Renewable and Sustainable Energy Reviews 56 (2016) 1008–1021

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review on electric vehicle battery modelling: From Lithium-ion toward Lithium–Sulphur

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ARTICLE INFO

Article history:
Received 28 March 2015
Received in revised form
31 July 2015
Accepted 10 December 2015

Keywords:
Battery modelling
Electric vehicle
Lithium sulphur
Equivalent circuit
Electrochemical

ABSTRACT

Accurate prediction of range of an electric vehicle (EV) is a significant issue and a key market qualifier. EV range forecasting can be made practicable through the application of advanced modelling and estimation techniques. Battery modelling and state-of-charge estimation methods play a vital role in this area. In addition, battery modelling is essential for safe charging/discharging and optimal usage of batteries. Much existing work has been carried out on incumbent Lithium-ion (Li-ion) technologies, but these are reaching their theoretical limits and modern research is also exploring promising next-generation technologies such as Lithium–Sulphur (Li–S). This study reviews and discusses various battery modelling approaches including mathematical models, electrochemical models and electrical equivalent circuit models. After a general survey, the study explores the specific application of battery models in EV battery management systems, where models may have low fidelity to be fast enough to run in real-time applications. Two main categories are considered: reduced-order electrochemical models and equivalent circuit models. The particular challenges associated with Li–S batteries are explored, and it is concluded that the state-of-the-art in battery modelling is not sufficient for this chemistry, and new modelling approaches are needed.

Contents

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http://dx.doi.org/10.1016/j.rser.2015.12.009
1364-0321/

1. Introduction

Hybrid vehicles are well-established in the market, and electric vehicles are growing in popularity. This trend is likely to continue for the foreseeable future. There is a strong scientific consensus in the reality of human-made climate change [1,2], which is reflected in national and international legislation on point-of-use emissions: in Europe, we are already seeing the introduction of stringent regulations. The UK Government has estimated that by 2030, average 'new car' tailpipe emissions will need to fall to around 50–70 g/km – a rough halving from the present day [3]. In discussions with our international academic colleagues, it is clear that in the relatively new, rapidly expanding markets such of China and India, there is a strong consciousness of the need to develop sustainably and without over-dependence on scarce foreign oil imports. There have been many studies that have considered the use of renewable energy sources in next generation of transport systems, and various new technologies have been applied [4–6]. The powertrain of the future is likely to be increasingly hybridised, increasingly electrified, and increasingly dependent on high quality, effective and affordable traction batteries.

In the UK, we have some uptake of electric vehicles, but EVs still represent a small market sector and there are challenges associated with their introduction [7]. Although it has been shown that in their present form, electric vehicles are suitable for the day-to-day needs of the typical urban motorist [8], consumers still have concerns about cost, longevity and range [7]. Charging times and safety are also well-known concerns.

Development of energy storage systems is at the heart of vehicle electrification process. Many new technologies for batteries, fuel cells, ultracapacitors, etc. have been developed for implementation in hybrid and electric vehicles. A good example is the Lithium-ion (Li-ion) battery, one of the most widely used technologies in advanced electrified vehicles. Li-ion batteries have been developed to meet different specifications, each with different chemical compositions. Key design objectives for automotive applications include battery energy density, safety and reliability [9]. Among the different types of Li-ion batteries used in EVs are Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Lithium Iron Phosphate (LFP) and Lithium Nickel–Manganese–Cobalt Oxide (NMC) [10]. Table 1 shows some of the battery pack manufacturers and the EVs in which their batteries are used [11].

As Li-ion batteries have been developed to maturity, they have begun to approach their theoretical energy density limits (200–250 W h/kg [12]). Ongoing electrochemical research on Li-ion batteries aims at increasing cycle life, safety, and other performance characteristics [13]. At the same time, researchers are investigating other types of electrochemical energy storage systems with higher energy density for use in EV applications. One such electrochemical system is the Lithium–Sulphur (Li–S) battery. The Li–S battery offers potential advantages over Li-ion, such as higher energy density, improved safety, a wider operating temperature range, and lower cost (because of the availability of Sulphur); this makes it a promising technology for EV application. However, Li–S technology has not been widely commercialised yet because it suffers from limitations such as self-discharge and capacity fades due to cycling and high discharge current [14]; research into these areas is ongoing.

Battery modelling is a significant task within battery technology development, and is vital in applications. For example, EV range prediction is only possible through the application of advanced battery modelling and estimation techniques to determine current state and predict remaining endurance. In addition, battery modelling is essential for safe charging and discharging, optimal utilisation of batteries, fast charging, and other applications. In this study, modelling of batteries is addressed with a focus on their EV applications. Different modelling approaches are reviewed and explained, considering three categories of models: mathematical models, electrochemical models and electrical equivalent circuit networks. The first part of the paper considers these techniques in general, and is potentially useful to a wide range of readers who are interested in understanding the breadth of techniques available for battery modelling, with many different possible applications. The paper then considers our specific application: hybrid and electric vehicles. This considers modelling approaches which are applicable in EV battery management systems: the discussions presented in this part are mainly focused on low-fidelity models which are fast enough for real-time applications. For this purpose, our review focuses on reduced-order (simplified) electrochemical models, and equivalent circuit network models. The last part of this study specifically considers Li–S battery technology which some researchers view as promising technology for the next generation of hybrid and electric vehicles. Previous studies about Li–S battery modelling are reviewed

Table 1
Different Li-ion battery packs manufacturers and EVs in which battery is used [11].

Cathode material types	EVs battery packs manufacturers	EVs developers and EV models	Battery packs usable capacity (kW h)	Approx. range under normal driving conditions (mile)
Lithium Cobalt Oxide (LCO)	Panasonic,	Tesla–Roadster	56	245
	Tesla	Daimler Benz–Smart EV	16.5	84
Lithium Manganese Oxide (LMO)	AESC, EnerDel,	Think–Think EV	23	99.4
	GS Yuasa, Hitachi, LG Chem, Toshiba	Nissan–Leaf EV	24	105
Lithium Iron Phosphate (LFP)	A123, BYD, GS	BYD–E6	57	249
	Yuasa, Lishem, Valence	Mitsubishi–iMiEV	16	99.4
Lithium Nickle–Manganese–Cobalt Oxide (NMC)	Hitachi, LG Chem, Samsung	BMW–Mini E	35	150