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Real Time Estimation of SoC and SoH of Batteries

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Abstract- This paper presents the real time estimation of State of Charge and State of Health of a battery using a hybrid technique. The technique described in this paper employs: (1) Coulomb Counting Method, (2) Electrical Circuit Model and (3) Mathematical model based on Peukert Law to estimate these parameters. The paper presents the method of estimating the internal resistance of the battery to determine the open-circuit voltage to estimate the State of Charge and State of Health. The proposed technique simulated using Simulink/MATLAB and results were validated experimentally.

Keywords State-of-Charge, State-of-Health, Battery, Discharging Current.

1. Introduction

Batteries play a very significant role in various areas such as consumer electronics, automotive electronics, and renewable energy systems. Many industrial applications have been using chemical batteries as the main energy sources. These are being used as the primary energy sources in electric car industry. The major drawbacks of these types of batteries are short life cycle, low power density and high cost [1-2]. Yukihiro Tanaka et al [3] have indicated that the amount of carbon dioxide emission by the use of fossil fuels accounts for 60% of the total greenhouse gas. On the other hand, transportation sector alone accounts for 13% of the emission of the carbon dioxide in global average. The expected duration of available fossil fuel is about 56 years only [3]. Zn-Cu and Al-Cu electrodes could be used to generate electricity from seawater,for operating electrical equipment at a distance [28]. A recent trend shows that the Electric Vehicles/Hybrid Electric Vehicles (EV/HEV) [26] have been the new paradigm of transportation in resolving the global warming by reducing the pollution in the environment.

All these areas have posed a great challenge in terms of battery life expectancy, efficiency, energy consumption, and cost of use. Therefore, battery must be reliable, able to deliver the required power and energy based on the demand. To ensure the efficient use of battery, a continuous vigil on its parameters such as State of Charge (SoC) and State of Health (SoH) is necessary. Since these parameters not only determines remaining capacity of the battery but also reflect its performance, thus the estimation of SoC and SoH is extremely important [4]. The efficient operation and management of battery based systems become very critical if proper estimation of SoC and SoH not done. This situation can very well expect in the electric car application and may result in dire consequences due to depletion of the battery pack [5]. Battery has thus become one of the critical components of the EV and other allied electric and electronic systems.

Thus, the estimation of SoC and SoH of any battery is extremely important in ensuring the efficient delivery of energy to the applications such as EV/HEV, consumer electronics so on and so forth.

2. Review of Literature

With the development of EV/HEV, and Plug–In Hybrid Electric Vehicle technologies several current and new trends in estimation of SoC and SoH for batteries have been proposed. An over view of the various categories, and mathematical principles of estimating the SoC/SoH presented in [4]. The paper also has done the assessment of different methods and proposed the direction for future areas of development. This paper also dealt in detail the review of the SoC estimation under fixed and variable discharging conditions. They have also presented the classification of SoC estimation methods. The classification of these methods is different in different literatures. The major classifications listed in Table 1 [4].

A hybrid backup system for controlling EV based on optimized gain is tested in [27] for multiple objectives such as effective dynamical speed reference trajectory tracking, efficient power utilization, limited inrush current conditions and reduced AC-DC side transients and voltage excursions.

Table 1: Classification SoC Estimation Categories

Sl No	Categories
1	Direct Measurement Methods
2	Book-keeping Methods
3	Adaptive Systems
4	Hybrid Methods

John Cannarella, et al [5] presented a method of estimating SoC and SoH of a lithium-ion cell using mechanical stress, which can be either stack stress or strain. This paper indicates that the stress is related to SoH linearly. Therefore, it is advantages to complicated models. The paper also concluded that the mechanical measurements of SoC can detect self-discharge and do not rely on integration, which are two advantages over conventional Coulombs counting. Due to this mechanical measurements are being utilized in estimation of SoH/SoC. Xidong et al [6] has presented an adaptive algorithm to estimate the SoC of the LI-Ion batteries where in six electrical parameters were determined to estimate the SoC of the LI-Ion batteries.

Since the batteries are most commonly used for storing the energy in various applications, it is necessary that its behavioral study is important during charging and discharging cycle, which requires an appropriate model. S.M.Mousavi G. et al [7], have presented an over view of several electrical battery models. These models are classified into six categories. In this paper, electrical circuit modeling of batteries was classified into six main types of models consisting of (a) simple models, (b) Thevenin-based models, (c) impedance-based models, (d) runtime-based circuit models, (e) combined electrical circuit-based models, and (f) generic-based models. The electrical circuit models are implemented in dynamic simulation studies such as wind energy conversion systems, photovoltaic systems[30], and electric/hybrid vehicles systems[29]. The Thevenin models have a good transient response in a significant SoC and in a constant Voc; however, DC response and the battery run time predictions are not adequately carried out. Although some components have been augmented to the models in order to improve these defects (such as utilization of a variable capacitor), the run time error, voltage error and complication increase. The effects of temperature and SoC variations have not been generally considered in this model.

Liuis Farre, et al [8] has designed a microcontroller base Ampere hour meter to estimate the SoC of Lead-Acid batteries. Meter is designed based on the mathematical (Peukert law) model of a battery. Guoliang Wu et al [9] have established a method of determining the available capacity of the NIMH batteries with temperature correction at 25°C. With a correction factor, the estimation SoC of NiMH battery improves the precision. On a similar ground Noshin Omar et al [10] proposed a method based on Peukert law with modifications to estimate the available capacity of the lithium ion batteries. Zhiwei et al [11] has proposed on unscented Kalman's filter algorithms based adaptive SoC estimation method for lithium (Li)-ion batteries and shown that the method is accurate and computationally efficient. Results of the work show that it is suitable for embedded system implementation. SoC and SoH can be estimated with an accuracy error @3% between actual and estimated values.

The various existing methods of estimating SoC and SoH have been detailed in the review of literature. These methods have certain draw backs. For example, Coulombs counting method [4]-[6] suffers due to unknown initial SoC, effect of temperature and battery discharge current. Kalman filter method suffers [11] as it can only be employed for laboratory experiments. Mathematical model based methods have inaccurate value due to temperature effect and discharge current. It has been observed that the Peukert law can be used to other batteries such as Li-Ion, Ni-Mh with modifications. In order to mitigate the accuracy issue, a hybrid model consisting of Coulomb Counting method, Electrical Circuit model and mathematical model has been proposed.

