

A Multi-tiered Real-time Pricing Algorithm for Electric Vehicle Charging Stations

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Abstract— With the increase in the market penetration of Electric Vehicles (EVs) and Plug-in hybrids (PHEVs), there is need for charging stations to charge them rapidly and price the user appropriately. In order to encourage the customers to charge their vehicles during load valley and minimize peak loads due to multiple EVs charging, this paper analyzes the charging impact on the load cycle and designs an innovative real-time multi-tiered electric pricing system. Subsequently, a new display board design for EV charging stations depending on the charging effect is proposed applying the designed electric pricing system.

Keywords- *electric vehicles, charging stations, multi-tiered electric pricing system, display algorithm*

I. INTRODUCTION

Climate change is becoming more and more challenging in many countries in the 21st century. Environmental issues are given higher priority in electric energy industry. The largest contributing source of greenhouse gases is the burning of fossil fuels leading to the emission of carbon dioxide [1]. Also, low thermal efficiency of internal combustion engines and its associated air pollution have led to transportation electrification become an attractive trend [2]. Electric vehicles have gained significant attention in recent years due to their prospects in reducing greenhouse gas emissions benefitting both the transportation sector and the electricity sector.

However, once substantial numbers of EVs are used, the electric power industry would face a new challenge of power surge, especially if the customers would prefer a rapid charging of their vehicles similar to the fast gasoline refilling. The financial benefits can hence encourage customers to choose an optimal time for charging their vehicles. If the pricing is calculated with reference to the total available power in the grid, it will encourage the customer to charge the vehicles during off-peak hours and will avoid vehicles being charged at the peak load periods. This will lead to an increase in the utilization of the power grid. Currently in China, the electricity pricing mechanism includes catalog price, stepwise power tariff (SPT) and time-of-use (TOU) price [3-5]. TOU price varies in different periods of a day based on the electricity demand, e.g. peak load, load valley, while stepwise

tariff has incremental prices for higher consumption levels. Some research has been focused on controlling EV charging loads using TOU price [3-10]. Most of the papers investigated how to apply TOU price to formulate charging scheme. Although most of the papers utilized fixed value of prices, real time pricing schemes has also been studied to fluctuate on a day-ahead or hour-ahead basis [11]. The real time electricity consumption has not been taken into account to decide the real time price settings in the above-mentioned pricing schemes. In this paper, a new multi-tiered pricing system has been developed for charging the customers based on the data from predicted and actual load cycle. The logic of the proposed pricing structure is similar to the combination of the existing TOU electricity pricing and the stepwise electricity pricing. The difference is that the proposed pricing structure takes both day-ahead forecasted data and real-time load data into consideration and the zone partitions are updated every day automatically. In addition, the proposed display board will not only show the customers the real time charging price but also the customers will be aware of the predicted price variation.

This paper is organized as follows. Section II analyzes the effect of EV charging on daily load cycles. After describing the pricing zones identification for the pricing system in section III, section IV introduces the flowchart of the proposed algorithm. Subsequently, section V shows some important calculation formulas for intersection points for the zones and cost analysis and other specifications of the algorithm. A case study is demonstrated applying the proposed pricing system and display board in section VI. The paper findings are summarized in section VII. References are given at the end.

II. EFFECT ON LOAD CYCLE

Figure 1 depicts how the load cycle of a typical city with the population of approximate 300,000 is modified when an average 100 electric vehicles are charged every hour. It is assumed that each EV is charged at the rate of 60 kW/h using fast charger at charging stations. The load profile is obtained from Electric Reliability Council of Texas [12].

In practice, the EVs plugged in for charging varies indeterminately, depending on customers' inclination and convenience. Figure 2 predicts such a scenario with a random number of vehicles charging over time. Heavy intermittent charging load of EVs may create bottlenecks in the supplying capacity and expose power system to severe security risks [3].

In order to have a closer picture for individual charging, Figure 3 provides how load cycle is affected when 10 electric vehicles are charged at 3 different specific times.

