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# Charge Estimation of Selected Rechargeable Batteries in the Nigerian Market

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**ABSTRACT**

*Deep Cycle Batteries are used in renewable energy systems that require the storage of electricity. Many challenges remain unsolved to characterize and manage the battery. Among them, one fundamental issue is the estimation of state of charge (SoC). SoC, expressed in percentage, refers to the amount of capacity available in a battery. The aim of this research is to carry out State of Charge Estimation of some selected Rechargeable lead-acid batteries available in the Nigerian market, using the open circuit voltage method. The batteries were selected based on affordability and availability in the Nigerian market. The SoC of three selected 100AH rechargeable batteries was estimated from open circuit voltage method, by using data obtained from controlled charging and discharging of the batteries under review, for the three batteries considered, graphs of open circuit voltage versus SoC and discharge curve were developed. Results from analysis of the developed curves, would guide battery users in making informed decision before purchasing any of the batteries reviewed. It was observed that mercury has the highest operating voltage range, with that of Safepower battery the lowest.*

## 1. Introduction

The today world depends largely on fossil fuels namely coal, gas and oil for energy supply. However, their reserves are limited and the environmental concerns are haunting the society but a sustainable utilization of energy is the only achievable solution to cope with these problems. Thus, the conversion and storage of energy is a necessary step for global efficiency of the energy generation and utilization process. Battery is the most widely used energy storage device [1]. An electric battery is a device that directly converts chemical energy into electrical energy. State of Charge (SoC) estimation is a fundamental challenge for the use of battery. The SoC of a battery is used to describe its remaining capacity, and it is a very important parameter for a control strategy [2]. The SoC as an important parameter of measuring battery performance helps to protect the battery, prevent over discharge, improve the battery life and allows the application to make rational control strategies to save energy [3]. It is difficult to estimate the SoC of a battery because as a chemical energy storage source, its chemical energy cannot be directly accessed [4]. Accurate estimation of the SoC remains very complex and it is difficult to implement. This is because battery models are limited and there are parametric uncertainties [5]. Many examples of poor accuracy and reliability of the estimation of the SoC are found in practice [6]. Rechargeable batteries have lower total cost of use and environmental impact than disposable batteries. They have higher initial cost, but its long term benefits outweigh this initial cost as it can be recharged very cheaply and used many times. Rechargeable batteries are used in both high and low drain applications. They are used for portable consumer devices, automobile starters, light vehicles, such as motorized wheelchairs, golf carts, electric bicycles, electric forklifts, tools and uninterrupted power supplies. Rechargeable batteries are found in different shapes and sizes ranging from a button cell to megawatt systems. Some of the commonly used chemistries include; Nickel Cadmium (NiCd) Battery, Lead Acid Battery, Lithium Ion (Li-ion) Battery, Nickel Metal Hydride (NiMH) Battery, Silver Zinc (Ag-Zn) Battery and Lithium Polymer (Li-Pol) Battery [7]. State of charge is important for modelling and battery management. A well estimated SoC presents many advantages such as longer life of battery, increased reliability and better battery performance. This study aims to carry out State of Charge estimation of selected rechargeable lead-acid batteries in the Nigerian market using the open circuit voltage method. This will help projective users of these batteries make informed decision before purchasing.

**1.1 Lead Battery Chemistry**

Gaston Planté invented lead acid batteries in the year 1859. They are of low cost, robust and has the ability to withstand some rough conditions. However, lead batteries are too heavy and big to be subjected for intermittent loads in power applications leading to shorter life cycle as against its use in automobiles. Lead acid batteries are made up of a lead-dioxide cathode, a sulphuric acid solution electrolyte and lead anode [8]. During discharge, the lead (negative plate) and lead dioxide (positive plate) react with the electrolyte to produce lead sulfate, water and energy. There is reverse in the circle when it is charging. Water and lead sulfate are converted to lead oxide, sulfuric acid and lead oxide through an electro-chemical process by an external charging source [9].
The lead-Acid battery stores voltage (potential energy) in electrons form. When a resistive load in connected across the battery's negative and positive terminals, the circuit is closed and energy is taken from the battery. The following is the chemistry behind a lead-acid battery [10];

$$Pb + PbO_2 + 4H+ + 2SO_4^{2-} \rightarrow 2PbSO_4 + 2H_2O$$

Which can be broken up into the following half reactions:
Oxidation at the Anode:

$$Pb \rightarrow Pb_2^{+}$$
$$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^{-}$$

