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Battery State of Charge Estimation Based on Internal Resistance and Recovery Effect Analysis

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ABSTRACT

State of Charge (SoC) is a parameter used to determine the current capacity on a battery as well as indicate the operational characteristics. The SoC is an important parameter for optimizing battery utilization in many applications requiring DC current source. However, estimating the SoC value is the major problem since it cannot be measured directly. In this study, we proposed SoC measurement method based on analysis internal resistance of battery. The internal resistance is correlated with the parameters of the magnitude of the terminal voltage and open circuit. Both voltages come from the influence of current during the charging-discharging process. We report that the proposed method has successfully obtained the correlation between the SoC and the internal resistance value for two process, which are the charging- and discharging process.

1. INTRODUCTION

A battery collects electrochemical cells that store and converts chemical energy into electrical energy, which Alessandro Volta first discovered in 1800 [1]. The application of rechargeable batteries continues to increase for electric vehicles, household furniture, satellites, electric equipment, to renewable energy storage, for that, an accurate estimate of battery management is efficient, and reliable [2]. The SoC is an essential parameter for estimating the remaining battery capacity and is necessary to improve security and performance in battery usage and extend battery lifetime or efficient utilization.

In simple terms, the Coulomb counting technique is the integration of battery current that flows over time. This method requires accurate current measurement; therefore, the estimation results are influenced by the accuracy of the current sensor, especially measurement drift, which will produce a cumulative effect [3],[4]

With advances in computer technology and several machine learning tools, SoC estimation can be performed using several measurable parameters as input, such as battery voltage, temperature, current and so on, to produce accurate SoC estimates [3].

However, the SoC cannot be measured directly because the open stress curve has a flatness and hysteresis effect [4]-[6]. Generally, there are two primary methods used to estimate the SoC value of a battery. The first is the direct measurement method referring to several physical properties of the battery such as terminal voltage, current, and temperature. This method directly measures the battery to estimate the SoC based on its intrinsic characteristics, which naturally decrease proportionally to its energy loss.

Two types of direct measurement methods can be used. The first is the V_{OC} method, which is the battery contains no current to or from the battery. This voltage is linearly correlated with SoC, although it only occurs in lead acid batteries

Because the relationship between V_{OC} and SoC differs between battery types [7], [8]. There is a phenomenon where the V_{OC} of the battery will slowly change shortly after the charging or discharging process. This recovery occurs because of a chemical reaction in the form of a diffusion process that compensates for the consumption or charging of the active material [9]-[12].

The second method is to take the value of VT when the battery is charged and discharged which changes due to the characteristics of the internal impedance. So the value of V_{OC} is proportional to the value of VT. And since the battery V_{OC} is directly proportional to the SoC, the battery VT is also estimated to be directly proportional to the SoC.

The battery's internal resistance parameter is defined as the resistance to current flow in the battery. Two basic components affect a battery's internal resistance: namely ohmic resistance and ionic resistance. Both are referred to as the total effective internal resistance [13]. Ohmic resistance also includes the resistivity of battery components such as the anode and cathode active materials, current collectors, and electrolytes. The internal resistance is affected by material contact such as, between the current collector

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and the active material, the electrode geometry, and the internal construction. The effect of these parts occurs very quickly and can be seen during the first at the earliest change after the battery is discharged or recharged [10]-[14]. The measurement of the internal resistance of a battery is difficult, which represents an example of a non-linear and time-dependent system. The internal resistance is also the main parameter to determine the power, energy efficiency, and heat loss of the battery cells.

The internal resistance of a battery cell can be determined by electrochemical impedance spectroscopy, alternating current methods and heat loss methods. Under the high current, the internal resistance determines the battery heat increment and energy efficiency. Therefore, in-depth knowledge of internal resistance is required to design a particular application [14].

The main problem for estimating the SoC value is due to a chemical process (diffusion) in the battery, resulting in the nonlinearity of battery charge, especially after being discharged or charged. This results in a continuous battery voltage recovery event to achieve a stable voltage equilibrium). The recovery voltage is the open-circuit voltage $V_{OC,}$ where the battery's current during that time is 0 (zero). Therefore, this paper proposes a method for measuring the SoC. The method uses coulomb counting to analyze SoC and battery's internal resistance from the direct experiment. The acquisition of terminal voltage and open voltage through direct measurements in the experiment and adapt them to obtain the battery's internal resistance value. This paper also describes V_{OC}, V_T, Recovery Effect, and the relationship between these parameters based on the measurement results. Hence, the SoC estimation calculation is performed based on the results of the experiment.

