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Research paper

A Study on Single-Mode Charger Using DC modeling Equivalent Estimation of the Battery

Byeong-Kak Kim[1],Seong-Mi Park[2], Sung-Jun Park[*3]

[1,3]*Dept. of Electrical Engineering, Chonnam National University, Korea*
[2]*Dept. of Lift Design, Korea Lift College, Korea*
[*]*Corresponding author E-mail: sjpark1@jnu.ac.kr*

Abstract

Background/Objectives: Recently, with the increase of DC devices like mobile phones and the appearance of smart grid equipped with a means of storage with possible energy time slot drift, demands for devices have increased. Because of serious risks, like explosion in overcharge for the typical battery of energy storage devices, studies of battery charging method are actively conducted.
Methods/Statistical analysis: The representative battery charging method is the CC-CV charging method, which charges the battery in CC mode in early charging to shorten the battery charging time and charges it in CV mode to prevent battery overcharge in the end of charging. CV charge operates when there is a little difference between supply voltage and battery voltage and can charge over 95%, since the battery is continuously charged by the current determined by supply voltage, battery voltage and battery internal impedance. However, CV charge has a weakness that it takes much time to charge the battery fully since there is little electricity supplied to it.
Findings: This study excludes the CV charging method that requires much charging time and proposes a charging method to complete charging the battery only with the CC charging method. For this purpose, this study proposes a simplified algorithm that can estimate a battery voltage by estimating the battery parameter necessary for CC charge. In addition, this study verified the validity of the proposed method through simulations.
Improvements/Applications: This study proposed simplified modeling of a battery for CC and its parameter charging method to complete charging only with the CC charging method in order to shorten the charging time. In addition, through simulations, the validity of the proposed method was verified.

Keywords: *Single-Mode Charger, Battery charging, CC-CV charging method, CV charging method, Battery charging method*

1. Introduction

As environmental problems, such as global warming due to depletion of petroleum resources and greenhouse gas come to the fore as global issues, the paradigm shifts from an age of dependence on fossil energy to an age of new and renewable energy[1- 3].In terms of the production of electricity, many studies are conducted on the use of new and renewable energy, and to cope with irregular outputs of new and renewable energy, a battery becomes an alternative as a method of storing energy and sending stabilized outputs to systems[4, 5].For the use of the battery as a means of storing energy, for efficient operation, electric charge and discharge technologies become the core. An important element of the core technology is the time for the completion of charging, and for this, various studies are actively conducted on a high-speed charging method. The high-speed charging method has a weakness that its battery charging rate is lower than that of a slow-speed charging method. This is because of the complicated battery modeling and the burden of overcharge due to the error in real-time modeling[6,7].This study proposed simplified modeling of a battery for CC and its parameter charging method to complete charging only with the CC charging method in order to shorten the charging time. In addition, through simulations, the validity of the proposed method was verified.

2. Real-Time Battery Modeling and Charging Method

2.1. Battery Modeling for CC Charging

Because of the importance of battery modeling, there is a variety of modeling, including the modeling applying the fuzzy theory, but this study proposes modeling for CC charge based on simplified Randles modeling of the various modeling methods. The Randles model is a model like figure 1, made by the equalization of electrolyte resistance (Rs) connected in series in the battery, charge double layer (Cdl) connected in parallel, charge transfer resistance (Rct) showing impedance by the induced reaction, and diffusion (Zw) as an electric circuit. This model is usually used in the form in which an equivalent circuit is provided, which can analyze the characteristics of the battery by component with a mechanism of electrochemical reactions along with Electro-chemical Impedance Spectroscopy (EIS) [8].Solution resistance (Rs) is the value that equalizes hindrance when electricity flows in the battery, and as it ages, charge transfer deteriorates since the chemical reaction of the electrode occurs hardly. The characteristic of this value differs depending on the electrolyte ionic concentration in the battery, and the characteristic of the ionic concentration, too, differs depending on the battery temperature and battery structure and shape, so it is hard to understand it accurately. Especially, the fluctuation of this value is not uniform as time passes, and its characteristic differs depending on the battery) [9-10].

