International Journal of Aquatic Science
ISSN: 2008-8019
Vol 12, Issue 02, 2021

Lead-Acid Battery Modelling For Parameter Estimation, Simulation And Real-Time Verification For Electric Vehicle Application

Dr. P. Sivakumar[1], Mr. Thiruvarasan A[2]

[1]Assistant professor, EEE Department, PSG College of Technology,Coimbatore, Tamil Nadu, India.
[2]M.E Embedded and Real-Time Systems, EEE Department,PSG College of Technology, Coimbatore, Tamil Nadu, India.

Email: [1]psk.eee@psgtech.ac.in,[2]athiruvarasan108@gmail.com

Abstract: The lead-acid battery is known for deep discharge cycle and load balancing capability since a long time and even today an intensive study goes on. Because of the economic interest to use lead-acid battery in the automotive industry mostly in Electric Vehicle Applications. Researchers give more important to lead-acid battery than lithium-ion battery. Monitoring SoH (State of Health) of a battery is complicated because of the electrochemistry system and non-linear behavior related to internal and external conditions and also SoH recovery and predicting SoH behavior is critical aging of batteries.There are major criterions and computational limitations for development of SoH and predicting behavior of lead-acid battery. Also estimating the battery parameters theoretically is risk factor and variations when comparing theoretical and simulation results of battery model. Major objectives are modeling lead-acid battery using effective Equivalent Circuit Models (ECM) and also estimating parameters of the battery model by using first-order and second-order, by determining how good the batter is under charging and discharging states. For this estimation several load tests are taken to compare with theoretical calculations.Finally comparing and analyzing theoretical calculations with simulation results and Real-Time behavior of lead-acid battery to match results approximately. The lead-acid battery modeling and battery parameter estimation are validated by simulation using MATLAB/Simulink.

Keywords: Lead-acid battery modelling, State of Health, Equivalent Circuit Models,Battery Parameter Estimation.

1. INTRODUCTION

In today's world of automotive industry, they are filled with various new types of batteriesamong them one of the oldest and most popularly used batteries are lead-acid batteries. Lead-acid batteries are most preferred in automotive industry than other type of batteries. Main features of lead-acid battery are load balancing, discharge rate, more robust and withstand deep cycling mechanism abilities made to choose lead-acid battery use most widely in automotive industry [7],Especially in EV Applications.

Even though there are many new type of batteries emerged in the automotive industry are having many features, but not up to the performance level of lead-acid batteries.The lead-acid battery has many types each type consisting of unique features and designed for many purposes in the automotive industry and also Electric Vehicle Application, the lead-acid battery types include vented/wet cell (Flooded) batteries these type of flooded lead-acid batteries are most commonly used in recent days because of their low cost comparing the other type of lead-acid batteries. Flooded means the large amount of electrolyte fluid contained and plates are submerged. Applications are stable in high temperature (above 32°c), high reliability and usefulness also have higher discharge rate than other type of batteries. The next type is AGM (Absorbed Glass Mat) batteries are VRLA(Valve Regulated Lead-Acid) batteriesfiber separators are used to prevent from leakage of acid by absorption of liquid electrolyte applications are slowest self-discharge, best shock/vibration resistance [2]. Then next is gel cell (gelified electrolyte) batteryhas higher self-discharge rate than AGM batteries. In this paper floodedlead-acid battery is used for testing to acquire Real-Time data from the battery.

Lead-acid batteries has become significant in automotive industry, it serve as starter for many type of vehicles, mostly for Electric Vehicles and Electrical Systems. VRLA batteries are having deep discharge ability, and called as maintenance free VRLA batteries [9]. Maintaining State of Health for long cycles is critical task when battery under aging conditions [8]. Also maintaining State of Charge and extracting the behavior of aged batteries is a tuff task. So as to predict the behavior of the batteries by estimating the parameters by using equivalent circuit models are done in this paper.