Reduction at the Cathode:

$$PbO_2 \rightarrow Pb_2^{+}$$
$$PbO_2 + SO_4^{2-} + 4H^{+} + 2e^{-} \rightarrow PbSO_4 + 2H_2O$$

**1.2 Battery Storage**

Electrical energy is stored in battery in a reversible chemical reaction. It is storage capacity is rated in amp-hours. 1 amp-hour amounts to taking 1 amp steadily for one hour. A conventional 12V system can have 800 amp-hours of battery capacity. It implies that the battery can take 100 amps for 8hours if fully discharged from its fully charged state. However, discharging a battery completely reduces its life duration. Most batteries have discharge depth of 50%, that is, it discharges to 50% or more of its capacity before recharging. As compared to other batteries, lead acid batteries have been in use since 19$^{th}$ century. And they remain indispensable because they are safe, dependable, durable and cheap. Lead acid battery is simple and easy to manufacture, with a strong global supply chain [11].

## 1.3 State of Charge

State of Charge (SoC) of a battery shows the remaining capacity inside the battery and it is usually expressed in percentage. If SoC is 100%, it indicates that the battery is fully charged. If SoC is 0%, it indicates that the battery is empty. The SoC of a battery is simply calculated using Equation (1) below [8],

$$SoC = SoC_i - \frac{\int I \, dt}{Q_{nom}} \tag{1}$$

Where,
$SoC_i$ = Initial SoC.
$Q_{nom}$ = Nominal Capacity of the battery.
I = Current flowing through the battery.
The current magnitude is positive for the process of discharging and negative for charging process. Having a good knowledge of State of Charge gives additional control over the process of discharging and charging which can be applied for better utilization of stored energy.
A good estimation of SoC results to better utilization of stored energy, longer battery life, improves convenience of the user and increased reliability of the battery pack. SoC is strongly dependent on temperature and age of the battery. The battery parameters which are directly measurable are the voltage terminals, operating currents and surface temperatures. But, the complex inter-relationship among these parameters makes the estimation of SoC a difficult task [12]. Developing efficient yet accurate SoC estimation algorithms remains a challenging task.

### 1.3.1 Factors affecting state of charge (SOC)

There are many factors that affects the operation of batteries. It is worthy of note that due to many interactions, the effects can generally be presented and each factor poses more influence under the more stringent operating conditions. For instance, storage effect is more notable with high storage temperatures, long periods and other more severe discharge conditions following storage. After a given period of storage, the loss of capacity compared with a fresh battery will be greater under heavy loads than under light loads. On a similar note, the noted capacity loss at low temperatures (compared with normal discharge temperature) would be greater at heavy load than at light or moderate loads. It should be noted that within a battery design, there are bound to be differences in performance from various manufacturers and between various versions of the same battery be it standard, heavy-duty or premium. There are also deviations in performance from production lot to production lot, which are experienced in the process of manufacturing [13]. Factors that affect the accurate SoC estimation of a battery include the following;

i. Temperature
ii. Ageing
iii. Self-discharge.

## 1.4 Methods of SoC Estimation

There are three methods existing in literature for SoC estimation of a battery.

ii) Direct Measurements
iii) Book-Keeping Systems
iv) Adaptive Systems

For simplicity, only the direct measurement is discussed.

### (i) Direct Measurements

The method is based on the relation between a measured SoC and battery variable. This battery variable can be electrically measured in the practical set-up. The variables can be given as battery impedance (Z) and terminal voltage (V). Most of the battery variables relatively depend on the temperature (T). Therefore, the battery's temperature should be measured aside the voltage and impedance. The relation "$f_T$" is between the SoC and the measured battery variable, can be stored in the system [12]. The principle for estimation of SoC using direct measurement is in Equation (2) below.

$$SoC = f_T(V, Z) \tag{2}$$

A version of the direct measurement method of SoC estimation is the open circuit voltage measurement method. For lead-acid battery, SoC and open circuit voltage ($V_{(oc)}$) have a linear relationship between them and it can be represented by Equation (3) below [14]:

$$V_{(oc)} = a_1 x\, SoC_{(t)} + a_0 \tag{3}$$

Where:
SoC(t) = SoC of the battery at time t. a0 = battery terminal voltage when SoC= 0%.
a1 = value of SoC at 100%.
The estimated SoC is proportional to its open circuit voltage ($V_{(oc)}$) [15]. This relationship, which varies for different batteries can be plotted to show variation of SoC with $V_{(oc)}$ of the batteries [16].