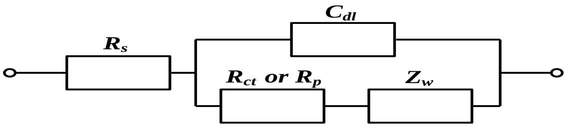


Figure 1:.Randles model

Charge transfer resistance (Rct) means the loss of potential appearing in the battery's electro-chemical reaction, and in early electric discharge, the electrochemical reaction forms a double layer of charge, and the resistance rapidly increases up to the step before the formation of over-potential, and the oxidation reaction progresses at more than sufficient potential. The transfer of the electrons is made actively, so the charge-transfer resistance decreases. Thus, the charge-transfer resistance is characterized by the variation like variable resistance, instead of a fixed value, and this can be expressed in the form of a sign like variable resistance[11,12].The charge-transfer resistance is a parameter for which the loss of charge-transfer resistance should be considered enough when it is in high-speed charge or has a large discharge quantity. As for the electric double layer, if the oxidation-reduction reaction begins, an interface is made between an electrode and an electrolyte, and this interface expands, forming layers. Like this, an electric structure like a capacitor appears between an electrode and an electrolyte, which is called electric double layer (Cdl). According to the type of electrode, its characteristic is the form of a capacitor or a combination of a capacitor with a resistance component. In the battery charge and discharge, the electro-chemical reaction takes place from the surface of the electrode. In other words, the oxidation-reduction reaction begins from the electrode to which a conducting wire is connected and spreads to the surrounding (Zw), so the oxidation-reduction reaction keeps occurring. However, since this diffusion does not have constant electrolyte concentration either, but show a little deviation, there is a phenomenon in which the external terminal voltage decreases. In this part, a phenomenon takes place, in which the external terminal voltage is not accurate when measured after charge and discharge and keep rising or falling, which is the phenomenon occurring by diffusion. This diffusion can be stabilized at least 10 min. to more than one hour later, the external terminal voltage can be measured accurately with the Open Circuit Voltage (OCV) method[13].

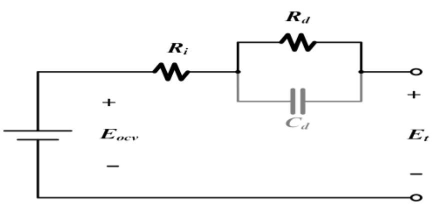


Figure 2:. Simplified equivalent circuit model of batteries

The Randles model is complex, and it is difficult to estimate the parameter in real time, so a simplified Randles model like figure 2 is used as a battery equivalent model. In other words, internal resistance is integrated with charge transfer to create new equivalent resistance Ri, and the diffusion model is simplified as an RC parallel circuit. And yet, since the battery internal voltage and serial impedance component include temperature characteristics, they cannot be set to constant values during charging. In the battery equivalent model in Figure 2, at the beginning of electric discharge, the capacitance stage is shortened by capacitance Cd component and operates only with resistance Ri, and since in the nominal status in CC mode, the capacitance is considered open, so it operates with the sum of resistance Ri and Rd, and Cd can be calculated from the time constant. Thus, in CC charge, the information necessary for battery modeling can be solved just with the internal voltage and the sum of resistance Ri and Rd.

