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BY
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DENMARK

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CV

From June 2013 to May 2016 I pursued my PhD in Battery Management Systems at Aalborg University, Denmark, being involved in the ALPBES project and in a number of other industrial projects. During my PhD studies, I was a visitor researcher at RWTH ISEA Aachen University, Germany, in 2015, and at FEUP and INES TEC Porto, Portugal, in 2014.

Previously, I obtained a MSc in Power Electronics and Drives also in Aalborg and a MSc in Electrical Engineering at University of Vigo, Spain. Then, I co-founded a photovoltaic consulting company in Spain, serving as business development manager from 2010 to 2012. Moreover, I was a researcher at Aalborg University from 2011 to 2013.

From June 2016, I am a Postdoc in Battery Management at University of Oxford. I am involved in AMPLiFII, a project aimed at laying the foundations of a new UK automotive supply chain. Panasonic, WMG, HORIBA MIRA, JCB, Ariel Motor Company, Potenza Technology, Delta Motorsport, Jaguar and Land Rover are some of the main project partners. My duties within the project are to develop high level software for Battery Management Systems in the context of high power and high energy automotive battery applications.

My current research focus is on novel electric vehicle concepts and Lithium-ion battery modeling, simulation, testing, diagnosis, balancing and management systems.

SYNOPSIS

This thesis presents, as a collection of papers, practical methods in Li-ion batteries for simplified modeling (Manuscript I and II), battery electric vehicle design (III), battery management system testing (IV and V) and balancing system control (VI and VII).

Manuscript I tackles methodologies to parameterize electrical equivalent circuit models of Li-ion cells based solely on manufacturer's datasheets. A topic that, despite its significance, has not enjoyed much attention in the literature. Results demonstrate that it is possible to implement high accuracy steady-state models that reflect open circuit voltage or resistance dependencies on state-of-charge, current or temperature.

Manuscript II presents a parameterization method for linear static electrical equivalent circuit models based on the notion of direct current resistance. The idea is to exclude from the parameterization the influence of diffusion polarization effects, which are non-dominant in applications like e-mobility. Results show that, in comparison with other pulse response parameterization methods, significant gains are achievable in terms of voltage and power losses estimation. In addition, this method does not show the limitations, complexity or infeasibility problems of optimal approaches.

Manuscript III proposes a battery electric vehicle design that combines fixed and swappable packs. In this way, long-range capability is feasible with both packs, while the weight can be reduced under fixed-pack operation. Moreover, the cost of the swappable pack can be accounted as a usage-cost per mile. The efficiency and range of the vehicle are estimated in simulations and the swap-costs via economic models. The total cost of ownership of the proposed vehicle is compared with a Tesla Model S 85. Results show the potential for major improvements in fuel economy and costs.

Manuscript IV focuses on the development of a real-time capable battery system model for battery management system testing on a state-of-the-art hardware-in-the-loop simulator. The proposed model is able to test for the majority of the funtional and non-functional requirements, including fault insertion testing. Results from exemplary tests are shown for purposes of validation and performance evaluation of the model, which takes a qualitative step forward in the state-of-the-art.

Manuscript V extends the previous work, introducing theoretical principles of battery management system testing and presenting a practical method to develop ad hoc software and strategies for testing at system level. Extensive results presented illustrate the immense possibilities of such software and strategies for testing.

Manuscript VI presents a preliminary offline evaluation of a 'multi-objective' control approach for balancing systems. It demonstrates that other control features can be offered, such as minimization of power losses, temperature equalization or maximization of usable capacity.

Manuscript VII presents a comprehensive offline evaluation of the impact on battery performance of the additional control features introduced in Manuscript VI. It is observed that the impact can vary, depending on a number of factors related or not with the balancing system. Several scenarios are identified where significant gains can be achieved, in terms of temperature distribution, power losses or available capacity.

Apart from the papers, this dissertation provides a framework for understanding the motivations and background for the research and the current state-of-the-art. It presents the problem statement; gives an overview of the main modeling methods; summarizes the papers and discusses the contributions, limitations and directions for future work; and gives an overall conclusion.

DANSK RESUME

Denne afhandling er baseret på en artikelsamling, og præsenterer praktiske metoder indenfor lithium-ion (Li-ion) batterier til forenklet modellering (Manuskript I og II), batteri elektrisk køretøjsdesign (III), test af batteri styringssystemer (IV og V) og balanceringskontrol (VI og VII).

Artikel I omhandler metoder til at parametrisere elektriske ækvivalent kredsløbsmodeller af Li-ion-celler udelukkende baseret på producentens datablade. Et emne, der på trods af dens betydning, har ikke haft meget opmærksomhed i litteraturen. Resultaterne viser, at det er muligt at gennemføre nøjagtige statiske modeller, der afspejler tomgangsspændings eller den indre modstands afhængighed af lade tilstand, strøm eller temperatur.

Artikel II præsenterer en parametriseringsmetode for lineære statiske elektrisk ækvivalente kredsløbsmodeller baseret på begrebet jævnstrømsmodstand. Ideen er at udelukke indflydelsen af diffusionspolariseringen, som er ubetydelig for nogle applikationer, såsom elektro-mobilitet. Resultaterne viser, at i sammenligning med andre puls respons parametreringsmetoder, kan der opnås betydelige gevinster med hensyn til estimering af spænding og effekttab. Hertil kommer, at denne metode ikke viser begrænsninger i kompleksitet eller er uoverkommelig, ligesom nogle optimeringsmetoder.

Artikel III forlægger et elbils batteridesign, der kombinerer fast installerede og udskiftelige pakker. På denne måde, er lang rækkevidde muligt med begge pakker, mens vægten kan reduceres under kørsel kun med den fast installerede pakke. Desuden kan omkostningerne ved den udskiftelige pakke afregnes per kørte km. Effektiviteten og rækkevidden af køretøjet er estimeret i simulationer og udskiftningsomkostninger via økonomiske modeller. De samlede omkostninger ved ejerskab af det foreslåede køretøj sammenlignes med en Tesla Model S 85. Resultaterne viser potentiale for store forbedringer i brændstoføkonomi og omkostninger.

Artikel IV fokuserer på udvikling af et realtids batterisystemsmodel til test af batteri styringssystemer på en state-of-the-art hardware-in-the-loop simulator. Den foreslåede model er i stand til at teste størstedelen af de funtionelle og ikke-funktionelle krav, herunder test af fejlinjeksering. Resultater fra tests er vist med henblik på validering og evaluering af modellens ydeevne, hvilket er en udbygning af den kendte viden indenfor området.

Artikel V er en videreudvikling af tidligere arbejde, og indfører teoretiske principper for test af batteri styringssystemer og præsenterer en praktisk metode til at udvikle ad hoc software og strategier for test på systemniveau. Omfattende resultater viser de enorme muligheder for sådan software og strategier til test.

Artikel VI præsenterer en foreløbig offline vurdering af en "multi-objective" kontrol tilgang til balanceringssystemer. Det viser sig, at andre kontrolfunktioner kan udføres, såsom minimering af tab, temperaturudligning eller maksimering af brugbar kapacitet.

Artikel VII præsenterer en omfattende offline evaluering af konsekvenserne for batteriets ydeevne af de ekstra kontrolfunktioner indført i Artikel VI. Det bemærkes, at virkningen kan variere, afhængigt af en række faktorer, relateret eller ej, med balanceringssystemet. Flere scenarier er identificeret, hvor der kan opnås betydelige gevinster i form af temperaturudligning, tab eller tilgængelig kapacitet.

Bortset fra artiklerne, giver afhandlingen en ramme for at forstå motivationen og baggrunden for forskningen og den nuværende state-of-the-art. Den præsenterer problemformuleringen, giver et overblik over de vigtigste modelleringsmetoder, opsummerer artiklerne, diskuterer de bidrag, begrænsninger og retninger for det fremtidige arbejde, og giver en samlet konklusion.

SINOPSIS EN ESPAÑOL

Esta tesis presenta, a través de una colección de artículos, métodos prácticos en baterías de ion de litio para modelado simplificado (Artículos I y II), diseño de vehículo eléctrico (III), ensayo de sistemas electrónicos de gestión (IV y V) y control de sistemas de equilibrado (VI y VII).

El Artículo I aborda metodologías para parametrizar modelos eléctricos de circuito equivalente de células de ion de litio, basándose únicamente en hojas de datos del fabricante. Un tema que, a pesar de su relevancia, no ha disfrutado de demasiada atención en la literatura. Los resultados demuestran que es posible implementar modelos estacionarios de gran precisión que reflejen las dependencias de la tensión de circuito abierto o la resistencia en el estado de carga, la corriente o la temperatura.

El Artículo II presenta un método de parametrización para modelos eléctricos de circuito equivalente lineales estáticos basado en el concepto de resistencia de corriente continua. El objetivo que se persigue es excluir de la parametrización la contribución de los efectos de la polarización por difusión, efectos no-dominantes en aplicaciones como movilidad eléctrica. Los resultados demuestran que, en comparación con otros métodos de parametrización de respuesta a impulso, se pueden lograr mejoras significativas en la estimación de la tensión de terminales y las pérdidas de potencia. Además, este método no muestra las limitaciones, complejidad o problemas de inviabilidad de los enfoques óptimos.

El Artículo III propone un diseño de vehículo eléctrico de baterías que combina packs fijos e intercambiables. De este modo, es posible disponer de gran autonomía si se opera con ambos packs, así como reducir el peso si se opera únicamente con el pack fijo. Además, el costo del pack intercambiable puede ser considerado como un costo de uso por milla. La eficiencia y la autonomía del vehículo se estiman en simulaciones y los costos del pack intercambiable a través de modelos económicos. El coste total de propiedad del vehículo propuesto se compara con el de un Tesla Model S 85. Los resultados muestran importantes ventajas potenciales en el consumo de energía y los costes de propiedad del vehículo.

El Artículo IV presenta un modelo de sistemas de baterías que puede usarse en tiempo real para llevar a cabo ensayos en sistemas de gestión electrónica de baterías sobre modernos simuladores con hardware en lazo. El modelo propuesto puede utilizarse para probar la mayoría de los requerimientos funcionales y no funcionales de un sistema de gestión electrónica de baterías, incluyendo ensayos de faltas. Resultados ejemplares se facilitan con objeto de validar y evaluar el funcionamiento del modelo, que supone un salto cualitativo en el estado del arte.

El Artículo V amplía el trabajo anterior, proporcionando una introducción a los principios teóricos de los ensayos de sistemas de gestión de baterías y presentando un método práctico para desarrollar ad hoc software y estrategias de ensayo a nivel de sistema. Una gran cantidad de resultados experimentales son facilitados para ilustrar las inmensas posibilidades del software y de las estrategias de ensayo.

El Artículo VI presenta, preliminarmente, una evaluación offline de un método de control "multi-objetivo" para sistemas de equilibrado de baterías. Se demuestra que otras capacidades de control pueden ofrecerse, como minimización de las pérdidas de potencia, equilibrado de temperatura o maximización de la capacidad útil de la batería.

El Artículo VII presenta una exhaustiva evaluación offline del impacto de las capacidades de control adicionales introducidas en el Articulo VI en la operación de una batería. Se observa que dicho impacto puede variar, dependiendo de una serie de factores relacionados o no con el sistema de equilibrado. Se identifican varios escenarios donde se pueden lograr ganancias significativas, en términos de distribución de temperaturas, pérdidas de potencia o capacidad útil de la batería.

Aparte de tratar los artículos, esta disertación sienta las bases para el entendimiento de las motivaciones y los antecedentes de la investigación y el actual estado del arte. Presenta un planteamiento formal del problema; proporciona un resumen de los principales métodos de modelado; sintetiza los artículos y discute sus contribuciones, limitaciones y direcciones para trabajo futuro; y ofrece una conclusión general.

SINOPSE EN GALEGO

Esta tese presenta, mediante unha colección de artigos, métodos prácticos en baterías de ion de litio para modelaxe simplificada (artigos I e II), deseño de vehículo eléctrico de baterías (III), ensaios de sistemas de xestión electrónica (IV e V) e control de sistemas de equilibrado (VI e VII).

O artigo I aborda metodoloxías para parametriza-los modelos eléctricos de circuíto equivalente das células de ion de litio, con base só nas follas de datos do fabricante. Unha cuestión que, a pesar da súa relevancia, non gozou de moita atención na literatura. Os resultados mostran que é posíbel aplicar modelos estacionarios de alta precisión que reflicten as dependencias da tensión en circuíto aberto ou da resistencia no estado de carga, a corrente ou a temperatura.

O artigo II presenta un método de obtención de parámetros para modelos eléctricos de circuíto equivalente lineais estáticos baseado no concepto de resistencia de corrente continua. O obxectivo que se persegue é eliminar da parametrización a contribución dos efectos da difusión de polarización, efectos que resultan non-dominantes en aplicacións como a mobilidade eléctrica. Os resultados mostran que, en comparación con outros métodos de parametrización de resposta a impulso, melloras significativas poden ser acadadas na estimación das perdas de potencia e da tensión dos terminais. Ademais, este método non presenta as limitacións, a complexidade ou os problemas de inviabilidade das abordaxes óptimas.

O artigo III propón un deseño de vehículo eléctrico de baterías que combina packs fixos e intercambiabeis. Así, é posíbel acadar grandes autonomía mentras é operado con ámbo-los packs, e reduci-lo peso cando é operado só co pack fixo. Ademáis, o custo do pack intercambiábel pode ser considerado coma un custo de uso por milla. A eficiencia e a autonomía do vehículo estímanse en simulacións e os custos do pack intercambiábel mediante modelos económicos. O custo total de propiedade do vehículo proposto é comparado cun Tesla Model S 85. Os resultados mostran vantaxes potenciais significativas tanto no consumo de enerxía como nos custos de propiedade do vehículo.

O artigo IV presenta un modelo de sistemas de baterías que pode ser usados en tempo real para realizar ensaios sobre sistemas electrónicos de xestión de baterías en modernos simuladores de hardware en lazo. O modelo proposto pode empregarse para ensaiar a meirande parte dos requisitos funcionais e non funcionais dun sistema de xestión electrónica de baterías, incluíndo ensaios de fallas. Resultados exemplares preséntanse co fin de validar e avaliar o rendemento do modelo, que supón un salto cualitativo no estado da arte.

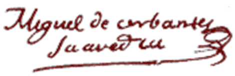
O artigo V é unha extensión do traballo anterior, é contén unha introdución aos principios teóricos de ensaio de sistemas electrónicos de xestión de baterías, ademáis de presentar un método práctico para desenvolver software ad hoc e estratexias de ensaio a nivel do sistema. Facilítanse un gran número de resultados experimentais, co obxectivo de ilustrar as inmensas posibilidades do software e das estratexias de ensaio.

O artigo VI presenta, preliminarmente, unha avaliación offline dun método de control "multi-obxectivo" para equilibrado dos sistemas de baterías. Demóstrase que outras capacidades de control poden ser ofertadas, como o minimizado das perdas de enerxía, o equilibrado de temperatura ou o maximizado da capacidade útil da batería.

O artigo VII presenta unha extensa avaliación offline do impacto dos recursos de control adicional introducidos no artigo VI durante a operación dunha batería. Nótase que o seu impacto pode variar en función dun número de factores relacionados ou non co sistema de equilibrado. Por último, diversos escenarios nos que beneficios significativos poden ser acadados en materia de distribución de temperaturas, perdas de enerxía ou capacidade útil da batería son identificados.

Ademáis de recolleita-los artigos, esta disertación establece as bases para comprende-las motivacións e os antecendentes da investigación e do estado actual da arte. Presenta unha visión formal do problema; facilita un resumo dos principais métodos de modelado; sintetiza os artigos e discute as súas contribucións, limitacións e direccións para traballos futuros; e ofrece unha conclusión xeral.

“—One of the greatest sins that men are guilty of is – some will say pride – but I say ingratitude, going by the common saying that hell is full of ingrates. This sin, so far as it has lain in my power, I have endeavored to avoid ever since I have enjoyed the faculty of reason; and if I am unable to requite good deeds that have been done me by other deeds, I substitute them by the desire to do so; and if that be not enough I make them known publicly; for he who declares and makes known the good deeds done to him would repay them by others if it were in his power, and for the most part those who receive are the inferiors of those who give; (…) I therefore, grateful for the favour that has been extended to me here, and unable to make a return in the same measure, restricted as I am by the narrow limits of my power, offer what I can and what I have to offer in my own way;”[1]



Miguel de Cervantes, “Don Quixote of La Mancha”, Part Two: Chapter LVIII.

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[1] Original in Spanish: *“—Entre los pecados mayores que los hombres cometen, aunque algunos dicen que es la soberbia, yo digo que es el desagradecimiento, ateniéndome a lo que suele decirse: que de los desagradecidos está lleno el infierno. Este pecado, en cuanto me ha sido posible, he procurado yo huir desde el instante que tuve uso de razón, y si no puedo pagar las buenas obras que me hacen con otras obras, pongo en su lugar los deseos de hacerlas, y cuando estos no bastan, las publico, porque quien dice y publica las buenas obras que recibe, también las recompensara con otras, si pudiera; (…) Yo, pues, agradecido a la merced que aquí se me ha hecho, no pudiendo corresponder a la misma medida, conteniéndome en los estrechos límites de mi poderío, ofrezco lo que puedo y lo que tengo de mi cosecha;” Miguel de Cervantes, “Don Quijote de La Mancha”, Segunda Parte: Capítulo LVIII.*

ACKNOWLEDGEMENTS

My PhD journey came to an end by submitting and defending the PhD dissertation that you are now reading. This will hopefully open the door to new opportunities. In fact, just one day after the end of my 3-year period as A PhD student at Aalborg University, I started a new academic position in the UK. For these reasons, after many years here, I am leaving the Department of Energy Technology, which gives me mixed feelings.

On one hand, I feel really lucky to be able to continue developing my academic career, But on the other hand I know that I will miss you, my travel companions. I would like to say that I truly loved this trip and that I will always carry the moments together with me forever.

It is impossible to mention everybody here… However, I would like to give special thanks to at least some of you:

- @Erik Schaltz for being more than a PhD supervisor, I really appreciate not only his intellectual level but also his profound human values
- @Søren Juhl Andreasen for providing my first job as a researcher (an extremely courageous feat)
- @Maciej Swierczynski for invaluable technical discussion, especially at the beginning of my PhD (when I needed it the most!)
- @Remus Teodorescu for giving me the chance to come as guest exchange student in 2007 and to get a student job (a real survival issue!)
- @Peter Omand Rasmussen for his exceptional guidance during my time as Master student (when I was speaking Spanglish)
- @Ewen Ritchie and @Thomas Condra for always keeping their doors open for discussions about the past, the present and the future (i.e. the meaning of life)
- @Søren Knudsen Kær for hosting me as a researcher in his group (despite my tendency towards speaking too much)
- @Tina Larsen for helping with so many issues that I can barely remember (and for telling me NO when she had to! ☺)
- @Corina Busk Gregersen for dealing with my (always wrong) travel expenses (after many years I did not manage to make one right on the first try… I give up…)

- @Eva Janik for dealing with the grumpy @Jorge and putting a smile on my face (when I needed it the most)
- @Karina Kjeldgaard Ludvigsen for giving her helping hand, without asking for anything in return (sorry for all the delays in my timesheets…)
- @Nick Ilsø Berg and @Rasmus Koldborg Holm for all the work done in the ELBIL project (weekends included...)
- @Walter Neumayr, @Mads Lund and @Jan Christiansen for being my ‘guardian angels’ in the lab (great job guys!)
- @Claus Leth Bak for giving me the chance to be the PhD mentor (I hope that I lived up to the expectations!)
- @John K. Pedersen and @Tamas Kerekes for finding some time in their busy agendas to hear my opinions
- @Tomislav Dragicevic, @Andres Revilla and @Waruna P. Wijesekara Dissanayaka for being the best friends in the world (and pretty good scientists!)

In addition, I cannot forget my closest collaborators from other institutions, with whom I have shared, apart from long working hours, a part of my life, my hopes, efforts, failures and yes, sometimes even success. Special thanks for all your contributions to:

- @Cláudio Pinto (FEUP/INESC), I cannot imagine a better partner, I honestly admire you and your discipline, efficiency and seriousness
- @Ricardo de Castro (FEUP/INESC-DLR), we met in Seoul, for those things of fate, and nowadays I can say that this was a milestone in my career
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- @Christian Fleischer (RWTH-NEVS), a real pleasure and a learning experience to work with somebody who is so generous, personally and professionally
- @Dirk Sauer (RWTH), your work is an essential point of reference in my career
- @Andreas Elkjær Christensen (Lithium Balance), you made easy the difficult
- @Michael Schier (DLR), for sharing all your experience and good mood
- @Ahmed Masmoudi (University of Sfax), for giving me invaluable opportunities as an early career researcher
- @David Howey (University of Oxford) for your support and understanding while this work was being completed

- @Robert Richardson (University of Oxford) and @Cath Arakelian, for all the amazing proofreading work done in this dissertation
- All the colleagues from the OxRSS and the EPG (University of Oxford) for your help to make my life easier during this long writing process

Neither can I forget the unconditional love, trust and support that I have always enjoyed from my family and friends. You are sitting in my heart and your names are well known to you. Thank you for being the balance and the (electric) motor of my life.

Finally, I hope that this is not "goodbye", but "see you later". I certainly look forward to continuing to build and strengthen our professional and personal relationships. In every language that we have shared, honestly: *thank you very much, mange tak, muito obrigado, vielen dank, merci beaucoup, muchas gracias.*

PREFACE

In March 2013, Aalborg University (AAU) launched the ALPBES project in consortium with Dong Energy, Lithium Balance, Leaneco, GMR maskiner, the Technical University of Denmark (DTU), the Danish Technological Institute (DTI), the Royal Institute of Technology (KTH) and the Institute for Power Electronics and Electrical Drives (ISEA) RWTH Aachen. ALPBES, which stands for "Advanced Lifetime Predictions of Battery Energy Storage", is a project founded by The Danish Council for Strategic Research and led by Prof. Søren Knudsen Kær, from AAU.

The main goal is to establish expertise and state-of-the-art knowledge about mission related aging mechanisms of batteries. This thesis is the result of the PhD project entitled "BMS for Li-ion batteries", whose research activities lie within Working Package (WP) 2.2 of the ALPBES project. While the overall project aims to close the knowledge gap between cell and system level, WP 2.2 focused mainly on enhancement of the current BMS state-of-the-art at battery pack level[2] (Fig. P-1).

Cooperation was set among all the partners involved in this WP, AAU, ISEA RTWH Aachen and Lithium Balance, with focus on BMS testing on a state-of-the-art commercial Hardware-In-the-Loop Simulator (HILS) . This valuable setup, at that time the third in the world and the only one located in a university, was acquired by AAU in September 2013, with support from the Obel Family Foundation.

In parallel to these activities, more exploratory research studies were undertaken during this PhD project in collaboration with FEUP and INESC TEC, taking advantage of complementary expertise. AAU contributed with knowledge on Battery Energy Storage Systems (BESSs) and BMSs, while FEUP and INEST TEC provided know-how on optimization methods. Topics covered ranged from battery modeling to sizing of Hybrid Energy Storage Systems (HESSs), control of active balancing systems and novel Battery Electric Vehicle (BEV) concepts.

As will be shown in this dissertation, a fruitful cooperation was established between all parties, as evidenced by the joint publications attained. Creation and transfer of knowledge were boosted through cross-visits and research stay periods.

Finally, although this PhD project concludes here, this one should not be the last page of the research activities presented in this dissertation, since a number of publications are still in the pipeline and postdoctoral research activities are being carried out.

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[2] Source: Department of Energy Technology, AAU, "Advanced Lifetime Predictions of Battery Energy Solutions", project description, 2013.

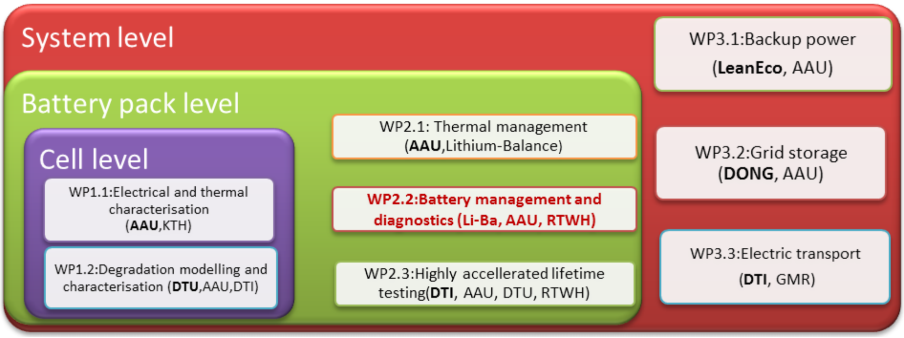

Fig. P-1. ALPBES project structure: from cell to system level.

LIST OF APPENDED PAPERS

- Paper I[3]: J. V. Barreras, E. Schaltz, S. J. Andreasen, T. Minko, "Datasheet-based modeling of Li-Ion batteries," 2012 IEEE Vehicle Power and Propulsion Conference, Seoul, 2012, pp. 830-835.

- Paper II: J. V. Barreras, C. Pinto, R. de Castro, E. Schaltz, M. J. Swierczynski, S. J. Juhl Andreasen, R. E. Araújo, "An improved parameterization method for Li-ion linear static equivalent circuit battery models based on direct current resistance measurement," 2015 International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART), Kuwait (Kuwait), 2015.

- Paper III: J. V. Barreras, C. Pinto, R. de Castro, E. Schaltz, S. J. Andreasen, P. O. Rasmussen, R. E. Araújo, "Evaluation of a novel BEV concept based on fixed and swappable Li-ion battery packs," in *IEEE Transactions. on Industry Applications,* vol. 52, no. 6, pp. 5073-5085, Nov.-Dec. 2016.

- Paper IV: J. V. Barreras, C. Fleischer, A. E. Christensen, M. J. Swierczynski, E. Schaltz, S. J. Andreasen, D. U. Sauer, “An Advanced Hardware-in-the-loop Simulation Battery Model for Battery Management System testing,” in *IEEE Transactions on Industry Applications,* vol. 52, no. 6, pp. 5086-5099, Nov.-Dec. 2016.

- Paper V: C. Fleischer, J. V. Barreras, A. E. Christensen, E. Schaltz, D. U. Sauer, “Development of software and strategies for Battery Management System testing on HIL simulator,” Proceedings of the 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER), Monte-Carlo (Monaco), IEEE Press, 2016.

- Paper VI: J. V. Barreras, C. Pinto, R. de Castro, E. Schaltz, S. J. Andreasen and R. E. Araujo, "Multi-Objective Control of Balancing Systems for Li-Ion Battery Packs: A Paradigm Shift?" 2014 IEEE Vehicle Power and Propulsion Conference (VPPC), Coimbra (Portugal), 2014.

- Paper VII: C. Pinto; J. V. Barreras; E. Schaltz; R. E. Araujo, "Evaluation of Advanced Control for Li-ion Battery Balancing Systems using Convex Optimization," in *IEEE Transactions on Sustainable Energy*, vol. 7, no. 4, pp. 1703-1717, Oct. 2016.

[3] Published before this PhD project. This work, as part of the ELBIL project, was financially supported by The European Regional Development Fund grant number ERDFK-08-0011.

LIST OF NON-APPENDED PAPERS

- Paper 1: J. V. Barreras, C. Fleischer, A. E. Christensen, M. J. Swierczynski, E. Schaltz, S. J. Andreasen, D. U. Sauer, “Functional Analysis of Battery Management Systems using Multi-Cell HIL Simulator,” Proceedings of the 2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER). Monte-Carlo: IEEE Press, 2015.

- Paper 2: J. V. Barreras, C. Pinto, E. Schaltz, S. J. Andreasen, P. O. Rasmussen, R. E. Araújo, “A novel Battery Electric Vehicle concept based on fixed and swappable Li-ion battery packs,” Proceedings of the 2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER). Monte-Carlo: IEEE Press, 2015. s. 1-8.

- Paper 3: C. Pinto, J. V. Barreras, R. de Castro, E. Schaltz, S. J. Andreasen and R. E. Araujo, "Influence of Li-Ion Battery Models in the Sizing of Hybrid Storage Systems with Supercapacitors," 2014 IEEE Vehicle Power and Propulsion Conference (VPPC), Coimbra (Portugal), 2014.

- Paper 4: C. Pinto, J. V. Barreras, R. de Castro, R. E. Araujo and , E. Schaltz, “Study of the combined influence of battery models and sizing strategy in the size of hybrid and battery-based electric vehicles,” in *Energy*, 2017, Submitted for publication.

- Paper 5: P. C. Gonzalez; Y. Pang; P. D. Reigosa; E. Dimopoulos; J. V. Barreras; E. Schaltz, “Tvindkraft: Implementing a 500 kW 21-IGBT-Based Frequency Converter for a 1.7 MW Wind Power Conversion System,” Proceedings of the 2013 IEEE International Conference on Renewable Energy Research and Applications. IEEE Press, 2013. s. 482-487.

- Paper 6: M. R. Khan; J. V. Barreras; A. I. Stan; M. J. Swierczynski; S. J. Andreasen; S. K. Kær, “Behavior Patterns, Origin of Problems and Solutions Regarding Hysteresis Phenomena in Complex Battery Systems,” Hysteresis: Types, Applications and Behavior Patterns in Complex Systems, Nova Science Publishers, Incorporated, 2014. s. 215-226.

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GLOSSARY

1D	One-Dimensional
3D	Three-Dimensional
AAU	Aalborg University
AC	Alternating Current
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BMS	Battery Management System
BOL	Begginning-Of-Life
CAGR	Compound Annual Growth Rate
CC	Constant-current
CCCV	Constant-current constant-voltage
CCU	Controller Central Unit
CV	Constant-voltage
DC	Direct Current
DCR	Direct Current Resistance
DLR	German Aerospace Center
DoD	Depth-of-Discharge
DOE	Department of Energy
DTI	Danish Technological Institute
EECM	Electrical Equivalent Circuit Model
EIS	Electrochemical Impedance Spectroscopy

EMS	Energy Management System
EOL	End-Of-Life
EPA	Environmental Protection Agency
ESS	Energy Storage System
EV	Electric Vehicle
EVER	Ecological Vehicles and Renewable Energies
FEUP	Faculty of Engineering University of Porto
FTP	Federal Test Procedure
HIL	Hardware-In-the-Loop
HILS	Hardware-In-the-Loop Simulator
HESS	Hybrid Energy Storage System
HEV	Hybrid Electric Vehicle
HVAC	Heating, Ventilation and Air Conditioning
HW	Hardware
HWFET	Highway Fuel Economy Test
IC	Integrated Circuit
KTH	Royal Institute of Technology
LIB	Lithium-Ion Battery
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
LTO	Lithium Titanate

NCA	Lithium Nickel Cobalt Aluminum Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
NTC	Negative Temperature Coefficient
NYCC	New York City Cycle
OCV	Open-Circuit-Voltage
PCB	Printed Circuit Board
PHEV	Plug-in-Hybrid-Electric-Vehicle
PPC	Pulse Power Characterization
RC	Resistor-Capacitor
RQ	Research Questions
RUL	Remaining-Useful-Life
RWTH	Rheinish-Westphalian Technical University
R&D	Research and Development
SOA	Safe Operating Area
SoC	State-of-Charge
SoF	State-of-Function
SoH	State-of-Health
SW	Software
TCO	Total Cost of Ownership
TECM	Thermal Equivalent Circuit Model
UPS	Uninterruptible Power Supply
USABC	United States Advanced Battery Consortium

VCU	Vehicle Central Unit
WP	Working Package
ZARC	Arc in the Z plane

1 INTRODUCTION

This chapter is divided into three sections: Section 1.1 (Motivation), which presents an explanatory overview of the motivations behind this work; Section 1.2 (Background), which establish the background of the problems addressed in this dissertation; and Section 1.3 (Outline), which describes the outline of this document.

1.1 MOTIVATION

Nowadays, the outstanding performance of LIBs makes them the standard choice for Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs) or consumer electronics products as mobile phones, tablets, laptops or portable tools. In fact, LIBs are currently the second rechargeable battery market in volume and value, after lead acid, and have great market expectations for the following decade [1] – [6].

However, their range of applications and overall market penetration is still constrained by cost [1] – [6]. This in turn, keeps the door open for hybrid solutions and other creative designs, like the novel BEV concept based on fixed and swappable LIBs proposed in this work (Manuscript III [8]). This concept could enable BEVs with longer ranges at lower initial purchase price.

These cost limitations also promote research in other areas, like second life use of automotive batteries [9], [10] or lifetime modeling and related algorithms [11] – [20], in order to analyze convenience of the initial investment and to find ways to extend life or increase battery's residual value.

Apart from that, the main limitation of LIBs, which may also affect costing, is the need of reliable battery management due to the prone to poorer performance, accelerated degradation or failure, even in the form of a thermal runaway in case of electrical, thermal or mechanical abuse [12] – [16]. Regardless, it is well known that the performance is safe if cells are handled, interconnected, packaged, stored and operated according to manufacturer's recommendations, accepted industry practices and common sense.

Regarding the electronic management of the electrical and thermal environment, it is the function of a Battery Management System (BMS) to ensure that each cell of a battery pack is dis/charged properly, operating always inside a certain Safe Operating Area (SOA) limited by current, voltage and temperature thresholds.

But an advanced BMS does not only ensure safe operation, also optimizes the use made of the energy inside the battery according to internal and external conditions, controls charging process minimizing energy losses and charging time or provides an accurate estimation of internal states such power capability, State-of-Charge (SoC) or State-of-Health (SoH) [12] – [20].

Nevertheless, since LIBs are not ideal devices and limited sensing and actuation is possible, this is not a trivial task. Pack and cell voltages, current(s) and (some) surface temperatures are the only measurable variables and are linked to the battery internal states according to highly non-linear relationships. In addition, to makes things more complex, there is no universal agreement on the definition of these states. Hence, there is still a lot of effort to improve modeling and diagnosis methods [11] – [26].

In this work, the topic of battery modeling is addressed, focusing on offline rather than online applications, with the aim to improve battery design tools. In particular, attention is drawn on two simplified modeling approaches: datasheet-based (Manuscript I [27]) and Direct Current Resistance (DCR) based (Manuscript II [28]) parameterization of electrical equivalent circuit models.

Following on with the consequences of the non-ideal behavior of the LIB, due to the cell-to-cell differences in SoC, usable capacity or temperatures, packs made up of (a group of parallelized) cells connected in series require a BMS that integrates balancing circuits for better performance and longer lifetime. Nowadays, so called passive balancing systems are the preferred industrial solution over active balancing systems. It seems that modest improvements in efficiency or charging time are not enough to bring a paradigm shift [12] – [16], [31] – [40].

However, as discussed in recent studies, e.g. in Manuscripts VI [36] and VII [37], under certain circumstances novel control strategies for active balancing systems may bring significant advantages in terms of thermal equalization, losses minimization or available energy maximization [36] – [40]. As a result, in certain cases, active balancing systems could be seen as an appealing solution for the industry.

