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Performance Simulation Of Photovoltaic System Battery

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ABSTRACT
Solar energy, despite being inexhaustible, has a major shortcoming; it is intermittent. As a result, there's a need for it to be stored for later use. The widely used energy storage in photovoltaic system applications is the lead-acid battery and the knowledge of its state-of-charge (SOC) is important in effecting efficient control and energy management. However, SOC cannot be measured while the battery is connected to the system. This study adjusts and validates two estimation models: battery state-of-charge model using ampere-hour counting method and battery charge voltage model. For the battery state-of-charge model, the SOC is estimated by integrating the charge/discharge current over time while the battery charge voltage characteristic response is modelled by using the equation-fit method which expresses the battery charge voltage variations by a 5th order polynomial in terms of the state-of-charge and current. These models are realized using the MATLAB program. The battery charge voltage model is corrected for errors which may result from reduced charge voltage due to variation of solar radiation using the battery state-of-charge model. Moreover, the starting SOC needed in the state-of-charge model is estimated using the charge voltage model. The accuracies of the models are verified using various laboratory experiments.
Keywords-Charging efficiency, Lead–acid battery, Photovoltaic system, State-of-charge

I. INTRODUCTION

The rate of industrial growth is a function of the amount of energy available and the extent to which it is utilized. Nigeria is blessed with diverse fossil resources such as crude oil, natural gas, coal and renewable energy resources like solar, wind, water, biomass and biogas [1-5].

Fossil fuels are hydrocarbons formed from the remains of dead plants and animals [6]. The energy stored in fossil fuels can be released through combustion. This energy which is in the form of heat is converted to electrical energy in power generating plants. However, burning of fossil fuels has its negative effects, one of which is climate change and this is already evident in our environment. In 2012, climate change greatly affected the environment such that many lives and properties were lost. Nigerians lost their homes and farmlands; there was flooding in the South-South, desertification in the North-East, gully erosion in the South-East and rising sea levels. There is therefore a need to focus on the alternative, which is the use of renewable energy, to develop our economy and reduce greenhouse gas emissions [7].

Renewable energy is energy generated from natural resources which are replenished constantly. The use of renewable energy sources in Nigeria is still limited. Renewable energy has enormous potential and as such can meet multiples of the world's energy demand.

Sustainable energy services can be provided routinely from indigenous resources [8]. The presence of abundant solar radiation in Nigeria has made solar energy an area of focus among the renewable energy resources. Nigeria receives an average solar radiation of about 7.0kWh/m^2-day (25.2MJ/m^2-day) in the far north and about 3.5kWh/m^2-day (12.6MJ/m^2-day) in the coastal latitudes [9, 10].

Solar energy has diverse applications. It can be converted to heat and used in solar thermal systems or converted to electricity using solar photovoltaic systems. Photovoltaic system is basically composed of photovoltaic modules, charge controller, battery, inverter and electrical connections. Recently in Nigeria, solar photovoltaic systems were reckoned to be viable alternatives for reliable power supply, particularly for small loads in remote areas and rural communities [11]. A substantial percentage of Nigerians live in rural communities with no good roads and access to the electricity grid. Thus, effective harnessing of solar radiation would improve the availability of energy for socio-economic activities in those communities.

Solar energy just like other renewable energy sources has a major drawback; it has intermittent production. Consequently, integrating these energy forms into the power system creates the challenge of finding a balance between energy supply and demand. The solution to this challenge is energy storage and it requires the development of technologies and approaches to store the energy produced during sunny periods for use at latter times [12].

For solar photovoltaic applications, batteries are the technological solution most commonly used for energy storage. Batteries provide the most cost-effective solution for energy storage for small- to medium-sized autonomous power systems [13]. The main functions performed by batteries in solar photovoltaic systems include storing energy when the sun shines for use at night or during cloudy days, supplying higher currents than what the photovoltaic modules can deliver when necessary, and regulating voltage fluctuations which could damage the connected loads.