2.2. Estimation of Battery Parameter for CC charge

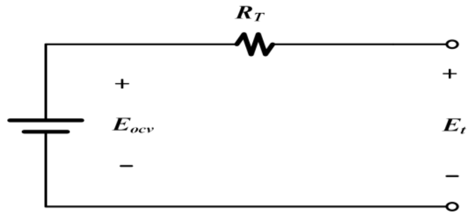


Figure 3:. Equivalent circuit model for CC Mode

Battery internal voltage (VOCV) and SoC have a linear relationship with each other, and the equivalent circuit for the estimation of internal voltage in CC charge can be used as a simplified model like figure 3. Infigure 2, battery internal equivalent resistance (RT) is the sum of resistance Ri and Rd in the simplified Randles Model infigure 2. Internal equivalent resistance in Figure 3 is the value of resistance of the direct component, and to estimate the battery internal voltage in the charging mode, the value of the internal voltage can be calculated by the detection of the voltage and current in the terminal just with the information on Rt. This study proposes a Level 2 CC mode technique to get the information on the battery resistance Rt value and the internal voltage value. In Level 2 CC mode, Rt of the voltage and current in each terminal is defined as follows:

$$R_T = \frac{V_1 - V_2}{I_1 - I_2} \quad (1)$$

Where, the battery internal voltage is defined like the below formula.

$$B_{OCV} = V_1 - RI_1 = V_2 - RI_2 \quad (2)$$

In Level 2 CC charging mode, Level 1 is the same as the existing CC charging, and Level 2 is a mode added to estimate the battery's parameter in real time. The duration of each mode should be longer than the time constant in figure 2.

2.3 Analysis of Battery Charging Method

To maintain the battery's original lifetime, the proper electric charge and discharge control is needed. Since there is a risk of explosion in battery overcharge, and its life comes to an end in excessive electric discharge, the proper protective function is required. Figure 4 shows a general curve of battery electric discharge characteristic. Electric discharge with a constant current, connecting a load to a completely charged battery rapidly decreases the voltage in the battery terminal at the beginning. This area is called exponential area. Later, voltage in the battery terminal slowly decreases, and this area is called nominal area. This area is the area where the battery actually operates. If there is no remaining battery capacity, voltage in the terminal rapidly declines. If more electric discharge progresses, and electric discharge is done below cut-off voltage, the battery's characteristic becomes poorer, and its life decreases.

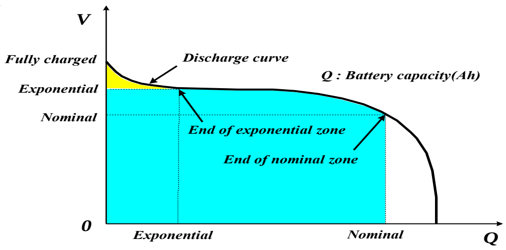


Figure 4: Characteristic curves of discharging batteries.

As shown in figure 5, CC-CV charge is used to prevent overcharge, while not having an adverse impact on the battery performance, and at the beginning of charging, the battery charging time is shortened by CC charge, while at the end of charging, the battery is charged, changing the mode from the CC charge mode to the CV charge mode to prevent the battery overcharge. The battery charging process generally goes through the following steps. In Step 1, the battery voltage is increased by CC charge. In this process, the battery is charged up to about 70%. In Step 2, the charging current slowly decreases as the battery becomes a saturated condition by CV charge. This is the general process in which most of the battery is charged. The voltage reaches the limit, and the current declines to below 3% of the rated current or remains level.

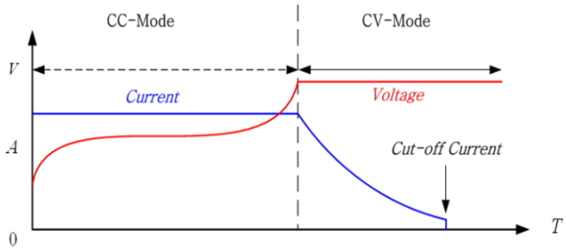


Figure 5:. Characteristic curves of CC-CV mode charging.

