Mathematical Statistician and Engineering Applications
ISSN: 2326-9865

Comparative Analysis of State-of-Charge Estimation for Lithimum Ion Battery in Electric Vechile Application

Ms. A. Jeyashree [1], Ms. K. Bavithra [2], Ms. C. V. Pavithra[3], Ms. Divya R[4], Mr. S. Ravikrishna
[1,2,3,4,5]Assistant Professor, Department of EEE, PSG Institute of Technology and Applied Research, India
jeyashreea@psgitech.ac.in, bavithra@psgitech.ac.in, pavithra@psgitech.ac.in, divya@psgitech.ac.in, ravikrishna@psgitech.ac.in

Article Info
Page Number: 1555 - 1573
Publication Issue:
Vol 71 No. 3 (2022)

Abstract
As the technology of electric vehicles are evolving rapidly, the battery has arisen as the most noticeable energy storage unit. Beside the growth of the battery technology, the battery management system (BMS) is a key element to utilize the battery in a protected, dependable and productive way. This paper has been developed to identify the most accurate SOC estimation method among various SOC estimation methods commonly used by the research workers. The various methods analysed in this paper include: Fuzzy Logic method, Internal Resistance method, Particle Filter method, and Coulomb Counting method. In each method, the normal parameters of Lithium-ion Battery such as temperature, current, voltage etc. are taken into account to estimate the SOC value by using the MATLAB simulation software. The simulated SOC values of all the four methods are compared based on their advantages and disadvantages. The most appropriate method with less operational difficulty is considered as the accurate method of SOC estimation which enhances the efficiency of BMS in a battery. The battery is also equipped with suitable power modules and sensors that provides necessary data inputs and the collected data is then sent to the controller and the level and status of the lithium ion battery is monitored and estimated to the user for the benefit of the customers.

Article History
***Article Received**: 12 January 2022*
***Revised**: 25 February 2022*
***Accepted**: 20 April 2022*
***Publication**: 09 June 2022*

Keywords: Energy Storage unit, Battery Management System, Lithium-ion Battery, SOC Estimation, Battery Monitoring System.

Introduction

The increasing demand for electrical energy leads to their storage in various perspectives, for example in ultra-capacitors, flywheels, and even in the compresses air. But for most application, the most ideal alternative is battery because of its portability, reusability and low contamination [2]. Battery-powered electronic gadgets have become a need of life in the current situation. Batteries can be utilized in small applications such as cell phones, medium-sized and hybrid electric vehicles, as well as for large applications such as electrical energy networks because it is exceptionally proficient and has a high energy proportion. Batteries have the advantages such as high energy density which helps in speed increase rate, low ecological contamination and long-life cycle [3]. Improper operations such as over-current, over-voltage or over charging or discharging will cause significant safety issue to the batteries, noticeably accelerate the aging process, and even cause fire or explosion. Therefore, we can ensure the safety and battery performance with the help of battery management system (BMS) [3]. In this paper the performance characteristics of lithium ion battery is considered for various SOC estimating methods. The invention of lithium ion cells paves the way for fulfilling future energy needs [4]. Although these cells have advantages they are restricted by voltage and capacity, battery charging speed, life extension and safety. The power and energy requirement of the load is satisfied by battery packs with hundreds or thousands of cells connected in parallel and/or in series [5]. The cell degradation and the battery pack capacity is reduced because of different self-discharge rates, different internal resistances, and the temperature variations [5].

Lithium cobalt oxide, Lithium-ion polymer, Lithium ion phosphate, Lithium Sulphur, etc. are the different chemical composition of lithium ion battery. The capacity, maximum and minimum voltage, energy density, power, self-discharge rate, number of cycles, life time etc. are the characteristics of every cell which is depends on the chemical composition. It became essential because of the utilization of batteries on a daily basis like mobile phones, electric vehicles, laptops etc. Therefore, it is necessary that for this equipment to have a voltage supply able to handle long periods of activation time and most importantly, can be fully charged in a short period of time with high efficiency without degrading the life cycle of a battery [6]. The effective activity of a battery is profoundly reliant upon the activity of battery management system (BMS). BMS is an embedded system which is purpose built and contains electronics and custom designed algorithms within itself. Algorithms are computer modes designed to accomplish a task. The BMS protects itself, protects the application, increase the performance and battery life [7]. The primary function of a BMS is to check that the batteries are not getting stressed even when working for a longer time to decrease the stress on the batteries and to increase its lifespan.