After the brief introduction of lead-acid batteries entering in to the main process of this project work is to model lead-acid battery using the effective equivalent circuit models.To find an effective Equivalent Circuit Model, various RC equivalent circuits are studied and simulated to understand the working behavior of the lead-acid battery model. Also for lead-acid battery parameter estimation,various load testexperiments from practical battery testingare takenand analyzed with calculated values toextract the actual Real-Time behavior of the lead-acid battery and comparing the simulation results with the Real-Time behavior results of lead-acid battery.

2. EQUIVALENT CIRCUIT MODELS

There are many equivalent circuits for modeling but here using the RC equivalent circuit models for lead-acid battery modeling. In this work three equivalent circuit models are studied to extract the actual behavior of the lead-acid battery by studying, analyzing and simulating all the three models with mathematically calculated values. The circuit models are first-order RC equivalent circuit model, second-order RC parallel circuit model and modified RC equivalent circuit model.

A. The first-order equivalent circuit model

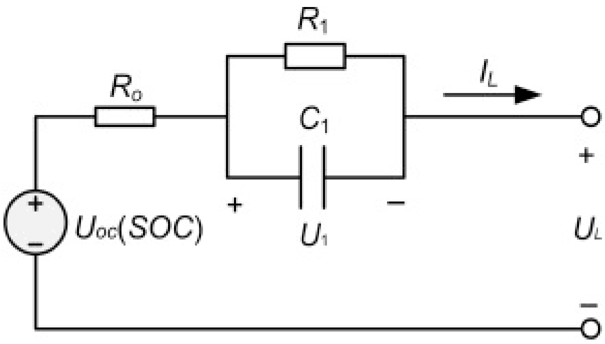

Fig. 1. First-order RC equivalent circuit model

The first-order equivalent circuit model shown in Fig. 1 consisting of R0, R1, C1. R0 is the internal resistance series with the pair of R1 resistor and C1 capacitor. Then R1 and C1 are the function of SoC, current and temperature. Addition of resistor R1 and capacitor C1 to the circuit gives better representation of true battery voltage response [1]. The inner dynamics discharge equation can be expressed as,

$$\boldsymbol{V_t = V_{(OCV)} - IR_0 - V_{C1}}$$

By Laplace transformation,

$$\boldsymbol{V_{C1} = IR_1\left[1 - e^{-\frac{T}{R_1C_1}}\right]}$$

By combining the above equations the expression is,

$$\boldsymbol{V_t = V_{(OCV)} - IR_0 - IR_1\left[1 - e^{-\frac{T}{R_1C_1}}\right]}$$

Where,

$$\boldsymbol{V_{(OCV)} = f(SoC, Temprature)}$$
$$\boldsymbol{R_0, R_1, C_1 = f(SoC, Temprature, I)}$$

By using the above expressions of the first-order model the battery resistance parameter is estimated and this model is somewhat close to the real lead-acid battery behavior.

This first-order model requires some computational power [5]. Then this model is extended by adding RC elements to predict the actual behavior of the true lead-acid battery.

B. The second-order equivalent circuit model

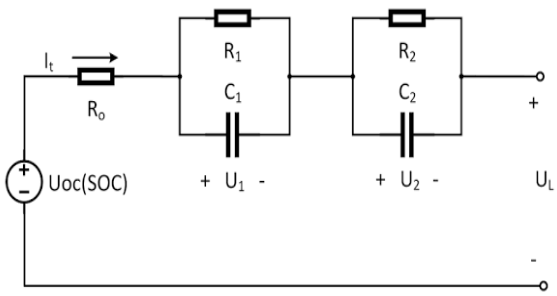

Fig. 2. Second-order RC equivalent circuit model

The second-order model shown in Fig. 2 consisting of R0,R1,R2,C1, C2. R0 is the internal resistance. More similar to first-order model, in addition to that one extra RC pair is added to increase the accuracy of second-order model in order to predict the exact behavior of the true lead-acid battery [1]. The second-order inner dynamics discharge equation is expressed as,

$$\boldsymbol{V_t = V_{(OCV)} - IR_0 - V_{C1} - V_{C2}}$$

By Laplace transformation,

$$\boldsymbol{V_{C1} = IR_1\left[1 - e^{-\frac{T}{R_1C_1}}\right]}$$

$$\boldsymbol{V_{C2} = IR_2\left[1 - e^{-\frac{T}{R_2C_2}}\right]}$$

By combining the above equations the expression is,

$$\boldsymbol{V_t = V_{(OCV)} - IR_0 - IR_1\left[1 - e^{-\frac{T}{R_1C_1}}\right] - IR_2\left[1 - e^{-\frac{T}{R_2C_2}}\right]}$$

