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Study on Battery Charging Strategy of Electric Vehicles Considering Battery Capacity

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ABSTRACT This paper proposes an improved fast charging strategy for electric vehicles (EVs) by considering available battery capacity. According to previous research and battery experiment reports, the energy capacity of batteries is not fixed, and it can decrease temporarily depending on the magnitude of charging or discharging power. This paper addresses the decreased capacity in proportion to the magnitude of the charging power which leads to a reduction in the driving range. For effective and practical use for EV users, the change in battery capacity is expressed through an equation, and a new state of charged indicator is proposed. To improve the conventional charging method that uniformly supplies power regardless of the battery capacity, this paper proposes an optimal charging strategy injecting constant power. The proposed charging strategy provides an optimal charging power reference to minimize costs considering charged energy, charging time, and usable energy loss based on billing system of EV charging. To verify the effectiveness of the proposed charging method, the optimal charging power reference for each battery is calculated based on capacity and characteristics, and the total cost is compared. The results show that the performance of the proposed charging strategy is effective in minimizing both the reduced battery capacity and economic burden on EV users.

INDEX TERMS Battery charger, coulombic efficiency, electric vehicle, energy storage, fast charging, estimation, state-of–charge, usable energy loss.

I. INTRODUCTION

Environmental issue such as global warming are becoming increasingly important, and EVs using secondary batteries are presented as a solution to replace fuel sources and gas emission from vehicles. Accordingly, charging stations for EVs have been established for public usage [1]. Additionally, there are emphases on environmental problems and marketability for stations. Therefore, many national research centers and companies have been studying charging stations to preoccupy the standards of EVs and charging stations [1]–[3]. As EVs are disseminated, efficient management of battery becomes important issue and research of battery's characteristics is receiving growing attention [4]–[7]. Previous studies have reported coulombic efficiency which is one of the main battery characteristics and is an important issue for the effective usage and improved life of batteries [8], [9]. The discharge characteristic of coulombic efficiency has been expressed as an exponential function. It has not been applied to charging strategies.

There is little charging strategy research considering the battery characteristics. There are only a few modes that consider charging time and maximum initial injected power [6]. With respect to battery capacity, charging or discharging power can cause a capacity drop. The existing charging standard does not consider this effect.

In this paper, the previous studies and experimental results regarding discharge capacity in the electro-chemical characteristics are mathematically formulated and applied to the battery model. Electricity flow in battery-connected systems

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is different from that in other power systems. Because batteries are comprised of chemical substances, energy storage devices are limited by their chemical reaction rates. EV users cannot discharge 100 % of the chemical energy in battery because this chemical reaction cannot wholly participate in transforming electrical energy simultaneously. To operate EVs efficiently, it is necessary to determine the state of charged (SOC) of the battery more accurately. The SOC is a dimensionless value that describes the amount of usable charge that remains in the energy storage system as compared with the total energy capacity. Accurate estimation of battery SOC helps to provide information about the real-time remaining capacity and energy of the battery and ensures reliable and safe vehicular operation.

The charged power is accumulated to measure the available energy, however, it is not an accurate indicator for users. The conventional estimation method of usable energy has been applied simply using look-up-table method or ignoring chemical characteristics. To provide more accurate SOC information, there have been many estimation models and studies on factors that affect the SOC [14]. In particular, factors influencing the driving range reduction such as temperature and state of health (SOH) that affect the capacity of the battery have been studied for more accurate SOC estimation.

In this paper, previous studies and experimental results regarding discharge capacity in the electro-chemicals are formulated and applied to the equivalent circuit model (ECM) and electrochemical impedance model (EIM). The term state of energy (SOE) is proposed rather than SOC to indicate the effective battery capacity in terms of energy content. The SOE is an important issue. However, previous research has not studied the charging strategy and billing model considering SOE.

The conventional battery charging method is constant current constant voltage (CCCV), in which the battery is charged from the beginning with a constant current. When the battery is nearly fully charged and its terminal voltage reaches the voltage limitation, the injected current decreases to ensure that the battery is charged within the voltage boundary. Because the constant-voltage mode reduces the level of charging power exponentially, EV charging has nonlinear relationships with respect to the charging time and injected power. The trade-off between fast charge and battery health should be considered at the same time.

To improve the conventional charging method, many methods such as multi-state CC have been proposed to improve this problem [15]–[17]. This paper suggests the constant power constant voltage (CPCV) method with optimal power references that fit each capacity of battery and the associated coulombic efficiency characteristics [6].

In [19], EV charging stations were considered free parking lot spaces and did not consider parking costs. There were no conditions or constraints for EV users and only constraints on the power allowed by the system when charging. Additionally, in [20], there was no consideration to increase the driving range for EV users. Charging stations were designed to operate the most economically and optimally considering electricity price and electricity load. Finally, other studies did not reflect the phenomenon that the amount of usable energy decreases because the magnitude of the charging power is too large for the capacity or characteristics of the battery. In contrast, the proposed charging strategy in this study reflects the capacity efficiency.

This paper proposes an advanced indicator SOE and an optimal charging strategy. This paper is organized as follows. The structure of the paper takes six sections including this introductory section. Section II describes the electrical equivalent circuit model of the battery and how to consider coulombic efficiency. Section III is concerned with the usable energy loss estimation. Section IV to summarizes the battery charging algorithms, presents how to establish the charging strategy with constant power (CP) and suggests an improved charging method. Their characteristics of charging methods are summarized and compared. Section V analyzes and conducts simulations based on the real experimental results of conventional EV batteries to verify performance of improvement. A general time-varying parking cost model and energy price are considered for comparison. Finally, in section VI, the conclusion gives a brief summary and critique of the findings.

II. BATTERY MODEL FOR ELECTRIC VEHICLES

A. ELECTRO-CHEMICAL CHARACTERISTICS OF BATTERY

When a battery is published, the rated capacity of the battery is fixed. However, the actual battery capacity is not a fixed value and changes depending on the magnitude of power. For this reason, this characteristic causes the SOC estimation error and expected driving range error. As the discharge current increases, the discharge capacity decreases. This phenomenon occurs because the chemical reaction rate is slower than the magnitude of power [8], [9]. The discharge capacity curve of the battery in [8] indicated that the capacity of the battery is reduced if the battery is discharged at a higher rate. It is called the capacity offset, and the performance is accepted to all energy storage devices. This effect is more noticeable as the magnitude of the current or power increases.