Finally, given the complexity and the multifaceted nature of the issues to be addressed by the BMS, it is easy to understand the need for better specification, verification and validation of BMS requirements. In this respect, tests conducted on a BMS connected to a state-of-the-art hardware-in-the-loop simulator (HILS) can certainly bring key advantages over test conducted on real batteries. For example, improvements in terms of cost and time effectiveness, reproducibility or safety beyond the normal range of operation, especially at early stages in the development process or during fault insertion [41] – [43].

Theoretical principles of BMS testing and practical approaches to develop ad hoc SW and strategies for BMS testing on a HILS are introduced in this work (Manuscript V [43]). Extensive laboratory results are presented based on a self-developed advanced battery model targeted for BMS testing at system level on a commercial HILS (Manuscript IV [42] and Manuscript V [43]).

1.2 BACKGROUND

The aim of this section is to provide a better understanding of the problems in the broader context of LIBs. The goal is to update and complement, from a higher-level perspective, the contents presented in the appended papers with respect to:

- Cost and market perspectives
- Applications, goals and Research and Development (R&D) fields
- The role of battery management

1.2.1 COST AND MARKET PERSPECTIVES

Due to cost and management limitations, first applications in the early 1990s of commercial LIBs were small battery systems for the consumer electronics market. Good performance and fast expansion of this market showed motivated efforts to improve the design of these batteries and related BMSs. Thus, driven by the consumer electronics market, the industry and the technology matured over time, thereby opening up new markets [1] – [6] (Fig. 1-1).

In addition, fueled by concerns over a petrol-based transportation system, a renewed interest in e-mobility emerged in last decades. Based on the superior performance of LIB, a rebirth of the e-mobility industry has been made possible, which is reflected not only in an emerging market in the early 2010s, but most importantly in ambitious EV adoption targets and policy support mechanisms set by many governments [1] – [6].

In this context, LIB achieved in 2015 sales of over 22B US$ in 2015, of which c. 10B US$ correspond to the consumer electronics market and c. 8B US$ to the automotive market (Fig. 1-2) [1]. LIB showed in the period 2005-2015 Compound Annual Growth Rates (CAGRs[4]) of +22 % in volume (MWh) and +15 % in value (at cell level), relegating nickel-based technologies and becoming the second rechargeable battery market after lead acid [1].

Furthermore, according to recent forecasts for the European market, penetration rates of BEV and PHEV are expected to grow up to c. 10% in 2025 [4], which means a giant leap forward for the LIB market. It is worth noting that even a tiny share of the automotive market means a huge market for batteries in volume and value.

In this context, a sharp fall in LIB pack cost up to 50-75 % over the next 10 years is expected [1] – [6] (Fig. 1-3 and Fig. 1-4). It is worth noting that costs of packs shown in Fig. 1-3 and Fig. 1-4 are composed of cell level costs (materials plus manufacturing),

[4] A geometric progression ratio that gives a constant rate of return over a certain time period.

packaging materials, pack manufacturing, heating/cooling system and BMS, and illustrate average costs for mass produced EV packs [1], [4].

Different overall costs and costs structures may exist depending on the size of the pack, volume of the production, the manufacturer or the specific application. For instance, Fig. 1-5 shows the cost structure for several e-vehicles with different battery sizes from several manufacturers: Nissan Leaf (30 kWh pack), Bluecar EV (30 kWh), Chevrolet Volt (18.4 kWh) and BMW Active Hybrid (1.4 kWh) [2].

Regarding hybrid electric vehicles (HEV) and stop-start vehicles, their market is still dominated today by nickel-based and lead acid batteries, respectively. However, the rapid fall of LIB costs may bring soon a paradigm shift [1] – [8], [15], [44].

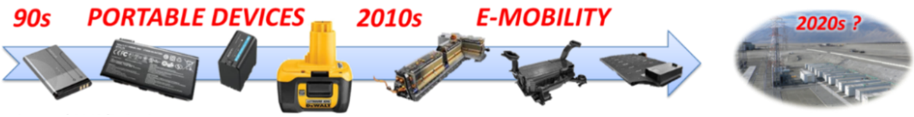

Fig. 1-1. Main applications of LIBs: past, present and future[5].

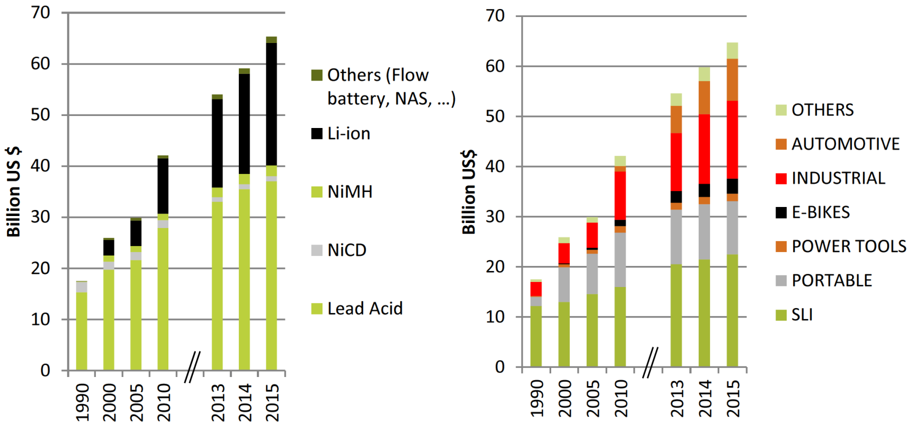

Fig. 1-2. Worldwide secondary battery market by chemistries and applications [1].

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[5] Source: modified from J. V. Barreras et al., "Review of BMSs for Li-Ion Batteries," poster presented at the Nordic Battery Conference (Nordbat), Uppsala (Sweden), Dec. 2013.

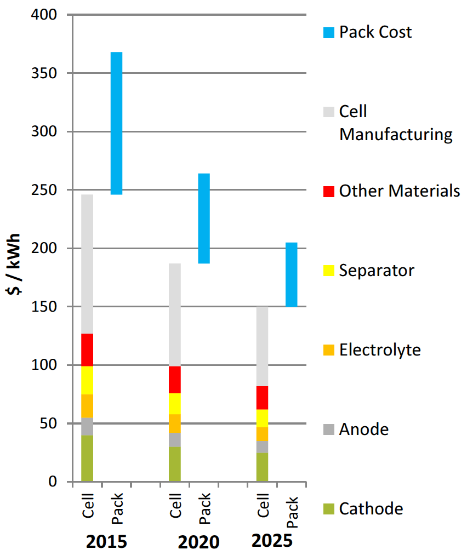

Fig. 1-3. LIB pack cost for 2015-2025: forecasts from Avicenne [1].

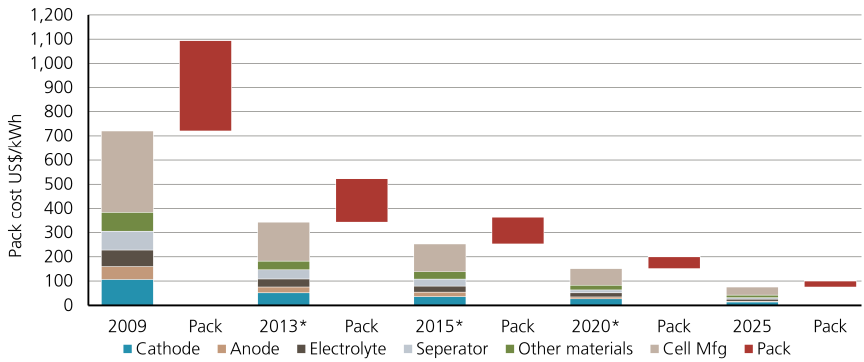

Fig. 1-4. LIB pack cost for 2009-2025: forecasts from UBS [4].

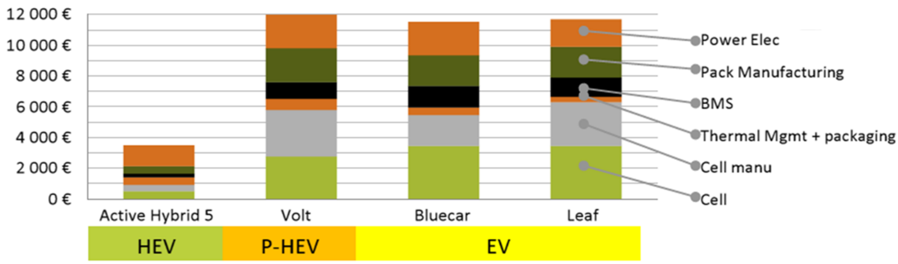

Fig. 1-5. Cost structure for different commercial x-EVs [2].

Other promising applications for LIBs are medical, telecom, uninterruptible power supplies (UPS), forklifts and residential or grid connected Energy Storage Systems (ESSs). In the next 15 years, a CAGR higher than 15% is expected for these applications [1].

Regarding ESS, nowadays t is a marginal market for batteries, dominated by pumped hydro installations at grid level, but there are great expectations in the next years in the context of smart grids. Difficulties regarding power system stability, quality and reliability due to higher penetration of solar photovoltaic and wind power plants can be overcome by Battery ESS (BESS) [4], [5], [15], [45] – [47].

1.2.2 APPLICATIONS, GOALS AND R&D fields

The state of the art progress of LIBs is nowadays driven mainly by more demanding characteristics of new advanced LIB applications (e-mobility, grid connected, UPS, etc.) than the traditional portable market. That said, although each LIB application presents particular requirements and therefore different goals (Fig. 1-6), all LIB applications could be benefited from improvements in LIB technology [12] – [15], [24], [25], [46] – [47].

Main Research and Development (R&D) fields and goals pursued are displayed in Fig. 1-7, correlated through a color code. It should be noted that materials science is involved in all these goals, playing a key role in future LIB technology development.

For example, regarding electrode materials, the combination of Lithium Cobalt Oxide (LCO) in the cathode and graphite in the anode has been widely used for +20 years. However, while LCO-based cells offer excellent specific energy, which is great for portable applications, other electrode materials may offer better specifications in terms of specific power, performance at extreme temperatures, lifespan or safety, which may be preferable for other applications, e.g. EVs or aerospace (Fig. 1-6). Regarding safety, it should be noted that LCO-based cells are especially prone to thermal runaway in case of overcharge (Table 1-1) [12] – [15], [24], [25], [44] – [49].

As a result, a number of other electrode materials have been developed, achieving commercial importance. Among them, the primary material families are Lithium Nickel Cobalt Aluminum Oxide (NCA), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Manganese Oxide (LMO) and Lithium Iron Phosphate (LFP) for the cathode, and Lithium Titanate (LTO) for the anode. As referred in the literature, different electrode materials lead to different features in terms of cost, lifespan, performance at high/low temperatures, safety or specific power or energy (Table 1-1).

However, at least by now, there is not a material able to fulfill all the R&D goals. Furthermore, supply issues must be faced along when talking about mass-adoption of a technology (Table 1-1). Thus, selection of the best LIB for a particular application

Fig. 1-6. LIB applications vs. goals[6].

is certainly a compromise. Alternative concepts, under heavy research during last decades, are Li-sulfur and metal-air batteries, which have a great theoretical potential to increase specific energy and energy density, but it is difficult to estimate when they will become commercially established [12] – [15], [24], [25], [44] – [49].

On the other hand, as shown in Fig. 1-7, progress towards more advanced BMS is underpinned by the fact that is a way to achieve goals like higher safety, reliability, usability, lifespan and performance in terms of power and energy. Furthermore, the BMS must be cost-effective, in order to avoid penalizing the cost reduction goal.

In this connection, while certainly the industry tendency is to keep the BMS costs as low as possible, one can argue that a higher initial investment in a more advanced BMS may bring a return on investment in the form of better performance, a longer life span or a higher residual cost at the end of life. For example, innovative features for active balancing circuits could potentially reduce the cell-to-cell parameter variation over battery life or, at least, reduce the influence of the parameter variation in the battery performance over time. This issue is addressed in two of the papers appended to this dissertation (Manuscript VI [36] and VII [37]).

[6] Source: J. V. Barreras, “BMSs for Li-ion Batteries with focus in Automotive Applications,” presentation at PhD/Industrial course, Universidad Carlos III, Madrid (Spain), June 2016.

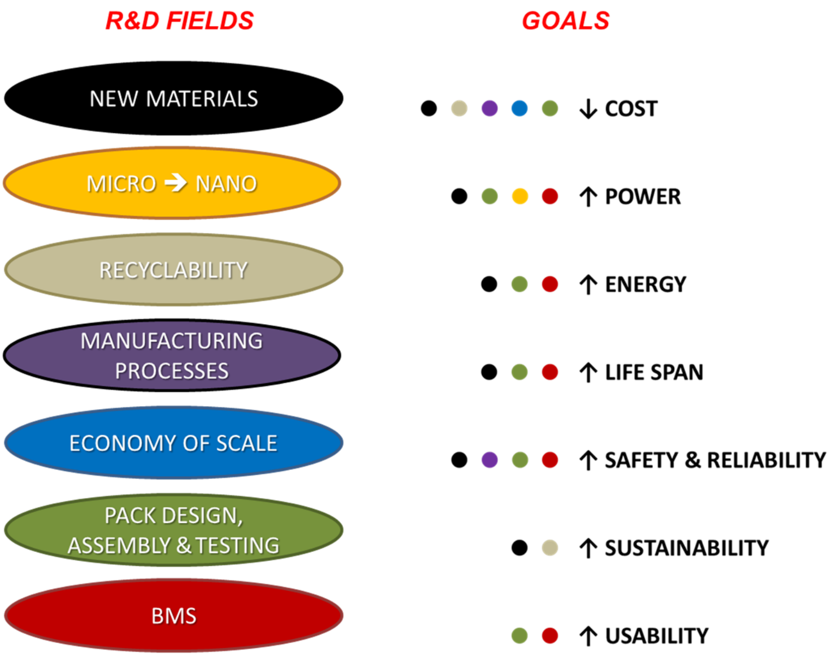

Fig. 1-7. LIB R&D fields vs goals[7].

With regard to the economy of scale, it is expected that increases in the cumulative production will bring relevant cost reductions. In the case of BEVs, according to recent studies [6], the learning rate[8] in the period 2011-14 was between 6 and 9 %.

Issues related with battery system design, assembly and testing are important to achieve almost all the R&D goals. In particular, they are critical in the case of safety, as has been demonstrated by latest incidents in the field (Table 1-2).

In addition, the still-high cost and high weight of large battery systems for e-mobility motivate the proposal of innovative designs. This is the case of the BEV concept based on fixed and swappable batteries presented in Manuscript III [8] appended to this document.

[7] Source: J. V. Barreras et al., "A survey of Battery Management Systems for Li-Ion batteries," poster presented at the 6th German Symposium Advanced Battery Development for Automotive and Utility Applications and their Electric Power Grid Integration (Battery Power), Muenster (Germany), March 2014.

[8] The cost reduction based on a cumulative doubling of production [6].

Table 1-1. PRIMARY FAMILIES OF ELECTRODE MATERIALS[9]

Characteristic	Graphite-LCO	Graphite-NCA	Graphite-NMC	Graphite-LMO/Blend	Graphite-LFP	LTO-LMO
Safety	+	+	++	++	+++	++++
Specific energy	++++	++++	+++	+++	++	+
Specific power	+	++++	+++	+++	+++	+++
Lifespan	+	++	+++	++	+++	++++
Performance at high/low temp.	++	++	++	++	+++	++++
Cost	+++	+++	+++	+++	++++	+
Typ. cell voltage range	2.5 – 4.2 V				2.0 – 3.7 V	1.5 – 2.9 V
Typ. temperature range	Discharging: -20 to 55 °C Charging: 0 to 45 °C					-40 to 55 °C
Cathode breakdown temperature	150 °C	160 °C	210 °C	265 °C	310 °C	265 °C
Automotive usage	-	Tesla Model S	VW eUP, eGold, BMW i3, Daimler, Fiat 500, Smart	Chevy Volt, Nissan Leaf, Renault Fluence, Zoe	Chevy Spark EV, Coda EV, BYD E6, eBuses	Mitsubishi i-MiEV, Honda Fit, eBuses, ECVs
Prominent suppliers	-	Panasonic	Kokam , Samsung, Li-Tec	AESC, LG Chem, Li Energy Japan	Saft, A123, ATL, Calb, BYD, Lishen Tianjin	Altairnano, Toshiba, Tiankang

[9] The information presented above is displayed for illustrative purposes and does not pretend to be exhaustive. This overview is a modification and extension of [53] based on [45] – [48], [52] and [54].

1.2.3 THE ROLE OF BATTERY MANAGEMENT

Besides market issues, the predominance of LIB is based on its superior performance. In comparison with lead acid and Ni-based technologies, LIB shows high gravimetric energy density (up to 250 Wh/kg); high volumetric energy density (up to 640Wh/l); lower self-discharge rate (2-8% per month); high voltage output (nominal voltage up to 3.7 V); good cycle life (>1000 cycles); no memory effect; maintenance free design; wide operating temperature range (charge 0 to 45°C, discharge -40 to 65°C); high coulombic and energy efficiency and a broad range of sizes, shapes and energy-power balances, able to fulfill multiple design requirements [13] – [15], [17], [21] – [24].

On the other hand, as discussed previously, the main disadvantage of LIBs is the need of careful management for various reasons, the foremost being safety concerns. Consequences of electro-thermal or mechanical abuse for some types of LIB and alternative technologies may only range from higher degradation to permanent cell damage, while some other types of LIB are especially prone to thermal runaway [13], [17], [21] – [23], threatening the safety of the system's operator and its environment.

Several safety events have been reported in last decades, involving mobile phones, laptops, EVs or aerospace applications, resulting in some cases in large economic-losses for involved parties [1], [2] (Table 1-2). It has been remarkable the press coverage of these events, which certainly have raised safety concerns among users and manufacturers. On the other hand, there have been also reported excellent safety records, with failure rates at cell level as low as 1 per 40 million at cell level [23] or 0.01% at pack level [51].

As can be observed from Table 1-2, failures might occur at pack level due to different reasons. This includes, but is not limited to, the following: low quality cells, non-mature products, poor manufacturing processes, poor integration of large number of cells in large packs, poor testing and validation processes, poor cell packaging, extreme mechanical stress due to eventual external impacts, underestimation of potential hazards or loose safety guidelines.

Therefore, as sketched in Fig. 1-7, several R&D routes should be taken in parallel to improve safety. That is new or improved materials; improvements on manufacturing processes; better pack system design, integration in the application and testing; and adoption of more advanced BMS. The latter is the only one that can be referred to as active safety.

With respect to materials and manufacturing processes, some issues that could be considered are:

- Improved over-pressure valves and predetermined breaking points
- Use of ceramic separators

Table 1-2. RELEVANT SAFETY EVENTS REPORTED IN LAST DECADE[10]

No.	Application	Description	Date	Causes	Technical counter measures
1	Portable Sony laptops	A number of fires due to overheating	2006	Not revealed, but related to charging process at pack level	Largest product recall in history – about 10M batteries, ~400M US$
2	PHEV Chevy Volt	Fire after crash test	June 2011	Crash provoqued intrusion to the LIB and coolant leakage that lead to short circuit	Enhancements presented in June 2012: strengthened vehicle structure and anti-leakage design
3	Aerospace Boeing 787 Dreamliners	A number of battery thermal run-away events aboard	Jan. 2013	Still unknown, but are related to integration issues and poor BMS	All planes grounded until April 2013. Improve-ments made in housing to better contain battery fires
4 & 5	BEV Tesla Model S	Fire after hitting debris on a highway	Oct. 2013	Underbody strikes	SW to increase ground clearance at high speed, new 3 layer Ti underbody shield, new Al deflector plates
		Fire after striking a tow hitch on the road	Nov. 2013		
6	BEV Tesla Model S	Fire while connected to supercharger	Jan. 2016	Short in the distribution box on-board	SW update to provide extra safety during charging: short-circuit detector algorithm
7	Portable Samsung Galaxy Note 7	A number of battery thermal run-away events	Sept. 2016	Poor packaging, manufacturing, testing & validation of cells	Recall of 2.5M with a cost of ~1B US$ and +26B US$ in market cap (Nov. 2016)

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[10] The information presented above is displayed for illustrative purposes and does not pretend to be exhaustive. It was collected on public available sources, including a scientific publication [50], press coverage, press releases and statements from manufacturer's and institutions like the US National Highway Traffic Safety Administration, the US consumer Product and Safety Commission or the US Federal Aviation Administration.

- Usage of materials that are inherently safer, e.g. Graphite-LFP or LTO-LMO
- Increasing the adoption of cell formats easier for the industry to automate, e.g. pouch cells

Regarding the pack system design and integration in the application, both mechanical and thermal aspects should be taken into account:

- Mechanical: cell swelling, modularity, mechanical integrity, crash safety, stability of the housing, cable routing, tab welding, weight, volume, vibrations, etc.
- Thermal: thermal integration of cells, thermal conditioning requirements (heating/cooling), coolant flow routing, tightness of the gasket (coolant leaking), fire propagation, temperature sensor placement, location with respect to other heat sources within the application, etc.

With regard to the BMS, it contributes to achieving the safety goal by protecting against hazards, keeping the battery within its SOA. For illustrative purposes, Fig. 1-8 shows failures modes with respect to SOA in terms of voltage/temperature.

This task may involve a number of BMS functions and that therefore could be carried out in many different ways, as explained in the following section. As a rule of thumb, more advanced BMS are more expensive, due to the costs associated to both the hardware (HW) and the software (SW). Hence, they are usually targeted for mission-critical applications and large battery packs [12] – [15], such as e-mobility traction batteries (Fig. 1-9).

Apart from safety, other primary management goals are to improve usability, reliability, lifespan and performance, which can be defined in this context as follows:

- Usability: the ease of use, i.e. user friendliness.
- Reliability: the ability to perform all functions according to its specifications.
- Lifespan: the useful life, durability or longevity.
- Performance: dis/charge in an effective and efficient manner.

As can be seen in Fig. 1-7, progress in the BMS field may lead to improvements in all these management goals. For instance, advanced BMS may contribute to the aforementioned goals as follows:

- Usability: diagnosis algorithms, the user-friendly definition of states, communications, holistic recharging management, etc.
- Reliability: protection against hazards, thermal management, fault prediction and fault tolerance routines.
- Lifespan and performance: diagnosis algorithms, thermal management, balancing, protection, dis/charge management.

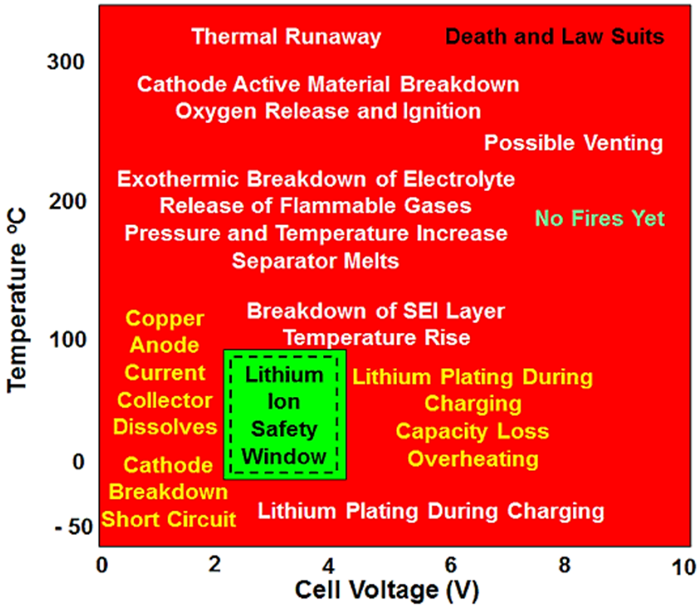


Fig. 1-8. Failure modes with respect to SOA in terms of voltage/temperature [55].

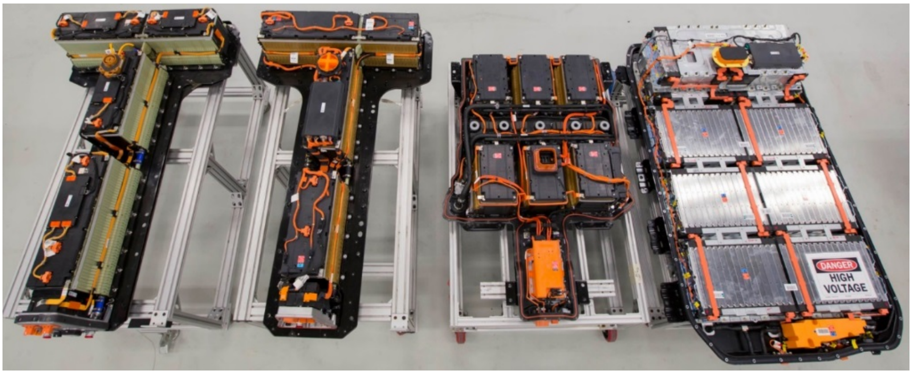


Fig. 1-9. First- and second-generation Chevy Volt, Spark, and Bolt packs (left to right) [56].

1.3 OUTLINE

Chapter 1 (Introduction) has given an explanatory overview of the motivations behind this work and has established the background of the problems addressed in this dissertation.

Chapter 2 (State of the art of BMS) defines in a generic way what is a BMS, presents an overview of its functionalities and classifies the different types of BMS according to their functionality, applicability, technology, topology and design.

Chapter 3 (Problem statement) defines the 'Research questions' tackled in the appended papers, describes the research hypothesis and introduces the research methods with special focus on the links between papers.

Chapter 4 (Modeling) explains the criteria followed to select the Li-ion cells to be modeled and provides an overview of the main modeling methods used in the appedend papers, i.e. the thermal and electrical battery performance modeling approaches and the BEV modeling methods.

Chapter 5 (Summary, contribution, limitations and future research areas) summarizes all the work undertaken in the appended papers, discusses their findings or contributions, points out limitations and suggests directions for future research.

Chapter 6 (Conclusion) gives the overall conclusion of this dissertation.

References provides the list of references of this thesis (does not include all the references cited in the appended papers).

Appendix A (Formulation of the EECMs) gathers the equations that express the electric behavior of the static and dynamic EECMs used in the appended papers.

Appendix B (Thermal resistances) summarizes the equations that describe the conductive, convective and radiative thermal resistances used in the Thermal Equivalent Circuit Models (TECMs) used in some of the appended papers.

Appendix C (Standard driving cycles) presents the standard driving speed profiles used for purposes of BEV modeling.

Appendix D (Manuscripts) presents all the papers appended to this dissertation. Each paper is preceded by a title page that outlines title, list of authors and affiliations, and publication outlet.

2 STATE OF THE ART OF BMS

This chapter is divided into two sections: Section 2.1 (Definition), which defines in a generic way what is a BMS; Section 2.2 (Functional overview), which presents an overview of the BMS functionalities; and Section 2.3 (Classification), which classify briefly the different types of BMS according to their functionality, applicability, technology, topology and design.

2.1 DEFINITION

A BMS can be defined as a group of related HW and SW units, dedicated to deal with or to control the performance of a BESS according to a certain set of principles or procedures. Typically, apart from the BMS and the battery itself, a BESS may comprise the heating/cooling system, the fuse and a switch box, the charger, the load, the Controller Central Unit (CCU) and other electronic units for logging and telemetry [12] – [15], as shown in Fig. 2-1.

2.2 FUNCTIONAL OVERVIEW

A wide range of functions can be included in a BMS, such as measuring, protection, balancing, diagnosis, communications, logging or telemetry. All these functions are represented and classified in the functional tree given in Fig. 2-4.

In general, it can be stated that the BMS complexity comes from the sum of a variable number of relatively simple features. Some of the most complex are diagnosis and active balancing. In recent years, certainly a significant large part of the efforts in BMS-related research focused on these areas and the classical topic of battery modeling [11] – [43], [52]. In the followings, a comprehensive review of the state-of-the-art of all the BMS functions identified in Fig. 2-4 is presented.

At this stage, it is worth noting that, part of the work presented in this paper focuses on BMS-related research topics, in particular on balancing system control (Manuscript VI and VII) and BMS testing (Manuscript IV and V), which is, in fact, a field to be researched in parallel with the rising level of complexity of more advanced BMS.

2.2.1 MONITORING

Monitoring is a unique feature of digital BMS – logic of analog BMSs is typically based on simple comparators – and is the basis for safety and diagnosis. Sophisticated digital BMS may be able to measure pack current and pack voltage, voltages of cells (or blocks of cells in parallel) and temperatures. Isolation monitoring or ground fault

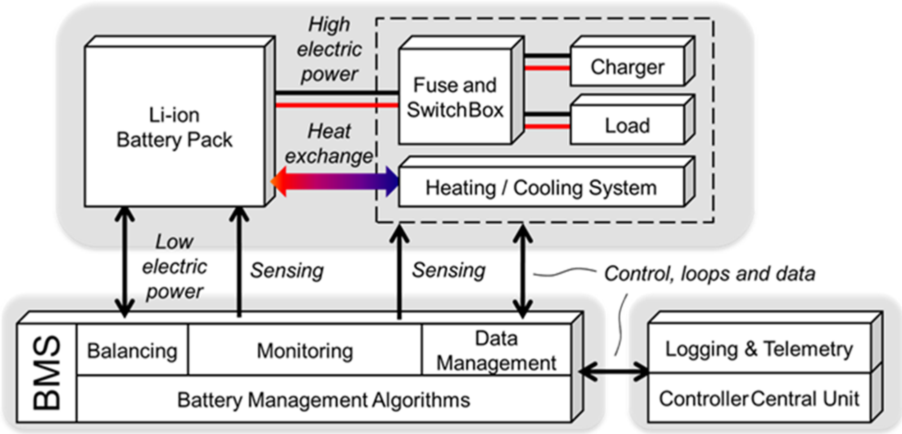


Fig. 2-1. High-level representation of a BESS for large LIBs (modified from [42]).

detection is also a must for floating voltage battery packs, which is the standard in e-mobility. Interlock lines, if any, should also be monitored on-line [12] – [15].

General requirements for the measurement function are high accuracy, high sampling rates and resolutions (for currents and voltages) and good performance under harsh environments (electromagnetic interferences, temperatures, vibration…). Depending on the application, there may be other specific requirements in terms of number and placement of sensors, accuracy, resolution, modularity, topology, cost or redundancy [12] – [15].

Pack current can be measured using a Hall effect sensor or a current shunt (Fig. 2-2). Hall effect sensors, unlike shunts, are isolated, non-resistive and stable over time and temperature, but may suffer from offset at zero current. This may be problematic, since minor errors in current monitoring may lead to large drift in the output of diagnosis algorithms due to the integration of the error in time [12] – [15].

Pack voltage can be measured or calculated from the sum of single cell voltages, whereas cell voltages can be measured either using one analog to digital converter per cell or a multiplexer. Nowadays modular, low-cost and high accuracy solutions for cell voltages measurement are offered by off-the-shelf Integrated Circuit (IC) solutions, like the LTC6803 from Linear Technology Corporation [12] – [15]. It should be noted that high common mode rejection and isolation of voltage signals from control signals is an issue in large packs.

Regarding temperature, sensing can be done at cell or battery level, as well as at balancing circuits, ICs or Printed Circuit Boards (PCBs). Battery temperatures are usually measured on the surface of the cells. Moreover, due to cable routing issues and the large amount of cells in certain designs, the number of sensors may be significantly lower than the number of cells in the pack. Thus, sensor placement is an issue and critical points of maximum and minimum temperature must be monitored. For instance, areas close to the inlet and the outlet of a liquid cooling jacket. Slow dynamics of temperature changes and limited range justify application of low-cost sensors like thermistors [12] – [15] (Fig. 2-3).

With regard to isolation monitoring, low voltage systems (<48V) are commonly grounded. For instance, the battery that powers the 12V system in automotive applications is grounded to the chassis. On the other hand, higher voltage batteries, like traction batteries in EVs are not grounded but floating systems.

In this way, a single isolation fault does not lead to short circuit or direct risk to human health. Isolation monitors, also called ground fault detectors, can detect and communicate single isolation faults, either on the negative or positive side of the battery [12] – [15]. However, they are inherently slow devices, not designed to detect and clear short circuit faults. This is the function of the relays or fuses, which are installed in the current path between the battery and the charger/load.

Fig. 2-2. Shunt resistors (left) and Hall effect sensor (right)[11].

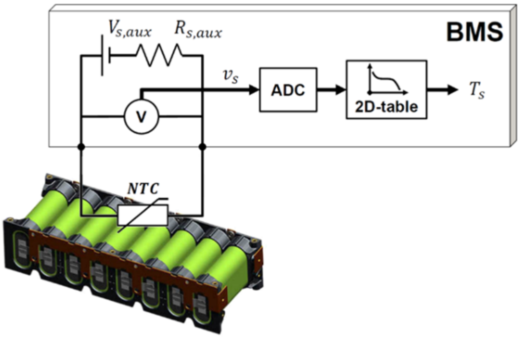


Fig. 2-3. NTC thermistor-based temperature measurement (modified from [42]).

[11] Pictures downloaded from *Wikimedia Commons* and *Wikiwand*, respectively.

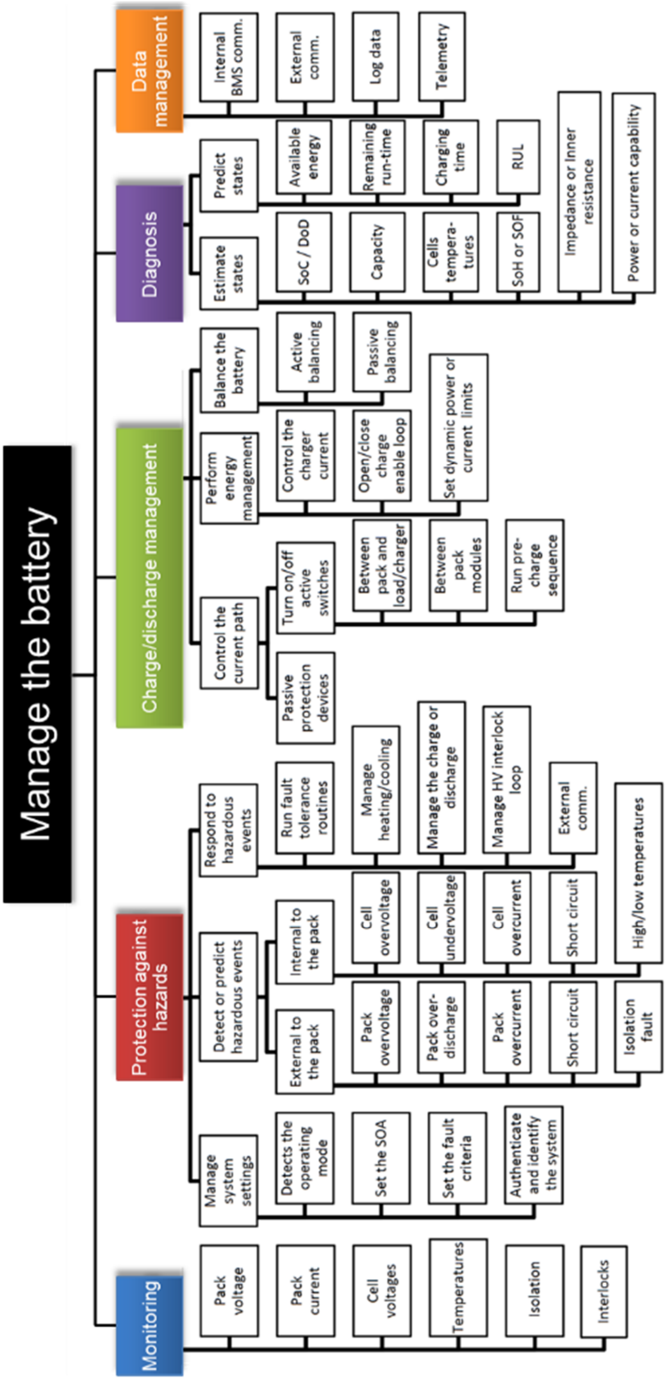


Fig. 2-4. Functional tree of an advanced BMS for large packs (modified from [43]).

