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Estimation of State-of-Charge (SOC) of Lithium Batteries in Electric Vehicles

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ABSTRACT

The state of charge (SOC) of the Lithium Ion Batteries (LIBs) is a core parameter in the implementation and development of batteries management systems which requires the accurate measurement of the battery capacity which is used in the development of EVs, and thus is becoming a very critical issue. Only with the accurate measurement of the SOC using various equations and parameters, it is possible to manage the battery energy effectively to prevent it from risks resulting from over-charging and over-discharging. It can also provide the necessary data and form a basis for other energy related system requirements as well. In the process of the SOC value estimation, we must consider the impact of various factors in the LIBs' working process like Cell Ageing, Cell Imbalance etc., using various reasonable equivalent circuit model of the LIBs. Appropriate estimation algorithms are used to measure and improve the accuracy of SOC estimation. The batteries and battery management systems (BMS) are the key components of EVs. The SOC value, which marks the remaining capacity or power in the batteries, is also the core parameter of the BMS. It is a reflection of the operational status of the main feature, providing basis for the vehicle control strategy judgement and management. And the accurate estimation and management of SOC can improve the battery state of life (SOL) and the vehicle or application performance. The indication of SOC is often referred to as an estimate rather than a measurement or determination as there is no single correct process to be employed. And also, it is not yet possible to determine the SOC one-hundred percent accurately. Our project uses some of the existing methods to determine the SOC estimate for an Electric Vehicle as accurately as possible and some modified algorithms to achieve more accurate results.

Keywords: State of charge, State of health and state of life.

1. INTRODUCTION

The world is seeing a spike in usage of energy resources. The existing and conventional sources of Energy such as the Fossil fuels (Petroleum, Natural Gas and coal) are getting difficult to harness. Thus, deeper oil wells are being dug in offshore locations, Hydraulic fracturing techniques and horizontal drilling techniques are being used to obtain shale gas. All these processes are expensive and damaging to the environment. Further the use of these energy sources adds to the greenhouse gas effects and global warming which are now playing havoc with weather all around the globe.

In this context, the past decade has seen a lot of interest in electric vehicles like Pure Electric Drives (EVs), Plug-in Hybrid Electric Vehicles (PHEVs) etc. All major automobile manufacturers have come up with an electric vehicle in their lineup. Everyone understands that the electrification of automobiles is inevitable in the immediate future.

However, the energy resources which produce electric power do not exist infinitely as conventional electric power is also produced by burning coal, oil or gas in Thermal power stations. Introduction of renewable energy is required in the power supply side, and efficient use of electric power is demanded by the power consumer. However, renewable energy such as solar power and wind power are difficult to harness as stable sources of power supply because of their inherent uncertain nature. Electric power obtained by these power generation methods is stabilized by using a power storage system [1-7].
Storage batteries are used as a representative of the power storage system. Storage batteries in conventional mainstream was lead-acid battery. In recent years, high-performance lithium ion batteries are becoming the mainstream. The lithium ion battery has excellent energy density and also have better charge and discharge mechanism in comparison. Therefore, the lithium ion battery has advantages in performance and efficiency. Also, it is very compact. However, there are problems related to safety and degradation of lithium ion batteries, so management and control of the lithium ion batteries is important. Hence, determination of accurate operating parameters of lithium ion batteries (such as State of charge) is gaining more importance as these Traction Batteries are the major source of power and thus one of the most important component in an Electric Drive Vehicle.

2. RELATED WORK

In general, the SOC of a battery is defined as the ratio of its current capacity (t) to the nominal capacity (Qn) [8-13]. The nominal capacity is given by the manufacturer and represents the maximum

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Asian Journal of Applied Science and Technology (AJAST)

Volume 1, Issue 5, Pages 91-94, June 2017

amount of charge that can be stored in the battery. The SOC can be defined as follows:
SOC(t) = [$Q(t)/Qn$]
The various methods of estimation SOC are classified according to following methodology.

There are 4 main divisions.
(i) Direct measurement: This method uses physical battery properties, such as the voltage and impedance of the battery to calculate SOC.
(ii) Book-keeping estimation: This method uses discharging current as the input and integrates the discharging current over time to calculate the SOC.
(iii) Adaptive systems: The adaptive systems are self-designing and self-learning set of algorithms that can automatically adjust the SOC for different discharging conditions.
(iv) Hybrid methods: These generally involves the combination of above mentioned methods in different ways as required for various different conditions.