Deep cycle battery is the battery type suitable for photovoltaic applications because it can withstand continuous deep discharges without damage. The amount of energy the battery can store and deliver is known as the battery capacity and it is rated in amp hour (Ah). The capacity of the battery is related to the amount of electrolyte in the battery, the quantity of the active materials and the surface area of the plates. It is determined by the manufacturer based on the battery's constant discharge over a period of time. The capacity is specified at a specific discharge rate, the most common rates being 20-hour rate and the 100-hour rate. For example, a battery rated at 200Ah for 20-hour rate will deliver a current of 10A for 20 hours under standard temperature conditions (25^oC or 77F). C-rate is also used in specifying the discharge rate; it is expressed as a multiple or fraction of the rated capacity of the battery. 1C- rate means that the discharge current will discharge the battery in 1 hour. 20-hour rate thus denotes C/20 rate while 100-hour rate denotes C/100 rate. Battery capacity decreases with increase in C-rate; the higher the discharge rate, the lower the battery capacity and vice versa.

An important parameter of a battery under use is the battery's state of charge (SOC). SOC is the amount of energy presently stored in the battery expressed as a percentage of its nominal rated capacity (0% = fully discharged; 100% = fully charged). Conversely, the depth of discharge (DoD) is the amount of energy drawn from the battery expressed as a percentage of its nominal rated capacity. For most battery types, total discharge is not recommended because it could damage the battery. Batteries are very sensitive to overloading and deep discharges; hence, knowledge of the battery's SOC during use is essential.

However, the battery's SOC is a non-measurable quantity. It can be deduced from the battery's open circuit voltage which cannot be measured without disconnecting the battery from the system [14]. SOC determination of the battery shows the user its remaining usable charge before recharging, and this prevents irreversible damage to the battery in a condition of extremely low or high state-of-charge [15,16]. To enhance battery performance, an adequate prediction of the SOC is necessary; hence the motivation for this research.

II. BATTERY PERFORMANCE MODELS

The battery performance models used are battery state-of-charge and battery charge voltage models.

2.1 Battery State-of-Charge Model

The SOC of a battery is the fraction of the battery's current capacity at any given instant relative to its nominal capacity [17].

$$SOC = \frac{C}{C_{bat}} \quad (1)$$

where C is the (available) current capacity of the battery and C_{bat} its nominal capacity.
The current state-of-charge can be estimated by adding the charge flow into the battery to the state-of-charge at the starting point.

$$SOC = SOC_0 + charge\ flow\ into\ the\ battery \quad (2)$$

To determine the SOC, it is essential to know the battery SOC at the starting point, the charge (or discharge) current and the charge (or discharge) time [18]:

$$SOC = SOC_0 + \int_{t_0}^{t} \left(\frac{I_{bat}}{C_{bat}}\right) d\tau \quad (3)$$

where SOC_0 is the battery SOC at the starting point; t_0 and t are the time of the starting point and the time of interest, respectively in hours; C_{bat} is the battery capacity in Ampere-hour; I_{bat} is the battery current in Amperes. (3)represents the calculation of battery SOC for ideal batteries.

The ampere-hour counting method estimates the remaining energy of the battery by accumulating the charge transported into or out of the battery by integrating the charging and discharging currents over time. Consequently, accurate measurements depend on accurate determination of the initial SOC and battery currents [19,20].

Losses occur during battery charging and discharging and during storing periods:

$$SOC = SOC_0[1 - \frac{\sigma}{24}(t - t_0)] + \int_{t_0}^{t} \left(\frac{I_{bat}\ \eta_{bat}}{C_{bat}}\right) d\tau \quad (4)$$

where σ is the daily self-discharge rate which depends on the accumulated charge and the battery state of health [21]. Self-discharge rate occurs naturally in primary and secondary batteries and it results in loss of capacity with storage time [22]. 0.2%/day is used in this study; η_{bat} is the battery charging and discharging efficiency. There is no opposition during discharge, so the discharge efficiency considered as 100%. However, the efficiency is lower during charge because a fraction of the input energy is stored in the battery; an approximation of 90% is used [19].