The usable energy changes depending on the discharge rate and battery capacity as a function of discharge current are often characterized by Peukert's empirical equation [18]. This is called Peukert's law or coulombic efficiency and is only considered in the discharging mode. However, chemical reactions should also occur in charging mode. The battery undergoes a chemical reaction in which the lithium ions move from the anode electrode to the cathode electrode in the electric discharge process. In the charging process, ions move in the opposite direction. The anode and cathode densities of battery are same, which are called cell-balanced. EV batteries have cell balanced characteristics. As a result, the charging mode can be applied equally with same electro-chemical characteristics. Previous research on coulombic efficiency

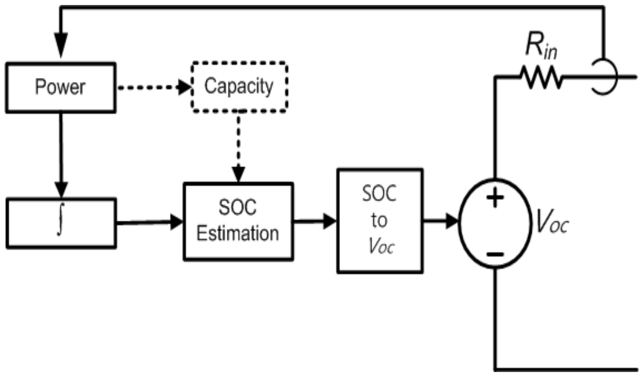

FIGURE 1. Structure of equivalent battery model.

TABLE 1. Specifications of selected batteries.

	Chevrolet Volt (large)	Ford C-Max Energi (middle)	Toyota Prius(small)
Nominal Voltage	355.2 V	310.8 V	207 V
Rated Capacity	45 Ah	26 Ah	21.5 Ah
Energy Capacity	16.5 kWh	7.6 kWh	4.4 kWh

has been conducted, and this characteristic did not apply to the charging strategy. Variable energy capacity was applied to the battery equivalent model and SOC estimation. Battery capacity has been applied to a fixed value and has not been specifically considered. In this research, variable capacity dependent on the magnitude of power is formulated.

B. EQUIVALENT STRUCTURE OF BATTERY

There are several studies on the equivalent structure of battery. The equivalent battery model is composed of many variables. It is very difficult to obtain an accurate model. Incorrect parameters of battery model may lead to the SOC estimation error. However, simple SOC estimation method based on the equivalent battery model has some advantages, such as real-time SOC estimation. In order to obtain more accurate SOC estimation results in real-time applications in vehicle operation, an equivalent model-based estimation method with ECM and EIM is proposed, as shown in Fig. 1. The battery can be expressed as an electric equivalent circuit. As shown in Fig. 1, the equivalent circuit of the battery consists of voltage source V_{oc} and internal resistance R_{in} based on the works in electric response and electro-chemicals.

Variable energy capacity is applied to the SOC estimation at the stage of power integration in Fig. 1. There are several factors such as temperature and SOC, and only two important factors are considered in this section. First, V_{oc} depends on the voltage source, and its voltage increases as the energy is charged in the battery, which has a nonlinear and directly proportional relationship. Because it is not an ideal source to fix voltage, its characteristics is important for the charging strategy in this research. In other words, V_{oc} is a function of the SOC and the V_{oc} curve is different from the battery cell and packages, which is needed experimental scanning.

Second, the internal resistance R_{in} is expressed as the response of the terminal voltage and voltage drop through the charging or discharging. To predict the voltage and current response more accurately, multi-RC model to the equivalent circuit of the battery was applied. However, it is not necessary to see the immediate change in the battery terminal voltage in this study. It is only necessary to determine whether to switch to CV mode due to internal resistance during charging/discharging. The average value of internal resistance versus capacity discharged in the experimental report is applied to build a battery model and simulations [7].

To support this model, a known amount of charged energy in the battery is the most basic information to utilize EVs and charging stations. Usually, the current integration method is used for energy counting, which is called ampere-hour counting. Power integration is not a common method in battery management. However, power integration is used to reflect the battery's state more accurately by sensing the terminal voltage and current. The billing model concerns charging time and power integration. Therefore, power integration is more appropriate for evaluating energy in EV charging systems.

To obtain more accurate SOC estimation results in real-time applications in vehicle operation, equivalent model-based estimation method is proposed and a study to accurately represent further the characteristic of the battery is also actively conducted. This research proposes usable energy in EVs based on this factor.

For detailed research, three different capacity sizes of EV battery are selected to simulate charging operation in Table 1 [10]–[12].

Because the EV charging standard is defined and divided by rated power regardless of battery capacity, three different batteries are selected and applied to the charging operation simulation to demonstrate the suggestion of this research. Reports [10]–[13] include the energy and power behaviors of each battery representing the graph of the capacity versus discharge power. This indicates the amount of usable energy as the magnitude of discharged power. And reports have SOC to V_{oc} curves and internal resistance versus SOC data and are used in this paper.

The manufacturer only discloses the results in the period where the reduction in usable energy is not significant (low power discharge). The driving range of an EV is determined by the amount of energy. For EV users, the amount of usable energy is more important than the amount of injected energy. However, the SOC used previously is an indicator of accumulated injected power. Therefore, most EV users experience inconvenience because the driving range is shorter than expected. The cause of the difference between the injected power and the usable power is regarded as the magnitude of the charging power in next section.

III. USABLE ENERGY LOSS ESTIMATION

A. CAPACITY EFFICIENCY EQUATION

Previous works on energy storage systems did not fully consider the characteristics of the coulombic efficiency of the SOC estimation method. To improve these issues, recent studies have considered the remaining capacity estimation method, such as the Kalman filter algorithm, utilizing V_{oc} for accurate SOC estimation [14]. In this paper, the power integration method and capacity efficiency equations are used to reflect coulombic efficiency. The capacity efficiency equations are estimated and fitted to the third-order polynomial function η_{bat}, reflecting coulombic efficiency changes.

