State of Charge (SOC) Estimation on Lead-Acid Batteries Using the Coulomb Counting Method

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***Abstract*—Batteries are an important component in the implementation of renewable energy. One type of battery that is often used in the implementation of renewable energy is lead-acid batteries. Accurate estimation of the SOC (state of charge) value is one of the important parameters in the design of a BMS (Battery Management System). Accurate determination of the estimation of the SOC value is necessary to avoid the battery operating in an over charge and over discharge state. One method of estimating SOC that is quite easy and often used is Coulomb Counting. The determination of SOC estimation by this method is carried out by adding up the incoming charge or the charge coming out of the battery within a certain period of time. Charge summation can be done by summing the current in the battery, both at the time of charging and discharge. In this research, SOC monitoring tool was designed using the coulomb counting method to monitor the SOC value of the battery both at the time of charging and discharge. In its implementation, this method is very dependent on the accurate initial SOC value and the accuracy of the current sensor used. The type of current sensor used in this SOC monitoring tool is ACS712 which has good accuracy. Based on the results of the tests carried out, the amount of charge on the battery is directly proportional to the SOC on the battery itself.**

Keywords—state of charge, coulomb counting, lead-acid, initial SOC

I. Introduction

Nowadays, the need for electrical energy is a factor that cannot be separated in human life. Along with the rate of population growth, this is also accompanied by an increase in the need for electrical energy in the country. The increasing need for electrical energy in Indonesia makes the sustainability of the electricity supply higher, thus making the workload from the generation side heavier, and the availability of fossil fuels used will be thinner. With the existing conditions, the use of New and Renewable Energy (EBT) is very necessary to meet the need for electrical energy in Indonesia, considering the potential for new and renewable energy in Indonesia is quite large. Based on the national energy policy, the fulfillment of national energy needs from the new and renewable energy (EBT) sector is targeted at 17% by 2025 [1].

Batteries are an important component in the implementation of renewable energy. Batteries are a type of storage technology that is often used, but batteries have several disadvantages. Such as the capacity of the power contained, the limitation of power that can be distributed, to the short life of the battery. Of course, this depends on the type and character of each battery. Batteries commonly used in the application of renewable energy are lead-acid batteries [2-7]. To maintain the performance of lead-acid batteries, a battery monitoring system is needed to determine the estimated calculation of the SOC (State of charge) value accurately.

The state of charge is the ratio of the remaining energy to the maximum energy capacity in the battery. The SOC value has a susceptible value of 0-1, where 0 states the battery is discharged, while 1 is the condition of the battery with a full state. The state of charge value can also be expressed in the form of a percentage, 0%-100%. Accurate estimation of the state of charge value is very necessary to avoid system damage, preventing the battery from overcharging and over discharge which can cause permanent damage to the battery [8-10].

One method of estimating SOC that is quite easy and often used is Coulomb Counting. Estimation of the SOC value using this method is carried out by adding up the incoming charge or the outgoing charge on the battery within a certain period of time. This summation can also be done by integrating the value of the current entering or leaving the battery. One of the important parameters in determining SOC by this method is the accuracy of the initial SOC value. To obtain an accurate initial SOC value, you can use the adaptive-modified Coulomb Counting method. The initial SOC value is obtained using another method, namely by using the VOC-SOC look up table method which considers the influence of temperature [11]. In addition, the accuracy of the current sensor used also has an important role in estimating the SOC with this method.

II. BATTERY MODELLING

A. Electric Circuit Based

Basically, there are 3 battery modeling that are often used to determine the SOC value on a battery, including: experimental, electrochemical and electric circuit-based, but the most appropriate model used to see the characteristics of a battery is electric circuit-based. In electric circuit-based modeling, battery modeling can be represented by one voltage source and one resistance in the battery. This modeling is the simplest type of modeling in electric circuit-based modeling. The following are simple models of electric circuit-based [12]:

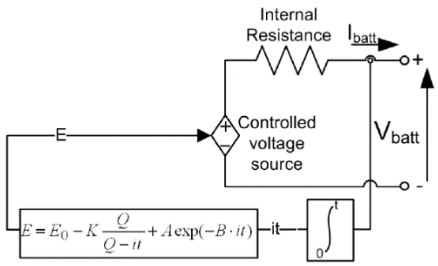

Fig. 1. Non linear battery model [12]