Characteristics of Battery

Batteries are assortment of at least one cells whose chemical reaction create a flow of electrons in a circuit [8]. Cells in most of the batteries are connected in series even though it can be connected in parallel so as to meet the required demands efficiently. Earlier Voltaic Pile found by Alessandro Volta consists of heaps of zinc and copper plates isolated by salty water. It formed the basis for future battery innovations. It formed the basis for future battery innovations. Lately, numerous battery models have been created going from extremely point by point electrochemical models to high level models [9]. When a battery is connected to any circuit, first Anode and electrolyte reacts together and performs oxidation reaction [10]. Next cathode and electrolyte react together and performs Reduction reaction. Thus, a battery usually undergoes Redox reaction (reduction + oxidation). So, electrons from anode side moves to cathode side. The electrolyte makes it truly challenging for the electrons to move from the anode side to cathode side. When the battery reaches the state of equilibrium they will not react i.e., electrons will stop flowing [10]. At this point the battery is dead. In general, a battery is composed of n number of cells. Cells are the small individual electrochemical storage units which satisfy the battery requirements by delivering required current or voltage depending on their capability [11]. Cells can be of a primary cell or a secondary cell.

In a primary cell, the reactions that take place are chemically irreversible because the reactants break and it is not possible to reconstitute them again if used once. In the other case it is possible for the cells to constitute the reactants again with the help of applied electric energy. Because of this ability these cells can be used again and again [12]. In this paper, in Figures 1 and 2 specifications used for the analysis along with the discharge characteristics are shown.

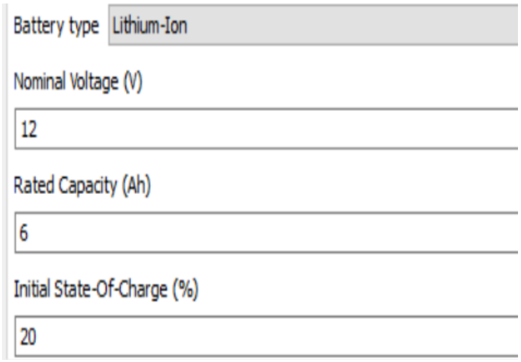

Figure 1. Lithium ion battery specifications

The general oxidation and reduction reactions for a lithium ion battery would be as given in equations 1 and 2.

$$X^{+}\overrightarrow{oxidation}X + e \qquad (1)$$

$$M^{+} + e\overrightarrow{reduction}\mathrm{M} \qquad (2)$$

The oxidation response happens at the anode and reduction response at the cathode individually.

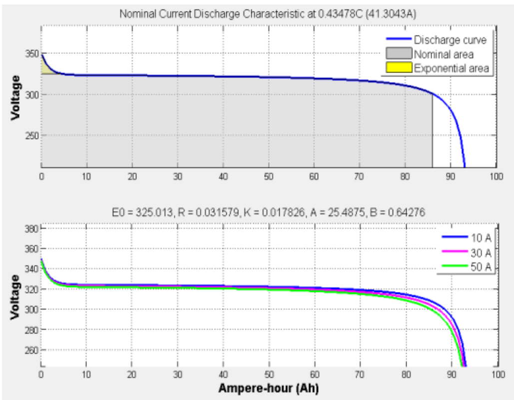

Figure 2. The discharge characteristics of a lithium ion battery.

Charging Process

When cell voltage is lower than external voltage there is a greater potential energy exterior to the cell [13]. So energy is pumped into the cell. During charge, cations move from positive to negative cathode through electrolyte and electrons move from positive to negative anode through outer circuit. The energy pumped into the cell changes it back to its unique state. The various charging techniques available for a battery are:

- Constant Current
- Constant Voltage.
- Pulse Charging
- Boost Charging

Constant voltage permits full current to stream until the battery's stockpile ranges to its preset voltage [13]. The current will then, at that point lessening to low esteem.

Constant current is simple form of charging batteries, with the current level set at around 10% of the most extreme battery rating [13]. The charge times are generally long with the burden that the battery may overheat in case it is overcharged and the battery should be detached. **Pulse Charging** compares the battery’s voltage when the circuit is open circuited with its minimum voltage when the charging exceeds the time specified [13].

Boost Charging is used when there is a heavy discharge of the battery [13]. So, in short time it takes high current to charge the battery.

Constant voltage/constant current is a blend of the over two techniques. The charger limits the measure of current to a preset level [14]. When the battery turns out to be completely energized the current worth abatements. This framework permits quick charging without the danger of overcharging and is appropriate for lithium ion and other battery types. The graph for the above method is shown in Figure 3.

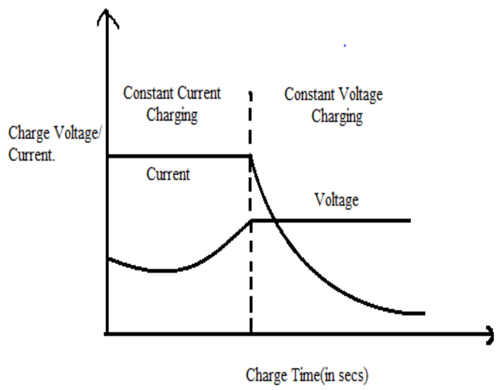

Figure 3. CC-CV Charging Curve.