Finding coefficients of capacity efficiency equations, charging, and discharging power values are divided by the battery's energy capacity for normalization. Describing the power in normalized form is applied to the real power value p divided by battery energy capacity E_{bat} as shown in (1) and it is expressed as P_{norm}.

$$P_{norm} = \frac{p}{E_{bat}} \tag{1}$$

η_{bat} is applied to the SOE estimation. When charging/discharging power accumulates without reflecting the capacity efficiency, the SOC can indicate the battery charge. To distinguish the difference between the charged energy and usable energy, the state is estimated by reflecting the change in capacity during charging and discharging. The SOE indicates the amount of energy that can be used, not the state used previously. The difference between SOC and SOE, ΔSOC, is used to infer the difference between the amount of injected energy and the power that can be used. The capacity efficiency equation is fitted to an exponential function. In this paper, it is represented as a 3rd order polynomial as in (2). This proposed function can express the increasing amount as charging or discharging power increases similar to an exponential function.

$$\eta_{bat}(P_{norm}) = a_3 P_{norm}^3 + a_2 P_{norm}^2 + a_1 P_{norm} + a_0 \tag{2}$$

As mentioned above, the capacity efficiency equation is expressed as the third polynomial with normalized power. When batteries are discharged with the same magnitude of power, there is different effect depending on the capacity size. It can be applied to energy management or charging strategies.

Previously, the Peukert equation, which indicated a decrease in battery capacity, was expressed as an exponential function. In this case, only discharge power can be applied. The function is not symmetrical, and it is not applicable in charging operations. In contrast, the curve is expressed as a 3rd order polynomial function. The proposed PMS updates the measurement, and it assigns the variables to the function.

TABLE 2. Coefficients of capacity efficiency equations.

	Chevrolet Volt (large)	Ford C-Max Energi (middle)	Toyota Prius(small)
a_3	$4.731\cdot10^{-4}$	$2.187\cdot10^{-4}$	$2.449\cdot10^{-4}$
a_2	$1.799\cdot10^{-18}$	$1.149\cdot10^{-18}$	$1.166\cdot10^{-18}$
a_1	0.01953	0.02216	0.051
a_0	1	1	1

The coefficient results are obtained through curve fitting as shown in Table 2. a_0 denotes that the coulombic efficiency is almost 100% at small power. a_1 and a_3 indicate the linear capacity change in battery capacity depending on charging or discharging power. Because a_2 denotes the capacity change regardless of charging or discharging, it is almost zero and has no meaning.

Additionally, to express both modes at once, the magnitude ratio of discharging power is applied to the capacity polynomial method as a negative quantity and that of charging power is applied as a positive quantity. This equation is designed to be symmetrical at the inflection point (0,1). Therefore, this curve can be used for both charging and discharging modes. This function is used to estimate the amount of usable energy loss.

As shown in Table 2, Ford (middle) and Toyota (small) use a more efficient battery for large power than that of Chevrolet (large) because Chevrolet(large) has the largest a_3. Additionally, this step makes the capacity efficiency equations applicable to other vehicle with same battery or different capacities with the same cell.

B. SOC AND SOE ESTIMATION

Referred experimental reports are based on charging or discharging power. Describing the charge and discharge power is based on normalized power. The power integrating method is applied for SOC estimation [4], [5].

$$\begin{aligned} SOE &= SOE_0 + \frac{1}{E_{bat}} \int_0^T p dt \\ &= SOE_0 + \int_0^T P_{norm} dt \end{aligned} \tag{3}$$

Equation (3) is a normal method for integrating power, which is applied directly to the SOE estimation. As mentioned above, injected energy and usable energy have the disaccords. Therefore, this method needs correction. There are many factors of SOC disaccord, and this research focused on energy capacity. To improve this, the research uses SOE, which is a replacement of the SOC to indicate the battery capacity in terms of energy content. It is applied to the capacity change depending on the magnitude of power. This effect is represented as a third order polynomial for reflecting the coulombic efficiency. The efficiency function is applied to the denominator of power integration for SOE estimation as shown in (4).

$$SOE = SOE_0 + \frac{1}{E_{bat}}\int_0^T \frac{p}{\eta_{bat}\left(P_{norm}\right)}dt = SOE_0 + \int_0^T \frac{P_{norm}}{\eta_{bat}(P_{norm})}dt \tag{4}$$

When the battery is in charging mode, the magnitude of the capacity coefficient equation η_{bat} should be larger than one. It derives slow charging because the denominator is expanded. In contrast, in the discharging mode, the capacity constant is smaller than one. It derives fast discharging as a decreased denominator. Therefore, the proposed mathematical method can reflect the coulombic efficiency of the battery. The improved SOC estimation and energy loss estimation can be more accurate and applied to optimal energy management system.

C. USABLE ENERGY LOSS ESTIMATION

The usable energy loss does not occur immediately. However, EV users cannot use full energy due to the chemical characteristics and charging operation. Therefore, usable energy is variable dependent on the magnitude of power and the difference between usable energy and the injected energy can be defined as the usable energy loss. In this paper, usable energy loss is formulated based on coulombic efficiency and the SOE estimation equation. Simple SOC accumulation does not consider the capacity drop. However, SOE estimation reflects coulombic efficiency. This makes the SOC difference ΔSOC. The usable energy loss caused by the capacity drop can be defined in (5) and (6).

In (6), E_{bat} is the rated value, which is the fixed value multiplied by ΔSOC to estimate usable energy loss.

$$\Delta SOC = SOC - SOE \tag{5}$$

$$E_{uel} = E_{bat} \cdot \Delta SOC \tag{6}$$

The usable energy loss, E_{uel}, is obtained by multiplying the rated capacity of the battery and ΔSOC. As given in (7), ΔSOC can be defined as the SOC shortage between SOC and SOE.

$$\Delta SOC = \left(SOC_0 + \int_0^T P_{norm}dt\right) - \left(SOC_0 + \int_0^T \frac{P_{norm}}{\eta_{bat}(P_{norm})}dt\right) = \int_0^T P_{norm} \cdot (1 - \frac{1}{\eta_{bat}(P_{norm})})dt \tag{7}$$

In (8), if the magnitude of power is small, and the capacity efficiency of the battery is close to 100%. Then, a_0 is one and ΔSOC is formulated as follows.

$$\Delta SOC = \int_0^T P_{norm} \cdot (1 - \frac{1}{a_3P_{norm}^3 + a_2P_{norm}^2 + a_1P_{norm} + a_0})dt = \int_0^T (\frac{a_3P_{norm}^4 + a_2P_{norm}^3 + a_1P_{norm}^2}{a_3P_{norm}^3 + a_2P_{norm}^2 + a_1P_{norm} + a_0})dt \tag{8}$$

However, the capacity efficiency equation's value is normally 0.9 to 1.1, and a_0 is dominant in the denominator. Only a_0 can be left, and another factor can be ignored. For the property of convexity, the denominator terms except for 1 are omitted to make the calculation easier. Even without the omission, the energy loss value can be inferred. However, the convexity of the objective function is more important. The energy loss can be constructed as a quadratic formula for P_{ref}. Fourth and quadratic polynomial functions are even functions, and their integration form has convexity.