The open voltage source values in this modeling are derived from a non-linear equation based on the SOC values on the battery. This modeling assumes the same battery characteristics in both the charging proses and the discharge process. The open voltage source is represented by the following equation:

$$E=Eo-K\frac{Q}{Q-it}+A\times\exp(-B\times it) \quad (1)$$

where:

E = No-load battery voltage (V)
Eo = Tconstant stretch of the battery (V)
K = Polarisation voltage (V)
Q = Battery capacity (Ah)
$\int$ i dt = Charging current (A)
A = *Exponential zone amplitude* (V)
B = *Exponentially zone time constant inversely* (Ah^{-1})
V *batt* = Battery voltage (V)
R = Internal resistance (Ohm)
i = *Battery current* (A)

B. Battery Parameter Determination

We can obtain these parameters from the modeled battery sheet data, as well as from the battery's characteristic discharge curve. The following is a parameter determination of the LC-V127R2NA lead-acid battery used in this modeling:

- *Internal Resistance*

Based on the data obtained from the battery sheet data Lead-acid LC-V127R2NA internal resistance on the battery is 0.024 ohms.

- *A : Voltage drop the exponential zone (V)*

$$A=E\ full-E\ exp \quad (2)$$

$$A=13-12{,}4$$

$$A=0{,}6\ V$$

- *B : Charge at the end of exponential zone (Ah)*

$$B=\frac{3}{Q\ exp} \quad (3)$$

$$B=\frac{3}{1{,}44\ Ah}$$

$$B=2{,}083\ Ah^{-1}$$

- *Determination of polarization voltage parameters*

The determination of the value of this parameter can be obtained from the voltage equation on the battery in full, so it is assumed that there is no electric current flowing into the battery.

$$K=\frac{(E\ full-E\ Nom+A(\ exp(-B.QNom)-1)).(Q-QNom)}{QNom} \quad (4)$$

$$K=\frac{(13-12+0{,}6.(\ exp(-2{,}083.7{,}2)\ -1)).(7{,}5-7{,}2)}{7{,}2}$$

- *Determination of constant voltage (Eo) value*

In this calculation, the discharge current value used is 1.44 A or with a C-rating of 0.2C. So, the battery takes about 5 hours of charging time.

The following is the calculation of the *Eo* parameter value in this battery modeling:

$$Eo=E\ full+K+R.i-A \quad (5)$$

$$Eo=13+0{,}017+0{,}024.1{,}44-0{,}6$$

$$Eo=12{,}45\ Vx$$

C. Calculation of Estimated SOC value

The following are some methods in determining the estimated *state of charge* value on a battery:

- *Coulomb Counting Method*

The calculation of the estimated state of charge (SOC) value is one of the important things in battery applications in renewable energy. Proper estimation of the SOC value can prevent the system from being faulty and prevent the battery from over-charge and over-discharge, which can create permanent damage to the battery. The method used in this final project is the coulomb calculation method. In this method, the estimated state of charge value on the battery can be calculated by adding up the electric charge (coulomb) entering or exiting the battery. Electric current is generated from a certain amount of electric charge moving per unit time. Therefore the coulomb value on the battery can be calculated by introspecting the amount of current entering and leaving per unit time. In general the method of coulomb counting is formulated in the equation of the following [7] :

$$I=\frac{dQ}{dt} \rightarrow Q=\int_{to}^{t} I\ dt \quad (6)$$

$$SOC(t)=SOC(to)-\frac{1}{Cn}\int_{to}^{t} I\ dt \quad (7)$$

where:

Q : Electric Charge

SOC (to): Initial SOC before charging/discharging process occurs

Cn : Maximum capacity of the battery

I : The amount of electric current entering or leaving the battery.

One of the important parameters for determining the SOC value using the coulomb counting method is the determination of the initial SOC value. An accurate initial SOC is indispensable to obtain the actual SOC value of the battery.

- *Open Circuit Voltage (OVC) method*

The calculation of SOC using the open circuit voltage (OCV) method can be done by measuring the voltage value of the battery during an open circuit state or without load. The initial condition of the battery is also required to perform SOC value relationship testing using the OCV method [8]. This method is quite effective for determining the estimated SOC value on the battery, but should consider the rest period on the battery.