The charging characteristics of a 12V, 5.8Ah lithium ion battery is simulated in MATLAB using MATLAB function and in shown in the Figure 4 below.

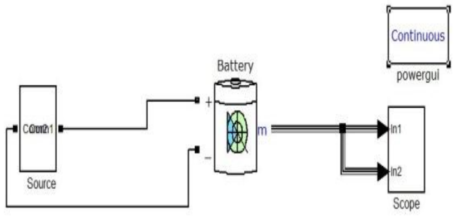

Figure 4. Simulink model for Charging of Lithium ion battery.

The graph in Figure 5 shows the charging waveform of lithium ion battery.

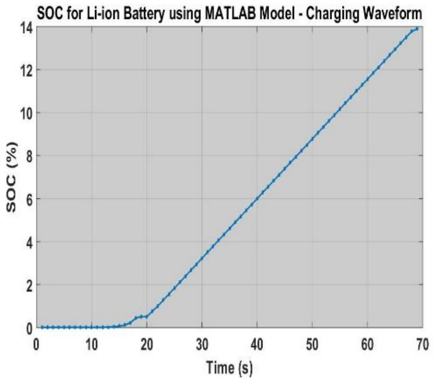

Figure 5. Output waveform for charging circuit.

Discharging Process

A charged battery cell has electrochemical potential energy. Electro chemical potential energy at negative terminal blessings a substance cycle that acknowledges the two electrons from outer circuit and cations from the electrolyte [15]. Thus, positive electrode (with potential energy stored), negative electrode, electrolyte and external circuit makes the discharge process possible. The Simulink model of discharge circuit of lithium ion battery of 12V, 5.8Ah is shown in Figure 6.

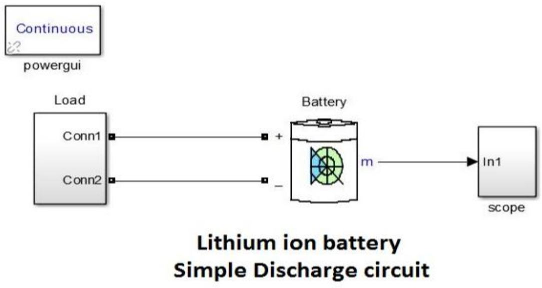

Figure 6. Simulink model for Discharging of Lithium ion battery.

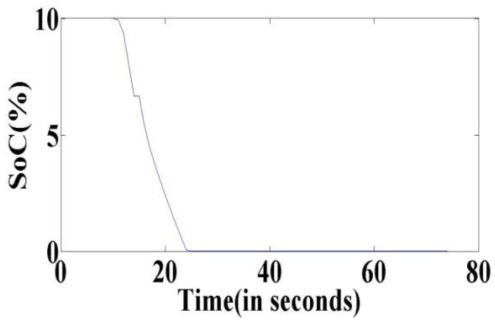

Figure 7. Output waveforms for discharging circuit

The output waveforms for discharging simulink model is shown in the Figure 7. The above figure shows the discharge circuit of a battery wherein an inductive load of certain value is connected across a lithium ion battery and its discharge characteristics are analysed through a scope with respect to time.

State of Charge (SOC) of a Battery

One of the goals is estimating the capacity of the battery. The battery limit should be checked on occasion to make battery utilize safer and productive. State of Charge is one of the imperative boundaries of BMS which means the measure of charge left in battery [15]. Proper SOC estimation prevents battery failure and increases life cycle of the battery also it has an incredible importance towards a proficient activity. This is not always easy to monitor SOC because it is dependent on factors such as battery age, temperature etc. and the stored energy of a battery cannot be accessed directly so these limitations makes its estimation complex [16].

The SOC is given by the ratio of capacity of charge that is left in a battery (Co) to the capacity of charge stored at the time of manufacturing the battery (Cn). It is given in equation 3.

$$soc(t) = \frac{Co}{Cn} \qquad (3)$$

The various estimating methods of SoC are

(i)**Direct estimation method** uses voltage and impedance of the battery to determine its SOC [16].

(ii)**Book-keeping estimation** coordinates the input releasing current over the long run to estimate SOC.

iii)**Adaptive systems techniques** are self-designing systems that consequently change the SOC for various discharging conditions.
(iv)**Data Driven method** runs complex algorithms to study the behaviour of the battery [17].