## 2. Materials and Method

### 2.1 Materials

1) 3 x 100Ah, 12V of Luminous, Mercury and Safepower deep cycle batteries each.
2) Digital multimeter.
3) Connectors (16mm$^2$ each).
4) 800W, 12V Synergy Inverter.
5) Load bank (6 x 100W incandescent bulb).
6) 12 – 48V, 30 amps Battery Charger.

### 2.2 Method

SoC can be estimated by means of the open circuit voltage measurement using Equation (3). The following steps were carried out to determine the values of V(oc) at SoC of 100% = $a_1$ and $a_0$ for each battery.

i) The batteries were charged in turn using the adjustable battery charger adjusted to 12V and a maximum charging current of 10amps. The charger was disconnected when the charging current indicator on the battery charger indicated zero, this suggests that the battery is fully charged.

ii) The charged battery was left for two (2) hours after the charger was disconnected; the open circuit voltage was then measured and recorded. This gives the value of V(oc) at SoC of 100% for each of the batteries.

iii) The fully charged battery was connected to an AC load of 400W through the inverter.

iv) The open circuit voltage of the battery being discharged was measured at interval of 130mins (i.e. after delivery current to the load for 10 minutes, the battery is disconnected from the load and allowed to settle for 120 minutes before measuring the terminal voltage).

v) Step four (4) continued till the battery was fully discharged, and the open circuit voltage taken. This gives the value of $a_o$.

vi) From the value of $a_{0,}$ V(oc) at SoC of 100%, the value of $a_1$ in Equation (3) was determined for each battery.

vii) The values of SoC for each value of V(oc) were determined for Safepower battery, Luminous battery and Mercury battery from Equation (3) and they are as tabulated in Table 1, Table and Table 3 respectively.

viii) Graphs of V(oc) versus SoC, V(oc) versus time (discharge curve for a given load) were plotted for each battery and they are as shown in Figure 1 to Figure 4.

## 3. Results and Discussion

The results and resultant graphs of the measurements carried out are as presented below;

**Table 1:** Variation of SoC, VoC with time on a 400W load for Safepower Battery.

**Voc @ SoC of 100% = 13.35V, a0=11.09V, a1=2.26V**

| Time (Mins) | V(oc) Volts | SoC (%) |
|---|---|---|
| 0 | 13.35 | 100 |
| 10 | 12.82 | 76.54 |
| 20 | 12.29 | 53.09 |
| 30 | 12.19 | 48.67 |
| 40 | 12.08 | 43.8 |
| 50 | 11.91 | 36.28 |
| 60 | 11.74 | 28.76 |
| 70 | 11.4 | 13.72 |
| 80 | 11.09 | 0 |

**Table 2:** Variation of SoC, Voc with time on a 400W load for Luminous Battery

**Voc @ SoC of 100% = 13.36V, a0=11.26V, a1=2.10V**

| Time (Mins) | V(oc) Volts | SoC (%) |
|---|---|---|
| 0 | 13.36 | 100 |
| 10 | 12.41 | 54.76 |
| 20 | 12.32 | 50.48 |
| 30 | 12.25 | 47.14 |
| 40 | 12.13 | 41.43 |
| 50 | 12.02 | 36.19 |
| 60 | 11.89 | 30 |
| 70 | 11.74 | 22.86 |
| 80 | 11.56 | 14.29 |
| 90 | 11.26 | 0 |

