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DESIGN AND ANALYSIS OF A STATE OF CHARGE MONITORING SYSTEM FOR A SOLAR-WIND HYBRID SYSTEM USING THE COULOMB METHOD

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Abstract. This paper presents an analysis of the design and implementation of a state of charge (SOC) monitoring system for solar-wind hybrid systems using the Coulomb Count method. The purpose is to obtain real time measurements of voltage, current, temperature and SOC according to the battery management system. It is observed that when the 4.2 Ah battery is discharged, there is a significant drop in voltage and SOC, which is at a value of 45% to 40%, so that the cut-off voltage, namely the voltage required to avoid overcharging, is chosen at to avoid overcharging. It is chosen at 50% SOC and the voltage of 12 volts. When charging the 4.2 Ah battery, the voltage reached 16 volts at 75% SOC, with the battery temperature rising above 40°C, this value shows the importance of the cut-off voltage limit to avoid overcharging. Charging a 110 Ah battery with a solar/wind hybrid system using a PWM charger controller through the bulk, absorption and float phases shows that the bulk phase lasts about 18 minutes with an initial SOC of 47% and the absorption phase lasts 21 minutes and the last is the float phase where constant voltage and current occur for only 5 minutes. It is also found that the system can effectively follow the battery charge curve, preventing damage and ensuring the optimal condition of the charge controller.

Keywords: *State of Charge (SOC), PWM Charge Controller, Coulomb Counting, Battery Management System (BMS), Solar Wind Hybrid System, Real Time Monitoring, Overcharge Prevention.*

1. INTRODUCTION

Renewable energy has become a key pillar in efforts to achieve global energy sustainability as it offers an environmentally friendly and sustainable solution to reduce greenhouse gas emissions and replace fossil fuels (Hocini et al., 2020). With their huge potential, solar and wind power are the main energy sources that can produce electricity without pollution. According to the International Renewable Energy Agency (IRENA), the global installed capacity of solar energy reached 910 gigawatts by the end of 2020, and is expected to continue to increase as technology costs and policy incentives decline (International Renewable Energy Agency [IRENA], 2017). In addition, wind power has also shown significant growth with global installed capacity reaching 743 gigawatts by the end of 2020 (Energy Information Administration [EIA], 2020).

In Indonesia, with its energy infrastructure challenges, solar and wind power offer effective solutions to meet electricity needs in remote areas. A report from the World Bank shows that Indonesia has huge potential for solar and wind energy, with more than 200 gigawatts of solar energy potential and 60 gigawatts of wind energy potential ((Sustainable Energy for All [SE4ALL] Database, 2019). Although the utilization of wind energy is still limited, the untapped potential shows great opportunities for further development.

In renewable energy systems, power optimization through technologies such as Maximum Power Point Tracking (MPPT) is key to overcoming power fluctuations from wind turbines and solar panels (Apata et al., 2020). However, efficient energy storage is also very important, especially in hybrid systems that combine these two energy sources.

Batteries serve as the primary energy storage in these systems, and State of Charge (SOC) management of batteries is critical to ensure optimal performance and longevity. The two main methods for SOC monitoring are Coulomb counting and Open Circuit Voltage (OCV). Coulomb counting tracks current flow to estimate SOC in real-time, while OCV measures battery voltage without current to provide a more stable estimate of SOC (Hocini et al., 2020) (Sustainable Energy for All [SE4ALL] Database, 2019).

This research aims to analyze and monitor SOC in solar/wind hybrid systems, focusing on developing more accurate and reliable methods. Results are expected to improve energy storage efficiency and ensure renewable energy systems operate optimally.

2. RESEARCH METHODS

2.1 *Research Location*

This research was conducted at the Center for Vocational Training and Productivity (BBPVP) located at JL. Raya Pandeglang Km 3, Karundang Village, Cipocok Jaya Subdistrict, Serang City, Banten. The focus of the literature review was on the use of new and appropriate technology in renewable energy systems especially for a hybrid solar/panel system. In this study, the Coulomb Counting method was used to calculate the SOC value, and the Arduino program, for real-time monitoring purposes, was implemented. The boundary condition of open circuit voltage (OCV). In this research, we used the hybrid solar and wind energy system training tool of the Festo Didactic brand with a charger controller as the battery charge as shown in Figure 1.