Where,

$$\boldsymbol{V_{(OCV)} = f(SoC, Temprature)}$$

$$\boldsymbol{R_0, R_1, R_2, C_1, C_2 = f(SoC, Temprature, I)}$$

The second-order model can predict the actual behavior of the lead-acid battery than the first-order model. By using above expressions lead-acid battery internal resistance and capacitance parameters are estimated.

C. Modified RC equivalent circuit model

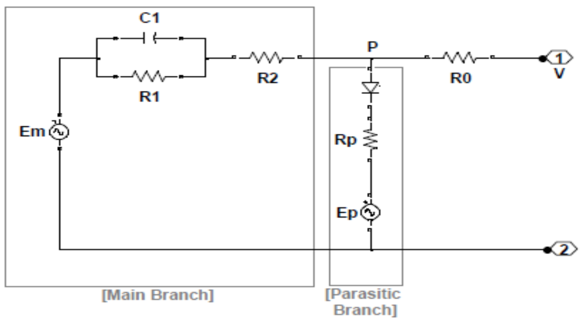

Fig. 3. Modified RC equivalent circuit model

The second-order equivalent circuit model is modified slightly by adding parasitic branch in order to extract the actual behavior of the true lead-acid battery model more accurately than the previous models shown in Fig. 3. The main branch consisting of R1, R2 and C1. R1 and C1 series with resistance R2represents the inner battery dynamics under most of the conditions [10]. The main branch acts during charging discharging and stable modes. Then parasitic branch consisting of parasitic resistance represents the behavior of at end of the charge. The parasitic branch acts during charging and discharging modes only.

The Em voltage source is a controlled by evolution of Battery State of Charge along with discharge process [3] and expressed as,

$$\boldsymbol{E_m = E_{m0} - K_E(273 + \theta)(1 - SOC)}$$

This modified equivalent circuit represents one battery cell, values 2 volts, likewise combination of 6 battery cell forms the complete battery to get 12 volts. This modified equivalent circuit is used in Simulink for lead-acid battery modeling.

LEAD-ACID BATTERY MODELLING

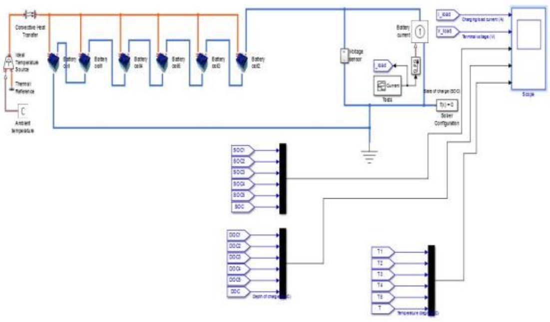

Fig. 4. Complete Lead-acid battery model in MATLAB.

The complete lead-acid battery model in MATLAB shown in Fig 4 consisting of series connection of 6 cells with each cell containing modified RC equivalent circuit model, forms the complete lead-acid battery. This battery modeling also consisting of various blocks like ideal temperature source, series of 6 battery cells, current signal builder for load, voltage sensor, controlled current source, scope for output waveform, scope consisting of charging input load current(A), terminal voltage(V), State of Charge(SoC), Depth of Charge(DoC), temperature in (degree C). The battery cell containing one Equivalent Circuit Model is modeled in MATLAB and is shown in Fig. 5.