**Table 3:** Variations of SoC, Voc with time on a 400W Load for Mercury Battery

**Voc @ SoC of 100% = 13.48V, a0=11.56V, a1=1.92V**

| Time (Mins) | V(oc) Volts | SoC (%) |
|---|---|---|
| 0 | 13.48 | 100 |
| 10 | 12.44 | 45.83 |
| 20 | 12.39 | 43.23 |
| 30 | 12.32 | 39.58 |
| 40 | 12.23 | 34.9 |
| 50 | 12.12 | 29.16 |
| 60 | 12.00 | 22.92 |
| 70 | 11.88 | 16.67 |
| 80 | 11.73 | 8.86 |
| 90 | 11.56 | 0.00 |

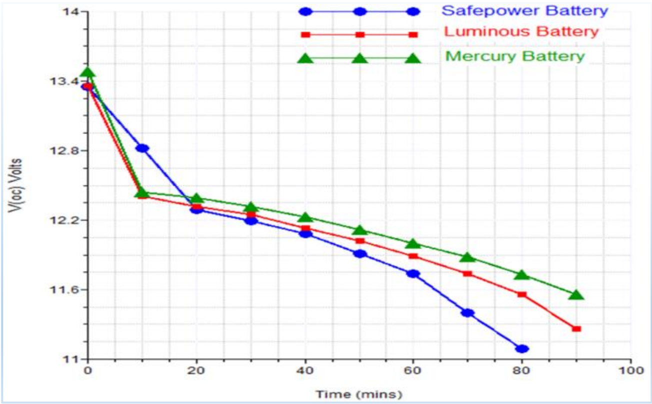


**Figure 1:** A graph of V(oc) against time for the three batteries

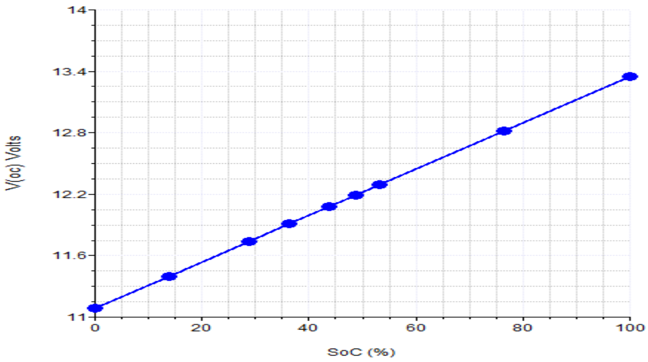


**Figure 2:** Graph of SoC against V(oc) for Safepower Battery

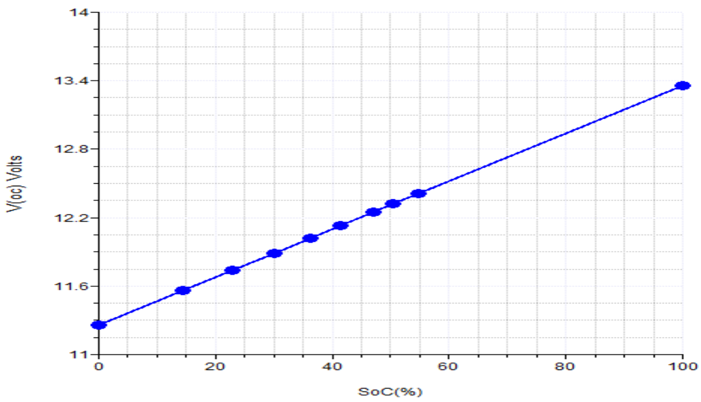


**Figure 3:** Graph of SoC against V(oc) for Luminous Battery

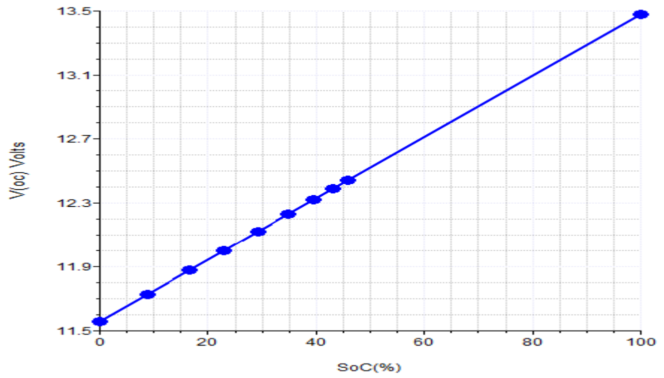


**Figure 4:** Graph of SoC against V(oc) for Mercury Battery

The results obtained as depicted in Figure 1 to Figure 4 show the status of the batteries under consideration.
The voltage threshold for Safepower, Luminous and Mercury battery is 13.35V, 13.36V and 13.48V respectively, while the depth of discharge is 11.09V, 11.26V and 11.56V respectively. This shows that out of the three batteries considered, mercury had the highest operating voltage range, while that of Safepower battery had the lowest considering their various level of discharge depth. Safepower battery had better response to switching transients than the other batteries as can be seen in Figure 1.

When a load of 400W was considered, the average rate of voltage decay was recorded to be 0.0283volts per minute for Safepower battery, 0.0233volts per minute for luminous and 0.0213 volts per minute for Mercury battery. This means that mercury battery had a slower rate of voltage decay. This voltage decay process takes place as a result of depletion of sulphuric acid in the electrolyte. Every battery applies electrochemical reaction in the conversion of chemical energy into electrical energy. As the 400W load was connected, the sulphate ions gave up its negative charge as they drifted to the negative plates, while other remaining sulphate reacted with the active material on the plate to give lead sulphate. Thus, the strength of the electrolyte was reduced and the plates acted as an insulator. This entire process resulted to movement of ions around the electrolyte, thereby leading to current flow. As the battery gets discharged, the ions in the electrolyte decreases as it gets coated with sulphate, leading to voltage decay. It was also discovered that it took 80 minutes for Safepower battery to drop from its threshold voltage to its cut off voltage, while for Luminous and Mercury batteries it took 90 minutes each. These variations in duration and rate of voltage decay in the various batteries is due to the level of internal resistance in the various batteries. It was deduced that energy available for Safepower, Luminous and Mercury batteries decreased by 1% for each voltage decay of 0.0226V, 0.021V and 0.0192V respectively.