Direct Measurement
Open Circuit Voltage Method.
There is a linear relationship between the SOC of the lead-acid battery and its open circuit voltage (OCV) given by the equation as follows
$VOC\ (t) = a1 \times SOC\ (t) + a0$,
Where SOC(t) is the SOC of the battery at the instant of time t, $a0$ is the battery terminal voltage when SOC = 0%, and $a1$ is obtained from knowing the value of $a0$ and $VOC(t)$ at SOC = 100%. By this equation, the estimation of the SOC is equivalent to the estimation of open-circuit voltage (OCV) of the battery pack.

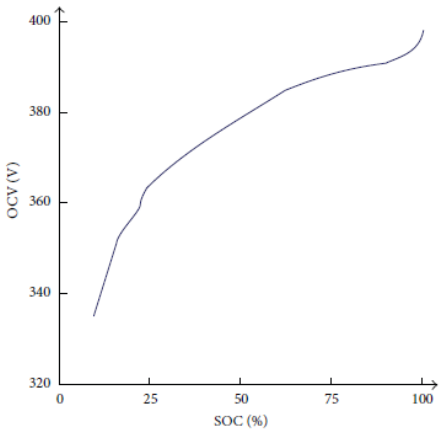


Fig 1. Typical relationship between SOC and OCV

But, there is a major drawback as this method is only valid when the batteries are disconnected from load for a long period of time, which may be difficult to implement. Unlike the lead-acid battery, the Li-ion battery does not have a linear relationship between the OCV and SOC. The relationship between the OCV and SOC can't be precisely the same for all batteries. As a result of the traditional OCV-SOC distinction among batteries, there's a drag in estimating SOC accurately.

Terminal Voltage Method
Based on the terminal voltage drops as a result of the inside physical phenomenon once the battery is discharging, thus the electrical phenomenon (EMF) of battery is proportional to the terminal voltage. Since the voltage of battery is roughly linearly proportional to the SOC, the terminal voltage of battery is to boot roughly linear proportional to the SOC. The terminal voltage technique has been used at altogether totally different discharge currents and temperatures. However, at the tip of battery discharge, the determinable error of terminal voltage technique huge, as a result of the terminal voltage of battery suddenly drops by an over-sized price at the tip of discharge.

Impedance Method
The impedance measurements provide knowledge of several parameters, the magnitudes of which may depend on the SOC of the battery. Although the impedance parameters and their variations with SOC are not unique for all battery systems, it appears to be imperative to perform a wide range of impedance experiments for identification and use of impedance parameters for estimating the SOC of a given battery.

Impedance Spectroscopy Method
The impedance spectroscopy method measures battery impedances over a wide range of ac frequencies at different charge and discharge currents. The values of the model impedances are found by fitting least squares to the measured impedance values. SOC may be indirectly estimated by measuring present battery impedances and correlating them with known impedances at various SOC levels.

Support Vector Machine
SVM has been applied for classification in various domains of pattern recognition. The SVM has also been applied for regression problem, even the regression problem is more difficult than classification problem. The SVM used as a nonlinear estimation system is more robust than a least-squares estimation system because it is insensitive to small changes. Hansen and Wang investigated the application of a SVM to estimate the SOC of lithium-ion battery. The SVM based estimator not only removes the drawbacks of the Coulomb counting SOC estimator but also produces accurate SOC estimates.

Asian Journal of Applied Science and Technology (AJAST)

Volume 1, Issue 5, Pages 91-94, June 2017

Adaptive methods

RBF Neural Network

The RBF neural network is used for systems with incomplete information. It can be used to analyze the relationships between one major (reference) sequence and the other comparative ones in a given set. Results show that the operation speed and estimation accuracy of estimating model can meet the demands in practice, and the model has certain value of application. The RBF neural network SOC estimation method uses the input data of the terminal voltage, discharging current, and temperature of battery to estimate the SOC for LiFePO4 battery under different charging conditions data was found to be in close agreement with each other.

Fuzzy logic method

The method involves the use of fuzzy logic models to analyze data obtained by impedance spectroscopy and/or Coulomb counting methods. The AC impedance and voltage recovery measurements are used as the input parameters for the fuzzy logic model. SOC is estimated by an improved Coulomb metric method, and the time-dependent variation is compensated by using a learning system. The learning system tunes the Coulomb metric method in such a way that the estimation process remains error free from the time-dependent variation. The learning system uses the fuzzy logic models, which is not used for estimation of SOC but performs as a component of learning system.

