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Optimal Charge-Discharge Scheduling of Electric Vehicles Considering Their Battery Lifetime

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Abstract *– Electric vehicles are increasingly became appear in power systems. Optimal scheduling of electric vehicles including the amount and the duration of charging and discharging their batteries can bring great benefits to power systems. By charging in low electricity price periods and discharging in high electricity price periods, energy prices in the whole power system can be more balanced. Furthermore it can help power system to meet electricity demand in high demand periods. However, when a large population of electric vehicles are considered, many practical factors including battery lifetimes could be effective on optimal scheduling of them. In this paper, a new formulation for optimal scheduling of electric vehicles in a real power system structure considering battery lifetime constraints is introduced and the results are compared with the case that these constraints are not included.*

Keywords*: Electric Vehicles, Optimal Scheduling, Battery Lifetime*

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INTRODUCTION

Plug-in Hybrid Electric Vehicles (PHEVs) and fully Electric Vehicles (EVs) are brought more attention in automotive industry for reducing air emissions and the dependency to the fossil fuels. Large number of EVs in a power system can increase electricity demand. However, it can deem to be a good opportunity for power system operators to utilize the benefits of integrating them in the network.

Charging and discharging the battery of EVs can change the load profile in a typical power system. On the one hand, electricity loads may be increased due to charging the batteries of EVs. In reference [1], it is estimated that when the penetration level of the EVs be 30%, the electricity load for charging EVs can be as high as 18% of the summer peak load in the US. On the other hand, the EVs can act like power generators; injecting electrical power to the grid. Today, the phenomenon of discharging EV battery to inject power to the grid is widely known as Vehicle-to-Grid (V2G) [2]. Thus, optimal scheduling of EVs including the amount and the duration of their battery charge and discharge can help balancing electricity demands. This, in turn, can lead to reducing power system operation and generation investment cost.

In the context of smart grids, optimal charge-discharge of EVs which has been an important issue, can avoid high capital costs [3, 4]. Balancing the electricity demands can be achieved by charging EVs when the demand and consequently the electricity price are low and discharging EVs when the demand and consequently the electricity price are high. However, finding the optimal solution of the associated optimization problem may be challenging. It is essentially due to difficulty of finding the global optimal solution.

Some scheduling schemes for charging and discharging the batteries of EVs have been proposed by the authors [5-8]. In works done by Shreshtha and Ang [5] and Mets et al. [6], the scheduling plan only includes the battery charging without discharging or V2G process. Although the existing literature which includes both charging and discharging the batteries of the EVs [7, 8], aims at minimizing the total cost, their schemes do not include the battery lifetimes. The batteries have a finite lifetime, and this is basically due to occurrence of unwanted chemical or physical alteration to them. Generally, these changes are irretrievable, thus affecting the electrical performance of the batteries of the EVs.

In this paper, optimal scheduling of the EVs including the charging and discharging patterns, considering the battery life times of the EVs, is investigated. A new problem formulation is introduced and the effects of the battery lifetime consideration are analyzed. It is good to note that by considering the battery lifetimes of the EVs, a more exact and practical model for optimal scheduling of high population EVs in long-term planning can be obtained.

The rest of the paper is organized as follows. First, the formulation of the optimal scheduling problem considering the battery lifetimes is introduced. Afterward,

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the simulation results are presented. Finally, the main findings of the paper are concluded.

MATERIAL AND METHODS

Optimal scheduling of electric vehicles

In this section, the optimal scheduling of electric vehicles including both charging and discharging their batteries is investigated. The resulted optimization problem which is a Quadratic Constrained Programming (QCP) one aims at minimizing the total operation costs of EVs in a log-term period. It is good to mention that the proposed formulation includes a constraint related to the battery lifetime of each EV which is a practical issue in long-term scheduling problem.

The battery charging and discharging of EVs is studied during three months, which is divided into a set of $N = 3 \times 30 \times 24$ intervals. Note that each interval models $\tau = 1$ hour in the whole time horizon.

All EVs which are considered in this paper are assumed to have V2G capability or both charging and discharging functions. The set of EVs is assumed to be M. Suppose that $x_{mi} (\forall \mathrm{m} \in \mathrm{M}, \forall \mathrm{i} \in \mathrm{N})$ be the charging or discharging power of EV m in time period i. Positive and negative values of x_{mi} represent the charging and discharging of EV m in time interval i, respectively.

The arrival and departure time of EV m are represented by t_m^{arr}, t_m^{dep}, respectively. The charging or discharging period of EV m is indicated by T_m. This expresses the set of periods between arrival and departure time of EV m. The capacity of the battery of EV m is denoted by E_m^{cap}. The initial and final energy of EV m are defined by E_m^{ini} and E_m^{fin}, respectively. In this paper, a final energy ratio is defined as $\gamma_m = E_m^{fin} / E_m^{cap}$ which has a quantity between 0 and 1. When an EV is connected to a charging station, its arrival and departure time, initial and final energy, battery capacity and final energy ratio are detected. Finally, the charging period T_m is determined by the charging station.

