different players of the problem are evaluated.

It should be noted that in this paper, in order to cover different possible scenarios, the studies are carried out in macro and micro scales. In macro scale, the year is divided into two seasonal periods including summer and winter [8], while in micro scale the week is divided into weekdays and weekend days. In other words, the simulations are run for four different days including a weekday and a weekend day in the summer, and a weekday and a weekend day in the winter.

Assumptions and Input Data

In this paper, in order to realistically model and precisely study the operation of the parking lot, the authors have used actual data and reasonable assumptions to carry out the simulations. These assumptions and input data can be categorized into the following three groups:

1) Parking Lot Traffic Data: These data, which include the arrival and departure times of the vehicles that enter the parking lot all day long, are borrowed from a parking lot in Iran (Laleh Parking) to model the EV owners' behavior in a realistic manner. Figs. 2 and 3 respectively show parts of the borrowed data on two typical days

including a weekday and a weekend day in the summer.

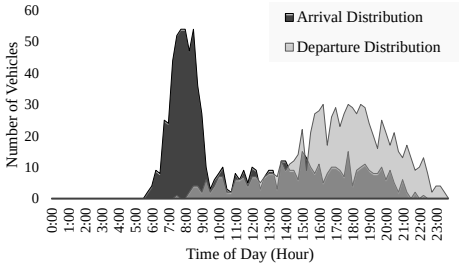

Fig. 2. Parking lot traffic data on a weekday in the summer.

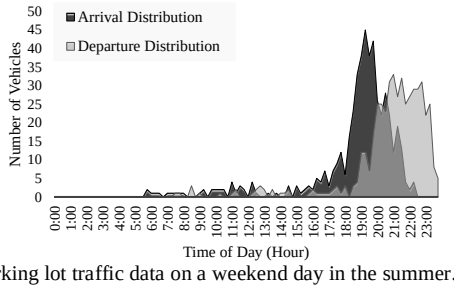

Fig. 3. Parking lot traffic data on a weekend day in the summer.

2) Electricity Price Data: These data, which include the wholesale market price and the TOU tariff, are borrowed from the Ontario Independent Electricity System Operator (OIESO) [9] and the Ontario Energy Board [10]. Moreover, the electricity delivery cost paid for the "wires" activities of the power distribution company, based on [11], is considered to be equal to 40% of the TOU tariff. Parts of these data on a weekday and a weekend day in the summer are illustrated in Figs. 4 and 5, respectively.

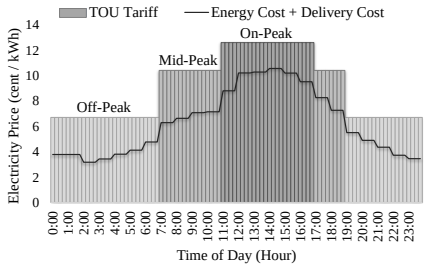

Fig. 4. Electricity price data on a weekday in the summer.

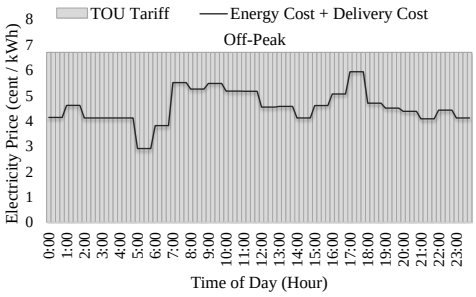

Fig. 5. Electricity price data on a weekend day in the summer.

3) Characteristics of EVs: These characteristics, due to the lack of real data, are specified using some reasonable assumptions. I this regard, it is assumed that the initial SOCs of EVs obey a normal distribution with the average value of 50% and the standard deviation of 30% [12]. The desired SOCs are considered to be a set of random numbers in the range of 80% to 100%. The battery capacities are defined as some random numbers between 5 and 35 kWh. The maximum allowable charging and discharging powers of EVs are presumed to be a factor of their battery capacities (C) [8], [13]. That is, this characteristic for EVs that use Level 2 (i.e. 240 V, and 30 A) facilities is chosen equal to 0.2C, and for EVs connected to Level 3 (i.e. 480 V, and 85 A) facilities is chosen equal to C.

An Analysis on the Impacts of V2G Capability of EVs

In the following, the results obtained from applying the proposed energy management framework to the parking lot under study are presented in order to analyze the impacts of V2G capability from the viewpoints of different players. In this regard, the roles of this capability in increasing the parking lot operator's profit, decreasing EV owners' charging costs, and improving the load profile seen by the grid are thoroughly investigated.