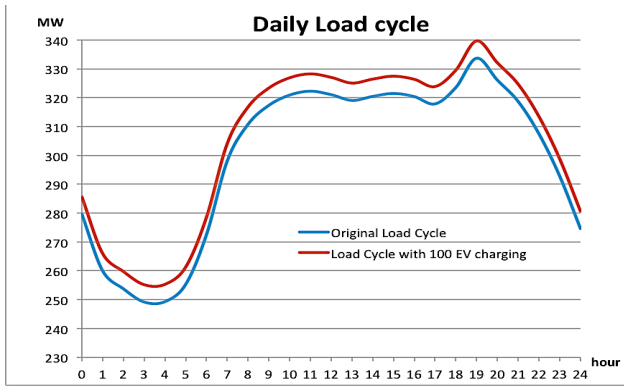


Figure 1- Effect on load cycle when 100 EVs charging

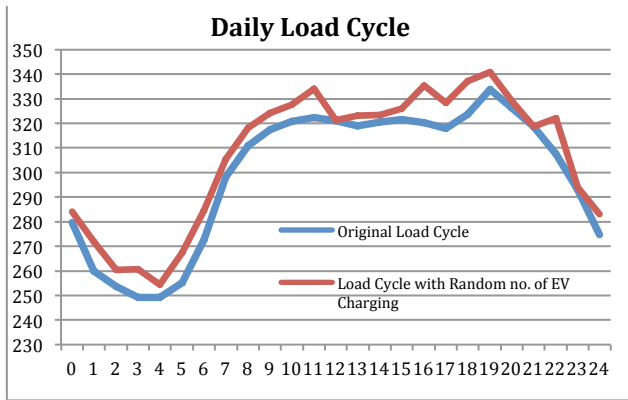


Figure 2- Effect on load cycle with random no. of EVs

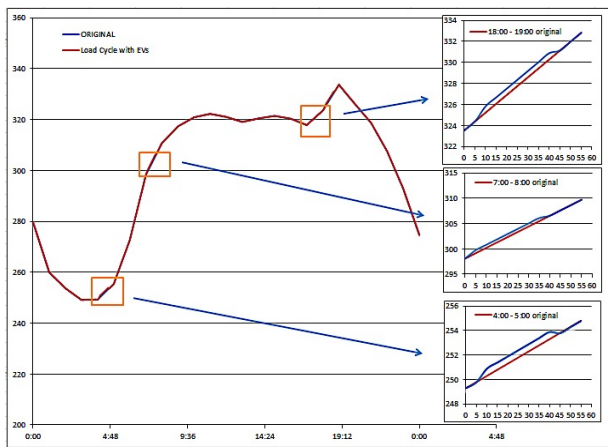


Figure 3 – Effect on load cycle with 10 EVs at different charging times

III. IDENTIFICATION OF ZONES FOR PRICING

Figures 1 and 2 indicate that the charging of EVs has the potential to increase the peak load of the day. It may create much higher burden on reserve and backup generation resources and may exceed the transformer capacity, which may mean a need to upgrade the utility's local transformer or lead to early replacement [13]. In some cases, the transmission constraints may be reached so that the locational marginal prices of the whole region will be affected. Therefore, charging the EVs during load valley hours and not during peak load hours should be highly encouraged to balance the supply and demand and flatten the load profile. To achieve that, a new real-time multi-tiered system for pricing of electric vehicles charging is proposed in this paper. In this section, the formation of multiple tiers is investigated.

First, based on the day-ahead load forecast, we locate the region between the peak load and the minimum load, and then divide the obtained region into 4 equal zones. Each zone will have a unique pricing. Figure 4 shows zones 1 to 4 between peak load and the minimum load for the forecasted day.

The price of zone 3 depends on the locational marginal pricing (LMP) of that region which is updated every 15 minutes [3] while the price of zone 2 is lower than that of zone 3, the price of zone 1 is lower than that of zone 2 while the price of zone 4 is higher than zone 3. We also set zone 0 with much lower price and zone 5 with much higher price in case the real time load cycle is lower or higher than the boundaries identified earlier based on the forecasted data. Since the average electricity price of U.S. is about 0.11\$/kWh, we assume the value to be the price for zone 3 in our calculation and the price difference between neighboring zones is \$0.04/kWh if the zones are between peak and minimum loads.