Regarding interlock lines, they are a must in large battery packs. For example, charge coupler connectors for EVs that comply with SAE J1772 standard [57] should include a latch that interacts with a proximity circuit, as represented in Fig. 2-5. That latch has to be pressed to unplug the connector from the vehicle. When pressed, the HV interlock line that interfaces the CCU / BMS and the charge adaptor is opened by the proximity circuit. In this way the CCU / BMS controller can detect if the adaptor is going to be removed and therefore interrupt the charging process, avoiding the risk of an electrical shock.

2.2.2 PROTECTION AGAINST HAZARDS

Protection against hazards may be achieved through: detection or prediction of hazards; response to hazards; and management of the system settings (Fig. 2-4). Regarding the latter, some manufacturers of BMS, like Lithium Balance, provide ad hoc SW to deal with the management of the BMS settings, as shown in Fig. 2-6, which are not meant to be operated by regular users but qualified personnel.

To manage the system settings involves (Fig. 2-4):

- Detecting the operating mode
- Setting the SOA
- Setting the fault criteria
- Authenticate and identify the system

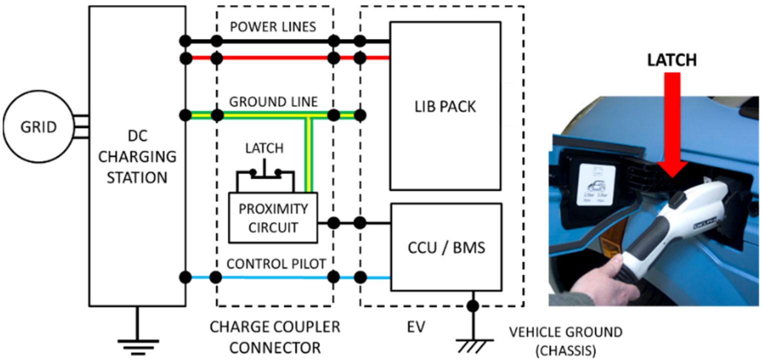


Fig. 2-5. DC charger connected to an EV through a SAE J1772 coupler connector[12].

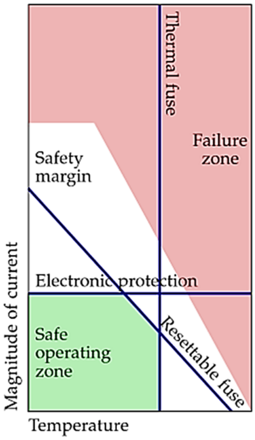
[12] Picture corresponds to a Delphi charge coupler connector. Retrieved from Delphi's webpage: http://www.delphi.com/manufacturers/auto/hevevproducts/charging-cordsets/charge-coupler-con-cable

In general, the battery operating mode is set by the CCU and detected online by the BMS. It can be either “discharge mode”, “charge mode” or “stand-by mode”. In e-mobility applications, other operating modes under non-conventional operating conditions may exist, for instance:

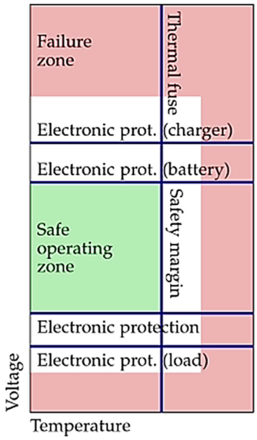
- “Fail-safe mode”, which should be triggered when a critical-error is detected and consists in a gradual decrease of the battery power to avoid risks for the drivers in case of an instantaneous power loss;
- “Limp home mode”, which allows the user to still drive the vehicle when the battery is close to full discharge, but under a power limitation scheme [12] – [15].

Setting the SOA means establishing hard limits for the temperature, voltage and current during dis/charge. For this purposes, the cell manufacturer recommendations given in the datasheet should be followed. It is worth noting that not only the battery, but all system level components (cells, cables, fuses, relays, DC-capacitor, shunt resistor, charger/load protection...) should be considered when setting the SOA [12] – [15], as illustrated in Fig. 2-7.

Fig. 2-6. Snapshot of ad hoc SW to manage BMS settings by Lithium Balance [42].



(a) Current-temperature



(b) Voltage-temperature

Fig. 2-7. Exemplary SOA, safety margin, failure zone and protection limits [12].

First step for setting the fault criteria is to classify faults, since different actions could be associated depending on the error level. For instance, if the system operates outside the SOA a critical error could be triggered. On the other hand, if the system operates inside the SOA but close to its limits, a non-critical error (or warning) signal could be triggered. Thus, setting the fault criteria may involve to establish a certain set of soft and hard limits for the temperature, voltage and current during dis/charge.

Furthermore, additional safety layers can be implemented based on setting criteria for:

- Max. voltage summation difference: status of the voltage sensors or problems in the current path could be detected by comparing pack voltage vs sum of cell voltages.
- Max. short term increase of cell inner resistances: status of the cell-to-cell and BMS-to-cell interfaces could be checked by looking into these resistances.
- Isolation faults: calibration of the isolation monitor can be a tricky task. In e-mobility applications, when the vehicle is connected to a DC charger, there may be another isolation monitor at the charger-side (off-board). This may be seen as a fault by the on-board monitor, and therefore should be taken into account during calibration.

Another practical issue that may also be considered when setting the fault criteria is the definition of signal processing methods to avoid false triggering of errors, e.g. implementation of moving average filters (Fig. 2-8) and limit-crossing counters.

Protection against hazards also involve the detection (or even prediction) of hazardous events internal and external to the pack like (Fig. 2-4):

- External to the pack: pack overvoltage, pack under voltage, pack over-charge, pack over-discharge, pack overcurrent, short circuit, isolation fault.
- Internal to the pack: cell overvoltage, cell under voltage, cell overcurrent, short circuit, high/low temperatures.

Methods to respond to hazardous events may comprise (Fig. 2-4):

- Running fault tolerance routines, for example: by-passing a cell or a group of cells if an abnormal status is detected; or in BMS with redundant designs, when a primary component fails, activating outputs from alternate components, e.g. in the case of errors in the cell voltages monitoring ICs.
- Managing the heating/cooling system: for example, controlling the direction and magnitude of the coolant flow by managing the system's pump(s) and/or fan(s) depending on the system temperatures.
- Managing the HV interlock loop: in some cases, chargers may also monitor the HV interlock loop, hence it can be used by the BMS to stop the charging process in case of a critical error.
- Performing external communications: to receive/send error or alert signals from/to charger/load/CCU/user.
- Managing the dis/charge

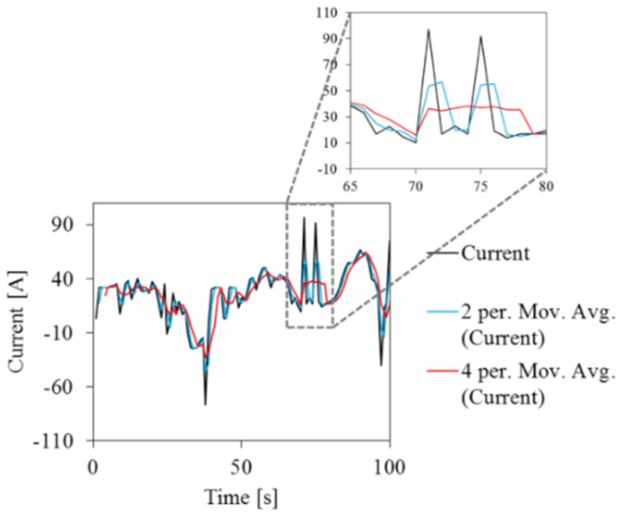


Fig. 2-8. Effect of moving average filters on LIB system current.

2.2.3 DIS/CHARGE MANAGEMENT

Dis/charge management can comprise the following functions (Fig. 2-4):

- Control of the current path, achieved by means of passive devices (fuses) and control of active devices (switches or relays) within the BESS.
- Energy management, which can involve controlling the charger current, managing the charge enable loop (used to enable/disable the charger) and/or setting dynamic operational limits (typically power or current).
- Balance the battery, which can be implemented through passive or active systems.

To allow control of the current path and therefore connecting and disconnecting the pack from the load/charger, devices able to interrupt the current such fuses and switches are installed. While typically small BESS systems for portable applications use solid-state switches, large BESS – such as those used in e-mobility applications – implement relays.

The relays are usually integrated in a switch box (Fig. 2-9) with other components: a pre-charge circuit, used to energize the DC-link capacitor; a current measurement device, i.e. a shunt resistor or a Hall Effect sensor; and external communication channels with the BMS. The switch box sends/receives signals to/from the BMS in order to control the relays according to the BESS operating mode or to measure the pack voltage and current [12] – [15], [41] – [43].

Some characteristics of the (fuse and) switch box may differ widely depending on the specific design of the BESS system, particularly its topology (Fig. 2-10), its location within the application and the devices selected. Important aspects to be considered are the fuse and switch box weight, volume and cost; the devices self-heating; the proximity to other heat sources; isolation between the low voltage and high voltage circuits; or the ease of access to fuses and switches [12] – [15], [58], [60].

Furthermore, the component selection is influenced by the battery system layout, which, in turn, may affect the system’s response, specifically under short-circuit conditions. Higher currents imply bulkier and costlier components. On the other hand, modular solutions may bring more degrees of freedom and reliability, but also involve higher no. of components. Fuses and switches may be placed within the battery pack and/or between the pack and the load/charger [12] – [15], [58], [60].

It is worth noting that a safety switch or contactor, which can be pulled out manually, is also placed in the middle of the pack in large BESS, in order to open the current path during maintenance operations or in the case of an emergency [60].

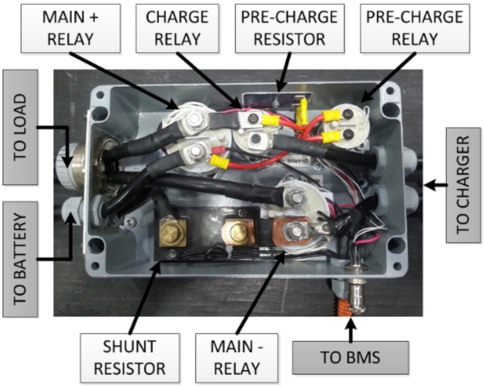


Fig. 2-9. Example of a custom design of a switch box of a BEV (from *AAUDI*).

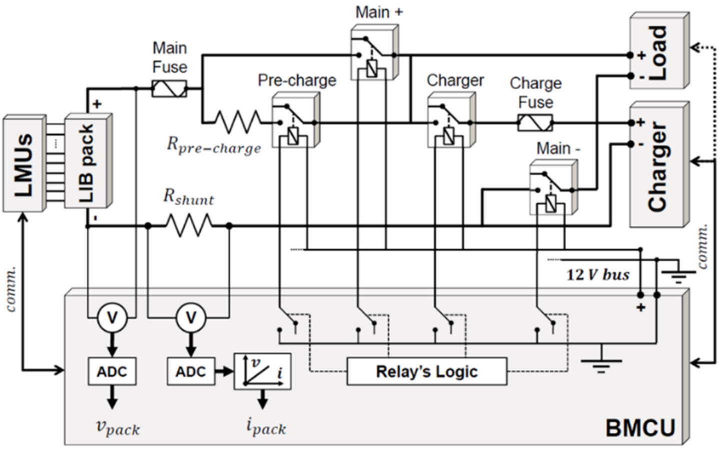


Fig. 2-10. Example of a high level representation of a fuse and switch box [42].

The control of the charging process is also an important function of the BMS. Constant-current constant-voltage (CCCV) approach is the standard when charging a single cell (or block of cells in parallel). However, when the cells are connected in series cell-to-cell differences come into play[13]. As a result, other current control strategies, which also involve a balancing system, are followed in order to bring all the cells up to (or close to) a full-charge state at the end of charge [12] – [15].

[13] The origins of the unbalance may be related to the interconnection of cells with different SoC levels when the pack is built or differences between single cells that show distinct self-discharge rates, capacity or inner resistance/impedance under certain operating conditions [12] – [15], [31] – [40], [52].

A conventional method to calculate the charge current set point, I_{chg}^{ref} [A], is to multiply the max. continuous charge current allowed, I_{chg}^{max} [A], by a target charge voltage-based current limiter factor, γ_{chg} [-], which is estimated through a look-table (Fig. 2-11). Then, depending on the status of the 'balancing logic', either this charge current set point value or a zero current value is transmitted to the charger as a set point. The reason why that zero current periods are sometimes needed is to provide additional time to the balancing system for equalization. Finally, if the charger is enabled, it will return a charging current, I_{chg} [A], according to the set point received. Fig. 2-12 illustrates how to this pseudo-CCCV charge strategy can be implemented.

It is worth noting that, in order to obtain the voltage-based current limiter factor, the maximum instantaneous cell voltage, $max_i(v_{cell}^i)$ [V], is considered (or cell block voltage, in case of cell parallelization). In addition, it should be noted that the gradual reduction of the current could follow linear or exponential trends. Exponential decrease in current is typically recommended for LIB that show a significant non-linear terminal voltage increase at the end of charge, e.g. LFP cathode cells [59].

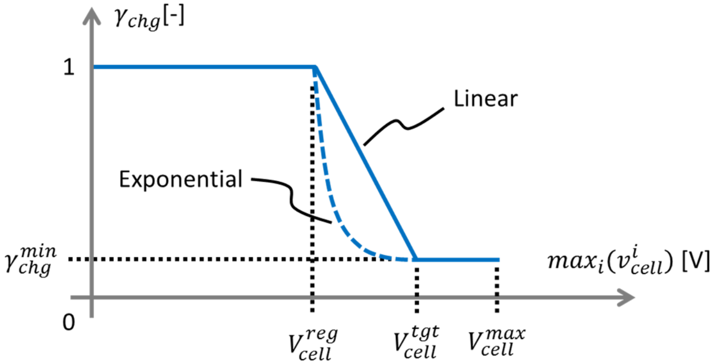


Fig. 2-11. Target charge voltage-based current limiting factor γ_{chg} [59].

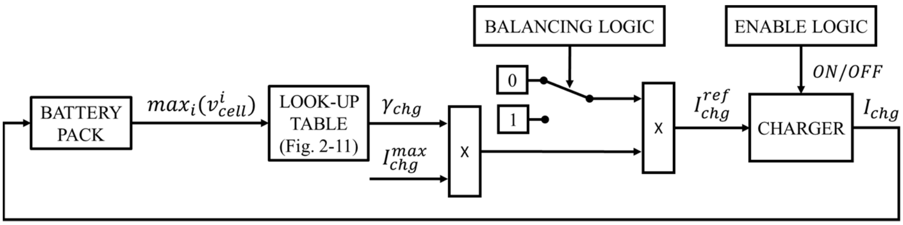


Fig. 2-12. Implementation of a pseudo-CCCV charge strategy.

As aforementioned, the charge current limitation has to be combined with a balancing system. Currently the industry widely adopts passive balancing systems instead of active. Hence, equalization is usually achieved based on selective discharging by placing resistive loads across the cell terminals. The balancing control scheme typically applied is the so called top balancing. This means that the equalization is done based on cell terminal voltages measurements conducted when the battery is near to full charge. A target-balancing window is defined. When all the cells are within the balancing window, the charging process is considered finished. Then the regular charge current can be set to zero [59].

Due to a number of reasons, e.g. relaxation, leakage currents or self-discharge effects on terminal voltages, it is possible that after a certain time one or more cells are not within the balancing window. In that case, as soon as the charge operating mode is still enabled, the charging process is re-started again [59].

As aforementioned, passive balancing circuits reach equalization based on dissipative equalization, i.e. drawing energy from single cells through Joule losses. i.e. heat generation. On the other hand, active balancing circuits are non-dissipative equalization methods, where energy can be transferred e.g. from cell-to-cell, pack-to-cell or cell-to-pack, depending on the circuit topology. Cell bypassing is also fitted in this category. In Fig. 2-13 balancing systems are classified by the energy transfer category [36], [37].

Passive systems are usually implemented using external switch transistors and resistors, being heat dissipation an issue to be considered (Fig. 2-14). Low power solutions integrated in ICs are also available. In the case of active systems, a great number of topologies have been proposed in literature. Many active circuits proposed consist of some type of DC-DC converter(s) interconnected with or without transformers (Fig. 2-14). Work is being done to improve cost, reliability, volume and standby power consumption of active systems [12] – [15], [31] – [40], [52].

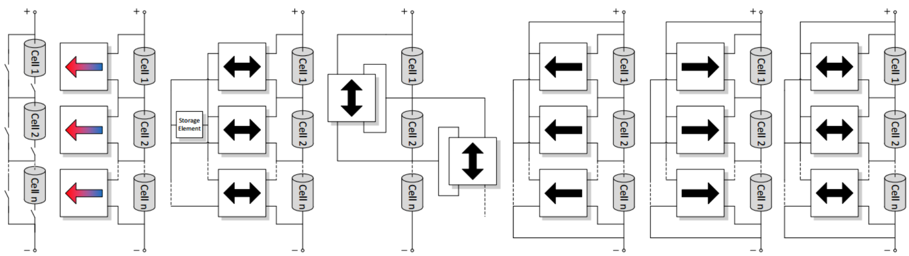


Fig. 2-13. Energy transfer in passive and active balancing systems [37] (from left to right): cell bypass, cell-to-heat, cell-to-cell shared, cell-to-cell distributed, cell-to-pack, pack-to-cell or cell-to-pack-to-cell

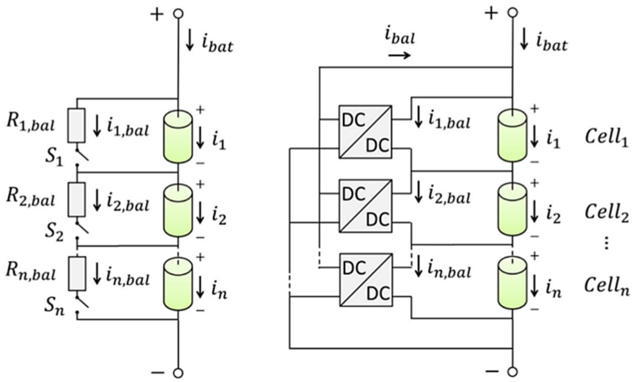


Fig. 2-14. Example of passive (left) and active (right) balancing (modified from [36]).

These shortcomings, combined with the fact that only modest improvements are offered – in terms of energy efficiency or balancing time – are seen by the industry as main barriers for active systems to entry in the market [12] – [15], [31] – [40], [52].

However, as investigated in this work [36], [37], active balancing systems can offer other control features like losses minimization, thermal equalization or maximization of usable capacity through equalization of available dis/charge current or power. These developments may lead to the promotion of a paradigm shift under some circumstances or, at least, to some relevant use cases for active balancing systems with improved control features [36] – [40].

Regarding the calculation of the max. allowable dis/charge current (or power), it forms an integral part of the energy management functions of the BMS related with setting dynamic operational limits for the charger and the load (i.e. the powertrain in EVs) [12] – [15], [59].

Methods to calculate the max. allowable dis/charge current (or power) usually involve the prediction of the available dis/charge current (or power) plus the implementation of a dis/charge current (or power) de-rating strategy. In turn, the prediction of the available dis/charge current (or power) involves a number of diagnosis functions, e.g. to estimate the Open-Circuit-Voltage (OCV) and SoC of each cell (or block of cells in parallel) and the parameters of a certain battery performance model, as discussed in following sub-section and illustrated in Fig. 2-15 [12] – [15], [59].

As regards the de-rating current (or power) strategy, usually involves the use of a number of de-rating or limiting factors. In general, the factors can be grouped according to the direction of the currents, e.g. discharge or charge, and the basic concept on which is founded, e.g. temperature, SOC, internal resistance, etc. Moreover, in applications with regenerative currents like EVs, many of the factors can be used for the calculation of either the regen or the regular charge current.

Table 2-1 presents exemplary current de-rating or limiting factors, summarizing on what basis each factor is developed, giving a brief description of how it works and identifying its calculation level, horizon and target [59].

Table 2-1. SUMMARY OF COMMON CURRENT DE-RATING FACTORS [59]

Basis of the de-rating factor	Generic description	Level		Horizon		Target current	
		Cell	Pack	Instantly	5 - 10 s	Discharge/regen	Regular charge
Temperature	If the temperature is too high, the dis/charge currents are limited gradually to avoid risk of thermal runaway and excessive degradation. If it is too low, they are limited to avoid degradation due to Li-plating.	X	X	X		X	X
SOC	To keep the battery within a certain SOC window, the dis/charge currents can be limited gradually if certain SOC limits are exceeded. Typically, this feature is enabled in HEV, but not in BEV, in order to prevent loss of driving range due to uncertainty in SOC estimation. “Limp home” modes are implemented based on this limiter.		X	X		X	X
Internal battery resistance	A battery model can be proposed to predict the voltage response to pulse currents over short time horizon. By means of basic theory of circuits and using the battery model, the estimated OCV and the max. and min. voltage limits, the max. available dis/charge currents over a short time horizon can be predicted (and therefore the de-rating current factor).	X	X	X	X	X	
Voltage limits	If for any reason, the above current limiting factors are not sufficient to avoid an overvoltage or under voltage event, the BMS implements a second layer of safety. This function is used to limit rapidly the dis/charge current if a voltage over the max. or below the min. allowable voltage limit is measured.	X	X	X		X	X
Critical errors	If certain critical hazard is detected the BMS or the VCU goes into “fail-safe” operating mode. Under a “fail-safe” operating mode the dis/charge current limits should be reduced to zero. If the EV was on the road, i.e. in “discharge operating mode”, the limits are reduced gradually to allow a safe stop.	-	-	X		X	X

2.2.4 DIAGNOSIS

An advanced BMS is supposed to provide an accurate estimation of internal states such as State-of-Charge (SoC), power capability or State-of-Health (SoH) [12] – [20]. However, as discussed in the background, this is not at all a trivial task.

Early SoC indication systems for lead acid batteries were based on voltage and temperature measurements. These are no longer valid for the new LIBs and their more demanding applications. Actually more advanced algorithms are required to address the management challenges of each specific application, as introduced by Fig. 1-6.

For example, a BMS for a mobile phone must include not only accurate SoC estimation, but also remaining run-time prediction for user convenience. Meanwhile, prediction of current or power capability may be of secondary importance and could be disregarded. In contrast, prediction of current or power capability is a primary issue for e-mobility applications, in particular for HEV and PHEV, due to high power charge and discharge pulses [11] – [15], [20], [52].

Hence, as shown in Fig. 2-4, under the name of diagnosis, several functions related with the estimation and/or prediction of battery pack states are grouped, namely:

- States to be estimated: SoC, capacity, temperatures, SoH or State-of-Function (SoF), battery performance model parameters (e.g. impedance or inner resistance) and current or power capability.
- States to be predicted: available energy; remaining run-time; charging time; Remaining-Useful-Life (RUL); and available current or power, which forms part of the current or power capability estimation.

More demanding diagnosis functions require the implementation of battery electro-thermal performance models and complex estimation or prediction algorithms in the BMS. Although there are many different approaches for its implementation, all of them have to deal with similar requirements: suitability for real-time implementation, accurate estimation of electrical and/or thermal performance and robustness to sensor-noise and sensor-biases. Moreover, implicit in these requirements is the ability for online parameter calibration, i.e. real-time estimation of model parameters [11], [12], [20], [23] – [27], [52], [61] – [64].

Fig. 2-15 shows a high level representation of an advanced diagnosis SW, which includes a battery electro-thermal performance model that interacts with a number of other diagnosis functions. Other architectures are possible, depending on the application, and other diagnosis functions may be included or removed. Similarly, each diagnosis function could be implemented in many different ways, affecting or not the interfaces with the rest of the functions [20], [59]. However, it is out the scope of this paper to provide a detailed overview of the all-existing approaches.

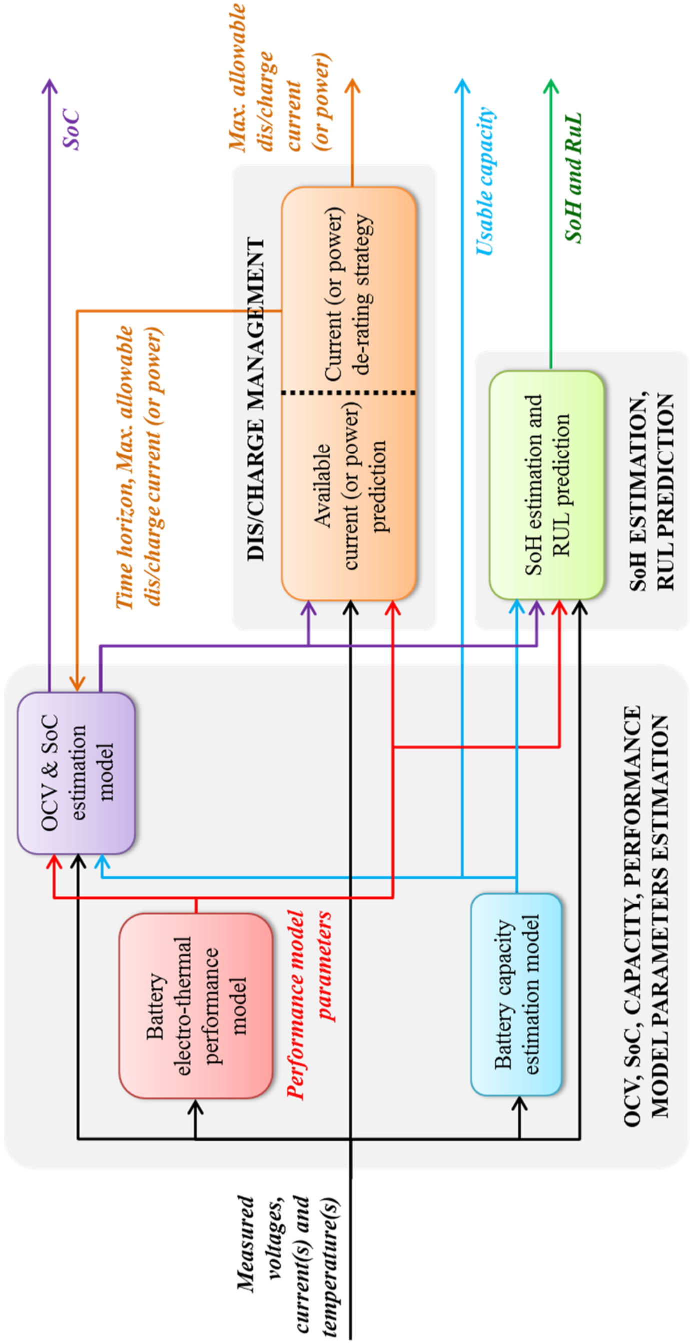


Fig. 2-15. High-level representation of diagnosis SW (modified from [59], inspired by [20]).

2.2.5 DATA MANAGEMENT

Regarding external communications, if any, they can include the transmission of a wide variety of information from and to the BMS through different channels [12] – [15], as summarized in Fig. 2-16.

On the other hand, logging and telemetry are commonly not included in BMSs, which usually just store few data in an error log. However, a BMS with external communications can allow the installation of an external data logger to record both the BMS and the system data and even to transmit this information remotely (telemetry).

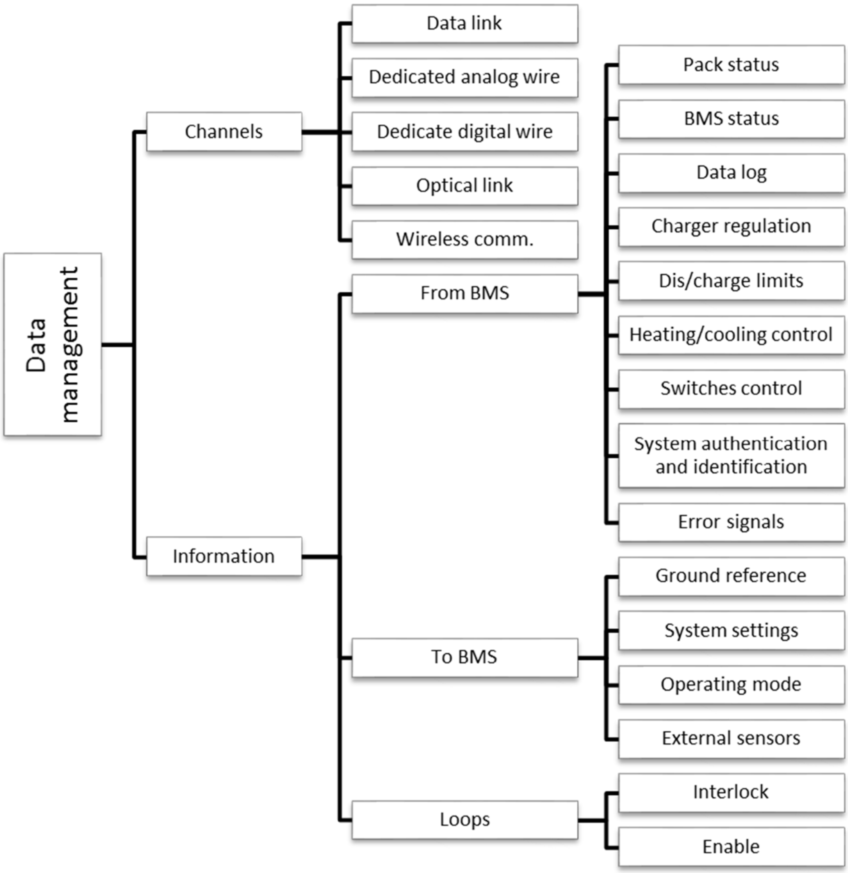


Fig. 2-16. BMS data management: information and channels.

2.3 CLASSIFICATION

BMSs could be categorized according to their functionality, applicability, technology, topology and design [12] – [15], [52], existing numerous types of BMS. In order to facilitate analysis, BMSs are classified in Fig. 2-17.

Regarding functionality, BMSs could be classified in three main groups: monitors, protectors and balancers. Most simple forms of BMS, so called monitors, may only include measuring, protection and communication functions, while most complex forms of BMS, so called balancers, may include all the aforementioned functions. While monitors are popular in laboratory setups, balancers are used in large battery packs (e.g. automotive, ESS).

On the other hand, BMSs used in small packs (e.g. consumer electronics, power tools, electric bikes, etc.), so called protectors, include as balancers all those functions, but are typically stand-alone self-contained systems. Protectors are placed inside a sealed battery pack, without external communications, and incorporate low power solid-state switches to interrupt the power path [12] – [15], [52].

Regarding the technology used to implement a BMS, while there is always analog circuitry related to measuring or balancing tasks, the rest of the system used to process this data could be implemented in both analog and digital circuitry, the latter being the preferred for more sophisticated BMSs [12] – [15], [52].

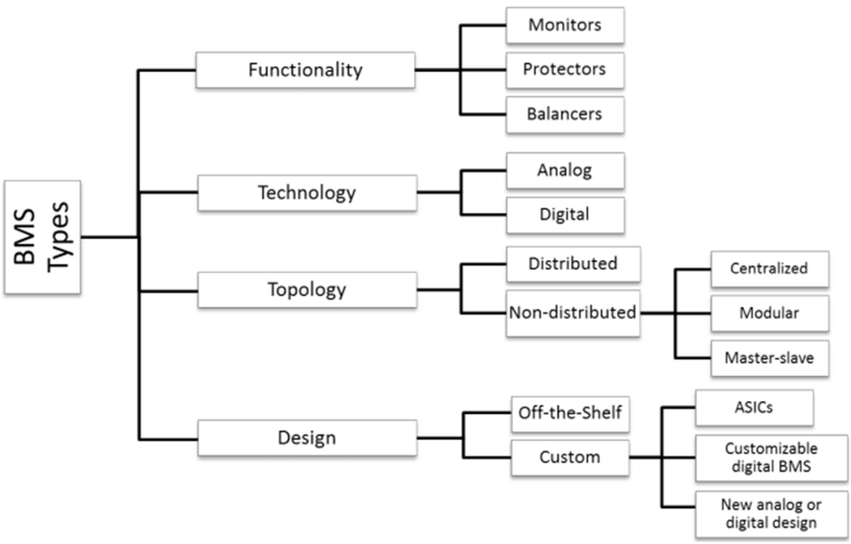


Fig. 2-17. Classification of BMSs.

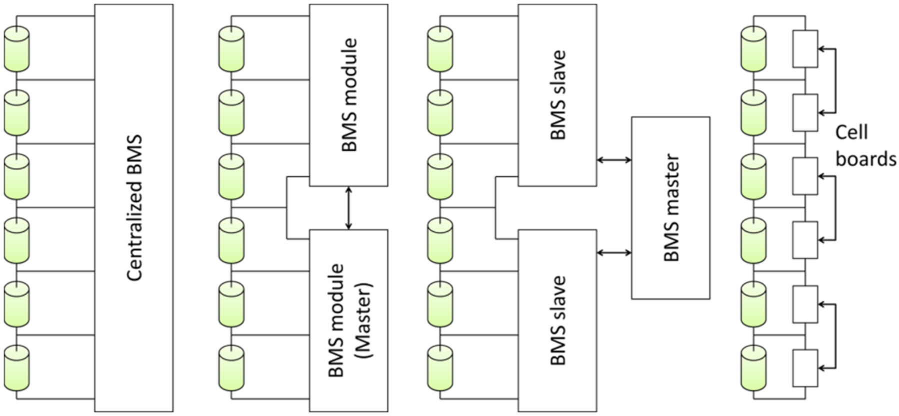


Fig. 2-18. BMS topologies: centralized, modular, master-slave and distributed (left to right) (modified from [13]).

With regard to topologies, BMSs can be classified according to the installation mode into distributed and non-distributed, as shown in Fig. 2-18, showing each topology different advantages and disadvantages, being the choice for a given application a compromise between safety, costs and reliability [12] – [13].

There are as well many ways to design a BMS. The fastest, easiest and cheapest is to select an off-the-shelf product with suitable features for a specific application. However, custom designs are beneficial with regard to ownership, controllability and cost per unit, despite long-term development and higher development cost [12], [13].

2.4 CONCLUSION

More demanding battery applications, e.g. e-mobility, require more advanced electro-thermal management systems, which means more complex BMS. In general, the BMS complexity comes from the sum of a large number of relatively simple features, which can be implemented in many different ways. Among them, probably the most complex features are diagnosis and active balancing, which nowadays is not adopted by industry. Moreover, different topologies and designs are possible.

Certainly, this makes the process of development an advanced BMS product very complex, not only from the point of view of SW and HW development, but also from the perspective of embedded SW validation and testing.