Kalman Filter

Using real-time measurement road data to estimate the SOC of battery would normally be difficult or expensive but the application of the Kalman filter method is shown to provide verifiable estimations of SOC for the battery via the real-time state estimation. Barbarisi presented an extended Kalman filter (EKF) to estimate the concentrations of the main chemical species which are averaged on the thickness of the active material in order to obtain the SOC of the battery, by using the terminal current and voltage measurements. Based on unscented Kalman filter (UKF) theory and a comprehensive battery model, a novel SOC estimation method is proposed in which is superior to extended Kalman filter method in SOC estimation for battery. Sun presented an adaptive UKF method to estimate SOC of a lithium-ion battery for battery electric vehicles. The adaptive adjustment of the noise covariance in the SOC estimation process is implemented by an idea of covariance matching in the UKF context.

Hybrid Methods

Coulomb Counting and EMF Combination

This method combines direct measurement method with the battery EMF measurement during the equilibrium state and book-keeping estimation with Coulomb counting method during the discharge state. Any battery will lose capacity during cycling. In order to calculate SOC and remaining run-time (RRT) accurately and to improve the SOC estimation system capability to cope with the aging effect, a simple Qmax adaptation algorithm is introduced. In this algorithm, the stable conditions of the charge state are exploited in order to adapt Qmax with the aging effect. The Qmax adaptation algorithm can improve the SOC and RRT estimation accuracy even for a fresh battery. Since a battery loses capacity during cycling, it is concluded that the Qmax adaptation algorithm will increase substantially.

Pre-Unit System and EKF Combination

Kim and Cho described the application of an EKF combined with a per-unit (PU) system to the identification of suitable battery model parameters for the high accuracy SOC estimation of a lithium-ion degraded battery. To apply the battery model parameters varied by the aging effect, based on the PU system, the absolute values of the parameters in the equivalent circuit model in addition to the terminal voltage and current are converted into dimensionless values relative to a set of base values. The converted values are applied to dynamic and measurement models in the EKF algorithm which is then used to estimate the SOC.

3. SYSTEM OVERVIEW

Our project aims at acquiring the utmost level of accuracy in determination of state of charge in electric vehicles and also to try and determine the battery's state of health. We have divided our project into three distinct stages or levels. Level one consists is the very initial stage in which we designed simple voltage level indicator for 24V system designed using Zener diodes with different breakdown voltages and resistors along with LEDs to indicate Second stage aims to achieve a higher level of accuracy for voltage determination. To achieve this, ICs are used. These ICs are generally comparators which work on the principle of differential comparison. The input to these ICs are compared with respect to a reference voltage that is fixed for a particular voltage and thus gives the required output to indicate the battery voltage at any given time. The ones we used are LM339 Quad Comparators that are manufactured by Texas Instruments. The main advantage of this stage over the previous one is that here we can use this same circuit for different supply voltages or battery systems like 24V, 36V or 48V just by changing the value of the registers or by changing the reference voltage. So, the accuracy is increased as we now have wider range of voltage indications and also the system becomes semi-

Asian Journal of Applied Science and Technology (AJAST)

Volume 1, Issue 5, Pages 91-94, June 2017

intelligent. Simply the voltage level to study the approaches required to display different voltage capacities.

Third level gives most accurate and automated adaptive output as here we design the system which can be used for any conventional electric vehicle. The changes in the voltage is because of the chemical reactions taking place in battery pack, the idea behind this method is to predict this chemical change taking place in the battery of the vehicle because of the distance it is travelling and convert that into the voltage indications. A protection circuit is employed to prevent the battery from any damage. The main function of the protection circuit is to prevent the battery from over-charging or over-discharging and thus preserve its health so that it can work for a long period. To make the circuit artificially intelligent we interface the above circuitry with the Arduino module which acts as the interactive environment between the user and the hardware. The Arduino board is programmed to provide the SOC, SOH and the distance left to travel with the remaining power left in battery. Then a GUI based console is designed which indicates the above parameters conveyed by the Arduino.

A. Level One

In this section, the design and hardware used are described.

This part acts as the initial stage of approach for our learning on basic voltage indicator. There are three basic circuits designed that are described below:

1. Using only resistors, LEDs and Zener diodes

It comprises of a reference LED i.e. LED_{REF}, which operates at a constant current of 1 mA and provides reference light of constant intensity regardless of battery voltage. Resistor R_1 is connected in series with the diode. So, even if the battery voltage changes from a charged to a discharged state, the change in current is only 10%. Thus, the intensity of LED_{REF} remains constant for battery from a fully charged state to a fully discharged state. The light output of the variable LED changes with respect to changes in battery voltage. The side-by-side mounted LEDs let you easily compare light intensities and, thus, battery status.

