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An Optimized EV Charging Algorithm Using Control Horizon Method

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Abstract. In this paper, the optimized charging algorithm in electric vehicle (EV) is proposed using control horizon method. A model predictive control (MPC) with linear programming (LP) is used for optimal control, and the time-of-use (TOU) price is included to calculate the energy costs. Simulation results show that the reductions of energy cost and peak power can be obtained using proposed algorithms.

1 Introduction

The development of EV is an important direction of modern automobile vehicles. However, the restriction of the EV's rapid growth is the lack of the EV charging facilities [1]. With incremental development in EV charging facilities, EV loads are expected to increase dramatically in the near future and this will bring negative impacts on the stability of power grids. EV loads are seldom controlled in current practice of power system planning, which results in risks in power system operations and management.

The electricity pricing policy provides guides for power demand and consumption mode of customers. Customers will respond to variable electricity prices, decide whether they prefer charging or discharging, and actively adjust charging rate and time. For countries with mature electricity market environment, research has been focused in this area. For instances, Cao et al. used time-of-use price to find optimal charging loads, which minimize the charging cost in a regulated market [1]. Deliami et al. proposed a two-stage control strategy to maximize profits of the charging station and minimize the peak load of the distribution transformer [2].

At present, the electricity pricing mechanism in Korea mainly includes the stepwise power tariff and the TOU price. Based on the state-of-charge (SOC) value, this paper focuses on the application of MPC to electric vehicle that is charged on TOU rates. An MPC approach with LP is selected to model and simulate the EV systems. An MPC strategy is selected, because its periodic re-optimization characteristic provides stability during external disturbances [3]. By using the proposed method, EVs are able to adjust charging power and reduce the cost of costumers in load demand.

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2 Proposed Method

An EV is an automobile which is propelled by an electric motor that uses electrical energy stored in a battery pack. The battery pack of an EV is the major component that determines the range and recharging times, and it tends to be heavy and expensive. The capacity of the battery pack varies depending on the type and size of the vehicle. For example, there is a 24 kWh capacity battery for Nissan Leaf, but only 15.6 kWh of the full capacity (65%) is available for consumption.

2.1 Energy cost function for EV charging

Since the purpose is to ensure EV charging with minimal energy consumption, the proposed cost function minimizes energy consumption, subject to constraints on SOC. This formulation being linear, allows the use of the LP method for solving the optimization problem. In this paper, we used the following cost function to represent the daytime electricity expense, which is a combination of energy and demand costs.

$$\min J = \sum_{k=1}^{N} \left\{ \sum_{i=1}^{M} u_i(k) \cdot p_i(k) \right\} \cdot c(k) \qquad \textbf{(1)}$$

where the variable $u_i(k)$ need to be solved by the optimization algorithm over the control horizon (H), $p_i(k)$ is the power consumption at the time *k*, *M* is the number of charging stations, and $c(k)$ accounts for the TOU electricity rates in the *k*-th switching interval. If a control horizon (H) of daytime is divided into 15 min switching intervals, then, $N = 36$ is the total number of time steps per daytime.
SOC is defined as the remaining capacity of a battery and it is affected by its operating conditions such as load current and temperature. The time duration T_i in minutes of the charging process can be derives as [4]

$$T_i = \frac{(SOC_{i,tar} - SOC_{i,init}) \cdot E_i}{\varepsilon P_{c,i}} \times 60 \qquad \textbf{(2)}$$

where $SOC_{i,init}$ and $SOC_{i,tar}$ represent the initial and target SOC of EV battery, respectively, E_i is the battery capacity in kWh, $P_{c,i}$ is the power level of charging stations in kW, and ε is the charging efficiency.
Eq. 1 is an optimization problem. Additional inequality constraints can also be directly imposed on the charging to regulate them within a range with respect to time.

$$SOC_i(k) \le SOC_{i,tar} \qquad \textbf{(3)}$$

The On/off charging algorithm of the EV systems is based on the revised switching levels, and it is defined as

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$$u_i(k) = \begin{cases} 1 & \text{when } SOC_i(k) \le SOC_{i,tar} \\ 0 & \text{when } SOC_i(k) \ge SOC_{i,tar} \end{cases} \quad \textbf{(4)}$$

2.2 MPC Control Algorithm using Linear Programming

The MPC control strategy can be explained further with Fig. 1, which shows the result of a hypothetical controller that controls the SOC levels of EV. The control model in Fig. 1 uses 15 min switching intervals, and a control horizon (H) of 9 h. The process of the MPC controller in Fig. 1 can be described as follows [5]: The current time is 11 h which means that the inputs and output prior to 11 h are historical and the inputs and output after 11 h are the future predicted values. However, once the predicted inputs are calculated only the first predicted input is implemented and the rest of the predicted inputs are discarded. After the first predicted input is implemented the entire optimization process is repeated.

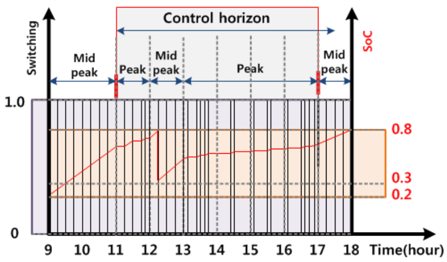

Fig. 1. Control horizon switching strategy

3 Computer Simulation

In order to verify the effectiveness of optimized charging model presented, we consider the multi-EV and multi-station case for performance comparison. The number of EVs and charging stations are 4 and 2, respectively. It is assumed that the initial SOCs of 4 EVs at 9 o'clock are 0.2, 0.3, 0.31, 0.41 and the target SOC of all vehicles is set to 0.8 at 18 o'clock. The total battery capacity of all vehicles and the power level of charging stations have 24 kWh and 6.6 kW, respectively. The charging efficiency ε is considered as 0.9.

This paper simulates and compares the following two control algorithms.

(1) On/off control algorithm ($u_i(k) = 0$ or $1, \quad k = 1, \cdots, N$).

(2) MPC control algorithm with LP ($0 \le u_i(k) \le 1, \quad k = 1, \cdots, N$).

Fig. 2 shows the results of two control algorithms. We see that when MPC with LP method is used, the loads are moved out of the peak periods and the energy level of power with MPC control method at peak period is lower than the On/off control method. This is caused by the moving control horizon (H) of the MPC control method,

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which means that after each implemented control step the MPC algorithm is optimizing more into the next cycle. Fig. 2 shows that MPC control method result in a TOU saving of 4.7% for On/off per a day. This shows that the MPC with LP control method is better than the On/off control algorithm.

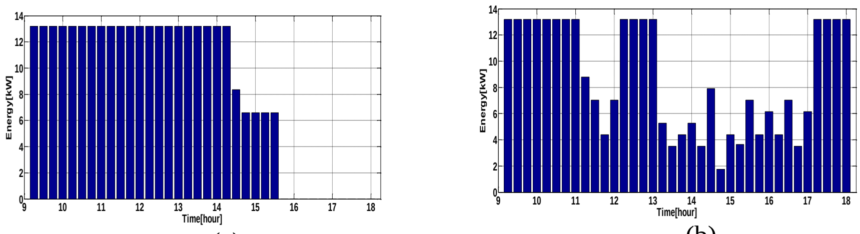

Fig. 2. Energy rate for temperature control: (a) On/off, (b) MPC with LP

4 Conclusion

This paper proposed the MPC control algorithm with LP for saving energy cost and reducing peak demand. In the MPC algorithm, the optimization problem with constraints is transformed into a LP algorithm and solved in each time step. Future works include the applications of the MPC controller for various types of electric vehicles when the simulation is mature.

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