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A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications: Challenges and recommendations

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ABSTRACT

Due to increasing concerns about global warming, greenhouse gas emissions, and the depletion of fossil fuels, the electric vehicles (EVs) receive massive popularity due to their performances and efficiencies in recent decades. EVs have already been widely accepted in the automotive industries considering the most promising replacements in reducing CO_2 emissions and global environmental issues. Lithium-ion batteries have attained huge attention in EVs application due to their lucrative features such as lightweight, fast charging, high energy density, low self-discharge and long lifespan. This paper comprehensively reviews the lithium-ion battery state of charge (SOC) estimation and its management system towards the sustainable future EV applications. The significance of battery management system (BMS) employing lithium-ion batteries is presented, which can guarantee a reliable and safe operation and assess the battery SOC. The review identifies that the SOC is a crucial parameter as it signifies the remaining available energy in a battery that provides an idea about charging/discharging strategies and protect the battery from overcharging/over discharging. It is also observed that the SOC of the existing lithium-ion batteries have a good contribution to run the EVs safely and efficiently with their charging/discharging capabilities. However, they still have some challenges due to their complex electro-chemical reactions, performance degradation and lack of accuracy towards the enhancement of battery performance and life. The classification of the estimation methodologies to estimate SOC focusing with the estimation model/algorithm, benefits, drawbacks and estimation error are extensively reviewed. The review highlights many factors and challenges with possible recommendations for the development of BMS and estimation of SOC in next-generation EV applications. All the highlighted insights of this review will widen the increasing efforts towards the development of the advanced SOC estimation method and energy management system of lithium-ion battery for the future high-tech EV applications.

1. Introduction

The world is moving towards some serious consequences such as global warming, greenhouse gas (GHG) emission caused by extensive use of diesel, petrol in vehicle operation, which emits tons of CO_2 every year [1–3]. Besides, the rising crude oil price also causes serious setback of the automobile industry and urges the necessity to develop alternative fuel-driven vehicles. To address the problems, the implementation of EV has gained huge attention and become attractive choices for academic researchers and automobile specialists due to their promising features in reducing GHG [4–7].

Implementation of rechargeable battery in EV application has become very popular in recent years [8–10] since renewable energy sources such as solar energy, wind energy, are intermittent in nature and could not be applicable where continuous and reliable supply is required [11]. Various energy storages, such as lead acid, NiMH, lithium-ion batteries have been used in an EV [12]. Among them, lithium-ion battery is widely accepted due to its high energy density, long lifespan and high efficiency [13,14]. Because of its lucrative features, a lot of investments have already been made to enhance the stability and robustness of lithium-ion battery [15]. Even though of high primary cost, market growth of lithium-ion battery has been increasing steadily and is expected to continue its growth [16].

An effective BMS using the lithium-ion battery is compulsory so that battery can operate safely and reliably, prevent any physical damages, and handle thermal degradation and cell unbalancing [17,18]. Moreover, different states of the battery such as the SOC, state of health (SOH) can be assessed through an efficient battery management system, which can sense temperature, measure voltage and current, regulate safety alarm to avoid any overcharging/over discharging. Furthermore, a BMS is essential for controlling and updating data, detecting faults, equalizing battery voltage that are the important factors for achieving a good accuracy of SOC and SOH.

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Nomenclature

ANFIS	Adaptive Neural Fuzzy Interface System
ANN	Artificial Neural Network
ASGSMO	Adaptive Switching Gain Sliding Mode Observer
BI	Bi-linear Interpolation
CC	Coulomb Counting
EIS	Electrochemical Impedance Spectroscopy
EKF	Extended Kalman Filter
EMF	Electro-Motive Force
FL	Fuzzy Logic
FNN	Fuzzy Neural Network
GA	Genetic Algorithm
IR	Impulse Response
KF	Kalman Filter
MARS	Multivibrate Adaptive Regression Splines
NLO	Nonlinear Observer
NN	Neural Network
OCV	Open Circuit Voltage
PF	Particle Filter
PIO	Proportional-integral Observer
RBFNN	Radial Basis Function Neural Network
RLS	Recursive Least Square
SMO	Sliding Mode Observer
SPKF	Sigma Point Kalman Filter
SVM	Support Vector Machine
UKF	Unscented Kalman Filter
UPF	Unscented Particle Filter

SOC in battery management system is considered as one of the critical and important factors, which have been researched in recent decades. Battery SOC does the similar operation of the fuel gauge in a gasoline-driven vehicle which indicates how much energy is left inside a battery to power a vehicle [19]. Accurate estimation of battery states not only helps to provide information about the current and remaining performance of the battery but also gives assurance of a reliable and safe operation of the EV. However, battery SOC estimation is one of the main challenges for the successful operation of EVs. Due to non-linear, time-varying characteristics and electrochemical reactions, battery SOC cannot be observed directly [20]. Furthermore, the performance of the battery is highly affected by aging, temperature variation, charge-discharge cycles which make the task of estimating an accurate SOC very challenging [21].