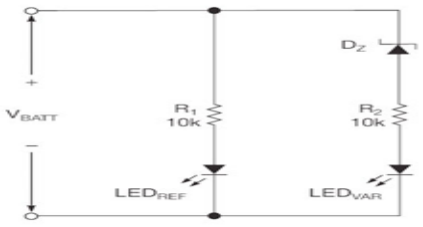


Fig.2. Voltage Indication circuit using single diode

Zener diode D_Z in series with resistor R_2 causes the current to change w.r.t battery voltage. The sum of the Zener voltage and the drop across the LED appears across R_2. As the battery voltage varies, it produces a large variation of current in R_2. If the voltage is approximately 1V, then 10 mA will flow through LED_{VAR}, which is much brighter than LED_{REF}. If the voltage is less than 0.1V, then the light intensity of LED_{VAR} will be less than LED_{REF}, indicating that the battery has discharged.

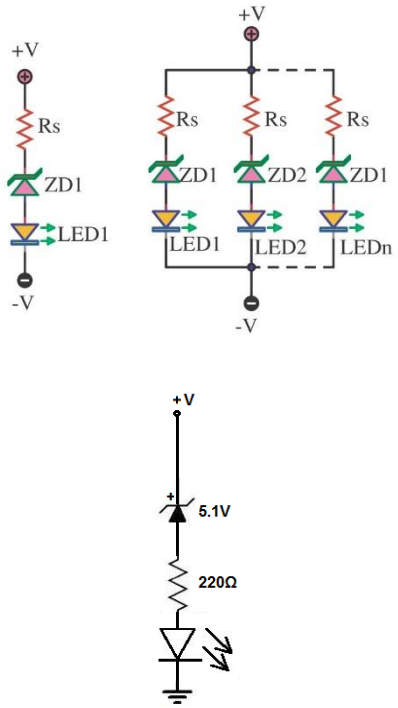


Fig.3.Voltage indication circuit using three diodes in parallel

2. Using Zener diode in parallel

The Zener diode is connected in reverse biased to the power source. After this comes the 220Ω resistor that limits current to the LED and then we have the LED. The power source feeds voltage to the circuit. When the voltage goes above the 5.1V threshold, then the Zener diode breaks down and begins to conduct current across from its cathode to its anode. This current then powers on the LED, lighting it up. The LED needs a forward voltage of about 2-3V across it in order to turn on, the LED won't turn on until the voltage fed into the circuit is about 7-8V. This is because the Zener diode consumes 5.1V and then the LED needs about 2-3V of forward voltage in order to turn on. So this circuit really is an indicator that the voltage in the circuit is greater than 7V. If the LED is on, then the voltage is definitely greater than 5.1V, which is the breakdown of the Zener diode. But we have to take into account the voltage needed for the LED to turn on too. So, we

Asian Journal of Applied Science and Technology (AJAST)

Volume 1, Issue 5, Pages 91-94, June 2017

have to add that voltage amount to truly see the level the voltage is at.

To get the more accurate value, this circuit can be modified by changing the Zener values as shown in the figure below. So, the gap between the voltages can be reduced.

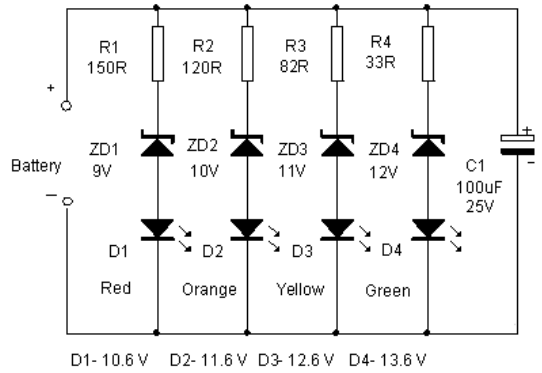


Fig 4. Voltage indication using different colour LEDs

3. Battery Voltage Indicator using Transistors

We can also employ a voltage indicator using transistors as they are fast switching components that provides faster results.