In its application to obtain a stable OCV measurement value, the battery takes 30 minutes - 2 hours. The time span during which the battery does not receive current or provide current is called the "Rest Period". The rest period on the lead-acid battery is shown in Fig. 2. When the battery is in a state of no load, the voltage value of the battery initially experiences a fairly significant increase, but over time the increase in the value of this voltage will decrease until the voltage is in a stable state. Therefore battery measurement using the OCV method should consider the factor of battery rest periods to obtain a stable voltage [9].

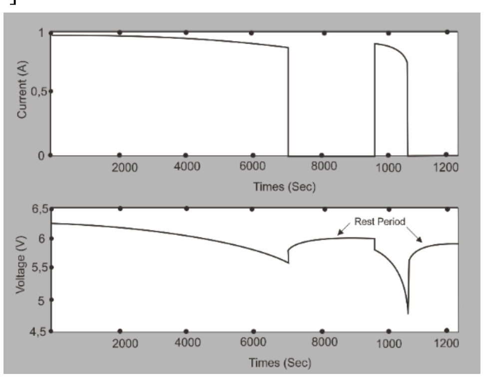

Fig. 2. Current time and Voltage versus time discharges curve containing rest periods [9]

The following is the equation of the battery when it reaches the rest period state [10]:

$$Voc = Vtr \pm Kv \tag{8}$$

where:

Voc = Equilibrated OCV
Vtr = Voltage at measurement
Kv = Constants of the Vtr-Voc equation

- *Adaptive-modified coulomb counting SOC estimation*

In the coulomb counting method, the initial SOC determination is an important variable for determining the accurate SOC value on the battery. The condition of the battery that is getting older is something to consider, because this method does not have the ability to follow the changes that occur along with the aging that occurs in the battery.

To obtain an accurate initial SOC value, you can use the adaptive-modified Coulomb Counting method. In order to get an accurate initial SOC value, it is necessary to measure the terminal voltage and temperature on the battery. The measured terminal voltage must be corrected based on the temperature conditions at that time. Meanwhile, to determine the estimated value of the open circuit voltage , it can be measured by measuring the corrected voltage drop value of the current and impedance. Battery impedance values are modeled with dynamic values. Correction of open circuit test voltage values is converted using the VOC-SOC Lookup table [11]

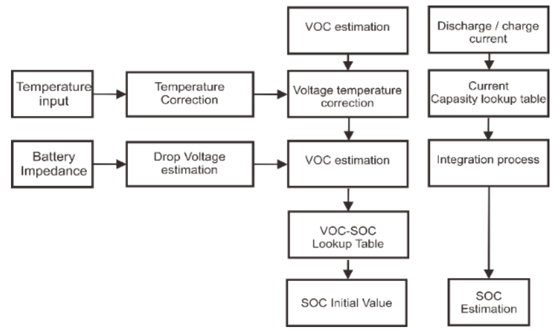

Fig. 3. Adaptive-modified coulomb counting SOC estimation method block diagram [11]

III. SYSTEM DESIGN

A. Discharge

In the block diagram below, the workflow of the system starts from the voltage dividing circuit. This voltage divider circuit is later connected with a *lead-acid battery.* the main function of this circuit is to divide the voltage released by the battery so that it can be read by the microcontroller device (Arduino). In addition, this voltage divider circuit can also be replaced with a BMS cell board circuit as a voltage sensor. This cell board can also be used to set up a battery circuit of more than 1. Another function of this BMS cell board is to divide the voltage released by the battery. The provision of the load is carried out so that the current can flow from the battery to the load, so that the value of the output current from the battery can be detected using a current sensor. The current and voltage data obtained will be connected to the microcontroller (Arduino). This process will be continued by sending data from the microcontroller (Arduino) to the PC *(*Personal Computer*).* In THE PC, the soc value calculation process is carried out based on existing data, the calculation of the SOC value is carried out using the *coulomb counting* method.