The battery capacity is dependent on temperature. It reduces as temperature decreases. Varying methods of estimating the dependence of nominal battery capacity on temperature have been proposed [19,23,24].

The changes in battery capacity can be expressed by using the temperature coefficientδ_c:

$$C_{bat} = C'_{bat}(1 + \delta_c(T_{bat} - 298.15)) \quad (5)$$

where C_{bat} is the available or practical capacity of the battery when the battery temperature is T_{bat} in Ampere-hours; C'_{bat} is the nominal or rated capacity of the battery, which is the value of the capacity given by the manufacturer as the standard value that characterizes this battery; δ_c =0.006, a temperature coefficient of 0.6%/^{0}C, is usually used unless otherwise specified by the manufacturer [25].

Batteries have their best performance at room temperature, and any variation towards high or low temperature changes the performance and/or longevity. At higher temperature, the battery performance is improved by lowering its internal resistance and speeding up its chemical activity. However, the battery life is shortened if the battery is operated in that state for a long period of time [26].

If the cable losses in the system are neglected, then the battery current I_{bat} can be simply described by:

$$I_{bat} = \frac{P_{solar} - P_{Load}/\eta_{inverter}}{V_{bat}} \quad (6)$$

whereP_{solar} and P_{load} are the power of the PV array and load respectively in Watts. V_{bat} is the battery voltage in Volts.

2.2 Battery Charge Voltage Model

The equation-fit method is used to model the battery floating charge voltage characteristic response under both charging and discharging conditions. This expresses the battery charge voltage variations by a polynomial in term of the battery SOC and the battery current [19]:

$$V'_{bat} = a(SOC)^5 + b(SOC)^4 + c(SOC)^3 + d(SOC)^2 + e(SOC) + f \quad (7)$$

whereV'_{bat} is the battery floating charge voltage. To account for the temperature effect on battery voltage predictions, the temperature coefficient is applied [25]:

$$V_{bat} = V'_{bat} + \delta_v(T_{bat} - 298.15) \quad (8)$$

whereV_{bat} is the calibrated voltage of the battery considering the temperature effects. The temperature coefficient δ_v is assumed to be constant of -4 mV/^{0}C/2 V cell (away from 25^{0}C) for the considered battery temperature range

Parameters a–f in (7)are functions of the battery current I_{bat} and can be calculated by a fourth degree polynomial equation:

$$\begin{pmatrix} a \\ b \\ c \\ d \\ e \\ f \end{pmatrix} = \begin{pmatrix} a1 & a2 & a3 & a4 & a5 \\ b1 & b2 & b3 & b4 & b5 \\ c1 & c2 & c3 & c4 & c5 \\ d1 & d2 & d3 & d4 & d5 \\ e1 & e2 & e3 & e4 & e5 \\ f1 & f2 & f3 & f4 & f5 \end{pmatrix} \begin{pmatrix} I_{bat}^4 \\ I_{bat}^3 \\ I_{bat}^2 \\ I_{bat} \\ 1 \end{pmatrix} \quad (9)$$

The parameters a_1, a_2, a_3, …, f_3, f_4, f_5 are determined using the Least Squares Fitting method by fitting the equations to the battery performance data, which are acquired by experimental tests.

III. EXPERIMENTAL VALIDATION OF THE PERFORMANCE MODELS

3.1 Measurement and Data Acquisition System

Cadex C8000 which is an advanced programmable battery testing system was used to measure the voltages and state-of-charge of the battery. It was also used to charge and discharge the battery at different currents.