Fuzzy Logic Method

FLC comprise of the accompanying parts: Fuzzification, Knowledge base, Inference machine and Defuzzification. FLC produces nonlinear planning job among sources of info and yields. The contributions of FLC are mathematical worth which is changed over to fluffy set utilizing participation work [18]. The membership function here is determined from the voltage and current measurements which are the inputs and SOC is the output of the battery. The information base has two fundamental capacities: the first is to figure out which rules are associated with the current input [19]. Here rules are framed for charging and releasing of a battery dependent on the inputs. The second is to use the input and the rule base to deduce the result. Then, the fuzzy set will be utilized to compute the SOC fuzzy result by inference machine. Finally, the defuzzification is done to convert the fuzzy result of SOC into numerical output values [20].

Fuzzy logic is a form of many-valued logic where the truth value varies between completely true and completely false. Here the source for the fuzzy block is voltage and current, the output is SOC. The SOC from the fuzzy block is compared with the battery's SOC. The Simulink model for fuzzy logic method to estimate SOC is shown in Figure 8.

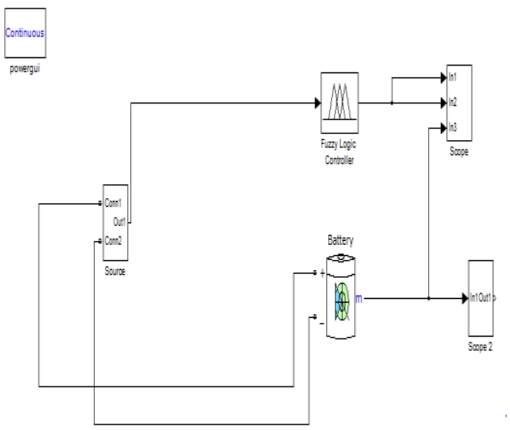

Figure 8. Simulink model for Fuzzy Logic method.

The Figure 9 shown below depicts the SOC waveform using fuzzy logic method during charging. From the below graph, it is shown that the SOC of a battery increases up to 10% for a period of 60 seconds.

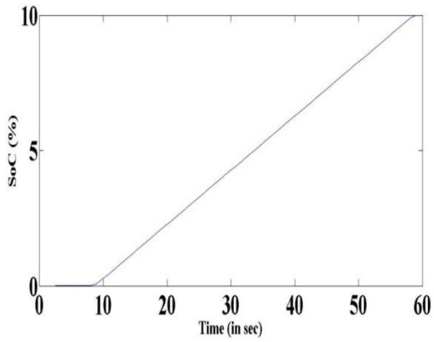

Figure 9. Output Waveform of Fuzzy Logic Method

Internal Resistance Method

The lithium-ion battery internal resistance can be used to describe the electric characteristic if its temperature, SOC, and SOH are fixed [21]. To obtain the internal resistance, direct current (DC) and value of the voltage and current at a small-time interval is taken. However, it is difficult to observe SOC because change in internal resistance is very slow [22]. The Simulink model of this method is shown in Figure 10.

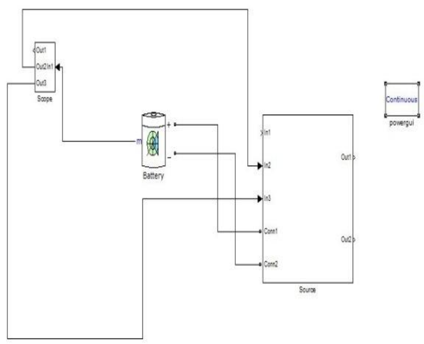

Figure 10. Simulink model for Internal Resistance Method.

The simulated output waveforms are shown in Figure 11. From the above graph, it is shown that the SOC of a battery increases upto 10% for a period of 60 seconds.

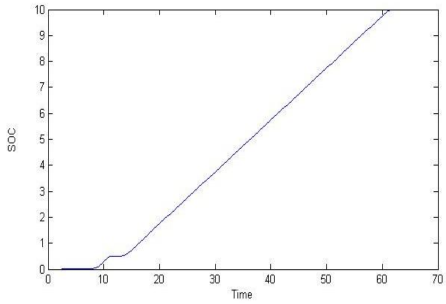

Fig. 11. Output waveform for Internal Resistance method.

Particle Filter Method

The Particle filter method uses algorithms to carry out cell balancing and it produces accurate results with less computational time [22]. The Simulink model and the output waveforms are shown in Figures 12 and 13 respectively.

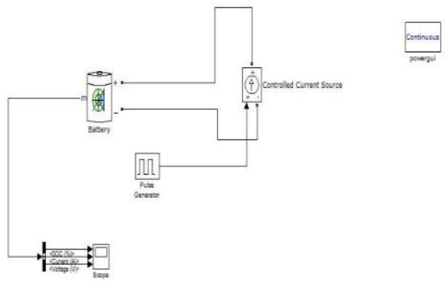

Figure 12. Simulink model for Particle Filter method

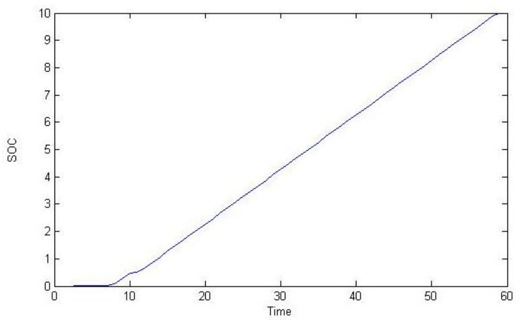

Figure 13. Output Waveform for Particle Filter method.

