MECHENG 754
Management and Control of Electric Vehicle Batteries
Fall 2023 Course Outline

Department of Mechanical Engineering
McMaster University

COURSE OBJECTIVE

The purpose of this course is to provide learners with knowledge of the critical aspects of managing Li-Ion battery systems in Hybrid Electric Vehicles (HEVs) and Battery Electric Vehicles (BEVs). This course provides a fundamental understanding of battery modeling, analysis, aging, thermal management, state of charge, and state of health estimation. Concepts such as parameter estimation, system identification, optimization, filtering, and control theory will be applied to battery systems. This course also covers advanced strategies for battery management and control using artificial intelligence and machine learning techniques.

INSTRUCTOR AND CONTACT INFORMATION

Time: Thursday 1:00 PM – 4:00 PM

Instructor: Dr. Ryan Ahmed
ryan.ahmed@mcmaster.ca

Office: Center for Mechatronics & Hybrid Technologies (CMHT) – Room 224
McMaster Automotive Resource Center (MARC)

COURSE ELEMENTS

Avenue:	Yes	Innovation:	Yes	Numeracy:	Yes
Participation:	Yes	Guest speaker(s):	Yes	Final Exam:	No
Experiments:	Yes	Written skills:	Yes	Group Project:	Yes

COURSE DESCRIPTION

This course covers the principles of Battery Management Systems (BMS) for monitoring, diagnosis, and control of batteries in Hybrid Electric Vehicles (HEVs) and Battery Electric Vehicles (BEVs). The course is targeted toward systems engineers, research scientists, and academics who want to gain a fundamental understanding of battery modeling, analysis, state of charge, and state of health estimation. Topics include an introduction to battery systems, battery equivalent circuit-based modeling, battery electrochemical modeling, reduced-order modeling, cell balancing, thermal management, state of charge, and state of health estimation. Concepts such as parameter estimation, system identification, machine learning, optimization, filtering, and control theory will be applied to battery systems. The techniques covered in this course are mostly related to Li-ion cells and packs as used in automotive applications. These can, however, also be applied to other battery chemistries.

LEARNING OUTCOMES

Upon completion of this course, students will be able to complete the following essential tasks:

- Understand the basic principles of batteries and battery management systems for electric vehicle applications.
- Develop an understanding of battery testing techniques and procedures used in the automotive industry.
- Apply their programming skills to develop code scripts and models for battery modeling, optimization, state of charge, and state of health estimation.
- Develop an understanding of battery aging and degradation mechanisms.
- Appy artificial intelligence and machine learning techniques for battery monitoring and control.
- Understand the basics of electrochemical battery modeling (physics-based modeling).

COURSE PREREQUISITES

1. MATLAB/Simulink/SimScape
2. Basic chemistry and materials background
3. Control theory background

- State Space representation
- Transfer functions
- PID controllers
- Root Locus techniques
- Optimization
- Stability analysis
- Z-domain, S-Domain analysis
- State estimation techniques

REQUIRED COURSE MATERIALS AND READINGS

Books:

- Battery Systems Engineering, Christopher D. Rahn, ISBN-13: 978-1119979500.

- A Systems Approach to Lithium-Ion Battery Management, Phil Weicker, ISBN-13: 978-1608076598.

Research Papers:

Artificial Intelligence Strategies for Li-Ion Batteries Monitoring and Control

- Ephrem Chemali, Phil Kollmeyer, Mattias Preindl, Ryan Ahmed, Ali Emadi (2018): "Long Short-Term Memory-Networks for Accurate State of Charge Estimation of Li-ion Batteries", IEEE Transactions on Industrial Electronics.

- Ryan Ahmed, Mohammed El Sayed, S. Andrew Gadsden, Jimi Tjong, Saeid Habibi (2016): “Artificial neural network training utilizing the smooth variable structure filter estimation strategy”, *Neural Computing and Applications, Volume 27, Issue 3, pp 537–548*.