3.2 Experimental Set Up

Fig. 1 shows the set up for the experiment. It includes the advanced programmable battery testing system (Cadex C8000) with its accessories such as the alligator clips, a computer system (used for real time monitoring of the experiment and data storage), and the battery. The battery used is a Newmax SG 800H SOLAR GEL Battery which is a sealed rechargeable solar gel battery. Its capacity is 12V 80Ah / 10Hr rate with cyclic use of 30% DOD - 1800 cycles or 50% DOD - 1000 cycles. Its dimensions (LxBxH) are 260mm x 169mm x 208mm with terminal height of 228mm and weight of 21.5kg. It has anti-corrosive lead calcium alloy used in harmony with the GEL electrolyte to reduce sulfation effect. It is maintenance free and has anti-explosion filter and safety valves prevent gas leakage when overcharged [27].

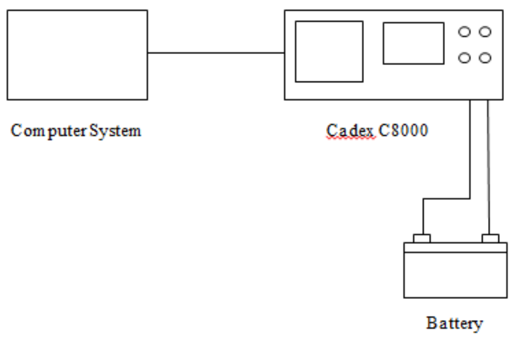


Figure 1: Experimental Set Up

3.3 Experimental Test Procedure to Determine Parameters a, b, c, d, e and f

In order to obtain the battery voltage response under different currents, the following procedures are taken [19]:

i. The battery is charged with a constant charging current I_{charge} to the maximum charge voltage of 14.4V with the voltages recorded at regular intervals.
ii. The battery is then held at the maximum charge voltage for 20 hours.
iii. The battery is discharged at a constant discharging current $I_{discharge}$ until the battery voltage drops to the end-of-discharge voltage of 10.5V. The voltages are also recorded at regular intervals.
iv. These two steps constitute a testing cycle. Then, the current rate is changed and the two procedures repeated to finish other cycles.

The data logging rate used is 60 seconds intervals.

The battery SOC under charging conditions can be calculated using the equation:

$$SOC = \frac{Q_{bat}}{C_{bat}} = \frac{\int_0^t I_{charge}\, \eta_{bat}\, dt}{C_{bat}} \qquad (10)$$

where Q_{bat} is the ampere hour number charged to or discharged from the battery in Ah.

The battery SOC under discharging conditions is calculated by:

$$SOC = \frac{C_{bat} - Q_{bat}}{C_{bat}} = \frac{C_{bat} - \int_0^t I_{discharge}\, dt}{C_{bat}} \qquad (11)$$

Parameters a–f are computed for different values of battery currents using MATLAB. Least square fitting is used to fit the polynomial equations into experiment data.

3.4 Battery Charging Efficiency

Since there is no opposition to the flow of current during discharge and the discharging efficiency is considered to be 100%, therefore, the charging efficiency can be calculated as:

$$Efficiency = \frac{E_{out}}{E_{in}} \times 100\% \qquad (12)$$

E_{out} is the output energy from the battery and E_{in} is the total energy input.

$$\eta = \frac{E_D}{E_C} \times 100\% = \frac{\int_0^t I_{discharge} V_{bat}\, dt}{\int_0^t I_{charge} V_{bat}\, dt} \qquad (13)$$

E_D is total energy during discharging and E_C is total energy during charging. The integration in (13) is solved using Simpson's rule.

3.5 Model Application to Measured Data

An experiment [28] was conducted at the University of Lagos, Akoka-Yaba, Lagos (GPS Coordinates: 6.519162°N, 3.399284°E) where solar photovoltaic module current readings were taken starting at 8:30am to 5:00pm at an interval of 30mins over a month period. The average daily values of the current readings are shown in Fig. 2.