1) From the Parking Lot Operator's Viewpoint: Table 1 shows the parking lot operator's total profits on the days under study with and without considering V2G capability. As expected, when considering V2G capability, the parking lot operator's total profit is significantly increased. Obviously, the reason is that in this case the profit is earned from not only fulfilling the energy requirements of EV owners, but also selling V2G power to the power distribution company. Moreover, it can be seen that the amount of increase in the total profit on weekend days is substantially lower than that on weekdays. This is because of the following three reasons: 1) the number of vehicles that enter the parking lot on weekend days are considerably decreased in comparison to weekdays, 2) as can be seen in Fig. 5, the TOU tariff is set at its lowest level on weekend days and this notably decreases the obtained V2G profit, and 3) as can be traced in Fig. 3, on weekend days, EVs are parked at the parking lot for relatively short time periods.

Table 1. Parking lot operator's total profits on four different days with and without considering V2G capability

Days under Study		Without V2G Capability ($)	With V2G Capability ($)
Summer	Weekday	218.02	385.4
	Weekend Day	94.4	123.7
Winter	Weekday	237.91	423.43
	Weekend Day	40.6	52.99

2) From EV Owners' Viewpoints: One of the most important concerns of EV owners is the cost they pay for charging their batteries. Taking this point into account, Table 2 represents the average charging costs imposed to EV owners on the days under study with and without considering V2G capability. As previously mentioned, in this paper it is assumed that the V2G profit gained from each EV is equally divided between its owner and the parking lot operator. This share of profit, as can be seen, has compensated part of the charging costs. The amount

of decrease in EV owners' charging costs on weekdays is significantly higher than that on weekend days. The reason lies in the fact that on weekend days, it is not possible to generate high V2G profits because the TOU tariff is considered at its lowest level and also EVs are available for relatively short time periods. Therefore, it can be concluded that from EV owners' point of views, using V2G capability is not much effective on weekend days.

Table 2. EV owners' average charging costs on four different days with and without considering V2G capability

Days under Study		Without V2G Capability (¢)	With V2G Capability (¢)
Summer	Weekday	86.47	66.33
	Weekend Day	54.11	48.15
Winter	Weekday	88.56	64.25
	Weekend Day	50.25	47.73

3) From the Grid Operator's Viewpoint: The most important concern of the grid operator is that EVs, to the extent that is possible, be charged during off-peak hours and discharged during on-peak hours. In order to evaluate the ability of the proposed energy management framework to address this issue, the load profile of the parking lot on a weekday in the summer with and without considering V2G capability has been extracted and shown in Fig. 6. In this figure, positive and negative values represent charging and discharging of EVs, respectively. As can be seen, during on-peak hours, the parking lot not only does not receive any power from the grid, but also injects a considerable amount of V2G power into it. This can obviously reduce power losses and mitigate congestion in the system. Moreover, it is evident that using V2G capability has caused charging load of EVs to be shifted towards the times other than on-peak hours, which is completely desirable from the grid operator's point of view.

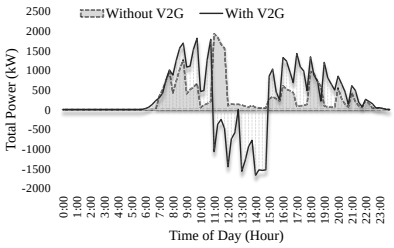

Fig. 6. Load profile of the parking lot on a weekday in the summer with and without considering V2G capability.

CONCLUSION

In this paper, an efficient energy management framework for a large number of V2G-capable EVs parked at a parking lot was proposed. The main purpose of the presented method was to optimally determine the charging and discharging schedules of EVs in such a way that the major concerns and priorities of different players of the problem can be appropriately covered. In this regard, the authors designed a linear optimization framework with the objective function of maximizing the parking lot operator's profit, which not only satisfies the energy requirements of EV owners, but also considers proper operation of the power grid. The results obtained from applying the proposed energy management framework to a real parking lot in Iran demonstrated its efficiency from different financial and technical aspects. In this way, it was shown that using V2G capability along with the presented method, besides significantly increasing the parking lot operator's profit and decreasing EV owners' charging costs, considerably improves the load profile of the parking lot and provides an effective energy storage system for the grid.

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