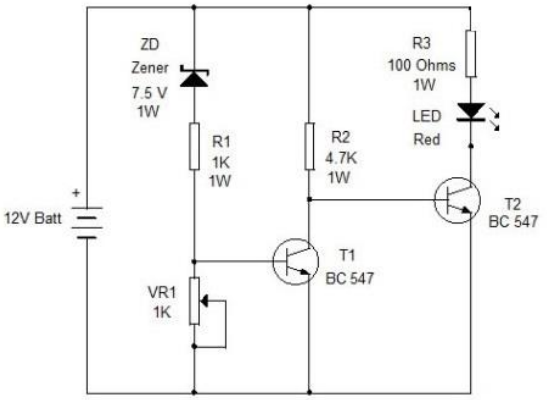


Fig 5. Battery capacity indication using transistors

Here, the two N-P-N transistors T1 and T2 act as Voltage Controlled Switches that are controlled by the Zener diode. Here, a Zener having breakdown voltage of 7.5V is connected between the positive rail and the 1K Preset (VR1). Resistor R1 limits the current through the Zener. To the junction of R1 and VR1, the base of T1 is connected. T1 will conduct when it gets base voltage from the Zener. When the battery voltage is above 9 volts, Zener conducts and T1 switches on. As a result, the collector voltage drops and it switches off T2 because the base of T2 will be at ground potential. So, LED remains off. That means, the battery voltage is above 9 voltage and the battery condition is good. When the battery voltage drops below 9 volts, Zener switches off. T1 also turns off. At this time, the collector of T1 becomes high through R2 and T2 gets base bias and it turns on. The LED connected to the collector of T2 turns on to indicate low battery level. VR1 adjust the exact point of the LED switching.

The transistors can be used in a more complicated circuit based on the similar principle to indicate different levels of voltage more accurately and thus compute faster too as follows: -

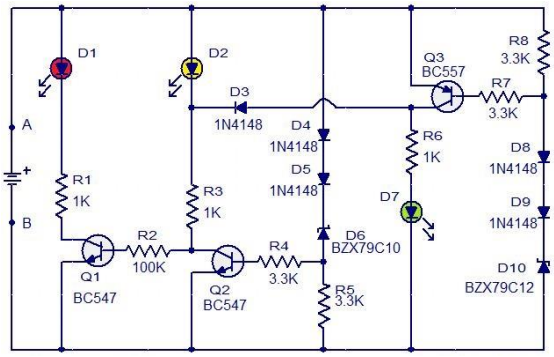
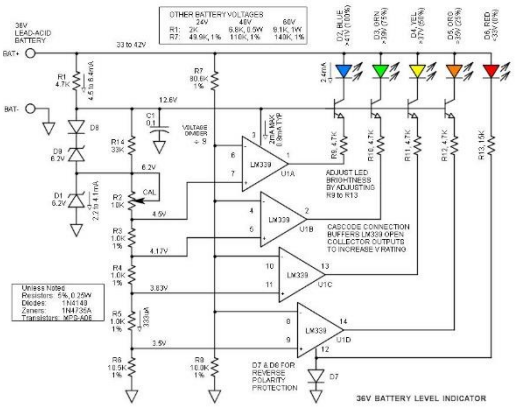


Fig 6. Voltage Indicator using Transistors and Diodes

This circuit can be employed for heavy electrical systems.

B. Level Two



In this level, we are making use of operational amplifiers and integrated chips because of their more robust nature and better performance along with easy deployment in required scenarios.

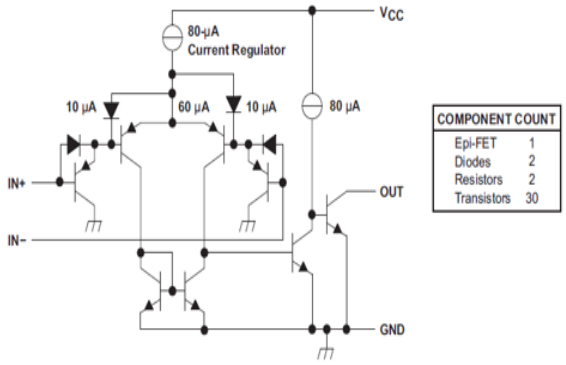
1. Simple Low Battery Indicator Circuit Using IC 741

The entire configuration is wired around the IC 741 which is configured as a comparator with one of its inputs clamped to a fixed reference level while the other input used as the sensing terminal. Here, the non-inverting input is provided with a fixed reference voltage through a resistor Zener network.

Asian Journal of Applied Science and Technology (AJAST)

Volume 1, Issue 5, Pages 91-94, June 2017

This input is fixed to about 5 volts. The other inverting input pin #2 is wired via a preset to sense



the input supply voltage from the source. The preset is adjusted such that the voltage level at this input becomes lower than the fixed reference voltage at the other pin of the IC as soon as the source voltage becomes lower than the desired threshold level. When this happens the output of the IC immediately becomes high, illuminating the connected LED.

