

A NEW STATE-OF-CHARGE ESTIMATION METHOD FOR VALVE REGULATED LEAD ACID BATTERIES

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Abstract

In this paper, a new improved coulomb counting method is proposed to estimate the State-of-Charge (SOC) of a 12V valve regulated lead acid (VRLA) battery. The conventional coulomb counting method estimates the SOC with a high error rate for high discharge current. Experimental results show the error in the conventional SOC estimation is as high as 16% for higher discharge currents. This error in the SOC estimation is due to the underestimation of the battery capacity. To compensate this error, a new charging coefficient is proposed. The inclusion of this charging coefficient could accurately estimate the SOC of the battery during the charging process.

Keywords: State-of-charge, Lead acid battery, Charging coefficient, Coulomb counting.

1. Introduction

To ensure the reliability of a battery, the state of charge (SOC) of the battery is an important parameter because it relates to the remaining run time of the system when there are main power outages. Over the years, many methods are developed in determining the SOC accurately. Coulomb counting is the most common method as compared to other methods [1-8]. This method works by measuring and summing the current that is flowing in or out of the battery. The main advantage of this method is that the current measurement can be measured on-line; therefore, the SOC can be updated in real time. However, this method requires the initial capacity to be known before the SOC can be determined. Furthermore, calibration needs to be performed regularly to reduce large cumulative errors. Therefore, this method is often used with open circuit voltage (OCV) method because the OCV method can be used to calibrate the SOC value

Nomenclatures

C	Rate capacity at 20-hours discharge rate
C_a	Battery capacity when discharged at constant rate to 1.75V/cell
k_{chr}	Charging loss coefficient
k_{dc}	Product of k_{ev} and k_{dis}
$k_{dis}(i)$	Loss coefficient at current i
k_{eff_chr}	Charging coefficient
k_{ev}	Ratio of C to C_a
t_a	Time to discharge to end-of-discharge voltage, s
t_b	Time to discharge to recommended end-of-discharge voltage, s

Abbreviations

AGM	Absorbed Glass Matt
EV	Electrical Vehicle
HEV	Hybrid Eclectic Vehicle
OCV	Open Circuit Voltage
sbRIO	single-board reconfigurable input-output
SOC	State of Charge
VRLA	Valve Regulated Lead Acid

or to generate an initial capacity value provided that sufficient rest period is allowed [1, 3, 5-7]. Apart from the cumulative error, this method also needs to account for the losses when charging and discharging the battery. This is because the battery capacity reduces at a higher discharge current and not all current is accepted by the battery during charging.

In this paper, a new improved coulomb counting method is proposed to estimate the State-of-Charge (SOC) of a 12V valve regulated lead acid (VRLA) battery. The proposed method is useful for backup supply, electrical vehicle (EV), hybrid electric vehicle (HEV) and renewable energy system which the batteries always experience irregular charging and discharging current. The conventional coulomb counting method [2, 6] estimates the SOC with a high error rate for high discharge current. To compensate this error, a new charging coefficient is proposed. The monitoring of the status of the battery and data acquisition are performed by using NI Reconfigurable single-board RIO platform (sbRIO) and under LabVIEW development environment. Charge and discharge tests are conducted to test the performance of the proposed method in estimating the SOC of a 12V VRLA battery.

2. State-of-Charge Estimation

In this paper, a Yuasa NP1.2-12 VRLA AGM battery is used. VRLA AGM battery is chosen because it is commonly found in the backup power supply systems as compared to VLA batteries. Yuasa NP1.2-12 is a 12V VRLA battery rated at 1.2 Ah when discharged at 0.05C (0.06 A) for 20 hours [9]. The method of SOC estimation during discharge is based on Coulomb counting [2] which requires information from the battery discharge characteristics. The discharge characteristic of the battery used is shown in Fig. 1. The magnitude of the

discharge current is normally denoted in terms of C rate where “C” is the rated capacity of the battery. Therefore, discharge rate of 0.05C for a 1.2Ah rated battery refers to $(0.05 \times 1.2) \text{ A} = 0.06 \text{ A}$. The dotted line represents the recommended end of discharge voltage for different discharge rates. It is shown that the battery could discharge to a lower voltage at higher discharge rates.

