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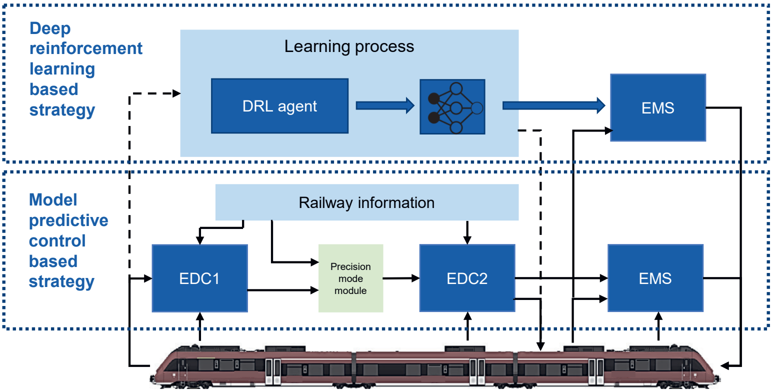
Kai Deng

Adaptive Online Energy Management Controls for Fuel Cell and Battery Hybrid Vehicles



SHAKER VERLAG

Band 51

Adaptive Online Energy Management Controls for Fuel Cell and Battery Hybrid Vehicles

Von der Fakultät für Elektrotechnik und Informationstechnik der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

vorgelegt von

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Acknowledgement

In the past five years, I have had the honor to engage in research and work at the Institute of Electrical Machines, which is a valuable experience and wealth in my life. I still remember vividly that five years ago, as a fresh graduated master's degree student in automotive engineering, I wanted to change my major direction from conventional to electric drive and applied for the position. What attracted me very much at that time was this project of hydrogen electric vehicle. I think using my knowledge of automotive and energy, and holding my interest in control, I can definitely make something new in energy management of electrical vehicles.

During the five years, I experienced several challenges. My first conference paper was rejected, I was confused about the direction of my dissertation, and due to the constraints of the COVID pandemic, I was limited in my project testbed. In addition, my first journal publications were met with critical questions. However, during this time, I received support from many people, especially from my supersivor, professor Hameyer. I would like to express my sincere gratitude for his invaluable guidance and support throughout my doctoral journey. His expertise and mentorship have been instrumental in shaping my research and academic growth. Many thanks also go to my second supervisor, professor Pischinger.I still remember when he handed me the award for the best poster in mobilEM and from which I got the networking with different research areas. I would especially like to thank Hujun for his support with my project and thesis, and Andreas for his help with my work. I would also like to thank Groshup for his comments with the presentation format, Johann for his support with the NVH project, and Jan and Sveto for their support with the microcontroller. In addition, thanks to Max, Fabian and Xiao for their pleasant and open communication, Liguo for her collaboration with LEGO Mindstorms, my office mate Niklas for his support in the classroom, Schauert for his daily jokes, and Petra, Isabel and Denis for their support in the daily stuff. Furthermore, I would like to express my heartfelt thanks once again to my Chinese IEM friends, whose support in my daily life has kept me worry-free, happy and feel always be accepted. Finally, I would like to give a special thank to Shubin, my mother and father for their continuous support.

Abstract

Hydrogen energy is one of the most promising energy sources of the future, and its use in transportation is thought to lead to revolutionary zero-pollution environmental improvements. Therefore, hybrid systems utilizing hydrogen fuel cells and batteries are a focal point of transportation electrification. Because of their significantly longer driving range, higher power and faster charging speed, fuel cell hybrid systems are considered both more environmentally friendly than conventional powertrains and more reliable than pure battery electric drives for heavy-duty transportation. However, hybrid systems due to more than one energy source inevitably involve energy management issues. The energy management strategy (EMS) has a huge impact on the performance of any hybrid powertrain, as it determines the operating point of almost all the components associated with the powertrain. As a result, there are a number of objectives that must be considered from a complete vehicle perspective, and these factors often include fuel consumption, energy efficient driving, and component aging. For fuel cell and battery hybrid electric railway vehicles, the major research case for this work, the EMS must not only minimize hydrogen consumption and maintain sustained battery charge, but also try to take advantage of the route information such as speed limitations and slope profile to enhance energy efficient driving, adapt to disturbances, and maximize fuel cell lifetime. Of note is that fuel cell aging is one of the major barriers to commercial use of fuel cell systems.

In this work, the influencing factors are considered together by multi-objective optimization methods in order to reduce the operational costs of a fuel cell hybrid system in a comprehensive way. However, disturbances such as temporary speed limits and passenger loads are random in realistic driving situations, which leads to uncertainty in the load power. Although the use of route information can bring enhancements as assisted driving is developing, drivers still have to make independent decisions in unexpected situations at this stage. So far, no complete solution has been proposed in the literature. Therefore, a solution is provided here with two new strategies that complement each other to solve the above-mentioned energy management problem.

As the first strategy, a hierarchical structure with model predictive control (MPC) is proposed using the route information. It transforms the problem mathematically, performs rational expression of the objective and solves the control strategy from far to near in multi-level prediction horizons. As the focus regarding the energy distribution, a Pontryagin's Minimum Principle (PMP)-based MPC strategy is developed in which the component constraints are considered internally in the controller, solving the difficulty of handling constraints such as SoC limitations in the PMP strategies. The equivalent cost derived from the PMP is used in the cost function, where the power consumption of the battery is rationally transformed into hydrogen consumption. In addition, a weight of fuel cell power increments to manage fuel cell power fluctuations is introduced considering the aging of the fuel cell.

As the second strategy, which performs as a complementary strategy to the case of insufficient or no timely route information, a deep reinforcement learning (DRL)-based EMS is proposed to train neural networks using a large amount of training data. It improves the value of a pre-defined reward function containing the optimization objective and builds its adaptability, where the latest deep reinforcement learning method, twin delayed deep deterministic policy gradient (TD3), is integrated into the EMS for the first time up to now. In order to achieve a near-realistic simulation and to overcome overfitting problem, several settings in the reward function and training environment are taken.

A new operation-based fuel cell aging estimation model is presented to evaluate the fuel cell aging. The model is developed based on measured data and is suitable for energy management use. It provides an estimate of voltage degradation based on the input fuel cell power.

Finally, several simulative validation and hardware-in-the-loop tests of the studied strategies is performed for different factors. The results showed that the proposed strategy can save from 14 % to 40 % of the operational cost compared to several conventional strategies, and can meet various design requirements such as sustainable battery charging and constraint compliance. The test results in the hardware-in-the-loop test bench shows the expected results as simulation and prove the ability of strategies to operate in real-time environments.

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