In order to express the relationship between charging states and time periods of EVs, a matrix $F \subset \{0,1\}^{|M| \times |N|}$ is defined. If time period i falls between the charging period T_m of EV m, the element f_{mi} will be 1; otherwise it will be zero.

In this paper, the electricity price, which is shown in (1), is formulated as a linear function of the spot load [1].

$$g(z_t) = k_0 + k_1 z_t \tag{1}$$

It is good to mention that the total load in time period i is assumed to consist of two parts: the base load L_i^b and the charging load y_i. The associated formulation is as follow:

$$z_i = L_i^b + y_i = L_i^b + \sum_m x_{mi} f_{mi} \tag{2}$$

The charging cost in time period i, which is denoted as C_i, can be obtained by integrating of the electricity price. Its final formulation is as follow:

$$C_i = (k_0 z_i + \frac{k_1}{2} z_i^2) - (k_0 L_i^b + \frac{k_1}{2} (\mathrm{L}_i^b)^2) \tag{3}$$

Because of many charging and discharging imposed to the battery of an EV, its lifetime is going to be reduced. In this paper, this phenomenon is modeled by reduction in the EV capacity. In fact, EV m has a maximum capacity until reaching each time period i which is denoted by $\psi_{m,i}$ and formulated as follow:

$$\psi_{m,i} = (1 - \sum_{k \le i} \beta x_{mk}^2 - \sum_{k \ge 2, k \le i} \eta (x_{mk} - x_{m(k-1)})^2) E_m^{cap} \tag{4}$$

As it can be seen from (4), two components play the essential role in capacity reduction. One component is related to the amount of charging/discharging until each time period. This term is proportional to the sum of the squares of the charging power of EV m until reaching to time period i. The other is created because of shifting between charge and discharge states in two successive time periods. It is proportional to the sum of the squares of the difference between charging powers of two successive time periods until reaching to the time period i. It is good to mention that β and η are constant coefficients related to the lifetime reduction effect in the battery of an EV. Note that if β and η are assumed to be zero, this effect is not considered and E_m^{cap} will be constant during the whole time horizon.

In order to being able to formulate the problem, some assumptions must be considered as follows:

1- EV users signed the charging contract and according to it, the arrival and departure time of each EV are known prior to solving the problem.

2- The initial and the final energy for all EVs are given.

3- The base load in each period over the time horizon is given.

4- All the information is collected by the central controller, which is responsible for solving the optimization problem.

The objective function of the resulted optimization problem is to minimize the total costs of charging/discharging all EVs over the whole time horizon. The Quadratic terms for modeling the battery lifetime reduction phenomenon make the problem nonlinear. Thus the resulted problem will be a quadratic constrained programming optimization problem. The optimization problem is formulated as follow:

$$Minimize\ TC = \sum_i ((k_0 z_i + \frac{k_1}{2} z_i^2) - (k_0 L_i^b + \frac{k_1}{2} (L_i^b)^2)) \quad \text{(5-a)}$$

Subject to:

$$z_i = L_i^b + \sum_m x_{mi} f_{mi}, \forall i \in N \quad \text{(5-b)}$$

$$0 \le E_m^{ini} + \sum_{k \in Q^{(i)}} x_{mk} f_{mk} \le \psi_{m,i} \quad \forall m \in M, \forall i \in N \quad \text{(5-c)}$$

$$E_m^{ini} + \sum_i x_{mi} f_{mi} \ge \gamma \psi_{m,N}, \forall m \in M \quad \text{(5-d)}$$

$$-P^{max} \le x_{mi} \le P^{max}, \forall m \in M, \forall i \in N \quad \text{(5-e)}$$

The objective function (5-a) in the QCP optimization problem (5) is to minimize the total cost of charging/discharging all EVs during the whole time horizon. The relationship between the total load, the base load and the charging load is indicated in constraint (5-b). Constraint (5-c) represents the limits for the EV energy in each time period i. It expresses that this energy cannot be negative or lower than the EV capacity in time period i. The final energy constraints are represented in constraint (5-d), which indicates that the final energy of EV m must be less than the certain or defined energy level. Finally, the limits on the charging power of EVs are imposed in constraint (5-e).

RESULTS

In previous section, the EV scheduling problem formulation is given. The problem is formulated as an QCP optimization problem, which is implemented in GAMS software and solved by the CPLEX solver. All the simulations are performed on a 2.13 GHz PC with 4 GB of RAM.