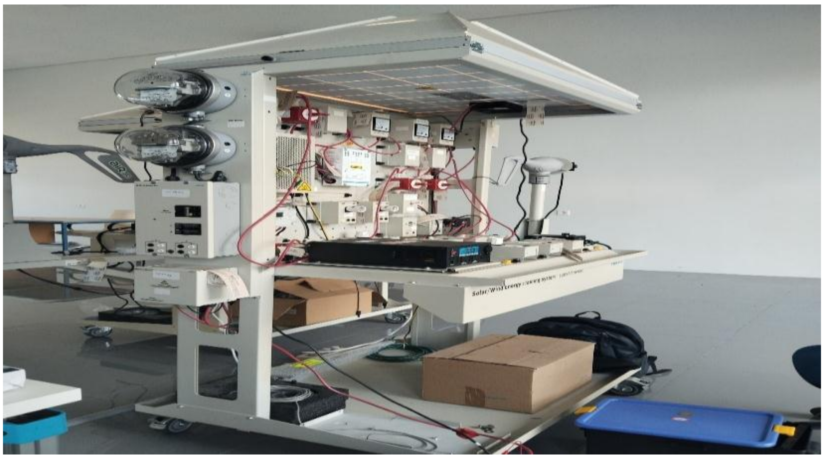


Figure 1. System hybrid solar/wind training Festo Didactic

2.2 Research flowchart

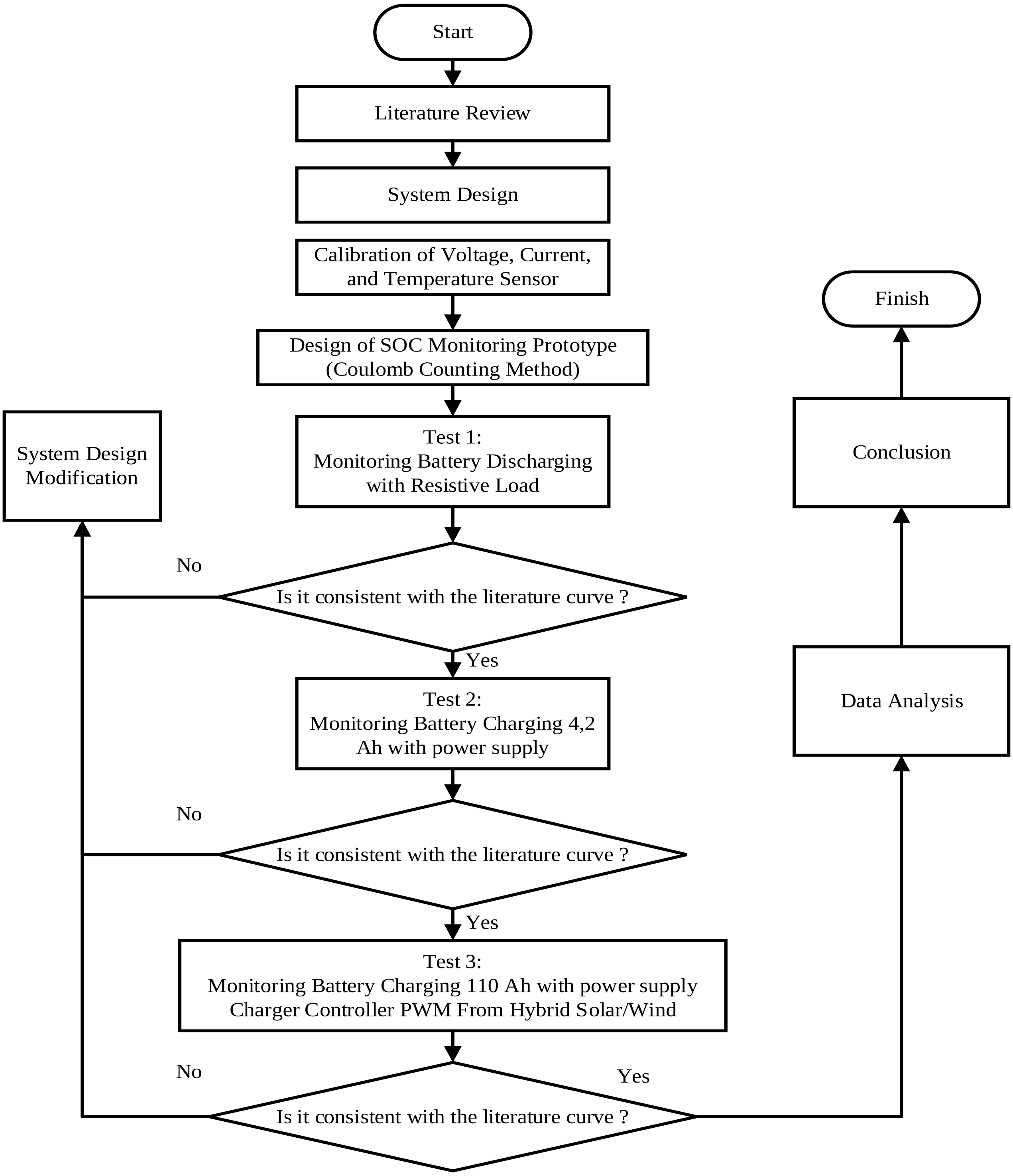


Figure 2. Research flowchart

2.2 Monitoring Testing

- Calibration of the voltage sensor, current sensor, and temperature sensor using an Amprobe multimeter and an infrared thermometer.
- Monitoring the charging of a 4.2 Ah Lead Acid-AGM-Gel battery with the energy source from a power supply.
- Monitoring the discharging of a 4.2 Ah Lead Acid-AGM-Gel battery with the energy source from a power supply.

Monitoring the charging of a 7.2 Ah Lead Acid-AGM-Gel battery with the energy source from a Festo Didactic hybrid solar/wind system

2.3 Diagram Hybrid Solar/Wind System

In this solar/wind hybrid system, researchers use a charger controller with Pulse width modulation (PWM) for battery charging. For Solar panels, the power used is 600 watts with a current of 5 Amperes, and the panel size used is 66.0 x 101.6 x 35.6 cm. As for the wind turbine, its power capacity is 600 watts. The solar/wind hybrid system diagram is illustrated in Figure 2.