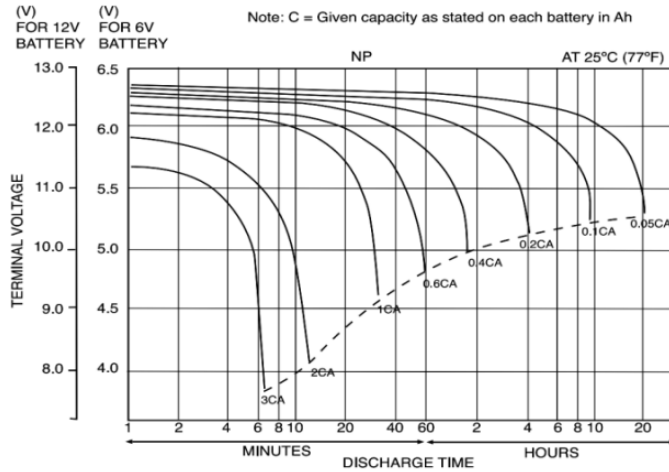


Fig. 1. Discharge characteristic of Yuasa NP series VRLA battery [7].

Generally, manufacturers rate the VRLA battery at 0.05C discharge rate. However, the actual capacity of the battery decreases as the magnitude of the discharge rate increases. If the battery is connected to a variable load which is the usually the case, the SOC estimation would generate a large error by simply assuming that the battery capacity is constant. Therefore, the SOC estimation needs to account for capacity loss due to higher discharge rates. Hence, a loss coefficient which is dependent on the magnitude of the discharge rate has to be employed during current integration.

In order to estimate the SOC, the initial capacity of the battery has to be known. In this paper, it is assumed that the battery is new and given a full recharge before integrated into the system. Therefore, the initial capacity of the battery is similar to the rated capacity. The SOC of the battery can be determined by using Eq. (1). The used battery capacity at time t is expressed in Eq. (2).

$$SOC(t) = \frac{\text{Initial Capacity at } t_0 + C(t)}{\text{Rated capacity}} \times 100\% \tag{1}$$

$$C(t) = \int_{t_0}^t k_{dis}(i) \cdot i \cdot dt \tag{2}$$

where C is the rated capacity at 20-hour discharge rate, i is the discharge current and $k_{dis}(i)$ is the loss coefficient at current i . The loss coefficient, $k_{dis}(i)$ can be determined using battery datasheets. Usually, the required time to discharge the battery down to 1.75V/cell for different constant discharge rate is shown.

Therefore, assuming the end of discharge voltage is 1.75V/cell (10.5V for 12V battery) for different constant discharge rate, the capacity of the battery can be expressed as

$$C_a = \int_{t_0}^{t_a} k_{dis}(i) \cdot i \cdot dt \tag{3}$$

where C_a is the battery capacity when discharged at a constant rate to 1.75V/cell and t_a is the required time to discharge the battery to 1.75V/cell at constant discharge rate. Since the i is constant for a given discharge current, Eq. (3) can be expressed as

$$k_{dis}(i) = \frac{C_a}{i \cdot t_a} \tag{4}$$

It is known that a battery could discharge to lower voltage for higher discharge rate. Therefore, the battery capacity now is expressed as

$$C(t) = C_a + \int_{t_a}^{t_b} k_{dis}(i) \cdot i \cdot dt \tag{5}$$

where t_b is the required time to discharge battery to the recommended end of discharge voltage. By referring to the battery discharge characteristic in Fig. 1, the ratio of C to C_a , C/C_a can be determined for the given constant discharge rate.

Another coefficient, which is k_{ev} is used to denote C/C_a . The relationship between C to C_a can be calculated by using Eq. (6) and is applicable for VRLA batteries from different manufacturers with negligible variation [2].

$$k_{ev}(i) = \frac{C}{C_a} = \begin{cases} 1, & \text{for } q \leq 0.17 \\ (5.05 \ln(q - 16) + 100)/100, & \text{for } q \geq 0.17 \end{cases} \tag{6}$$

where $q = i/C$.