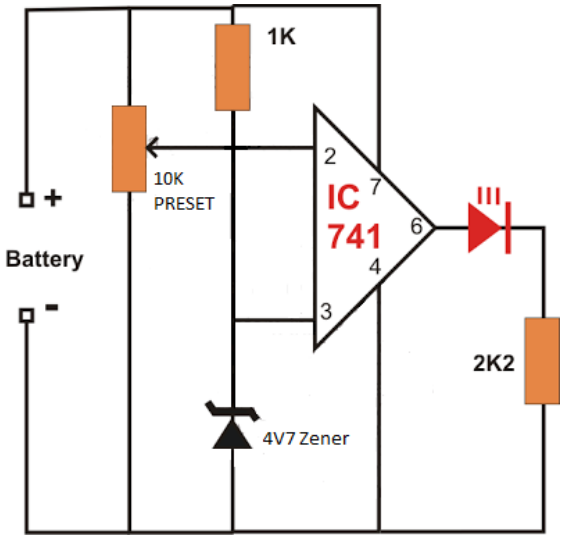


Fig 7. Battery Indicator Using Op-Amp 741

2. Using LMX39 Quad Comparator

This battery level indicator offers (5) LEDs, that light up progressively as the battery voltage increases. This is an update of the 24V Battery Level Indicator. While being designed for 36V systems, it is easily modified to 24V, 48V or 60V simply by changing two resistor values namely R1 and R7.

Fig 8. Schematic of the 36V Battery Level Indicator Circuit

Here, a cascade configuration of the transistors is used. A cascade arrangement is a configuration where a first transistor feeds a second transistor and so on as the transistors' bases are connected via a common link. This configuration is generally used for RF amplifiers. In this circuit, it offers one great property –low voltage in, high voltage out.

LEDs	Voltage (V)
Red	Power Connected (0%) (essentially always on)
Orange	Greater than 35V (25%)
Yellow	Greater than 37V (50%)
Green	Greater than 39V (75%)
Blue	Greater than 41V (100%) (full charge is about 41 to 42V)

By tying the bases of these transistors to the 13V bus, the LM**339** open collector drive transistors never exceed more than 13V. However, the cascade transistors may drive LEDs that are tied to a much higher voltage. By limiting the emitter current, the LED current is automatically limited to the same value. While this is relatively busy, it places virtually no burden on the shunt regulator. All of the four different comparators in the schematic are present inside one IC only and thus forms one-fourth of the LM339 the schematics of which are shown below.

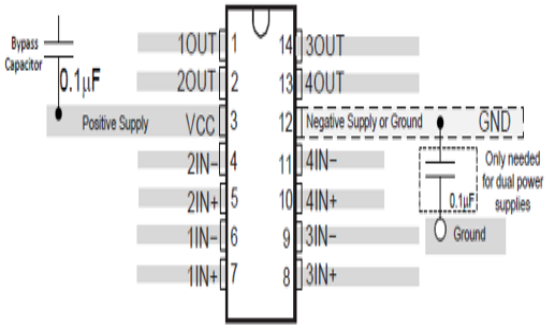


Fig. 9. LMX39 Layout Example

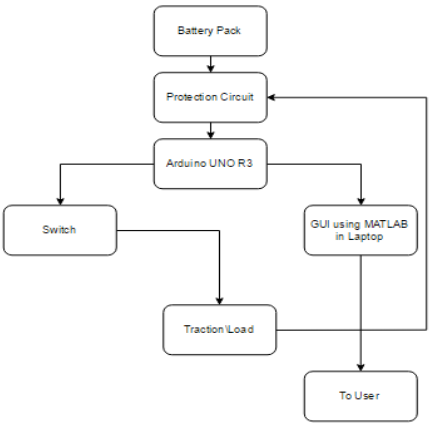


Fig. 10. Functional Block Diagram of each comparator

The circuit operation is as follows: D1 is the voltage reference Zener. Tied to this is a string of divider resistors (R2-6) that set the various fixed voltage

Asian Journal of Applied Science and Technology (AJAST)