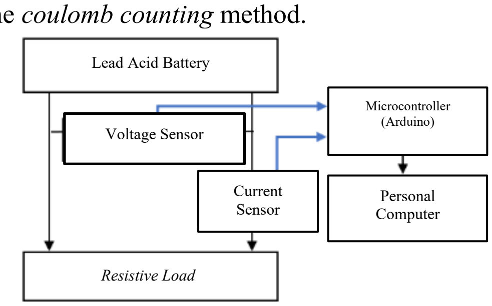

Fig. 4. Tool designing in the battery discharge process

B. Charge

The system workflow in this process starts from charging the current coming from Supply 12 VDC, this is so that the current can flow to the battery so that the voltage in the battery will increase until it reaches the required voltage. A supply of 12 VDC is connected by a current sensor to detect a given current value. The function of the voltage dividing circuit / BMS cell board in this system is also the same as the battery discharge system, namely as a voltage sensor and plays a role in the voltage division process that goes to the microcontroller device (Arduino). The current and voltage data obtained from the current sensor and voltage sensor will be connected to the microcontroller (Arduino). This process will be continued by sending data from the microcontroller (Arduino) to the PC (Personal Computer). In the PC, the soc value calculation process is carried out based on existing data, the SOC value calculation process is carried out using the coulomb counting method.

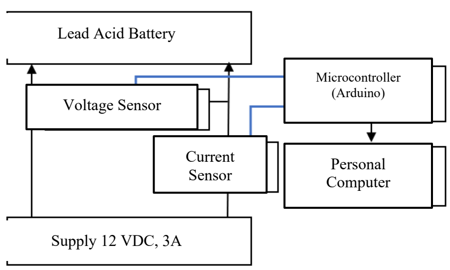

Fig. 5. Tool designing on the battery charging process

IV. Simulation Result

A. Simulation

The following is battery modeling on Matlab Simulink:

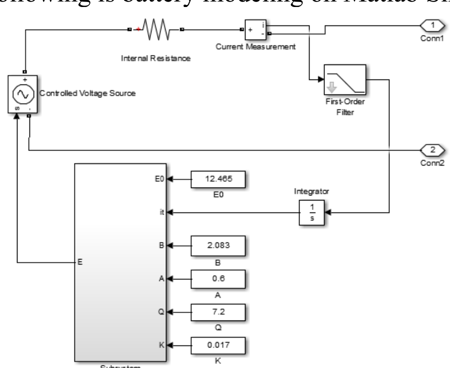

Fig. 6. Battery modeling on Matlab Simulink

E0	: 12,465 Volt
B	: 2,083 Ah^{-1}
A	: 0,6 V
Q	: 7,2 Ah
K	: 0,017
R	: 0,24 ohm

From the modeling of the battery, the *discharge* curve of the following characteristics is obtained:

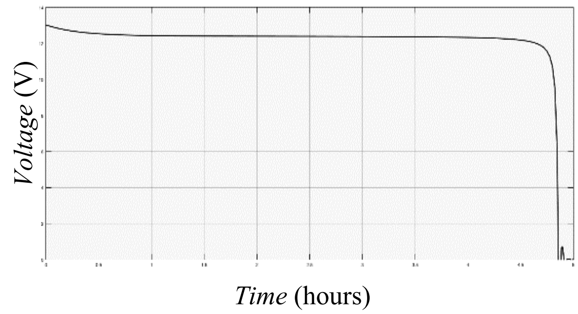

Fig. 7. Characteristic discharge curve (simulation)

The simulation is run using a resistive load with a value of 8.33 ohms. The simulation process is run for as long as 5 hours. This is because the *discharge* current used is 1.44 A (0.2C). Based on the simulation results that have been obtained, it can be concluded that this battery modeling can already model the characteristic *discharge* curve in accordance with the LC-V127R2NA lead-acid battery sheet data.

In addition, a simulation of the calculation of the SOC value was also carried out using the *coulomb counting* method.

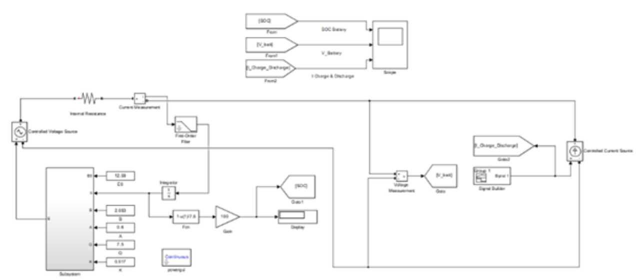

Fig. 8. Simulation of SOC calculation with coulomb counting method

In this simulation, the battery is set to a full state, so that the initial SOC of the battery is 100%. The simulation process of discharge and charging the battery is carried out for 10 hours. In the discharge process, the battery will be connected with a resistive load. when the battery SOC is 20% then the discharge process will be stopped. Furthermore, the battery will be charged until the battery SOC is 100%. Based on the simulation Fig. 9 obtained, information can be obtained that the battery voltage value will tend to be higher when the battery is in a charge state. In its implementation, batteries are strongly discouraged from operating with too low SOC values, for example with an SOC of less than 20%. This is because the greater the DOD value used, the number of cycles on the battery will decrease.