IV. FLOW CHART OF THE PROPOSED ALGORITHM

The flow chart of the proposed algorithm is shown in Figure 5. The first step is to draw the day-ahead forecasted load cycle [12] and then update it with real time load data. Once the zones are identified and the prices are allotted for each zone,

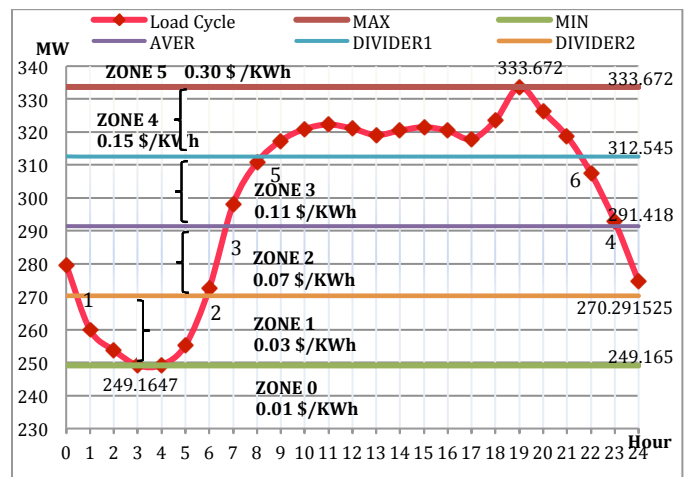


Figure 4 – Identification of zones for pricing

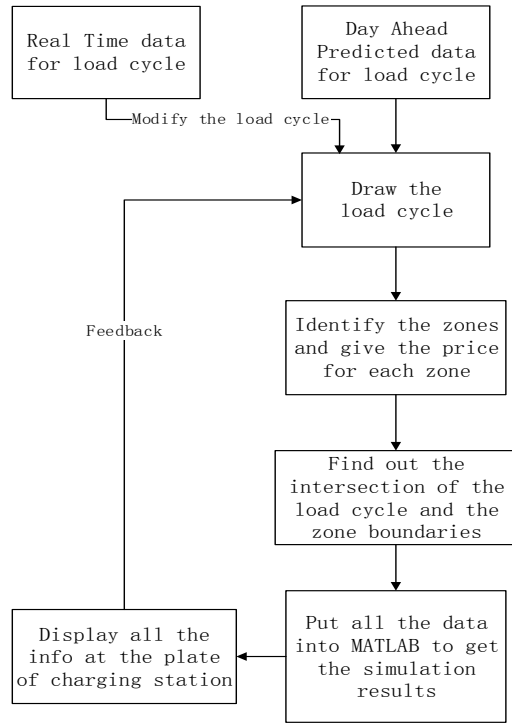


Figure 5 – Flow chart of the proposed algorithm

the zones are fixed for that particular day. This will lead to the formation of zone 0 to zone 5. The intersection points of the load cycle with zone boundaries are found which are used to calculate the total cost per charging at every minute in the MATLAB program. We input zone data and load cycle data to the MATLAB program to calculate the current charging price, the total current charging cost, number of vehicle left to be charged at that price, etc. The results are displayed in the proposed “Display board of a charging station” for the customers to decide their vehicle charging time. Finally, the current charging status will be reflected in the real time load cycle.

V. CALCULATIONS FOR PRICING ALGORITHM

A. Calculation of Intersection points

Load cycle-zone boundaries intersection points are important factors that affect total cost per charging. There will be different charging prices before and after intersection.

We can see from Figure 4 that the intersections of load cycle curve and the boundary line of DIVIDER2 are between 0:00 - 1:00 am (intersection 1) and 5:00 - 6:00 am (intersection 2) respectively. By applying linearization and assuming x to be the time difference between 6:00 am and intersection 2, we have

$$\frac{L_6 - B_{12}}{L_6 - L_5} = \frac{x}{1} \quad (1)$$

where L_6 is load demand at 6:00 am, L_5 is the load demand at 5:00 am, B_{12} is the value of upper boundary of ZONE 1. Then the x is obtained as $x=0.131$ h. Thus the intersection 2 at the upper boundary of ZONE 1 for that day is at 5:52:14 am. We set it to be 5:52 am.

