Journal of Power Sources 324 (2016) 388–401

Contents lists available at ScienceDirect

Journal of Power Sources

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

Experimental analysis of Hybridised Energy Storage Systems for automotive applications

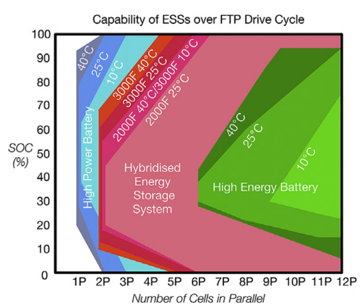
Wasim Sarwar [a], Timothy Engstrom [a], Monica Marinescu [a], Nick Green [b], Nigel Taylor [b], Gregory J. Offer [a, *]

[a] Department of Mechanical Engineering, Imperial College London, UK
[b] Hybrids and Electrification Research, Jaguar Land Rover, Warwick, UK

HIGHLIGHTS

- Hybridised system is shown to perform similarly to a specialised high power battery.
- Hybridised system exhibits lower temperature sensitivity than battery only systems.
- Battery current and energy throughput reduced by over 80% in hybridised system.
- Degradation occurs at a similar rate for all systems tested.
- Battery current demand and temperature rise reduce as hybridised system degrades.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 March 2016
Received in revised form
18 May 2016
Accepted 23 May 2016
Available online 30 May 2016

Keywords:
Hybridised Energy Storage
Lithium battery
Supercapacitor
Automotive
Degradation
Passive

ABSTRACT

The requirements of the Energy Storage System (ESS) for an electrified vehicle portfolio consisting of a range of vehicles from micro Hybrid Electric Vehicle (mHEV) to a Battery Electric Vehicle (BEV) vary considerably. To reduce development cost of an electrified powertrain portfolio, a modular system would ideally be scaled across each vehicle; however, the conflicting requirements of a mHEV and BEV prevent this. This study investigates whether it is possible to combine supercapacitors suitable for an mHEV with high-energy batteries suitable for use in a BEV to create a Hybridised Energy Storage System (HESS) suitable for use in a HEV. A passive HESS is found to be capable of meeting the electrical demands of a HEV drive cycle; the operating principles of HESSs are discussed and factors limiting system performance are explored. The performance of the HESS is found to be significantly less temperature dependent than battery-only systems, however the heat generated suggests a requirement for thermal management. As the HESS degrades (at a similar rate to a specialised high-power-battery), battery resistance rises faster than supercapacitor resistance; as a result, the supercapacitor provides a greater current contribution, therefore the energy throughput, temperature rise and degradation of the batteries is reduced.

1. Introduction

It is desirable for an automaker to create a modular electrified powertrain to enable the usage of the same base components

* Corresponding author.
E-mail addresses: w.sarwar@imperial.ac.uk (W. Sarwar), gregory.offer@imperial.ac.uk (G.J. Offer).

http://dx.doi.org/10.1016/j.jpowsour.2016.05.114
0378-7753/

Nomenclature

A, B	experimentally derived constants
ATM	Active Thermal Management
BEV	Battery Electric Vehicle
CTR	Charge Transfer Resistance
EIS	Electrochemcial Impedance Spectroscopy
ESR	Equivalent Series Resistance
ESS	Energy Storage System
ET	Energy Throughput
FTP	Federal Test Procedure
HEB	High Energy Battery
HESS	Hybridised Energy Storage System
HEV	Hybrid Electric Vehicle
HPB	High Power Battery
$I_{0_{Batt}}$	instantaneous battery current in HESS
$I_{0_{SC}}$	instantaneous SC current in HESS
I_{Batt}	battery current in HESS
I_T	total applied current
I2kF	Ioxus 2000F Supercapacitor
I3kF	Ioxus 3000F Supercapacitor
mHEV	micro Hybrid Electric Vehicle
n	number of cells
NEDC	New European Drive Cycle
P18650BD	Panasonic 18650BD cylindrical cell
PHEV	Plug-in Hybrid Electric Vehicle
$\dot{Q}_{El_{Loss}}$	rate of heat generation due to electrical losses
R	resistance
SC	supercapacitor
SEI	Solid Electrolyte Interphase
SoC	State of Charge
UDDS	Urban Dynamometer Driving Schedule
WLTP	Worldwide Light Vehicle Test Procedure
η	overpotential

across its portfolio of vehicles. The energy and power requirements of the Energy Storage System (ESS) vary significantly for different vehicle types; the requirements are summarised in Fig. 1.