3 PROBLEM STATEMENT

This chapter seeks to move the discussion around the motivations, background and state of the art from general to specific issues. It is divided into three sections: Section 3.1 (Research questions), which defines the RQs tackled in the appended papers; Section 3.2 (Research hypothesis), which describes the research hypothesis, i.e. the expected outcomes; and Section 3.3, which introduces the research methods with special focus on the links between papers.

3.1 RESEARCH QUESTIONS

As discussed previously, there are a number of good reasons to justify efforts in the field of LIB systems. Among others, LIB market has grown enormously based on the consumer electronics market and there are great expectations for the future in emerging markets like e-mobility and grid connected applications [1] – [6].

However, despite of the widely recognized superior performance of LIB over other rechargeable battery systems, new applications demand higher and higher requirements with regard to their battery management. In other words, new applications demand improvements in safety, reliability, usability, lifespan and performance of the LIB systems. This demands simultaneous and complementary actions in several R&D fields, as summarized in Fig. 1-7 [1], [2], [12] – [15], [20], [24], [25], [46], [47].

Furthermore, the increasingly dynamic, innovative and complex characteristics of the battery market, taken together with the global competition and market pressures, leads the companies to seek for novel methods to increase productivity or quality with shorter development and cycle times [1], [2], [20], [42], [43].

Motivated by this background, and considering the general guidelines given in the ALPBES project description[14], the work presented in this dissertation aims at studying multiple practical methods in the field of LIB systems, as detailed in the followings.

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[14] This PhD project falls within the activities WP 2.2. of the ALPBES project, which general purpose is defined as "enhancement of the current BMS state-of-the-art". More specifically, according to the project description, this work should aim to investigate issues at pack level, like "pack performance vs. single cell, differences in single cell performance, procedures for handling these at battery pack level, issues related with equalization of large battery packs, enhancement of the BMS to include features integrating developed battery models, planning of charge/discharge limits or implementation of new algorithms or techniques for improving determination of LIB status."

3.1.1 SIMPLIFIED MODELING

In last decades, a great number of modeling methods for battery electrical performance have been presented in the literature, based on mathematical, physic-chemical, empirical or mixed approaches. As a rule of thumb, it can be stated that more complex models give more accurate results, but at the price of computational power and configuration effort, as shown in Table 3-1.

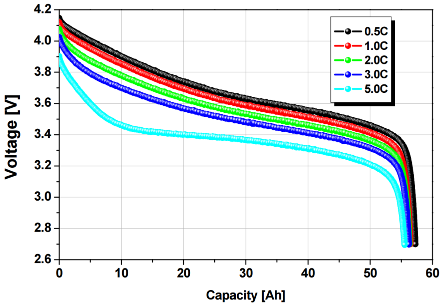
Under some circumstances, more simple models may be preferred. For instance, when there is limited information available for parameterization, in early stages of the application design process, in non-battery focused systems, when the applicability of a mathematical tool is limited, or when computational power or configuration effort are aspects to be considered. In particular, in the absence of experimental data, it becomes valuable to develop a methodology for deriving battery models, as accurate as possible, from solely the limited information available on the battery's datasheets (Fig. 3-1) [27], [84].

On the other hand, improvements on the parameterization methods for linear static Electrical Equivalent Circuit Models (EECMs) could contribute to enhance their accuracy and reduce the effort put in their characterization [28]. This can be more important than it seems, since this kind of models are widely used in the context of the sizing and energy management problem of ESS and HESS, for instance when the powerful mathematical tool of convex optimization is applied, a topic widely covered in the literature [28], [29], [71] – [77].

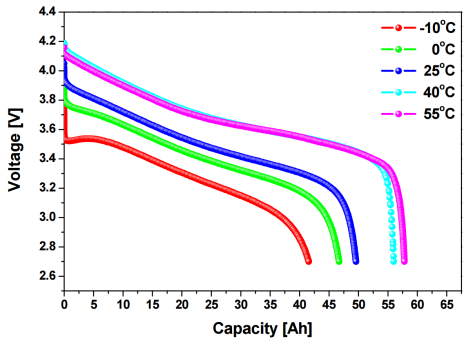
In this regard, a parameterization based on the so-called concept of Direct Current Resistance (DCR) may be advantageous since, in concept, only pure ohmic and charge transfer effects would be taken into account to estimate the battery internal resistance [28], as illustrated in Fig. 3-2.

This can be an advantage, since parameterization methods based on either the pure ohmic resistance or the pure ohmic plus the total polarization resistance[15] may tend, respectively, to under- or overestimate the battery overpotentials under dynamic dis/charge conditions. Thus, resulting in larger errors in battery voltage or losses estimation. Exemplary differences in magnitude between the ohmic, the DCR and the ohmic plus polarization resistances are shown in Fig. 3-3.

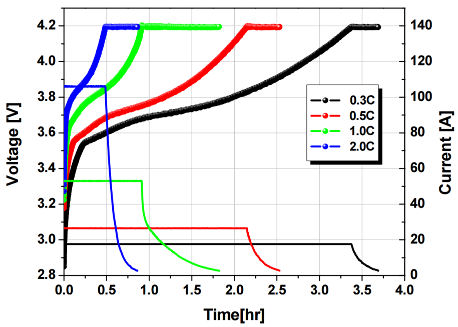
[15] The total polarization resistances is the sum of the charge transfer and the diffusion polarization resistances.



(a) CC discharge at different C-rates



(b) CC discharge at different temperatures



(c) CCCV charge at different C-rates

Fig. 3-1. Exemplary datasheet's steady-state dis/charge curves [84].

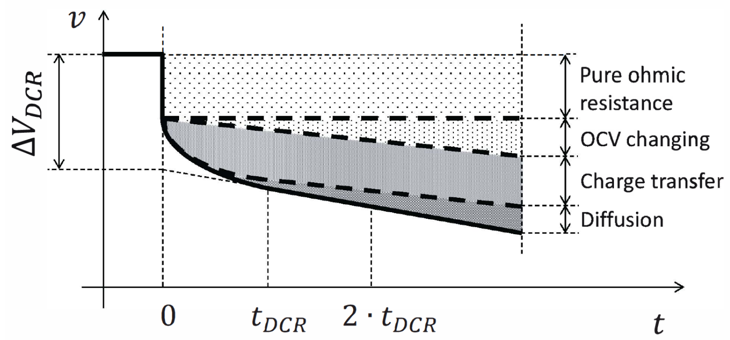


Fig. 3-2. Voltage changes during a CC discharge pulse (including the DCR voltage).

Table 3-1. LIB MODELING APPROACHES AND APPLICATIONS [27]

Model approach	**Accuracy**	**Computational complexity**	**Configuration effort**	**Analytical insight**	**Purpose**
Physic-chemical	Very high	High	Very high	Low	Battery design and model
Empirical (e.g. Peukert law)	Low-Medium	Low	Low	Low	Battery performance estimation
Abstract (e.g. EECM)	Low-High	Low-Medium	Low-High	Medium	Battery performance estimation
Mixed	High	Medium	Low-Medium	High	Battery performance estimation

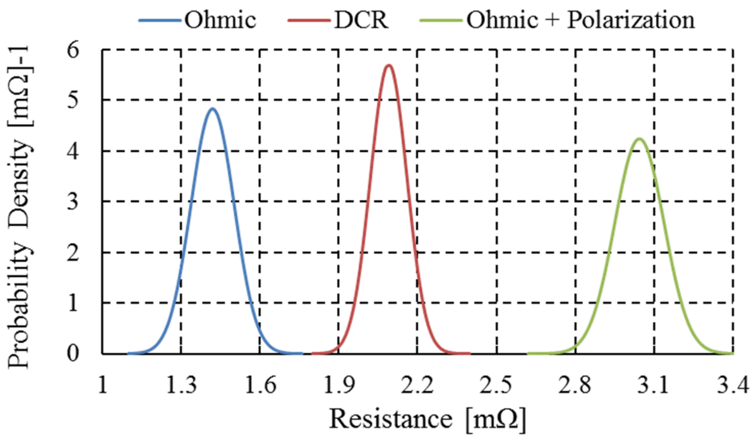


Fig. 3-3. Normal fits of resistances calculated from tests on +200 Kokam cells.

Hence, the next research questions are addressed in relation to this topic:

RQ1: How could a LIB model be derived solely from datasheets?

RQ2: Can DCR-based parameterization of linear static EECM be advantageous?

3.1.2 BATTERY ELECTRIC VEHICLE DESIGN

According to mobility studies, a relatively low range vehicle could meet the transportation needs of most of the people worldwide. On the other hand, social studies underline that the limited range of affordable BEVs is seen as the major obstacle for their mainstream adoption [7], [8], [66], [67]. Moreover, it is true that a sharp fall in cost of LIB packs is expected in the following decade [1] – [6], overcoming the cost-range problem

However, it is still unclear whether a battery pack that provides ranges longer than the demanded by the costumer's daily life should be used. This means, after all, that battery packs larger, costlier and heavier than usually needed would be always used, what might be understood as uneconomic and anti-ecological [8]. The introduction of BEVs that combine a fixed pack, suited for daily needs, and a swappable pack, to extend the range on certain occasions, could solve these problems [7], [8]. Its generic configuration is shown in Fig. 3-4.

Therefore, the next research questions are defined concerning this issue:

RQ3: Can a BEV with fixed and swappable packs offer long ranges at a lower cost?

RQ4: How to evaluate the performance of such BEV in comparison with other BEV?

RQ5: What would be the impact of this concept in the context of the broader field?

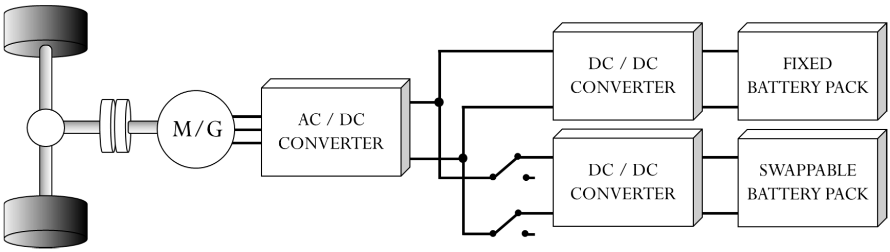


Fig. 3-4. Configuration of a BEV with fixed and swappable battery packs [7], [8].

3.1.3 BATTERY MANAGEMENT SYSTEM TESTING

As mentioned previously, companies are looking for methods to increase productivity or quality of their products with shorter development and cycle times. In the case of a BMS, this can translate into better methods for specification, verification and validations of its requirements [43]. As exemplified by the well-known V-model for

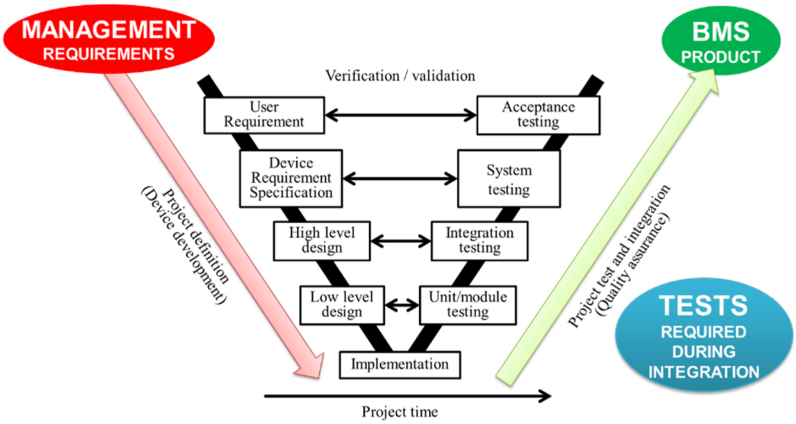


Fig. 3-5. V-model of product development process (modified from [43]).

product development process (Fig. 3-5), which is considered an industrial standard, appropriate testing of the BMS would be required at different stages of development [43], [68] – [70].

Although BMS tests conducted on real batteries may be sufficient in some cases, tests conducted on a HILS may provide key advantages (Fig. 3-6) in terms of cost, test time, reproducibility or safety. The latter is especially relevant when a large battery system is tested at extreme operating conditions, under faults conditions or at early stages in the development process [42], [43].

Nevertheless, choosing the HILS path entails the development of suitable SW and strategies for testing. As a rule of thumb, the more complex the BMS tests, the higher the demands for specific SW and strategies [43]. When referring to SW, it refers, essentially, to BESS models and related controllers able to run and interface in real time with the HILS HW, not only a battery performance model [42]. Thus, the next research questions are raised in this work:

RQ6: What features should an online model offer to be suitable for BMS testing on a HILS at system level?

RQ7: How could BMS strategies be classified and which ones are more suitable for HILS-based testing?

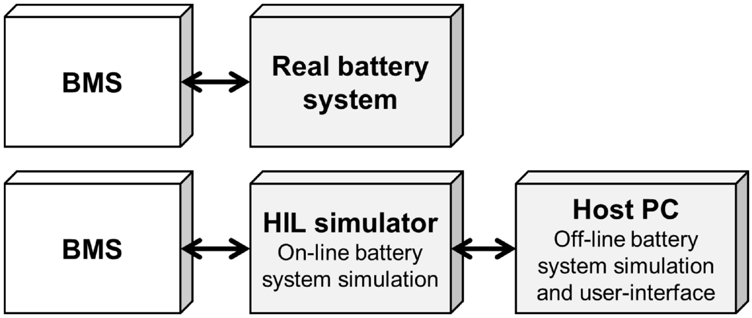


Fig. 3-6. BMS testing approaches: real battery vs. HILS [42].

3.1.4 BALANCING SYSTEM CONTROL

As aforementioned, nowadays passive balancing systems are certainly the solution broadly adopted by the industry. It seems that, although a lot of work have been done to improve cost, reliability, volume and standby power consumption of active systems, improvements achieved in terms of energy efficiency or balancing time are not appreciated as much as the simplicity and cost of their counterparts [12] – [15], [31] – [35], [52]. However, while it is entirely true that a large number of active balancing circuit topologies have been described in the literature, relatively little work has been done in relation to the control strategies [36] – [40].

Undoubtedly, active balancing systems could offer more control features than the equalization of single cell charge, for instance losses minimization, thermal equalization or maximization of usable capacity based on the equalization of available dis/charge current power [36] – [40]. This issue has not yet been explored with enough thoroughness [36]. Consequently, appealing research questions are:

RQ8: What additional control features could be offered by balancing systems?

RQ9: What could be the impact of those features?

3.2 RESEARCH HYPOTHESES

Following the scientific method, once the research questions have been identified and, in agreement with good research practices, the corresponding research hypotheses are defined [78], [79]. In other words, a statement on *what is the expected outcome of the research* is formulated. Table 3-2 lists the RQs and their corresponding hypotheses.

Table 3-2. RESEARCH QUESTIONS AND CORRESPONDING HYPOTHESES

RQ no.	Research question	Research hypothesis
1	How could a LIB model be derived solely from datasheets?	Steady-state data typically provided by manufacturer's datasheets (Fig. 3-1) [24] can be used for parameterization of different linear or non-linear static EECM that reflect capacity or internal resistance dependencies in SoC, current or temperature.
2	Can DCR be an advantageous method for parameterization of linear static EECM of LIB?	A DCR-based parameterization can empirically exclude from the estimation of the battery internal resistance the influence of diffusion polarization effects and changing of OCV, taking into account only pure ohmic and charge transfer effects (Fig. 3-2 and Fig. 3-3). This is advantageous, since the latter effects dominate the battery dynamic power response in e-mobility [80] – [84].
3	Could a BEV that combines fixed and a swappable packs offer long ranges at moderate cost?	The adoption of a novel dual battery concept may allow the repartition of the costs of the large swappable pack over all the users of the swapping infrastructure. Thus, the initial vehicle purchase price may be reduced significantly. However, the achievement of long term economic benefits depends on the specific value of the swapping-services usage-costs, which are connected with the development and maintenance of the swapping infrastructure.
4	How could the performance of such BEV be evaluated in comparison with a single pack BEV?	By means of advanced simulation tools, the efficiency and range of a virtual BEV with fixed and swappable packs can be compared with a commercial BEV with a single pack configuration and similar total battery capacity. The usage-costs of swapping services that can lead to long term economic benefits can be estimated via economic models that compare the total cost of ownership of the novel BEV and the commercial BEV with a single pack.
5	What would be the impact of this concept in the context of the broader field?	The introduction of this novel BEV concept can impact the purchase price, the cost-performance ratio, the weight and the efficiency of the vehicle, the configuration of the chargers or the energy manegement strategies.

6	What features should an online model offer to be suitable for BMS testing on a HILS at system level?	The developed model should simulate in real-time the electrical and thermal performance of each cell within a battery pack; generate realistic cell-to-cell differences in capacity, SoC or overpotentials; include, apart from the battery pack model, models of other components of the battery system like relays, DC-link capacitor or sensors; simulate realistic charging and discharging conditions according to the application; allow multiple configuration of simulation parameters and scenarios; enable testing for the majority of the BMS funtional and non-functional requirements; enable fault insertion testing; control, monitor and log the experiments in real-time.
7	How could BMS strategies be classified and which ones are suitable for HILS-based testing?	Certainly, a great number of strategies could be followed for BMS testing. Strategies that can be classified into many different ways, according to e.g. the testing level, method or process. The most suitable strategies for HILS-based testing are most likely pragmatic, dynamic, black-box, non-destructive, functional and non-functional.
8	What additional control features could be offered by balancing systems?	Apart from SoC equalization, an active balancing system can offer control features related with minimization of energy losses, thermal equalization, maximization of usable capacity based on equalization of available power. On another level, certain balancing systems could offer additional features like by-passing of faulty cells or active diagnosis.
9	What could be the impact of those features?	The impact of those features can range from minor to major depending on a number of factors related or not with the characteristics of the balancing system itself. Among other factors: energy transfer configuration of the balancing system; balancing system current or power level; balancing system efficiency; series-parallel arrangement; total battery capacity; battery aging scenario; characteristics of the power demand, according to the specific application; heating/cooling system characteristics; environmental temperature; desired operating windows in terms of temperature or SoC; chemistry-specific characteristics of the battery dynamic power response.

3.3 RESEARCH METHODS

Once the research questions and hypotheses have been described, the research methods can be described. It should be noted that, in this dissertation, the answer to a certain research question can be investigated either in one or multiple of the appended papers. Similarly, while some papers investigate only one of the questions previously formulated, some other papers cover several questions. The connection of each research question to the paper where it is addressed is shown in Table 3-3. On the other hand, an overview of the papers appended in this dissertation is given in Table 3-4. In addition to describing and explaining the relationships between the research topics and the appended papers, a Venn diagram is given in Fig. 3-7.

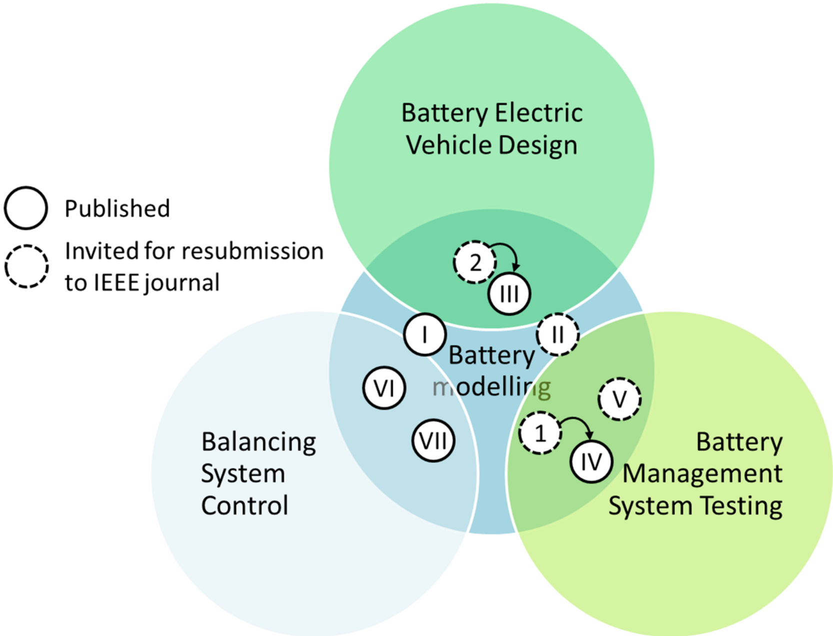


Fig. 3-7 Venn diagram to illustrate the topics covered by the author's papers (appended and non-appended[16]).

[16] Roman numerals I – VII are used to identify the appended papers, as referred in the List of Appended Papers. On the other hand, Arabic numerals are given to non-appended paper, as referred in the List of Non-appended papers. Numbers 1 and 2 correspond to references [41] and [7], respectively. These papers are omitted since Paper IV [42] and Paper III [8], respectively, are their extended and reviewed versions.

Table 3-3. CONNECTION BETWEEN RESEARCH QUESTION AND PAPERS

RQ no.	Research question	Appended paper no.
1	How could LIB models be derived solely from datasheets?	I
2	Can DCR be an advantageous method for parameterization of linear static EECM of LIB?	II
3	Could a BEV that combines fixed and swappable packs offer long ranges at a lower cost?	III
4	How could the performance of such BEV be evaluated in comparison with a single pack BEV?	III
5	What could be the impact of this concept in the context of the broader field?	III
6	What features should a model offer to be suitable for BMS testing on a HILS at system level?	IV, V
7	How could BMS strategies be classified and which ones are suitable for HILS-based testing?	V
8	What additional control features could be offered by active balancing system?	VI, VII
9	What would be the impact of those features?	VI, VII

As shown in Fig. 3-7, four main research topics are covered in this dissertation:

- Battery modeling
- Battery Electric Vehicle Design
- Battery Management System Testing
- Balancing System Control

With respect to the battery modeling , it serves as a central hub for all the research activities carried out under this work. In some manuscripts, working as the core topic of the paper, i.e. in Manuscript I [27] and II [28], which focused on simplified modeling approaches. In all the other cases, serving as an essential tool towards the achievement of the results.

Table 3-4. OVERVIEW OF THE APPENDED PAPERS

Appended paper no.	Title	Ref. no.
I	Datasheet-based modeling of Li-Ion batteries	[27]
II	An improved parameterization method for Li-ion linear static equivalent circuit battery models based on direct current resistance measurement	[28]
III	Evaluation of a novel BEV concept based on fixed and swappable Li-ion battery packs	[8]
IV	An Advanced Hardware-in-the-loop Simulation Battery Model for Battery Management System testing	[42]
V	Development of software and strategies for Battery Management System testing on HIL simulator	[43]
VI	Multi-Objective Control of Balancing Systems for Li-Ion Battery Packs: A Paradigm Shift?	[36]
VII	Evaluation of Advanced Control for Li-ion Battery Balancing Systems using Convex Optimization	[37]

Furthermore, it should be noted that not only the electrical performance of the batteries can be modeled, but also their thermal performance. But that it is not all, in fact the electro-thermal battery performance model can be, in some cases, also coupled to an aging model or models of other system level components of the battery system, e.g. a load, a charger, a switch box, a DC-link capacitor or a temperature or current sensor.

In relation to the load model, since some methods presented in this work are oriented to e-mobility applications, a BEV model is implemented in some cases too.

Hence, taking into account the variety of modeling methods used in the appended publications, it is decided to address the topic of modeling in a dedicated chapter of this dissertation, i.e. Chapter 4.

4 MODELING

This chapter justifies the selection of cells and provides an overview of the main modeling methods used in the appended papers. It is divided into four sections: Section 4.1 (Li-ion cell selection), which explains the criteria followed to select the Li-ion cells to be modeled; Section 4.2 (Electrical performance modeling approaches), which surveys the EECMs employed; Section 4.3 (Thermal performance modeling approaches), which review the TECMs implemented; and Section 4.4 (Battery Electric Vehicle modeling approach), which describes the approaches used for BEV modeling.

It should be noted that, in this section, the goal is to provide a qualitative overview of these methods with focus on the high level links between papers. More details, qualitative and quantitave descriptions of the specific methods may be given within each paper, avoiding unnecessary repetition.

It must be pointed out that the different notations given in each of the papers appended to this dissertation (Chapter 5) are simplified and unified in the rest of the document, for ease of comparison and better readability. In general, this simplification can be attained since the most detailed descriptions of the specific methods, which require more complex notations, are only given within each paper, while only higher level descriptions are presented in the rest of the dissertation.

4.1 LI-ION CELL SELECTION

There are different criteria that could be considered in respect of the selection of the Li-ion cells to be used in a certain scientific study. In general, the main criterion that has been followed in this work is to choose a type of cell (format, size, electrode material) that is able to fulfill the more demanding requirements of advanced LIB applications in the field of e-mobility.

It should be noted that, as previously discussed, BEV and HEV applications are not only more demanding from the perspective of the energy storage and conversion device itself, but also from a battery management perspective.

Based on these premises, all the manuscripts appended to this dissertation consider for modeling purposes experimental results from large format Li-ion pouch cells with an NMC cathode material manufactured by Kokam. More specifically, either from 40 Ah cell type SLPB100216216H [42], [43] or a 53 Ah cell type SLPB 120216216 [8], [27], [28],[36], [37].

As illustrated in Table 1-1, Graphite-NMC cells are used nowadays by major automotive manufacturers like Volkswagen, Smart, Daimler, Fiat or BMW. Moreover, large format pouch cells are being used not only by the aforementioned manufacturers, but also by others like Chevrolet, Cadillac, Ford or Nissan.

4.2 ELECTRICAL PERFORMANCE MODELING APPROACHES

Runtime-based low order lumped parameter EECMs are perhaps the most popular approach in the literature for efficient electrical performance modeling. By using lumped systems instead of distributed systems, it is possible to reduce computational burden, since it involves solving a set of ordinary differential equations at fewer points, which may be achieved analytically. On the other hand, distributed systems may involve solving a larger set of partial differential equations at more points, which could be difficult to solve analytically [11], [12], [20], [23] – [27], [52], [61] – [64].

Furthermore, low order approaches are easier to implement, since they require a reduced number of calibration parameters. It should be noted that, the most common battery modeling calibration techniques rely on some kind of electrical system characterization methods, i.e. step response and frequency response tests, rather than on more complex electro-chemical techniques. Thus, the only variables that are measured directly are the currents, voltages and surface temperatures. As a result, only a limited number of calibration parameters can be easily inferred from these few variables, due to identifiability issues [11], [12], [20], [23] – [27], [52], [61] – [64].

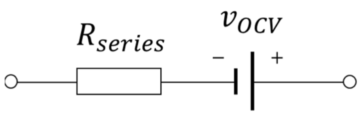
In this work, as illustrated in Fig. 3-7, all the appended papers make use of some sort of battery modeling approach in their methodology. In fact, in all the cases an EECM is used to simulate the electrical battery electrical performance. Although there are significant differences between all the developed models, as summarized in Table 4-1 according to their specific purposes within each study.

Regarding the topologies, four types of EECMs are considered: linear static, non-linear static and non-linear dynamic with single or multiple RC elements. These static and dynamic EECMs are represented in Fig. 4-1, where

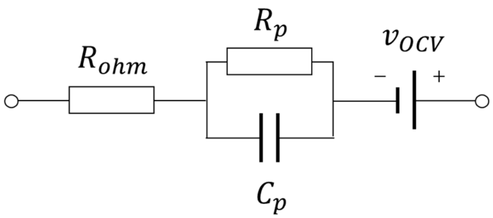
R_{series}	[Ω] is the series resistance, typically parametrized either as the DCR, R_{ohm} or $(R_{ohm} + R_p)$
v_{OCV}	[V] is the Open Circuit Voltage (OCV), i.e. the equilibrium voltage
R_{ohm}	[Ω] is the pure ohmic resistance
R_p	[Ω] is the polarization resistance of the first-order model
C_p	[F] is the polarization capacitance of the first-order model
$R_{p,x}$	[Ω] is the polarization resistance x of the n-order model, where x ∈ N and 0 < x < n
C_(p,x)	[F] is the polarization capacitance x of the n-order model.

Table 4-1. SUMMARY OF ALL THE EECM APPROACHES USED

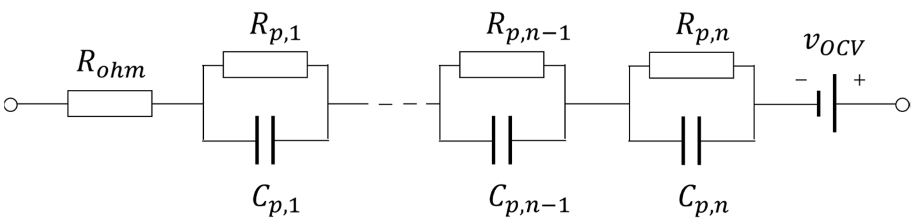
Appended paper no.	**Type of EECM**				**Experimental characterization methods**					**Run mode**		**Model level**		**EECM coupling**						**EECM dependencies**			
	Linear static	Non-linear static	Non-linear dynamic	No. of RC elements	Capacity check and OCV test	Steady-state dis/charge curves	Pulse power characterization	DCR	EIS	Offline	Online (real-time)	Single cell (X) or aggregated (•)	Multi-cell pack	With thermal model	With aging model	With balancing circuit model	With BEV model	W/model of other BESS parts	With real-time SW and HW	SoC	Temperature	Current	Aging
I	X	X		-	X	X				X		X								X	X	X	
II	X		X	1	X		X	X		X		X					X			X		X	X
III			X	1	X					X		•			X		X			X		X	
IV			X	5·2	X		X		X		X		X	X	X		X	X	X	X	X	X	X
V			X	5·2	X		X		X		X		X	X	X		X	X	X	X	X	X	X
VI	X		X	1	X					X			X	X	X	X	X			X		X	X
VII	X			-	X			X		X			X	X	X	X	X			X			X



(a) Static



(b) Dynamic with 1 RC element



(c) Dynamic with multiple RC elements

Fig. 4-1. Different types of EECMs.

The equations that express the electric behavior of these EECMs are presented in Appendix A, both in continuous and in discrete time. Linearity or non-linearity properties are given depending on the kind of functions used to express the relationships between the battery states and the parameters of the EECM, e.g. the OCV vs. SoC characteristic.

In respect of the parameterization of the EECMs, all of them are characterized by means of steady-state dis/charge tests – similar to the ones typically found in datasheets[17] (Fig. 3-1) – and/or step-response tests, i.e. DCR measurements (Fig. 3-2), OCV tests (Fig. 4-2) or pulse power characterization (PPC) tests (Fig. 4-3).

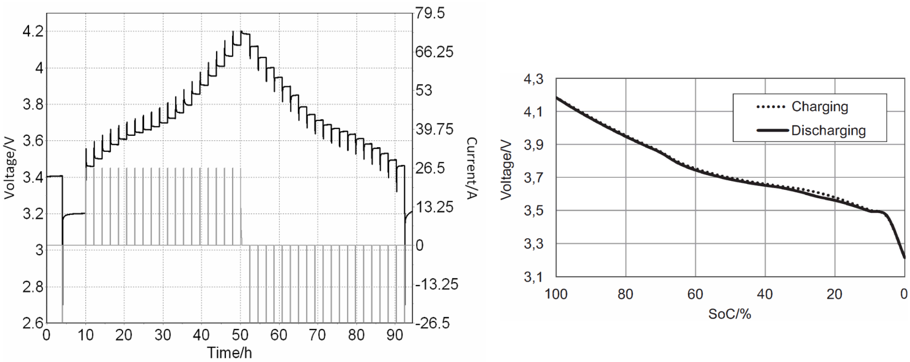
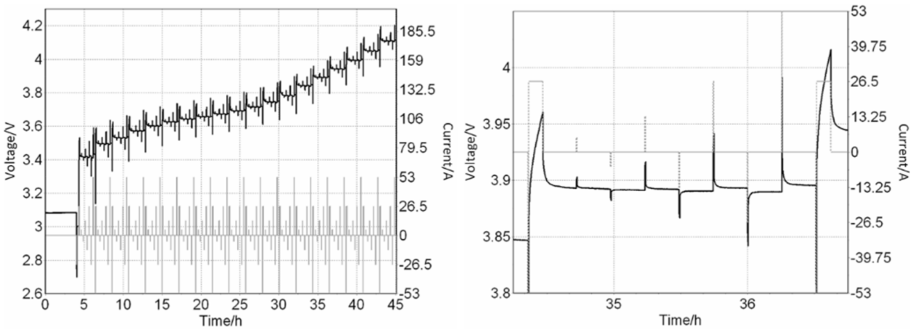


Fig. 4-2. OCV test (left) and OCV vs. SoC characteristic (right) of a Kokam 53 Ah cell (at Beginning-of-Life (BOL) and room temperature) [28].



(a) General view

(b) Detailed view

Fig. 4-3. PPC test of a Kokam 53 Ah cell (at BOL and room temperature) [28].

[17] In fact, in Manuscript I [27], EECMs are parameterized using only datasheet's steady-state curves. More details about the modeling methods are given in the manuscript and Appendix A.

Moreover, the characterization of the dynamic EECM with multiple RC elements also involves frequency response tests, i.e. Electrochemical Impedance Spectroscopy (EIS) (Fig. 4-4). As explained in [41] – [43] an impedance-based model that considers two ZARC elements in series is characterized in the frequency domain (Fig. 4-5).

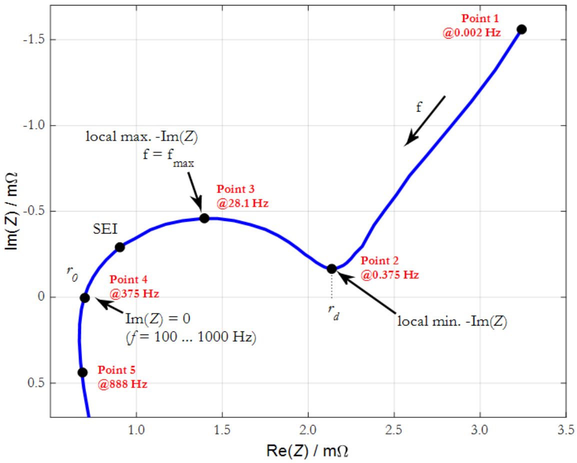


Fig. 4-4. Nyquist plot: impedance spectrum of a Kokam 40 Ah cell [42].

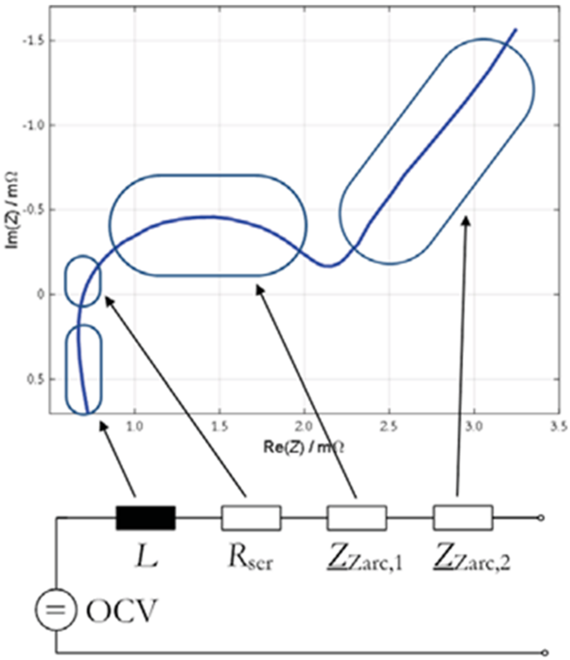


Fig. 4-5. Links between the impedance spectrum and the EECM components [41].