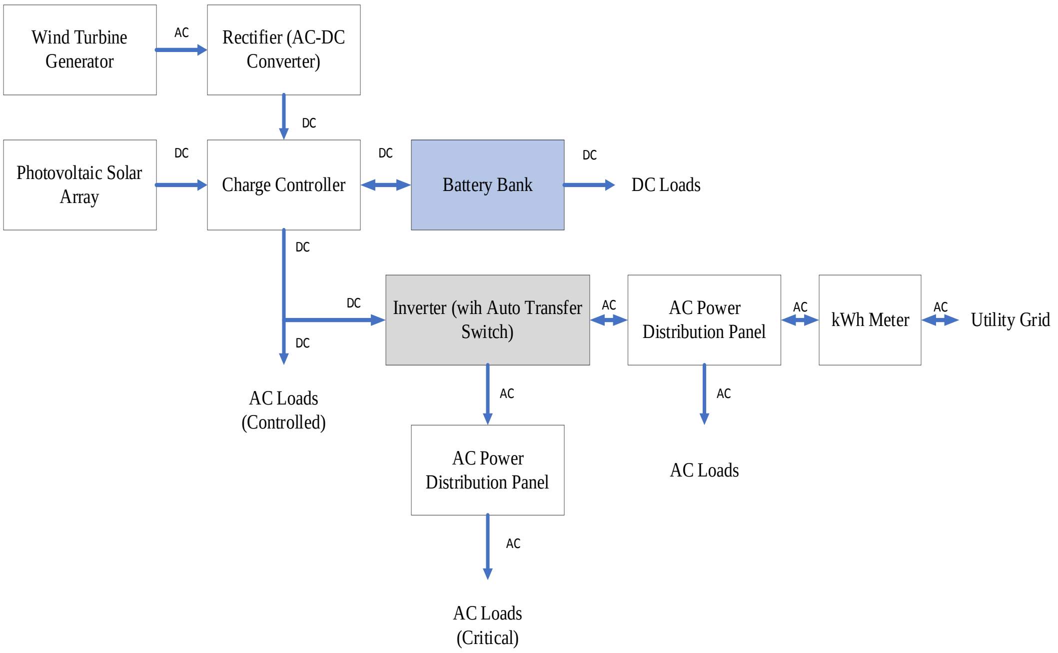


Figure 3. *Bimodal Grid-Connected System*

In a hybrid solar/wind system, the output of the wind turbine is a single-phase AC voltage that is rectified using an AC to DC rectifier, and the output of the solar panels is a DC voltage. The output of both sources is connected to the charging controller to stabilize the voltage when charging a 12V battery. The charge controller in this system can be connected to the battery for charging or directly to the inverter. The inverter is a converter of DC electricity to AC, it can be distributed in the AC power distribution panel for home electricity use.

The research was conducted on how the charger controller works with PWM as battery charging to prevent and maintain the battery life cycle, which is an important factor in battery maintenance and the effectiveness of renewable energy storage, the monitoring of SOC, voltage, current, and temperature. The use of the Coulomb counting method in real-time will be proven effective by measuring and monitoring the work of the charger controller with PWM to ensure that the charger controller is working properly.

2.4 Design Scheme Monitoring

Figure 3 shows the Design Scheme Monitoring as well as the layout of the Monitoring System, here the system consists of several main components, namely:

1. Microcontroller (Arduino Uno): As the center of data processing from connected sensors.
2. Temperature Sensor (MLX90614): To measure the system temperature, connected to the SDA and SCL pins.
3. LCD Display 16x2: To display the measurement data from the sensor, connected to the Arduino digital pin through the I2C module.
4. Current Sensor (ACS712): Measures the current flowing to/from the battery, connected to analog pin A1.
5. Voltage Sensor: Measures the battery voltage, connected to analog pin A0.
6. Solar Panel and Wind Simulator: Renewable energy sources to charge the battery.
7. Power supply: Alternative power source to charge the battery.
8. Battery: The storage of electrical energy.
9. Lamp (Resistive Load): Used for battery discharge testing.

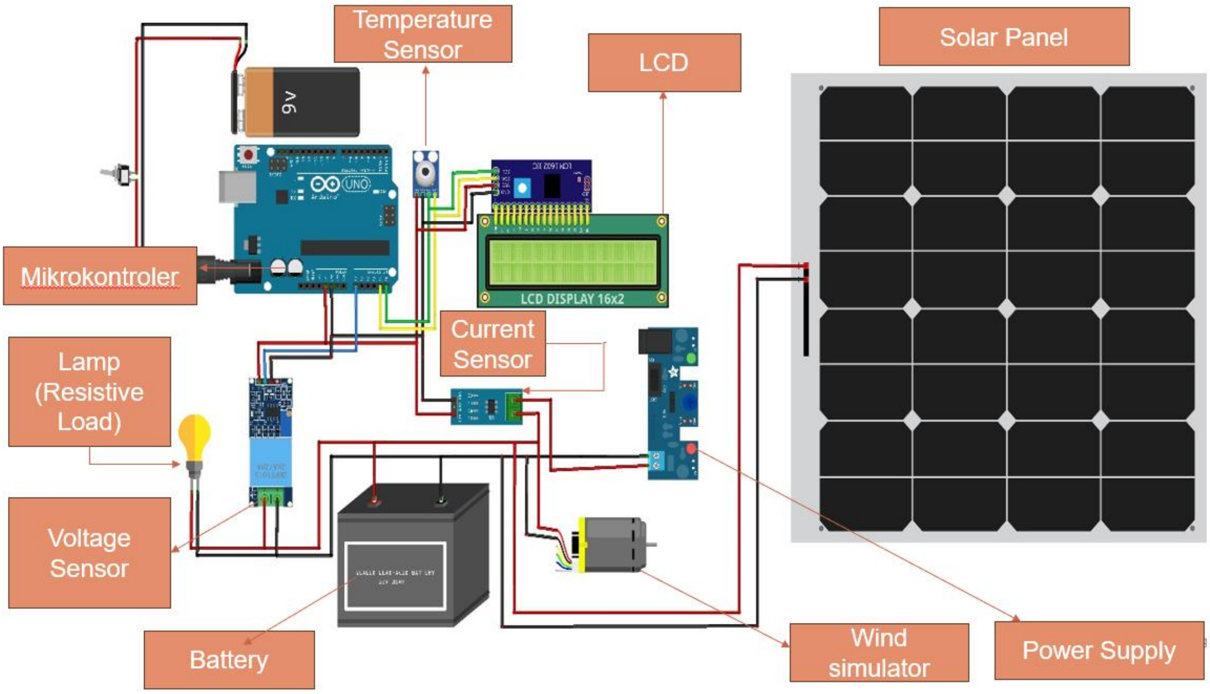


Figure 4. Layout Monitoring System

2.5 *Open Circuit Voltage* (OCV)

The Open Circuit Voltage (OCV) method is used to estimate the State of Charge (SoC) of a battery by utilizing the linear relationship between voltage and SoC value. This method is considered accurate and simple, however, the measurement of the SoC value can only be executed after the diffusion process in the battery is complete, called the "rest period". This means that after the load is removed from the battery, there needs to be a waiting period for the battery voltage to stabilize before accurate OCV measurements can be made.