Coulomb Counting Method

Coulomb counting is one of the book-keeping methods used to estimate the SOC of a battery. This method gives the amount of charge given into or discharged from the battery [23]. Hence it is easy to determine the SOC of a battery accurately. In this method, the amount of charge is calculated using the formulae (3) and (4) given below,

$$q = CV \quad (4)$$

$$C = \int i * dt \quad (5)$$

where, q is the amount of charge, I is the current value integrated over time dt, C is the capacitance, and V is the voltage. The capacitance C is calculated by integrating the current values with respect to time. The voltage is taken into account with respect to the set minimum and maximum values. Thus, the product of capacitance C and voltage V gives the amount of charge to be calculated that helps in finding the SOC of a battery. Coulomb counting is not affected by any battery power fluctuations so the SOC value mostly remains unaffected [24]. The Simulink model is shown in Figure 14.

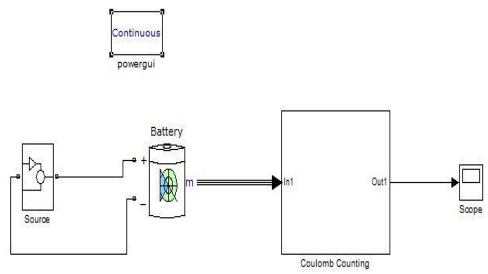

Figure 14. Simulink model for Coulomb Counting method.

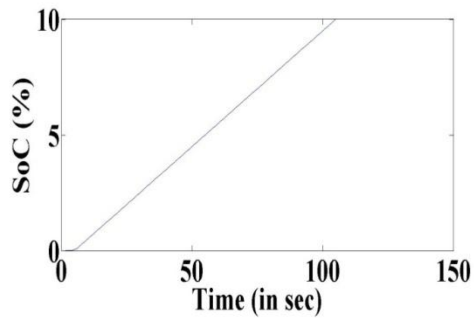

Figure 15. Output waveform for Coulomb Counting method

Simulation Results Comparison

The SOC of a battery is given by the ratio of capacity of charge that is left in a battery (Co) to the capacity of charge stored at the time of manufacturing the battery (Cn). It is given in Equation 6.

$$\mathbf{SOC\ (t) = C_o / C_n} \quad (6)$$

The error rate for SOC estimation methods can be obtained by using Equation 7.

$$\mathbf{Error = (Estimated\ SOC\ Time\ (\%SOC) - Actual\ SOC\ Time\ (\%SOC))/100 * 10} \quad (7)$$

Here, Actual SOC = 56 s

Table 1 Comparative Analysis of Simulation Results.

S.No	Method	Nominal Voltage (in V) & Rated Capacity (in Ah)	Time taken (in Sec) to reach 10% of SOC	Error Percentage (%)
1.	Internal Resistance	12 , 6.5	62	6
2.	Coulomb Counting	12, 6.5	90	34
3.	Particle Filter	12, 6.5	59	3
4.	Fuzzy Logic	12, 6.5	58	2

The above table illustrates that Fuzzy Logic method of SOC estimation takes a short duration of 58 seconds to reach 10% of SOC when compared to normal charging using MATLAB/Simulink around 56 seconds as shown in the charging waveform. The error percentage calculated as per the equations also depicts that Fuzzy Logic method of SOC estimation is more accurate with a minimum error value of 2%.

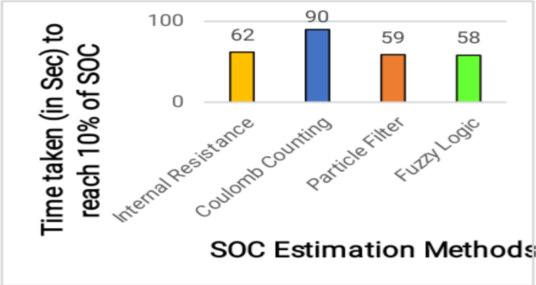

Figure 167. SOC Estimation methods comparison graph

From the above graph, the required time to reach SOC is same. Thus, it is inferred that Fuzzy Logic method of SOC Estimation of a battery showed the accurate results compared to other SOC estimation methods.