2. THE PARAMETERS TO ESTIMATE THE SoC

Several intrinsic parameters are used to estimate the value of SoC. The SoC value of the battery at any time is divided into four states: before the battery is operated (the battery is not loaded), when the battery is operated (the battery is loaded), when the battery is charging, and when the battery is resting again.

2.1. Open Circuit Voltage

The open-circuit voltage is expressed when the battery is in an open state where the voltage changes less than 0.5 mV/cell for 2 hours [15]. Thus, the battery SoC can be describe as follows:

$$\text{SoC} = 1 - \frac{a - V_{oc}}{a - b} \qquad (1)$$

Where a is an open circuit voltage when the SoC is full, and b is the open-circuit voltage when the battery is fully discharged [15].

The V_{OC} parameter is technically a function of the battery's internal stable SoC. To achieve this state, the battery must be idle for a long time before taking measurements. The V_{OC} method is a simple and easy-to-implement method. The SoC estimates at the end and the beginning of the charge and discharge stages are effective, but the battery has to be directly tested for a while. This approach is used to estimate the battery charging efficiency in the laboratory and the accuracy of SoC estimation [16], [17]. Many factors affect the estimation results of V_{OC}, so V_{OC} is not the only parameter for estimating SoC. although in general the accurate V_{OC} reflects the SoC [18].

The disadvantage of the direct V_{OC} measurement is the dynamic behavior caused by the overvoltage. A break of five hours or more is required to get the true value of V_{OC}. The improved method predicts Voc by interpolating the voltage curve [19], which yields good results after 5-10 min. Battery V_{OC} naturally decreases in proportion to energy release and is widely used for SoC indication. The application of the existing SoC determines the method that can be limited to certain types of batteries.

2.2 Battery Load Mode

There are three modes of battery load during discharging [20];

- Load mode with a fixed resistance carries current due to the load with a constant resistance value.
- Constant current load mode, the battery discharge current is kept constant during the loading period. The decrease in the value of the load resistance follows the decrease in the value of the voltage according to Ohm's law.
- Load mode with constant power, as the load is applied to the battery, when the battery voltage will decrease then the current output will increase. to keep the load power constant

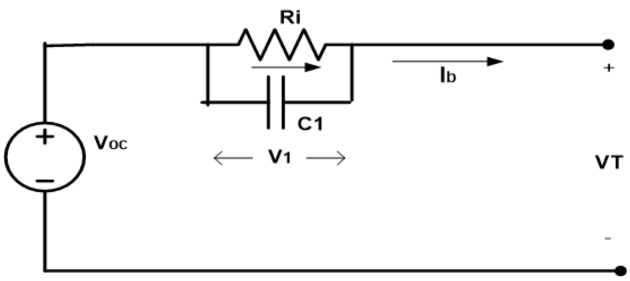


Fig. 1. First-order battery model.

A load with a constant resistance will carry current at a fixed resistance value so that the current value will change with a decrement in battery voltage. The decrement in the current rate is proportional to the decline in the battery voltage rate. While the constant current load flows, a constant current until the battery drop voltage is reached. In this case, the battery cut-off voltage according to the datasheet is 9.6 – 10.8 V. The V_{OC} was obtained from the charge and discharge experiments. The dynamic behavior pattern of the battery is shown in Equation (2) [21], [22].

$$V_{OC} = V_T + V_1 \tag{2}$$

where,

V_{OC} Open circuit voltage,
V_T Terminal voltage;
I_b Battery current;
V_1 the voltage along with the R_1C_1 as branch time constant component.

The equation for the current value in a parallel RC network is written as follows [23],

$$I_b = C_1 \frac{dV_1}{d_t}, \tag{3}$$

while the value of SoC at any time is expressed by,

$$SoC_{(t)} = SoC_0 + \Delta SoC \tag{4}$$

$$SoC_{(t)} = SoC_0 + \frac{-\int_{t_0}^{t} I_{b(t)dt}}{Q_o} \text{ x } 100 \tag{5}$$

$$r_{in}(t) = \frac{V_{oc}(\text{t}) - V_T(\text{t})}{i(\text{t})} \tag{6}$$

SoC_0 is the SoC of the battery at the beginning measurement, which is the ratio of the initial state of the battery charge to the nominal battery charge. In an application, the SoC_0 changes all the time based on the battery's current capacity. For this reason, an accurate estimate is needed in determining the size of the SoC_0.

SoC_0 the first time after the charging or discharging process is the last SoC condition from the previous state. Of course, there must be an algorithm that continues to calculate the last SoC value of the two processes. This can be done by utilizing the memory system in the battery circuit. The SoC is theoretically a function of the long-rested V_{OC} voltage of the battery.