The OCV generally refers to the specifications in the battery datasheet, where the maximum voltage represents 100% SoC and the cut-off voltage represents 0% SoC. The relationship between OCV and SoC is described in several equations. (Anggita et al., 2017) as follows:

1. **Relationship between Terminal Voltage (V_{tr}) and OCV**

$$V_{oc} = V_{tr} + K_v \tag{1}$$

Here:

- V_{oc} is the OCV voltage after reaching the rest period.
- V_{tr} is the terminal voltage measured during the measurement.
- K_v is a constant obtained from the difference between OCV and terminal voltage.

2. **OCV Equation Based on Charging and Discharging**

$$V_{bd}/V_{bc} = E_0 + R\ x\ I_{bt} + A\ x\ exp(-B\ x\ t) \tag{2}$$

Here:

- V_{bd} is the cell voltage at charging.
- V_{bc} is the cell voltage at discharge.
- E_0 is the constant voltage of the battery.
- R is the internal resistance.
- I_{bt} is the filtered charge or discharge current.
- A and B are the exponential zone amplitude and inverse time constant.

3. **Simplified Equation for OCV after Rest Period:**

$$V_{oc} = V_{tr} + K_v \tag{3}$$

In equation (3), the V_{oc} is the equilibrated OCV, V_{tr} is the voltage during measurement, and K_v is a constant that represents the difference between OCV and terminal voltage. The following is a table of voltage measurement results with SOC values with Open circuit voltage (OCV) shown in Table 1.

Table 1. Validation of predicted OCV voltage error with OCV (Anggita et al., 2017)

No	SOC Discharge	V calc	V real (Open circuit)			Error (v)	error relative(%)
			30 min	180 min	240 min		
1	80%	12.75	12.74	12.77	12.78	0.03	0.235
2	70%	12.47	12.48	12.48	12.48	0.01	0.080
3	60%	12.23	12.22	12.23	12.24	0.01	0.082
4	50%	11.98	11.96	11.97	11.98	0	0.000
5	45%	11.86	11.83	11.86	11.87	0.01	0.084
6	40%	11.77	11.74	11.75	11.76	0.01	0.085
7	35%	11.69	11.59	11.63	11.64	0.05	0.430
8	30%	11.62	11.55	11.58	11.59	0.03	0.259
9	25%	11.52	11.47	11.5	11.51	0.01	0.087
10	20%	11.5	11.45	11.48	11.48	0.02	0.174
11	15%	11.49	11.44	11.46	11.47	0.02	0.174
12	10%	11.44	11.39	11.43	11.43	0.01	0.087
13	5%	11.31	11.25	11.3	11.3	0.01	0.088
14	0%	11.24	11.2	11.25	11.25	0.01	0.089

Error validation of the OCV prediction is obtained by comparing the predicted value of the OCV voltage of the battery just before the load is removed with the value of the direct measurement of the battery after reaching the rest period or about 240 minutes after the load is removed. The validation results of the predicted OCV voltage and the actual OCV voltage of the battery are shown in Table 1. From the table 1 of validation results, the error of the predicted OCV voltage (Vcal) with the actual OCV voltage from direct measurement (Vreal) shows that the error of the largest OCV prediction is ±0.4% where for the predicted OCV voltage in the SoC range of 100% to 40% is relatively small in the range of 0.00% to 0.008% with the difference between the predicted battery voltage and the measurement results using a multimeter is 0.01 volts while the largest error is ±0.2% when the SoC is measured at 80% where this can be caused by unstable voltage from the battery side due to loading.

2.6 Metode Coulomb Counting

The Coulomb counting method is a technique that can be used to estimate the State of charge (SOC) of a battery by counting the amount of charge (in Coulomb units) of charging and discharging the battery. This method is often used in battery management systems (BMS) due to its simplicity and the accuracy that can be achieved if the measured current is accurate. The Coulomb counting method is based on the basic law of electrochemistry which states that the capacity of a battery can be measured by counting the electric current entering and leaving the battery.

The SOC calculation can be obtained by using the following formula

$$SOC_{(t)} = SOC_{(t_0)} + \frac{1}{C_{nom}} \int_{t_0}^{t} I_{(\tau)}\, d\tau \qquad (4)$$

Dimana :

- $SOC_{(t)}$ is the State of charge at the time$T$
- $SOC_{(t_0)}$ is the State of charge at the initial time t_0
- C_{nom} is the nominal capacity of the battery (in Ah or mAh)
- $I_{(\tau)}$ is the battery current at the time T

The Coulomb counting method is useful in portable battery applications and renewable energy systems. With proper measurement and good calibration, this method can provide fairly accurate SOC estimates for various applications. The following is the formula for calculating the SOC value using the Arduino programming-based coulomb counting method as in the following equation:

$$SOC' = SOC - \left(\frac{I_{in}\ x\ timestep}{battery\ Capacity\ x\ 3600}\ x\ 100\right) \qquad (5)$$

SOC = Initial SOC value

- I_{in} = Average incoming current
- *Timestep* = time interval of read current
- *Battery Capacity* = the battery capacity