From Eq. (6),

$$C_a = \frac{C}{k_{ev}(i)} \tag{7}$$

Substituting Eq. (7) into Eq. (4),

$$k_{dis}(i) = \frac{C}{k_{ev}(i) \cdot i \cdot t_a} \tag{8}$$

Let $k_{dc}(i)$ denotes $\frac{C}{i \cdot t_a}$,

$$k_{dis}(i) = \frac{k_{dc}(i)}{k_{ev}(i)} \tag{9}$$

where C is known, i and t_a can be obtained from the datasheet, and $k_{dc}(i)$ can be determined. In this paper, the coefficient of $k_{dc}(i)$ is predetermined by requesting user to enter the constant discharge currents and respective discharge durations of 0.5, 1, 3, 5, 8, 10 and 20 hours to reach 1.75V/cell. After the system acquires the data, polynomial curve fitting can be performed. The data of the battery is acquired from [11]. The polynomial curve fitting for the data of the battery is shown in Fig. 2 and the resultant polynomial equation is shown in Eq. (10). It is

determined that the polynomial order of 3 is best to represent the relationship between k_{dc} and discharge current.

$$k_{dc}(i) = 0.3608i^3 - 1.2360i^2 + 1.95375i + 0.9217 \quad (10)$$

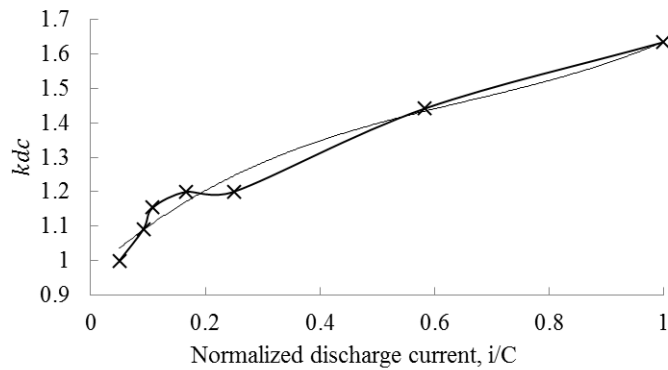


Fig. 2. Polynomial curve fitting for k_{dc} and normalized discharge current.

3. Proposed State-of-Charge (SOC) Estimation

The SOC estimation during charging uses Coulomb counting method and uses the same equation as Eq. (1). However, the coefficient during charging is constant. The charging coefficient is determined to be 0.95 which is also used in [4]. The charged capacity is expressed as

$$C(t) = \int_{t_0}^t k_{chr} \cdot i dt \quad (11)$$

where k_{chr} is the charging loss coefficient.

Due to the underestimation of battery capacities, high error rate is usually observed in the SOC estimation for high discharge currents. In this paper, we propose to correct this error by introducing a charging coefficient. The charging coefficient can be determined by tracking the actual discharged capacity and effectively discharged capacity. Therefore, when the battery recharges, the effective discharged capacity is being charged and the SOC update can be reflected accordingly. Taking the charging loss coefficient of Eq. (11) into account, the charging coefficient $k_{eff_chr}(i)$ can be determined using Eq. (12). By including the charging coefficient into the current integration, the SOC of the battery can be updated correctly.

$$k_{eff_chr}(i) = \frac{\text{Effectively discharged capacity (mAh)}}{\text{Actual discharged capacity (mAh)}} \times k_{chr} \quad (12)$$

4. Experimental Setup

Figure 3 represents practical situation whereby the charger is always connected to the battery and the load in parallel. In normal operation, the charger always charges the battery and supplies the load at the same time. In case of power outage, the battery will supply the load. The National Instruments (NI) single-board reconfigurable input-output (sbRIO) development board measures the

operational parameters of the battery by using DS 2438 smart battery monitoring sensor and displays the measurements on the host machine. The relays are driven by the sbRIO development board to control the operation of the battery such as charging, discharging and so on. The electronic load is used to simulate the load current profile to test the battery at different discharge rates.