Vehicles classified as micro Hybrid Electric Vehicles (mHEVs) typically utilise low voltage (48 V) energy storage to enable high power functions and features to reduce CO_2 emissions, such as electronic Power Assisted Steering, electric turbocharging, capturing regenerative energy from the vehicle, and enabling the engine to be switched off for extended periods of time. The ESS in a mHEV must provide or accept very high power for its size (commonly refereed to as 'C-Rate') for short time periods with minimal thermal management (passive cooling), therefore it must have the attributes of high power, low energy, large thermal operating window, and high cycle life.

Hybrid Electric Vehicles (HEVs) can be electrically propelled for short distances and require significantly more power than a mHEV, therefore HEVs typically utilise high voltage ESSs (200–450 V). A HEV is less cost sensitive than the mHEV, therefore semi-active thermal management (indirect liquid cooling) can be used to improve system performance. Additionally, the usage profile dictates a lower cycle requirement than a mHEV as the larger energy capacity ESS is subject to fewer cycles for a given driving distance. Plug-in Hybrid Electric Vehicles (PHEV) have a similar use-case to HEVs, however they must electrically propel the vehicle for longer distances and therefore require more energy and consequently lower power density. Greater value exists in thermal management of larger battery packs, therefore the required thermal operating window is smaller.

Battery Electric Vehicles (BEVs) require significantly more energy and power than PHEVs, consequently larger ESSs are used. As with PHEVs, in a large ESS the use of active thermal management (system consisting of heating and cooling loop) provides good value, therefore a large thermal operating window is not required. Further, a comparatively shorter cycle life is sufficient in order to meet the vehicle life requirements.

As the requirements of the ESS for each vehicle configuration differ, it follows that a different battery or EDLC cell would be implemented in a module for each. However, the research and development required for the implementation of previously unused cells is costly, resource intensive and highly time consuming. It is therefore desirable to commonize cells across vehicle types.

SCs or High Power Battery (HPB) cells can be used to satisfy the

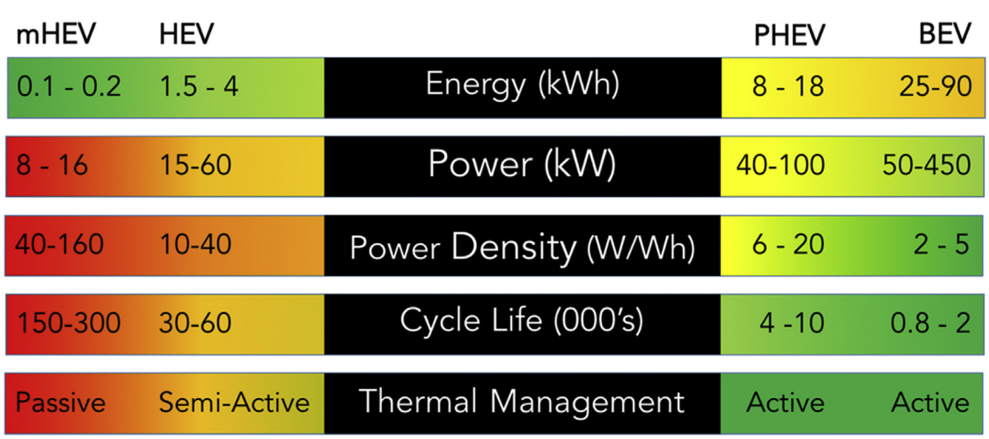


Fig. 1. Energy storage system requirements for electrified vehicles that fall under the broad categories of mHEV, HEV, PHEV and BEV. In addition to a numerical quantification of the requirement, a colour scale indicates the most challenging factors in the design of an energy storage system for the particular application. The scale passes from green to red, with green requirements proving the least challenging for traditional battery technology, and red requirements the most challenging. Sources – [1–14]. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)