Battery Monitoring System

According to the block diagram, the entire system consists of sensors, power modules, controller, displaying unit and load in order to achieve its functionality. The various parameters such as temperature, humidity, voltage, and current of the lithium ion battery considered are measured by means of their respective sensors and power modules.The measured data from the battery is finally displayed through the LCD display circuit. The core part of system design is the controller. The detected data about voltage, current, humidity and temperature is directly sent to MCU. After MCU processing, data is sent to display. Figure 17 shows the block diagram of the battery monitoring system.

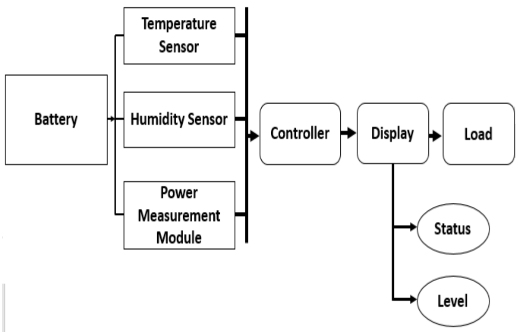

Figure 17. Block Diagram of battery monitoring system.

The components used for the battery monitoring system identified from the block diagram are given below in Table 2.

Table 2 Components used for Hardware Implementation.

S.No.	COMPONENTS USED	RANGE
1.	Lithium ion battery	12V,6Ah
2.	Temperature sensor DHT11	-55 to150 C
3.	Power measurement module INA219	20A
4.	Controller (Raspberry Pi 3)	-

Hardware Implementation

The diagram that gives the detailed description of the connection of various components for battery monitoring system is shown in Figure 18.

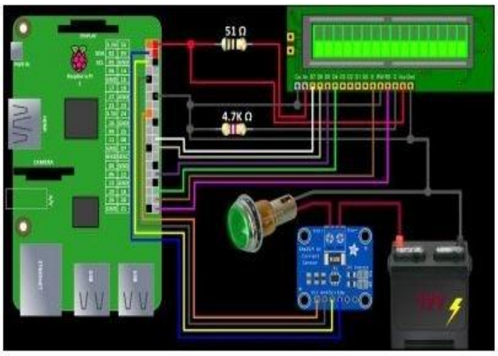

Figure 18. Connection Diagram for Battery Monitoring System

The implementation of the battery monitoring system according to the connection diagram is shown in Figure 19.

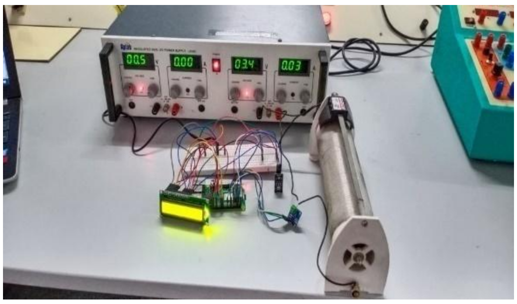

Figure 19. Battery Monitoring System Implementation

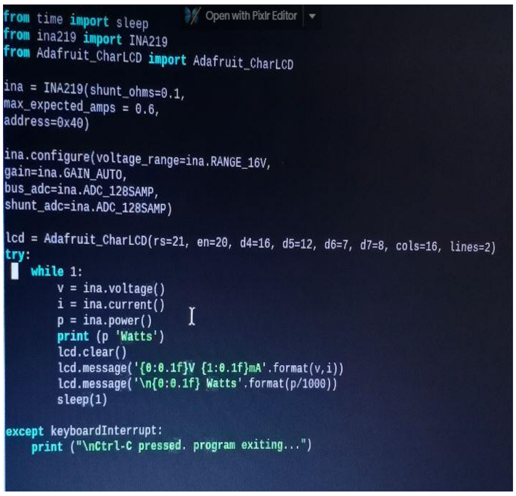

Figure 20. Battery Monitoring System Program

The controller is configured with the program which is shown in the Figure 20.

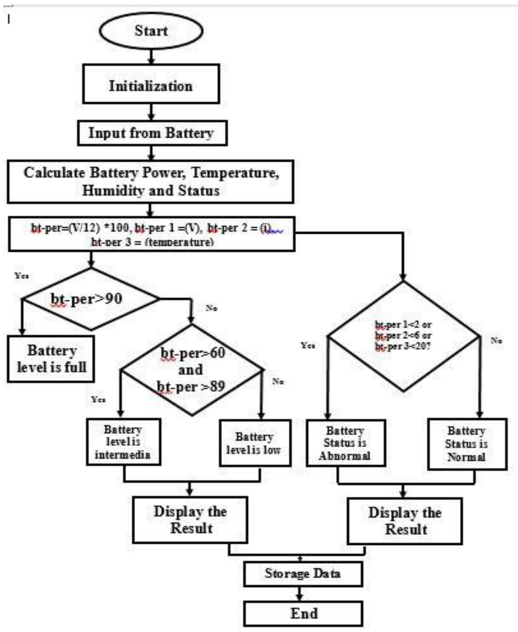

Figure 21. Hardware Setup Flowchart

Hardware Results

The tabulated values of various parameters of the battery obtained through battery monitoring system is shown in Table 3 and the output is shown in the figure 22.