The remainder of the paper is organized as follows: State of charge, state of health and their definitions are given Section 3. The basic constituent's methods and parametric modifications to them in the proposed hybrid method are presented in Section 4. Simulation of the proposed method is explained in Section 5. Experimental validation is detailed in Section 6. The Section 7, presents the results and analysis. Finally, the Section 8 gives conclusion

3. Definitions of SoC and SoH

3.1. State of Charge

The most expensive and critical component of EV/HEV/PHEV is battery. The performance if these vehicles directly depend upon the efficient utilization of the battery. Battery reliability, sustainability under various operating/environmental conditions can only be determined by way of continuous monitoring its parameters known as SoC and SoH. These parameters describe the remaining capacity, which in turn defines the run time of the vehicle. Estimation of these parameters protects the battery by preventing it from deep discharge, and improves the life expectancy. Short term capability of the battery is known as its SoC. In general, the SoC is defined as the ratio of its current capacity Q_t to the rated capacity Q_r as given in Equation (1)[4]. Rated capacity is generally defined by the manufacturers.

$$SoC_t = \frac{Q_t}{Q_r} \quad (1)$$

Where Q_t is capacity of the battery at time 't' and Q_r is rated capacity of the battery specified by the manufacturers.

From Equation (1) the initial SoC of the battery can be found by equating t=0.

$$SoC_0 = \frac{Q_0}{Q_r} = 100\% \quad (2)$$

Further, the current capacity of the battery can be expressed in terms of released capacity as shown in Equation (3).

$$Q_t = Q_0 - Q_{rl} \quad (3)$$

Where Q_0 is the initial capacity (100%) of the battery

and Q_{rl} is the released capacity of the battery to the load.

Hence, from (1) and (3) the SoC of the battery at any point of a time can be expressed as shown in Equation (4).

$$SoC_t = \frac{Q_0 - Q_{rl}}{Q_r} \quad (4)$$

From Equations (2) and (4) the SoC is expressed as in Equation (5).

$$SoC_t = \left(1 - \frac{Q_{rl}}{Q_r}\right) x\ 100\ \% \quad (5)$$

From Equation (5) it is clear that, the previous history and the amount of charge delivered to the load can be used to estimate the SoC

3.2. State of Health

The SoH is a “figure of merit” of the present condition of a battery compared to its ideal conditions. It decreases over time and use. It is an indication of the how much of the useful lifetime of the battery has been consumed and how much remains before it must be replaced. It must be noted that the SoH must be dealt or represented in terms of hours to indicate that the battery can safely supply or last for these many hours at the rate at which load is being supplied.

SoH of a battery is a subjective term and mainly depends on the application. The SoH indicates the state of the battery between the beginning of life (BoL) and end of life (EoL) in percentages. The EoL of a battery is reached when the battery cannot perform according to the minimum requirements.

The fully charged battery has its maximum charge that can be released to the load on demand. This charge varies from time to time based on charging and discharging rate of current, ageing etc. [22]. Hence, it is different from the rated capacity. Therefore, the SoH of a battery is defined as the ratio of maximum charge capacity to the rated capacity of the battery [22] as given in Equation (6).

$$SoH = \frac{Q_M}{Q_r} \quad (6)$$

Where Q_M is maximum releasable capacity battery and Q_r is rated capacity of the battery.

4. Proposed Method

As discussed in the previous sections, the proposed method is a hybrid model, consisting of coulombs counting method [4] [22], Electrical Circuit Model [7], and Mathematical Model [8] with corrections. The details of these basic constituent models and the parametric corrections are briefed in proceeding sections along with the estimation of final SoC and SoH.

4.1. Coulombs Counting Method

The Coulomb counting is the most commonly used method of estimating SoC as indicated by [4-6],[11-13]. In this method, the measured discharging current is integrated over time to determine the SoC. As given in Equation (7).

$$SoC_t = \left(1 - \frac{1}{Q_r}\int_0^{\tau} i_{\tau}\, d\tau\right) x\ 100\ \% \quad (7)$$

Where i_{τ} discharging current. The greatest advantage of this method is that the current can be estimated in real time and hence the SoC. The SoC estimated using this method is not accurate due to unknown initial value, and cumulative error that occurs during integration of current.

4.2. Electric Circuit Model

Since battery is used in various applications, an accurate modelling and simulation of a battery are necessary to evaluate the performance. Many researchers have presented the electrical model of a battery for the purpose[4][7]. In this model, electrical characteristics of the battery are considered and passive elements are used. There are various classes of models of which Thevenin-based models are shown in Figure 1[7].

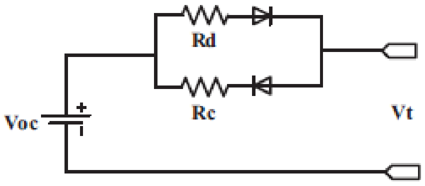


Figure 1: Modified Thevenin Battery Model.

The modified Thevenin battery model shown in Figure 1 consists of an ideal voltage source and two series internal resistance. Where Discharging (Rd) or charging (Rc) internal resistance of the battery. The respective internal resistances are bypassed while charging or discharging due to presence of two diodes and are ideal in nature. The typical discharge curve of a battery is shown in Figure 2, [14]. Considering, the linear part of the battery discharge curve the open circuit voltage of a battery is given by Equation (8).

$$V_{oc} = V_t \pm IR \quad (8)$$

Where: V_{oc} is open circuit voltage or EMF of battery; V_t is terminal voltage; I is discharge/charge current; R is internal resistance of battery either Rd or Rc.