Then, the equation representing the energy loss becomes a convex function in which the quadratic equations are integrated. In addition, this is a condition in which the solution is optimal.

$$\Delta SOC \approx \int_0^T a_3P_{norm}^4 + a_2P_{norm}^3 + a_1P_{norm}^2 dt \tag{9}$$

Therefore, ΔSOC can be inferred in (9). As shown in Table 2, the coefficient of the second order term a_2 has a minor role and can be ignored as in (10).

$$\Delta SOC \approx \int_0^T a_3P_{norm}^4 + a_1P_{norm}^2 dt \tag{10}$$

Finally, by (6) and (10), the usable energy loss can be approximated to a quadratic function in (11). According to the convexity of even order polynomials, they can be applied to a part of the optimization problem, and there can be a solution.

$$E_{uel} \approx E_{bat} \cdot \left(\int_0^T a_3P_{norm}^4 + a_1P_{norm}^2 dt\right) \tag{11}$$

As mentioned above, usable energy loss, E_{uel}, is not the actual energy loss. However, EV users experience usable energy loss from charging or discharging processes. The discharge capacity decreases as the magnitude of the discharging power increases. By analyzing this phenomenon, it is defined as usable energy loss that cannot actually be used in driving. This usable energy loss must occur in charging or discharging operations.

Where the (2) is established, the capacity efficiency equation is the third order polynomial and a_2 is negligible. Then, $\{\eta_{bat}\left(P_{norm}\right) - 1\}$ is an odd function consisting of the a_3 term and a_1 term. They are the main factors representing the performance of coulombic efficiency. The estimated usable energy loss is estimated as an integration of even function, as shown in (11). Comparisons are required to verify the suggested model and experimental reports. The estimated usable energy loss and usable energy versus power curve are similar for each battery as shown in Fig. 2.

When batteries are charged with large power, it is shown that the reduced usable energy between the experimental results and the estimated results does not have much difference. The smaller the battery's capacity is, the less accurate it is. Additionally, as shown in Table 2, at the characteristics of the battery applied to (c), the value of a_1 is larger than that of the other batteries. Therefore, in the approximation process, the error increases. The large value

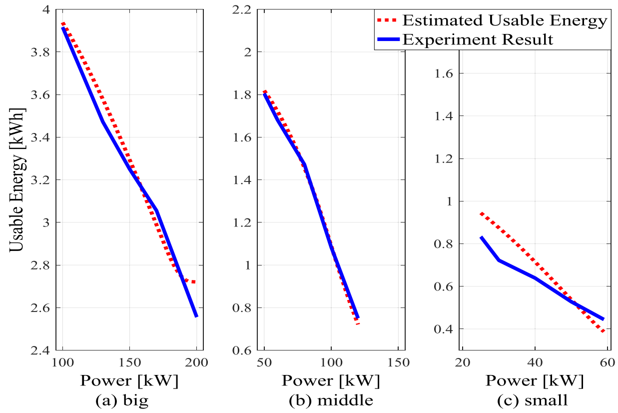

FIGURE 2. Comparison between estimated and experimental usable energy for its battery size and charging power.

of a_1 indicates that the capacity decrease is large even if the charging power is small. The battery used in EVs increases and the performance improves. Accurate values can be applied to batteries of EVs that will be distributed in the future.

IV. CHARGING STRATEGY IMPROVEMENT

It is impossible to avoid driving range decrease or aging. However, it is possible to charge efficiently when the charger reflects the characteristics and capacity of the battery. When an EV is in fast charging mode, usable energy loss becomes more remarkable. This section focuses on improvement by suggesting the CPCV charging method.

A. CONVENTIONAL CHARGING STRATEGY

First, the CCCV is a standard method to charge the energy storage devices. CC mode charging is conducted until the terminal voltage reaches its threshold value. In the case study, the voltage limitation was set to V_{oc} at 100% and the power integration method was applied to SOC counting. With the constant current mode, the terminal voltage increases slowly as V_{oc} increases until the terminal voltage reaches the voltage limit. Then, the charger switches to constant-voltage mode, fixes the terminal voltage and reduces the magnitude of the current.

This is because the internal voltage, V_{oc}, increases as energy is charged and it is suggested for charging battery safety. The charger needs to ensure that the charging current should be lower than the maximum charging current that battery can accept. This method causes chargers to distribute the energy unevenly, energy distribution unbalancing and capacity reduction to occur more. When the EV is charged in the CC mode, the charged power increases marginally because V_{oc} and the terminal voltage rise as the SOC increases as shown in Fig. 3.

After the CC mode, the battery charger switches to the CV mode, and the charging current decreases exponentially. The injected power is the product of the current and terminal voltage. Accordingly, the increment of injected power in the CC mode is obvious, and it is necessary to modify the charging strategy for a constant power supply.

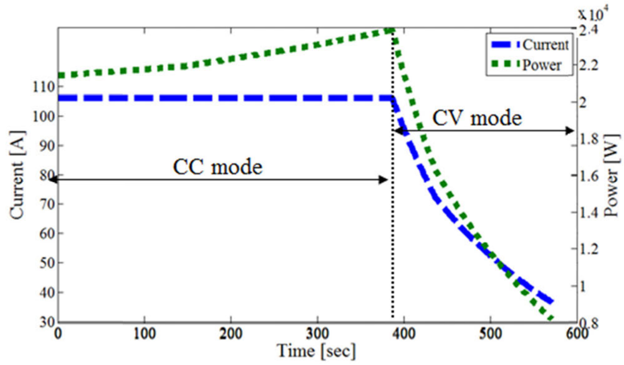

FIGURE 3. Current and power results for the CCCV method.

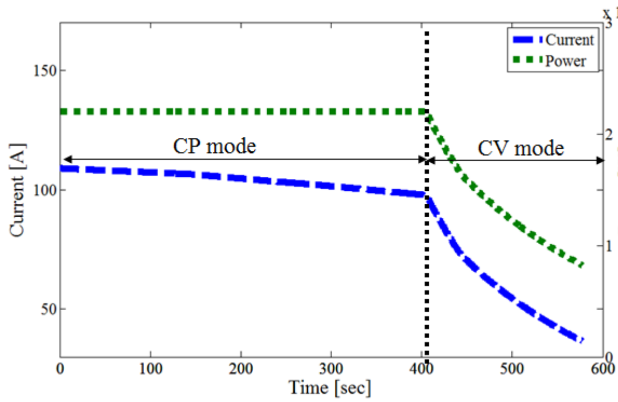

FIGURE 4. Current and power results for the CPCV method.