Very few literature have been found which provide a detailed explanation of all the methods to estimate SOC of EV [22–25]. The literature has demonstrated some common methods to estimate SOC; however, each method has shortcomings in terms of accuracy and lack of data. In addition, complex calculation and high computation cost are the others concerns which make the estimation process very difficult. Hence, the academics, researchers, scientists have performed an extensive research to enhance the accuracy of battery SOC. Nevertheless, the issues in estimating an accurate SOC have not resolved yet. Besides, the challenges in estimating the SOC have not been identified. Thus, this research paper fills up the gap by exploring different existing methodologies and addressing the key issues and challenges for the estimation of SOC. This research will be very helpful for the automobile manufacturers and engineers in terms of deciding the appropriate method and identifying challenges.

This paper briefly discusses the lithium-ion battery state of charge estimation and management system in EV applications. The main concern is to develop an efficient SOC estimation method/algorithm of lithium-ion batteries. In addition, there are some issues and challenges regarding its estimation methodologies. This paper reviews the published articles to gain knowledge on SOC estimation methods in order to propose the most efficient model/algorithm. A detailed SOC estimation methods with its benefits and drawbacks is briefly elaborated. The issues and challenges of implementing various SOC methods along with possible solutions are also addressed to provide information and knowledge to the vehicle manufacturer. This knowledge will be important for future development of implementing new SOC methods or upgradation of earlier SOC methods.

2. Status of lithium-ion battery

There are many energy storages, such as lead acid, NiMH, lithium-ion batteries, which have been used widely for EV application. However, among them, lithium-ion batteries have been an attractive choice among automobile engineers in spite of its high capital cost [26]. Due it its promising performance in the application of automobile, cellular phone, notebook computers [27], a significant research and development have been performed to enhance the performance of lithium-ion batteries in terms of safety, reliability, and durability [28]. Conte et al. [29] made a comparative study of various energy storage devices, as reported in Table 1. It is clearly visible that, lithium-ion battery has better power and energy density compared to other energy storage devices. In addition, it has some attractive features such high efficiency, long cycle life, low discharge rate and high voltage.

Table 2 presents the main components of lithium-ion batteries and their characteristics. The table shows which electrode (particularly positive electrode) made the lithium-ion battery is suitable for specific application in terms of power, safety, cost, and lifespan.

A schematic of a lithium-ion battery is presented in Fig. 1 [31]. The cell has five regions, including composite negative electrode (anode), the composite positive electrode (cathode), a separator and two electrode current collectors; made of copper and aluminum respectively. The composite negative electrode (anode) and the positive (cathode) electrode are divided by an electrolyte separator such as $LiPF_6$. Lithium metal oxides (e.g., $LiCoO_2$, $LiNiO_2$, $LiMn_2O_4$) is used to build a positive electrode while graphite or petroleum coke is used to make a negative electrode. The composite electrodes are held together with carbon black. When the discharge process initiates, lithium ions are readily available to be accepted by positive electrode while a complete lithiation occurs in the negative electrode. During discharge, there is deintercalation between negative electrode particles and solution phase. During the same time, there is an intercalation between

Table 1
Performance comparison among various energy storage devices [29].

	Temperature [°C]	η (%)	Energy		Power [W/kg]	Voltage [V]	Self-discharge [%/Month]	Cycle life @80%DOD	Cost estimation	
			[Wh/l]	[Wh/kg]					[$/kWh]	[$/kW]
Lead Acid	−30–60	85	50–70	20–40	300	2,1	4–8	200	150	10
NiMH	−20–50	80	200	40–60	1300–500	1,2	20	> 2500	500	20
Li-ion	−20–55	93	150–200	100–200	3000–800	~3,6	1–5	< 2500	800	50–75
EDLC	−30–65	97	5	5–20	1500	~2,5	30	Not applicable	2000	50