Table 3 Results of Battery Monitoring System.

S. No.	PARAMETER	RESULT
1.	Voltage	12V
2.	Current	6Ah
3.	Temperature	30ºC
4.	SOC	20%

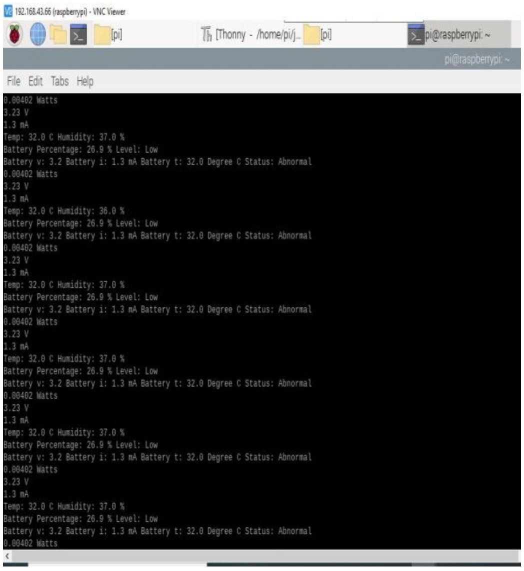

Figure 22. Output of Battery Monitoring System

Conclusion

The electric vehicle has revolutionised the modern transport sector. Among various electric vehicles, battery operated electric vehicle is used. The battery-operated electric vehicle has its advantages such as high power density, high energy density and economic to use. The battery management system is used to monitor the various parameters employed in electric vehicle. The State of Charge (SoC) is the main parameter responsible for the performance analysis. The SOC is used to predict the range of travel, prevent overcharging and under discharging, enhance safety and life cycle of the battery. The SoC is determined based the data obtained from the voltage and current sensors. The board classification of SoC prediction is classified such as direct measurement method, book-keeping estimation, adaptive systems techniques, data driven methods etc. The different methods of SOC determination such as internal resistance, coulomb counting, particle filter and fuzzy logic methods are discussed. From the compared analyses of different SOC estimation methods, Fuzzy Logic method which is one of the Data-Driven methods is found to be more appropriate for determining the SOC of a battery. The proposed battery algorithm can be easily applied to any type of battery packs due to its simplicity. The battery management system is implemented for a cylindrical Li-ion pack with 12 Volt. The BMS monitors and displays voltage, current and determine the SOC using the voltage sensors, current sensors, temperature sensors and raspberry-pi as a controller. The algorithm is proposed to determine the SOC. This SOC prediction is used to safe the battery from uncertained conditions as mentioned above. This type of analysis is used to maintain the proper health of the battery pack. The proposed system can also be extended by creating a mobile app and monitoring the battery status from any locations with its performance parameters.

References

1. Prakash Venugopal, Vigneswaran T, “State- of-Charge Estimation Methods for Li-ion Batteries in Electric Vehicles”, IEEE Transactions on Power Electronics, Vol. 8, May 2019.
2. Bian X, Liu L, et al., “A model for state-of-health estimation of lithium-ion batteries based on charging profiles.”, Energy, Vol. 177, pp. 57–65, 2019.
3. D Stroe, M Swierczynski, et al., “Degradation behavior of lithium-ion batteries during calendar ageing-The case of the internal resistance increase.”, IEEE Transactions on Industry Applications, Vol. 54, No. 1, pp. 517–525, February 2018.
4. Z Yang, D Patil, et al., “Online estimation of capacity fade and power fade of lithium-ion batteries based on input–output response technique.”, IEEE Transactions, Vol. 4, No. 1, pp. 147–156, March 2018.
5. Hongbin Ren, Taipeng Wang, “Design and Implementation of a Battery Management System with Active Charge Balance Based on the SOC and SOH Online Estimation.”, Elsevier, Vol. 166(C), pp. 908-917, July 2018.
6. Y Zhang, R Xiong, et al., “Long short-term memory recurrent neural network for remaining useful life prediction of lithium-ion batteries.”, IEEE Transactions on Vehicular Technology, Vol. 67, No.7, pp.5695-5705, July 2018.