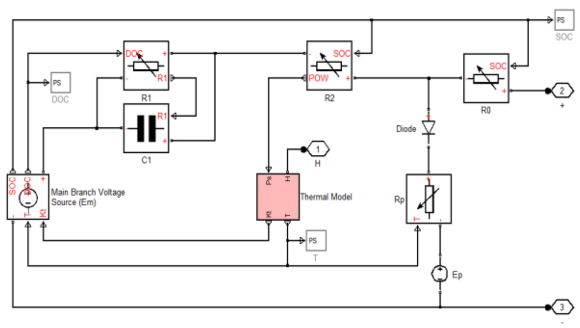

Fig. 5. Modified RC equivalent circuit model in MATLAB

By simulating this lead-acid battery model in MATLAB, the behavior of the lead-acid battery representation is observed throughthe scope results. For example, thedischarging load current is set as 10 Amps. Then by simulating we get the scope result shown in Fig. 6.

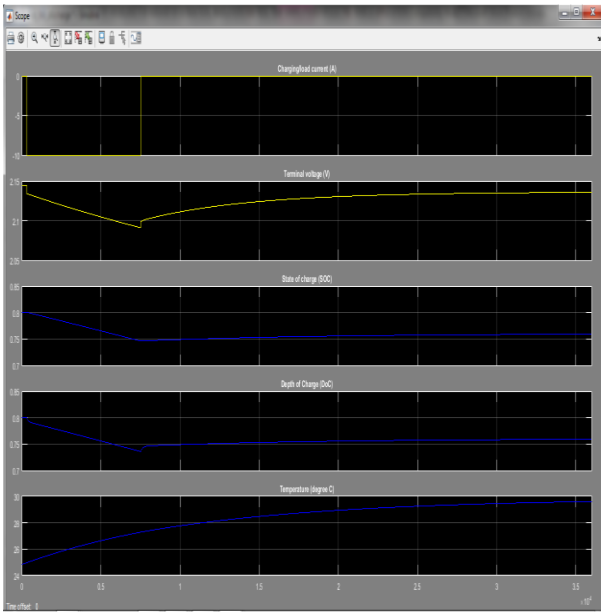

Fig. 6. Simulation result through Scope for Lead-acid battery model.in MATLAB.

REAL-TIME BATTERY TESTING

A. Testing procedure:

The test experiment is conducted for true lead-acid battery 12 V 20 Ah, to extract the Real-Time behavior of the lead-acid battery. There are some procedures for conducting the test,

1. Battery must be fully charged for testing.
2. Initially connecting 10Amps load to the battery.
3. Note the terminal voltage V0 before turning on the load.
4. When the load is turned on, initially there will be sudden voltage drop, voltage decrease from the terminal voltage that is V2.
5. There will be floating voltage in every battery.
6. Then discharge the battery, drain completely from 100% to 0% SoC
7. After four hours of discharge note the voltage V3.
8. After full discharge of the battery, the voltage will gradually increase, because there will be some amount of current left in the battery.
9. In this test after 45 minutes at discharge ideal state the voltage is noted as V1.
10. The voltage between V2 and V3 is assumed and noted as V4.
11. Temperature is noted at initial and final state.

Initial values taken by procedure are shown in Fig. 7.

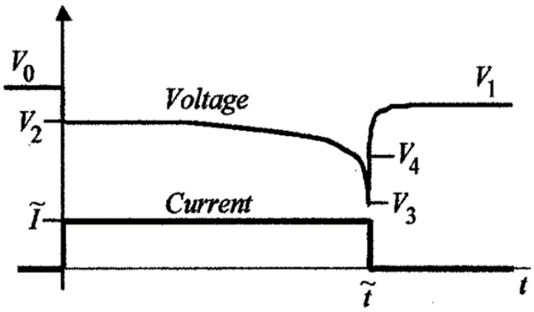

Fig. 7. Sample of real battery behavior

By following the test procedures various load test experiments are conducted under charging and discharging conditions [6] and by using the real-time behavior of the lead-acid battery results battery parameters are estimated.