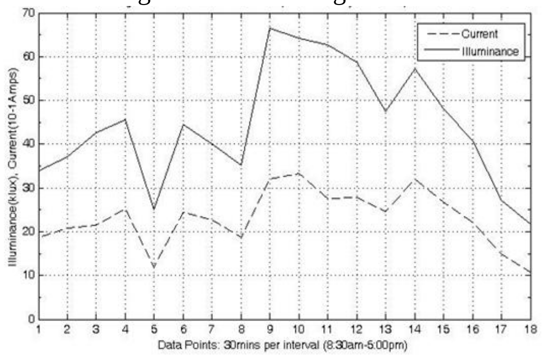


Figure 2: Variation of average daily illuminance and current output at regular time intervals

The time series current is simulated using the advanced programmable battery testing system (Cadex C8000) with the following custom program used:

- Discharge at 0.1C
- Charge battery at 1.875A for 30 minutes
- Charge battery at 2.083A for 30 minutes
- Charge battery at 2.15A for 30 minutes
- Charge battery at 2.517A for 30 minutes
- Charge battery at 1.2A for 30 minutes
- Charge battery at 2.45A for 30 minutes
- Charge battery at 2.283A for 30 minutes
- Charge battery at 1.88A for 30 minutes
- Charge battery at 3.2A for 30 minutes
- Charge battery at 3.333A for 30 minutes
- Charge battery at 2.75A for 30 minutes
- Charge battery at 2.7865A for 30 minutes
- Charge battery at 2.457A for 30 minutes
- Charge battery at 3.2A for 30 minutes
- Charge battery at 2.671A for 30 minutes
- Charge battery at 2.2A for 30 minutes
- Charge battery at 1.486A for 30 minutes
- Charge battery at 1.071A for 30 minutes

The corresponding time series battery voltages are obtained and the graphical illustration shown in Fig. 3.

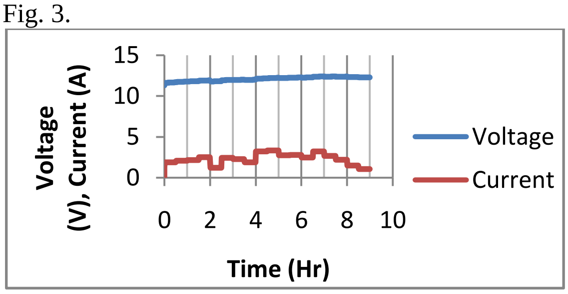


Figure 3: PV module currents and the corresponding battery voltages simulated using Cadex C8000

The battery state-of-charge is estimated using the battery state-of-charge and charge voltage models. (7)is solved using bisection method.

By experiment, the state-of-charge at the end of each interval is gotten by discharging the battery to end-of-discharge using the following custom program:

- Discharge at 0.1C
- Charge battery at 1.875A for 30 minutes
- Discharge at 0.1C
- Charge battery at 1.875A for 30 minutes
- Charge battery at 2.083A for 30 minutes
- Discharge at 0.1C
- Charge battery at 1.875A for 30 minutes
- Charge battery at 2.083A for 30 minutes
- Charge battery at 2.15A for 30 minutes
- Discharge at 0.1C etc.

IV. RESULTS AND DISCUSSION

4.1 Estimation of Parameters $a_1, a_2, a_3, \ldots, f_3, f_4, f_5$

The parameters are determined using the Least Squares Fitting method. From experimental tests, the parameters calculated using MATLAB are:

$$\begin{pmatrix} a1 & a2 & a3 & a4 & a5 \\ b1 & b2 & b3 & b4 & b5 \\ c1 & c2 & c3 & c4 & c5 \\ d1 & d2 & d3 & d4 & d5 \\ e1 & e2 & e3 & e4 & e5 \\ f1 & f2 & f3 & f4 & f5 \end{pmatrix} = \begin{pmatrix} -0.4927 & 7.8651 & -45.3569 & 112.6562 & -72.6767 \\ 1.2816 & -20.3373 & 116.4895 & -285.5322 & 176.8800 \\ -1.2527 & 19.7574 & -112.3796 & 271.6327 & -160.6257 \\ 0.5706 & -8.9518 & 50.6277 & -120.8717 & 67.9411 \\ -0.1184 & 1.8481 & -10.3942 & 24.5316 & -11.5586 \\ 0.0067 & -0.1036 & 0.5873 & -1.4283 & 11.8298 \end{pmatrix} \quad I < 0$$