B. EFFICIENT CHARGING STRATEGY

The time portion of the CV mode in the total charging process can be the dominant factor causing usable energy loss in EVs. Because of coulombic efficiency, when the battery is charged at the same time and with the same energy, higher power causes larger usable energy loss. The injected power increases as charging proceeds in CC mode as shown in Fig. 3. Making charging power flat can be a more efficient charging method. If constant power is injected when the same amount of energy is charged at the same time as shown in Fig. 4, it can reduce the usable energy loss in the charging operation.

Compared to the CCCV and the CPCV charging methods, there should be an usable energy advantage in CPCV. If the magnitude of power is changed during the charging operation, usable energy loss will be larger than that of constant power with the same SOC update.

This paper suggests replacing the CC with the CP charging method before the CV mode operates as shown in Fig. 4. With this conclusion, it is applied to the entire EV charging scenario and case studies. To evaluate the performance of the proposed method based on coulombic efficiency, 50 kW fast charging to 20% to 90% of SOC with CCCV and CPCV is implemented in the simulation. Specifically, both charging

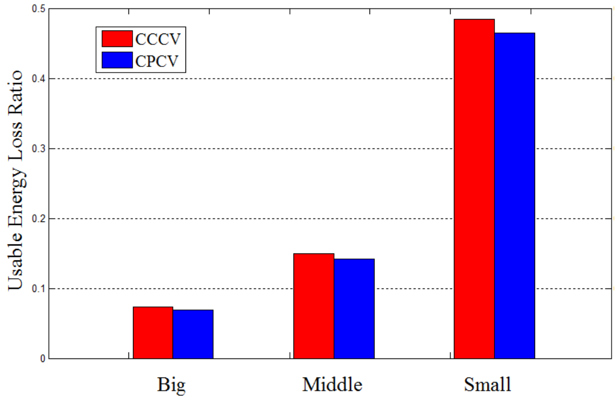

FIGURE 5. Usable energy loss ratio on charged energy for each battery.

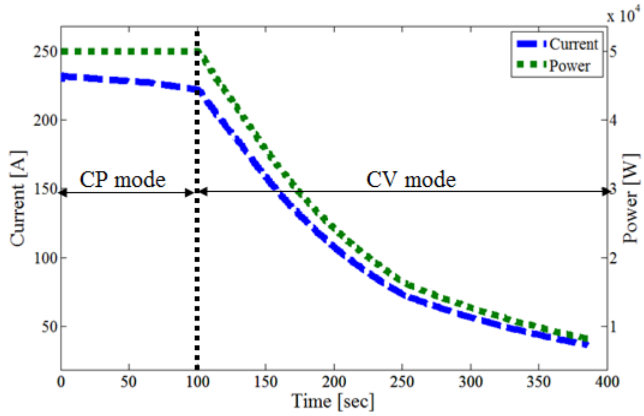

FIGURE 6. Current and power result of 50 kW fast CPCV charging with small capacity battery.

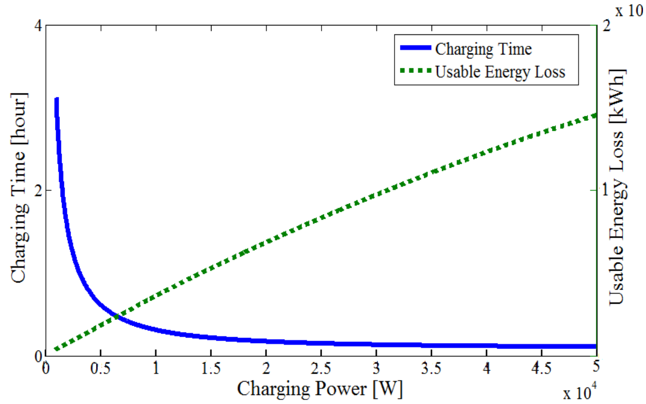

FIGURE 7. Charging time and usable energy loss relationship as charging power.

methods charge the same energy. According to the statistical result, even though the same magnitude of power is charged initially, the injected power of the CCCV increases because the voltage increases.

Therefore, there is more usable energy loss in CCCV than in CPCV. The ratios of usable energy loss to the injected energy are represented for a detailed comparison as shown in Fig. 5.

Even though the CPCV method requires considerable time marginally, the charging time increases marginally by 1.2%, and the usable energy loss ratios decreases by approximately 4%. This result indicates that CPCV is more efficient and can be a more appropriate charging method. In particular, a small size capacity has a higher usable energy loss ratio than that of the other sizes, which indicates that 50 kW fast charging is not appropriate for small capacity even though its coulombic efficiency is better than that of other batteries.

C. CHARGING POWER ADJUSTMENT

When the charging power is much larger than its battery capacity size, the usable energy loss ratio is very high, it is necessary to regulate the fast-charging power. As shown in Fig. 6, a small capacity battery is connected to a fast charger and applied to 50 kW CPCV charging. This charging operation has a higher CV portion, which is inefficient for fast charging for small capacity EVs [15].

There is much time in CV mode when charged power is much larger than EV's battery capacity in Fig. 6. In CV mode, the injected energy is insufficient, and it only extends the charging time. The CV mode is essential for safety. This prevents lithium deposition caused by over-potential. In CV mode, the charger supplies power below a certain fraction of the battery's maximum charge rate when the maximum charging voltage has been reached. However, that distributes the power unevenly and causes more structural stress on the battery.

The charging time portion of the CV mode becomes larger when the initial injected power is much larger than the battery capacity. As the higher portion of the CV mode in the charging process, the total charging requires considerable time. An initially injected power value can be suggested that can consist of the CP mode only in the charging operation.

In this research, $V_{oc.100}$ is the voltage boundary for the CV mode, and $V_{oc.90}$ is the internal voltage of the target SOC 90% in fast charging. The equation to find initial power reference for CP charging, p_{cp}, can be established as (12).

$$p_{cp} = \frac{(V_{oc.100} - V_{oc.90}) \cdot V_{oc.100}}{R_{in}} \tag{12}$$

To charge batteries with maximum power except the CV mode, V_{oc} and R_{in} information are essential and experimental results in [10]–[12] are applied to (12).