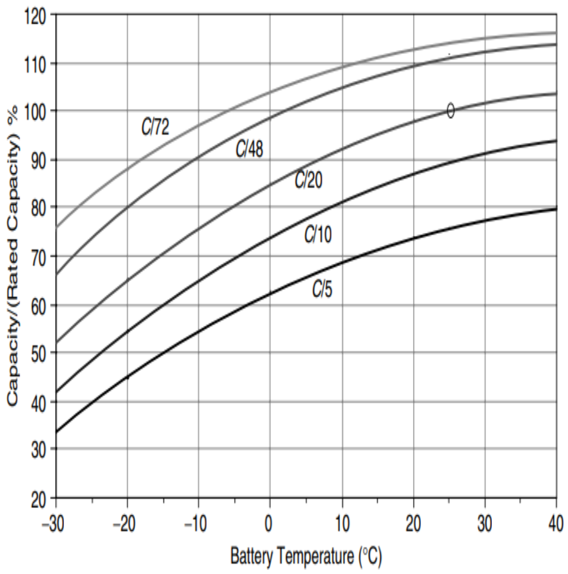
The following program is simulated to the Arduino program using the calculation of the coulomb counting method:

```
Vaverage = Vsamp / 1000;
Iaverage = Isamp / 1000;

// Scale voltage reading using calibration equation and subtract 1 volt
Vin = 0.0248 * Vaverage + 0.01 - 1.0;

// Calculate current using calibration equation
Iin = -0.0282 * Iaverage + 13.788 + 0.65;

// Calculate State of Charge (SOC)
soc = soc - ((Iin * 100) / (4.2 * 3600));
soc_batt = soc;
```

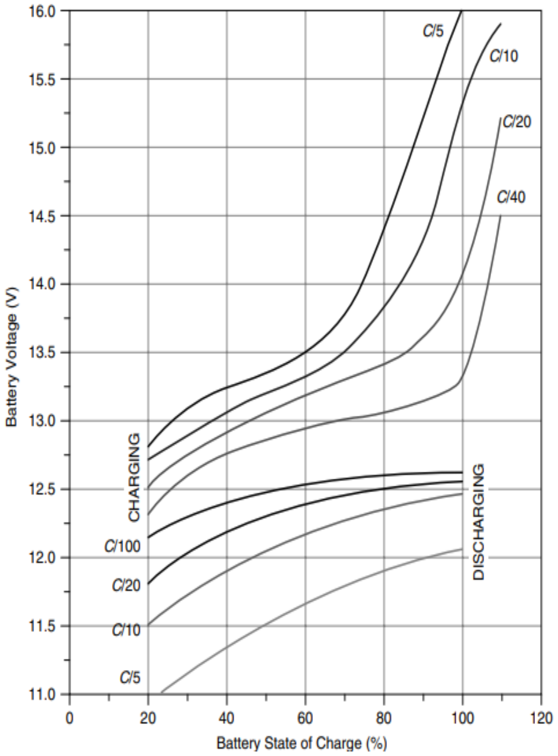
The graph of charging and discharging of a lead-acid battery.

In Figure 5, the graph of battery voltage versus State of Charge (SOC) represents the charging and discharging of the battery at different C-ratings. The higher the C-rating during charging, the steeper the increase in voltage relative to the SOC. This means that a higher C-rating results in a quicker cut-off voltage at a lower SOC level. Conversely, during battery discharging, a higher C-rating leads to a steeper decrease in voltage relative to the SOC. The C-rating indicates the rate of charging/discharging current relative to the battery capacity; a higher C-rating means a higher current and faster charging or discharging time. In graph (b), which shows battery capacity versus temperature, it can be observed that a higher C-rating

results in a greater increase in temperature at a lower battery capacity. Similarly, during battery discharging, a higher C-rating leads to a less steep decline in temperature relative to the battery capacity.



(a) Capacity vs Temperature



"Figure 5: Graph of charging and discharging of a lead-acid battery showing voltage, battery capacity, SOC, and temperature. (Wiley, et al., 2023)

The graph of battery charging using a PWM Charge Controller.

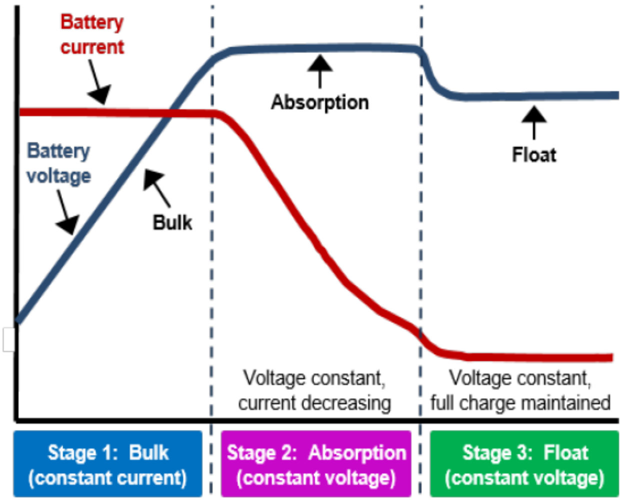


Figure 6, Battery Charging Stages in a PWM (Pulse Width Modulation) Solar Charge Controller. (Hossein, et al.,2018)

The graph of battery charging using a PWM charge controller is used for energy sources that fluctuate, such as renewable energy from solar or wind. By using a PWM charge controller, the battery charging system becomes more efficient and stable. There are three stages in the charging process. The first stage is the bulk stage, which occurs when the current is constant, and the battery voltage rises significantly. This stage is used for faster and safer battery charging. However, when the battery is charged too high, charging at this voltage and using the maximum current can damage the battery. Therefore, the charge controller moves to the next stage, which is absorption charging.