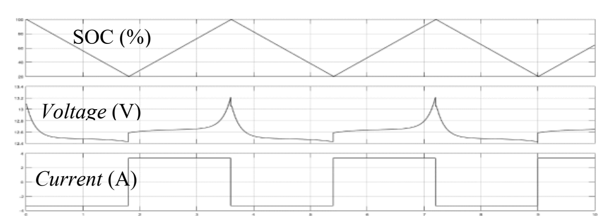

Fig. 9. Simulation of the filling and discharging process

V. Battery Discharge and Charging Tests

A. Discharge Test

Testing of SOC monitoring equipment is carried out on the filling process and the discharge process. The following is a series of tests on the discharging process:

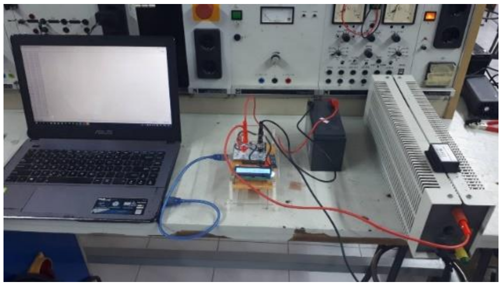

Fig. 10, Circuit of tests on the discharge process

The battery used in this discharge process has the following specifications:

Manufacturing	: Lead-Acid Battery LC- V127R2
Battery Capacity	: 7,2 Ah
V Nominal battery	: 12 volts
Internal resistance (25C)	: 24 m ohms

Before the discharge process, the battery is first *charged* with a certain charging current until the battery reaches its maximum voltage (*Voc* is about 13 V). When the battery has reached its maximum voltage, it is assumed that the soc of the battery is worth 100%. Furthermore, the emptying process is carried out with the following data collection provisions:

Total charging time	: 85 minutes
Average discharge current	: 3.08 A
Data retrieval time interval	: 1 second
Average payload used/second	: 0.000855 Ah
Total payload used	: 4.25 Ah
Initial SOC	: 100

Fig. 11. SOC (discharging) monitoring

The following figure of the test results of the SOC monitoring tool in the emptying process:

- *Voltage-to-Time*

The following figure of the relationship between battery voltage and time in the discharge process:

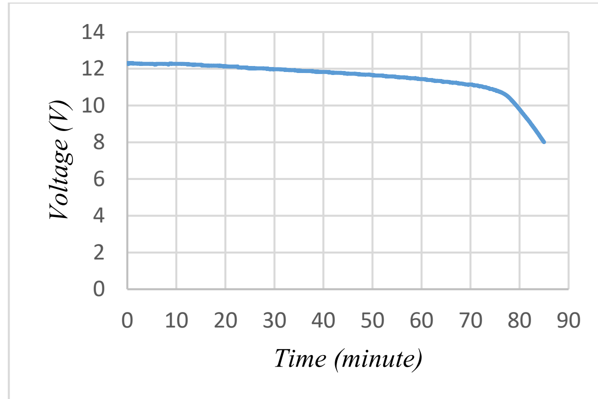

Fig. 12. LC-V127R2NA lead-acid battery discharge

From the Fig. 12, initially the battery voltage value tends to have a not too significant decrease, where the battery voltage value is still in the range of 11 V-12 V. However, when the battery is used close to 90 minutes the battery voltage tends to experience a significant decrease until it reaches 8 V. figure of the results of this test can be said to be in accordance with the discharge curve characteristic of the LC-V127R2NA lead-acid battery. Based on the figure that has been obtained, the battery needs to be operated at a certain time interval to get the optimal voltage value, so that the electrical equipment supplied by the battery can work properly.