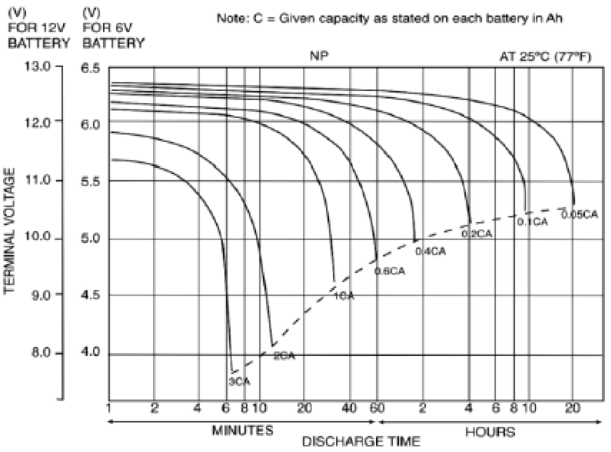


Fig. 2: Discharge characteristics of 12V/6V batteries [14]

The instantaneous EMF (V_{oc}) and the SoC are given as in Equation (9) and validated in [15] and [4]:

$$V_{oc} = \alpha\ SoC \pm V_{min} \tag{9}$$

Where V_{min} is the open circuit voltage at zero SoC i.e. 11.4V (For 12V nominal batteries). Note: Sometimes it is considered to be 10.5V. $\boldsymbol{\alpha}$ is the slope of $V_{oc}\ V_S\ SoC$ curve and has a value of 0.013 to 0.018V as indicated by manufacturers. [15]. SoC can be found by rewriting Equation (9), as in Equation (10):

$$SoC = \frac{V_{oc} - V_{min}}{\alpha} \tag{10}$$

4.3. Mathematical Model

Peukert Law [8], [9] is the most widely used method to estimate the discharging and charging efficiency of the batteries. In 1897, W. Peukert demonstrated that the discharge capacity, discharge current and time are related by an empirical Equation (11).

$$Q_{rl} = i^n \times t \tag{11}$$

Where Q_{rl} is released capacity; ‘i’ is actual Discharge Current; ‘t’is discharge time; ‘n’ is the constant.

Equation (11) indicates the discharged capacity with a one ampere discharge rate, which is actually not true for practical cells or battery. Therefore, for all practical purposes, the equation is reformulated [8], [9] and is given by:

$$Q_{rl} = K \times i^{(1-n)} \tag{12}$$

Where K and n are constants and are calculated from two different discharging currents with two discharge times as in Equation (13) and (14) respectively.

$$\mathrm{K} = {i_1}^n \times t_1 = {i_2}^n \times t_2 \tag{13}$$

$$n = \frac{lg(t_2|t_1)}{lg(i_1|i_2)} \tag{14}$$

From Equation (12), the coefficient of efficiency for a battery can be derived as in Equation (15):

$$\eta_d = i^{(1-n)} \tag{15}$$

Where: η_d =>Coefficient of efficiency (discharge). The value of ‘n’ varies between 1-1.3. Typically, it is 1.2.

4.4. Modifications to CCM

As discussed in sections (2), (4.1) the SoC estimated using Coulombs Counting Method (CCM) is inaccurate due to unknown initial SoC and cumulative error in current integration. To mitigate this inaccuracy issue, the coefficient of efficiency (Discharge) determined from Peukert Mathematical model (4.3) above is applied to the total power/energy released to the load over the entire period. This coefficient of efficiency (Discharge) called as a correction factor in the proposed method since it is applied to correct the cumulative error due to integration of discharge current. This correction factor of discharge is estimated from Equation (15). Now on applying this correction factor determined from (15) into Equation (7), the modified corrected SoC equation is given by Equation 16.

$$SoC_{tc} = \left(1 - \frac{1}{Q_r}\int_0^{\tau} \eta_d\ i_\tau\, d\tau\right) x100\% \tag{16}$$

Where: SoC_{tc} is corrected SoC.

4.5. Estimation of $\mathbf{V_{oc}}$ *by ECM*

As discussed in section (4.2) to estimate the SoC it is necessary to findV_{oc}. In the proposed method, V_{oc} is estimated in two ways - by internal resistance method and with rest period during discharge of a battery.

4.5.1 $\mathbf{V_{oc}}$ *Estimation by Internal Resistance Method*

As discussed in section (4.2), the $\boldsymbol{V_{oc}}$ can be determined using Equation (8) and is reproduced as $V_{oc} = V_t \pm IR$. Where V_{oc} is Open circuit voltage or EMF of battery; V_t is Terminal voltage; I is Discharge/charge current; R is Internal resistance of battery.

When battery is subjected to discharge, the terminal voltage and the discharge current can be easily measured. But the internal resistance is an unknown element and is the required parameter to determine the open circuit voltage. Therefore, it is now necessary to estimate internal resistance of the battery. As per the IEC 61951-1:2002/2005, internal resistance is found by a method called two-tier DC Load and the method is adopted in various works of researchers [24-25].

In this method, two sequential discharge loads of different magnitude currents and time durations are utilized. In the first instant battery discharges for 10 seconds at low current. In the second instant battery discharges for 3 seconds at high current. With voltage and current values, the resistance value is determined by Ohm's law. The load pattern of the battery in two tier DC load method is represented in Figure 3.

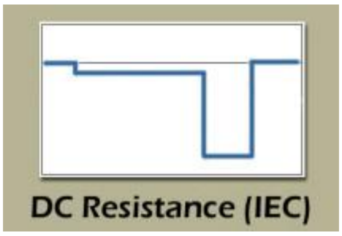


Fig. 3: Two-tier DC load pattern (IEC)

The internal resistance is found by using a relation in (17).

$$R = \frac{V_1 - V_2}{I_2 - I_1}\ \Omega \qquad (17)$$

Where V_1 Voltage is measured during low current and longer instant of time; V_2 is Voltage measured during the high current and shorter instant of time; I_1 is Current measured during longer instant of time; I_2 is Current measured during the shorter instant of time. On determining the internal resistance, the open circuit voltage is calculated using Equation (8). Then, the SoC is estimated by Equation (10).

4.5.2 $\mathbf{V_{oc}}$ *Estimation with Rest Period during Discharge of a Battery.*

Here, the battery is subjected to discharge with a particular load pattern shown in Figure 4 with fixed and variable load. The battery discharges for an hour and rests for 2 hours. The terminal voltage, current are measured for every discharge period and tabulated. Similarly, for every end of rest period the battery voltage is measured, which represents the open circuit voltage at that instant of time.

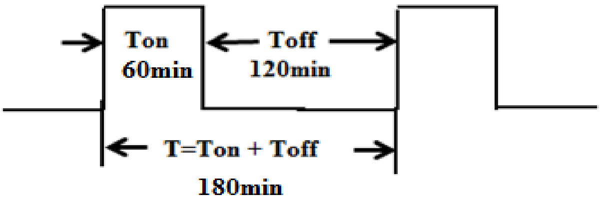


Fig. 4: Load Pattern to Estimate V_{oc}

The open circuit voltage measured at every rest period of battery, terminal voltage and current during the discharge period are used to estimate the SoC using the relation (10). The measured open circuit voltage is compared with that of calculated using internal resistance method.