The first-order battery model is a basic circuit for measuring the open-circuit voltage and then finding the SoC value. The advantage is that the V_{OC} is accurate and reliable at the end of a battery charge or discharge operation.

However, there are two disadvantages that are strongly influenced by the presence of voltage stability. First, because the self-recovery effect will make achieving a stable voltage take a long time, especially if the SoC value is high. secondly there is no set target time to reach a stable voltage [24], [25].

3. SETUP OF EXPERIMENT

The experiment was carried out at room temperature 30° C - 32°C, using a new 12V, 100 Ah lead-acid VRLA battery. With the threshold voltage is 12.7V. The charging and discharging test are taken with a constant current 4.5 A. Between charging and discharging for one hour, the current is made to 0 (I_L and I_{ch} = 0) for 15 minutes to see the Voc curve at any time.

Data acquisition using LabVIEW software which is connected to the National Instrument module NI9206 device with a USB *CompactDAQ* interface, where the specifications can be stated as follows,

- DC coupling input,
- Nominal input ranges ±10 V, ±5 V, ±1 V, ±0.2 V,
- Minimum overrange (for 10 V range) 4%.

The load used is an electronic load with a current range of 0-20A DC. And a timer switch to connect/disconnect current, to the load and power supply. The experimental diagram for data collection is shown in Figure 2. Battery loading and charging are cared out alternately. However, the timer switch is still used to get the recovery effect value when discharging or charging the battery.

The voltage curve when discharging process with a constant current is shown in Figure 4. where the circuit is closed for 1 hour and then released for 15 minutes until the battery experiences depletion which is indicated by the voltage drop to 6V. At this point, the battery could still discharge the same 4.5 A for the next few minutes and finally drop to its lowest point. Further, the battery that has been discharged is then recharged with a constant initial current until the threshold voltage of 12.7 V is reached

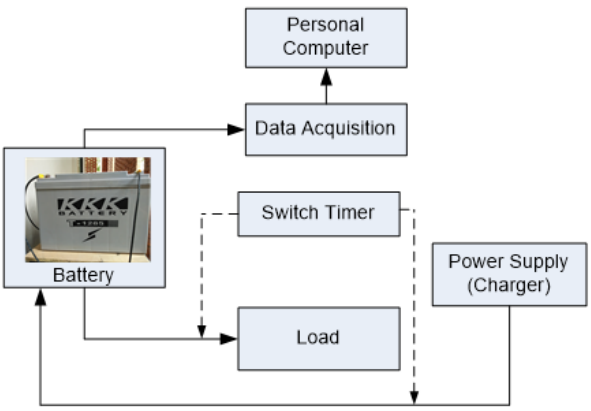


Fig. 2. Diagram of experimental setup.

3.1 Discharging Mode

The terminal voltage V_T of the battery in this case is when there is a current flow into or delivery from the battery (i_L or $i_{ch} \neq 0$). While the open-circuit voltage V_{OC} is when no current flows from/to the battery (i_L or I_{ch} = 0).

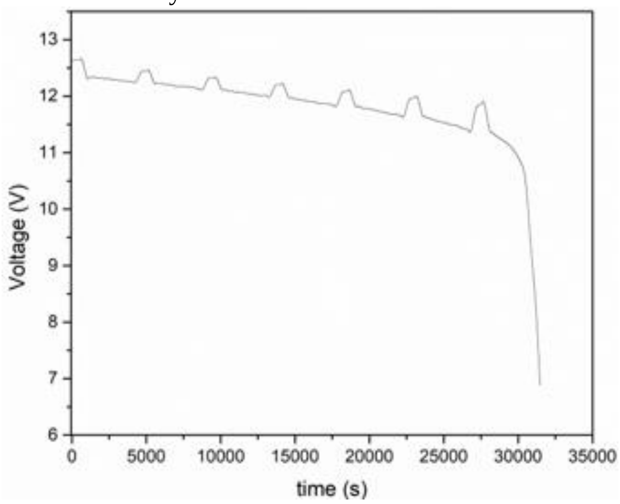
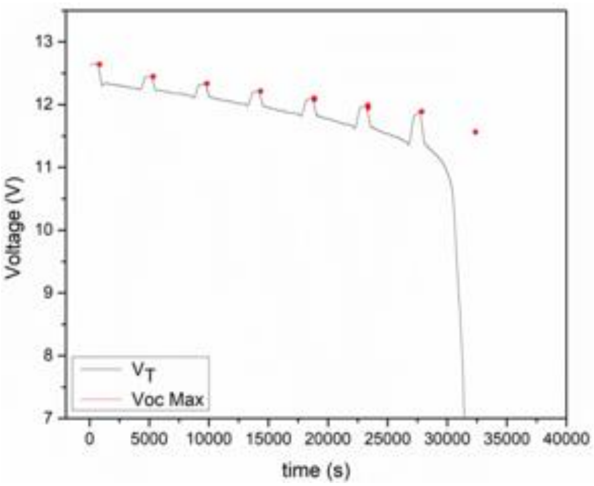
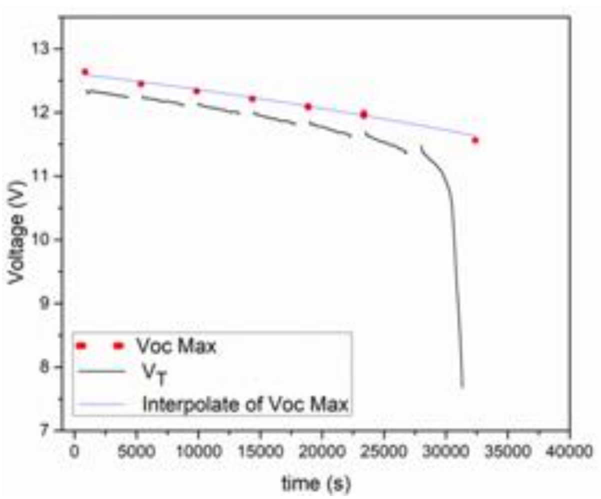