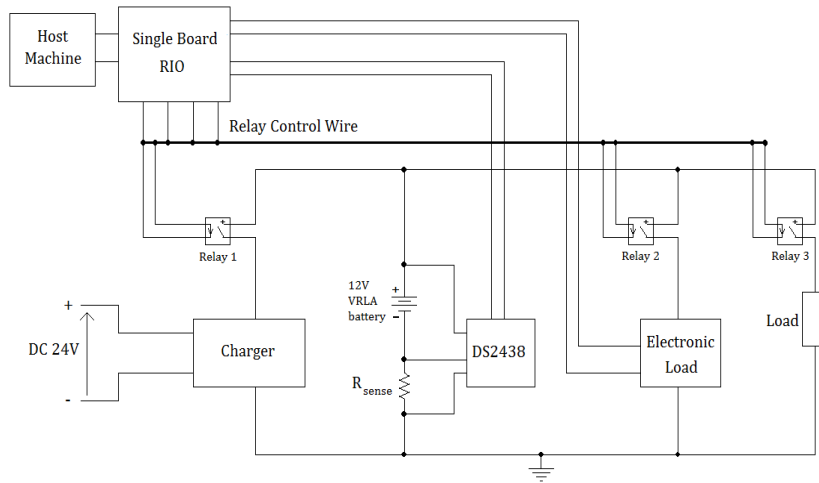


Fig. 3. Hardware block diagram.

5. Result and Discussion

A reference point is required to compare the results of the SOC estimation. It can be obtained by acquiring the relationship between the SOC and the battery open circuit voltage (OCV). It is known that the battery OCV has a linear relationship with the SOC of the battery. From the capacity test, the capacity of the battery is 1400mAh. Therefore, two points are required to determine the linear relationship between the SOC and the OCV: when the battery is fully charged and when battery is fully discharged. The OCV is obtained after the battery has been put to rest for approximately 12 hours. The OCV of the battery is 13.18V when fully charged. The OCV is 11.8V when the battery is fully discharged. Figure 4 shows the obtained OCV and SOC results.

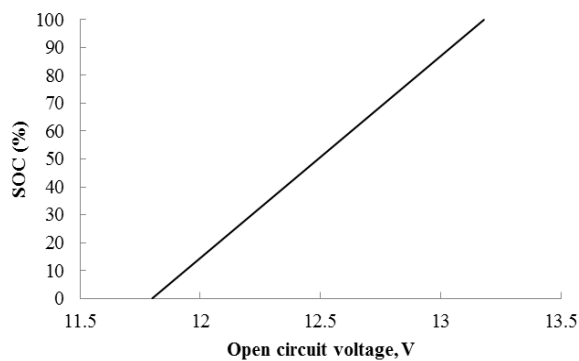


Fig. 4. Battery SOC against OCV.

From Fig. 4, the linear line determines the relationship between the SOC and the OCV of the battery. Therefore, a linear curve fitting is performed and Eq. (13) shows the resultant linear curve fit equation.

$$SOC(\%) = 72.464V_{OCV} - 855.07 \quad (13)$$

According to Fig. 1, the level of discharge rate affects the capacity loss of the battery. The accuracy of the SOC estimation is determined by conducting a number of discharge tests. Table 1 shows the discharge test results. After testing the battery, the OCV of the battery is measured after 2 hours instead of a longer duration because it is determined that the battery voltage does not change significantly after 2 hours. When the battery is fully discharged under constant discharge current, the error of the SOC estimation is within 6% for -0.36A and -0.2A discharge current. At higher discharge currents, such as -0.72A, the error in SOC estimation increases to 13.04%. By looking at the partial battery discharge, a similar outcome is observed. When the battery is partially discharged at -0.25A for 2 hours, the error in SOC estimation is small at 1.19%. As the discharge current increases to -0.5A and -0.72A, the error in estimation increases to 3.71% and 5.38% with the measured SOC values being similar. Therefore, it is observed that the error in SOC estimation increases as the magnitude of the discharge current increases. It is believed that there are two factors contributing to this error in SOC estimation. The first factor is, after discharging a VRLA battery and putting it at rest, the battery can be discharged further due to the recovery (hydration) of active centers in the electrodes as explained by Pavlov [12] and determined experimentally by Doerffel and Abu Sharkh [13]. Therefore, the battery can actually be discharged further if the battery was discharged at a higher current and allowed to rest. The second factor could be the battery's discharge coefficient used is not accurate for the battery.

Table 1. Summary of the SOC estimation test results under various discharge conditions.