By applying the same linearization method and assuming y to be the time difference between 0:00 and intersection 1, we have

$$\frac{L_0 - B_{12}}{L_0 - L_1} = \frac{y}{1} \quad (2)$$

where L_0 is load demand at 0:00 am, L_1 is the load demand at 1:00 am. The y is obtained as $y=0.475$ h. Thus the intersection 1 at the upper boundary of ZONE 1 for that day is at 0:28:51 am. We set it to be 0:29 am.

For the upper boundary of ZONE 2, the two intersections of load cycle curve and AVER line are between 6:00-7:00 (intersection 3) and 23:00-24:00 (intersection 4) respectively. By linearization, we have

$$\frac{L_7 - B_{23}}{L_7 - L_6} = \frac{x}{1} \quad (3)$$

where L_7 is load demand at 7:00 am, L_6 is the load demand at 6:00 am, B_{23} is the value of upper boundary of ZONE 2, x is the time difference between 7:00 am and intersection 1. The x is obtained as $x=0.262$ h. Thus the intersection 1 at the upper boundary of ZONE 2 for that day is at 6:44:30 am. We set it to be 6:44 am.

$$\frac{L_{23} - B_{23}}{L_{23} - L_{24}} = \frac{y}{1} \quad (3)$$

where L_{23} is load demand at 23:00, L_{24} is the load demand at 24:00, y is the time difference between 23:00 and intersection 2. The y is obtained as $y=0.077$ h. Thus the intersection 2 at the upper boundary of ZONE 2 for that day is at 23:04:64. We set it to be 23:05.

Applying the same method to calculate the intersections of load cycle curve and the line of DIVIDER1, the two intersections are obtained as 8:16 and 21:33.

B. Calculation of total cost per charging

The intersection points obtained above will be used to calculate the total cost per charging. Figure 6 shows the load cycle from 7 am to 10 am. Let's consider several charging scenarios, assuming the load is 60 kW:

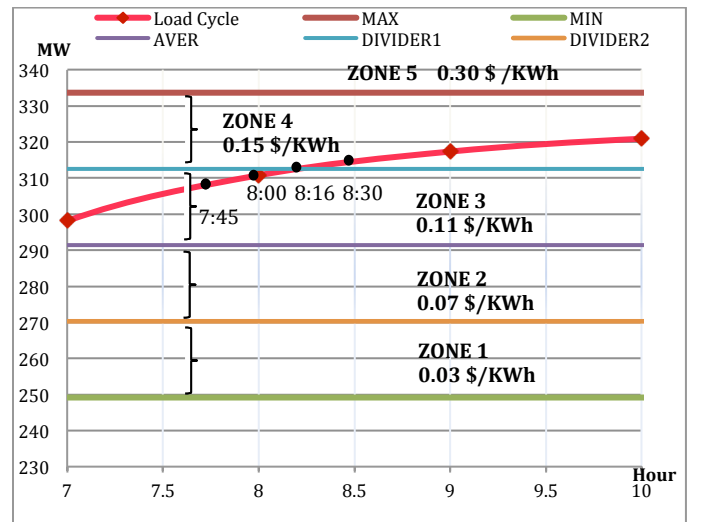


Figure 6 Load cycle from 7 am to 10 am

- Start charging at 7:45 am for 30 minutes:

When the customer starts charging at 7:45, the charging time 30 minutes are all within zone 3. Thus, charging from 7:45 to 8:15 am costs,

$$\frac{30}{60} \text{hour} * 0.11\$/KWh * 60KW = 3.3\$ \quad (4)$$

- Start charging at 8:00 am for 30 minutes:

When the customer starts charging at 8:00, the time interval 8:00-8:30 crosses two zones with the intersection point 8:16, then the total cost per charge will be the combination of two parts.

From 8:00-8:16,

$$\frac{16}{60} \text{hour} * 0.11\$/KWh * 60KW = 1.76\$ \quad (5)$$

From 8:16-8:30,

$$\frac{14}{60} \text{hour} * 0.15\$/KWh * 60KW = 2.1\$ \quad (6)$$

Consequently, the total cost per charge is,

$$\$1.76 + \$2.1 = \$3.86 \quad (7)$$

C. Feedback from electric vehicle charging

Figure 7 shows how the load cycle is modified and the interaction points are updated with the feedback from the real-time electric vehicle charging data. Point 1 indicates the intersection at the original load cycle, while point 2 indicates the intersection at the updated load cycle.