Fig. 3. Typical discharge model 4.5 A constant current profile.



(a)



(b)

Fig. 4. Profile V_{OC} and V_T (a) Terminal voltage change(b) The interpolation of V_{OC} maximum.

The load circuit released every 15 minutes shows a recovery voltage towards a stable open-circuit voltage. The V_{OC} follows the terminal voltage V_T. There is a difference in magnitude between the V_T and the V_{OC} divided by the current during the discharging process. This difference occurs because, in the relaxation state, the battery voltage will go towards the equilibrium state

[26], [27]. Meanwhile, the relaxation state is a condition where the battery voltage is still changing due to the temporary process of stopping the incoming or outgoing battery current, while the equilibrium state is a condition where the battery voltage is completely stable and does not change anymore.

The voltage profile during the rest can be patterned according to Figure 4, where each rest period of the discharge process describes the interpolation curve in Equation (7).

$$V_{\mathrm{OC}}(t) = -2.10^{-10}\,t^2 - 2.10^{-5}\,t + 12.66 \qquad (7)$$

The red dots are the endpoints (maximum points) of every 15 minutes of unloading time lag (r_{in} = 0). This value is the highest value of battery relaxation during that time. From Equation (6), the internal resistance value is obtained as shown in Figure 5 the internal resistance curve is the relationship obtained from the terminal voltage to the open-circuit voltage at all times, where t = 15 minutes

From Figure 4, it is shown that V_{OC} and V_T curves will reach the cut-off voltage when the battery is no longer be loaded. The cut-off voltage value of the battery ranges from 6-8V if the battery is discharged continuously. Internal resistance is the difference in value between V_{OC} and V_T (which has a different magnitude) divided by the current during the discharging process. As the internal resistance value increases in the discharge process, the difference between those variables also increases as well.

From Equation (5) we will get the SoC curve against the loading time which shows a decrement in SoC due to reduced battery capacity. The comparison of the two voltages (V_{OC} and V_T) from the experimental is shown in Figure 6.

Figure 7 shows the SoC curve in the discharging process where every hour the load is released for 15 minutes. The curvature at the beginning of loading indicates that the battery energy does not necessarily decrease linearly, even though the current is constant.

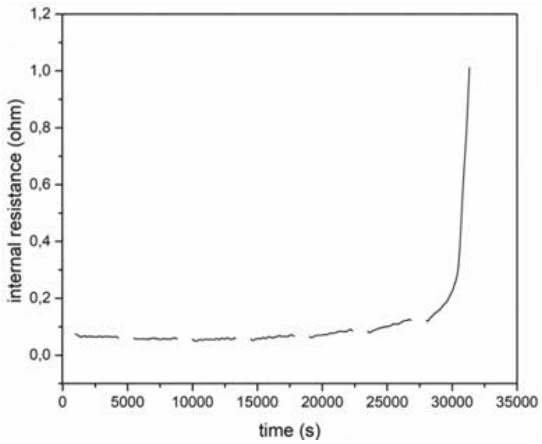


Fig. 5. Internal resistance at any time t.