Discharge Test	Battery OCV (V)	SOC from OCV (%)	SOC measured (%)	Absolute error (%)
Constant current discharge at -0.2A	11.88	5.80	0	5.80
Constant current discharge at -0.36A	11.86	4.35	0	4.35
Constant current discharge at -0.72A	11.98	13.04	0	13.04
Partial discharge at -0.25A for 2 hours	11.58	56.53	57.72	1.19
Partial discharge at -0.5A for 45 minutes	12.74	68.12	64.41	3.71
Partial discharge at -0.72A for 30 minutes	12.74	68.12	62.74	5.38
Pulse discharge test at -0.72A	12.36	40.59	25.51	15.08
Pulse discharge test at -1.2A	12.7	65.22	53.49	11.73
Variable discharge 1	11.94	10.15	0	10.15
Variable discharge 2	12.02	15.95	0	15.95
DC motor fan discharge	11.94	10.15	0	10.15

In [13], the coefficient, $k_{ev}(i)$, is assumed to be applicable for VRLA batteries of different capacities and made by different manufacturers. The current discharge coefficient is expressed as, $k_{dis}(i) = k_{dc}(i) / k_{ev}(i)$, where the $k_{ev}(i)$ could be

underestimated as the SOC determined from the battery OCV is always higher than the SOC measured.

The SOC of the battery during charging can be corrected by introducing a charging coefficient. The charging coefficient can be determined by tracking the actual discharged capacity and effective discharged capacity. Therefore, when the battery recharges, the effective discharged capacity is being charged and the SOC update can be reflected accordingly. Taking the charging loss coefficient into account, the charging coefficient $k_{eff_chr}(i)$ can be determined using equation Eq. (12). By including the charging coefficient into the current integration, the SOC of the battery can be updated correctly as shown in Figs. 5 and 6 (black coloured curves).

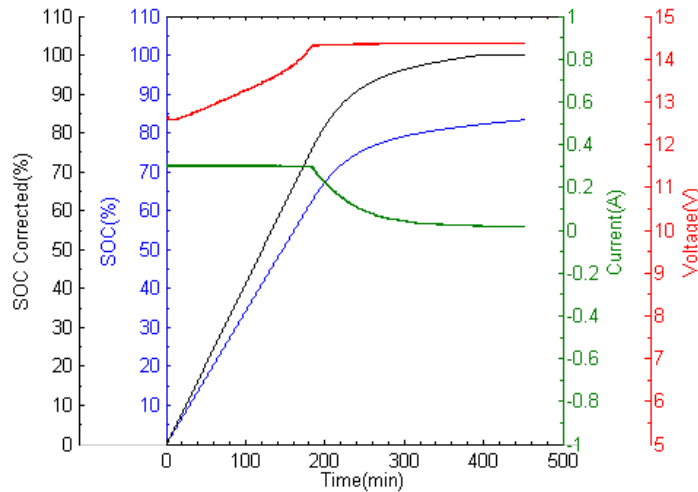


Fig. 5. Charge test after the battery is fully discharged at -0.2A.

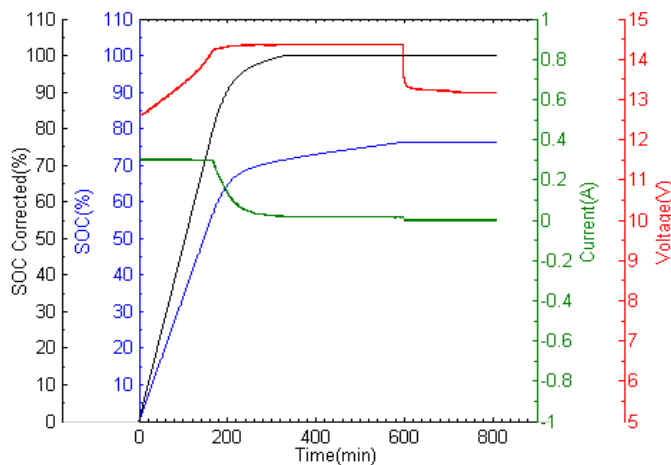


Fig. 6. Charge test after the battery is fully discharged at -0.72A.