4.5.3 Final SoC Estimation

The estimated state of charge of battery discussed in preceding sections (4.4), (4.5.1) and (4.5.2) are compared with each other and average of these three values is considered to indicate the final SoC.

4.6. Maximum Charge Capacity and SoH

As discussed in section (4.3), the Peukert Model is used to find the discharge capacity, which represents the maximum amount of releasable capacity Q_M. Using Equation (6), the SoH of a battery is estimated.

5. Simulink/Matlab Models

In this section, the proposed method is divided into various blocks. These blocks are modelled in Simulink and are presented along with simulation results.

5.1. Internal Resistance Estimation-Simulink

The internal resistance of a battery is estimated using a two tier DC load method described in section 4.5.1. In this model, two loads are selected such that one draws low current for 10 seconds and the other draws large current for 3 seconds as per IEC 61951-1:2002/2005. The Simulink model of this method is shown in Figure 5.

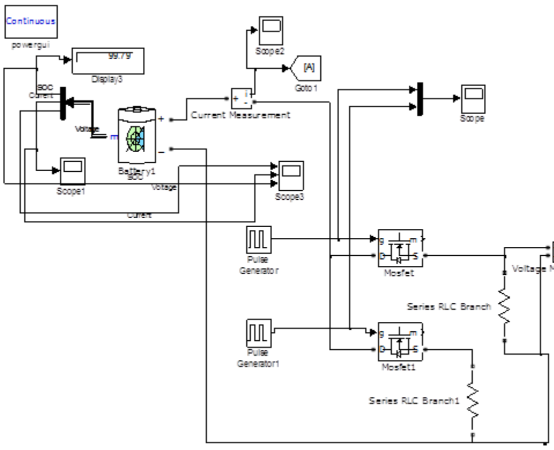


Fig. 5: Simulink Model of Internal Resistance Estimation.

The simulated waveforms are shown in Figure 6 indicating current, voltage and SoC. The voltage and current values derived from the simulation waveforms are tabulated in Table 2.

Battery Type: 12V, 7.5Ah, Lead Acid $R_i \leq 33m\Omega$					
Discharge Time (Sec)	V_1 Volts	V_2 Volts	I_1 Amps	I_2 Amps	R mΩ
10 + 3 =13	13.99	13.96	0.7A	1.7A	30

Table 2: Internal Resistance Estimation- Simulink/Matlab

5.2. Battery Discharge Constant load –Simulink

Here the battery is discharged with a constant load of 5W LED bulb (Approx 32Ω Load) to estimate the SoC and SoH. The battery is discharged with a load pattern described in section 4.5.2. The battery discharges till the SoC reaches 10%. This condition is derived using logical and relational operators of the simulnik/Matlab. The Simulink model of the same is shown in Figure 7 and the corresponding waveforms in Figure 8. The load pattern implemented in simulink is shown in Figure 9. The results of simulation are tabulated in Table 3.