B. Test experiments conducted:

1. Variable load test
2. Continuous load test
3. Step input load test
4. Two hours Ten Amps discharge test.
5. Ten minutes Ten Amps discharge test
6. 0 to 10 minutes, five minutes on-off at 10 Amps discharge test
7. 0 to 20 minutes, 0_5_10_5_0 Amps discharge test.
8. 0 to 10 minutes, five minutes on-off at 10 Amps discharge test for 1 hour.

Among all these tests experiments conducted for lead-acid battery, in this work considering one test, 0 to 10 minutes, five minute on-off at 10 Amps discharge test experiment for battery parameter estimation. By following the test procedures this test was conducted for lead-acid battery and the voltages are noted as mentioned. The lead-acid battery is discharged for four hours by setting the load at 10 Amps. Totally 0 to 10 minutes, for first five minutes 0 Amps load, (five minutes off) and next five minutes 10 Amps load, (five minutes on).This discharging sequence continuous for every 10 minutes. The battery is made to drain completely up tothe cut-off voltage.Initial voltage is 12.5 V and cut-off voltage is 10.5 V. This test was conducted using the load discharger testing machine.

REAL-TIME BATTERY BEHAVIOUR

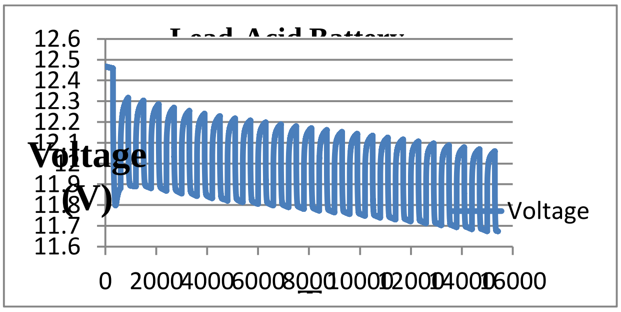

Fig. 8. Lead-acid battery practical test result.

The extracted Real-Time behavior of lead-acid battery is shown in Fig. 8 describes voltage with respect to time for four hours of discharge. The part of battery voltage behavior shown in Fig. 9. By using the charging and discharging curve data waveform, the battery parameters are estimated by using the expressions,

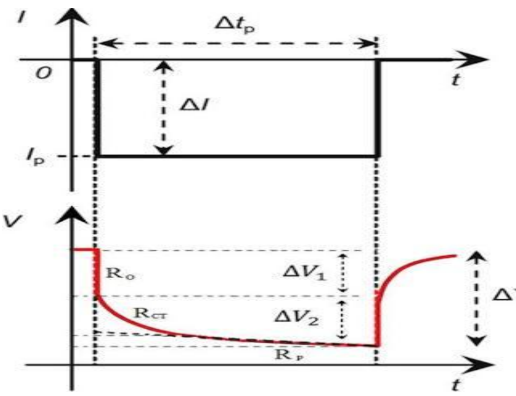

Fig. 9. Part of Battery Voltage behavior.

PARAMETER ESTIMATION

The practical results of lead-acid battery is used to estimate the battery parameters by various methods and expressions,

A. Resistance parameter

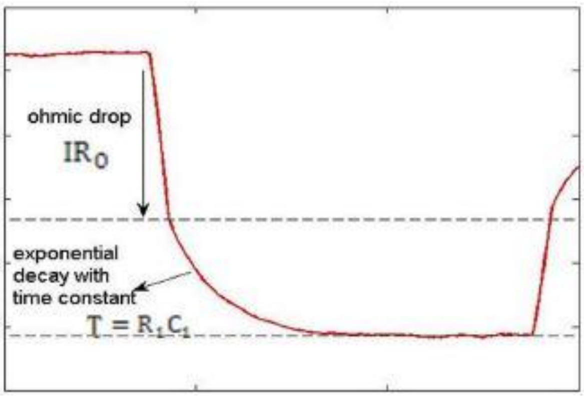

Fig. 10. Effect of Internal resistance

By taking the discharge and charging curve from the practical behavior of lead-acid battery. The resistance parameter is estimated. There is an ohmic drop in the discharging curve indicates the effect of resistance in the second-order circuit model [4]. There is a voltage drop behavior in the curve shown in Fig 10.