- *Voltage and SOC*

The following figure of the relationship between the SOC value and battery voltage in the discharge process:

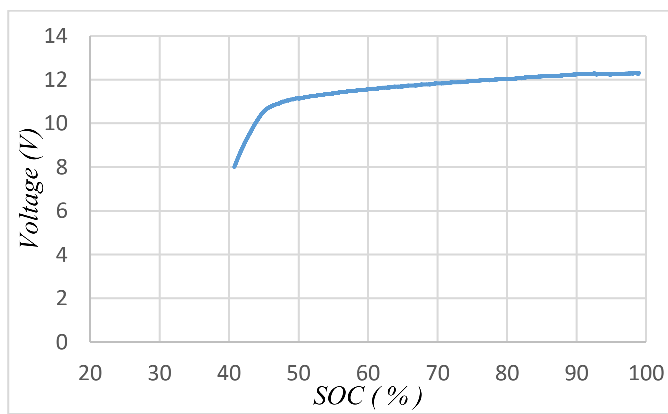

Fig. 13. Relationship of the battery voltage value and SOC in the discharge process

This figure of test results shows the relationship of the battery voltage value with the battery SOC value. From Fig.13, it can be seen that the battery voltage value tends to have a not too significant decrease in value, with the battery voltage value ranging from 11V-12V which occurs when the battery SOC is 60%-100%. However, the battery voltage will experience a significant decrease (until it reaches 8V) when the soc of the battery is below 50%. From the above review, the result can be used as a reference in the operation of the battery as an energy storage medium. Considering that the battery when operated below 40% SOC will have a low voltage value, so it will affect the performance of the existing equipment. In addition, the operation of the battery with too large DOD (Depth of discharge) will affect the lifetime of the battery itself. In its implementation, the greater the DOD value used, the more the battery life will decrease.

Another factor that causes there to be a voltage drop of up to 8V when the battery SOC is 40% is the discharge current value used. The use of too large a discharge current will cause the available capacity in the battery to decrease. Based on the existing theory according to the peukert equation, with a discharge current of 3.08 A, there is an available capacity that can be used at 50% of the rated capacity in the battery. [13].

- *Result of Number of charges and SOC of the battery*

The following figure of the relationship between the amount of charge and the SOC of the battery:

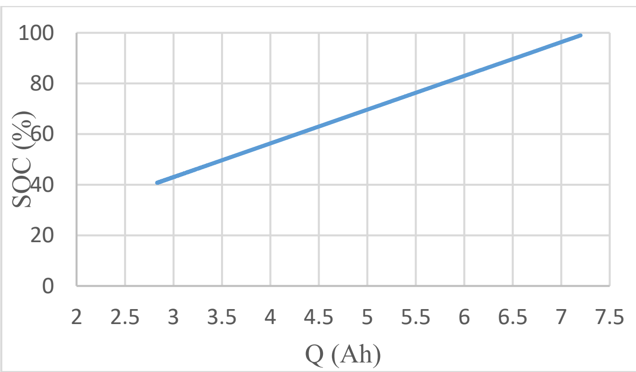

Fig. 14. Relationship of the amount of charge on the battery and the SOC in the discharge process

In this discharge process, the initial SOC of the battery is 100%, from the Fig. 14 generated in the discharge process, the less charge there is on the battery, the smaller the SOC value of the battery will be. So that the relationship between the total charge on the battery and the SOC of the battery is directly proportional.

B. *Charge Test*

In this testing process, the battery is connected to the DC Supply with a constant current mode of 3.06 A. Battery is also connected to an SOC monitoring device to display the value of battery voltage, battery current and battery SOC. Furthermore, the data on the value of current, voltage and SOC will be displayed and stored on a PC (personal computer) for the data processing process.