D. Display board specifications

The proposed display board includes:

- Current time t : standard GPS time and local time.
- Current charging price $Pr(Z(t))$: the price of the zone that the current load demand lies in.
- Total charging cost C : the total estimated cost that EV users need to pay if the vehicle starts charging at this moment and fast charging takes $d=30$ min. Assuming the charging power at time t is $P(t)$, the function of the cost will be:

$$C = \int_t^{t+d} Pr(Z(t)) * P(t) dt \quad (8)$$

- Charging time d : in this case, the charging time is assumed to be 30 min. Charging time may vary depending on different EV battery capacity and initial state-of-charge (SOC_i). For each EV, the charging time will have to satisfy the constraint:

$$\int_t^{t+d} P(t) dt = (1 - SOC_i\%) * Capacity (kWh) \quad (9)$$

- Number of vehicles left to be charged at current price: it is calculated by the difference of the current load demand and the upper boundary of the current zone. Assuming the current load is $L(t)$, the number can be expressed as:

$$N_{current_limit}(t) = (B_{Z(t),Z(t)+1} - L(t))/P(t) \quad (10)$$

- The next charging price after that number of vehicle being charged: it is the price of the next higher zone $Z(t)+1$.
- Total vehicles left to be charged at regular price: it is calculated by the difference of the current load demand and the maximum load demand of the forecasted load cycle M .

The charging price will become twice or more if the real load exceeds the maximum forecasted load of the day.

$$N_{regular_limit}(t) = (M - L(t))/P(t) \quad (11)$$

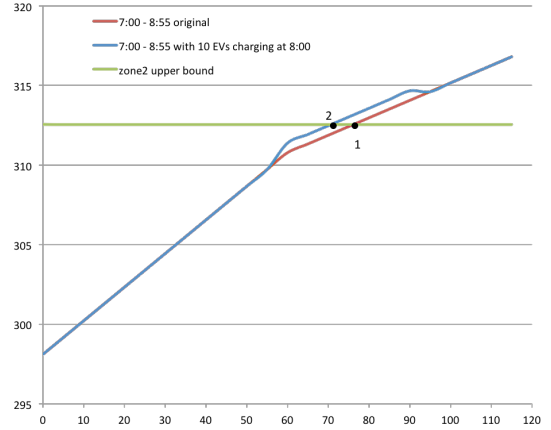


Figure 7 – Feedback from the EV charging

- The predicted maximum number of electric vehicles left to be charged within the next 30 minutes: it is calculated by the difference of the forecasted maximum load demand within the next 30 minutes and the maximum load demand of vehicle left to be charged at regular price, it means the total cost per charging will increase within the 30 minutes.

- The number of vehicles that are currently charging $N_{current}(t)$: the customers can compare the number of vehicles left to be charged at the current price with the number of vehicles currently charging to decide when to charge his car.

This data will be sent to the ISO so that the load cycle is updated. Hence this algorithm ensures dynamic operation.

VI. SIMULATION RESULTS

The input to the MATLAB program that runs the algorithm and its simulation results showing the price for charging and other important information are presented in this section.

The MATLAB program requires the zone information and load cycle data. The load cycle data is obtained from ISO every 15 min. The set of information delivered by the MATLAB program is shown in Figure 8. Figure 8 shows the proposed display board of charging station at 7:45 am and Figure 9 shows the display board at 1:00 am.

A comparison between fossil fuel and electric fuel is stated below:

- Assume a regular car with a tank of 14 gallons and the average miles per gallon rate is 25, the user fills it with fuel twice a month, then the total cost of the gas for one month with a total miles driving of 700 miles is calculated as,

$$3.09 \$/\text{gallon} * 14 \text{gallon} * 2 = 86.52 \$/\text{month} \quad (12)$$

- Assume an electric vehicle with the battery size of 30 kWh, charging power of 60 kW and charging time of 30 min, the user charges it per day at night, then the total cost for one month using the price for zone 1 is calculated as,

$$0.9 \$/\text{day} * 30 \text{day} = 27 \$/\text{month} \quad (13)$$

According to the specification of Nissan Leaf, we assume the electricity consumption of the EV to be 40 kWh/100 miles. Thus, the total electric range of the EV per month is 2250 miles, which is three times of a regular car, in this case.