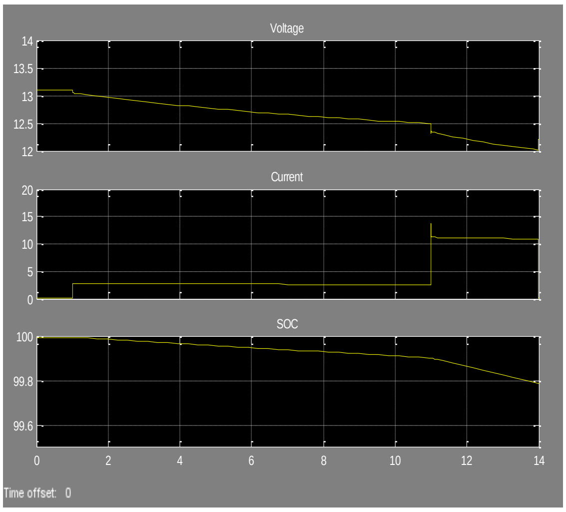


Fig. 6: Waveforms of Simulink model

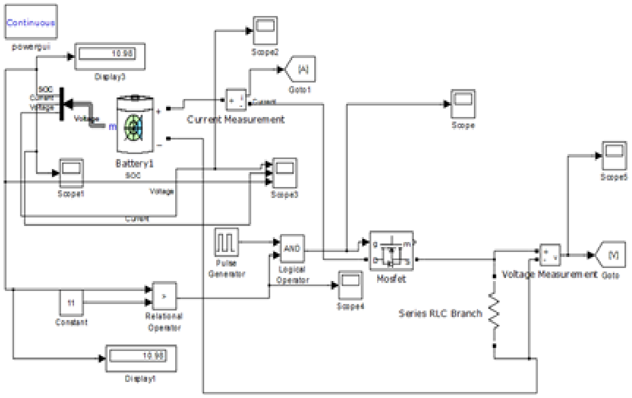


Fig. 7. Battery discharge model-Constant load

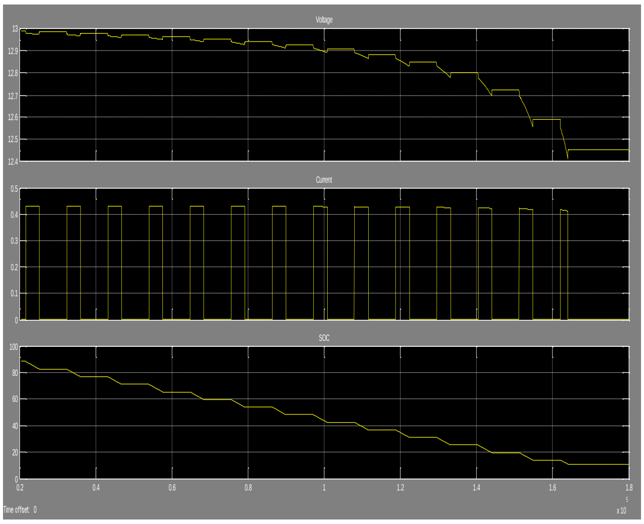


Fig. 8. Waveforms for Constant load

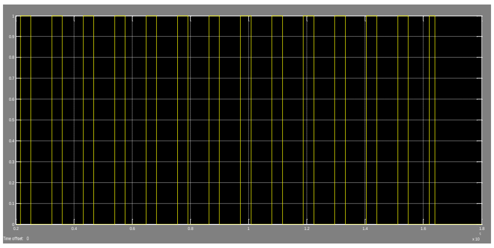


Fig.9. Load pattern – 1hr ON, 2hr OFF

Table 3. Simulation values derived from Simulink

Battery:12V,7.5Ah, Load: 31 Ω (Approx) Discharge Current:0.43A				
Sl No	Vt (V)	I (A)	Voc (V)	SoC (%)
1	12.98	0.43	12.99	90.6
2	12.975	0.43	12.985	89.5
3	12.97	0.43	12.98	82.5
4	12.96	0.43	12.975	77
5	12.954	0.43	12.965	71
6	12.943	0.43	12.955	65.5
7	12.93	0.43	12.943	59.5
8	12.91	0.43	12.925	54
9	12.893	0.43	12.921	48.2
10	12.865	0.43	12.91	36.5
11	12.83	0.43	12.884	31
12	12.78	0.43	12.85	25.4
13	12.70	0.43	12.8	19.7
14	12.55	0.43	12.73	14.15
15	12.44	0.43	12.6	11

5.3. Battery Discharge Constant load –Simulink

Here the battery is discharged with a variable load of 20Ω, 10Ω and 5Ω to estimate the SoC and SoH. The battery discharged till the SoC reaches 10%. Similar to constant load discharge, the logical and relational operators of the simulnik/Matlab are derived as shown in Figure 10 and the corresponding waveforms in Figure 11. The various parametric values derived from the Simulink waveforms of variable load are tabulated in Table 4.

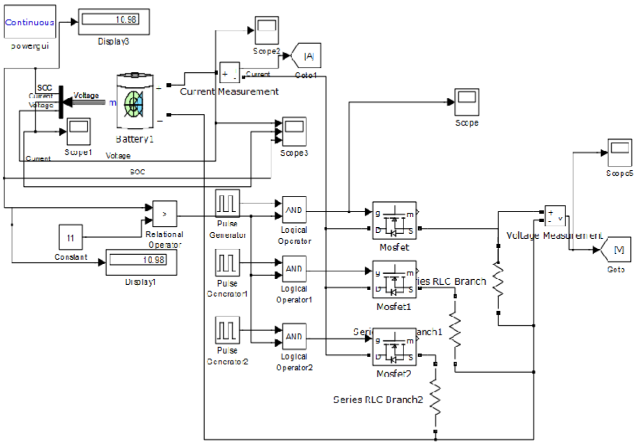


Fig. 10. Battery discharge model-Variable load

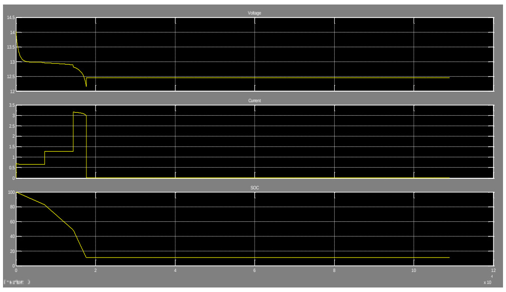


Fig. 11. Waveforms for Variable load

Table 4: Simulation values for Variable load

Battery:12V,7.5Ah, Load: variable				
Sl No	Vt (V)	I (A)	Load Ω	SoC (%)
1	12.97	0.65	20	82
2	12.8	1.28	10	49
3	12.35	3.1	5	10

6. Experimental Validation of Proposed Method

Experimental validation of the proposed method consists of estimating internal resistance, open circuit voltage, discharge current and terminal voltage.

6.1. Internal resistance measurement

The experiment is conducted on 12V, 7.5Ah, Lead Acid Battery. The experimental setup is shown in Figure 12 and Figure 13. As discussed in section (4.5.1) battery is discharged as per two-tier DC load method and the values are tabulated in Table 5.

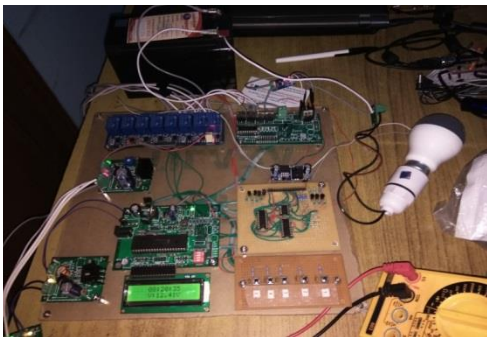


Fig. 12: Load OFF Condition

Fig. 13: Load ON Condition

Table 5: Test results of 12V, 7.5Ah Lead Acid Battery

Battery Type: 12V, 7.5Ah, Lead Acid					
Discharge Time (Sec)	V_1 Volts	V_2 Volts	I_1 Amps	I_2 Amps	R mΩ
10 + 3 =13	12.67	12.64	0.57	1.12	54

6.2. $\mathbf{V_{oc}}$ *Estimation –Constant load*

In this experiment, the battery is discharged with a constant load of 5W LED bulb. The parameters obtained during experiments are tabulated in Table 6. The load pattern described in section 4.5.2 is followed during experimental validation. Here the battery is put to rest for 2 hrs on discharging it for an hour.

Table 6: Battery discharge w. r. t. Figure 4

Battery:12V,7.5Ah, Load: 5W LED Bulb Discharge rate 0.055C.				
Sl No	Vt (V)	I (A)	Voc (V)	SoC (%)
1	12.77	0.41	12.78	100
2	12.67	0.41	12.71	93.5
3	12.53	0.41	12.67	90.7
4	12.47	0.41	12.62	87.14
5	12.41	0.41	12.58	84.28
6	12.38	0.41	12.43	73.57
7	12.27	0.41	12.37	69.28
8	12.20	0.41	12.30	64.28
9	12.17	0.41	12.24	60
10	12.08	0.41	12.18	55.71
11	12.02	0.41	12.10	50.1
12	11.98	0.41	12.09	49.30
13	11.86	0.41	12.0	42.85
14	11.79	0.41	11.98	41.43
15	11.71	0.41	11.88	34.29
16	11.63	0.41	11.79	13.57
17	11.51	0.41	11.54	10

6.3. $\mathbf{V_{oc}}$ *Estimation –Variable load*

Here the battery is discharged with a variable load of 20Ω, 10Ω and 5Ω to estimate the SoC and SoH. The battery discharged till the SoC reaches 10%. The results are tabulated in Table 7.