The following is a picture of a series of tests in the filling process:

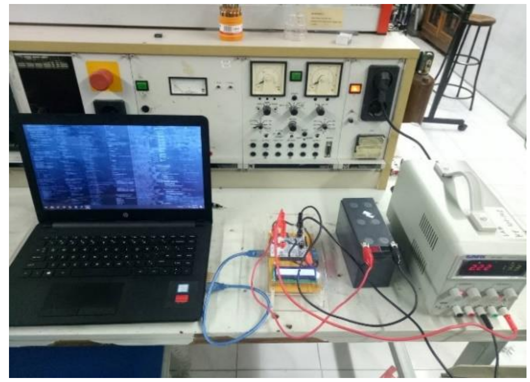

Fig. 15. Circuit of tests on the charging process

In this filling process, the initial SOC value comes from the emptying process in the first test, with an initial SOC of 40%. Furthermore, the filling process is carried out with the following data retrieval provisions: In this filling process, the initial SOC value comes from the emptying process in the first test, with an initial SOC of 40%. Furthermore, the filling process is carried out with the following data retrieval provisions:

Total charging time	: 85 minutes
Average *charge* current	: 3.06 A
Data capture time interval	: 1 second
Average payload every second	: 0.00085 Ah
Total charge during charging process	: 4,335 Ah
Initial SOC	: 40 %

The following are test of SOC test results in the discharge process:

- *Voltage-to-Time*

From this charging process, the result of the battery voltage against the time is obtained at Fig. 16. Based on the figure obtained, the voltage value of the battery when undergoing the charging process (charge) tends to have a higher voltage value compared to the discharge process (discharge). In addition, another characteristic that can be observed is that the battery voltage will experience a not too significant increase at a time interval of 0-75 minutes. However, when it reaches a time of more than 75 minutes, the battery will experience a significant increase in voltage value until it reaches a value of 17 V. The following figure of voltage to time in the charging process:

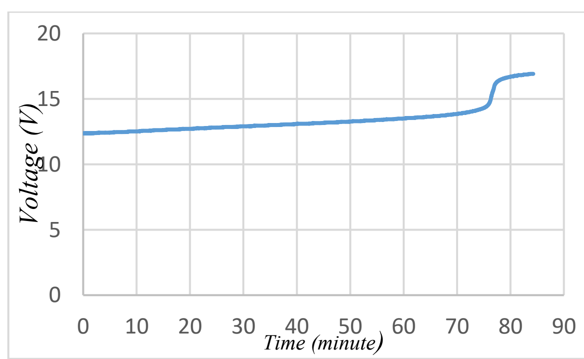

Fig. 16. Relationship of Voltage and time on the charging process.

- *Voltage and SOC*

The following is a condition of the relationship of the voltage value in the battery with the SOC of the battery in the charging process:

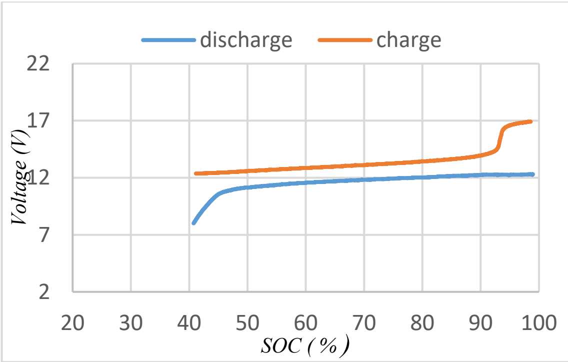

Fig. 17. Comparison of voltage and SOC charts on the charging process and discharge process

Based on the chart above, when the SOC value is 40%-90% the battery voltage tends to experience a not very significant increase, with a battery voltage value of 12V-14V. However, when the BATTERY SOC is close to the value of 95%-100% the battery voltage will experience a significant increase until it reaches 17V. This can be interpreted when the battery capacity is close to 100% then the battery voltage will experience a significant increase until it reaches 17 V. Battery voltage value in the charging process will have a higher voltage value than in the discharge process. The results of this test are in accordance with the typical curve of a 12 V lead-acid battery in general.

- *Results of Number of charges and SOC of the battery*

The following figure of the relationship between the amount of charge and SOC in the charging process:

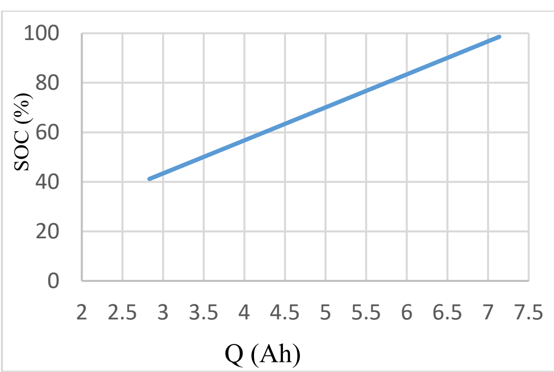

Fig. 18. Relationship of the number of charges

In this charging process, the initial SOC value of the battery is 40% based on the results obtained in the charging process, the more the amount of charge on the battery, the more the SOC value of the battery will increase. So that the relationship between the total charge and the SOC of the battery in the charging process is directly proportional.