However, the CP charging can be inefficient. This is dependent on the battery's equivalent circuit specification, not the coulombic efficiency characteristics or any other optimal conditions.

According to the increase in initial charging power, usable energy loss increases linearly. However, charging time decrease nonlinearly. The charger meets the CV mode earlier as the initially charged power is larger. CV mode charging is not efficient for fast charging, as shown in Figs. 6 and 7. Therefore, it is necessary to regulate the initially charged power considering the trade-off relationship between charging time and usable energy loss.

TABLE 3. Billing model of electric vehicle charger.

	Value
Bill by parking time (J_p)	\$1 per hour
Bill by energy (J_e)	\$0.2 per kWh

V. OPTIMAL CHARGING STRATEGY AND RESULTS

A. OPTIMAL POWER REFERENCE

The CPCV charging strategy is proven to be more efficient than CCCV in usable energy loss. Therefore, proper power values for each battery should be found. This is applied to the charging operation in different sizes of EV batteries. Because coulombic efficiency depends on the energy capacity size, they have their trade-off relationship between charging time and usable energy loss. The optimal injected power in each battery should be different.

The EV user should pay the charging fee for parking and energy. A public charging rule is applied for the optimization problem. The price of the electricity and parking bill are shown in Table 3 [16].

Based on the billing model and trade-off relationship, the optimization problem can be set as (13) and the optimal power value can be found to minimize the total price and energy loss cost.

$$\min \left\{ J_p \cdot T + J_e \cdot E_{uel} \right\} \tag{13}$$

It is preserved that convexity of functions with operations such as addition, scaling. These properties can extend to infinite sums and integrals [21]. The equation (11) is integral of even function and coefficient J_p and J_e are positive then the equation (13) is convex.

The process to find the optimal power reference P_{ref} is presented in Fig. 8. First, the proposed method updates the EV information and sets the initial P_{ref} as E_{bat}. Thereafter, the EV is charged in CP mode until the terminal voltage, V_t, reaches the maximum internal voltage, $V_{oc.100}$. When V_t exceeds $V_{oc.100}$, the CP mode switches to the CV mode and the charged power, P_{ch}, is regulated until V_{oc} becomes $V_{oc.90}$ which is the internal voltage of the target SOC of 90%. When V_t is larger than $V_{oc.100}$ and V_{oc} becomes smaller than $V_{oc.90}$, P_{ch} is changed for CV charging operation. After CPCV charging is completed, the total cost is calculated by aggregating the total charging time, charged energy and usable energy loss.

To ensure that the solution is optimal, the total cost is calculated by adding 1 W to P_{ref}, and this process is repeated until the magnitude of the charging power became 12 times the capacity of the battery.

Finally, the optimal charging power reference is found to minimize the cost consumers have to bear.

The capacity size and coefficients of the capacity efficiency equations of batteries are different, and they have each power value for constant power charging and optimal value for

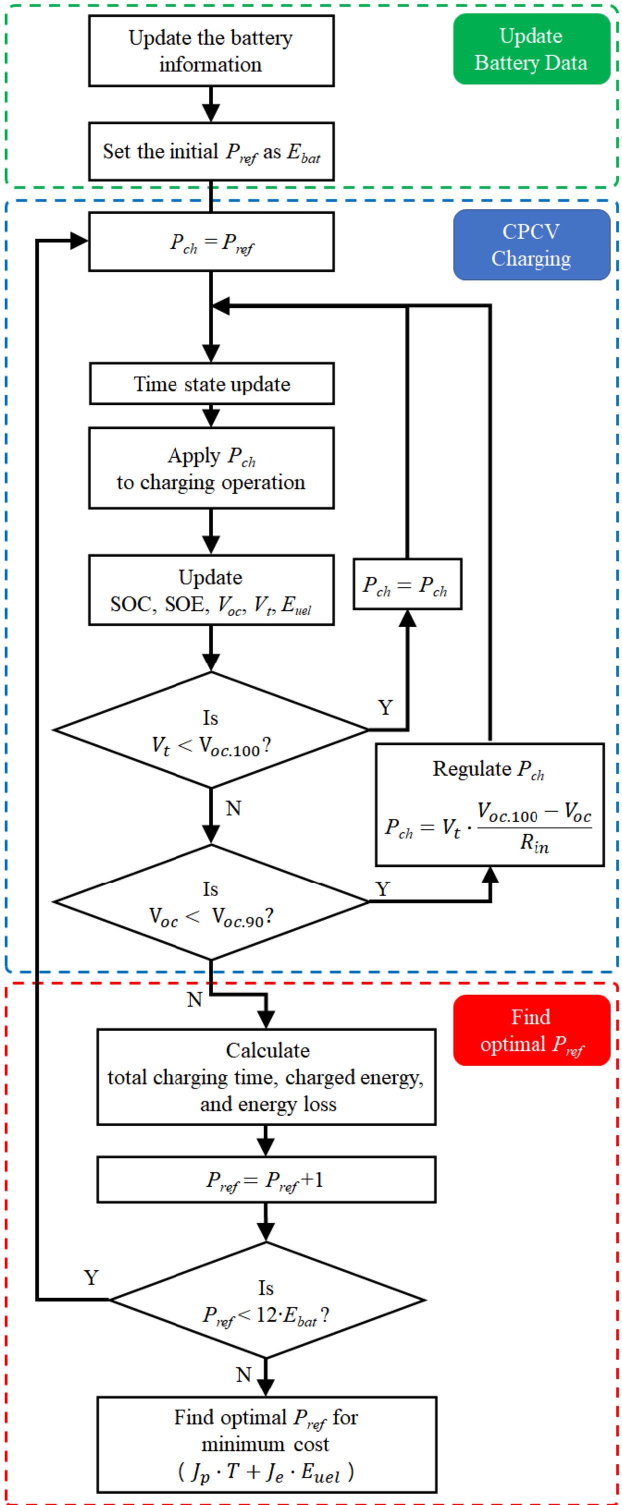

FIGURE 8. Comparison of the proportional to the capacity and the optimal charging power reference.

minimizing the total price and energy loss cost. By changing the charging power and applying it to the CPCV charging simulation, an optimal power that minimizes the cost is found, and the final results represent Table 4. Since the same

TABLE 4. Reference powers for each battery.