State of Charge Estimation

- Sara Rahimifard, Ryan Ahmed, Saeid Habibi (2021): “Interacting Multiple Model Strategy for Electric Vehicle Batteries State of Charge/Health/ Power Estimation”, *IEEE Access Journal, Volume 9, pp 109875–109888*.
- Dianxun Xiao, Gaoliang Fang, Sheng Liu, Shaoyi Yuan, Ryan Ahmed, Saeid Habibi, Ali Emadi (2020): “Reduced-Coupling Co-estimation of SOC and SOH for Lithium-Ion Batteries Based on Convex Optimization”, IEEE Transactions on Power Electronics.
- Marvin Messing; Tina Shoa; Ryan Ahmed; Saeid Habibi (2020): “Battery SoC Estimation from EIS using Neural Nets”, 2020 IEEE Transportation Electrification Conference & Expo (ITEC).
- G. L. Plett, "Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs: Part 3. State and parameter estimation," vol. 277–292, no. 134, 2004.
- G. L. Plett, "Sigma-point Kalman filtering for battery management systems of LiPB-based HEV battery packs," *Journal of Power Sources,* vol. 2, no. 161, p. 1369–1384, 2006.
- D. Domenico, G. Di Fiengo, and A. Stefanopoulou. Lithium-ion battery state of charge estimation with a Kalman filter based on an electrochemical model. In Proc. IEEE International Conference on Control Applications CCA, pages 702-707, Sep 2008.
- I. Arasaratnam, Ryan Ahmed, M. El-Sayed, S. Habibi, and J. Tjong, (2013): Li-Ion Battery SOC Estimation Using a Bayesian Tracker, SAE World Congress, and Exhibition, Detroit, Michigan.
- Arasaratnam Ienkaran, Jimi Tjong, and Ryan Ahmed (2014): Battery Management System in the Bayesian Paradigm: Part I, Transportation and Electrification Conference and Expo, 2014.
- Carmelo Speltino, Domenico Di Domenico, Giovanni Fiengo, and Anna G. Stefanopoulou. Experimental validation of a lithium-ion battery state of charge estimation with an extended Kalman filter: Part i. In The European Control Conference, 2009.

Battery Modeling

- Ryan Ahmed, Javier Gazzarri, Simona Onori, Saeid Habibi, Robyn Jackey, Kevin Rzemien, Jimi Tjong, and Jonathan LeSage (2015): “Model-Based Parameter Identification of Healthy and Aged Li-ion Batteries for Electric Vehicle Applications”, *SAE Journal of Alternative Powertrains*.
- Ryan Ahmed; Sara Rahimifard; Saied Habibi (2019): “Offline Parameter Identification and SOC Estimation for New and Aged Electric Vehicles Batteries”, 2019 IEEE Transportation Electrification Conference and Expo (ITEC).
- Atriya Biswas, Ran Gu, Phil Kollmeyer, Ryan Ahmed, Ali Emadi (2018): “Simultaneous State and Parameter Estimation of Li-Ion Battery with One State Hysteresis Model Using Augmented Unscented Kalman Filter”, *2018 IEEE Transportation Electrification Conference and Expo (ITEC).*
- Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs: Part 1. Background, Journal of Power Sources, vol. 134, pp. 277–292, 2004.
- 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, no. 2, pp. 262-276, 2004.

- Domenico Di Domenico, Anna Stefanopoulou, and Giovanni Fiengo. Lithium-ion battery state of charge and critical surface charge estimation using an electrochemical model-based extended kalman filter. Journal of Dynamic Systems, Measurement, and Control, 132(6):061302, 2010.
- Ryan Ahmed, Mohammed El Sayed, Saeid Habibi, and Jimi Tjong (2014): Reduced-Order Electrochemical Model Parameters Identification and SOC Estimation for Healthy and Aged Li-Ion Batteries. Part I: Parameterization Model Development for Healthy Batteries, IEEE Journal of Emerging Technologies, Special Issue on Transportation and Electrification.
- Ryan Ahmed, Mohammed El Sayed, Saeid Habibi, and Jimi Tjong (2014): Reduced-Order Electrochemical Model Parameters Identification and SOC Estimation for Healthy and Aged Li-Ion Batteries. Part II: Aged Battery Model and State of Charge, IEEE Journal of Emerging Technologies, Special Issue on Transportation and Electrification.
- K. Smith and C.-Y. Wang, "Solid-state diffusion limitations on pulse operation of a lithium-ion cell for hybrid electric vehicles," *Journal of Power Sources,* vol. 161, no. 1, pp. 628-639, 2006.
- Carmelo Speltino, Domenico Di Domenico, Giovanni Fiengo, and Anna G. Stefanopoulou. Comparison of reduced order lithium-ion battery models for control applications. In Joint 48th IEEE Conference on Decision and Control and 28th Chinese Control Conference, October 2009.
- Carmelo Speltino, Domenico Di Domenico, Giovanni Fiengo, and Anna G. Stefanopoulou. On the experimental identification of an electrochemical model of a lithium-ion battery: Part ii. In The European Control Conference, 2009.
- K. A. Smith, C. D. Rahn, and C.-Y. Wang, "Model-Based Electrochemical Estimation of Lithium-Ion Batteries," in *IEEE International Conference on Control Applications*, San Antonio, Texas, USA, September 3-5, 2008.