Volume 1, Issue 5, Pages 91-94, June 2017

levels. R7 & 8 form a voltage divider that divides the battery voltage by a factor of 9. The quad comparator compares the various voltages from the two dividers. For calibration, connect to a voltage source that can be set to the highest LED threshold (41V in this case). Then adjust the calibration pot until D2 flickers. The remaining LEDs will switch on close to the indicated voltage –accuracy of those voltages may suffer slightly, but should be close. The LEDs are biased to operate at 2.3mA which is reasonably bright for high efficiency LEDs. This current can be adjusted simply by varying the emitter driver resistors (R9 through R13). To reduce standby power, a push-to-test pushbutton may be used. Different voltage levels are indicated as represented in the figure 11.
Fig. 11. Different Voltage indication with respect to different color LEDs

C. Level Three

Here, we are implementing a digital SOC indicator using complex algorithms and various protocol. The indication will be for the remaining capacity of the battery or the current voltage present in battery which will be displayed on the digital LCD display module in the form of percentage. Here, we are using the laptop that resembles the dashboard of a car and in which we will develop a graphical user interface to display the SOC status.

Along with this we can also show the current speed, date and time etc. The main aspect of this project is to calculate and show the distance that the vehicles can cover based on certain parameters with respect to the SOC estimate at any given time.

These parameters include constant speed, inclination of the road, regenerative braking, condition of the roads, air conditioning and infotainment services because these all exert pressure on the battery. We can also implement a battery State-of-Health (SOH) indication telling us how long will the battery be working properly.

This SOH indication will prevent the sudden breakdown of the battery during operation as it will warn the owner of its current state of health so that it can be replaced before permanent damage. A model of third level is shown in figure 12.

We started level three by making an arduino based voltmeter to measure the voltage of the battery pack at all times. For measuring voltages, less than or equal to 5V, first circuit can be used as shown in figure 13. For measuring voltages up to 50V, second circuit can be used as shown in figure 14. The LCD part in both the circuits are same.

In the first circuit, which is used to measure voltages up to 5V, there are no additional connections and the voltage to be measured is connected directly to the analog input A0 of the Arduino UNO.

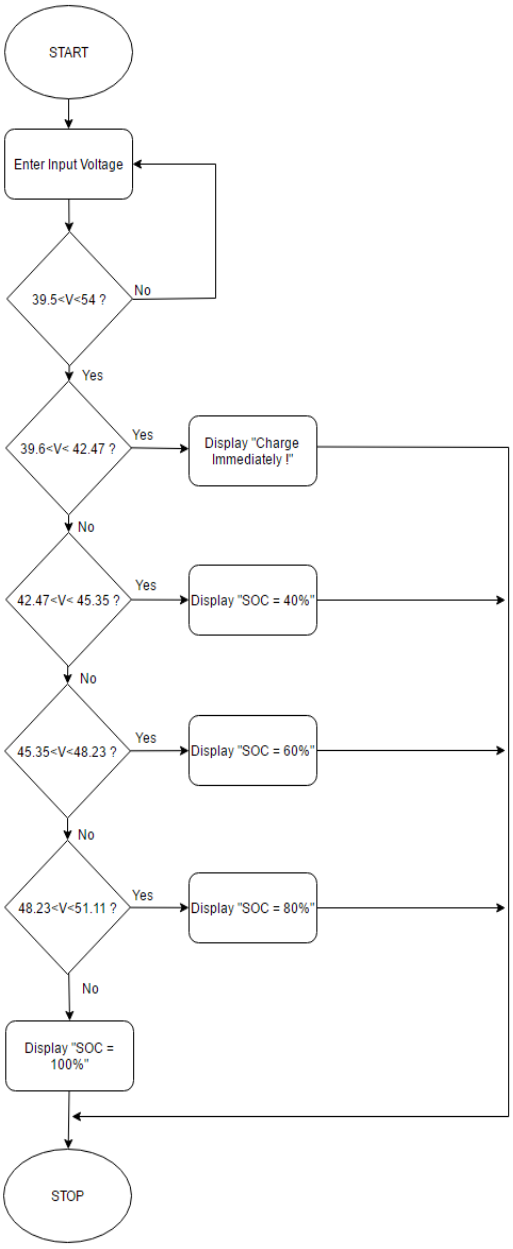


Fig. 12. Schematic of proposed model

In the second circuit, which is used to measure voltages up to 50V, we need to connect a voltage circuit additionally. The output of the voltage divider circuit consisting of 100KΩ resistor and 10KΩ resistor is connected to the analog input pin A0 of the Arduino UNO with other end of the 100KΩ resistor connected to the voltage to be measured and the other end of the 10KΩ resistor connected to the ground.