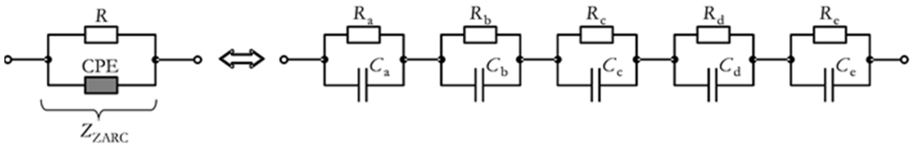


Fig. 4-6. Frequency-to-time domain approx. of a ZARC element by RCs [42].

Then, since the model will be used in the time domain, each ZARC element is approximated as a series of five RCs elements (Fig. 4-6).

Regarding the modeling of the OCV vs. SoC characteristic, the method followed in all the appended papers, but Manuscript I[17] [27], involves the next steps:

1) Estimation of the charging and discharging OCV vs. SoC curves from experimental OCV tests..
2) Averaging of the OCV vs. SoC curves. Noting that hysteresis effects are negligible for the selected cells (Fig. 2-11), the average of both curves is assumed for modeling purposes.
3) Non-linear or linear implementation: once the non-linear averaged OCV vs. SOC curve is obtained, it may be linearized or not depending on the modeling needs. The formulation of the linear and non-linear models is fully described in Appendix A.

With regard to the battery model level, three different approaches are followed: single cell, multi-cell pack and aggregated pack.

Single cell models are used to evaluate DCR- and datasheet-based modeling approaches, since in these cases there is no need to use a pack level model for purposes of model validation [27], [28]. Moreover, in the latter case, only cell level information is provided by manufacturer's datasheet.

Multi-cell pack modeling, i.e. interconnection of a number of single cell models, is considered for studies dealing with balancing systems [36], [37] and BMS testing [42], [43]. For intrinsic reasons, the ability to simulate independently single cell performance is a must in these cases.

Aggregated battery pack models are used for the sake of simplicity when, under the application scenario of the study, cell-to-cell differences do not play a dominant role in the battery pack performance [8], [29].

4.3 THERMAL PERFORMANCE MODELING APPROACHES

In this work, as shown in Table 4-1, a thermal model is sometimes coupled to the EECM [36], [37], [42], [43]. The most simple models have been proposed for purposes of evaluation of innovative control features of balancing systems by means of offline optimization methods [36], [37], while the most sophisticated for online BMS testing on a HILS [42], [43].

While models with different levels of complexity at cell and pack level are presented, in all cases the basic approach is to use some sort of lumped Thermal Equivalent Circuit Model (TECM). TECMs have been widely proposed for low-order application-oriented battery thermal modeling at cell or pack level [85] – [96].

All the TECMs presented assume a lumped capacitance model, i.e. the temperature differences within the cell are neglected. This assumption works well under non-extreme heating/cooling conditions. Therefore, the relationship between the temperature change and the accumulated heat transfer rate in a cell, $\dot{Q}_{acc}$ [W], can be expressed for each cell j as [36], [37], [42], [43], [85] – [96]:

(1) $$\dot{Q}_{acc}^{j}(t) = mC_{bat}\frac{dT_{bat}^{j}(t)}{dt}$$

where m [kg] is the mass of the cell, C_{bat} [J/(kg.K)] is the specific heat and T_{bat}^{j} [K] the temperature of the cell j. Furthermore, the accumulated heat transfer rate in a cell j is related to the heat transfer rate generated, $\dot{Q}_{gen}$ [W], and dissipated, $\dot{Q}_{dis}$ [W], through the differential thermal balance equation [36], [37], [42], [43], [85] – [96]:

(2) $$\dot{Q}_{acc}^{j}(t) = \dot{Q}_{gen}^{j}(t) - \dot{Q}_{dis}^{j}(t)$$

With regard to the heat generated, it can be defined as the sum of reversible and irreversible heat sources. The reversible heat generation can be caused by the change of entropy and the irreversible heat generation by over-potential heating, material phase changes and mixing [37], [92]. In this work, as in many others [37], [91] – [93], over-potential heating is assumed as the dominant source of heat generation, so other sources are omitted. Considering this, the heat generated by a cell j is defined as:

(3) $$\dot{Q}_{gen}^{j}(t) = p_{l}^{j}(t) = i_{j}(t)(v_{OCV}^{j}(t) - v_{t}^{j}(t))$$

where p_{l}^{j} [W] are the internal losses of the cell j, i_j [A] is the cell's operating current, v_{OCV}^{j} [V] is the cell's OCV and v_{t}^{j} [V] is the cell's terminal voltage. Depending on the type of EECM, the terminal voltage is calculated differently, according to the equations presented in Appendix A.

Regarding the heat dissipated, there are three heat transfer phenomena that are modelled at cell’s boundaries, individually or combined: conduction, convection and radiation. Conduction is the transfer of heat energy transferred between two solid materials in physical contact, convection is the transfer between a solid material and its surroundings by means of fluids motion, and radiation is the transfer by the emission of electromagnetic radiation [85] – [96].

The equations that describe the thermal resistances of these three fundamental heat transfer modes are given in Appendix B. In cases where the heat is transferred through a combination of heat transfer modes, an equivalent thermal resistance can be calculated by summing the individual thermal resistances in series or parallel.

Based on Fourier’s law of heat conduction, in an analogous way to Ohm’s law, the dissipated heat transfer rate, $\dot{Q}_{dis}^{j}$ [W], can be expressed as a function of the equivalent thermal resistance, R_{eq} [K/W], and the temperature potential, ΔT [K]:

$$\dot{Q}_{dis}^{j}(t) = \frac{\Delta T(t)}{R_{eq}} \quad (4)$$

In this work, different approaches have been followed to model the heat dissipated, assuming different heat transfer modes at the cell’s boundaries, within the cell or between neighboring cells, as summarized in Table 4-2.

The most simple TECM used is a lumped capacitance 1-D TECM that only accounts for convective heat transfer at the cell’s boundaries and does not consider heat transfer within the cell or between neighboring cells [36]. This model is used for preliminary evaluation of the potential of innovative control features for balancing systems. The diagram of this TECM is presented in Fig. 4-7.

Table 4-2. SUMMARY OF THE ALL THE TECM APPROACHES USED

Appended paper no.	Type of TECM		Running mode		Heat transfer modes at cell’s boundaries			Heat transfer assumptions		Heating/ Cooling methods	
	Lumped capacitance 1-D	Lumped capacitance 3-D	Offline	Online (real-time)	Conduction	Convection	Radiation	Heat transfer within the cell	Cell-to-cell heat transfer	Forced air	Heating/cooling plate
IV		X		X	X	X	X	X	X	X	X
V		X		X	X	X	X	X	X	X	X
VI	X		X			X				X	
VII	X		X		X	X			X	X	

On the other hand, the more extensive and comprehensive evaluation of the potential of aforementioned control features presented in [37] makes use of a similar lumped capacitance 1-D TECM, but considering also conductive heat transfer between neighboring cells. In this case, the heat conduction rate term between cell j and neigbouring cells $(j+1)$ and $(j-1)$ can be expressed as follows [37], [94]:

$$(5) \qquad \dot{Q}^{j}_{cond}(t) = (2T^{j}_{bat}(t) - T^{j+1}_{bat}(t) - T^{j-1}_{bat}(t))/R_{cond}$$

The diagram of this TECM is shown in Fig. 4-8. This diagram aims to show a simplified graphical representation of the thermal performance of a battery with parallel cooling based on forced air.

A 2-D schematic of such an exemplary battery pack is provided in Fig. 4-9. It is worth noting that, since parallel cooling is considered rather than series, it is assumed an even distribution of the air temperatures within the pack, i.e. all cells experience the same ambient temperature, T_{amb} [K] [37], [93], [94].

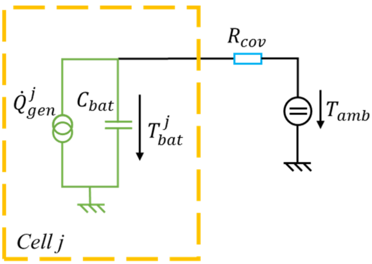


Fig. 4-7. 1-D TECM of a pouch cell without links to neighboring cells.

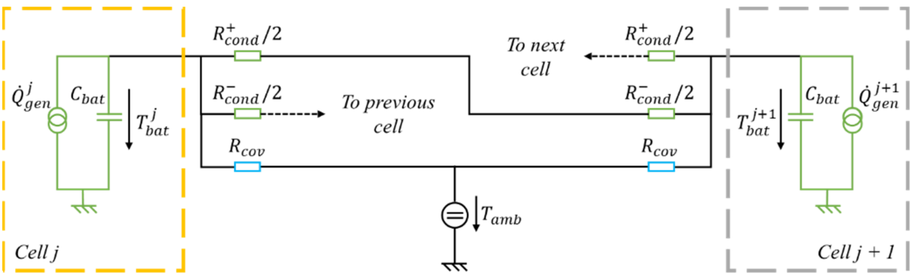


Fig. 4-8. 1-D TECM of a pouch cell linked to neighboring cells.

Furthermore, although a lumped capacitance model is considered, the heat transfer mechanisms within the cell can be modelled for higher accuracy. In fact, in this dissertation, for purposes of more accurate battery modeling in a HILS, an anisotropic multi-dimensional TECM is developed [42], [43].

Thereby, in this case, different thermal conductivity values are considered within the cell depending on the direction and sense of the heat transfer. The equations that describe the corresponding anisotropic thermal resistances are given in Appendix B.

Diagrams of the more sophisticated lumped capacitance 3-D TECM are given in Fig. 4-10 and Fig. 4-12. It should be noted that this model considers convective and radiative heat transfer both between neighboring cells and to the environment, conductive heat transfer to a cooling plate and anisotropic thermal conduction within the cell, as illustrated in the 3-D schematic of Fig. 4-11.

Parameterization of the 3-D TECM is based on the offline characterization tests described briefly in [42] and physical properties of the cell. These parameters are not updated over battery lifetime, a common assumption in the literature [85] – [96].

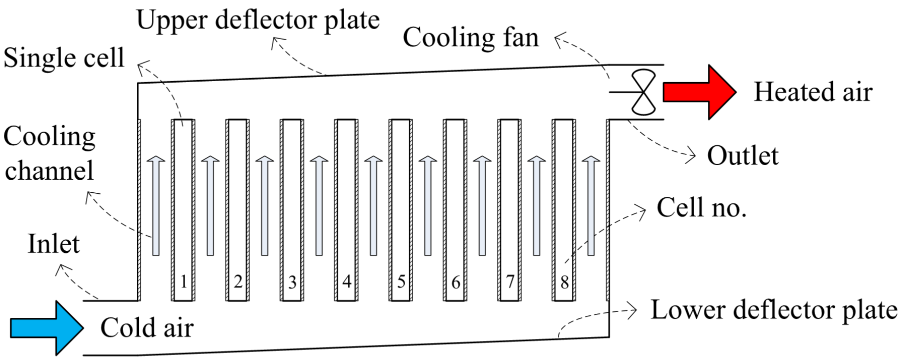


Fig. 4-9. 2-D schematic of an exemplary battery pack with parallel air-cooling (modified from [94]).

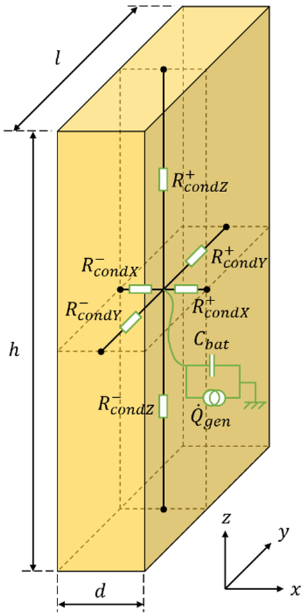


Fig. 4-10. 3-D schematic of a 3-D TECM of a single pouch cell (inspired by [90]).

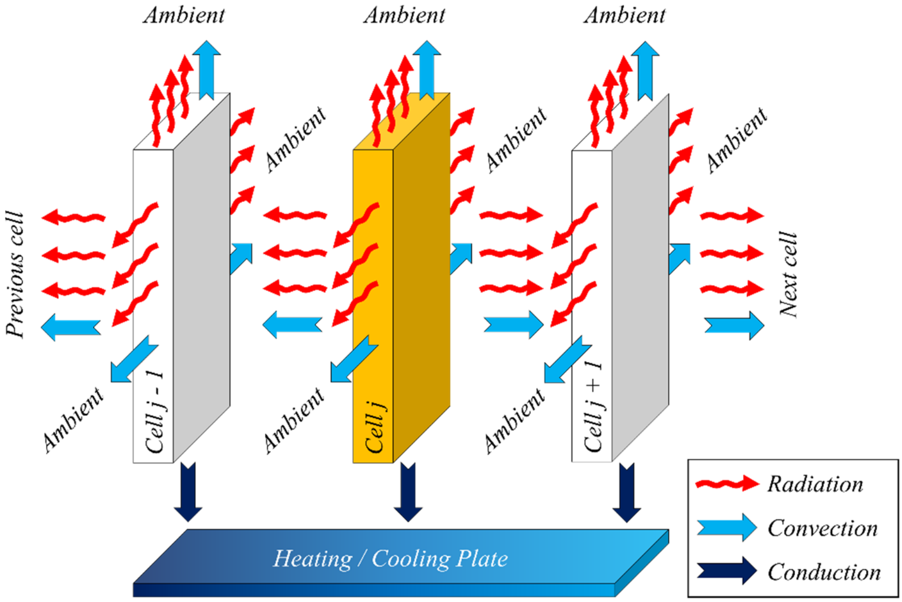


Fig. 4-11. 3-D schematic of an exemplary pack with a heating/cooling plate.

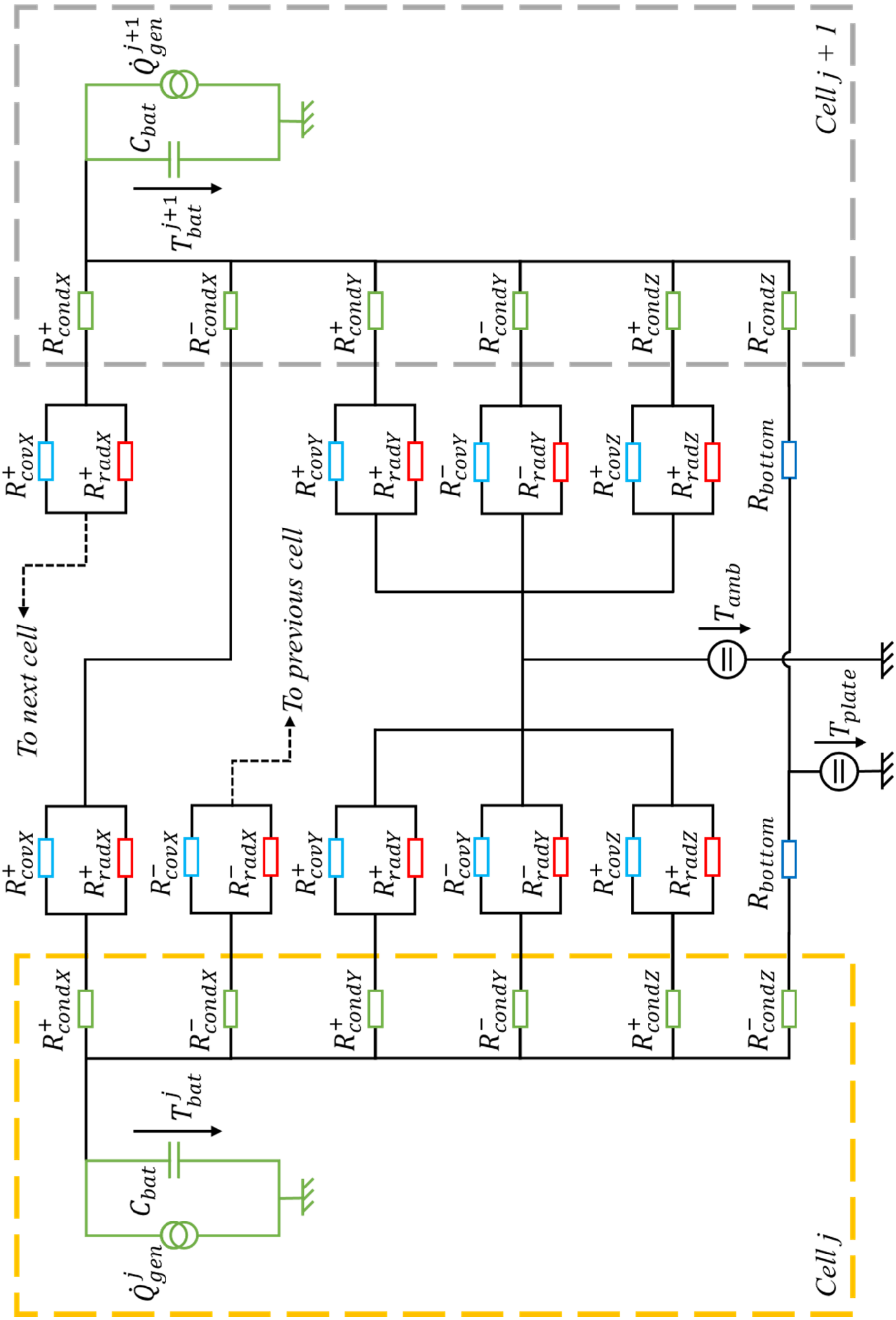


Fig. 4-12.More sophisticated 3-D TECM of a pouch cell linked to other cells.

4.4 BATTERY ELECTRIC VEHICLE MODELING APPROACHES

In this work, as illustrated in Table 3-3, a BEV model is implemented in a number of cases. In its simplest form, the BEV model only consists of a simple algorithm that scales a pre-recorded current profile according to the voltage specifications of the battery pack under simulation. This current profile has been logged from a real BEV and provided by RWTH ISEA Aachen. This is the approach followed in Manuscript IV [42] and V [43].

In the other cases, i.e. Manuscript II [28], III [8], VI [36] and VII [37], a complete BEV model is implemented, in order to generate power profiles from a number of standard driving cycles (Table 4-3). The formulation of this BEV model is provided into detail in Manuscript III [8], while in rest of the manuscripts is omitted, but referenced to other publications of the authors that are non-appended to this dissertation [29], [74].

In all the manuscripts, but Manuscript III [8], the general configuration of the BEV model corresponds to a single battery pack linked to the motor through an AC/DC inverter (Fig. 4-13). The model is parameterized based on real data from the *uCar*[18], a concept vehicle developed at FEUP (Fig. 4-14) [111].

Table 4-3. SUMMARY OF ALL THE STANDARD DRIVING CYCLES USED[19]

Appended paper no.	Standard driving cycles					
	Aggressive driving US06	City driving FTP-75	Highway driving HWFET	Artemis rural road driving	Artemis motorway 130	FTP-Highway
II	X					
III		X	X			
VI				X		
VII	X	X			X	X

[18] "Official video from FEUP that summarizes the *uCar* features," https://wn.com/ucar__electric_vehicle_in_feup, Accessed: 2017-03-11.

[19] More information about the standard driving cycles is provided in Appendix C.

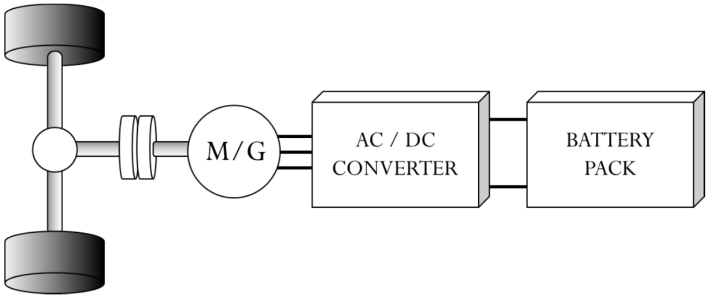


Fig. 4-13. Configuration of the BEV model used in most of the papers [8].

(a) (b)

Fig. 4-14. Picures of (a) the *uCar* [111] and (b) the *AAUDI* [8].

In Manuscript III [8], the configuration of the BEV corresponds to a modular battery pack, where each module is connected to the DC-link through a DC/DC converter, which is in turn connected to the motor through an AC/DC inverter (Fig. 3-4).

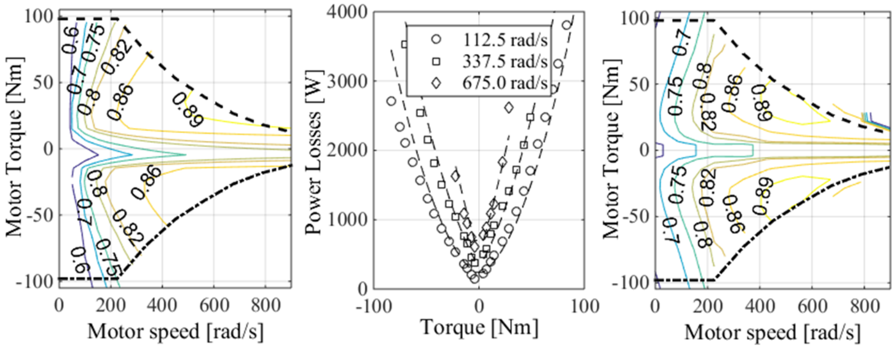
The model is parameterized based on real data from the *AAUDI*, a concept vehicle developed at AAU[20] (Fig. 4-14), and a number of assumptions based on the scientific literature and public available sources, including the DOE technical targets and USABC goals.

The general BEV modeling assumptions are summarized below:

- A straight path with zero road angle is assumed (no turns, no up/downhill)
- Rolling resistance and aerodynamic losses are considered
- Transmission is fixed-gear and has a constant efficiency

[20] ”Official website of the ELBIL project (where the *AAUDI* platform was developed),” http://www.elbil.et.aau.dk/, Accessed: 2017-03-11.

- Motor plus inverter losses are approximated from efficiency maps by means of polynomial fitting dependent on the vehicle speed and output torque (Fig. 4-15), following the methodology presented in [74]
- DC/DC converter(s) (if any) losses, are calculated using a non-linear function that is fitted in such a way that the converter's efficiency is higher than certain value for a certain current
- Regenerative braking is considered and for the highest braking powers, mechanical brakes dissipate the excess power that cannot be absorbed by the battery pack
- Auxiliary power demand (lights, radio, HVAC…) is assumed constant
- Passengers and cargo weight is neglected
- Vehicle body and battery weight is estimated based on experimental data from the *AAUDI*
- Power electronics weight is estimated based on DOE technical targets



(a) (b) (c)

Fig. 4-15. Motor plus inverter losses for the *uCar*: (a) original efficiency map, (b) power losses polynomial fitting and (c) approximated efficiency map [74].

5 SUMMARY, CONTRIBUTION, LIMITATIONS AND FUTURE RESEARCH AREAS

This dissertation presents a collection of manuscripts that explore practical methods in Li-ion batteries for four different purposes. Accordingly, this chapter is divided in four sections, one for each topic: Section 5.1 (Simplified Modeling); Section 5.2. (Battery Electric Vehicle Design); Section 5.3 (Battery Management System Testing); and Section 5.4 (Balancing System Control). Within each section, the corresponding manuscripts are summarized and discussed their contributions, methodological limitations and potential for future research.

5.1 SIMPLIFIED MODELING

The topic of simplified modeling of electrical performance of LIBs is addressed in two of the manuscripts appended to this dissertation, i.e. Manuscript I [27], entitled "Datasheet-based modeling of Li-Ion batteries," and Manuscript II [28], entitled "An improved parameterization method for Li-ion linear static equivalent circuit battery models based on direct current resistance measurement."

5.1.1 SUMMARY

MANUSCRIPT I

Manuscript I [27] presents three easy-to-follow methodologies to implement EECM based solely on information contained in manufacturer's datasheet. Runtime-based non-linear static EECMs are presented. The diagrams of the three EECM used are summarized in Table 5-1. Note that, depending on the specific EECM, temperature dependency of the OCV and current and SoC dependency of the series resistances are considered or not. Furthermore, both Peukert[21] and temperature effects on the battery capacity are considered for the *Extended Thevenin model 1*, and only Peukert effects for the *Extended Thevenin battery model 2*.

The methodologies to implement all the EECMs summarized in Table 5-1 are validated at steady state, comparing simulation results and typical curves from a commercial datasheet.

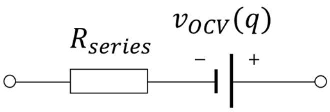
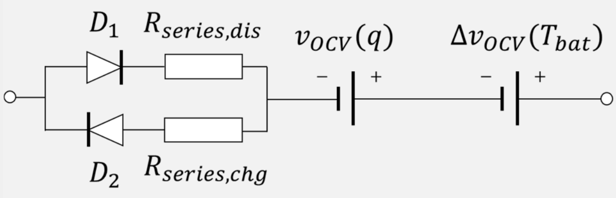
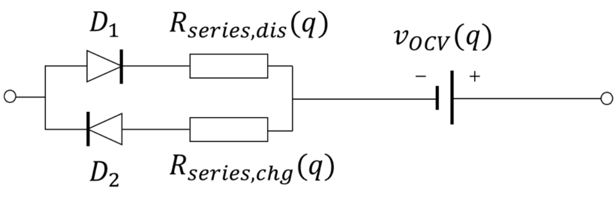
[21] *Peukert effects* stands for battery capacity dependency on current level [97], [98].

Moreover, for the *Extended Thevenin battery model 2*, datasheet-like profiles are obtained experimentally and used for further validation. In this case, the OCV vs SoC characteristic and the charging and discharging series resistances estimated from those datasheet-like profiles are compared with parameters obtained from pulsed tests.

MANUSCRIPT II

Manuscript II [28] presents an improved parameterization method for a linear static EECM based on the concept of DCR. The rationale for using a DCR-based parameterization is to exclude the influence of both diffusion polarization effects and changing of OCV from the estimation of the battery's series resistance. Thus, the DCR-based parameterization aims to account only for pure ohmic and charge transfer effects. This can be advantageous if simple electrical performance models are required for applications where these effects dominate the dynamic power response of the battery, as in the case of e-mobility.

Table 5-1. OVERVIEW OF THE EECMs PRESENTED IN MANUSCRIPT I[22]

Type of EECM	Types of EECMs
Thevenin battery model	
Extended Thevenin battery model 1	
Extended Thevenin battery model 2	

[22] The diodes D1 and D2 are ideal and have only symbolic meaning.

Model validation and performance evaluation are based on simulations over a dynamic discharge driving profile. A quantitative comparison of the results obtained using a linear static EECM parameterized in four different ways is presented. A high-level representation of three of these parameterization approaches, including the DCR-based one, is given on Fig. 5-1.

In contrast, the fourth approach is represented at high-level in Fig. 5-2. This consists in an optimal parameterization solved as a linear least squares problem. The optimum series resistance is obtained considering the change of voltage caused by the series resistance over a dynamic discharging current profile. The current profile has been calculated previously by means of simulations. Firstly, a standard driving cycle is applied to a BEV model in order to obtain the power demand of the battery pack. Then, the power demand is scaled to a single cell and applied to a non-linear dynamic first-order EECM. In addition, the latter non-linear EECM is used as a reference to evaluate the performance of the linear static EECM parameterized in four different ways.

The results are analyzed quantitatively, from the point of view of cell voltage mean squared error, max. voltage error and total cell power losses. It is shown that significant improvements in terms of terminal voltage and power losses estimation can be achieved by a DCR-based parameterization.

5.1.2 CONTRIBUTION

MANUSCRIPT I

Although LIB electrical performance models based on EECMs have been widely proposed in the literature during the last decade [11], [12], [20], [23] – [27], [52], [61] – [64], very little work [91], [99] has focused on methodologies to implement EECMs based on manufacturer's datasheets before the publication of Manuscript I [27].

In [91] a non-linear dynamic first-order EECM that accounts for Peukert and temperature effects is presented. However, regarding the dynamic behavior, while in the abstract it is claimed that the implementation of the model “is based on publicly available data such as the manufacturer’s datasheets,” it is clarified later on that the values of the components of the RC element “are found by fitting to measured data of battery transients”.

Notwithsating this, a useful methodology is presented in [91] to calculate from datasheet’s discharge profiles a number of factors to account for temperature effects on the OCV and Peukert and temperature effects on the battery capacity. A similar methodology is followed in Manuscript I [27] to implement the *Extended Thevenin battery model 1* (Table 5-1).

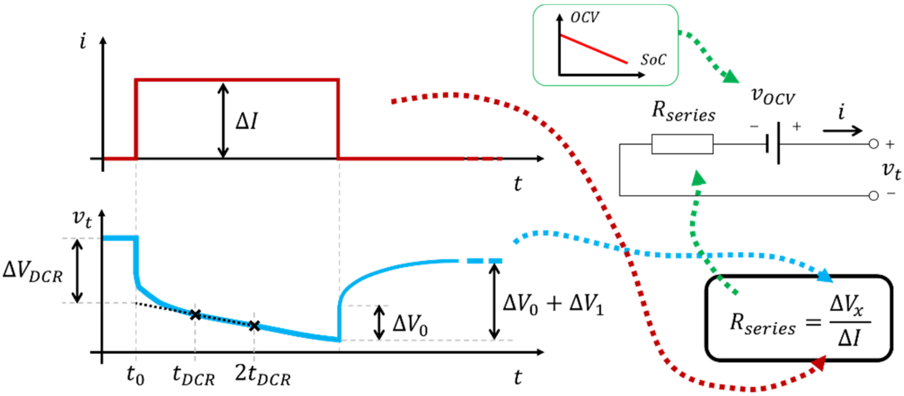


Fig. 5-1. Three approaches to estimate the series resistance from pulse tests.

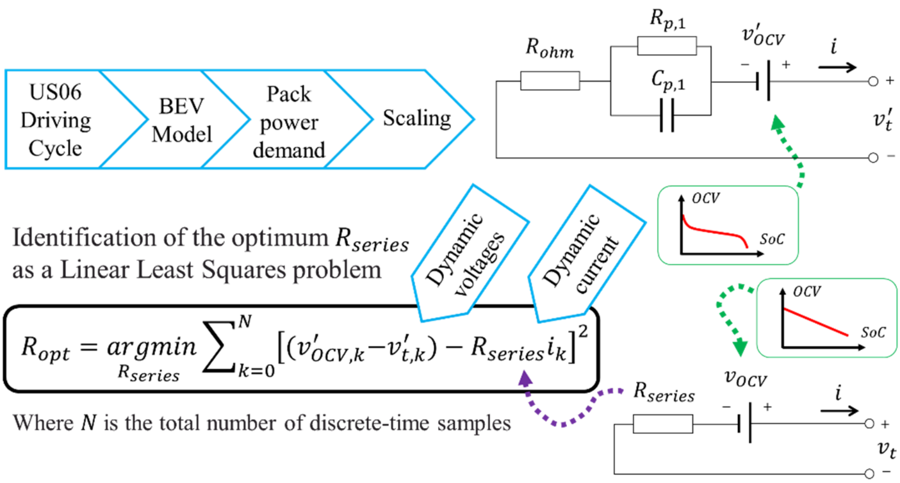


Fig. 5-2. Estimation of the optimum resistance from dynamic discharge data.

Apart from the absence of the RC element, the main difference between the model presented in [91] and the *Extended Thevenin battery model 1* presented in Manuscript I [27], it is that the latter takes into account different constant series resistance during charge and discharge.

Furthermore, in [91] the OCV vs. SoC characteristic is estimated by subtracting the voltage drop due to a constant series resistance from a steady-state Voltage vs. SoC discharge curve. This is the same approach followed in Manuscript I [27] to implement the *Thevenin battery model* and the *Extended Thevenin battery model 1* (Table 5-1). Therefore, it should be noted that [91] proposes an approach less advanced than the one followed in Manuscript I [27] for the *Extended Thevenin battery model 2*.

On the other hand, in [99] a non-linear static EECM is implemented assuming the next modified Shepherd model to represent the OCV vs. SoC characteristic:

(6) $$v_{OCV} = v_0 - v_{pol} \frac{Q_{bat}}{Q_{bat} - Q_{avl}} + Ae^{-BQ_{avl}}$$

where v_0 [V] is the so called battery constant voltage, v_{pol} [V] is the so called battery polarization voltage, Q_{bat} [Ah] is the actual cell or battery capacity, Q_{avl} [Ah] is the remaining available cell or battery capacity calculated by means of coulomb counting and A [V] and B [Ah]$^{-1}$ are non-linear fitting constants estimated from datasheet's curves.

This modified Shepherd model is applied to different types of cell and batteries, including a Li-ion cell. However, in contrast with the methods presented in Manuscript I [27], the model does not consider Peukert effects, temperature effects or a variable series resistance. With regard to the latter, a constant value is proposed for the series resistance that can be found iteratively, by comparing the discharge voltage curves from the model and the datasheet, or by estimating directly using:

(7) $$R_{series} = \frac{V_{nom}}{I_{nom}} \cdot (1 - \eta/100)$$

where V_{nom} [V] is the battery nominal voltage, I_{nom} [A] is the battery nominal current and η [%] is the battery discharge efficiency obtained experimentally.

MANUSCRIPT II

Manuscript II [28] provides quantitative evidence that a DCR-based linear static EECM may achieve "significant improvements in terms of cell terminal voltage and power losses estimation" in comparison with other linear static EECM parameterized by means of "conventional pulse characterization methods, which tend to overestimate or underestimate the battery dynamic power response." This agrees with the qualitative expectations defined in advance.

It is also pointed out in [28] that the DCR parameterization "in its simplest form, can only consist on one short pulse characterization test within a relatively wide range of SoCs and currents," which opens the door to real-time implementation.

Furthermore, a DCR parameterization "may not present the limitations, complexity or infeasibility problems of a statistical regression analysis" used to obtain an optimal parameterization [28]. In comparison with optimal parameterization techniques based on statistical regression analysis, DCR parameterization:

- Does not require a simulation with a complex battery model or a real battery dynamic test in order to obtain the dynamic voltage profile

- Does not need upfront data from the battery current demand

The latter feature makes DCR-parameterization promising in the context of energy optimization problems at a system level. This research approaches broadly implement linear static aggregated pack EECM, and consider the battery power allocation as an output [28].

5.1.3 LIMITATIONS

MANUSCRIPT I

In general, it should be noted that the performance of the models is limited by the accuracy and veracity of the results provided in the manufacturer's datasheet. Moreover, all the models proposed are static, since the information required to parameterize dynamic models is not found in typical datasheets.

The latter means that the accuracy of the simulation under dynamic performance has not been validated. It may be expected an overestimation of the cell's overpotentials, due to the combined influence of pure ohmic, charge transfer and diffusion polarization effects in the parameterization of the series resistance. In this respect, the findings of Manuscript II [28] shed light on the effects of different parameterization approaches on the accuracy of static EECMs.

It should be also noted that the models are validated only for a particular Li-ion cell. It may be assumed that a similar performance is expected for cells of different sizes, formats or electrode families, some issues may arise with certain technologies, e.g. hysteresis effects with LFP cathode's cells.