Battery Parameters Identification

- J. C. Forman, S. J. Moura, J. L. Stein, and H. K. Fathy, "Genetic identification and fisher identifiability analysis of the Doyle–Fuller–Newman model from experimental cycling of a LiFePO4 cell," *Journal of Power Sources,* no. 210, pp. 263-275, 2012.

Estimation Strategies

- S. A. Gadsden, "Smooth Variable Structure Filtering: Theory and Applications," Hamilton, Ontario, 2011.
- S. R. Habibi, "The Smooth Variable Structure Filter," *Proceedings of the IEEE,* vol. 95, no. 5, pp. 1026-1059, 2007

Genetic Algorithm Optimization

- D. Goldberg, "Genetic Algorithms in search, Optimization, and Machine Learning," Addison-Wesley, Reading, Massachusetts, 1989.
- MathWorks Inc., "www.mathworks.com/help/grads/how-the-genetic-algorithm-works.html," 2013. [Online].

Thermal Management

- Ienkaran Arasaratnam, Jimi Tjong, Ryan Ahmed, and Saeid Habibi, (2013): Adaptive Temperature Monitoring for Battery Thermal Management, SAE World Congress, Detroit, Michigan.
- Xinfan Lin, H.E. Perez, J.B. Siegel, A.G. Stefanopoulou, Yonghua Li, R.D. Anderson, Yi Ding, and M.P. Castanier. Online parameterization of lumped thermal dynamics in cylindrical

lithium-ion batteries for core temperature estimation and health monitoring. Control Systems Technology, IEEE Transactions on, 21(5):1745-1755, Sept 2013.

Battery Testing

- Battery Test Manual for Plug-In Hybrid Electric Vehicles, March 2008, Idaho National Laboratory.
- M. Conte, V. C. Fiorentino, I. D. Bloom, K. Morita, T. Ikeya and J. R. Belt, "Ageing Testing Procedures on Lithium Batteries in an International Collaboration Context," China, November 2010.
- "www.epa.gov/nvfel/testing/dynamometer.htm," EPA United States Environmental Protection Agency.

Additional readings and handouts are to be assigned/provided by the instructor.

EVALUATION

All work will be evaluated individually except when group work is expected. In these cases, group members will share the same grade adjusted by peer evaluation. Your final grade will be calculated as follows:

Components and Weights

Final Project	40%
Assignments	35%
Midterm Exam	25%

Conversion

At the end of the course, your overall percentage grade will be converted to your letter grade in accordance with the following conversion scheme.

LETTER GRADE	PERCENT
A+	90 - 100
A	85 - 89
A-	80 - 84
B+	75 - 79
B	70 - 74
B-	60 – 69
F	00 - 59

Communication and Feedback

Students who wish to correspond with the instructor directly via email must send messages that originate from their official McMaster University email account. This protects the confidentiality and sensitivity of information as well as confirms the identity of the student.

Instructors are encouraged to conduct an informal course review with students by Week #4 to allow time for modifications in curriculum delivery. Instructors should provide evaluation feedback for at least 10% of the final grade to students before Week #8 in the term.

- ***Final Project Team Assignment (40%)***

Final Report/Paper (25%)
For your group project, you must select one of the topics/strategies discussed in class and further develop or compare strategies. Ultimately, students are required to summarize the results attained in the form of a conference or journal paper. This assignment will be conducted in groups of 4 to 5 students. The assignment should be approximately **10 typed pages, spaced at 1.5, excluding exhibits and appendices**. Most of your research will likely involve reading journal papers related to the topic.