The resistance parameter is expressed by.

$$\boldsymbol{R_0 = \frac{\Delta V}{\Delta I} = \frac{V_{MAX} - V_{MIN}}{I_{MAX} - I_{MIN}}}$$

$$R_1 = \frac{\Delta V_1}{\Delta I_1} = \frac{V_{MAX} - V_{MIN}}{I_{MAX} - I_{MIN}}$$

$$R_2 = \frac{\Delta V_2}{\Delta I_2} = \frac{V_{MAX} - V_{MIN}}{I_{MAX} - I_{MIN}}$$

B. Capacitance parameter

The effect of resistance R1 and capacitance C1, there is an exponential decay with time constant is shown in the Fig. 10.The capacitance parameter is expressed by,

$$\tau = R_1 C_1$$

$$C_1 = \frac{\tau_1}{R_1}$$

$$C_2 = \frac{\tau_2}{R_2}$$

CURVE FITTING

Curve fitting method is the process of constructing a curve, or mathematical function that has best fit to a series of data points, possibly subject to constraints. Curve fitting involves interpolants, regression, smoothing spline and least square method. Thismethod is used for fitting discharging, charging curve and also for OCV analysis.

A. Discharge curve

The part of practical data from lead-acid battery behavior is taken and voltage is plotted with respect to time for curve fitting. The discharge curve data in Excel is shown in Fig. 11.

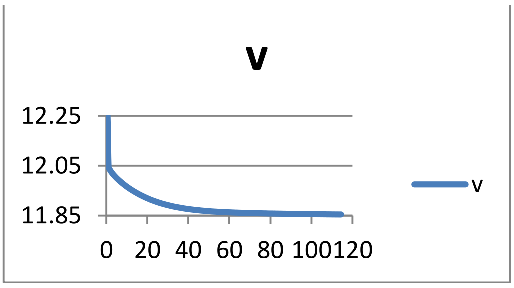

Fig. 11. Discharge curve in excel

The second-order equation for curve fitting is expressed,

$$y = a - (I * b) - \left((I * c) * \left(1 - exp(-d * x)\right)\right) - \left((I * e) * \left(1 - exp(-f * x)\right)\right)$$

This expression is relatively derived from second-order dynamics. By applying the expression the discharge curve fits approximately, shown in Fig. 12.

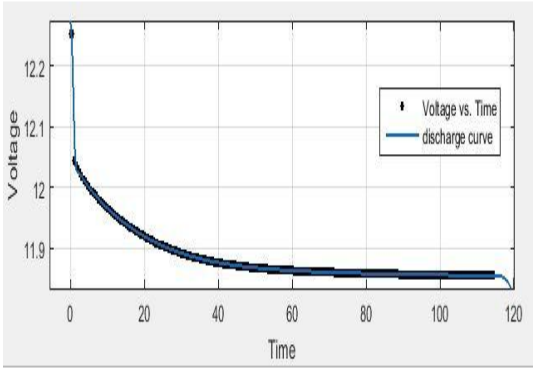

Fig. 12. Discharge curve in MATLAB

B. Charging curve

The part of practical data from lead-acid battery behavior is taken and voltage is plotted with respect to time for curve fitting. The charging curve data in Excel shown in Fig. 13.

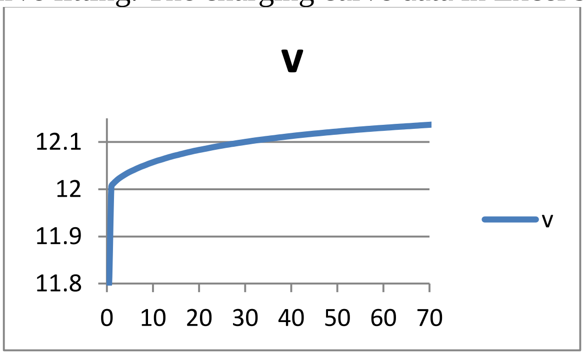

Fig. 13. Charging curve in Excel

The second-order equation for curve fitting is expressed,

$$\boldsymbol{y = a - (b * exp(-c * x)) - (d * exp(-e * x))}$$

This expression is relatively derived from second-order dynamics. By applying the expression the charging curve fits approximately, shown in Fig. 13.