7. Z Liu, G Sun, et al., "Particle learning framework for estimating the remaining useful life of lithium-ion batteries.", IEEE Transactions on Instrumentation and Measurements, Vol.66, No. 2, pp. 280-293, February 2017.
8. Frost, D Howey, "Completely decentralised active balancing battery management system", IEEE Transactions on Power Electronics [J], Vol. 99, pp. 1-1, 2018.
9. Liu K, Li K, et al., "A brief review on key technologies in the battery management system of electric vehicles [J].", Frontiers of Mechanical Engineering, Vol.99, pp. 1-18, 2018.
10. Lipu M, Hannan M, et al., "A review of state of health and remaining useful life estimation methods for lithium-ion battery in electric vehicles: Challenges and recommendations.", J. Clean. Prod., Vol.205, pp. 115–133, 2018.
11. Meng, Jinhao, et al. "An Overview and Comparison of Online Implementable SOC Estimation Methods for Lithium-ion Battery.", IEEE Transactions on Industry Applications, Vol. 54, No.2, pp 1583-159, 2018.
12. Zhang, Zhiliang, et al., "SOC Estimation of Lithium-ion Battery Pack C Considering Balancing Current.", IEEE Transactions on Power Electronics, Vol. 33, No. 3, pp. 2216-2226, 2018.
13. Xiong R, Yu Q, et al., "A novel method to obtain the open circuit voltage for the state of charge of lithium-ion batteries in electric vehicles by using H infinity filter.", Applied Energy, Vol. 207, pp. 346-53, 2017.
14. Baojin Wang, Zhiyuan Liu, "State of Charge Estimation for Lithium-Ion Batteries Based on a Nonlinear Fractional Model.", IEEE Transactions on Control Systems Technology, Vol. 25, pp. 3-11, January 2017.
15. M. Kauer, S. Narayanaswamy, et al., "Rapid analysis of active cell balancing circuits.", IEEE Transactions on Computer-Aided Designing of Integrated Circuits Systems, Vol. 36, No. 4, pp. 694–698, April 2017.
16. Y. Gao, J. Jiang, et al., "Lithium-ion battery aging mechanisms and life model under different charging stresses.", Journal of Power Sources, Vol. 356, pp. 103–114, July 2017.
17. Rui Xiong, Jinpeng Tian, "A Systematic Model-Based Degradation Behaviour Recognition and Health Monitoring Method for Lithium-Ion Batteries", Elsevier, Vol. 207, pp. 372-383, 2017.
18. Z. Deng, L. Yang, et al., "Online available capacity prediction and state of charge estimation based on advanced data-driven algorithms for lithium-ion battery.", Energy, Vol. 201, pp.257-269, 2017.

19. Yang D, Wang Y, et al., "A Neural Network Based State-of-Health Estimation of Lithium-ion Battery in Electric Vehicles.", Energy Procedia Vol. 105, pp. 2059–2064, 2017.
20. A. Guha and A. Patra, "State of health estimation of lithium-ion batteries using capacity fade and internal resistance models," IEEE Trans.Transp. Electrific., Vol. 4, No. 1, pp. 135–146, March 2018.
21. Chen C, Xiong R, et al., "A lithium-ion battery-in-the-loop approach to test and validate multi-scale dual H infinity filters for state of charge and capacity estimation.", IEEE Transactions on Power Electronics, 2017.
22. R. Xiong, Y. Zhang, et al., "A double-scale, particle-filtering, energy state prediction algorithm for lithium-ion batteries.", IEEE Transactions on Industrial Electronics, Vol. 65, No. 2, pp. 1526-1538, 2018.
23. Ye, Min, et al., "A Double-Scale and Adaptive Particle Filter-Based Online Parameter and State of Charge Estimation Method for Lithium-ion Batteries.", Energy, Vol. 144, pp.789-799, 2018.
24. Z Zhang, H Gui, et al., "A Hierarchical Active Balancing Architecture for Lithium-ion Batteries.", IEEE Transactions on Power Electronics, Vol. 99, pp. 1-1, 2017.
25. Xiong R, Cao J, et al., "Critical Review on the Battery State of Charge Estimation Methods for Electric Vehicles.", IEEE Access, Vol. 6, pp. 1832–1843, 2017.
26. Li Z, Xiong R, et al., "A novel parameter and state of charge determining method of Lithium-ion battery for electric vehicles.", Applied Energy, Vol. 207, pp. 363-71, 2017.
27. Becker J, Lelie M, et al., "Impact of low Temperatures on Performance and Ageing of Lithium-Ion Batteries and Strategies for Heading. In Proceedings of the 11th Symposium on Hybrid and Electric Vehicles.", Braunschweig, Germany, February 2014.
28. Sheikh Ferdoush, Xinrong Li, "Wireless Sensor Network System Design using Raspberry Pi and Arduino for Environmental Monitoring Applications", Elsevier, 2014.
29. E Din, C Schaef, et al., "A Scalable Active Battery Management System with Embedded Real-Time Electrochemical Impedance Spectroscopy [J]." IEEE Transactions on Power Electronics, Vol. 32 (7), pp: 5688-5698, 2017.
30. MA Hannan, MSH Lipu, et al., "A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications; Challenges and recommendations [J].", Renewable & Sustainable Energy Reviews, Vol. 78, pp. 834-854, 2017.