$$= \begin{pmatrix} 0.6280 & -6.3319 & 14.9344 & 10.6099 & 10.5067 \\ -0.9391 & 7.0908 & 4.5169 & -108.8711 & 37.3174 \\ 0.1520 & 3.3143 & -50.6570 & 188.7088 & -96.2568 \\ 0.3143 & -6.6296 & 46.0140 & -125.8403 & 71.1605 \\ -0.1573 & 2.6526 & -15.5703 & 37.3023 & -20.9687 \\ 0.0276 & -0.4506 & 2.5796 & -5.9765 & 16.0140 \end{pmatrix} \quad I > 0 \qquad (14)$$

where I>0 represents charging process and I<0 the discharging process. The parameters can be used in the battery model for multi-purpose simulations.

4.2 Validation of Battery Charge Voltage Model

The battery charge voltage model's accuracy is shown in Fig.4 which compares the simulated and experimental values. The results show that the model can accurately predict the relationship between battery voltage and state-of-charge during charging and discharging process.

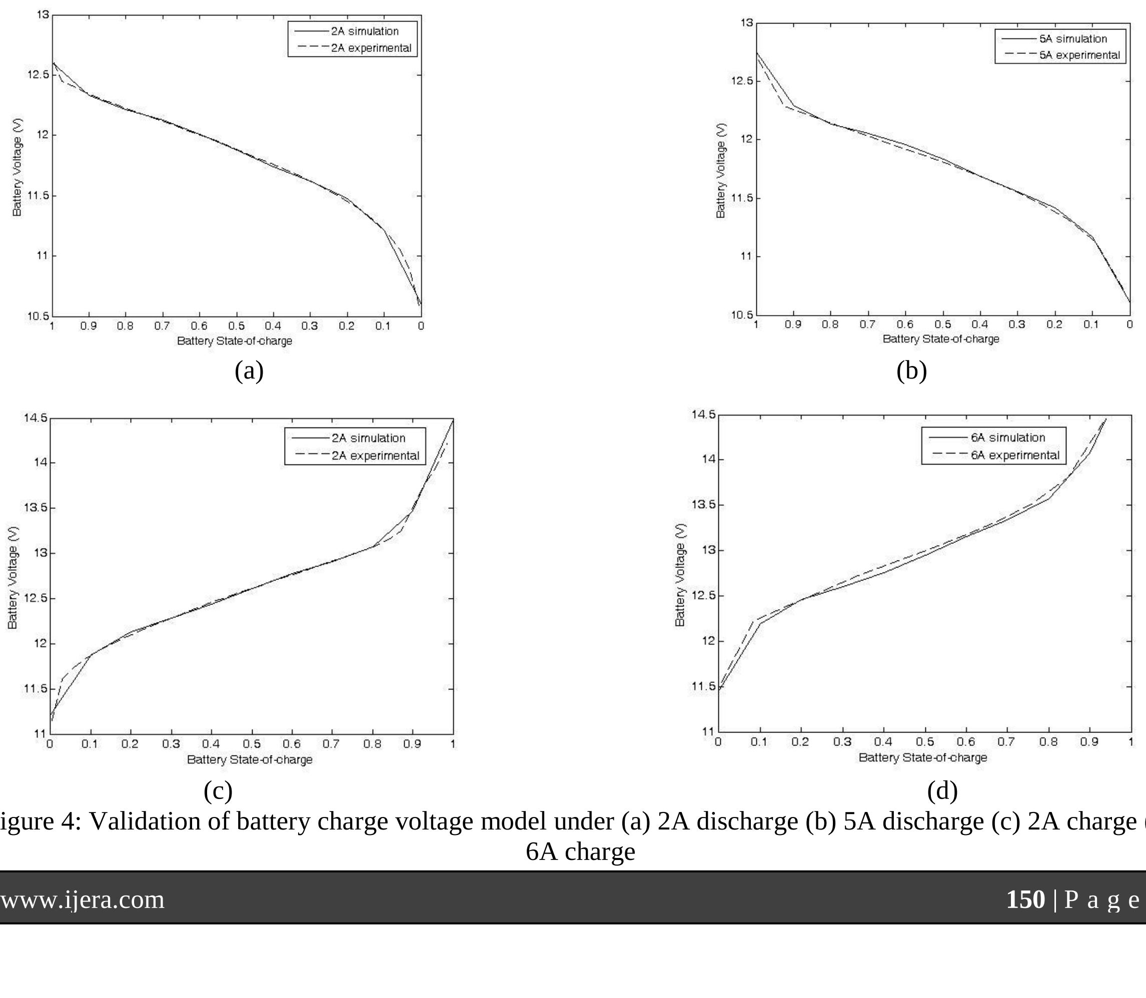


Figure 4: Validation of battery charge voltage model under (a) 2A discharge (b) 5A discharge (c) 2A charge (d) 6A charge