Table 7: Battery discharge-variable load

Battery:12V,7.5Ah, Load: Variable Discharge time: Continuous			
Sl No	Vt (V)	I (A)	Load Ω
1	12.68	0.57	20
2	12.20	1.12	10
3	11.41	2.57	5

7. Test Results and Analysis

In this section, results are computed from various equations using the values obtained from simulation and experiments.

7.1. Internal Resistance

Two tier DC load method described in section 4.5.1 was used to estimate the internal resistance of the battery by simulation and experimentally. The internal resistance is estimated by using Equation (17).

$$R = \frac{V_1 - V_2}{I_2 - I_1}\ \Omega$$

$$R_{isim} = \frac{13.99-13.96}{1.7-0.7}\ \Omega \text{ Hence, } \quad R_{isim} = 0.03\ \Omega \qquad (18)$$

Where R_{isim} resistance estimated from simulation results.

Similarly, experimentally the internal resistance is given by using relation (17) again and let this be R_{iexp}

$$R_{iexp} = \frac{12.67-12.64}{1.12-0.57}\ \Omega \text{ Hence } R_{iexp} = 0.054\Omega \qquad (19)$$

7.2. $\mathbf{V_{oc}}$ *Estimation –Constant load*

The internal drop of the batter is calculated from the internal resistance and the load current. This drop is given by:

$$V_{irsim} = I\ x\ R_{isim} = 0.43\ x\ 0.03\ \Omega \text{ Hence, } V_{irsim} = 0.0129V \qquad (20)$$

The $\mathbf{V_{oc}}$ calculated using this drop and terminal voltage derived from simulation is tabulated in Table 8. Similarly, the internal drop is calculated from the internal resistance and load current obtained from experiment and is given by;

$$V_{irexp} = I\ x\ R_{iexp} = 0.41\ x\ 0.054\ \Omega \text{ Hence } V_{irexp} = 0.0221V \qquad (21)$$

Table 8: $\mathbf{V_{oc}}$ by Simulation- Constant Load

Battery:12V,7.5Ah, Load: 31 Ω (Approx) Discharge Current:0.43A (Simulated)				
Sl No	Vt (V)	I (A)	Voc (V)	Voc (V) Calculated
1	12.98	0.43	12.99	12.993
2	12.975	0.43	12.985	12.987
3	12.97	0.43	12.98	12.982
4	12.96	0.43	12.975	12.973
5	12.954	0.43	12.965	12.966
6	12.943	0.43	12.955	12.956
7	12.93	0.43	12.943	12.943
8	12.91	0.43	12.925	12.923
9	12.893	0.43	12.921	12.906
10	12.865	0.43	12.91	12.879
11	12.83	0.43	12.884	12.843
12	12.78	0.43	12.85	12.792
13	12.70	0.43	12.8	12.713
14	12.55	0.43	12.73	12.563
15	12.44	0.43	12.6	12.452

The $\mathbf{V_{oc}}$ calculated using this drop and terminal voltage obtained from experiment is tabulated in Table 9. Here the load pattern followed during simulation and experiment is shown in Figure 4.

Table 9: $\mathbf{V_{oc}}$ by Experiment- Constant Load

Battery:12V,7.5Ah, Load: 5W LED bulb Discharge Current:0.41A (Experiment)				
Sl No	Vt (V)	I (A)	Voc (V)	Voc (V) Calculated
1	12.77	0.41	12.78	12.792
2	12.67	0.41	12.71	12.692
3	12.53	0.41	12.67	12.552
4	12.47	0.41	12.62	12.492
5	12.41	0.41	12.58	12.433
6	12.38	0.41	12.43	12.402
7	12.27	0.41	12.37	12.292
8	12.20	0.41	12.30	12.222
9	12.17	0.41	12.24	12.192
10	12.08	0.41	12.18	12.102
11	12.02	0.41	12.10	12.042
12	11.98	0.41	12.09	12.002
13	11.86	0.41	12.0	11.882
14	11.79	0.41	11.98	11.812
15	11.71	0.41	11.88	11.732
16	11.63	0.41	11.79	11.652
17	11.51	0.41	11.54	11.533

7.3. $\mathbf{V_{oc}}$ *Estimation –Variable load*

On the similar lines of Section 7.2, the various parametric values are tabulated in Table 10, Table 11 corresponding to simulation and experimental values.

Table 10: $\mathbf{V_{oc}}$ by Simulation-Variable Load

Battery:12V,7.5Ah, Load: variable Discharge time: Continuous (Simulation)				
Sl No	Vt (V)	I (A)	Voc (V)	SoC (%)
1	12.97	0.65	12.99	82
2	12.8	1.28	12.84	49
3	12.35	3.1	12.44	10

Table 11: $\mathbf{V_{oc}}$ by Experiment-Variable load

Battery:12V,7.5Ah, Load: Variable Discharge time: Continuous (Experiment)				
Sl	Vt (V)	I (A)	Voc	SoC (%)

No			(V)	
1	12.68	0.57	12.71	93.63
2	12.20	1.12	12.26	61.46
3	11.41	2.57	11.55	10.6

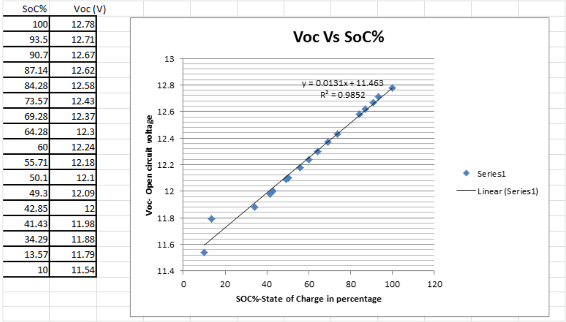
7.4. SoC and SoH estimation

7.4.1.SoC and SoH estimation from VoC and Internal Resistance

SoC and SoH are estimated using the relation (10) with $\mathbf{V_{oc}}$ estimated using IR drop and direct measurement. The values are tabulated in Table 12. The $\mathbf{V_{oc}}$ Vs SoC% measured and calculated are shown in Figure 14 and Figure 15 respectively. The $\mathbf{V_{oc}}$ Vs Time measured and calculated are shown in Figure 16 and Figure 17 respectively. The $\mathbf{V_{oc}}$ Vs SoC% calculated for variable load is shown in Figure 18.

