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Using Virtual Product Development with Design of Experiments to Design Battery Packs for Electrified Powertrain

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Abstract

Stringent automotive legislation is driving requirements for increasingly complex battery pack solutions. The key challenges for battery pack development drive cost and performance optimisation, growth in architecture solutions, monitoring and safety through lifetime, and faster-to-market expectations.

The battery Virtual Product Development (VPD) toolchain addresses these challenges and provides a solution to reduce the battery pack development time, cost and risk. The battery VPD toolchain is built upon scalable, validated sub-models of the battery pack that capture the interactions between the various domains; mechanical, electrical, thermal and hydraulic. The model fidelity can be selected at each stage of the design process allowing the right amount of detail, and available data, to be incorporated. The toolchain is coupled with vehicle simulation tools to rapidly assess performance of the complete electrified powertrain.

The aim of this study is to demonstrate an agile approach to battery pack concept development using VPD, enabled by Design of Experiments (DoE) and optimisation. Key battery parameters such as cell type, electrical configuration, thermal heat path design and cooling strategy are chosen as the design variables of a multi-staged DoE. The DoE test matrices of these parameters are generated and imported into the battery VPD toolchain with the vehicle simulation model to perform the energy efficiency and performance simulations.

Finally, the simulation results are analysed to create surrogate models which can be used to predict powertrain attributes and optimise the battery pack design. The ability to front-load virtual battery pack concepts with vehicle simulations allow for wholistic performance assessment, ensuring that vehicle attribute targets such as pure electric range of WLTP, acceleration and maximum speed are met and reducing concept development time by up to 50% compared to the baseline approach.

Introduction

The increasing adoption of grid connected electric vehicles (BEV and PHEV) worldwide is driving significant advances in battery technology. Indeed, such widespread electrified vehicle adoption calls for more robust system design, capable of operating efficiently in different terrains and climates. Furthermore, as automakers seek to allay end-user fears such as limited range and long charging time, there is a drive on designing for higher power levels [1]. These challenges have placed increasing demand on improved physical understanding and modelling of automotive battery packs and have brought more challenges to battery pack management and powertrain control [2, 3, 4]. The key challenges for battery pack development drive cost and performance optimisation, growth in architecture solutions, monitoring and safety through lifetime, and faster-to-market expectations.

Battery pack model is a key element in the battery pack development and can be a big potential to reduce the development cost and time when its capabilities have been fully explored. Normally, a battery pack physical model includes at least the electrical sub-model with optional thermal and/or ageing sub-models. For the battery pack electrical model, electrochemical model and Equivalent Circuit Model (ECM) are the two most common choice [5, 6, 7, 8, 9]. Battery temperature is known to have a critical influence on overall battery pack performance [10]. Therefore, it creates the need for battery thermal models to monitor the temperature. One such type of model is a 1-D lumped thermal model which can be applied to analyse single cells and battery modules [11, 12, 13, 14]. Computational Fluid Dynamics (CFD) packages are commonly used tools for studying battery cell thermal behavior and pack thermal management system analysis at later stages in a battery design process [15, 16]. Investigation of battery aging mechanisms is a hot topic in both academia and industry currently. The cause and effect of various battery ageing mechanisms is discussed in detail in [17]. Also, lots of experimental work focusing on application of EIS, Voltammetry and EPMA to investigate ageing exists in the literature [18, 19]. Although there are already lots of studies

FIGURE 34 Battery pack heat release of the vehicle Co-Simulation

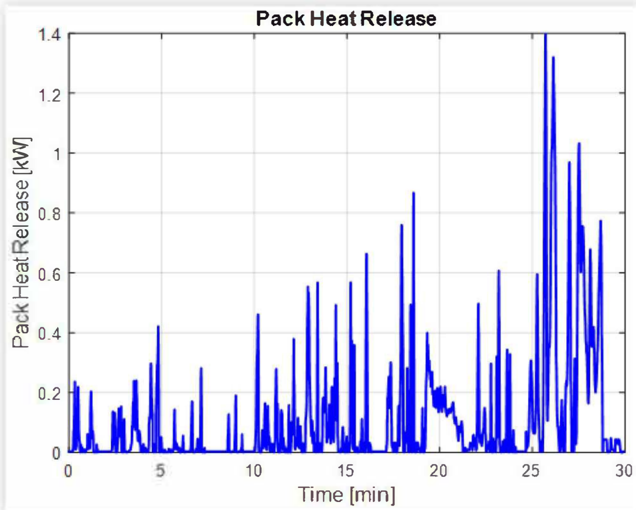

TABLE 2 Vehicle Co-Simulation performance metrics table

Metric	Value
SoC Drop per WLTC	4.5%
Vehicle Predicted WLTC Range (85% Usable SoC)	420 km
Battery Peak Discharge Power	62 kW
Battery Peak Discharge Current	74 A
Regenerative Braking Energy per WLTC	0.443 kWh