Battery state-of-charge is a measure of how much current the battery can deliver after a discharge or charge. SOC has its value between 0 and 1. 0% SOC does not mean that the battery can no longer deliver an amount of current; it means the battery cannot go below this value without causing some kind of (possibly irreversible) damage [29]. Figure 4 shows that the relationship between battery terminal voltage and SOC is fairly linear except at the initial and final stages of SOC.

4.3 Battery Voltage Curves for Different Current Rates

Fig. 5 and Fig.6 show battery voltage variations measured under charging and discharging currents respectively. From Fig. 5, as the fully discharged battery is charged, the voltage initially rises quickly; but as the charging progresses, the rate of voltage rise slows down; as the battery approaches full charge, the voltage rises quickly again. A similar condition is seen in Fig. 6 where the voltage decreases quickly at the initial and final stages of the discharge process.

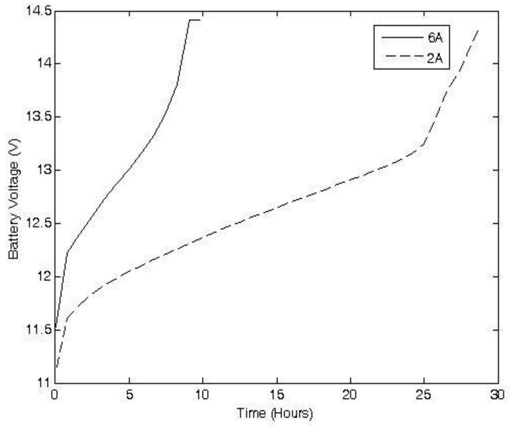


Figure 5: Battery voltage variations measured under charging currents of 6A and 2A

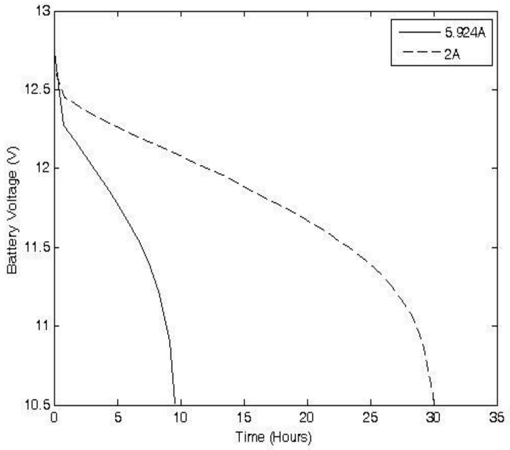


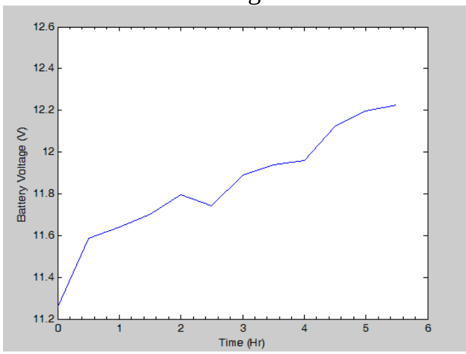
Figure 6: Battery voltage variations measured under discharging currents of 5.924A and 2A