As it is indicated in previous section, the considered time horizon is assumed to be 3 months. This time horizon is divided evenly into 2160 periods. Each time period is consisted of one hour. The base load is picked from the PJM independent system operator in the US for three last months of year 2014 [9]. In equation (1), the value of coefficients are $k_0 = 10^{-4} \$ / kWh$ and $k_1 = 1.2 \times 10^{-4} \$ / kWh / kW$. The characteristics of EV batteries are taken from Chevrolet Volt [10]. The total number of EVs is assumed to be 2000. The required energy level for all EVs is assumed to be 90% of the battery capacity in the last time period. The arrival times of the EVs have a uniform distribution across the whole time horizon. The uniform distribution between 4 and 12 hours is also considered for charging periods of the EVs. A uniform distribution between 0 and 80% is taken into account for the initial energy of EVs.

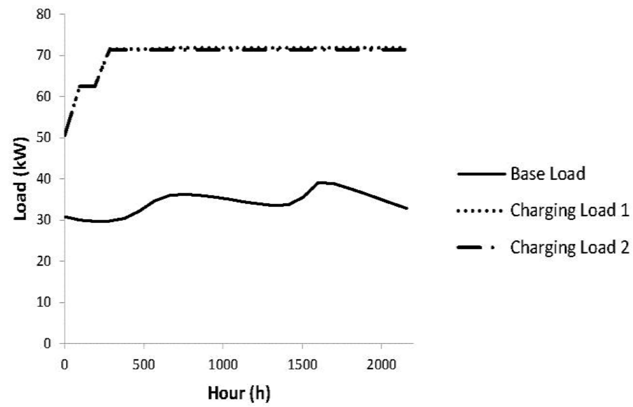

Fig. 1 – Comparison of base load with charging loads in different scenarios.

In order to being able to comprise the effects of battery lifetime reduction, two scenarios are considered in this paper. These scenarios are as follows:

1. Battery lifetime reduction is not considered. Therefore, the coefficients β and η are assumed to be zero.
2. Battery lifetime reduction is considered. The value of coefficients are set to $\beta = 5 \times 10^{-6}$ and $\eta = 5 \times 10^{-7}$.

Figure 1 shows the charging power in two scenarios in the whole time horizon. Also, the base load is shown in the figure for better understanding the situation. Note that charging EVs leads to increase in the amplitude of total electric load than that of the base load. In order to better show the differences between scenarios 1 and 2, Fig. 1 must be magnified. The magnified figure is depicted in Fig. 2. As it can be seen from this figure, the charging power in scenario 2 is less than that of scenario 1 in the whole 24 hours of the simulation. This is because of the battery lifetime reduction constraint, which leads to decreasing the amount of charging and discharging power in the batteries of the EVs.

DISCUSSION

Considering the role of a huge increasing number of EVs in the future electric power systems, having a precise and practical formulation to mathematically model them is of great interest. Battery lifetime reduction is one of the significant characteristics of the EVs, which has not been appropriately taken into account by the previous literature. The results of applying this phenomenon to the optimal scheduling of the EVs, in this paper, show that a different scheduling program will be obtained. In fact, this new scheduling program does not utilize the EVs in unnecessary conditions, considering the battery lifetime effect of the EVs. The authors are strongly believed that such important effect has to be taken into account in a real scheduling application of the EVs.

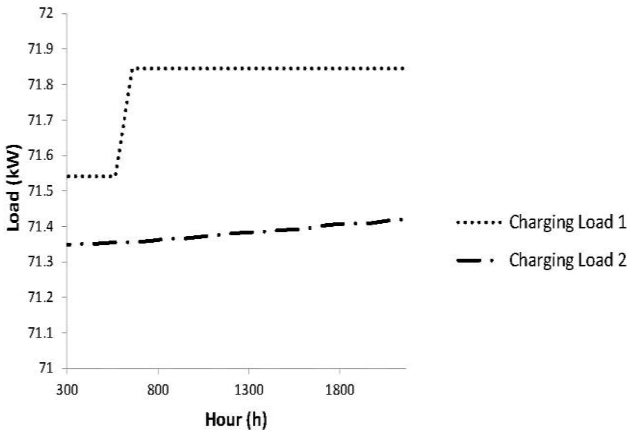

Figure 2. Comparison between charging load in scenario 1 and 2.

CONCLUSION

In this paper, a new scheduling plan for charging and discharging the batteries of electric vehicles is proposed. An optimization problem is formulated considering battery lifetime reduction effects. The reduction of battery lifetime is modeled by reduction in the battery capacity. This reduction is depended on the amount and the fluctuation of charging power of the battery of EV. The resulted optimization problem is a QCP one which is solved using GAMS package. The results show that by considering the battery lifetime reduction effect, a more practical model can be obtained. The results represent that when this effect is considered, the amount of charging power will be reduced.

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