In contrast, CC charge is a charging method in which a battery is charged at a constant current from the beginning to the end of charging as shown in figure 6, and the time till the completion of charging differs depending on the set value of the charging current of CC charge, and if large CC is set, the time till the completion of charging is short, while if short CC is set, it becomes longer. A CC charging method can be classified into a general charging method and a high-speed charging method, and the general charging method charges a battery at a low current for a long time, which has a better charging efficiency than a high-speed charging method, and it is desirable to choose a charging current between 0.1[C] and 0.2[C] of the battery capacity (Ah). A high-speed charging method charges a battery at a high current in a short time, and it has a low charging efficiency and may damage the battery, so it is used only in limited cases[12, 13].

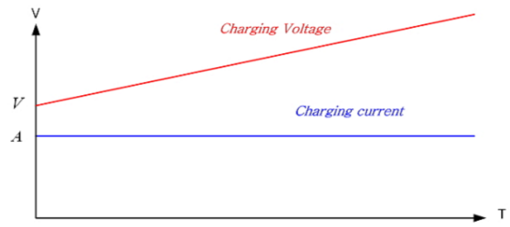


Figure 6:. Characteristic curves of CC mode charging.

2.4 Low Cost Charger Configuration

Figure 7 is an equivalent circuit of a series capacitor converter. It consists of a simple structure in which there is a capacitor connected to input voltage source in series, which flows through a rectifier. As for the characteristics of this serial capacitor converter, it is continued, and the current flows if the variable input voltage is larger than the battery voltage while there is a discontinuous section in which there is no continuity if the battery voltage is larger than the input voltage, like Figure 8.

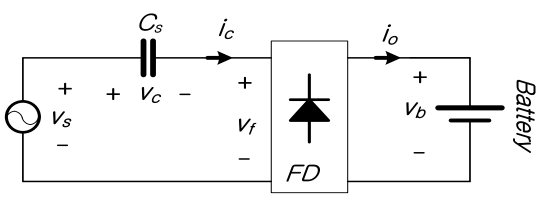


Figure 7: Battery charging circuit using a series capacitor

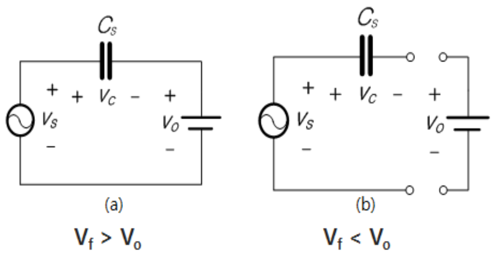


Figure 8: Characteristics between the input and battery voltages

Figure 9 is the output waveform of a serial capacitor battery charger. Mode 1 and mode 3 show the discontinuous section while Mode 2 and Mode 4 show the continuous section.

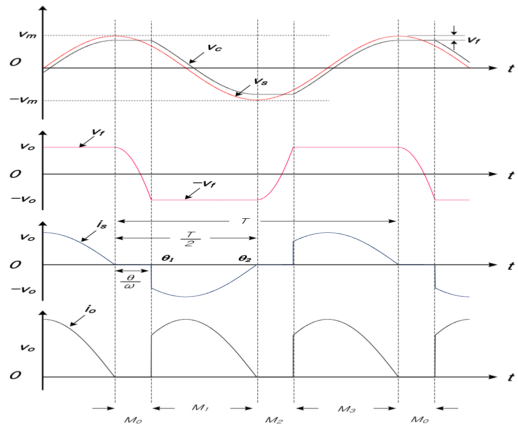


Figure 9: Characteristics waveforms of battery charger with a series capacitor

Voltage formula of [Figure 9] is like the below equation (3).

$$V_s = V_o + V_t = V_m \sin(\omega t) \quad (3)$$

Where, the current flowing from the input power to the battery through a series capacitor is like the below equation (4).

$$i_t = C_s \frac{dv_c}{dt} = C_s \frac{d(v_s - v_t)}{dt} \quad (4)$$

Bridge diode input voltageVt in the above formula is a positive or negative battery internal voltage according to the direction of current in the bridge diode, and since its derivative term becomes zero, the current flowing on a series capacitor can be defined as follows:

$$i_c = C_s \frac{dv_s}{dt} = \omega C_s \cos(\omega t)$$

(5)