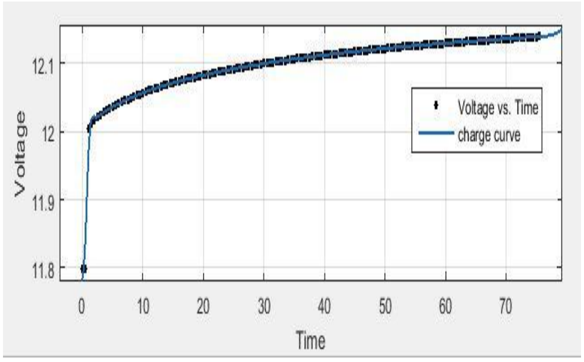

Fig. 14. Charging curve in MATLAB

By curve fitting method the dicharging and charging curve data from true battery behavior is fiited approximately shown in Fig. 14. by using second-order expressions in MATLAB. Alsothe effect of resistance R, capacitance C from the practical data are analysed and the battery parameters R0, R1, R2, C1, C2 are estimated using the expressions used for curve fitting.

C. OCV analysis

For this OCV (open circuit voltage) analysis the peak voltages of the Real-Time beahavior of lead-acid battery is taken and plotted with respect to SoC (State of Charge). The practical data from excel is shown in Fig. 15.

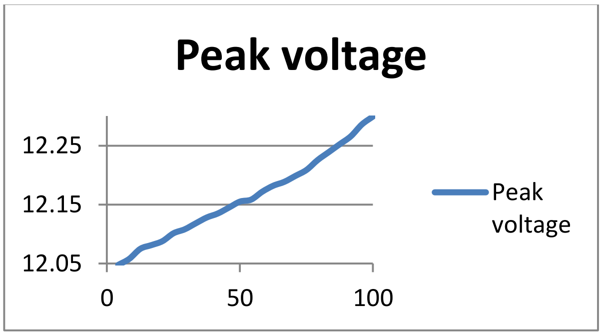

Fig. 15. Peak voltage with respect to SoC in Excel

The curve fitting equation for OCV analysis is expressed,

$$y = a - \left(b * 273 + \theta * \left(1 - (X/100)\right)\right)$$

This expression is relatively derived from modified equivalent circuit expression. By applying this expression the peak voltage with respect to State of Charge (SoC) is fitted approximately, shown in Fig. 16.

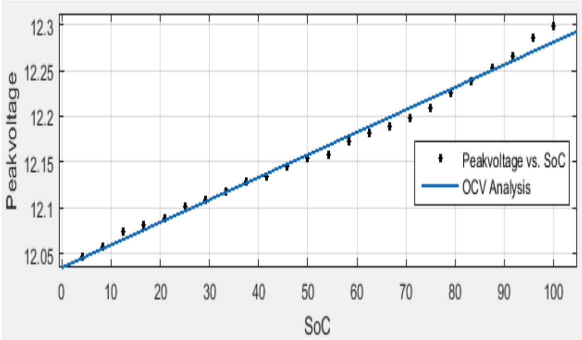

Fig. 16. Peak voltage with respect to SoC in MATLAB

When measuring SoC the battery voltage must be 'floating' with no load attached. Innovative BMS use rest period to adjust SoC reading as part of 'learn' function. By using this expression the OCV analysis is done and the battery SoC parameters are estimated.