In the absorption stage, the current decreases significantly, but the voltage is maintained at a constant level. During this stage, the battery is charged to full capacity without the risk of overcharging, which could damage the battery cells. Once the battery is nearly full, the float stage occurs, also known as the trickle charge phase. The float stage is crucial because it keeps the battery fully charged without causing overcharging. By lowering the voltage to a lower level (float), the battery can maintain its full charge without generating excessive heat or damaging the battery cells. Float charging keeps the battery in optimal condition for the long term and prevents sulfation in lead-acid batteries.

3. RESULT AND DISCUSSION

The results of this research include calibration measurement graphs for the voltage sensor, current sensor, and temperature sensor, as well as graphs showing the relationship between SOC, voltage, current, and temperature during battery charging, battery discharging, and battery charging using a hybrid solar/wind source with a charge controller. The following are the images and explanations of the results from this research:

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Calibration of voltage, current, and temperature sensors

Before the design of the SOC monitoring prototype, the calibration of the voltage sensor, the current sensor, and the temperature sensor is conducted to ensure that the measured

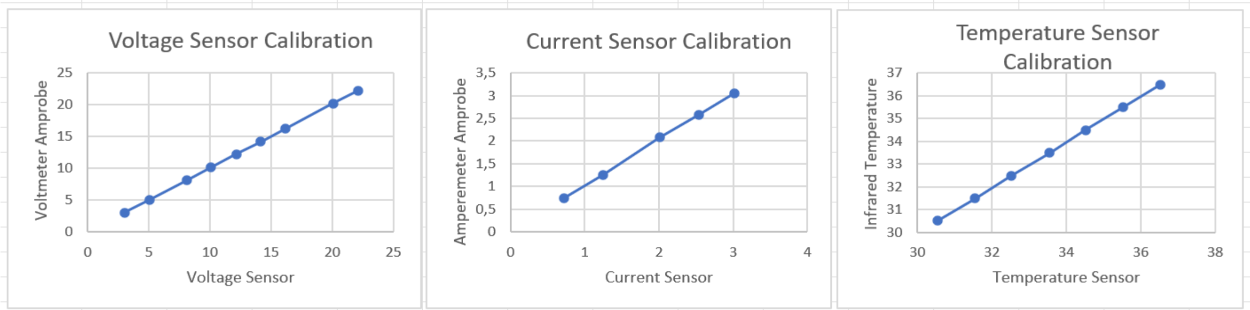
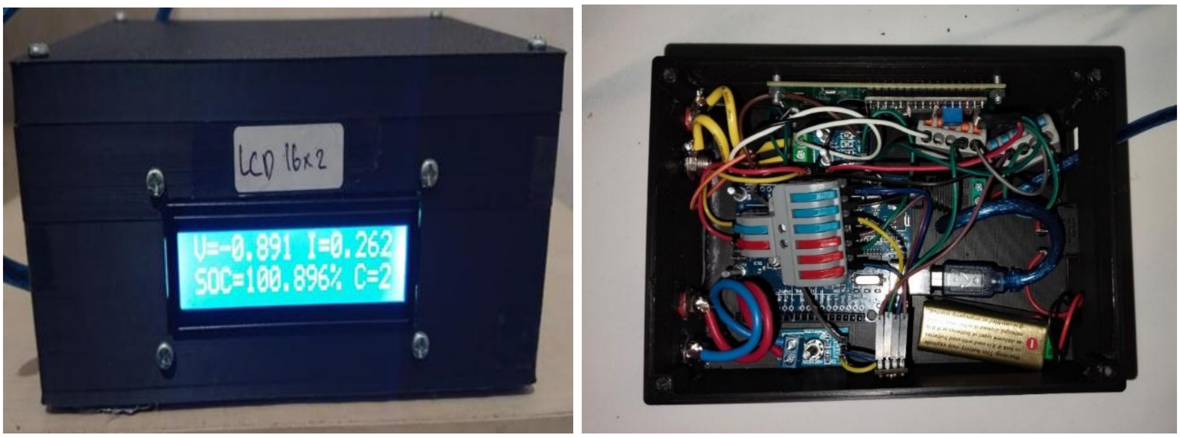


Figure 7, Plotting of Calibration Sensors results, (a) Sensor Voltage Vs Voltmeter-Amprobe Tegangan, (b) Sensor Current Vs Voltmeter-Amprobe Current, (c) Sensor Temperature Vs Voltmeter-Amprobe Temperature.

Figure 7(a) shows the plotting of the sensor voltage and the Multi-meter (Amprobe) voltage values, the graph shows the straight linear, which means the sensor has good precision. Figure 7(b) illustrates a graph between the sensor current and the current shown by the Amprobe, the graph also provides a straight linear, which means the sensor has good precision and Figure 7(c) depicts a graph of the sensor temperature with an infrared thermometer, the graph also shows a straight linear, here based on the three case calibration can be stated that the sensor has good precision.

Design result of the monitoring system



(a) (b)