The continued section of the bridge diode is determined by the peak value of the input voltage and the battery voltage (V_0) like the equation.

$$\theta_1 = \frac{1}{2T} - \sin\left(\frac{V_m - V_o}{V_m}\right) \quad (6)$$

$$\theta_2 = \frac{3}{4T}$$

The rated average current flowing in to the battery from equation (6) is as follows:

$$i_{rate_{ave}} = \frac{1}{T}\int_{\theta_1}^{\theta_2} \omega C_s V_m \cos(\omega t) \quad (7)$$

$$= \frac{2\omega C_s}{\pi}(V_m - V_0)$$

Thus, the capacitor's capacity can be calculated with the below formula if the voltage of the battery external terminal and the rated average current are given.

$$C_s = \frac{\pi i_{rateave}}{2\omega(V_m - V_0)} \quad (8)$$

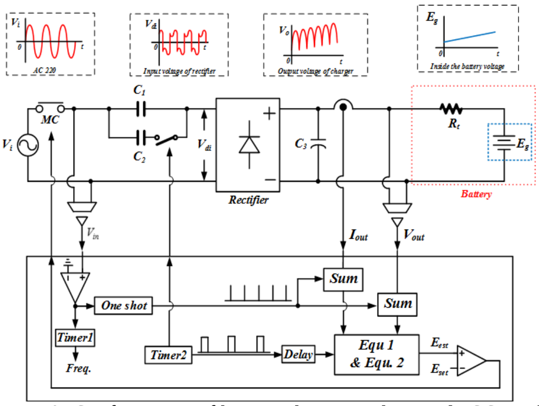


Figure 10: Configuration of battery charger with a single CC-mode

Figure 10shows a diagram of the proposed charger system with Level 2 single CC mode. As shown in the figure, measuring the grid null-voltage, the ripple of the voltage and current applied to the battery was removed, using a window filter, a Level 2 CC controller was composed, using Timer2, and by the delay function, the condenser's impact was removed when the level of current changed. In addition, if the battery internal voltage estimated by equation (1) and equation (2) and the set internal voltage are consistent, power was disconnected.

3. Simulation results

Figure 11 is a circuit diagram of the simulations to check the validity of the proposed method: Figure 11 (a) shows a low-price Level 2 CC charging device. [Figure 11](b) shows a battery equivalent circuit. Figure 11 (c) shows the interface part of the dll file for the implementation of the switching algorithm proposed in this study.