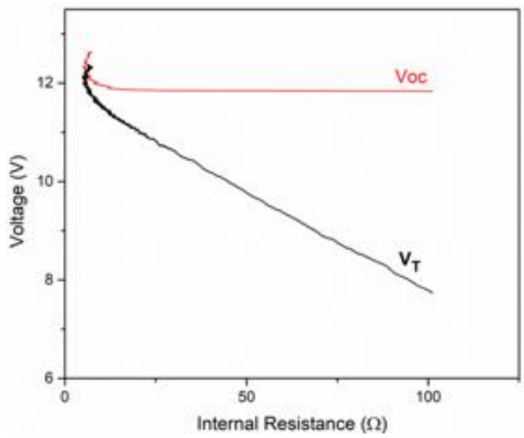


Fig. 6. Profile the difference of V_{OC} and V_T at discharging mode.

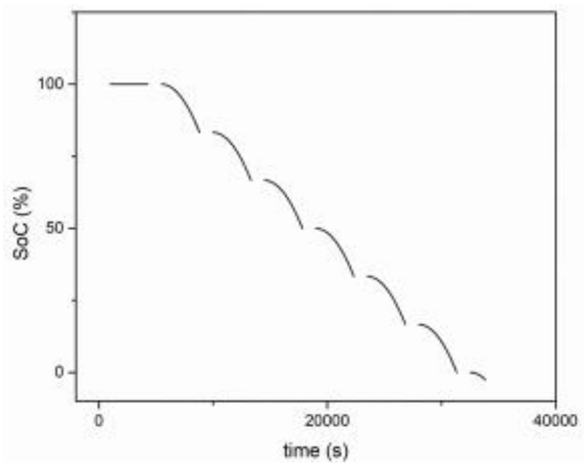


Fig. 7. State of charge at discharging time.

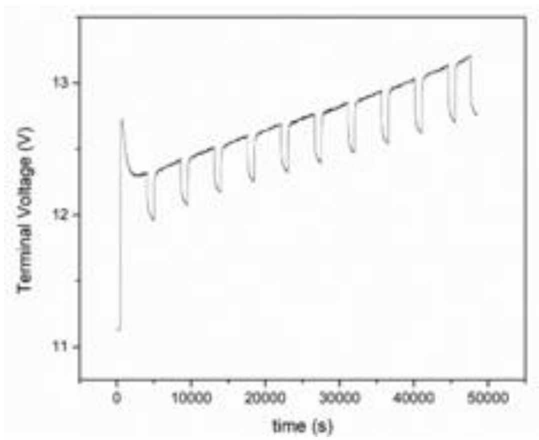


Fig. 8. Typical charge model 4.5 A constant current profile.

3.2 Charging Mode

In the case of charging, the opposite process occurs where the current enters the battery. With a current of 4.5A, the charging process is carried out continuously for 1 hour by disconnecting the supply current for 15 minutes as shown in Figure 8. This process is stopped when the value of the open-circuit voltage V_{OC} has reached 12.7 V.

During the charging period, the battery terminal voltage increases as the battery capacity increases. The value of the voltage V_{OC} also increases in each subsequent period when stopping the current. This can be seen in Figure 11 where the increase in the battery terminal voltage is accompanied by the rise of V_{OC}.

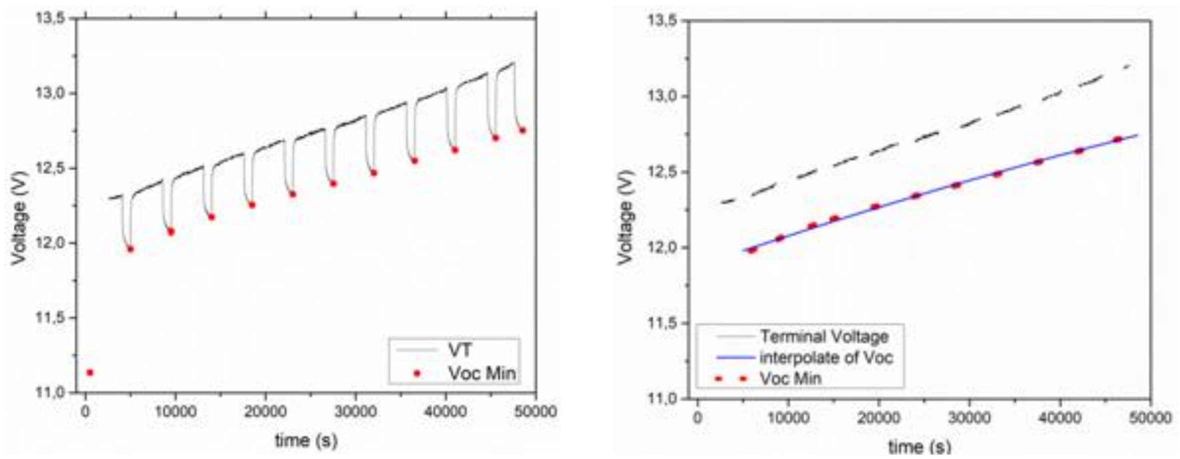
As shown in Figure 9a. the terminal voltage is the result of a charging experiment with a charging voltage of 14 V. The red dots are the minimum V_{OC} when the charge current is disconnected from the battery. During the charging period, the battery terminal voltage increases as the battery capacity increases. The value of the voltage V_{OC} also increases in each subsequent period at the time of stopping the current. This can be seen in Figure 9. Where the increment in the battery terminal voltage is accompanied by an increase in V_{OC}.