Conventionally, relationship between SoC and open circuit voltage (OCV) is considered when estimating the SoC for deep cycle battery. This relationship is linear in nature; it takes into account the point when the battery is fully charged to the point when it discharges completely. Therefore, we can see that the SoC and open circuit voltage (OCV) of the three batteries had linear relationships which is evident in Figure 2, Figure 3 and Figure 4.

## 4. Conclusion and Recommendations

Using the open circuit voltage method, the State of Charge of rechargeable lead-acid batteries was carried out. Batteries employed were three brands of batteries (Safepower, Mercury and Luminous) in the Nigerian market. These specific batteries were chosen based on the level of affordability and availability in the Nigerian market. From the test results carried out on the three batteries, it was

observed that mercury has the highest operating voltage range, with that of Safepower battery the lowest. Again, Safepower battery has better response to switching transients than the other batteries. Mercury was also observed to have the slowest voltage decay rate.
In the estimation technique, the aging factor was not considered. Thus, the batteries deterioration values were overlooked.
Conclusively, this method is a forward step in the estimation of SoC. However, more study and measuring can be carried out for more precise and efficient battery monitoring.
Every battery undergoes self-discharge, but the discharge rate is dependent on the chemical compositions in the battery. The following can be recommended for battery storage;
i) Deep cycle batteries should not be exposed to heat sources. Increase in temperature leads to increase in the reaction in a battery, as a result subjecting batteries to a hot environment speeds up the rate of self-discharge. Therefore, they should be stored in a dry and cool locations.
However, in extremely cold conditions batteries may be subjected to freezing and freezing leads to plate damages. Therefore, batteries subjected to such conditions should be fully charged and stored.
ii) The batteries should be recharged when the voltage drops below 50% of SoC, a 12.4 V(oc) is recommendable. To prevent sulphation, lead battery should be stored fully charged.
To prolong the life of battery, the batteries can be stored at $10^oC$, but care should be made to ensure that the battery does not freeze. Lead battery freezes at $-36^oC$, but increases to $0^oC$ when in a fully discharged state and at that point the electrolyte turns to water.

## 5. Acknowledgement

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## 6. Conflict of Interest

There is no conflict of interest associated with this work.

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