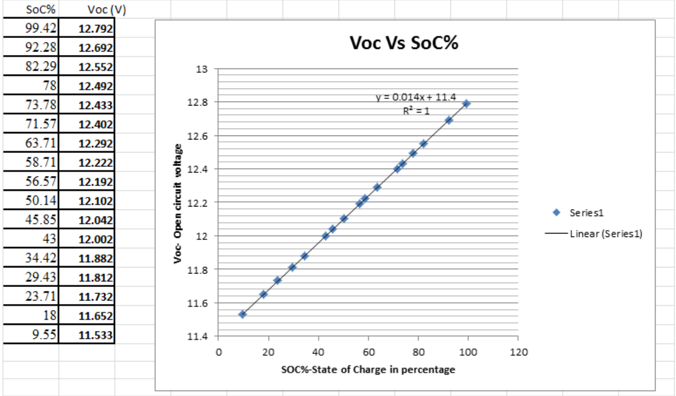
Table 12: Voc Calculated and measured with corresponding SoC%.

Battery:12V,7.5Ah, Load: 5W LED Bulb Discharge rate 0.055C.				
Sl No	Calculated		Voc (V)	SoC (%)
	Voc (V)	SoC (%)		
1	12.792	99.42	12.78	100
2	12.692	92.28	12.71	93.5
3	12.552	82.29	12.67	90.7
4	12.492	78	12.62	87.14
5	12.433	73.78	12.58	84.28
6	12.402	71.57	12.43	73.57
7	12.292	63.71	12.37	69.28
8	12.222	58.71	12.30	64.28
9	12.192	56.57	12.24	60
10	12.102	50.14	12.18	55.71
11	12.042	45.85	12.10	50.1
12	12.002	43	12.09	49.30
13	11.882	34.42	12.0	42.85
14	11.812	29.43	11.98	41.43
15	11.732	23.71	11.88	34.29
16	11.652	18	11.79	13.57
17	11.533	9.55	11.54	10



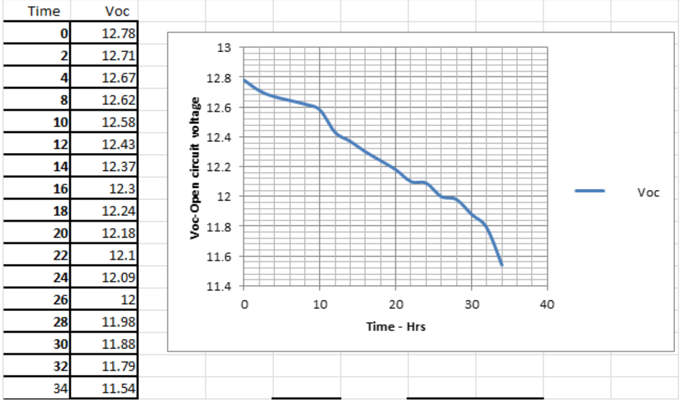
SoC%	Voc (V)
100	12.78
93.5	12.71
90.7	12.67
87.14	12.62
84.28	12.58
73.57	12.43
69.28	12.37
64.28	12.3
60	12.24
55.71	12.18
50.1	12.1
49.3	12.09
42.85	12
41.43	11.98
34.29	11.88
13.57	11.79
10	11.54

Fig. 14: $\mathbf{V_{oc}}$Vz SoC% Measured



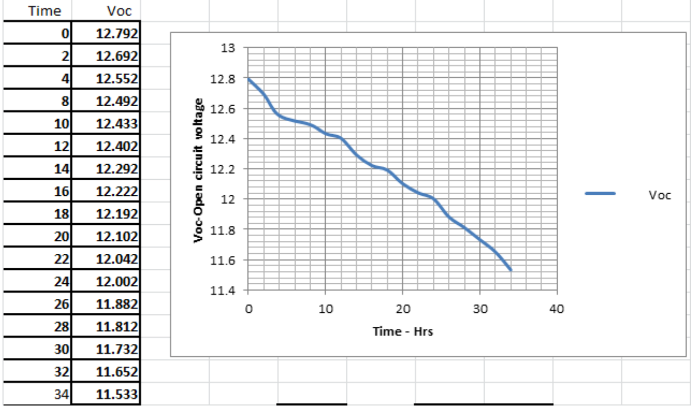
SoC%	Voc (V)
99.42	12.792
92.28	12.692
82.29	12.552
78	12.492
73.78	12.433
71.57	12.402
63.71	12.292
58.71	12.222
56.57	12.192
50.14	12.102
45.85	12.042
43	12.002
34.42	11.882
29.43	11.812
23.71	11.732
18	11.652
9.55	11.533

Fig. 15: $\mathbf{V_{oc}}$ Vs SoC%- Calculated



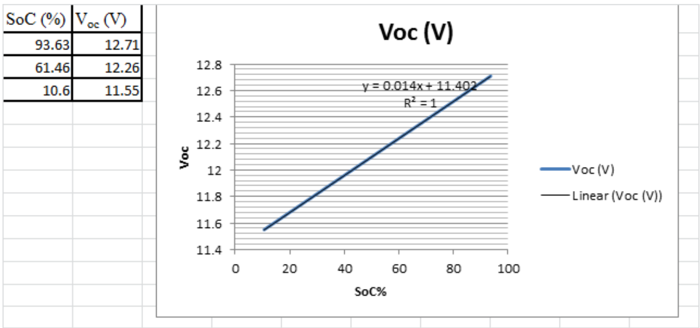
Time	Voc
0	12.78
2	12.71
4	12.67
8	12.62
10	12.58
12	12.43
14	12.37
16	12.3
18	12.24
20	12.18
22	12.1
24	12.09
26	12
28	11.98
30	11.88
32	11.79
34	11.54

Fig. 16: $\mathbf{V_{oc}}$ Vs Time- Measured



Time	Voc
0	12.792
2	12.692
4	12.552
8	12.492
10	12.433
12	12.402
14	12.292
16	12.222
18	12.192
20	12.102
22	12.042
24	12.002
26	11.882
28	11.812
30	11.732
32	11.652
34	11.533

Fig.17: $\mathbf{V_{oc}}$ Vs Time- Calculated



SoC (%)	V_{oc} (V)
93.63	12.71
61.46	12.26
10.6	11.55

Fig. 18: $\mathbf{V_{oc}}$ Vs Time- Calculated (Variable Load)