VI. Conclusion

The results of the tests that have been carried out show that using the coulomb counting method, the determination of the right initial SOC is needed to obtain an accurate SOC value. In addition, the use of acs712 current sensor in the manufacture of SOC monitoring systems has good accuracy. The test results also show the amount of charge on the battery is directly proportional to the SOC value of the battery itself. The use of discharge current can also affect the available capacity of the battery, the greater the value of the discharge current used, the more available capacity on the battery will be. Based on the peukert equation, with a discharge current of 3.08 A, there is an available capacity that can be used at 50% of the rated capacity on the battery.

The improvements that need to be added in the implementation of this SOC monitoring system include are perform additional tests to determine accurate initial SOC values, the use of other current sensors that are more accurate in making SOC monitoring systems in the future, the creation of an automatic cut-off system in the implementation of the SOC monitoring system based on the SOC value of the battery, both at the time of charging (charge) and discharging (discharge).

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References

[1] "Blueprint Pengelolaan Energi Nasional." Kementrian Energi dan Sumber Daya Mineral, 2006.

[2] P.Manimekalai, R.Harikumar, and S.Raghavan, "An Overview of Batteries for Photovoltaic (PV) Systems," Int. J. Comput. Appl. 0975 – 8887, vol. 82, pp. 1–5, Nov. 2013.

[3] Ahmad Faiz Farizy, Dimas Anton Asfani, and Soedibjo, "Desain Sistem Monitoring State of Charge Baterai pada Charging Station Mobil Listrik Berbasis Fuzzy Logic Dengan Mempertimbangkan Temperature," Institut Teknol. Sepuluh Nop., vol. 5, pp. 1–5, 2016.

[4] S. M. A. S. Bukhari, J. Maqsood, M. Q. Baig, S. Ashraf, and T. A. Khan, "Comparison of Characteristics -- Lead Acid, Nickel Based, Lead Crystal and Lithium Based Batteries," 2015, pp. 444–450.

[5] G. M. Masters, Renewable and efficient electric power systems. Hoboken, NJ: John Wiley & Sons, 2004.

[6] V. Quaschning, Understanding renewable energy systems. London; Sterling, VA: Earthscan, 2005.

[7] Asep Nugroho and Estiko Rijanto, "Simulasi Optimasi Pengukuran State of Charge Baterai dengan Integral Observer," Pus. Tenaga List. Dan Mekatronik LIPI, vol. 17, pp. 323–333, Dec. 2013.

[8] G. Fathoni, S. A. Widayat, P. A. Topan, A. Jalil, A. I. Cahyadi, and O. Wahyunggoro, "Comparison of State-of-Charge (SOC) estimation performance based on three popular methods: Coulomb counting, open circuit voltage, and Kalman filter," 2017, pp. 70–74.

[9] Septimiu Mischie and Liviu Toma, "Behavior of the Lead Acid Battery after the Rest Period," WSEAS Trans. POWER Syst., vol. 3, no. 3, pp. 111–117, Mar. 2008.

[10] Alessandro Mariani, Thomas Stockley, Kary Thanapalan, and Jonathan Williams, "Simple and Effective OCV Prediction Mechanism for VRLA Battery Systems," presented at the International Conference on Mechanical Engineering and Mechatronics, Prague, Czech Republic, 2014, pp. 1–10.

[11] A. Purwadi, A. Rizqiawan, A. Kevin, and N. Heryana, "State of Charge estimation method for lithium battery using combination of Coulomb Counting and Adaptive System with considering the effect of temperature," 2014, pp. 91–95.

[12] O. Tremblay, L.-A. Dessaint, and A.-I. Dekkiche, "A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles," 2007, pp. 284–289.

[13] A. R. Utomo, F. Husnayain, and P. S. Priambodo, "Analysis of Lead Acid battery operation based on Peukert formula," 2014, pp. 345–348.

[14] Data Sheet Baterai Leac-Acid LC-V127R2NA