3. CONCLUSION

The developed system consisting, the RC equivalent circuit models are studied and analyzed with various aspects and then second-order model is taken and modified with parasitic branch and this modified RC equivalent circuit is modeled and simulated, and the scope results including load current, terminal voltage, SoC, DoCand temperature are verified for lead-acid battery modeling in MATLAB/Simulink. Internal battery parameters are estimated and inner dynamics equation is derived by using the second-orderexpression gives better representation of the battery.Thenlead-acid battery Real-Time behavior is extracted by various load test experiment are conductedunder charging and discharging conditions by following the battery testing procedures. By choosing the preferred test experiment conducted for lead-acid battery, the practical data are taken for consideration.

By using the practical data of extracted from lead-acid battery, the effect of internal resistance and capacitance parametersare estimated and analyzed by various methods.The curve fitting methods are used to derive the expressions for charging and discharging curves taken from part of the practical data. By using the second-order expressions in the curve fitting the charging and discharging curve fits approximately than the first-order expression used. The second-order model gives the better representation of the battery behavior.SoH can be estimated by change of battery resistance and capacitance parameter. The OCV analysis is done for estimating SoC of battery. This battery modelling, parameter estimation and Real-Time verification gives better understandingof lead-acid battery Real-Time behavior and also predict the battery health condition for better performance of batteries.

4. REFERNCES

[1] Guoliang Wu , Chunbo Zhu , and C. C. Chan, "Comparison of the First Order and the Second Order Equivalent Circuit Model Applied in State of Charge Estimation for Battery Used in Electric Vehicles" Journal of Asian Electric Vehicles, Volume 8, Number 1, June 2010.

[2] Marko Gulin, Mario Vaˇsak, and Mato Baoti´c "Joint Estimation of Equivalent Electrical ModelParameters and State-of-Charge for VRLA Batteries"
[3] Shugang Jiang, "A Parameter Identification Method for a Battery Equivalent Circuit Model" Copyright © 2011 SAE International.
[4] Subrahmanyam, S.; Panicker, V. Microcontroller Based Self-Regulating Devices in Enclosed Environments. IARS' International Research Journal, v. 4, n. 1, 2014. DOI: 10.51611/iars.irj.v4i1.2014.35.
[5] Nazih Moubayed, Janine Kouta, Ali EI-AIi2, Hala Dernayka and Rachid Outbib, "Parameter Identification of The Lead-Acid Battery Model", 2008 IEEE.
[6] Stefano Barsali and Massimo Ceraolo "Dynamical Models of Lead-Acid Batteries" Implementation Issues" IEEE Transactions On Energy Conversion, Vol. 17, No. 1, March 2002
[7] Robyn A. Jackey, "A Simple, Effective Lead-Acid Battery Modeling Process forElectrical System Component Selection" Copyright © 2007 The MathWorks, Inc.
[8] Kentaro Ushiyama, Masayuki Morimoto,"SOH Estimation of Lead Acid Battery for Automobile" IEEE PEDS 2011, Singapore, 5 - 8 December 2011
[9] Alyas, T., Tabassum, N., Naseem, S., Ahmed, F. and Ein, Q. T. "Learning-Based Routing in Cognitive Networks", IARS' International Research Journal. Vic. Australia, 4(2) 2014. doi: 10.51611/iars.irj.v4i2.2014.40.
[10] J. M. Mbuthia, C.M. Kiruki, "Estimation of State of Charge of Lead-Acid GelBatteries for Micro grid /PV Applications" International Journal of Engineering Research & Technology (IJERT)
[11] Samantha S. Stephen, Zahi M. Omer1, Abbas A. Fardoun, Ala A. Hussein. "Parameter Estimation of Valve Regulated Lead Acid Batteries Using Metaheuristic Evolutionary Algorithm" 2016 IEEE 59th International Midwest Symposium on Circuits and Systems (MWSCAS), 16-19 October 2016, Abu Dhabi, UAE.
[12] XueZhe.Wei, XiaoPeng.Zhao,YongJun.Yuan. "Study of Equivalent Circuit Model for Lead-acid Batteries in Electric Vehicle" 2009 International Conference on Measuring Technology and Mechatronics Automation.