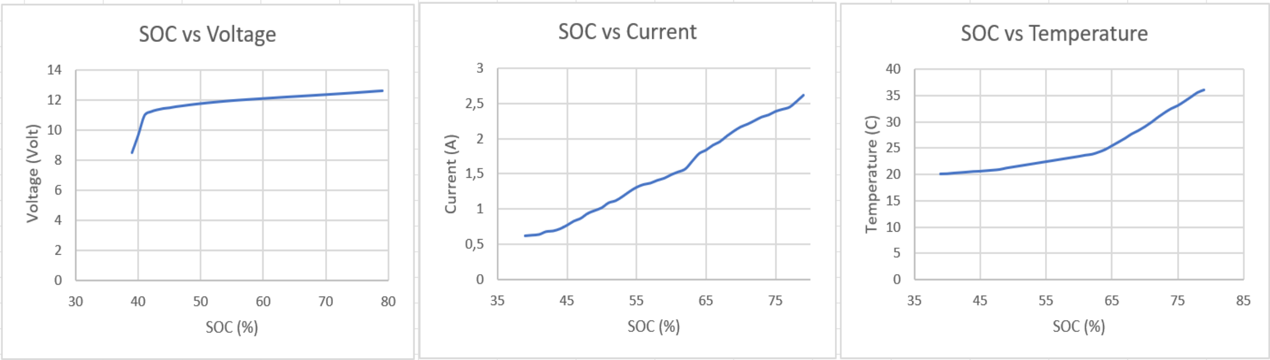
Figure 8, Design result of the panel monitoring system. (a) Front look, (b) Internal Wiring The monitoring system is created in the rectangular box shape of a special box equipped with an LCD screen on the front side and internal wiring inserted in the rectangular box. This rectangular box has three (3) holes for connecting the voltage sensor, current sensor, and non-contact temperature sensor. The screen displays voltage value and current value with three (3) decimal places accuracy, namely:

V = voltage value, I = current value, % (percentage) = SOC value in the percentage value,
Celsius Degree (^{0}C) = Temperature value.

The data collection of the SOC, V, I, and Temperature values is done in real time using an Arduino microcontroller system of Arduino UNO R3 ATMEGRA328P DIP 16U2. The data is then recorded using a data streamer in Microsoft Excel connected to the USB cable as a reading link to the microcontroller.

Battery discharge monitoring results with resistive load

In the implementation of battery discharge testing, is aimed at ensuring whether the monitoring tool can work properly to show or determine the SOC value. This is a validation that the SOC monitoring tool is matched with the literature graph. The following are the results of SOC readings of several measurement parameters in battery discharge monitoring:



(a)SOC vs Voltage (b) SOC vs Current (c) SOC vs Temperature

Figure 9. The graphical representation of Voltage, Current, and Temperature versus SOC

The battery is discharged using a 25-watt/12-volt resistive load lamp. Figure 9(a) is a graph of SOC vs. voltage, at SOC 45-40% it can be seen that the voltage value drops significantly, and in

Figure 9(b) it can be seen that at SOC 45-40% there is no current drop or the sloping, it means that the battery discharge rate starts to be small and in Figure 9(c) at SOC 45-40% it can be seen that the temperature starts to remain constant at an average of about 20 Celsius degree. In the literature graph, the greater the current used to discharge the battery, the more the voltage drops significantly above 20% SOC.

Results of monitoring battery charging with power supply

Battery charging tests are performed using a power source to charge the battery with a real-time SOC monitoring tool using the Coulomb Counting method. The following diagram is used to illustrate the Battery Charge Monitoring Test.

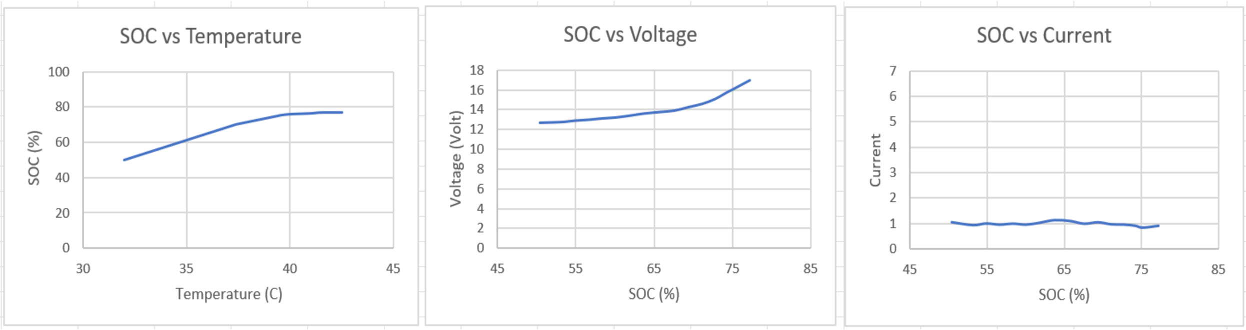


Figure 10. The graphical representation of monitoring battery charging with power supply.

In Figure 10(a), it can be seen that the higher the SOC, the higher the temperature. When SOC exceeds 75%, the temperature rises significantly. In Figure 10(b), when SOC is 75%, voltage increases sharply. Based on the literature study, the higher the SOC value, the higher the temperature and voltage rise. For this reason, it is necessary to monitor and control in real-time when charging the battery so that it can estimate the safety and health of the battery. for the average current in the power supply is constant at 1A.

Monitoring results of battery charging using a solar/wind hybrid source charger controller

In the results of this test, monitoring data was carried out in real-time, with a charging time of 52 minutes using a PWM charger controller on a hybrid solar/wind source from the Festo Didactic brand. Real-time monitoring data is made graphically, the following is a battery charging monitoring graph using a hybrid solar/wind system:

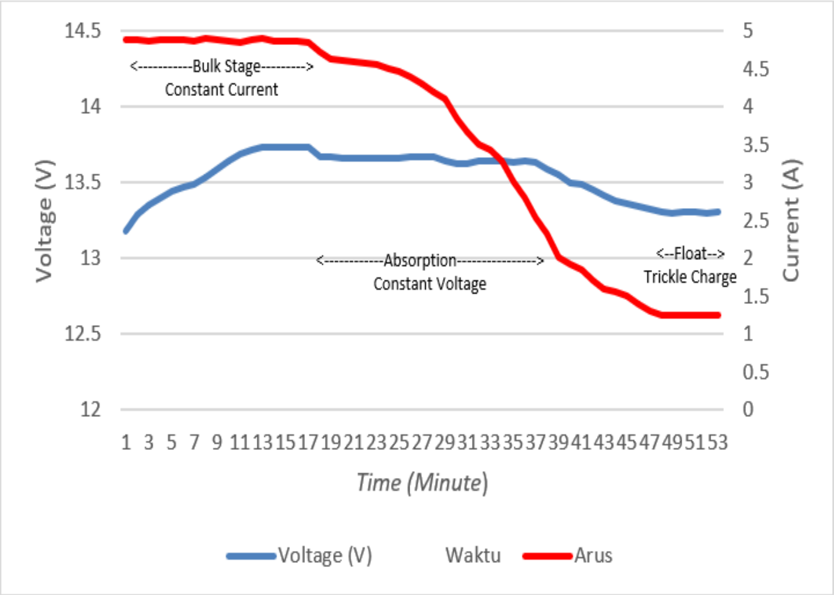


Figure 11. Voltage & Current vs Time

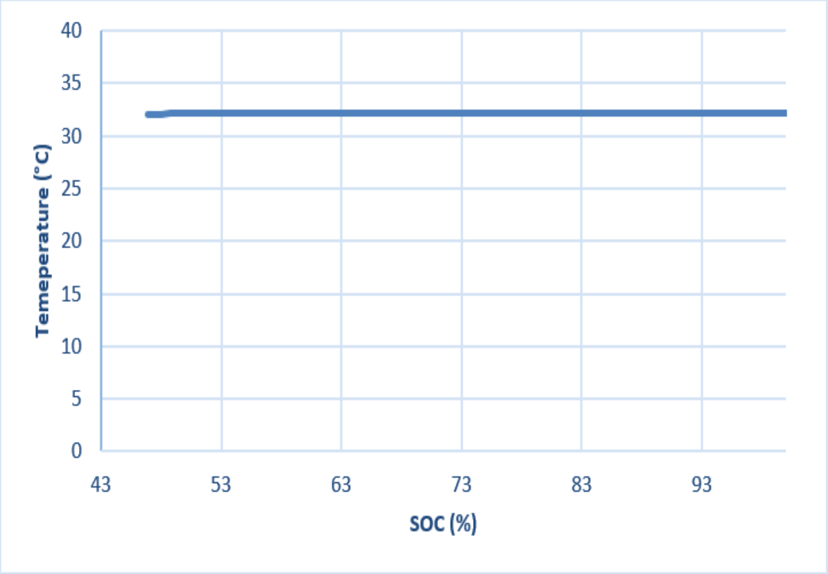


Figure 12. Temperature vs SoC

Figure 11 shows the voltage and current plotted against the time when the battery is being charged using a PWM regulator. There are 3 (three) stages in charging the battery with a PWM charger controller: Stage 1 is the bulk phase when the current is kept constant but the voltage increases, the graph shows that this phase lasts for 18 minutes. Stage 2 is the absorption phase, which is when the current decreases but the voltage is kept constant at around 13.6 volts, this phase lasts for 22 minutes, this phase is to prevent overcharging the battery because in this phase the battery SoC is above 60%, namely in minute 18 and finally the float phase is the drip phase in charging the battery because the SoC starts above 80% so the current used in this phase must be low and the voltage must be constant at around 13.2 volts to maintain the battery temperature and prevent overcharging. In this study, a graph of SoC and time was made separately, the following is a graph of ScC versus time. While on In Figure 11, the SoC starts at 46%, then when it is almost full the SoC reaches 98%. As it can be seen the graph rises over time.

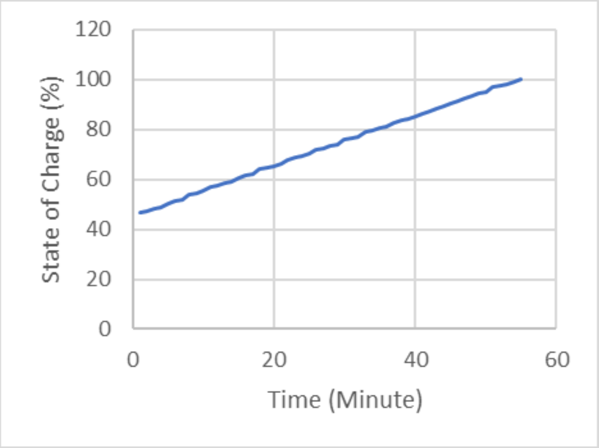


Figure 13. Plotting of the SoC vs Time

CONCLUSION

The design of a SoC monitoring system using the Coulomb Counting method in real-time during battery charging and discharging with a solar/wind hybrid power source has been successfully carried out.

It is found that: firstly, when the battery is discharged with a resistive load, it is shown that the battery discharge rate in SoC can decrease drastically by about 40 - 45%. Also, the voltage drops very sharply below 12 volts, which causes the battery to go below the standby voltage, and then the temperature continues to drop as the battery discharges, which affects the chemical reaction in the battery.

Secondly, when charging the battery using a power supply, the increase in charging voltage and battery temperature rises significantly at SoC 75% at an average current of about 1A, so it can be concluded that the use of SoC above 75% can cause the battery charging to slow down and the temperature to rise dramatically, so it is important to stop at SoC when charging using a power supply.

Finally, for the PWM charger controller monitoring test using the solar/wind hybrid source, the same curve is obtained as for the PWM charger controller charging curve in Figure 10, namely, there are 3(Three) phases when charging the battery: bulk phase, absorption phase, and float phase. These three phases are used to prevent the battery from overcharging and a significant increase in temperature, also seen in Figure 11, the temperature graph is fairly constant at 32 – 33 C degrees. So it can be concluded that the monitoring system that has been made in this study is feasible to be used for monitoring SoC, voltage, current, and temperature for estimating the safety and health of the battery when the battery is used or when the battery is charged and also can be used to monitor the working system of the charger controller on the solar/wind hybrid source.

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