The terminal voltage profile is shown in Figure 9b. The dashed line shows the battery is not carrying current (I_{ch} = 0). If the red dots are interpolated, the equation for the minimum V_{OC} condition will be obtained at all times. Equation (8) illustrates that the increase in the value of V_{OC} every 15 minutes is in line with the increase in the capacity of the battery being charged.

$$V_{OC}(t) = -5.812t^2 + 2.065t + 11.88 \tag{8}$$

The V_T and V_{OC} (in this case the result of interpolation) will obtain an internal resistance curve as shown in Figure 10. By taking Equation (6) again, the internal resistance curve for the charging process is obtained as shown in Figure 11. Internal resistance during the charging process has an increasing value along with the addition of battery capacity. Or it can be said that when the SoC close to 100%, the internal resistance value for the charging process becomes larger.

In Figure 11 between the battery terminal voltage and the V_{OC} curve, it is somewhat different from Figure 6. Where in the case of charging there are no V_{OC} and V_T values that coincide. This shows the different internal resistance values between the two conditions. The initial current that enters the battery is SoC = 0, as shown in Figure 13. The SoC reaches its maximum if the Voc reaches 12.72 V.



(a) (b)

Fig. 9. Profile V_{OC} and V_T at charge current 4.5 A. a) Terminal voltage change profile with. b) Interpolation of minimum V_{OC}.

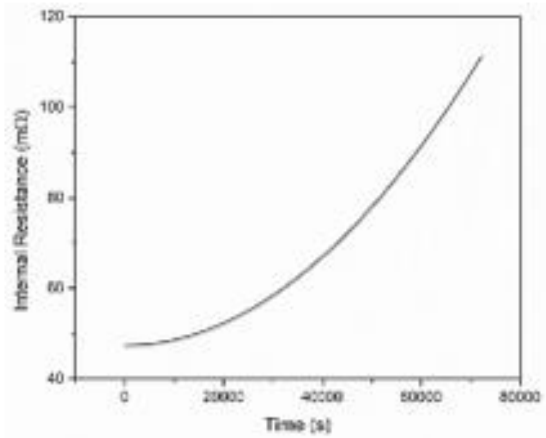


Fig. 10. Internal resistance on charging at 4.5 A.

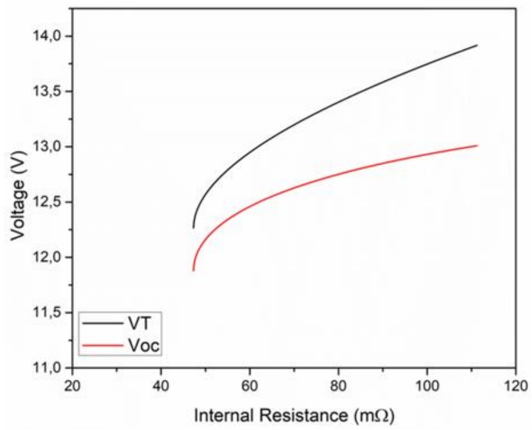


Fig. 11. Profile of the difference in V_T and V_{OC}.

4. RESULTS AND DISCUSSION

The relaxation voltage (recovery) that occurs and is measured every hour is then paused for 15 minutes in the discharging and charging processes. From the experimental results, the intrinsic parameters of the battery are obtained, namely terminal voltage, open-circuit voltage, internal resistance, so based on the formula that has been described in section II. We will get an estimate of the SoC and its relation to internal resistance over time. As for the SoC curve, we have obtained both the discharging and charging experiments as shown in Figure 8 and Figure 14.

Figure 12, referring to the relationship between V_{OC} and SoC, it can be said that the V_{OC} value will proportionally decrease with the range of SoC < 25% for the discharging process. Furthermore, the V_{OC} value will significantly differ with V_T when the battery voltage passes through the cut-off voltage.