The following assumptions and limitations apply for each of the models:

Thevenin battery model

- The series resistance and the actual cell's capacity are assumed constant, i.e. with no dependencies, and are estimated from 1C discharge profiles at room temperature

Hence, the accuracy of this model tends to be lower at extreme temperatures, C-rates or SoCs. The errors may be more or less relevant depending on the particular performance at extreme conditions of the modeled cell.

- The OCV vs SoC curve deduced from the 1C discharge profile is assumed to be the same during charging, i.e. no Peukert or temperature effects are considered

This means that the behavior of the model during charge may be less accurate. The errors may be more relevant for cells that show hysteresis effects and significant differences between charging and discharging resistances.

Extended Thevenin battery model 1

- The charging and discharging series resistances are assumed constant
- Peukert effects, SoC and temperature dependencies are factored into the calculation of the OCV

Therefore, the accuracy of the simulated cell's voltage is lower at extreme C-rates and SoCs. On the other hand, from the perspective of the simulated cell's capacity, the accuracy of the model is satisfactory at extreme temperatures or C-rates. Moreover, the performance of the model during charge is more accurate than for the previous *Thevenin battery model*.

Extended Thevenin battery model 2

- SoC dependencies are considered in the calculation of the charging and discharging series resistances
- Peukert effects and SoC dependencies are considered in the calculation of the OCV, but no temperature dependencies

Hence, the accuracy of this model at extreme C-rates and SoCs is the highest of all the models analyzed, during both charge and discharge. Although, the performance at extreme temperatures is less accurate than for the *Extended battery model 1*.

Finally, the lower accuracy of the *Extended Thevenin battery model 2* during charging at high C-rates can be attributed to the combined effects of: misleading information from the datasheet and the neglect of the C-rate effects on the charging series resistance. While nothing can be done about the datasheet, the C-rate dependencies can be implemented in a future model.

MANUSCRIPT II

- The DCR parameterization is validated only for a single Li-ion cell
- A limited range of temperatures and C-rates are considered on experimental studies at cell's BOL
- The parameterization problem is only studied from a macroscopic empirical perspective, on the basis of early theoretical insights
- Simulation-based validation is used, since a calorimeter would be required to measure the power losses under an experimental validation
- The dynamic EECM used for validation only considers first-order dynamics and a one parameterization approach

5.1.4 FUTURE RESEARCH AREAS

MANUSCRIPT I

Since the publication of Manuscript I [27], the implementation of a non-linear static EECM based on steady-state characteristics provided by a commercial datasheet has been an issue tackled in a number of publications, which either made use of some sort of EECM parameterized based on datasheets [100]–[102] or developed further the methods outlined in Manuscript I [27], [103]–[105].

Regarding the latter, in three interrelated publications [103]-[105] the authors developed publications an automated framework to generate EECMs based on datasheets. In general, the methodologies are similar to the ones presented in Manuscript I [27]. The key difference is that those preliminary models are extended in order to account for:

- So called "inter-cycle" effects, i.e. aging effects that are modeled in a simplified way based on information that may be included in the datasheet (Fig. 5-3)
- Second-order dynamics in the EECM, considering a simplified parameterization approach using information from pulse tests (which to the best of my knowledge is rarely provided by datasheets)

On the other hand, in [74] and [110], a linear static EECM is parameterized by means of the least squares method, which is used to fit the model with a set of datasheet-like CC discharge curves over a limited SoC window.

Hence, besides the topics that have already been addressed in [74], [103]-[105] and [110], future research in this field could focus on:

- State-of-the-art review of the existing methods for datasheet-based modeling
- Validation of existing methods in respect of commercial Li-ion cells of different sizes, formats or electrode materials
- Comprehensive evaluation of the performance of existing models under dynamic operating conditions and different aging states, followed by the development of new improved methods
- Consider non-linear regression least square methods to fit a non-linear EECM
- Propose a framework for standardizing the information provided by manufacturer's datasheets

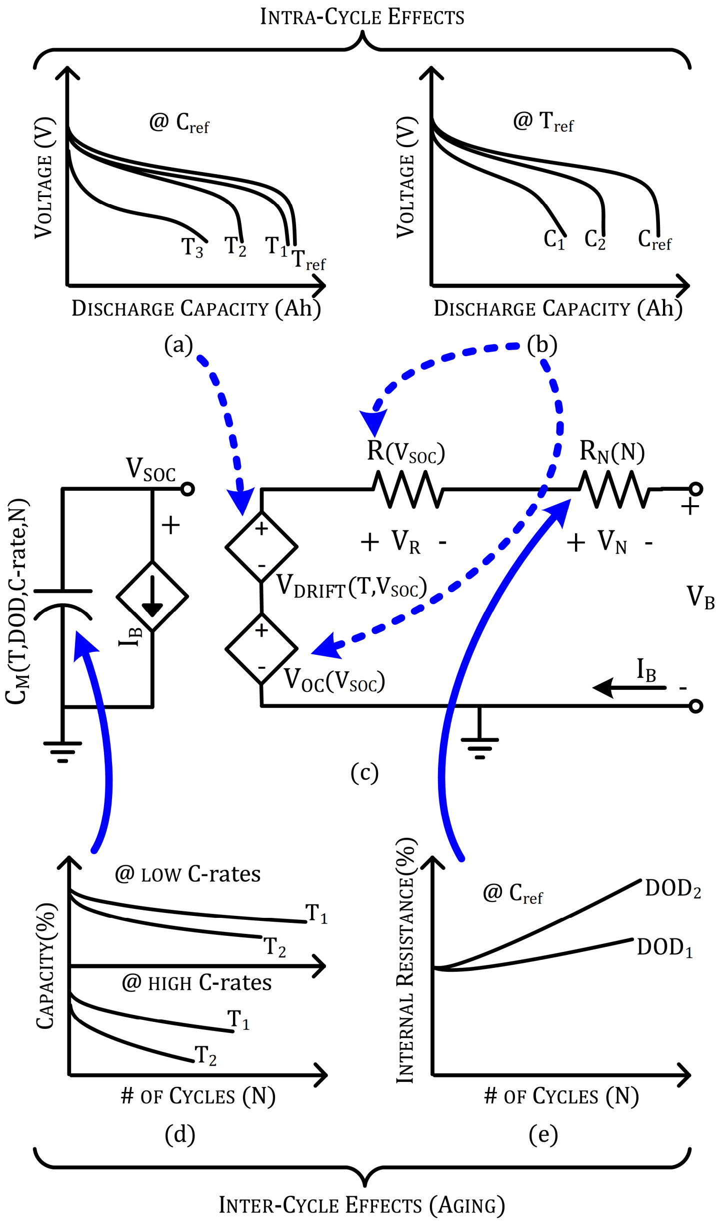


Fig. 5-3. Summary of the strategy for datasheet-based modeling used in [105], where:

(a) and (b) are the datasheet-like profiles used for modeling the intra-cycle effects
(c) is the diagram of the most complex non-linear EECM proposed
(d) and (e) are the datasheet-like profiles used for modeling the inter-cycle effects

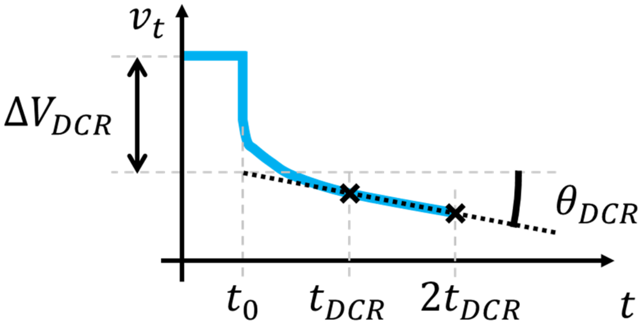


Fig. 5-4. DCR voltage and DCR angle estimated from a pulse test.

MANUSCRIPT II

- Study the linearization of the overpotentials not only as a macroscopic empirical problem, but from a theoretical electrochemical perspective, e.g. in relation with the electrochemical kinetics described by means of the Butler-Volmer equation
- Extend the empirical study to consider not only the DCR voltage, ΔV_{DCR} , but also the DCR angle, θ_{DCR} (Fig. 5-4)
- Study the impact of aging, higher currents and more extreme temperatures
- Consider Li-ion cells of different sizes, formats or electrode materials
- Further investigation of the impact of the DCR time on the parameterization, defining criteria and methods to estimate the optimum time
- Study the correlation of EIS data with DCR data, in order to gain more electrochemical insight
- Study possible applications of DCR parameterization within datasheet-based modeling
- Conduct tests on multiple cells to achieve statistical significance
- Consider for validation a EECM with higher-order dynamics and different parameterization approaches and/or a calorimeter

5.2 BATTERY ELECTRIC VEHICLE DESIGN

This topic is covered in Manuscript III [8] appended to this dissertation and entitled “Evaluation of a novel BEV concept based on fixed and swappable LIB packs”.

5.2.1 SUMMARY

MANUSCRIPT III

In Manuscript III [8], a BEV design is proposed, based on the combination of two LIB packs. One is swappable and three times larger than the other one, which is fixed. The total combined capacity of the packs is 85 kWh, i.e. equal to a Tesla Model S 85. The goal is to evaluate if this proposal makes it possible to achieve a BEV with a similar range, but a lower purchase price and a lower energy consumption than the Tesla.

In such a BEV, for short ranges or city driving, the vehicle could be powered only by the smaller fixed pack, without the larger swappable pack. Hence, the mass of the BEV would be less and therefore the energy consumed per unit distance decreased. On the other hand, for highway driving, the BEV could be powered by both packs simultaneously, to achieve longer ranges.

Regarding the reduction of the costs, the proposed BEV may facilitate the introduction of new ownership models to distribute the cost of the swappable pack over its lifetime. Although a large investment in swapping-stations may be required.

The methodology proposed for the evaluation of the proposed concept is summarized in Fig. 5-5. In short, the evaluation process involves the following seven stages:

1- Development of a model of the proposed BEV considering the motor, AC/DC inverter, DC/DC converters, transmission, wheels, battery and vehicle's body
2- Parameterization based on the *AAUDI* platform and certain design assumptions
3- Evaluation of the energy consumption by simulation of EPA testing procedures
4- Preliminary estimation of the impact of the proposed concept on battery lifetime
5- Estimation of selling price based on public data from other BEVs in the market
6- Preliminary swap-cost estimation based on Tesla predictions
7- Calculation and analysis of the results for the Total Cost of Ownership (TCO)

Table 5-2 summarizes the results and compare them with the specifications of a Tesla Model S 85. It appears likely that this BEV design can achieve higher city fuel economy (up to 14%) while keeping the long range capability, with economic benefits under several scenarios thanks to a 36–58 % reduction on the purchase price.

5.2.2 CONTRIBUTION

MANUSCRIPT III

Modular pack designs and single swappable packs for BEV applications have already been proposed independently [106]. However, to the best of my knowledge, Manuscript III [8], which is a reviewed and extended version of [7][23], is the first scientific publication proposing the combination of both concepts in the same BEV.

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[23] The paper received the only award in the "Best Paper on Ecological Vehicles" category in the 2015 International Conference on Ecological Vehicles and Renewable Energies [107].

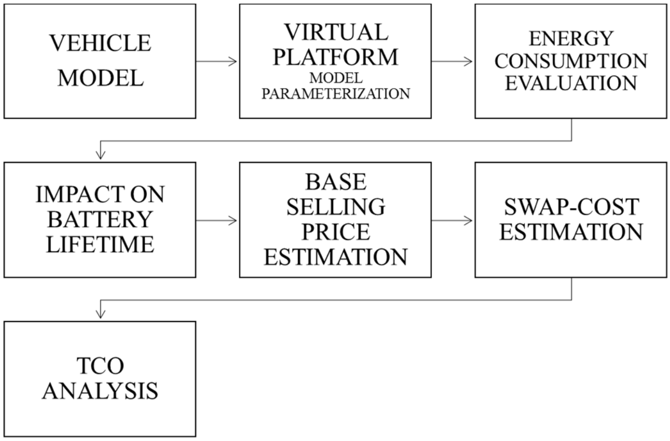
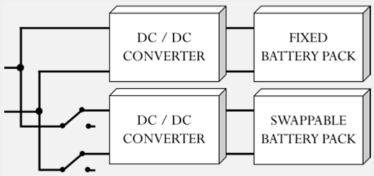


Fig. 5-5. Evaluation process for the novel BEV concept.

Table 5-2. SPECS OF TESLA MODEL S 85 VS. NOVEL BEV CONCEPT

Vehicle model	**Tesla Models S 85**	**Virtual platform based on *AAUDI* BEV**
Active/passive connection of the battery pack to the DC-link		
Pack size [kWh]	85	21.3 (fixed) / 63.7 (swappable)
Specific energy [Wh/kg]	142	107
Curb weight [kg]	2018	1581 / 2170
Motor nominal power [kW]	270	216
Vehicle power ratio [W/kg]	128	137 / 100
Fuel economy[24] [kWh/100mi]	38/ 38 / 37	34 / 32 / 37
Initial purchase price	US$ 79.900	US$ 34.305 – 51.305

[24] Combined / City / Highway.

Despite of the difficulty to assess such a novel BEV concept, a solid methodology is presented, based on certain assumptions, which appear to be reasonable. As a result, promising results are demonstrated from both technical and economical perspectives. These advantages, combined with the potential synergies with other green technologies and innovative business concepts, encourage further research in this field.

5.2.3 LIMITATIONS

MANUSCRIPT III

- A single type of commercial Li-ion cell is considered in series-only arrangements
- The non-linear dynamic EECM proposed only considers first-order dynamics
- Battery packs temperature is considered constant and equal to room temperature, i.e. no thermal model is implemented
- The proposed battery degradation models only consider a limited number of stress factors and are based on the literature
- Only one parallel active power system configuration is studied (Fig. 3-4)
- The swappable pack consist of three packs equal to the fixed pack, each one connected to the DC-link through it is own DC/DC converter. The reason to select this configuration is to simplify the modeling, since a simple power split strategy between each identical string can be considered, instead of implementing a more complex energy management strategy
- All the DC/DC converters are considered permanently on-board, although other configurations are possible
- Approximated models for the DC/DC converter and motor plus inverter losses are implemented (Fig. 4-15)
- The BEV model is parameterized based on real data from the *AAUDI* and a number of assumptions based on the scientific literature and public available sources, including the DOE technical targets[25] and USABC goals[26]
- The swapping cost ratios are estimated from Tesla public predictions only for illustrative purposes. For practical reasons, the general approach is not to estimate these ratios, but to consider them as outputs of the techno-economic analysis, in order to get insight about their target cost-windows
- In the economic analysis no tax credits, purchase incentives, financial resources, residual value, insurance rates and maintenance costs, battery degradation and replacement are considered
- Annual electricity prices come from official public forecasts

[25] ”Official website of the EV everywhere grand challenge: DOE’s 10-year vision for plug-in electric vehicles.” https://goo.gl/l1ZhT7, Accessed: 2017-02-20.

[26] ”Official website of the U.S. Advanced Battery Consortium (USABC)”, https://goo.gl/nZUH9z, Accessed: 2017-02-20.

- The base selling price of the proposed BEV before incentives is estimated based on statistical regression from public available data of BEVs in the market

5.2.4 FUTURE RESEARCH AREAS

MANUSCRIPT III

- Evaluation of multiple parallel active power system configurations to connect fixed and swappable packs to the powertrain
- Evaluation of the cost and availability of swapping, taking into account factors like the "number of subscribers or users, vehicle driving patterns, battery wear factors, battery manufacturing costs, number of battery swap-spots (i.e. battery swapping stations), battery swap-spot utilization rate, maximum time between swaps, time for swapping, number of chargers per swap-spot, operational and installation costs of the swap-spot, financing costs, return of equity, cost of debt, taxes, incentives, etc." [8]
- Study on-board and off-board solutions for battery charging
- Study the problem of sizing the battery based on different criteria and considering the Energy Management System (EMS) strategy
- Study EMS strategies, considering different operating modes, for instance "an operating mode designed to minimize the aging of the fixed pack or an operating mode designed to charge the fixed pack from the swappable pack in-motion" [8]
- Support "the development of standards in relation to the electrical, mechanical and communication interfaces of the swappable battery pack"
- Mobility studies to gain more understanding about the costumer's perspective
- Investigate synergies with "clean technologies and innovative business ideas, e.g. battery sharing, Vehicle-to-Grid or second life battery applications" [8]
- Investigate more thoroughly the impact of the proposed concept on the battery lifetime and utilization rates, considering different configurations and batteries
- Investigate the impact of the combination of batteries with different temperatures, SoH, SoC or power capabilities on the vehicle performance, considering different configurations and types of batteries
- A more complex techno-economic analysis, accounting for "incentives, taxes, form of payment, financial resources, driving patterns, cost and availability of swapping spots, energy costs, battery degradation and battery replacement cost and criteria, residual cost of the vehicle and battery at EOL, etc." [8]
- Propose a framework for standardizing the mechanic, electric and electronic interfaces between the swappable pack and the vehicle

5.3 BATTERY MANAGEMENT SYSTEM TESTING

This topic is covered in two of the manuscripts appended to this dissertation, i.e. Manuscript IV [42], entitled "An advanced HIL Simulation Battery Model for BMS

Testing," and Manuscript V [43], entitled "Development of Software and Strategies for BMS Testing on HIL Simulator."

5.3.1 SUMMARY

MANUSCRIPT IV

In Manuscript IV [42], a LIB model suitable for purposes of real-time testing of BMS units on a commercial HILS is developed (Fig. 5-6). The methodology proposed consisted of the following four stages:

1- Critical review of the state-of-the-art
2- Development of HILS battery model
3- LIB electro-thermal model validation in simulations
4- BMS testing on HILS

In order to get a critical understanding of the state-of-the-art, more than 30 manuscripts from the literature have been reviewed. The key findings from this critical review of the literature are summarized in Table 5-3.

Regarding the HILS battery model, a multi-cell non-linear dynamic 10th order EECM model is coupled with a 3-D TECM and an aging model (Fig. 5-7). The EECM, TECM and aging model are parameterized based on extensive experimental tests.

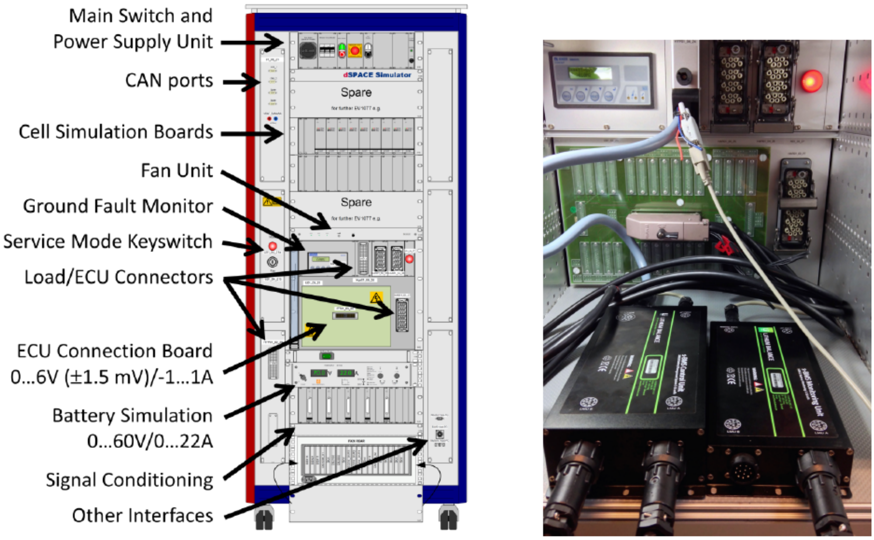


Fig. 5-6. HILS test bench: dSPACE setup (left) and commercial BMS unit under test from Lithium Balance A/S (right) [42].

It should be noted that the aim of including the aging model is only to enable the generation of realistic cell-to-cell parameter variations to reproduce different scenarios. The parameters are defined for each cell by means of a set of look-up tables that take as input values the on-line cell's temperature, on-line cell's SoC and off-line cell's aging factor[27].

For purposes of HILS implementation, the aforementioned electro-thermal model coupled with the aging model is integrated with other components in a system-level model (Fig. 5-7). The system-level model includes other elements of the LIB system, e.g. temperature and current sensors, DC-link capacitor, switch box, charger or load. Apart from that, a number of simulation controllers, data processing blocks and real-time interfaces with the Host PC and the HILS are included.

The system-level model is implemented off-line on MATLAB/Simulink. Then, with the support of dSPACE SW, C code that is suitable for compilation and on-line execution on the HILS dSPACE platform is generated automatically. Finally, making use of a Graphic User Interface (GUI) created ad hoc, exemplary real-time BMS tests are conducted in order to show the capabilities of the setup. The BMS under test is a sBMS v6 unit provided by Lithium Balance A/S (Fig. 5-6).

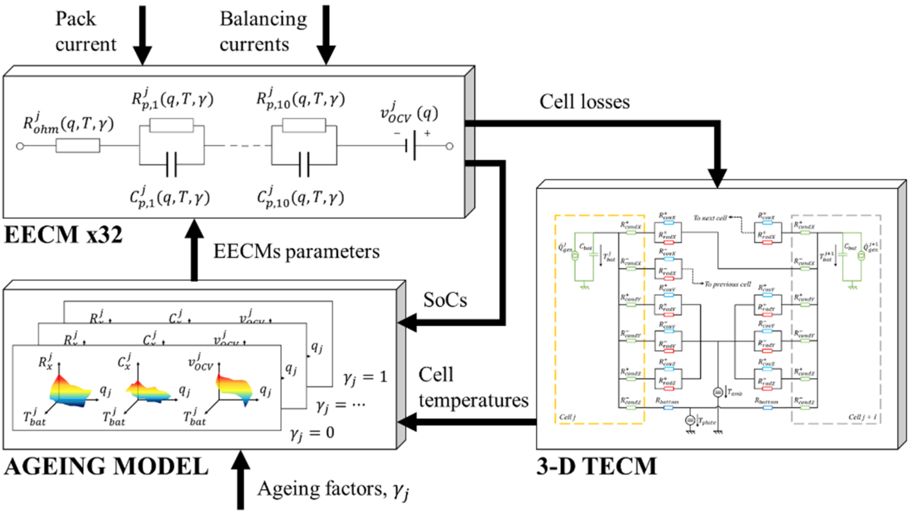


Fig. 5-6. LIB pack electro-thermal model coupled with aging model.

[27] Strictly speaking, it is possible to vary on-line the aging factors too, but taking into account the time ranges of the typical BMS testing scenarios and the aging effects [21, this approach would not appear to be of much value.

Table 5-3. STATE-OF-THE-ART OF BMS TESTING ON HILS.

Evaluated aspect	**Typical approach**	**Manuscript IV [42]**
Electrical model level	Pack-based	Multi-cell
Electrical model approach	Isolated low order EECM with simple or no dependencies	High order EECM with multiple dependencies, coupled with thermal and aging model
Balancing features	No	Yes (passive or active)
Thermal model	No	Yes (3-D TECM)
Aging model	No	Yes (to create cell-to-cell differences)
Other models	No	Yes (sensors, switch box…)
Parameterization	Lack of experimental data	Extensive experimental data
HW platform	Self-made	Commercial (dSPACE)
BMS testing capabilities	Partial	Full

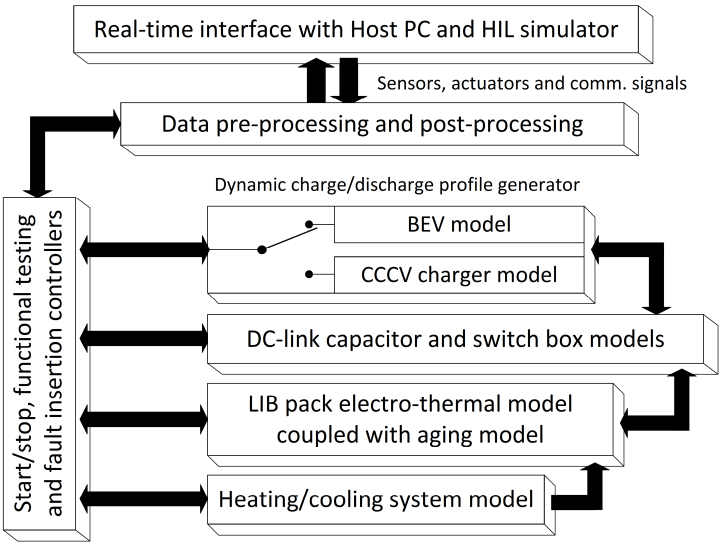


Fig. 5-7. Overview of the HILS battery model for BMS testing [42].

MANUSCRIPT V

Manuscript V [43] is, in fact, an extension of IV [42], which aims to "introduce the principles of BMS testing and to present a practical approach to develop SW and strategies for BMS testing on a HIL battery simulator at system level" [43].

Different perspectives on the art of SW, embedded SW and HW testing are discussed, with focus on the BMS unit. Definitions, examples and a comprehensive classification of BMS testing strategies are provided. The criteria to classify the BMS tests is shown in Table 5-4.

In general, it is concluded that pragmatic approaches for BMS testing may be preferred over pure theoretical ones, like exhaustive input testing, since they may request a huge amount of resources. Taking this into account, a universal and practical strategy to define the BMS functional and non-functional requirements and to design the BMS test cases is presented.

An overview of the test cases proposed to evaluate an advanced BMS for its functional and non-functional requirements is provided in Table 5-5. Apart from that, a number of fault insertion tests are defined too. Extensive experimental results are shown for most of these test cases.

Table 5-4. GENERAL CLASSIFICATION OF BMS TESTS [43]

Criteria	Types
Device under test	SW, embedded SW or HW
Development stage	Design, development, prototype, pre-release or release
Device state	Static (OFF) or dynamic (ON)
Box approach	Black-, white- or grey-box
Testing process	Functional or non-functional
Level	Unit or module (group of units), integration or system
Environment	(Near to) real, simulated or emulated (HIL or Power HIL)

Table 5-5. TEST CASES PROPOSED TO EVALUATE A BMS [43]

No.	Test Case	Description	End-of-test criteria
1	Idle or Stand-by	System settings are managed. The fault criteria are set in the BMS. Then next functions are checked in steady-state: data management, monitoring, detection of hazards or response to hazards	All functions tested in steady-state
2	Current, voltage, temperature	All sensors are calibrated, if possible. Then full-range accuracy test keeping the BMS at different conditions, e.g. in a temperature chamber	All conditions tested
3	Dynamic discharge	Using a real dynamic discharge profile from an EV, the pack is fully discharged at room temperature	BMS stops the discharge to avoid over-discharge
4	Overvoltage during regenerative braking	Using a real dynamic discharge profile from an EV, the pack is fully discharged when a very high regenerative current is experienced	The BMS interrupts the regenerative charging current
5	Overtemperature during discharge	Using a real dynamic discharge profile from an EV, the pack is discharged at high temperatures	Pack reaches max. temp. and BMS stops the discharge
6	Short circuit	Shorts at different places in the pack. Case1: internal or external short close to cell's tabs. Case 2: external short through fuses or shunt resistor. Case 3: External short through fuse and switch box (relays or fuses)	Short circuit current is zero
7	CCCV Charge	Conventional CCCV charge with active/passive balancing	End of charge
8	Charge test at low temperatures	Charge is enabled, but pack temperature is below limit for charging. Temperature increases progressively due to heating system.	Pack temperatures over threshold, charging starts
9	Diagnosis	Case 1. Emulated SoC vs BMS estimated SoC during real dynamic discharge profile from an EV. Case n. New cases according to the BMS diagnosis features	End of charge or discharge
10	Isolation Monitor	Single isolation fault on positive/negative terminal of a floating voltage pack	Isolation fault detected
11	Global power consumption	Case 1. Full discharge, considering a dynamic discharge profile from an EV, followed by CCCV charge. Case 2. Test on stand-by for a certain period of time	BMS power consumption is measured at all conditions

5.3.2 CONTRIBUTION

MANUSCRIPT IV

The HILS battery model presented in Manuscript IV [42], takes a qualitative step forward in the methods for real-time testing of BMS units. This statement is illustrated by Table 5-3 and supported by the discussion of the state-of-the-art given in [42].

In fact, the developed setup allows the testing of the BMS for a great majority of its functional requirements, as well as many of its non-functional requirements, e.g. fault tolerance or accuracy levels, an issue extensively discussed in Manuscript V [43].

This is due to the combination of a series of features that, to the best of my knowledge, have never been provided before by any setup in the literature. In short, the developed system provides an environment for real-time testing of BMS units that is able to:

- Simulate the electrical and thermal performance of each cell within a battery pack
- Generate realistic cell-to-cell differences in the parameters of the EECMs based on the definition of a so called aging factor, which is a new approach
- Include, in addition to the battery pack model, models of other components of the battery system like sensors, relays, DC-link capacitors, charger or load
- Interact in a closed-loop with the BMS unit under test through various channels, including sensors, actuators and communication interfaces
- Provide an isolated power interface to simulate each cell in series[28] and enable bi-directional exchange of real power between the HILS and the balancing system
- Simulate realistic application specific scenarios, with multiple configurations
- Enable fault insertion testing
- Control, monitor and log experiments in real-time

In order to prove the capability of the setup to provide all these features, a large number of examples of functional and non-functional tests is presented.

MANUSCRIPT V

More demanding battery applications, e.g. e-mobility, require more advanced BMS. In turn, more advanced BMS demand more complex testing at all stages of development. The greater the level of complexity of the tests, the higher the demands for ad hoc development of SW and strategies. Therefore, independent SW development processes for BMS's testing are requested, especially when HILS-based testing is planned.

[28] Or group of cells in parallel, in the case of a series-parallel connected pack.

In Manuscript V [43], for the first time in the scientific literature, a universal and pragmatic approach suitable for complete testing of an advanced BMS at system level is presented. The extensive experimental results demonstrate the immense possibilities of the ad hoc strategy and SW developed.

From a qualitative perspective, it can be inferred that a HILS “may offer, in comparison with tests on real-batteries, key advantages in terms of cost, testing times, flexibility, traceability, ease to reproduce or safety” [43].

5.3.3 LIMITATIONS

MANUSCRIPT IV

- The setup does not provide a high-voltage/high-current ouput in order to allow bi-directional power flow between powertrain components and the HILS, since it is not the goal to test powertrain components, but the BMS. In any case, if this is required, it may be possible to control from the HILS an external bi-directional supply in order to provide those features. Furthermore, instead of CAN-based simulation, a HILS controlled high-voltage/low-current supply could be used to provide a measurement point for the pack voltage sensor of the BMS
- The temperature distribution within the cells is assumed to be uniform, since the 3-D TECM is a lumped capacitance model. However, this asumption maybe not appropriate under extreme heating/cooling conditions, i.e. very low values of the thermal resistances between each cell and its surroundings
- The current dependencies are not considered in the parameterization of the R and C elements of the EECM. In other words, the model does not account for reaction kinetics, commonly expressed in the Butler-Volmer equation. Hence, the overpotentials at high currents may be overestimated. This also means that the suitability of the model to validate power capability estimation algoirthms may be limited. However, there is characterization data available that can be used to update the model in future iterations
- Parameterization for only one type of cell is presented, however there is data available for other chemistries, cell formats and manufacturers.
- Tests are only presented at system level for a commercial BMS. However, tests at earlier stages of the product development process can be required and could be conducted with a modified version of this setup

MANUSCRIPT V

In general, the same assumptions and limitations presented for Manuscript IV apply, since the same setup and base system model are used. Additionally, the following issues arise in Manuscript V:

- A universal and practical strategy it is followed to define the BMS functional and non-functional requirements and to design the BMS test cases. This means that, depending on user- or application-specific characteristics of the battery system, these requirements and test cases should be modified or extended
- Due to space limitations, experimental results for some of the proposed tests cases have not been presented, but will be included in a future version of the manuscript
- Although, key advantages of HILS vs. real-battery testing can be inferred from a qualitative perspective, quantitative metrics have not been defined to evaluate the pros and cons.

5.3.4 FUTURE RESEARCH AREAS

MANUSCRIPT IV

- Include current dependencies in the parameterization of the R and C elements, taking into account all the available experimental data for the Kokam 40 Ah cell
- Modify the 3D-TECM in order to account for internal cell temperature distribution under extreme heating/cooling conditions
- Parameterize the battery model for different types of cells and show experimental results from model validation and BMS testing
- Present tests at unit or module level, for BMS products under development
- All the issues that have already been tackled in Manuscript V, which is, as aforementioned, an extension of the work presented in IV

MANUSCRIPT V

In general, as commented in the limitations section above, the same future work directions presented for Manuscript IV apply. In addition, in particular for Manuscript V, next future work directions can be considered:

- Present experimental results for some of the test cases that, due to space limitations, could not be presented before
- Define a number of quantitative metrics and use them to evaluate the pros and cons of BMS testing on HILS vs. real-battery

5.4 BALANCING SYSTEM CONTROL

As already stated in this work, this research topic is covered in two of the appended manuscripts, i.e. Manuscript VI [36], entitled “Multi-Objective Control of Balancing Systems for Li-Ion Battery Packs: A Paradigm Shift?,” and Manuscript VII [37], entitled “Evaluation of Advanced Control for Li-ion Battery Balancing Systems using Convex Optimization.”

5.4.1 SUMMARY

MANUSCRIPT VI

In Manuscript VI [36], a multi-objective control approach for balancing systems is evaluated off-line by means of convex optimization. A ‘cell-to-cell shared’ energy transfer configuration (Fig. 2-13) is proposed for the balancing circuit, which is modeled based on current balance equations and assuming no losses.

Three control objectives are pursued simultaneously: SoC balancing, temperature equalization (based on minimization of internal cell losses) and maximization of usable capacity (based on terminal voltage equalization). It is also introduced the possibility of adding other control features to enable on-board diagnosis or fault detection tools.

With regard to the solving methods, as aforementioned, the problem is formulated as convex, in order to simplify the optimization. Practice teaches that, in this way, very large size problems (in terms of the number of variables and constraints) can be solved quickly, efficiently and reliably. While a detailed description of the problem formulation can be found in the original manuscript, a brief overview is given here. To begin with, the optimal convex problem formulation is summarized, from a high-level perspective, in Fig. 5-8.

In general, it should be noted that each of the three control objectives pursued is defined in the objective function (I) as a convex cost ($\mathrm{I}_{1,k}$, $\mathrm{I}_{2,k}$, $\mathrm{I}_{3,k}$) multiplied by a certain weight factor ($\omega_1, \omega_2, \omega_3$). The value of the first cost ($\mathrm{I}_{1,k}$) increases with the quadratic deviation of the cell SoC with respect to the pack mean. The value of the second cost ($\mathrm{I}_{2,k}$) increases linearly with the cell power losses, which depend on the quadratic value of the cell currents. Finally, the value of the third cost ($\mathrm{I}_{3,k}$) increases exponentially with the difference between the actual cell voltages and a predefined voltage threshold.

Regarding the inequalities ($g_{N_i,k} \leq 0$) and equalities ($h_{N_e,k} \leq 0$), they are used to describe the SoC, voltage and current constraints of the cells; the SoC calculation of each cell based on Coulomb counting; the terminal voltage of each cell according to the formulation of linear static EECMs; the current limits of the balancing circuit; and the relationships between cells, pack and balancing currents.

