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PhD Position:

Advanced and Efficient Observer Techniques for Monitoring Battery and Fuel Cell Systems

Context

Battery systems can be effectively modelled using nonlinear dynamics [Wang et al., 2020]. Nonlinearity arises from various factors such as the electrochemical reactions within the battery, non-uniform distribution of reactants, temperature effects, and the complex behavior of battery materials. Nonlinear models capture these complexities and provide a more accurate representation of battery behavior compared to linear models. Nonlinear battery models typically describe the relationships between voltage, current, the state of charge (SOC), the state of health (SOH), and other variables. These models can take different forms, such as physics-based models, empirical models, or a combination of both. Physics-based models incorporate fundamental principles and equations governing the battery's electrochemical processes, while empirical models are derived from experimental data. Common nonlinear battery models include the equivalent circuit models (ECMs), which represent the battery as an electrical circuit with various components such as resistors, capacitors, and nonlinear voltage sources. Other models, such as the Doyle-Fuller-Newman (DFN) model, the porous electrode model, or the dual-porosity model, capture the intricate dynamics of chemical reactions and transport processes occurring within the battery. Nonlinear battery models allow for a more accurate prediction of battery performance, including voltage response, capacity fade, power capability, and thermal behavior. These models are essential for designing advanced battery management systems (BMS) that optimize battery operation, enhance efficiency, and ensure safety.

While reliable nonlinear models for battery systems exist, accurately estimating the SOC and SOH of batteries and fuel cells from the modeling remains arduous. This is due to the complex nature of the system's behavior, which is modeled by a nonlinear ordinary differential equation. Additionally, the limited information available further complicates the task. Therefore, efficiently reconstructing the present states of batteries and fuel cells to obtain real-time information on the system for the purpose of control or monitoring, is a challenging endeavor. A common way of addressing this problem is to place some sensors on the physical model and design an algorithm, called observer, whose role is to process the incomplete and imperfect information provided by the sensors and thereby construct an estimate of the whole system state. Such an algorithm can exist only if the measurements from the sensor contain enough information to determine the unique state of the system; namely, the system is observable [Bernard, 2019].

Objective

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The objective of this PhD thesis is to encompass a larger class of nonlinearities than previously existing approaches [Lin et al., 2012; Couto and Kinnaert, 2018; Zhang et al., 2020] and to address the problem of designing set-membership observers [Chevet et al., 2022] including interval observers [Zhu et al., 2023] for nonlinear battery systems exposed to unknown inputs. Moreover, our design also aims at simultaneously returning estimates of states and unknown inputs for the purpose of quantifying the disturbances and detecting/mitigating the anomalies. Note that efficiency, performance, and accuracy of our proposed observer will be experimentally validated by employing the lab facilities available at the University of Oldenburg, Germany in the collaboration with Prof. Andreas Rauh.

Fulfilling the objective is to answer the following questions: (i) What model is best suited to deal with; (ii) How to choose a reversible change of coordinates transforming the given model into an identified-friendly form for which set-membership observers can be designed; and (iii) How to simultaneously reconstruct the unknown inputs, especially when they are distribution-free, large, and fluctuating.

The thesis pursues four concrete objectives:

- **Objective 1 - A suitable choice of battery modeling.** The objective is to do a literature study on structural properties of systems to find suitable design models of battery systems so that the design of an observer is feasible.
- **Objective 2 - Robust unknown input observer design in the context of nonlinear modeling.** Given the nonlinearity of the systems, it is crucial to carefully select the observer design coordinates. Normal forms, such as state-affine forms, linear parameter varying polytopic form, triangular forms, etc., have been identified for facilitating direct and straightforward observer construction. The objective is to find a reversible change of coordinates that transforms the nonlinear systems into normal form. Next, we design an observer in the new coordinates. Obtain an estimate for the system state in the initial coordinates by inverting the transformation.
- **Objective 3 - Unknown input reconstruction and observer optimization.** From an algebraic unknown input function represented by the output upper and lower boundary estimations, the system output and the state can be set up. On one hand, based on the algebraic unknown input function, a nonlinear state observer, together with an unknown input reconstruction, will be designed, forming an unknown input observer which can produce not only system state estimation but also unknown input reconstruction asymptotically and simultaneously. On the other hand, the gain parameter matrix in the estimator is optimized by minimizing the length of the interval, thus improve the estimation accuracy. It is formulated as L1 optimization problem or H infinity technique and can be efficiently solved by linear programming [Boyd and Vandenberghe, 2004]. This helps ensure that the maximum range of anomalies in batteries and fuel cells can be detected.
- **Objective 4 - Implementation of the observer techniques for batteries and fuel cells on simulation hardware.** The methodological results of Objective 2 and Objective 3 are validated for state and unknown input estimation of single and multiple battery

cells. For that purpose, the developed approaches will be interfaced with the simulators available at University of Oldenburg, Germany.

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Contact

Dr. Thach Ngoc Dinh
ngoc-thach.dinh@lecnam.net

Prof. Mathieu Moze
mathieu.moze@lecnam.net

Dr. Jérémy Van Gorp
jeremy.vangorp@lecnam.net