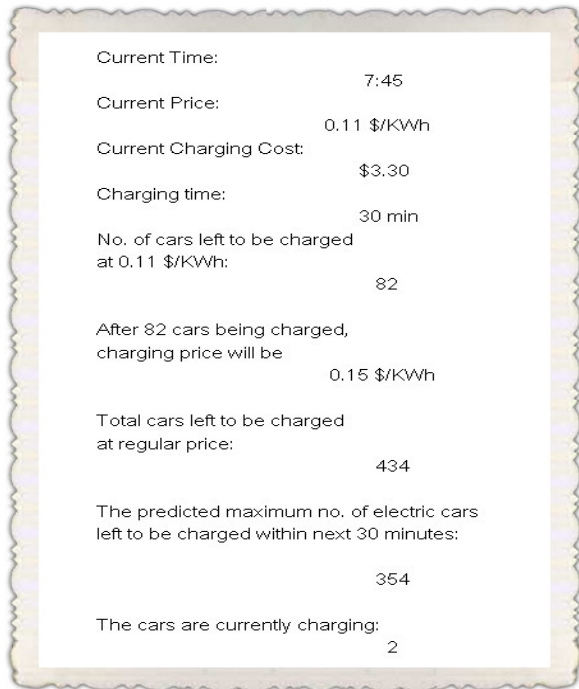


Figure 8 – Display board at a charging station at 7:45 AM

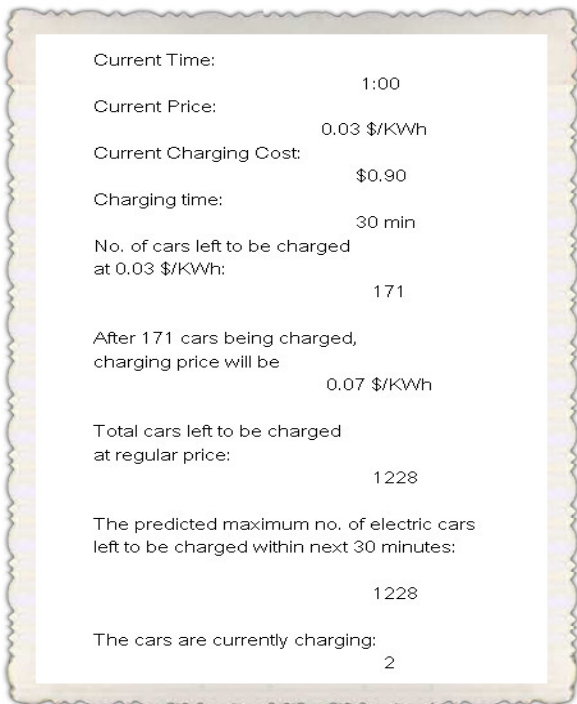


Figure 9 – Display board at a charging station at 1 am

VII. SUMMARY

A novel real-time multi-tiered electric pricing system has been proposed in this paper. It aims to achieve higher utilization of power from the grid and decrease the possibility of creating new peak load on account of EV charging by encouraging vehicle owners to adjust their charging time in return for reduced electricity bills. The following are the paper contributions:

- A multi-tiered pricing algorithm is designed with the charging price varying with the real time electricity consumption.
- A new display board design for electric vehicle charging stations is proposed, which demonstrates the new pricing system and help the customers make better decisions on their charging time.
- The influence on the customers' charging habit will significantly adjust the electricity demand in the distribution level and alleviate the burden it may bring to the electricity market with the increasing penetration of EVs. Thus, by applying the proposed electric pricing mechanism, the EV charging patterns can be better controlled so as to help improve the performance of electric grid in terms of the utility application of demand side management.

Future work will include more investigations on the price settings for each pricing zone and the analysis of implementation method.

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