The battery is charged using the battery charger with the charging voltage set to 14.4V and maximum current of 0.3A. When the battery is recharged after being fully discharged as shown in Figs. 5 and 6, the SOC of the battery does not recover to 100% even though the battery is fully charged. When a battery is fully charged, the battery voltage approaches the charger voltage and the charging current will decrease. IEEE standard [14] describes that when the charging current decreases and does not change significantly after three consecutive hours, the battery is near fully charged. From Fig. 5, the SOC of the battery should be 100% at 400 minutes since the charging current is decreased to a fairly constant value. On the other hand, the SOC of the battery in Fig. 6 should be 100% at approximately 380 minutes judging from the charging current. Since the SOC estimation during the discharge includes a coefficient in the current integration, the effective amount of capacity discharged under -0.2A for 5.365 hours is 1400mAh while the actual amount of capacity discharged is $5.4\text{ hours} \times 0.2\text{A} = 1080\text{mAh}$. When the battery is recharged, the SOC of the battery only reaches approximately 83% which means that the discharged capacity is only $83\% \times 1400\text{mAh} = 1162\text{mAh}$. Therefore, it appears that the battery only accepts charges up to its actual discharged capacity. A similar situation happens when the battery is fully discharged at -0.72A till 0% which takes 1.388 hours. The actual capacity discharged is $1.388\text{ hours} \times 0.72\text{A} = 1000\text{mAh}$ and the battery only recharges back up to approximately 74% (1036mAh).

After including the charging coefficient, the battery is tested for two different charging scenarios as shown in Figs. 7 and 8. Figure 7 shows that the battery is found to be charged up to 92% and the OCV after 2 hours is 13.14V. With this, the SOC according to Eq. (12) is 97.1%. Therefore, the error is calculated to be approximately 5.1%. In Fig. 8, the battery is charged up to 100% after pulse discharge, the OCV of the battery after 2 hours is 13.18V which represents 100% SOC. Therefore, there is no error in SOC estimation. After that, the battery is tested for alternate charge and discharge cycles as shown in Fig. 9. The measured SOC of the battery after alternate charge and discharge is 100%. The OCV of the battery is 13.18V after two hours which represents 100% SOC. Again, there is no error in SOC estimation. Therefore, the SOC estimation during charge is accurate regardless of the error in the SOC estimation during the discharge.

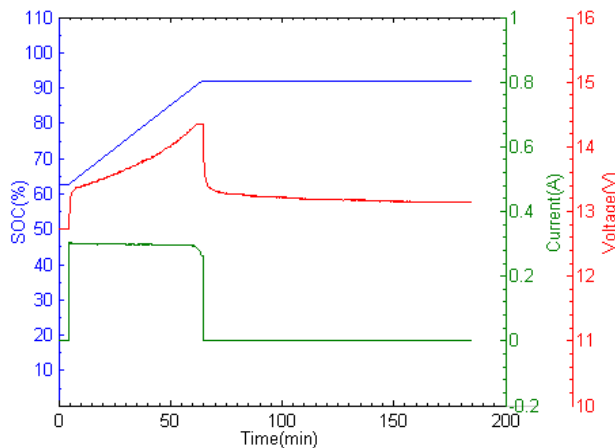


Fig. 7. Partial charge test after the battery is partially discharged at -0.72A (with correction factor).

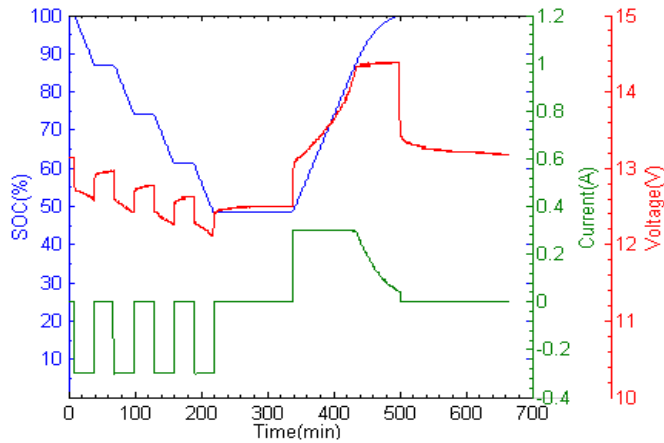


Fig. 8. Charge test after pulse discharge the battery at -0.3A for four pulses.