By means of this optimization tool, the multi-objective control concept is evaluated in simulations for one scenario: a group of three Kokam 53Ah LIB cells with large cell-to-cell differences, which are part of a 48S pack that is subjected to a dynamic discharge profile typical of an e-mobility application.

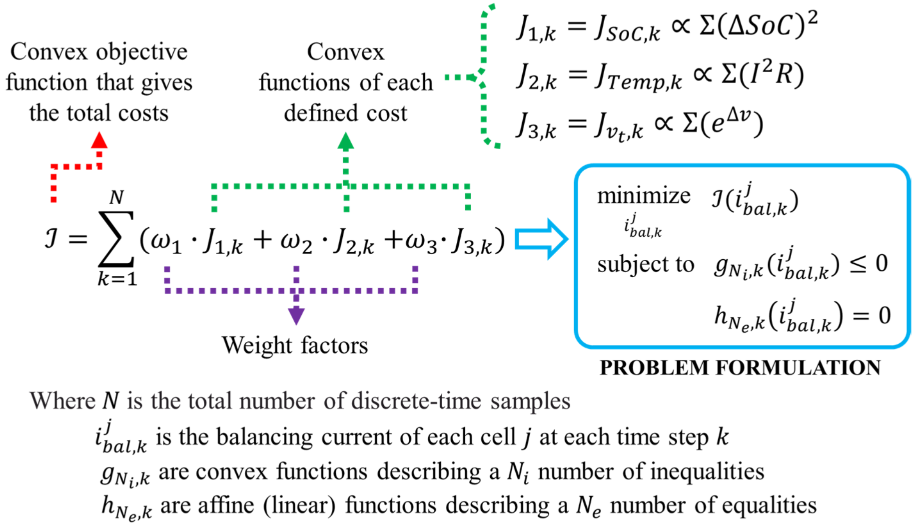


Fig. 5-8. High-level overview of the optimal convex problem formulation.

Experimental data is used to parameterize the base EECM and TECM of the cells and the BEV model used to generate the dynamic discharge profile. Differences in cell-to-cell resistances and capacities are created randomly from the base model.

Simulation results show that by means of a multi-objective control approach it may be possible to obtain advantages in terms of pack temperature distribution, SoC equalization or usable capacity. This may result in improved short-term performance and prolonged lifetime.

MANUSCRIPT VII

Manuscript VII [37] is inspired by the results and methods of Manuscript VI [36]. In this sense, advanced control strategies for balancing systems are also evaluated offline by means of convex optimization. However, substantial improvements are made to the parameterization of the models and the formulation of the optimal problem:

- Balancing circuit topology is taken into account by selecting a specific category of energy transfer (Fig. 2-13): bypass (CB), cell-to-heat (CH), cell-to-cell shared (CCS), cell-to-cell distributed (CCD), cell-to-pack (CP), pack-to-cell (PC) or cell-to-pack-to-cell (CPC)
- A different balancing circuit model and losses representation is considered, depending on the of the balancing circuit topology
- Five different scenarios are considered for the cell-to-cell parameter distribution, i.e. five different datasets are used to describe the capacity and internal resistance of the linear static EECMs of the cells: ‘BOL’, ‘End-of-Life (EOL)’, ‘mixed’,

‘accelerated aging’ and ‘cell replacement’. The datasets are built upon statistical-data from the literature and experimental tests conducted on 208 Kokam 53 Ah cells at BOL

- Performance under different dynamic power profiles is evaluated. The power profiles are estimated in simulations using a BEV model and different battery pack sizes and standard driving cycles

Taking this into account, more than a hundred study cases are evaluated, i.e. more than a hundred battery application scenarios. Hence, it can be stated that an extensive and comprehensive offline evaluation of the proposed ‘multi-objective’ control approaches has been conducted. An overview of the proposed offline assessment tool with the formulation of the control strategy is given in Fig. 5-9.

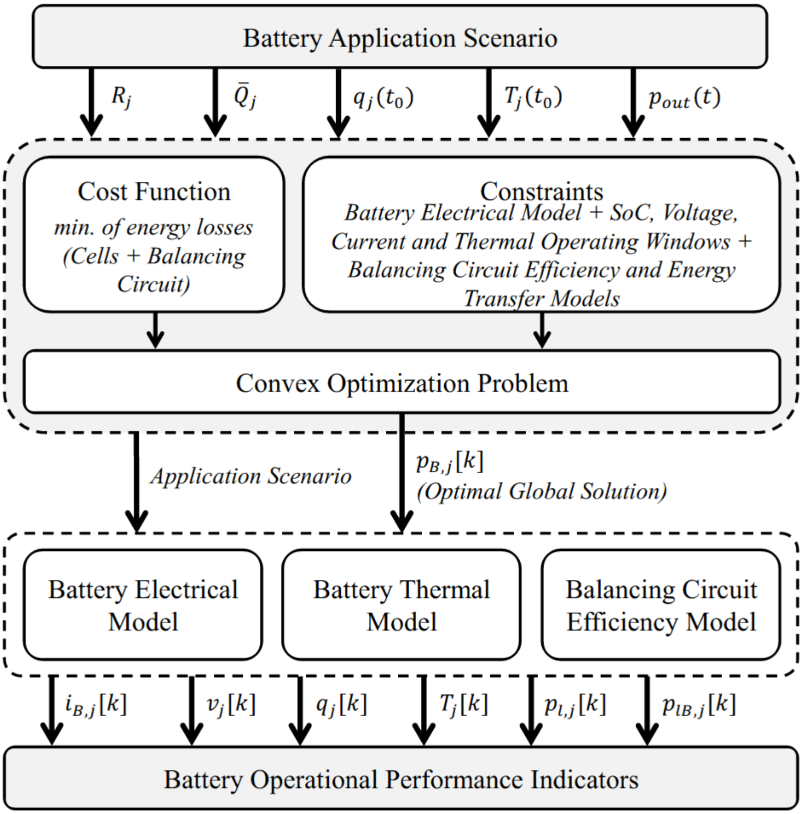


Fig. 5-9. Diagram of the offline assessment tool [37]
(with the formulation of the convex optimal control problem).

Where, following the original nomenclature of the manuscript [37]:

R_j	[Ω] is the static series resistance of cell j
$\bar{Q}_j$	[Ah] is the static capacity of cell j
q_j	[-] is the SoC of cell j
T_j	[K] is the temperature of cell j
p_{out}	[W] is the battery pack dynamic power profile
$p_{B,j}$	[W] is the power setpoint of the balancing circuit of cell j
$i_{B,j}$	[A] is the balancing current of cell j
v_j	[V] is the terminal voltage of cell j
$p_{l,j}$	[A] is the power losses of cell j
$p_{lB,j}$	[A] is the power losses of the balancing circuit of cell j

Therefore, as summarized in Fig. 5-9, each battery application scenario is defined by a dataset that list the values of the battery pack dynamic power profile and the series resistances, capacities, initial SoCs and initial temperatures of each cell of the battery pack. Then, for each application scenario the optimal problem, defined by a number constraints and the objective cost function, is solved in an iterative way (Fig. 5-11).

It is worth noting that the definition of the battery application scenario is not merely limited to the creation of the aforementioned datasets, but also involves changes in the formulation of the optimal problem. In fact, when a scenario is defined the SoC, voltage, current and temperature operating windows are set up, in the form of hard constraints, in order to limit the search space. In addition, the selected balancing circuit topology affects the balancing circuit efficiency models and energy transfer models that are taken into account, in the form of equality and inequality constraints,

With regard to the formulation of the objective cost function, in general, despite multiple control objectives are pursued (‘multi-objective’ control), mathematically a scalar function that accounts only for the total energy losses (cells + balancing circuits) is considered for evaluation purposes. Current, voltage, SoC and temperature windows are ensured via hard constraints. However, pure multi-objective formulation of the optimal problem is also presented, although no results were presented for this formulation.

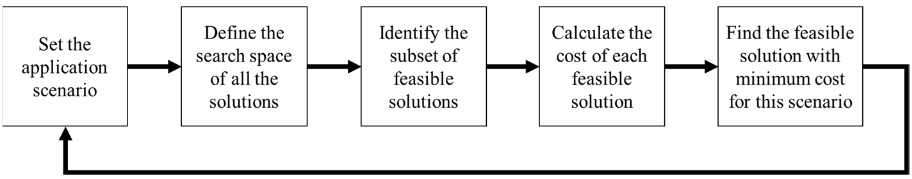


Fig. 5-10. Basis of the iterative solution of the offline optimal control problem.

The result of the optimal problem for each scenario is a dataset that lists the optimal power setpoints of the balancing circuit of each cell of the battery pack over a complete dynamic power profile. Using these setpoints and considering the predefined application scenario, a number of battery operational performance indicators are found in simulations, as shown in Fig. 5-9. The simulation model couples the balancing circuit models, the multi-cell linear static EECM of the battery pack and the 1-D TECM with links between neighbouring cells.

From the analysis of a broad spectrum of scenarios, it is concluded that the impact of these innovative control features can vary according to a number of factors related or not with the balancing system. This included, among other factors, the energy transfer configuration of the balancing system; the balancing system efficiency; the battery pack size; the battery aging scenario; the dynamics of the discharge profile; the cooling conditions; and the operating windows in terms of temperature, voltage or state-of-charge.

Ultimately, specific scenarios are identified, where significant gains can be achieved in terms of temperature distribution, power losses or available capacity. In general, better results in terms of power losses, available capacity and temperature are obtained for the CCS, CCD and CPC topologies (Fig. 5-12), even for moderate levels of balancing currents. In particular, remarkable improvements are observed under conditions of high power demand with high variability, i.e. smaller battery sizes and more demanding driving cycles.

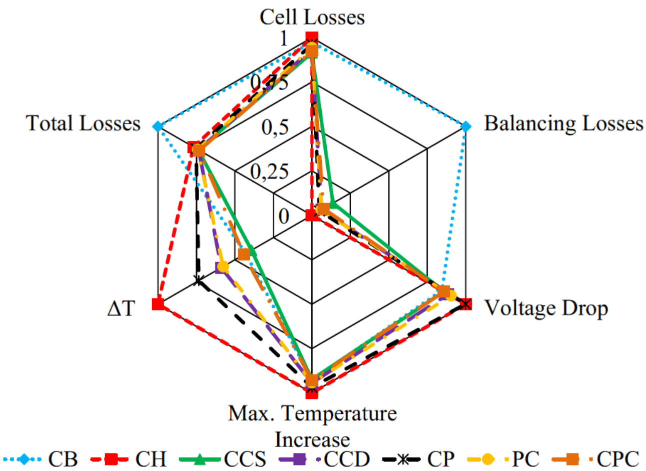


Fig. 5-11. General balancing circuit topologies comparison [37]
(results from an exemplary scenario that considers a ‘small’ pack and a ‘mixed’ cell-to-cell parameter distribution).

5.4.2 CONTRIBUTION

MANUSCRIPT VI

The concept of simultaneous SoC and thermal balancing of individual cells of a battery pack in an e-mobility application was proposed before in [108] and [109], as reviewed in [38]. However, it was applied to a cascaded multi-level converter used at the same time as integrated cell balancer and motor driver. As a novelty, this notion is proposed for the first time in a non-integrated approach in Manuscript VI [36].

In all these cases, a convex optimization problem is formulated in order to find off-line the optimal current setpoints, considering linear static EECMs for the cells and lossless models for the power electronics [36], [38], [108], [109]. Nevertheless, there are differences in the formulation of the optimal problem.

In the case of the work presented in [38], [108] and [109], the objective function to be minimized is defined as a cost that increases with the "temperature deviations among all cells", while the SoC equalization is just achieved by defining SoC constraints through inequalities. Hence, strictly speaking, a multi-objective approach is implemented for the first time in Manuscript IV [36], which evaluated simultaneously three weighted costs in the objective function.

Furthermore, in [38], [108] and [109], the cascaded multi-level converter is achieving a certain degree of control of the cell current(s) through bypassing or inverting the polarity of the cell(s)[29]. This means that the system relies on the battery pack dis/charge currents to dis/charge a certain cell and that the output voltage of the battery pack may be affected by the operation modes of the converter.

On the other hand, in Manuscript IV [36], a balancing system with a "cell-to-cell shared" energy transfer configuration is considered. Hence, it is possible to dis/charge a certain cell through the balancing circuit without having to rely on the dis/charge current of the battery pack and reducing the output voltage of the battery pack.

Finally, in a cascaded multi-level configuration there are always a number of switches in the battery pack current path, so the overall battery system losses are expected to be higher than in a 'cell-to-cell shared' configuration. However, these aspects are not evaluated in [36], [38], [108] and [109], since lossless models of the power electronics are considered.

[29] Although, in practice, it should be remarked that the operation modes considered in the problem formulation did not allow cells with different polarities at the same time [38], [108], [109].

MANUSCRIPT VII

The optimal control approach proposed is, to the best of my knowledge, unique in the literature in terms of flexibility, complexity and accuracy, and can be used as a powerful decision-making tool for battery system designers.

As is well known, passive balancing systems are nowadays the solution widely adopt by industry. Modest advantages provided by active systems with conventional SoC equalization control are not enough to bring a paradigm shift [36] – [38], [108], [109].

However, if innovative control features are considered, significant improvements in battery performance are observed under certain scenarios, which can be identified by the developed tool. The new insights provided help to establish the right directions for future research, towards a selective introduction of active balancing systems in the industry. Table 5-5 summarizes the potential impact of the control on some key battery system performance metrics depending on different aspects of the application scenario. Quantitative results shown in [37] support these qualitative views.

5.4.3 LIMITATIONS

MANUSCRIPT VI

- Only three cells of the 48S pack are simulated, due to the inherent complexity of the convex problem formulation
- Cell-to-cell differences are created randomly
- Power electronics of the balancing circuit model are not considered, a lossless model is implemented
- A 1D-TECM with links to neighboring cells is implemented
- In the formulation of the convex problem, EECMs that are static and consider only linear OCV dependencies with the SoC are considered. The more complex first-order non-linear dynamic EECM has only been used afterwards, taking into account the balancing current setpoints obtained from the simpler EECMs. Hence, the simulation results show only sub-optimal solutions, but for the most complex EECMs
- A single simulation scenario is evaluated, from the point of view of cell-to-cell differences, speed driving profile, battery pack size, balancing system energy configuration (cell-to-pack-to-cell with no losses) and weight factors
- The formulation of the 'cell-to-cell shared' energy transfer configuration in the optimal problem is based on a current balance equality constraint for simplification purposes, instead of a power balance. The impact of this assumption has been evaluated quantitatively and it seems to be negligible
- Although it is mentioned the possibility of implementing other control features to the balancing system to provide additional on-board diagnosis or fault detection

Table 5-6. IMPACT OF INNOVATIVE CONTROL FEATURES ON LIB PERFORMANCE.

System Performance Metrics vs. Application Scenario Factors		Max. useful capacity	Max. temperature difference	Max. temperature increase	Energy lost in balancing
Balancing circuit topology	CB	High	High	Low	High
	CP	Low	Low	Medium	Low
	PC	Medium	Medium	High	Low
	CCD	High	Medium	High	Low
	CCS, CPC	High	High	High	Low
Cell-to-cell parameter distribution	EOL	Low	Low	High	Medium
	Cell replacement	Low	High	Medium	Medium
	Mixed	Medium	Medium	Med	Low
	Accelerated aging	High	Low	Low	Low
	BOL	Low	Low	Low	Low
BEV battery pack size	Small (e.g. < 20 kWh)	High	High	High	-
	Large	Medium	Low	Low	-
BEV battery pack power demand	High (e.g. US06)	High	High	High	-
	Low (e.g. FTP-75)	High	Low	Low	-
Thermal window control	Narrow constraint	Low	High	High	Medium
	Wide constraint	Low	Low	Low	Low
Balancing circuit current level	Low (0.1 to 0.2C)	Low/Med	High	High	-
	High	High	High	High	-
Heating/cooling capacity	Low	-	High	High	
	High	-	Low	Low	-

- tools, this claim was neither discussed with enough thoroughness nor supported by experimental evidence
- The optimal control approach proposed is offline, oriented towards a preliminary evaluation of the concept, and not suitable for online implementation

MANUSCRIPT VII

- EECMs are static and consider only linear dependencies of OCV with SoC, due to limitations of the convex problem formulation. If non-linear dependencies of the OCV and the series resistances with SoC could be considered, larger cell-to-cell variations in battery performance would be observed with no control. Hence, higher potential improvements in battery performance would be expected with the proposed innovative control. On the other hand, with respect to the series resistance dependencies on temperature, certain self-equalization effect would be expected if they were considered, since the resistance decreases with the increase in temperature.
- A 1D-TECM with links between neighboring cells is implemented and only a single parameterization of the model is evaluated. Althoug, it is recognized that the design of the heating/cooling system is a critical factor that must be evaluated thoroughly
- The influence of the cell position within the battery pack is not studied, although it is not expected to be significant in most of the cases
- Pure 'multi-objective' control approach is only formulated, not evaluated quantitatively
- Parameterization and results for only one type of cell is presented
- Power electronics of the balancing circuits are simplified to a quadratic losses efficiency model and an energy transfer model
- Statistical-data of cell-to-cell differences is only available from experimental tests at BOL. In order to generate the rest of the datasets that describe the cell-to-cell parameter distribution, experimental data from similar cells given in the literature was used
- The optimal control approach proposed is offline and requires knowing all the inputs in advance, which means that the complete dynamic pack power profile is known when the problem is solved. Therefore, this approach is not suitable for online implementation and it is only developed as a decision-making tool aimed at providing a comprehensive evaluation of the concept under different scenarios

5.4.4 FUTURE RESEARCH AREAS

MANUSCRIPT VI

- All the issues that have already been tackled in Manuscript VII, which is in fact an extension of the work presented in VI

- Review of exemplary on-board diagnosis or fault detection tools that could be implemented in a BMS based on additional control features for the balancing system

MANUSCRIPT VII

- Evaluation of the impact of the design of the heating/cooling system in the performance of the battery under different scenarios
- Simulation-based development of online control strategies that implement all the innovative control features explored in the offline studies, which can be used as a benchmark. This also involves the development of diagnosis algorithms for SoC or power capability estimation
- Comprehensive study of the influence of dynamic and non-linear properties of the EECMs in simulations using online control strategies
- Real-time implementation of online control strategies and diagnosis algorithms in an ad-hoc HW platform
- Real-time testing of the embedded SW on a HILS test bench

6 CONCLUSION

This dissertation has given a number of good reasons to justify the research efforts in the area of Li-ion batteries. In short, the superior performance over other battery technologies, the great market expectations, the still-high cost and the more demanding requirements of new applications.

With regard to the latter, new applications of Li-ion batteries demand improvements in one or more of the following properties: cost, lifespan, safety, reliability, sustainability, usability, power or energy (either specific or density).

Contrary to what it might appear, developments in materials science is a necessary but not sufficient condition to attain these improvements. In fact, simultaneous and complementary actions should be carried out in other R&D fields like nano-technology, recyclability, manufacturing processes, economy of scale, management systems or battery pack design, assembly and testing.

Taking into account the scope and limitations of the ALPBES project, this work has focused on practical methods in the field of battery pack design and management systems. Regarding battery pack design, the topics of simplified modeling and BEV design have been addressed, respectively, by Manuscripts I-II and III. On the other hand, with respect to management systems, the topics of BMS testing and balancing system control have been tackled, respectively, in Manuscripts IV-V and VI-VII.

Beyond the field of application, these manuscriptsm are inter-related in other ways, in particular from the point of view of the modeling approaches. Hence, apart from the detailed descriptions provided within each paper, this document provided an overview of the main research methods used for modeling the BEVs and the battery electro-thermal behaviour.

In general, EECMs and TECMs with different levels of complexity have been proposed, using extensive experimental data for parameterization. With regard to the BEV models, longitudinal models were implemented, using real data from the *uCar* and *AAUDI* platforms for parameterization.

Furthermore, with respect to the cell selection, the same type of cells have been selected for all the manuscripts: a large format (40 Ah or 53 Ah) pouch cell with a NMC cathode material manufactured by Kokam. However, while in most of the studies data from a single cell was considered for model parameterization, in Manuscript VII statistical-data from tests conducted on +200 cells was used.

Moreover, though the selection of such cells has been well justified on the grounds of knowledge of the market, a broader selection of cells would be preferable and therefore should be considered for future research.

Regarding the problem statement, a number of research questions and related hypothesis have been defined. The questions were answered and the hypotheses confirmed, up to some extent, depending on the different limitations that have been discussed at length in each manuscript and this dissertation.

Manuscript I reviewed the existing methodologies and proposed new approaches to parameterize steady-state EECMs of Li-ion cells based solely on information from manufacturer’s datasheets. This paper aimed to add insight to this topic, which, surprisingly, was not studied in depth before. In general, it was concluded that the performance of the models will always be limited by the amount, accuracy and veracity of the data provided in the manufacturer’s datasheet, which is not guaranteed today. It was therefore concluded that it would be interesting, as an area of future research, to propose a framework for standardizing the information provided by datasheets.

Manuscript II studied a parameterization method for linear static EECMs based on the concept of DCR. It provided quantitative evidence of the potential advantages over other parameterization methods based either on pulse characterization, which tend to overestimate or underestimate the battery dynamic power response; or optimal approaches, which may suffer from limitations such as complexity or infeasibility in practice. However, the parameterization problem was studied only from a macroscopic empirical perspective, for a single type of cell and a limited range of temperatures and C-rates. Promising results motivate the future extension of the empirical studies and the introduction of theoretical electrochemical approaches to the theme.

Manuscript III proposed, for first time in the literature, a BEV design that combines fixed and swappable packs. Results from a comprehensive techno-economic evaluation showed that, in comparison with a single pack non-swappable BEV design, improvements in fuel economy are possible (up to 14% during city driving with fixed-pack), as well as economic benefits in the short-term (36–58 % reduction on the purchase price) and long-term (e.g. for 15 years in the case of an EPA standard driving pattern and a swap-cost window of 0.29-0.47 US$/mi). These advantages, combined with the potential synergies with other green technologies and innovative business concepts, encourage further techno-economic studies and standardization efforts in this field.

Manuscript IV addressed the development of a real-time capable battery system model for BMS testing at system level on a state-of-the-art HILS. The model implemented was able to simulate multi-cell electro-thermal performance; generate realistic cell-to-cell differences; add models of other components of the battery system; simulate realistic dis/charging scenarios, including fault insertion cases; interact with active or passive balancing systems; configure, control, monitor and log the experiments. The combination of these features enabled testing for practically all of the funtional requirements of the BMS and some important non-functional requirements. To the best of my knowledge, such a possibility was not presented before. Thus, the developed HILS battery system model took a step forward in the in the state-of-the-art.

Manuscript V extended the previous work, introducing theoretical principles of BMS testing and suggesting a practical method to develop ad hoc software and strategies for testing at system level. Using the model developed in Manuscript IV, an extensive collection of experimental results have been presented to illustrate the immense possibilities of the proposed software and strategies for testing. From a qualitative perspective, it can be inferred that testing on a HILS may offer major improvements over testing on real-batteries. For instance, with regard to cost, test times, versatility, traceability, reproducibility or safety. However, quantitative metrics were not defined to evaluate the pros and cons, and can be proposed in the future.

Manuscript VI provided an offline evaluation of an innovative control approach for balancing systems. It demonstrated that, apart from conventional SoC equalization, other control features can be offered by an active balancing system, achieving valuable performance gains in comparison with passive systems or active systems with conventional control. These include, minimization of power losses, temperature equalization and maximization of usable capacity. This problem was formulated mathematically, for the first time, as a ‘multi-objective’ optimal control problem. This was also the first time that the control was applied to a balancing system that was not integrated with the load driver. On the other hand, as a caveat, the on-line control strategy was only applied to a single scenario, which made impossible to extend its findings beyond this specific case.

Manuscript VII took the general ideas contained in Manuscript VI and developed them to another level. Substantial improvements were made to the parameterization of the models and the offline formulation of the problem. In addition, more than a hundred cases were evaluated, in order to give an extensive and comprehensive evaluation of the proposed ‘multi-objective’ control approaches. From the analysis of a broad spectrum of scenarios, it was concluded that the impact of these innovative control features can vary, as expected, depending on a number of factors related or not with the balancing system. This includes, among other factors, the energy transfer configuration of the balancing system; the balancing system current level and efficiency; the battery pack size; the battery aging scenario; the dynamics of the discharge profile; the cooling conditions; and the operating windows in terms of temperature, voltage, current or state-of-charge. Ultimately, specific scenarios were identified, where significant gains can be achieved in terms of temperature distribution, power losses or available useful capacity, which supports the idea of a selective introduction of active balancing systems in industry. Based on the partially encouraging results from these offline studies, the next logical step is to develop and test online methods in the scenarios with the most promising prospects.

REFERENCES

[1] C. Pillot, “The Rechargeable Battery Market and Main Trends 2015-2025,” Avicenne Energy, Presentation at 18th International Meeting on Lithium Batteries, Chicago (USA), June 2016.

[2] C. Pillot, “Battery Market Development for Consumer Electronics, Automotive, and Industrial: Materials Requirements and Trends,” Avicenne Energy, Presentation at Qinghai EV Rally 2015, Xining (China), June 2015.

[3] J. Gartner, B. Gohn, “Pike Pulse Report: Electric vehicle batteries. Assessment of strategy and execution for 10 leading lithium ion battery vendors,” Pike Research, 2012.

[4] P. Hummel et al., “Autos & Chemicals: Will solar, batteries and electric cars re-shape the electricity system?” UBS, Global Utilities, 2014.

[5] “Evolution - Electric vehicles in Europe, gearing up for a new phase?” Amsterdam Roundtable Foundation and McKinsey & Company, 2014.

[6] B. Nykvist and M. Nilsson, “Rapidly falling costs of battery packs for electric vehicles,” Nature Climate Change, vol. 5, pp. 329–332, 2015.

[7] J. V. Barreras, C. Pinto, E. Schaltz, S. J. Andreasen, P. O. Rasmussen, R. E. Araújo, “A novel Battery Electric Vehicle concept based on fixed and swappable Li-ion battery packs,” Proceedings of the 2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER). Monte-Carlo: IEEE Press, 2015. s. 1-8.

[8] J. V. Barreras, , C. Pinto, E. Schaltz, S. J. Andreasen, P. O. Rasmussen, R. E. Araújo, "Evaluation of a novel BEV concept based on fixed and swappable Li-ion battery packs," in *IEEE Transactions on Industry Applications,* vol. 52, no. 6, pp. 5073-5085, Nov.-Dec. 2016

[9] V. V. Viswanathan and M. Kintner-Meyer, "Second Use of Transportation Batteries: Maximizing the Value of Batteries for Transportation and Grid Services," in IEEE Transactions on Vehicular Technology, vol. 60, no. 7, pp. 2963-2970, Sept. 2011.

[10] P. Cicconi, D. Landi, A. Morbidoni and M. Germani, "Feasibility analysis of second life applications for Li-Ion cells used in electric powertrain using environmental indicators," Energy Conference and Exhibition (ENERGYCON), 2012 IEEE International, Florence, 2012, pp. 985-990.

[11] G. L. Plett, “Battery Management Systems, Volume I: Battery Modeling,” 1st ed., Norwood, MA: Artech House, 2015.

[12] G. L. Plett, “Battery Management Systems, Volume II: Equivalent-Circuit Methods,” 1st ed., Norwood, MA: Artech House, 2015.

[13] D. Andrea, “Battery Management Systems for large Li-Ion battery packs,” Artec House, ISBN-13 978-1-60807-104-3, Boston, 2010.

[14] H.J. Bergveld, W.S. Kruijt, P.H.L. Notten, “Battery Management Systems: Design by Modeling,” Springer, New York, 2002.

[15] H. Rahimi-Eichi, U. Ojha, F. Baronti, M. Chow, “Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles,” Industrial Electronics Magazine, IEEE, vol.7, no.2, pp.4,16, June 2013

[16] D. Linden, T.B. Reddy, “Handbook of Batteries,” McGraw-Hill, New York, 2002.

[17] V. Pop, H.J. Bergveld, D. Danilov et al., “Battery Management Systems: Accurate State-of-Charge Indication for Battery Powered Applications,” Springer, New York, 2008.

[18] M. Ecker et al., “Development of a lifetime prediction model for lithium-ion batteries based on extended accelerated aging test data,” Journal of Power Sources, vol. 215, 2012, pp. 248-257

[19] D.U. Sauer, H. Wenzl, “Comparison of different approaches for lifetime prediction of electrochemical systems - Using lead-acid batteries as example,” Journal of Power Sources, vol. 176, pp. 534 - 546, 2008.

[20] W. Waag, C. Fleischer, D. U. Sauer, “Critical review of the methods for monitoring of lithium-ion batteries in electric and hybrid vehicles,” Journal of Power Sources, Volume 258, 15 July 2014, Pages 321-339, ISSN 0378-7753.

[21] A. Jossen, “Fundamentals of battery dynamics,” Journal of Power Sources, Vol. 154, pp. 530–538, 2006.

[22] A. Jossen et al., “Reliable Battery Operation – A Challenge for a Battery Management System,” Journal of Power Sources, vol. 84, pp. 283-286, 1999.

[23] R. Spotnitz, “Battery Modeling,” The Electrochemical Society Interface, USPS 010-327, ISSN 1064-8208, pp. 39-42, Winter 2005.

[24] R. Rao, S. Vrudhula, D. N. Rakhmatov, “Battery Modeling for Energy-Aware System Design,” IEEE Computer, ISSN: 0018-9162, vol. 36, issue 12, pp. 77-87, December 2003.

[25] M. Chen, G. Rincon-Mora, “Accurate electrical battery model capable of predicting runtime and I-V performance,” IEEE Trans. Ener. Conv., vol. 21, issue 2, pp. 504-511, 2006.

[26] D. N. Rakhmatov, “Battery voltage modeling for portable systems,” Journal ACM Transactions on Design Automation of Electronic Systems (TODAES), ISSN 1084-4309, vol. 14, issue 2, March 2009.

[27] J. V. Barreras, E. Schaltz, S. J. Andreasen and T. Minko, "Datasheet-based modeling of Li-Ion batteries," 2012 IEEE Vehicle Power and Propulsion Conference, Seoul, 2012, pp. 830-835.

[28] J. V. Barreras et al., "An improved parametrization method for Li-ion linear static Equivalent Circuit battery Models based on direct current resistance measurement," 2015 International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART), Kuwait City, 2015, pp. 1-9.

[29] C. Pinto, J. V. Barreras, R. de Castro, E. Schaltz, S. J. Andreasen and R. E. Araujo, "Influence of Li-Ion Battery Models in the Sizing of Hybrid Storage Systems with Supercapacitors," 2014 IEEE Vehicle Power and Propulsion Conference (VPPC), Coimbra, 2014, pp. 1-6.

[30] C. Pinto, J. V. Barreras, R. de Castro, E. Schaltz, and R. E. Araujo, “Impact of battery models on the sizing of hybrid energy storage systems,” 2016, unpublished.

[31] J. Gallardo-Lozano, E. Romero-Cadaval, M. I. Milanes-Montero, M. A. Guerrero-Martinez, “Battery equalization active methods,” Journal of Power Sources, vol. 246, pp. 934-949, 2014.

[32] J. Cao, N. Schofield, A. Emadi, “Battery balancing methods: A comprehensive review,” Vehicle Power and Propulsion Conference (VPPC), IEEE, vol., no., pp. 1, 6, 3-5, 2008.

[33] S. Moore, P. Schneider, “A Review of Cell Equalization Methods for Lithium Ion and Lithium Polymer Battery Systems,” Proceedings of the SAE 2001 World Congress, 2001.

[34] K. Zhi-Guo et al., “Comparison and Evaluation of Charge Equalization Technique for Series Connected Batteries,” 37th IEEE Power Electronics Specialists Conference, pp. 1-6, 2006.

[35] M. Daowd, N. Omar, P. Van den Bossche, J. Van Mierlo, ”Passive and active battery balancing comparison based on MATLAB simulation,” Vehicle Power and Propulsion Conference (VPPC), 2011 IEEE , vol., no., pp.1, 7, 6-9, 2011.

[36] J. V. Barreras, C. Pinto, R. de Castro, E. Schaltz, S. J. Andreasen and R. E. Araujo, "Multi-Objective Control of Balancing Systems for Li-Ion Battery Packs: A Paradigm Shift?," 2014 IEEE Vehicle Power and Propulsion Conference (VPPC), Coimbra, 2014, pp. 1-7.

[37] C. Pinto; J. V. Barreras; E. Schaltz; R. Araujo, "Evaluation of Advanced Control for Li-ion Battery Balancing Systems using Convex Optimization," in *IEEE Transactions on Sustainable Energy*, vol. 7, no. 4, pp. 1703-1717, Oct. 2016.

[38] F. Altaf, L. Johannesson and B. Egardt, "Simultaneous Thermal and State-of-Charge Balancing of Batteries: A Review," 2014 IEEE Vehicle Power and Propulsion Conference (VPPC), Coimbra, 2014.

[39] F. Altaf; B. Egardt; L. Johannesson Mårdh, "Load Management of Modular Battery Using Model Predictive Control: Thermal and State-of-Charge Balancing," IEEE Transactions on Control Systems Technology, 2016.

[40] F. Altaf; B. Egardt, "Comparative Analysis of Unipolar and Bipolar Control of Modular Battery for Thermal and State-of-Charge Balancing," IEEE Transactions on Vehicular Technology, 2016.

[41] J. V. Barreras, C. Fleischer, A. E. Christensen, M. J. Swierczynski, E. Schaltz, S. J. Andreasen, D. U. Sauer "Functional Analysis of Battery Management Systems using Multi-Cell HIL Simulator," Proceedings of the 2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER). Monte-Carlo: IEEE Press, 2015.

[42] J. V. Barreras, C. Fleischer, A. E. Christensen, M. J. Swierczynski, E. Schaltz, S. J. Andreasen, D. U. Sauer "An Advanced Hardware-in-the-loop Simulation Battery Model for Battery Management System testing," in *IEEE Transactions on Industry Applications*, vol. 52, no. 6, pp. 5086-5099, Nov.-Dec. 2016.

[43] C. Fleischer, J. V. Barreras A. E. Christensen, E. Schaltz, D. U. Sauer, "Development of software and strategies for Battery Management System testing on HIL simulator," Proceedings of the 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER). Monte-Carlo: IEEE Press, 2016.

[44] A. Khaligh and Z. Li, "Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art," IEEE Trans. Veh. Technol., vol. 59, no. 6, pp. 2806–2814, July 2010.

[45] EPRI, "Electricity Energy Storage Technology Options – A White Paper Primer on Applications, Costs, and Benefits," December 2010.

[46] Z. Yang, J. Zhang et al, "Electrochemical Energy Storage for Green Grid," Chemical Reviews, vol. 111, pp. 3577-3613, March 2011.

[47] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, Y. Ding, “Progress in electrical energy storage system. A critical review,” Progress in Natural Science, vol. 19, pp. 291 – 312, 2009.