Conclusions

A battery Virtual Product Development (VPD) toolchain has been presented that enables rapid assessment of battery pack concepts with up to 50% reduction development time and can be used to address the key battery development challenges of today. The toolchain allows assessment of different battery concepts, assessment of packaging of cells into target envelopes and battery pack design optimisation using a DoE approach. The toolchain presents initial BoM and Heat Path analysis for all concepts studied. Finally, the battery pack concepts are seamlessly frontloaded with vehicle models to enable system level attribute assessment, including lifetime analysis against typical mission profiles.

A comprehensive demo case was presented that showcased the tool application to a typical battery pack concept design for a typical E segment passenger car detailing each phase of the workflow and explaining in detail the rationale behind certain decisions. Vehicle level performance metrics (including lifetime) for the proposed design were presented after front-loading of the battery concept with a vehicle model.

Future work will focus on application of the toolchain to diversified areas such as stationary, marine and aerospace battery pack developments. Further work will be carried out on feed-back of real in-service battery pack data to better inform actual product performance and provide insights into potential optimisation of future battery pack concepts.

References

1. Boulanger, A.G., Chu, A.C., . Maxx, S. and Waltz, D.L., “Vehicle Electrification: Status and Issues,” *Proceedings of the IEEE* 99(6):1116-1138, 2011.
2. Cordoba-Arena, A., Onori, S., and Rizzoni, G., “A Control-Oriented Lithium-Ion Battery Pack Model for Plug-In Hybrid Electric Vehicle Cycle-Life Studies and System Design with Consideration of Health Management,” *Journal of Power Sources* 279:791-808, 2015.
3. Li, J., and Mazzola, M.S., “Accurate Battery Pack Modeling for Automotive Applications,” *Journal of Power Sources* 237:215-228, 2013.
4. Uddin, K., Picarelli, A., Lyness, C., Taylor, N., and Macro, J., “An Acausal Li-Ion Battery Pack Model for Automotive Applications,” *Energies* 7(9):5675-5700, 2014.
5. Fan, G., Pan, K., Bartlett, A., Canova, M. and Rizzoni, G., “Electrochemical-Thermal Modeling of Li-Ion Battery Packs,” in *ASME 2014 Dynamic Systems and Control Conference*, San Antonio, Texas, USA, 2014.
6. Perez, H., Shahmohammadhamedani, N., and Moura, S., “Enhanced Performance of Li-Ion Batteries via Modified Reference Governors and Electrochemical Models,” *IEEE/ASME Transactions on Mechatronics* 20(4):1511-1520, 2015.
7. Guo, M., Jin, X., and White, R.E., “An Adaptive Reduced-Order-Modeling Approach for Simulating Real-Time Performances of Li-Ion Battery Systems,” *Journal of The Electrochemical Society* 164(14):A3602-A3613, 2017.
8. He, H., Xiong, R., and Fan, J., “Evaluation of Lithium-Ion Battery Equivalent Circuit Models for State of Charge Estimation by an Experimental Approach,” *Energies* 4(4):582-598, 2011.
9. Chen, M., and Rincon-Mora, G.A., “Accurate Electrical Battery Model Capable of Predicting Runtime and I-V Performance,” *IEEE Transactions on Energy Conversion* 21(2):504-511, 2006.
10. McGahan, P., Rouaud, C., and Booker, M., “Comparison of Model Order Reduction Techniques for Real-Time Battery Thermal Modelling,” SAE Technical Paper 2019-01-0503, 2019, https://doi.org/10.4271/2019-01-0503.
11. Pesaran, A.A., “Battery Thermal Models for Hybrid Vehicle Simulations,” *Journal of Power Sources* 110(2):377-382, 2002.
12. Johnson, V.H., Pesaran, A.A. and Sack, T., “Temperature-Dependent Battery Models for High-Power Lithium-Ion Batteries,” in *17th Annual Electric Vehicle Symposium*, Montreal, Canada, 2000.
13. Park, C., and Jaura, A.K., “Dynamic Thermal Model of Li-Ion Battery for Predictive Behavior in Hybrid and Fuel Cell Vehicles,” SAE Technical Paper 2003-01-2286, 2003, https://doi.org/10.4271/2003-01-2286.
14. Nelson, P., Dees, D., Amine, K., and Henriksen, G., “Modeling Thermal Management of Lithium-Ion PNGV Batteries,” *Journal of Power Sources* 110(2):349-356, 2002.
15. Sato, N., “Thermal Behavior Analysis of Lithium-Ion Batteries for Electric and Hybrid Vehicles,” *Journal of Power Sources* 99(1-2):70-77, 2001.