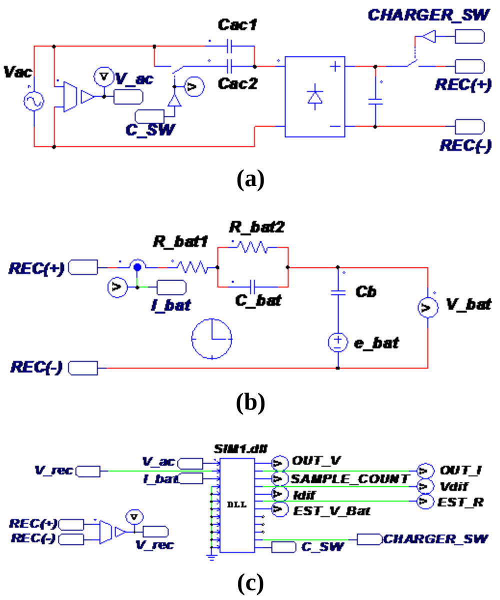
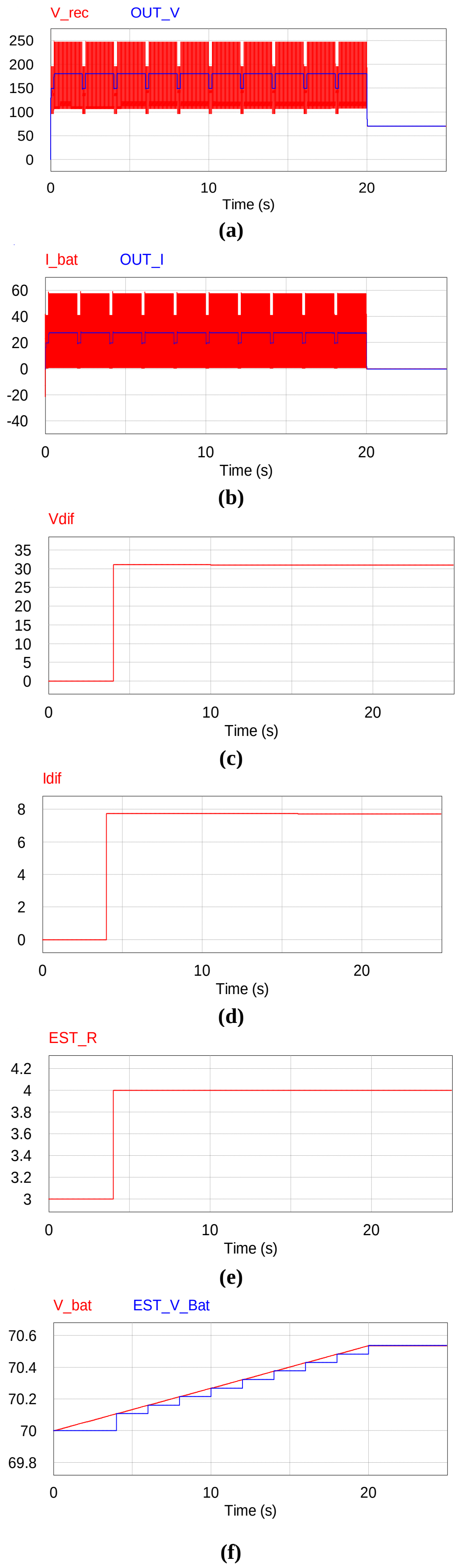
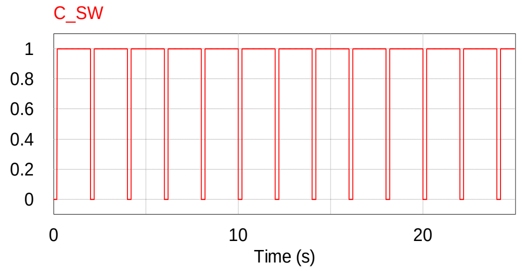


Figure 11: Simulation Circuits





(g)

Figure 12: Simulation Results

Figure 12 is the results of the simulations: figure 12 (a) shows the values of the voltage input to a battery terminal and the voltage that passed a window filter. Figure 12(b) shows the values of the current input to the battery terminal and the current that passed the window filter. Figure 12(c) shows the difference in the voltage input to the battery terminal in Level 2 CC mode. Figure 12(d) shows the difference in the current input to the battery terminal in Level 2 CC mode. Figure 12(e) is the estimated value of resistance, which is consistent with 4[Ω] actually set. Figure 12(f) is the battery internal voltage and the estimated voltage, and it is noted that they are estimated well upon each mode switch. figure 12(g) shows the mode change signal by a timer.

4. Conclusion

The representative battery charging method is the CC-CV charging method, which charges the battery in CC mode in early charging to shorten the battery charging time and charges it in CV mode to prevent battery overcharge in the end of charging. CV charge operates when there is a little difference between supply voltage and battery voltage and can charge over 95%, since the battery is continuously charged by the current determined by supply voltage, battery voltage and battery internal impedance. However, CV charge has a weakness that it takes much time to charge the battery fully since there is little electricity supplied to it. This paper proposed an algorithm for charging a battery only with the single CC charging method, based on the simplified equivalent necessary for CC charge for efficient charging when the battery is used as a means of energy storage. In paper addition, this verified its validity through simulations using a low-price charging device.

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