Power [W]	Chevrolet Volt (large)	Ford C-Max Energi (middle)	Toyota Prius (small)
Fast charging	50,000	50,000	50,000
CP charging	55,300	40,384	14,318
Optimal power	51,110	40,045	21,108

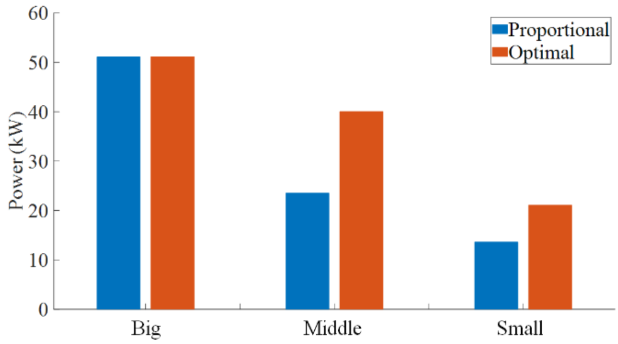

FIGURE 9. Comparison of the proportional to the capacity and the optimal charging power reference.

TABLE 5. Reference power ratio for battery capacity.

	Chevrolet Volt (large)	Ford C-Max Energi (middle)	Toyota Prius (small)
Ratio	3.0976	5.2691	4.7973

energy is charged at a similar time, the objective function does not include the charged energy price and only considers the additional cost. The optimal battery charging mode is compared with conventional fast charging standards CCCV, CPCV charging and CP charging.

The amount of capacity reduction varies from cell to battery, and the optimal power reference reflects these batteries' performances. It seems to be proportional to the capacity of the battery and the charge recharge rate. However, if the power in proportion to the battery capacity based on the large battery is calculated, the difference between the proportional value and the value reflecting the performance of the battery is shown in Fig. 9.

As seen in Table 5, there is a difference in the value of the optimal power reference versus capacity. The batteries applied to the Ford (middle) and Toyota (small) applications have greater charging power than the batteries used for the Chevrolet (large). Thus, if the battery cells are the same, even if the battery capacity applied to the vehicle is different, the optimum charging power reference for the vehicle can be obtained without a separate experimental result.

B. ANALYSIS AND COMPARISON OF CHARGING PRICE

An optimal value is applied to the CPCV charging. The results show the effectiveness of the proposed strategy. All charging battery operations were conducted on fast charging operation from SOC 20 % to 90 %.

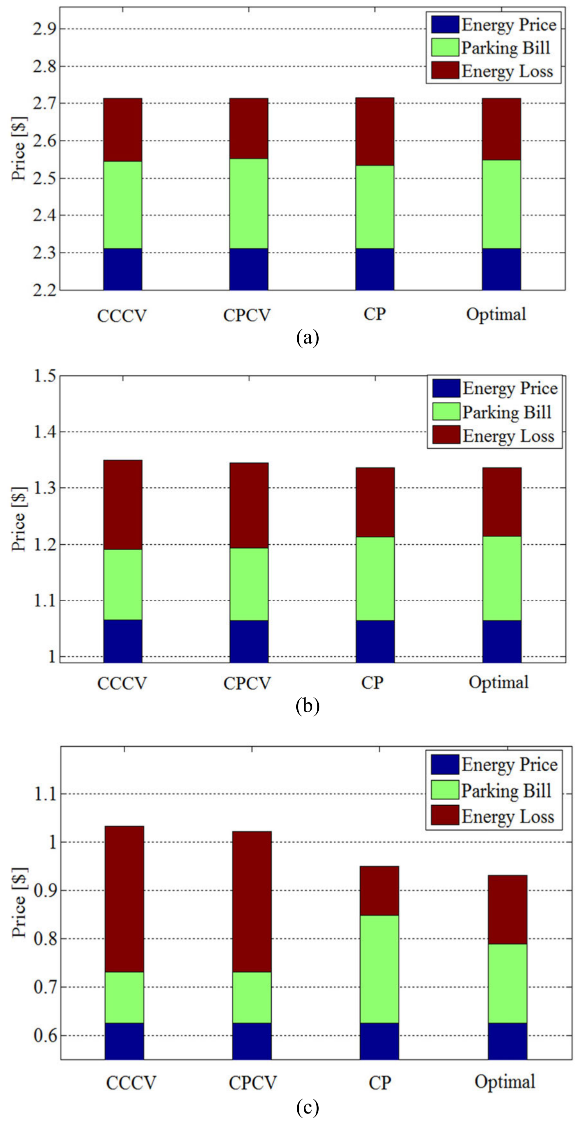

FIGURE 10. Total price results for CCCV, CPCV, CP and the optimal power charging method (a) Chevrolet Volt (large), (b) Ford C-Max Energi (middle), and (c) Toyota Prius (small).

The results in Fig. 10 and Table 6 presents that the proposed strategy, including the CPCV and optimal power value can offer economic benefits to EV users compared with the conventional charging method and other charging strategies.

Fig. 10 and Table 6 also show that there can be some improvement in the charging method and proper fast charging power can be suggested considering the battery's state and specification. Specially, when battery capacity is small, it is not fit to charge with large power. As mentioned above, the CPCV method is more efficient than the conventional method CCCV. However, the CP method can be inefficient and dependent on the battery's equivalent circuit specification, not the coulombic efficiency characteristics or optimal power reference. Therefore, it is necessary to regulate the initial charging power considering the trade-off relationship,

TABLE 6. Total price for each charging method.

Price [$]	Chevrolet Volt (large)	Ford C-Max Energi (middle)	Toyota Prius (small)
CCCV	2.7146	1.3492	1.0326
CPCV	2.7137	1.3448	1.0215
CP	2.7163	1.3360	0.9497
Optimal	2.7130	1.3356	0.9320

coulombic efficiency, and billing system. As the injected power is larger, the usable energy increases. The trade-off relation appeared between the charging time and usable energy loss in the CPCV charging operation as shown in Fig. 10. EV users can reach an impasse. If an EV is charged quickly, its parking bill will be smaller and some of the charged energy cannot be used, which would be worse. Even though EV users know this trade-off relationship, it is hard to know how much charging power is optimal and impossible to adjust charging power.

To summarize, for fast and optimal fast charging, the magnitude of power should be large as possible as the charger can be. However, the portion of the CV mode should be smaller, so the power is not too large.

The conventional charging method CCCV with a fast charging power of 50 kW is applied for comparison. In addition, the proposed method CPCV with 50 kW is conducted. The CP charging method is applied to the charging operation simulation. Finally, the CPCV charging with optimal power minimizes the total charging price. All cases of batteries show that the CP method reduces the total charging price of the battery. However, the CP method cannot reflect the battery's capacity and economic issues. It is not an optimized strategy.