[48] K. C. Kam and M. M. Doeff, “Electrode Materials for Lithium Ion Batteries,” Material Matters, vol. 7, pp. 56-60, 2012.

[49] William H. Woodford, R. Alan Ransil, Yet-Ming Chiang, “Advanced Batteries: Beyond Li-ion,” NPC Future Transportation Fuels Study, Topic Paper #17, 2012.

[50] J. Christman, "The Case of the Burning Laptops," Journal of Case Studies, vol. 30, no. 1, pp. 88-97, June 2012.

[51] Nissan Motor Company Ltd, “Nissan LEAF battery reliably outperforms cynics, critics and alternatives,” March 23, 2015. [Online]. Available: https://goo.gl/cvfmln. [Accessed Sept. 15, 2016].

[52] L. Lu, X. Han, J. Li, J. Hua and M. Ouyang, “A review on the key issues for lithium-ion battery management in electric vehicles,” Journal of Power Sources, vol. 226, pp. 272–288, 2013.

[53] S. Kukkonen, “Current Trends in Battery Technology,” ECV national seminar, Sept. 2014. [Online]. Available: https://goo.gl/zBDD3j. [Accessed Sept. 15, 2016].

[54] M. Anderman, “Assessing the future of hybrid and electric vehicles: The 2014 xEV industry insider report,” Tech. Rep., Dec. 2013. Available: https://goo.gl/Vk1nDy. [Accessed Sept. 15, 2016].

[55] “Lithium Battery Failures,” Electropaedia. [Online]. Available: https://goo.gl/eDA1N. [Accessed Sept. 15, 2016].

[56] F. Markus, “Should You Wait for a Tesla Model 3, or Go for a Bolt?,” Motor Trend, Apr. 2016. [Online]. Available: https://goo.gl/F1OSq5. [Accessed Sept. 15, 2016].

[57] SAE Surface Vehicle Recommended Practice J1772, SAE Electric Vehicle Conductive Charge Coupler.

[58] S. Rothgang, H. Nordmann, M. Masomtob, C. Schaeper, S. Ginsberg, D. U. Sauer, “Influence of the Switch Box Design on Costs, Size and Reliability of a Battery System,” Kraftwerk Batterie, Münster, 2012.

[59] J. V. Barreras, “AMPLiFII Dis/charge Management Module Specification,” University of Oxford, Oxford, UK, July 2016, unpublished.

[60] J. Wynne, “Isolation in High-Voltage Battery Monitoring for Transportation Applications,” Analog Dialogue vol. 43, Issue 10, October 2009.

[61] G. L. Plett, “Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs - Part 1. Background,” Journal of Power Sources, vol. 134, pp. 252-261, 2004.

[62] G. L. Plett, “Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs - Part 2. Modeling and identification,” Journal of Power Sources, vol. 134, pp. 262-276, 2004.

[63] G. L. Plett, “Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs - Part 2. Modeling and identification,” Journal of Power Sources, vol. 134, pp. 277-292, 2004.

[64] X. Hu, S. Li, H. Peng, “A comparative study of equivalent circuit models for Li-ion batteries,” Journal of Power Sources, vol. 198, pp. 359-367, 2012.

[65] S. Zhao, Duncan, S.R., and Howey, D.A., “Observability analysis and state estimation of lithium-ion batteries in the presence of sensor biases”, IEEE Transactions on Control Systems Technology, 2016.

[66] W. Ko and T.-K. Hahn, “Analysis of consumer preferences for electric vehicles,” Smart Grid, IEEE Transactions on, vol. 4, no. 1, pp. 437–442, March 2013.

[67] M. Broussely, P. Biensan, F. Bonhomme, P. Blanchard, S. Herreyre, K. Nechev, and R. Staniewicz, “Main aging mechanisms in Li ion batteries,” Journal of Power Sources, vol. 146, no. 12, pp. 90 – 96, 2005.

[68] Müller, T. et al., “Certified Tester Foundation Level Syllabus of the ISTQB”, 2011 version. [Online]. Available: https://goo.gl/s9i56D [Accessed Sept. 15, 2016].

[69] Jones, C., Applied Software Management: Assuring Productivity and Quality, 1996, McGraw-Hill.

[70] Everett, G. and McLeod Jr., R., Software Testing: Testing across the Entire Software Development Life Cycle, pp. 176-202, 2007, Wiley-Interscience.

[71] N. Murgovski, L. Johannesson, and J. Sjoberg, "Convex modeling of energy buffers in power control applications," in IFAC Workshop on Engine and Powertrain Control Simulation and Modeling, pp. 92-99, 2012.

[72] O. Sundstrom, L. Guzzella, and P. Soltic, 'Torque-assist hybrid electric powertrain sizing: From optimal control towards a sizing law;' Control Systems Technology, IEEE Transactions on, vol. 18, no. 4, pp. 837-849, July 2010.

[73] A. Ravey, B. Blunier, and A. Miraoui, "Control strategies for fuel-cell-based hybrid electric vehicles: From offline to online and experimental results,"

Vehicular Technology, IEEE Transactions on, vol. 61, no. 6, pp. 2452-2457, July 2012.

[74] R. E. Araujo, R. de Castro, C. Pinto, P. Melo, and D. Freitas, "Combined Sizing and Energy Management in EV s with Batteries and Supercapacitors," IEEE Transactions on Vehicular Technology, pp. 1-1, 2014.

[75] A. Jaafar, C. Akli, B. Sareni, X. Roboam, and A. Jeunesse, "Sizing and energy management of a hybrid locomotive based on flywheel and accumulators," Vehicular Technology, IEEE Transactions on, vol. 58, no. 8, pp. 3947-3958, Oct 2009.

[76] E. Schaltz, A. Khaligh, and P. Rasmussen, "Influence of battery/ultracapacitor energy-storage sizing on battery lifetime in a fuel cell hybrid electric vehicle;' Vehicular Technology, IEEE Transactions on, vol. 58, no. 8, pp. 3882-3891, Oct 2009.

[77] X. Hu, N. Murgovski, L. Johannesson, and B. Egardt, "Comparison of three electrochemical energy buffers applied to a hybrid bus powertrain with simultaneous optimal sizing and energy management," IEEE transactions on intelligent transportation systems, vol. 15, pp. 1193-1205, 2014.

[78] D. S. Bernstein, “A student’s guide to research,” IEEE Control Systems Magazine, vol. 19, pp. 102–108, February 1999.

[79] R. Nola, H. Sankey, “Theories of Scientific Method,” McGill-Queen's University Press, Montreal, 2007.

[80] W. Waag, S. Kbitz, and D. U. Sauer, "Experimental investigation of the lithium-ion battery impedance characteristic at various conditions and aging states and its influence on the application," Applied Energy, vol. 102, pp. 885 - 897, 2013, special Issue on Advances in sustainable biofuel production and use - {XIX} Intemational Symposium on Alcohol Fuels - {ISAF}.

[81] Y-S. Chen, K.-H. Chang, c.-C. Hu, and T.-T. Cheng, "Performance comparisons and resistance modeling for multi-segment electrode designs of power-oriented lithium-ion batteries," Electrochimica Acta, vol. 55, no. 22, pp. 6433 - 6439, 2010.

[82] G. L. Plett, "High-performance battery-pack power estimation using a dynamic cell model," Vehicular Technology, IEEE Transactions on, vol. 53, no. 5, pp. 1586-1593, Sept 2004.

[83] S. Wang, M. Verbrugge, J. S. Wang, and P. Liu, "Power prediction from a battery state estimator that incorporates diffusion resistance," Journal of Power Sources, vol. 214, pp. 399 - 406, 2012.

[84] Kokam Co. Ltd, “SLPB (Superior Lithium Polymer Battery) Technical Specification,” SLPB120216216 model, KD07-RC23-02 datasheet document, Mar. 2009 [Revised Mar. 2010].

[85] R. Mahamud. “Advanced battery thermal management for electrical-drive vehicles using reciprocating cooling flow and spatial-resolution, lumped-capacitance thermal model,” PhD thesis, University of Nevada, 2011.

[86] C. Forgez, D.V. Do, G. Friedrich, M. Morcrette and C. Delacourt, “Thermal modeling of a cylindrical LiFePO4/graphite lithium-ion battery,” J. Power Sources, vol. 195, no. 9, pp. 2961–2968, May 2010.

[87] X. Lin, H. E. Perez, S. Mohan, J. B. Siegel, A. G. Stefanopoulou, Y. Ding and M. P. Castanier, “A lumped-parameter electrothermal model for cylindrical batteries,” J. Power Sources, vol. 257, pp. 1–11, July 2014.

[88] X. Li, F. He and L. Ma, “Thermal management of cylindrical batteries investigated using wind tunnel testing and computational fluid dynamics simulation,” J. Power Sources, vol. 238, pp. 395–402, September 2013.

[89] X. Lin, H. E Perez, J. B Siegel, A. G Stefanopoulou, Y. Ding and M. P Castanier, “Parameterization and Observability Analysis of Scalable Battery Clusters for Onboard Thermal Management,” In Les Rencontres Scientifiques d’IFP Energies nouvelles, number December, 2011.

[90] N. Damay, C. Forgez, M. P. Bichat, G. Friedrich and A. Ospina, “Thermal modeling and experimental validation of a large prismatic Li-ion battery,” IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, pp. 4694–4699, Nov. 2013.

[91] L. Gao, S. Liu, and R. Dougal, “Dynamic lithium-ion battery model for system simulation,” Components and Packaging Technologies, IEEE Transactions on, vol. 25, no. 3, pp. 495–505, Sep 2002.

[92] S. Abada, G. Marlair, A. Lecocq, M. Petit, V. Sauvant-Moynot, and F. Huet, “Safety focused modeling of lithium-ion batteries: A review,” Journal of Power Sources, vol. 306, pp. 178–192, 2016.

[93] A. A. Pesaran, “Battery thermal models for hybrid vehicle simulations,” Journal of Power Sources, vol. 110, no. 2, pp. 377–382, 2002.

[94] C. Zhu, X. Li, L. Song, and L. Xiang, “Development of a theoretically based thermal model for lithium ion battery pack,” Journal of Power Sources, vol. 223, pp. 155–164, 2013.

[95] T. Huria, M. Ceraolo, J. Gazzarri and R. Jackey, "High fidelity electrical model with thermal dependence for characterization and simulation of high power

lithium battery cells," 2012 IEEE International Electric Vehicle Conference, Greenville, SC, 2012, pp. 1-8.

[96] R. R. Richardson, “Impedance-based battery temperature monitoring,” PhD thesis, University of Oxford, 2016.

[97] W. Peukert, “Ober die Abhangigkeit der Kapazitat von der Entladestromstarke bei Bleiakkumulatoren,” Elektrotechnische Zeitschriji 20, 1897.

[98] D. Doerffel, S. A. Sharkh, “A critical review of using the Peukert equation for determining the remaining capacity of lead-acid and lithium-ion batteries," Journal of Power Sources, vol. 155, issue 2, pp. 395-400, April 2006.

[99] O. Tremblay, L.-A. Dessaint, and A.-I. Dekkiche, “A generic battery model for the dynamic simulation of hybrid electric vehicles,” in Proc. IEEE Veh. Power Propulsion Conf., Sep. 2007, pp. 284–289.

[100] Y. Kim, D. Shin, M. Petricca, S. Park, M. Poncino, N. Chang, “Computer-aided design of electrical energy systems,” Computer-Aided Design Proceedings of the International Conference on, pp. 194-201, 2013.

[101] S. Chen, A. Saber, T. Khandelwal, “General battery modeling and simulation using non-linear open circuit voltage in power system analysis,” Power and Energy Society General Meeting (PESGM) 2016, pp. 1-5, 2016.

[102] Iker Diaz de Cerio Mendaza, Birgitte Bak-Jensen, Zhe Chen, "Alkaline electrolyzer and V2G system DIgSILENT models for demand response analysis in future distribution networks", PowerTech (POWERTECH) 2013 IEEE Grenoble, pp. 1-8, 2013.

[103] M. Petricca, D. Shin, A. Bocca, A. Macii, E. Macii, M. Poncino, “An automated framework for generating variable-accuracy battery models from datasheet information,” Low Power Electronics and Design (ISLPED) 2013 IEEE International Symposium on, pp. 365-370, 2013.

[104] M. Petricca, D. Shin, A. Bocca, A. Macii, E. Macii, M. Poncino, “A framework with temperature-aware accuracy levels for battery modeling from datasheets," Power and Timing Modeling Optimization and Simulation (PATMOS) 2013 23rd International Workshop on, pp. 265-268, 2013.

[105] M. Petricca, D. Shin, A. Bocca, A. Macii, E. Macii, M. Poncino, “Automated generation of battery aging models from datasheets,” Computer Design (ICCD) 2014 32nd IEEE International Conference on, pp. 483-488, 2014.

[106] J. Becker, C. Schaeper, S. Rothgang, and D. U. Sauer, “Development and validation of an energy management system for an electric vehicle with a split battery storage system,” Journal of Electrical Engineering & Technology (JEET), vol. 8, no. 4, pp. 920–929, 2013.

[107] J. V. Barreras et al., "Best Paper on Ecological Vehicles," 2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER), Monte Carlo, 2015, pp. 1-1.

[108] F. Altaf, L. Johannesson, B. Egardt, “On Thermal and State of-Charge Balancing using Cascaded Multi-level Converters,” Journal of Power Electronics, vol. 13, Issue 4, pp. 569-583, August 2013.

[109] F. Altaf, “Thermal and State-of-Charge Balancing of Batteries using Multilevel Converters,” Licentiate Thesis, Chalmers University of Technology, March 2014.

[110] R. E. Araújo, R. de Castro, C. Pinto, P. Melo and D. Freitas, "Combined Sizing and Energy Management in EVs With Batteries and Supercapacitors," in IEEE Transactions on Vehicular Technology, vol. 63, no. 7, pp. 3062-3076, Sept. 2014.

[111] R. de Castro, “Motion Control and Energy Management of Electric Vehicles,” Licentiate Thesis, Faculty of Engineering of the University of Porto, Sept. 2013.

[112] T. J. Barlow, S. Latham, I.S. McCrae, B.C. Boulter, “A reference book of driving cyles for use in the measurement of road vehicle emission,” TRL Project Report PPR 354, 2009.

[113] C. Pinto, J. V. Barreras, R. de Castro, R. E. Araujo and , E. Schaltz, “Study of the combined influence of battery models and sizing strategy in the size of hybrid and battery-based electric vehicles,” in Energy, 2017, Submitted for publication.

[114] P. C. Gonzalez; Y. Pang; P. D. Reigosa; E. Dimopoulos; J. V. Barreras; E. Schaltz, “Tvindkraft: Implementing a 500 kW 21-IGBT-Based Frequency Converter for a 1.7 MW Wind Power Conversion System,” Proceedings of the 2013 IEEE International Conference on Renewable Energy Research and Applications. IEEE Press, 2013. s. 482-487.

[115] M. R. Khan; J. V. Barreras; A. I. Stan; M. J. Swierczynski; S. J. Andreasen; S. K. Kær, “Behavior Patterns, Origin of Problems and Solutions Regarding Hysteresis Phenomena in Complex Battery Systems,” Hysteresis: Types, Applications and Behavior Patterns in Complex Systems, Nova Science Publishers, Incorporated, 2014. s. 215-226.

APPENDICES

Appendix A. Formulation of the EECMs

Appendix B. Thermal resistances

Appendix C. Standard driving cycles

Appendix D. Manuscripts

Appendix A. **Formulation of the EECMs**

The equations that express the electric behavior of the EECMs used in this work are summarized in this appendix, both in continuous and in discrete time. Firstly, a description of the static and dynamic models is given. Then, the differences between the linear and non-linear models are detailed. Finally, the diagrams corresponding to the static and dynamic EECMS are shown below in Fig. A-1 and Fig. A-2, respectively.

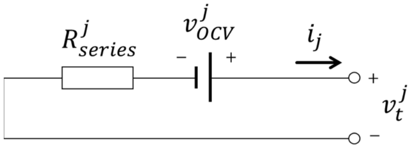


Fig. A-1. Diagram of the static EECM.

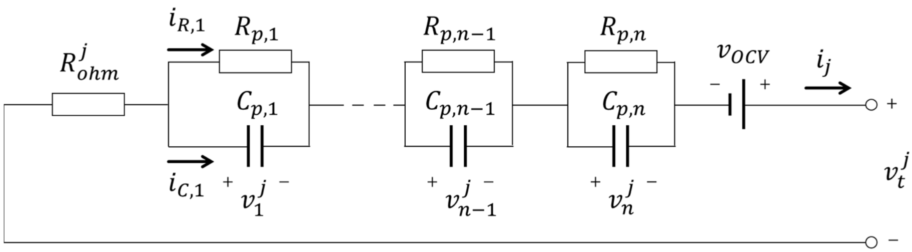


Fig. A-2. Diagram of the dynamic EECM.

Description of static and dynamic EECMs in continuous time

- Static EECM, zero-order

$$v_t^j(t) = v_{OCV}^j(t) - R_{series}^j i_j(t) \tag{6}$$

where v_t^j [V] is the terminal voltage of cell j, v_{OCV}^j [V] is the cell's OCV, R_{series}^j [Ω] is the cell's series resistance and i_j [A] is the cell's operating current with positive value when discharging and negative when charging.

- Dynamic EECM, n-order

$$v_t^j(t) = v_{OCV}^j(t) - \sum_{x=1}^{n} v_x^j(t) - R_{ohm}^j i_j(t) \tag{7}$$

$$\dot{v}_x^j(t) = \frac{-1}{R_{p,x}C_{p,x}} v_x^j(t) + \frac{1}{C_{p,x}} i_j(t) \tag{8}$$

where v_{OCV}^{j} [V] is the cell's OCV, R_{ohm}^{j} [Ω] is the cell's ohmic resistance, i_j [A] is the cell's operating current with positive value when discharging and negative value when charging, v_x^j [V] is the voltage across each RC element x, $R_{p,x}$ [Ω] is the polarization resistance of the RC element x, $C_{p,x}$ [F] is the polarization capacitance of the RC element x, n is the total number of RC elements, $x \in \mathbb{N}$ and $0 < x < n$.

Description of static and dynamic EECMs in discrete time

(9) $$t = kT_s$$

(10) $$\tau_x = R_{p,x}C_{p,x}$$

where t [s] is the continuous time index, k is the discrete time index, T_s [s] is the sampling period and τ_x [s] is the time constant of a RC element x.

- Static EECM, zero-order

(11) $$v_{t,k}^{j} = v_{OCV,k}^{j} - R_{series}^{j} i_{j,k}$$

- Dynamic EECM, n-order, exact discrete model assuming Zero-Order-Hold (ZOH) for the input

(12) $$v_{t,k}^{j} = v_{OCV,k}^{j} - \sum_{x=1}^{n} v_x^j - R_{ohm}^{j} i_{j,k}$$

(13) $$v_{x,k+1}^{j} = v_{x,k}^{j} e^{\frac{-T_s}{\tau_x}} + R_{p,x}\left(1 - e^{\frac{-T_s}{\tau_x}}\right) i_{j,k}$$

- Dynamic EECM, n-order, approximate discrete model employing Euler's forward approximation of the derivative (Eq. (15))

(14) $$v_{t,k}^{j} = v_{OCV,k}^{j} - \sum_{x=1}^{n} v_x^j - R_{ohm}^{j} i_{j,k}$$

(15) $$\dot{v}_{x,k}^{j} \approx \frac{v_{x,k+1}^{j} - v_{x,k}^{j}}{T_s}$$

(16) $$v_{x,k+1}^{j} = \left(1 + \frac{-T_s}{R_{p,x}C_{p,x}}\right) v_{x,k}^{j} + \frac{T_s}{C_{p,x}} i_{j,k}$$

Eq. (14) can also be derived from Eq. (13) using the Taylor series for the exponential function $e^{\frac{-T_s}{\tau_x}}$ around $t = t_0$, as shown in Eq. (17), and ignoring the quadratic and higher-order terms, as given in Eq. (18).

(17) $$e^{\frac{-T_S}{\tau_x}} = \frac{\left(\frac{-T_S}{\tau_x}\right)^0}{0!} + \frac{\left(\frac{-T_S}{\tau_x}\right)}{1!} + \frac{\left(\frac{-T_S}{\tau_x}\right)^2}{2!} + \frac{\left(\frac{-T_S}{\tau_x}\right)^3}{3!} + \cdots = \sum_{n=0}^{\infty} \frac{\left(\frac{-T_S}{\tau_x}\right)^n}{n!}$$

(18) $$e^{\frac{-T_S}{\tau_x}} \approx 1 + \frac{-T_S}{\tau_x}$$

Description of linear EECMs in continuous and discrete time

The linear EECMs presented in this work consider constant parameters for all the elements of the EECM but the OCV source, which is a variable that shows a linear dependency with the SoC. The OCV vs. SoC linear dependency is obtained by means of a linear regression analysis with experimental data. The continuous and discrete time expressions are detailed below.

- Linear EECM, OCV in continuous time

(19) $$v_{OCV}^{j}(t) = a + bq_j(t)$$

where a [V] is the intercept of the linear regression line (the value of v_{OCV}^{j} when $q_j = 0$), b [V] is the slope of the linear regression line and q_j[-] is the cell's SoC.

- Linear EECM, OCV in discrete time

(20) $$v_{OCV,k}^{j} = a + bq_{j,k}$$

Description of non-linear EECMs in continuous and discrete time

The non-linear EECMs included in this dissertation consider, for all the elements of the EECM, non-linear dependencies with the SoC, the temperature and/or the aging state. All the models implement the non-linear OCV vs SoC characteristics by means of either look-up tables or piecewise linear functions (PWL), depending on the coding strategy. In order to formulate the PWL, the SoC range is divided in a number of regular subintervals. In the followings, for the sake of simplicity, the formulation is presented only for the OCV variable, both in continuous and discrete time. In an equivalent way, the value of the all the other variables of the EECM are defined by PWL functions.

- Non-linear EECM, OCV in continuous time

(21) $$v_{OCV}^{j}(t) = \sum_{s=1}^{N_s} \left(a_s + b_s q_j(t)\right) \cdot F\left(s, q_j(t)\right)$$

where N_s [-] is the total number of subintervals s, each subinterval with lower and upper SoC limits $\underline{q}_s$ and $\overline{q}_s$ and $s \in [1, N_s]$ and F [-] is an indicator function that gives 1 if $q_j \in [\underline{q}_s, \overline{q}_s]$ and 0 otherwise.

- Non-linear EECM, OCV in discrete time

$$v^j_{OCV,k} = \sum_{s=1}^{N_s} \left(a_s + b_s q_{j,k}\right) \cdot F\left(s, q_{j,k}\right) \tag{22}$$

Moreover, in the particular case of the *Extended Thevenin Model 1* presented in Manuscript I [27], the temperature effects on the OCV are represented by means of a correction term, Δv_{OCV} [V], which is estimated from steady-state discharge profiels. This correction term is just added to the OCV estimated according from the non-linear OCV vs. SoC curves. The formulation is presented below only in continuous time.

- Non-linear EECM, OCV with temperature correction term in continuous time

$$v^j_{OCV,crt}(t) = v^j_{OCV}(t) + \Delta v^j_{OCV}\left(T^j_{bat}(t)\right) \tag{23}$$

Finally, also in Manuscript I [27], in the particular case of the *Thevenin model* presented, it is provided, only for illustrative purposes, the next emipirical equation to express the non-linear dependencies of the OCV with the SoC. The formulation is only given in continuous time.

- Non-linear EECM, OCV from empirical equation in continuous time

$$v_{OCV}\left(q_j(t)\right) = V_{max} \cdot \left[1 - \left(\frac{V_{max} - V_{min}}{V_{max}}\right)\left(\frac{\delta \cdot \left(1 - q_j(t)\right)}{1 - (1-\delta) \cdot \left(1 - q_j(t)\right)}\right)\right] \tag{24}$$

where V_{max} [V] is the full-charge OCV, V_{min} [V] is the full-discharge OCV and δ [-] is a constant that defines the shape of the curve.

Description of the SoC in continuous and discrete time

In order to calculate the cell's SoC, the same approach is followed for all the models, either static, dynamic, linear or non-linear. The formulation is presented below both in continuous and discrete time.

- SoC calculation in continuous time

$$q_j(t) = q_j(t_0) - \frac{3600}{Q^j_{bat}} \int_{t_0}^{t} i_j(t) dt \tag{25}$$

where q_j[-] is the cell's SoC and Q^j_{bat} [Ah] is the actual cell's capacity, which may account intrinsically for Peukert, temperature or aging effects.

- SoC calculation in discrete time

(26) $$q_{j,k+1} = q_{j,k} - \frac{3600}{Q_{bat}^{j}} \cdot T_s \cdot i_{j,k}$$

Furthermore, in the particular case of the *Extended Thevenin Model 1* presented in Manuscript I [27], the Peukert and temperature effects on the actual cell's capacity are not expressed intrinsically by means of a variable actual cell's capacity, but explicitly by means of two independent factors. These factors, namely α and β, are added as follows to the aforementioned equation in continuous time.

- SoC calculation in continuous time, considering current and temperature dependent factors

(27) $$q_j(t) = q_j(t_0) - \frac{3600}{Q_{bat}^{j}} \cdot \int_{t_0}^{t} \alpha(i_j(t)) \cdot \beta(T_{bat}^{j}(t)) i_j(t) dt$$

where T_{bat}^{j} [K] is the cell's temperature, α [-] is a current dependent factor and β [-] is a temperature dependent factor, both estimated from steady-state discharge curves at different C-rates and temperatures, respectively.

Appendix B. **Thermal resistances**

The equations that describe the conductive, convective and radiative thermal resistances used in the TECMs proposed in this work are given below [36], [37] [42], [43], [85] – [96].

- Conductive thermal resistance:

(22) $$R_{cond} = \frac{d}{k_{cond}A_{cont}}$$

where R_{cond} [K/W] is the conductive thermal resistance, d [m] is the thickness of the material, k_{cond} [W/m.K] is the thermal conductivity of the material and A_{cont} [m^2] is the surface area in contact between the two solid materials.

- Convective thermal resistance:

(23) $$R_{cov} = \frac{1}{h_{cov}A_{surf}}$$

where R_{cov} [K/W] is the convective thermal resistance, h_{cov} [W/m^2.K] is the convective heat transfer coefficient and A_{surf} [m^2] is the interface surface area of the solid material.

- Radiative thermal resistance:

(24) $$R_{rad} = \frac{1}{h_{rad}A_{emi}}$$

where R_{rad} [K/W] is the radiative thermal resistance, h_{rad} [W/m^2.K] is the radiative heat transfer coefficient and A_{emi} [m^2] is the area of the emitting surface.

(25) $$h_{rad} = \varepsilon\sigma\left(T^2 + {T_{amb}}^2\right)(T + T_{amb})$$

where ε [-] is the emissivity coefficient of the material, σ is the Stefan-Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8}$ [W/m^2.K^{-4}], T [K] is the surface temperature of the emitting surface and T_{amb} [K] is the temperature of the surroundings.

The thermal conductivity and the emissivity are intensive physical properties of the solid materials, while the convective heat transfer coefficient is not, since it depends on a combination of intensive and extensive physical properties of the fluid material (heat capacity, density, viscosity, thermal conductivity...) and the flow conditions (natural, forced, turbulent, laminar...).

In the case of the 1-D TECM used in [36] and [37], the equation presented above for the conductive thermal resistance (Eq. (23)) is used directly, estimating the surface area, A_{surf} [m^2], as:

(26) $$A_{surf} = 2 \cdot h \cdot l$$

where h [m] is the cell's height and l [m] is the cell's length, as shown in Fig. 4-10.

This means that convection is considered only on the two sides with the largest surface area, assuming an exemplary battery pack with parallel air-cooling, such as the one represented in Fig. 4-9.

With regards to the conductive thermal resistance of the 1-D TECM presented in [37], its value it is just estimated from the literature [94]. Its value corresponds to an equivalent resistance that accounts for all the possible conductive thermal resistances between neigboring cells that may exist in a multi-dimensional network.

In respect of the 3-D TECM proposed in [42] and [43], the values of the anisotropic conductive thermal resistances within the cell are derived from in-plane and through-plane thermal conductivity values obtained from experimental characterization tests. The equations that describe the conductive thermal resistance for each direction (x, y, z) and sense $(+, -)$ are presented below. These equations are derived from the general expression presented in Eq. (22).

(27) $$R^{+}_{condX} = R^{-}_{condX} = \frac{d/2}{k_{condX} A_X}$$

(28) $$A_X = h \cdot l$$

(29) $$R^{+}_{condY} = R^{-}_{condY} = \frac{l/2}{k_{condYZ} A_Y}$$

(30) $$A_Y = h \cdot d$$

(31) $$R^{+}_{condZ} = R^{-}_{condZ} = \frac{h/2}{k_{condYZ} A_Z}$$

(32) $$A_Z = l \cdot d$$

where k_{condX} [W/K.m] is the cell's thermal conductivity through-plane, k_{condYZ} [W/K.m] is the cell's thermal conductivity in-plane, h [m] is the cell's height, l [m] is the cell's length and d [m] is the cell's thickness, with the dimensions being shown in Fig. 4-10.

Appendix C. **Standard driving cycles**

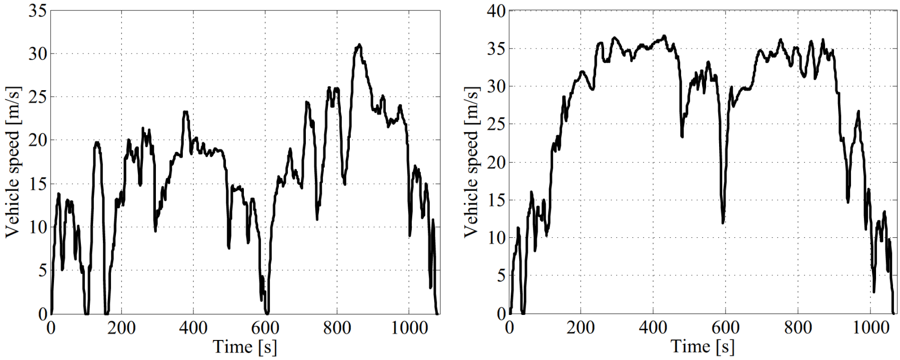


Fig. A- 3. ARTEMIS Road (left) and ARTEMIS Motorway 130 (right) driving cycles [112].

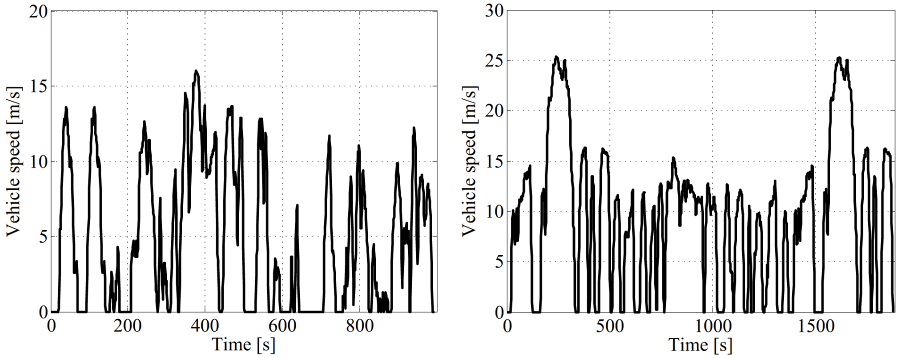


Fig. A- 4. ARTEMIS Urban (left) and FTP-75 (right) driving cycles [112].

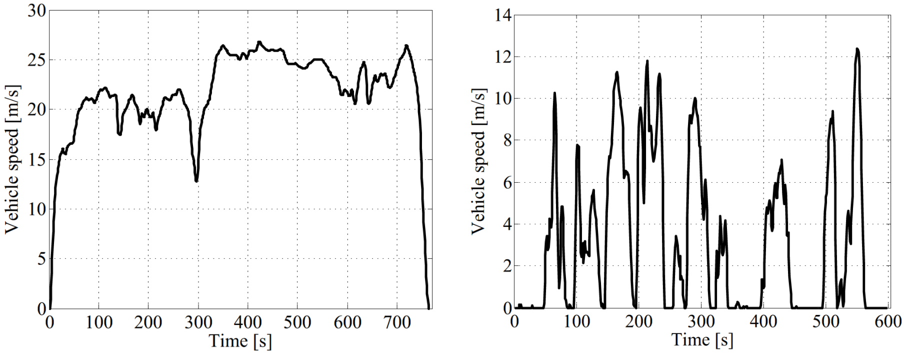


Fig. A- 5. EPA Highway Fuel Economy Test (HWFET) (left) and
EPA New York City Cycle (NYCC) (right) driving cycles [112].

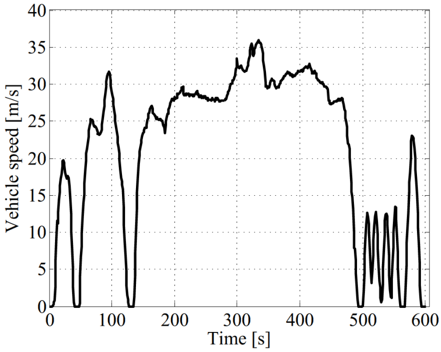


Fig. A- 6. US06 Supplemental FTP [112].

Appendix D. **Manuscripts**

This appendix presents all the papers appended to this dissertation. Each paper is preceded by a title page that outlines title, list of authors and affiliations, and publication outlet.

Table A- 1. OVERVIEW OF THE APPENDED PAPERS

Appended paper no.	**Title**	**Pages**
I	Datasheet-based modeling of Li-Ion batteries	122-128
II	An improved parameterization method for Li-ion linear static equivalent circuit battery models based on direct current resistance measurement	129-138
III	Evaluation of a novel BEV concept based on fixed and swappable Li-ion battery packs	139-152
IV	An Advanced Hardware-in-the-loop Simulation Battery Model for Battery Management System testing	153-167
V	Development of software and strategies for Battery Management System testing on HIL simulator	168-180
VI	Multi-Objective Control of Balancing Systems for Li-Ion Battery Packs: A Paradigm Shift?	181-188
VII	Evaluation of Advanced Control for Li-ion Battery Balancing Systems using Convex Optimization	189-204

SUMMARY

This thesis presents, as a collection of papers, practical methods in Li-ion batteries for simplified modeling (Manuscript I and II), battery electric vehicle design (III), battery management system testing (IV and V) and balancing system control (VI and VII).

- Manuscript I tackles methodologies to parameterize battery models based solely on manufacturer's datasheets
- Manuscript II presents a parameterization method for battery models based on the notion of direct current resistance
- Manuscript III proposes a battery electric vehicle design that combines fixed and swappable packs
- Manuscript IV develops a battery system model for battery management system testing on a hardware-in-the-loop simulator
- Manuscript V extends the previous work, introducing theoretical principles and presenting a practical method to develop ad hoc software and strategies for testing
- Manuscript VI presents a preliminary offline evaluation of a 'multi-objective' control approach for balancing systems
- Manuscript VII provides a comprehensive evaluation of the impact on battery performance of the additional control features introduced in Manuscript VI

In addition, this thesis gives an introduction; a state-of-the-art review; a problem statement; an overview of the modeling methods; and a summary of the papers and their contributions, limitations and potential for future work.

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