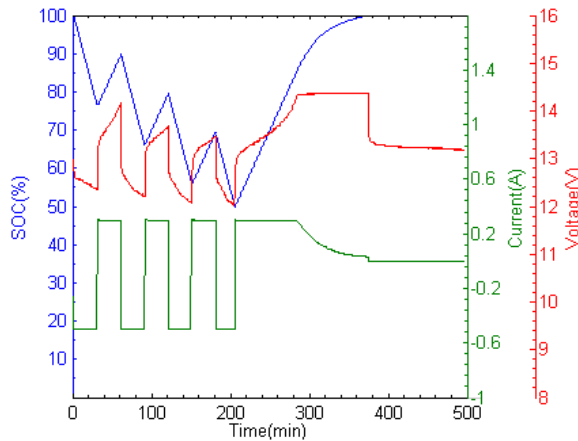


Fig. 9. Alternate charge and discharge test.

Lastly, the battery is tested for real world situations where the battery is connected to the charger and the load in parallel. Figure 10 shows that the charger is charging the battery and at the same time, supplying power to the load. After that, a power outage happens and the battery is used to supply to the load instead. After approximately 2.5 hours, the main power source recovers and we can see that the battery is being charged back up to 100%. Once the battery reaches 100%, the battery is disconnected from the charger and the load to measure the OCV. The OCV of the battery is 13.18V after two hours which represents SOC of 100%. Figure 11 shows another test whereby the power outages happen more frequently. It is shown that the battery is recharged back to 100% after the main power source is recovered and stable. The OCV of the battery is 13.18V which again represents 100% SOC.

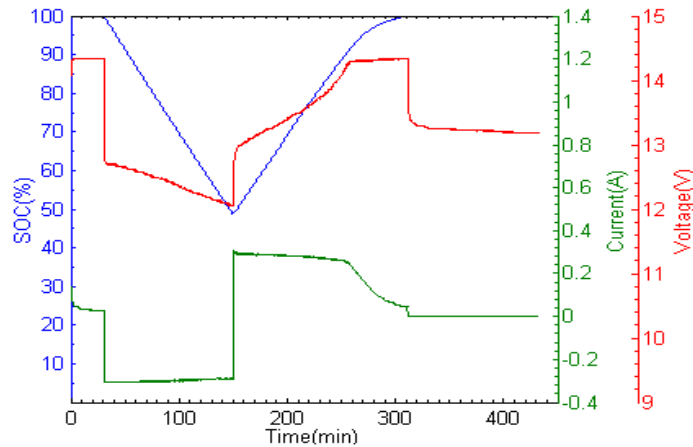


Fig. 10. Simulated battery operating condition where an outage occurred in the main power source followed by a recovery.

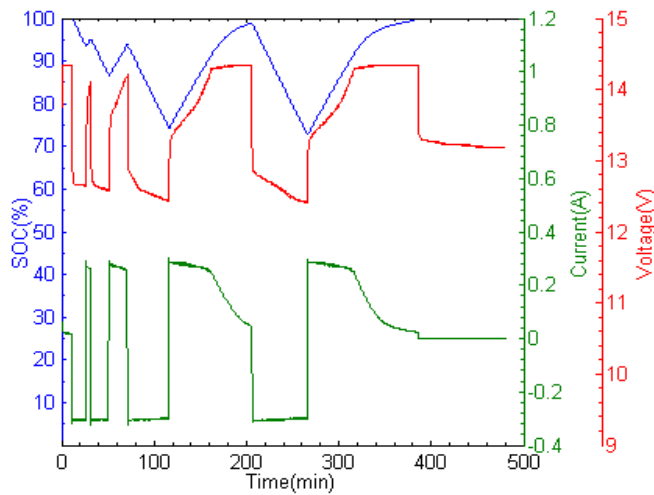


Fig. 11. Simulated battery operating condition where there are frequent outages in the main power source.

6. Conclusion

Due to the underestimation of battery capacities, high error rate is usually observed in the coulomb counting SOC estimation for high discharge currents. Therefore, a new charging coefficient is proposed to compensate this error. Experimental results show that SOC estimation upon discharging with a maximum error of 16% is achieved. It is observed that the battery charges up to actual discharged capacity instead of effective discharged capacity. After a new charging coefficient is integrated with the Coulomb counting, experimental results show that the SOC estimation accuracy during the battery charging process is improved when the charging coefficient is used.

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