7.4.2. SoC from CCM-Constant load

The battery discharging consists of 15 cycles of the load pattern described in section 4.5.1 consisting of 1 hr discharge followed by 2hrs rest period. Therefore, the total amount of energy released to the load in these 15 cycles is given by:

$$E_{sim} = I \; x \; T = 0.43 \; x \; 15 \; Ah, \tag{22}$$

hence $E_{sim} = 6.45Ah$ (23)

Now, the SoC is estimated from Equation (7) and is given by;

$$SoC_t = \left(1 - \frac{1}{Q_r}\int_0^{\tau} i_\tau \, d\tau\right) x \; 100\%$$

Hence, $SoC_t = \left(1 - \frac{6.45}{7.5}\right) x \; 100\% = 14\%$ (24)

From Equation (15),

$$\eta_d = \; i^{(1-n)} = 6.45^{(1-1.2)} = 0.6887. \tag{25}$$

From Equation (25) and (16),

$$SoC_{tc} = \left(1 - \frac{1}{Q_r}\int_0^{\tau} \eta_d \;\; i_\tau \, d\tau\right) x \; 100\%$$

Hence, $SoC_{tc} = \left(1 - \frac{6.45}{7.5} x \; 0.6887 \right) x \; 100;$

$$SoC_{tc} = 40.77\% \tag{26}$$

The energy released to the load indicated in (23) is equal to;

$$E_{sim} = \left(\int_0^{\tau} i_\tau \, d\tau\right) \tag{27}$$

This indicates the total amount of energy spent over a period of time. The results indicated in (22) to (26) are all based on the simulated values. Similarly, the experimental values are given below. Here the experiment has taken 17 cycles to completely discharge the battery, accordingly the values are determined.

$$E_{exp} = I \; x \; T = 0.41 \; x \; 17 \; Ah \tag{28}$$

$$E_{sim} = 6.97Ah \tag{29}$$

Now, the SoC is estimated from Equation (7) and is given by;

$$SoC_t = \left(1 - \frac{1}{Q_r}\int_0^{\tau} i_\tau \, d\tau\right) \text{x } 100\%$$

Hence,$SoC_t = \left(1 - \frac{6.97}{7.5}\right) x \; 100 = 7.06\%$ (30)

From Equation (15),

$$\eta_d = \; i^{(1-n)} = 6.97^{(1-1.2)} = 0.6781. \tag{31}$$

From Equation (25) and (16) ,

$$SoC_{tc} = \left(1 - \frac{1}{Q_r}\int_0^{\tau} \eta_d \;\; i_\tau \, d\tau\right) x \; 100\%$$

Hence,$SoC_{tc} = \left(1 - \frac{6.97}{7.5} x \; 0.6781 \right) x \; 100\%,$

$$SoC_{tc} = 36.98\% \tag{32}$$

The results indicated in (28) to (32) are all based on the experimental values.

7.5. SoH Estimation

SoH is given by (6). The total amount of energy delivered to the load is taken as the maximum releasable capacity/released capacity. Therefore, the SoH is given by;

$$SoH_{sim} = \frac{Q_M}{Q_r} = \frac{6.45}{7.5} = 0.86 \tag{33}$$

$$SoH_{sim} = \frac{Q_M}{Q_r} = \frac{6.45 \; x \; 0.6887}{7.5} = 0.59 \tag{34}$$

Values at (33) and (34) represents the SoH determined from simulation results.

$$SoH_{exp} = \frac{Q_M}{Q_r} = \frac{6.97}{7.5} = 0.93 \tag{35}$$

$$SoH_{exp} = \frac{Q_M}{Q_r} = \frac{6.45 \; x \; 0.6781}{7.5} = 0.63 \tag{36}$$

Values at (35) and (36) represents the SoH determined from experimental results.

7.6. Estimation of combined SOC/SOH

The open circuit voltage corresponding to the corrected SOC= 36.98% (32) is given by:

$$V_{oc} = \alpha \; SOC \pm V_{min}$$

$$V_{oc} = 0.034 \; x \; 0.3698 + 11.8$$

$$V_{oc} = 11.81V \tag{37}$$

From Table 12 the calculated and measured SOC corresponding to this Voc are 23.71 and 34.29 respectively.

Therefore the combined SOC is:

$$SOC = \left(\frac{SOC_1 + SOC_2 + SOC_3}{3}\right)$$

$$SOC = \left(\frac{36.98 + 23.71 + 34.29}{3}\right)$$

$$SOC = 31.66\,\% \tag{38}$$

On the similar lines the SOH is given by

$$SOH = \left(\frac{63+76.29+65.71}{3}\right)$$

$$SOH = 68.33 \tag{39}$$

From the results it is clear that the combined SOC/SOH values are almost in close proximity of those values obtained on the basis of open circuit voltage. Hence the proposed work of hybrid method to estimate SOC/SOH is suitable for real time applications.

7.7. Analysis of results

The proposed work was simulated and also experimental validation carried out. From the results, the following analysis are made. (1) From Equations (23) and (29) it is clear that the SoC estimation by coulombs counting method has higher variation. (2) From Equations (25) and (31) it is clear that SoC are very close to each other on application of correction factor derived from Peukert mathematical model. (3) From (i) and (ii) it is indeed clear that the CCM has cumulative effect of current and results in error while estimating SoC of a battery. (4) From Equations (32)–(35) it is also clear that the SoH estimation can be accurately done on application of correction factor. (5) The internal resistance measurement can be used to estimate Voc of a battery.

8. Conclusion

The experimental results were determined using the proposed method and equations of SoC/SoH. Results were tabulated for the easy reference and understanding.The proposed hybrid method consisting of coulombs counting, open-circuit voltage and Peukert law to estimate the SoC/SoH has been the greatest solution.The simulation results carried out using Simulink has counter validated the experimental results. The result shows that the correction factor plays great role estimation of SoC and SoH. The results of coulombs counting method with and without a correction factor are quite different. The SoC estimated with correction factor is quite satisfactory and is almost equal to the open circuit voltage method of estimating SoC and SoH. The analysis of both simulation and experimental results show clearly that the proposed method is suitable for the real-time estimation of SoC/SoH. The experimental value of SoC is 36.98% whereas simulated value is 40.77%. There is a difference of 40.77-36.98=3.79%.

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