4.4 Battery Charging Efficiency

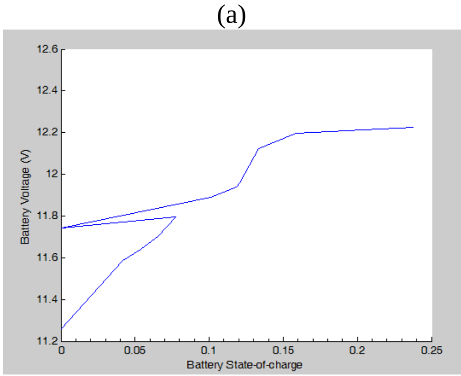
The charging efficiency of the battery estimated from (13) using experimental data is 0.8703. This value is close to 0.9 used in the simulation.

4.5 Battery Charge Voltage Model Application to Measured Data

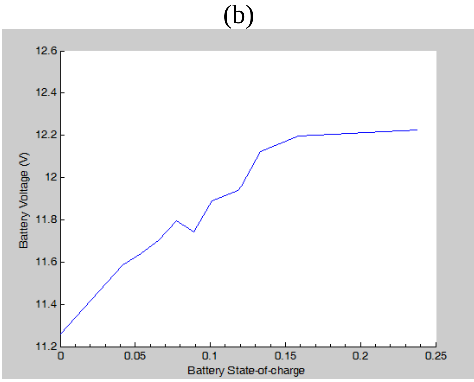
Variation in solar radiation results in the variation of photovoltaic module current and voltage. From Fig. 7, error occur using (7) directly because the model detects reduction in PV module voltage (which is as a result of lowering of solar radiation) as a reduction in battery state-of-charge. This error is corrected by compensating the battery charge voltage model with the state-of-charge model.



(a)



(b)



(c)

Figure 7: Matlab program display of (a) Battery voltage curve (b) Battery state-of-charge showing error (c) Adjusted battery state-of-charge

4.6 Comparison between Model Simulation Result and Measured Data

Fig. 8 shows the application of the simulation models to measured data. This confirms that the battery state-of-charge model is fairly accurate. The major concern is that the model results into errors if the initial/starting state-of-charge is not precisely determined. This however, can be estimated using the battery charge voltage model.

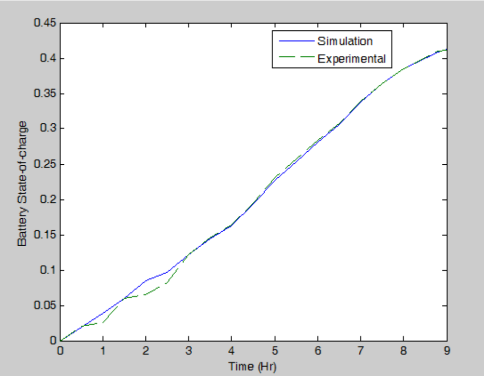


Figure 8: Comparison between Model Simulation Result and Measured Data

V. CONCLUSION

Energy storage through the use of battery is widely used in photovoltaic system applications to create a balance between the intermittent supply of solar radiation and energy demand. To manage the battery to its best potential, the prediction of its state-of-charge is essential. However, the state-of-charge of a connected battery cannot be measured, therefore, two estimation models are studied. These models are battery state-of-charge using ampere-hour counting method and battery charge voltage models. The battery charge voltage characteristic response is modeled by using the equation fit method which expresses the battery charge voltage variations by a 5th order polynomial in term of the battery state-of-charge and the battery current. This model which is implemented using MATLAB predicts the state-of-charge following the measure of the battery voltage under load. It is then corrected for errors which may result from reduced charge voltage due to variation of solar radiation. The accuracy of the models is verified in various experiments involving a number of charging and discharging cycles under laboratory experiments.

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