Asian Journal of Applied Science and Technology (AJAST)

Volume 1, Issue 5, Pages 91-94, June 2017

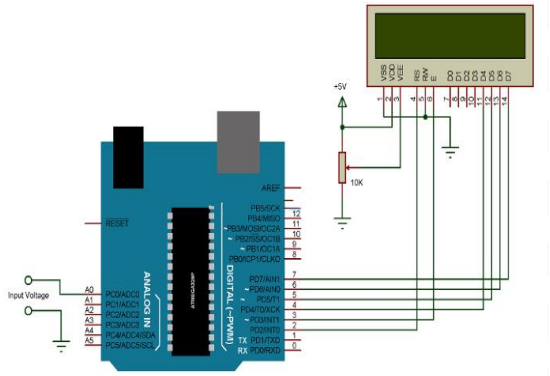


Fig. 13. Digital Voltmeter to measure up to 5V

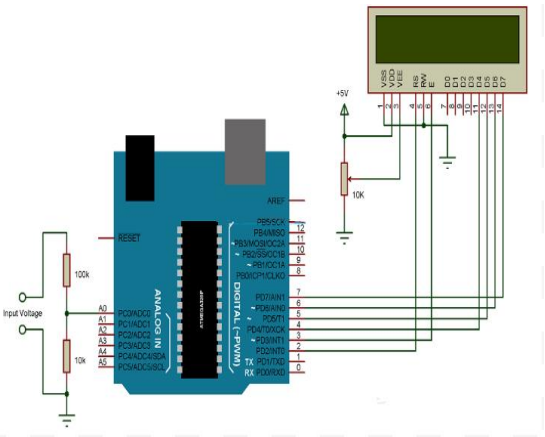


Fig. 14. Digital Voltmeter to measure up to 55V

In the first circuit, which is used to measure a maximum voltage of 5V, the input voltage is given to the analog input pin of the Arduino. The reference voltage of the ADC is 5V. The ADC in Arduino UNO is of 10-bit resolution. Hence, the input voltage is calculated by multiplying the analog value at the analog pin with 5 and dividing the value with 2^{10} i.e. 1024. The range of voltages for Arduino UNOs analog input is 0V to 5V. Hence, in order to increase this range, a voltage divider circuit must be used. In the second circuit, the range of the analog input of Arduino UNO is increased up to 50V by using a voltage divider consisting of 100KΩ resistor and 10KΩ resistor. With the help of the voltage divider circuit, the input voltage being measured is brought down to the range of Arduino UNOs analog input. The rest of the calculations are made in the programming part of the Arduino UNO. The output of this voltmeter is taken as the input by the algorithm designed to calculate the SOC of the battery. The flowchart is as follows.

The aforementioned algorithm can be used to indicate the SOC of the battery more precisely if modified for each voltage value.

The battery state of health (SOH) is a measure of the battery's ability to store and deliver electrical energy. Typical SOH methods characterize either the battery power or energy. This can also be implemented if required. But the main aspect of this project is to give an idea about Distance to Empty (DTE) that is how much more distance the vehicle can cover based on the remaining power of the battery. This property is not available in fuel gauge used in petrol or diesel vehicles, so, it is an added advantage of using an electric vehicle. The DTE can be estimated using the following algorithm.

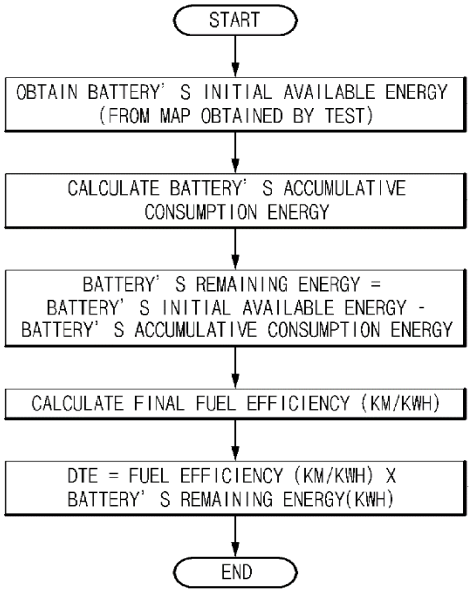


Fig. 15. DTE Algorithm using SOC Voltage

4. CONCLUSION

With the rising importance for battery, both in the automotive industry and the energy sector, it is of critical importance to develop more accurate algorithms for SOC estimation of the battery. This paper presents a novel technique for SoC estimation of the battery where the SoC estimated by sensing the voltage is formulated. For the future work more accuracy can be achieved by modifying the algorithms used above.

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Asian Journal of Applied Science and Technology (AJAST)

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