Furthermore, in Figure 13, it shows that the installed battery threshold voltage is lower than the V_T in the charging process. At that time the current that charges the battery is still constant at 4.5 A. If the threshold voltage has been reached, the battery charging process will be stopped. For this constant current, the V_{OC} value will be stable after the threshold voltage is reached.

Internal resistance is obtained from the difference in value between V_{OC} and V_T terminal voltage when loading or charging the battery. The internal resistance value can be correlated with the SoC value shown in Figure 13 and Figure 14. From Equation (5), we will get the SoC curve for the loading and charging time of the battery, where there is a decrement and increment in SoC due to changes in battery capacity. The internal resistance value is correlated with the SoC value in each of the above experimental modes. First, the value of the battery's internal resistance in the discharging condition correlates with the amount of internal resistance. As shown in Figure 9, the internal resistance stays below 10 mΩ for 15% < SoC < 100%. This means that the value of internal resistance has a very small gap to be correlated with the amount of SoC.

The correlation between internal resistance and SoC in the charging process can be seen in Figure 15. The curve that occurs is an exponential function where the value of internal resistance increases significantly with the amount of SoC. The higher the SoC, the greater the internal resistance value.

As shown in Figures 14 and 15, SoC estimation based on proportionally plotting from 0-100% to the r_{in} that exponentially rise shown good opportunity. Since the SoC have strong relation to the r_{in} although it is not linearly. For this reason, the r_{in} that is obtained from Equation (6), in each rest period will play a role in plotting the SoC. This last for 15 minutes in each charging and discharging period. Although the two curves in Figures 14 and 15 are different in terms of shape, they represent the value of r_{in} versus SoC at all times. The equation for the Coulomb calculation is shown in Equation (5), it can be interpreted as resetting the accumulated SoC during the rest period. From these characteristics, frequent SoC reset increases the SoC estimation accuracy of the Coulomb calculation method. The internal resistance equation of the battery circuit is selected as an RC ladder model as in Figure 1, and the time constant according to SoC can be extracted from it. This constant is displayed for about 15 minutes. Meanwhile, an accurate V_{OC} requires a sufficient rest time of 2 to 3 hours to get to a stable battery condition.

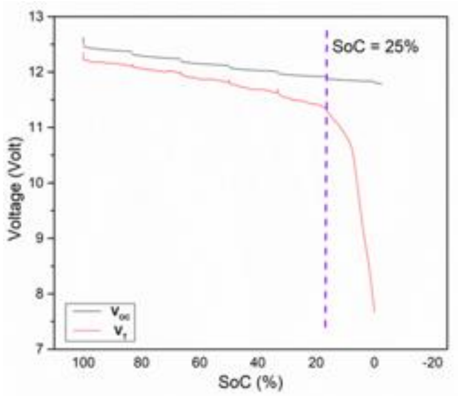


Fig. 12. Relationship between V_{OC}, V_T and SoC when discharging.