Optimal power charging can reduce, at most, 9% of the cost compared to the existing fast charging mode. All battery capacity sizes can also improve the economic benefit. The proposed method achieves profit improvement.

With this analysis, reducing the charging price and usable energy loss are improved by modifying the initial injected power value, which is observed in the result in Fig. 10. Optimal power requires more charging time than conventional 50 kW fast charging. However, the total price including loss is smaller than 50 kW charging and the CP charging mode. To summarize, this suggested strategy can reduce total price by extending time and reducing energy loss. Each case is considered for the battery's capacity and coulombic efficiency for charging.

VI. CONCLUSION

Usable energy conception is generally used in batteries. Most EV battery research has focused on the exothermic reaction or voltage balancing and coulombic efficiency. However, it is noteworthy that every EV user suffers from the problem of energy capacity decreasing even though the state of energy (SOE) is not the main topic in the EV research area. Charging EVs considering the SOE increases usable energy. This means that EV user can have more long driving range.

In this paper, electro-chemical characteristics of coulombic efficiency is expressed as a polynomial function and usable energy loss are estimated. By using battery experimental results, an improved charging strategy considering the coulombic efficiency and size of energy capacity was proposed for EV users. Based on the proposed method constant-power constant-voltage (CPCV), the reduction in usable energy loss and charging cost were evaluated. This paper proposes an optimal EV battery cahrging solution for EV users, and it was established that not only can this charging strategy expand the available range of EVs but it also gains profit. It is expected that the proposed method can suggest the optimal reference power and process in EV charging systems.

REFERENCES

[1] P. Fan, B. Sainbayar, and S. Ren, "Operation analysis of fast charging stations with energy demand control of electric vehicles," *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 1819–1826, Jul. 2015.

[2] S. Yarlagadda, T. T. Hartley, and I. Husain, "A battery management system using an active charge equalization technique based on a DC/DC converter topology," *IEEE Trans. Ind. Appl.*, vol. 49, no. 6, pp. 2720–2729, Nov. 2013.

[3] Y. Zheng, Z. Y. Dong, Y. Xu, K. Meng, J. H. Zhao, and J. Qiu, "Electric vehicle battery charging/swap stations in distribution systems: Comparison study and optimal planning," *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 221–229, Jan. 2014.

[4] Z. Miao, L. Xu, V. R. Disfani, and L. Fan, "An SOC-based battery management system for microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 966–973, Mar. 2014.

[5] L. Y. Wang, M. P. Polis, G. G. Yin, W. Chen, Y. Fu, and C. C. Mi, "Battery cell identification and SOC estimation using string terminal voltage measurements," *IEEE Trans. Veh. Technol.*, vol. 61, no. 7, pp. 2925–2935, Sep. 2012.

[6] X. Qu, H. Han, S.-C. Wong, C. K. Tse, and W. Chen, "Hybrid IPT topologies with constant current or constant voltage output for battery charging applications," *IEEE Trans. Power Electron.*, vol. 30, no. 11, pp. 6329–6337, Nov. 2015.

[7] H. Rahimi-Eichi, U. Ojha, F. Baronti, and M.-Y. Chow, "Battery management system: An overview of its application in the smart grid and electric vehicles," *IEEE Ind. Electron. Mag.*, vol. 7, no. 2, pp. 4–16, Jun. 2013.

[8] P. H. Smith, T. N. Tran, T. L. Jiang, and J. Chung, "Lithium-ion capacitors: Electrochemical performance and thermal behavior," *J. Power Sources*, vol. 243, pp. 982–992, Dec. 2013.

[9] I. S. Kang, Y. S. Lee, and D. W. Kim, "Improved cycling stability of lithium electrodes in rechargeable lithium batteries," *J. Electrochem. Soc.*, vol. 161, no. 1, pp. 53–57, Nov. 2013.

[10] U.S. Department of Energy. *2013 Ford Fusion Energi VIN 3875 Plug-in Hybrid Electric Vehicle Battery Test Results*. Accessed: Jul. 2014. [Online]. Available: http://energy.gov/eere/vehicles

[11] U.S. Department of Energy. *2011 Chevrolet Volt VIN 0815 Plug-in Hybrid Electric Vehicle Battery Test Results*. Accessed: Jul. 2013. [Online]. Available: http://energy.gov/eere/vehicles

[12] U.S. Department of Energy. *2013 Toyota Prius VIN 6237 Plug-in Hybrid Electric Vehicle Battery Test Results*. Accessed: Jul. 2014. [Online]. Available: http://energy.gov/eere/vehicles

[13] *U.S. Department of Energy Vehicle Technologies Program Battery Test Manual for Plug-In Hybrid Electric Vehicles*, U.S. Dept. Energy, Washington, DC, USA, Dec. 2010.

[14] R. Xiong, H. He, F. Sun, and K. Zhao, "Evaluation on state of charge estimation of batteries with adaptive extended Kalman filter by experiment approach," *IEEE Trans. Veh. Technol.*, vol. 62, no. 1, pp. 108–117, Jan. 2013.

[15] *Production EVSE Fact Sheet: DC Faster Charger: HasetecLI06-3P3W 50kW*, U.S. Dept. Energy, Washington, DC, USA, Feb. 2014.
[16] *Technical Specifications of Quick Charger for the Electric Vehicle*, CHAdeMO Assoc., Tokyo, Japan, Jul. 2015.
[17] S. G. Li, S. M. Sharkh, F. C. Walsh, and C. N. Zhang, "Energy and battery management of a plug-in series hybrid electric vehicle using fuzzy logic," *IEEE Trans. Veh. Technol.*, vol. 60, no. 8, pp. 3571–3585, Oct. 2011.
[18] J. Lee, Y. Kim, and H. Cha, "A new battery parameter identification considering current, SOC and Peukert's effect for hybrid electric vehicles," in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2011, pp. 1489–1494.
[19] Z. Wei, Y. Li, and L. Cai, "Electric vehicle charging scheme for a park-and-charge system considering battery degradation costs," *IEEE Trans. Intell. Vehicles*, vol. 3, no. 3, pp. 361–373, Sep. 2018.
[20] K. Ginigeme and Z. Wang, "Distributed optimal vehicle-to-grid approaches with consideration of battery degradation cost under real-time pricing," *IEEE Access*, vol. 8, pp. 5225–5235, 2020.
[21] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

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