Presentation (15%)
All teams must present their teamwork to the class. All team members are expected to be part of the presentation. The students will have 20 minutes plus a question-and-answer period. All team members will receive the same grade for their presentation.

- ***Written Assignments (35%)***

Students will be given five assignments to work on during the entire course. Assignments will include extensive programming using MATLAB/Simulink. The assignments will include hands-on experience with techniques currently implemented in battery management systems. Students will be given 2 weeks to solve each assignment.

ACADEMIC DISHONESTY

It is the student's responsibility to understand what constitutes academic dishonesty. Please refer to the University Senate Academic Integrity Policy at the following URL:

http://www.mcmaster.ca/policy/Students-AcademicStudies/AcademicIntegrity.pdf

This policy describes the responsibilities, procedures, and guidelines for students and faculty should a case of academic dishonesty arise. Academic dishonesty is defined as to knowingly act or fail to act in a way that results or could result in unearned academic credit or advantage. Please refer to the policy for a list of examples. The policy also provides faculty with procedures to follow in cases of academic dishonesty as well as general guidelines for penalties. For further information related to the policy, please refer to the Office of Academic Integrity at:

http://www.mcmaster.ca/academicintegrity

STUDENT ACCESSIBILITY SERVICES

Student Accessibility Services (SAS) offers various support services for students with disabilities. Students are required to inform SAS of accommodation needs for examinations on or before the last date for withdrawal from a course without failure (please refer to official university sessional dates). Students must forward a copy of such SAS accommodation to the instructor immediately upon receipt. If a student with a disability chooses NOT to take advantage of an SAS accommodation and chooses to sit for a regular exam, a petition for relief may not be filed after the examination is complete. The SAS website is:

http://sas.mcmaster.ca

POTENTIAL MODIFICATIONS TO THE COURSE

The instructor and university reserve the right to modify elements of the course during the term. The university may change the dates and deadlines for any or all courses in extreme circumstances. If either type of modification becomes necessary, reasonable notice and communication with the students will be given with explanation and the opportunity to comment on changes. It is the responsibility of the student to check their McMaster email and course websites weekly during the term and to note any changes.

COURSE SCHEDULE

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Department of Mechanical Engineering, McMaster University

WEEK	TOPIC
1	• Introduction to Batteries • Basic Definitions • Battery Characteristics • Kirchhoff's circuit Laws (Review) • Battery Pack Design • Battery Construction • Battery Operation • Battery Electrochemistry
2	• Introduction to Battery Management Systems • Coulomb Counting • Battery Modeling Overview • Lumped-Parameters (Behavioral) Models • Equivalent Circuit-based models • SOC-OCV Relationship Derivation – MATLAB Example • OCV-R Battery Model – MATLAB/Simulink Example • Battery Models simulation – MATLAB Example
3	• Genetic Algorithm Optimization • Model parameters identification: MATLAB EXAMPLE
4	• Introduction to Discrete-Time Domain • OCV-RRC Battery Model • Online Parameters Estimation – RLS • RLS Parameters Estimation: MATLAB Example • Battery Testing
5	• Control theory overview: transfer functions, stability, root locus, Observability and controllability • State Space Representation • Transformation from State Space to Transfer Function • Kalman Filtering • State of Charge Estimation
6	**MIDTERM EXAM**

7	• Introduction to Battery Degradation • Current Profile from Velocity Profile • Electric Vehicle Model • Driving Cycles – Battery Cycler • Battery Aging Tests
8	• Artificial Intelligence and Machine Learning techniques • Constant Current Constant Voltage (CCCV) Mode • Full-Order Electrochemical Battery Model • Reduced-Order Models • MATLAB Example
9	• Full-Order Electrochemical Battery Model – Continued • Reduced-Order Models – Continued • MATLAB Example – Continued
10	• Battery Pack design • Cell Balancing • Active and Passive Balancing – MATLAB/Example
11	• Thermal management • Pack observability • Core temperature estimation • MATLAB Example
12	**TEAM PRESENTATIONS – GROUP PROJECT**