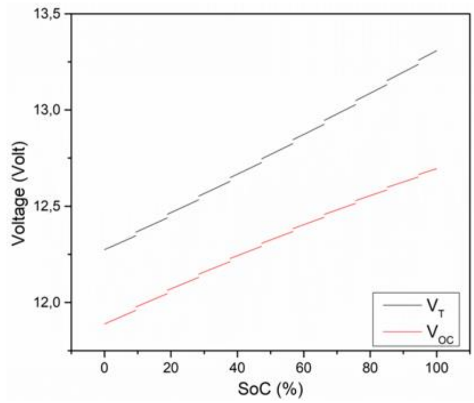
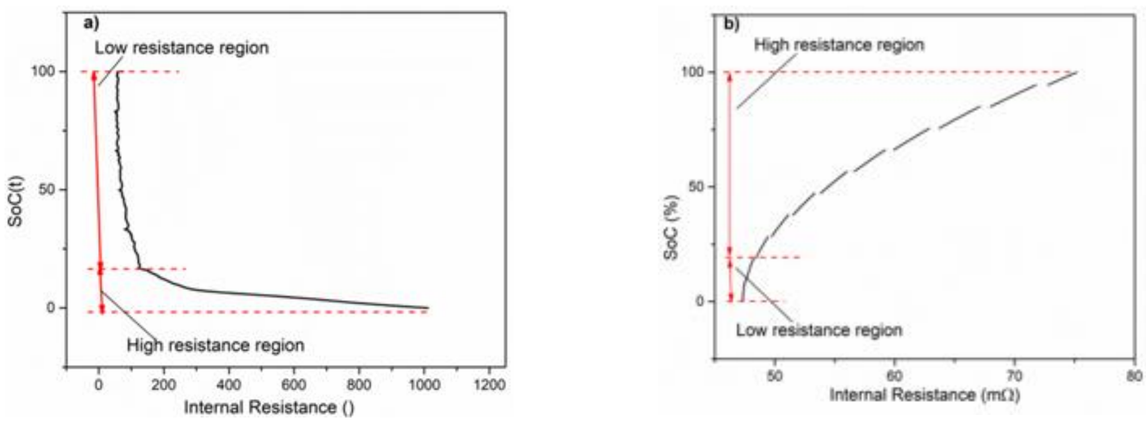
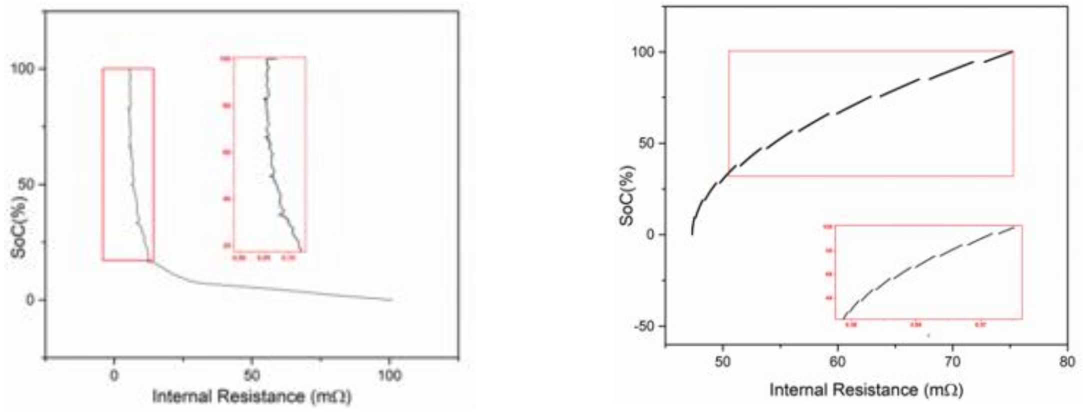


Fig. 13. Relationship between V_{OC}, V_T and SoC when charging.



(a) (b)

Fig. 14. SoC(t) compared to r_{in}(t) (a) at Discharging current 4.5 A (b) at Charging current 4.5 A.



(a) (b)

Fig. 15. Regime SoC(t) compared to r_{in}(t) from 23% to 100%. (a) at Discharging current 4.5 A (b) at Charging current 4.5 A.

Based on the experimental results in Figures 14 and 15, it can be seen that there are two different SoCs. The differences are as follows:

a) At the time of discharging, it was found that the SoC was inversely proportional to the r_{in}, where the SoC was 100% when the r_{in} was in minimal condition.

b) At the time of charging, it was found that the SoC was directly proportional to r_{in}, where the SoC was proportional to r_{in}, namely when the r_{in} was small the SoC also decreased and vice versa when the r_{in} increased exponentially to the maximum, the SoC headed to the 100% condition. Those aforementioned conditions in a and b can be explained as follows:

At the time of discharging, V_T and V_{OC} in Equation (6) have a gap value that is getting bigger so that the r_{in} is also getting bigger. On the other hand, when charging, the V_T and V_{OC} values will have a smaller gap, while the current flowing is constant, so the r_{in} value will also get bigger.

5. CONCLUSION

In this research, the coulomb counting method has shown success on estimating the SoC as demonstrated by the result of measurements. SoC can be estimated from the analysis of the relation between r_{in} and V_{OC}.

In this research we have succeeded in finding a direct relationship between the internal resistance r_{in} and V_{OC} with the SoC battery, for both charging and discharging conditions. Internal resistance is obtained by real-time measuring the terminal voltage V_T and load current I_L and involving V_{OC} that have been characterized at the initial conditions. The direct relationship between SoC with V_{OC} and SoC with r_{in}, allows us to perform real time SoC measurements based on V_T and I_L real time measurements. Moreover, in fact, the relationship between SoC and r_{in} is not perfectly linear, then it is suggested to use the linear part of the relationship curve to reduce the computational process of measurement.

Another important result of this research is the discovery of the transient time required by the lead acid battery, when it is switched off from discharging, for a while. The change in terminal voltage as a representation of the V_{OC} indicates the presence of a chemical transient process in the battery. The transient occurs in switched off conditions, whether in charging or discharging conditions. With careful measurement, we can obtain the value of SoC in the battery charging and discharging models as shown in Figure 1.

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