16. Pesaran, A.A., Keyser, M. and Burch, S., "An Approach for Designing Thermal Management Systems for Electric and Hybrid Vehicle Battery Packs," in *The Fourth Vehicle Thermal Management Systems Conference and Exhibition*, London, UK, 1999.
17. Vetter, J., Novák, P., Wagner, M.R., Veit, C. et al., "Ageing Mechanisms in Lithium-Ion Batteries," *Journal of Power Sources* 147(1-2):269-281, 2005.
18. Merla, Y., Wu, B., Yufit, V., Brandon, N.P. et al., "Novel Application of Differential Thermal Voltammetry as an In-Depth State-of-Health Diagnosis Method for Lithium-Ion Batteries," *Journal of Power Sources* 307:308-319, 2016.
19. Tröltzsch, U., Kanoun, O., and Tränkler, H.-R., "Characterizing Aging Effects of Lithium Ion Batteries by Impedance Spectroscopy," *Electrochimica Acta* 51(8-9):1664-1672, 2006.
20. Zhu, D., Pritchard, E.G.D., and Silverberg, L.M., "A New System Development Framework Driven by a Model-Based Testing Approach Bridged by Information Flow," *IEEE Systems Journal* 12(3):2917-2924, Sept. 2018.
21. Fisher, R.A., *The Design of Experiments* (Edinburgh: Oliver and Boyd, 1935).
22. Yates, F., "Complex Experiments," *Supplement to Journal Royal Statistical Society* 2:181-247, 1935.
23. Box, G.E.P., and Wilson, K.B., "On the Experimental Attainment of Optimum Conditions," *Journal of the Royal Statistical Society. Series B (Methodological)* 13(1):1-45, 1951.
24. Grove, D.M., and Davis, T.P., *Engineering, Quality, and Experimental Design* (UK: Longman Scientific & Technical, 1992).
25. Taguchi, G., *System of Experimental Design: Engineering Methods to Optimize Quality and Minimize Costs.* Vol. 1 (New York: UNIPUB/Kraus International Publications, 1987).
26. Bao, R., Baxter, J., and Revereault, P., "Simulation Based Hybrid Electric Vehicle Components Sizing and Fuel Economy Prediction by Using Design of Experiments and Stochastic Process Model," SAE Technical Paper 2019-01-0357, 2019, https://doi.org/10.4271/2019-01-0357.
27. Sacks, J., Welch, W.J., Mitchell, T.J., and Wynn, H.P., "Design and Analysis of Computer Experiments," *Statist. Sci* 4(4):409-423, 1989.
28. Bao, R., Baxter, J., and Revereault, P., "Using Design of Experiments to Size and Calibrate the Powertrain of Range-Extended Electric Vehicle," SAE Technical Paper 2020-01-0849, 2020, https://doi.org/10.4271/2020-01-0849.

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Definitions/Abbreviations

BEV - Battery Electric Vehicle

BMS - Battery Management System

BoM - Bill of Materials

CFD - Computational Fluid Dynamics

DoE - Design of Experiments

ECM - Equivalent Circuit Model

EIS - Electrochemical Impedance Spectroscopy

EoL - End of Life

EPMA - Electron Probe Microanalyzer

EV - Electric Vehicle

FuVA - Future Vehicle Architecture

GUI - Graphical User Interface

HIL - Hardware-In-Loop

IMBD - Integrated Model Based Design

PHEV - Plug-in Hybrid Electric Vehicle

RSM - Response Surface Methodology

SoC - State of Charge

SPM - Stochastic Process Model

V-SIM - Vehicle SIMulation

VPD - Virtual Product Development

WLTC - Worldwide harmonized Light vehicles Test Cycles

WLTP - Worldwide Harmonised Light Vehicles Test Procedure