Synthesis of the thesis

The automotive industry's transition toward electrification has been driven by the dual goals of improving energy efficiency and reducing emissions. Hybrid electric vehicles (HEVs) have emerged as a pivotal technology in this transition, offering an effective compromise between traditional internal combustion engine (ICE) vehicles and battery electric vehicles (BEVs). By combining ICEs with batteries and electric motors, HEVs can effectively reduce fuel consumption and emissions by optimizing the power split between the two power sources. However, realizing the full potential of HEVs requires advancements in two critical areas: energy management strategies (EMSs) and robust battery state estimation.

This dissertation addresses these challenges by proposing control strategies for HEV energy management and battery estimation algorithms. The thesis is divided into two primary parts. The first focuses on developing EMSs for HEVs to optimize powertrain control. The second part concentrates on enhancing battery state estimation, particularly the state of charge (SOC) and state of health (SOH), which are essential information for the BMS.

In the first part, the thesis begins by establishing a comprehensive framework for modeling HEV powertrains from both energetic and exergetic standpoint. In contrast with the traditional energetic models, which quantify energy transfers, exergy analysis is a thermodynamic analysis technique routed in the first and second laws of thermodynamics and provides new design and control opportunities over conventional energy-based approaches. Exergy analysis enables to quantify the irreversibilities of a process, identify the sources of inefficiency, and assess the quality, rather than just the quantity, of energy transfers. The energetic and exergetic vehicle models lay the foundation for the proposed control strategies.

First, the state-of-the-art EMSs based on optimal control theory are described, serving as benchmarks for innovative strategies. Then, the thesis presents exergy-based management strategies specifically designed for military HEVs. By relying on the optimal control theory and the exergetic vehicle model, two novel exergy management strategies are formulated to minimize genset exergy destruction and thermal emissions, respectively. Regarding the energy-based strategies instead, a machine learning-based EMS leveraging reinforcement learning (RL) is proposed. This RL-based controller incorporates an innovative exploration strategy that accelerates the training process and improves performance, significantly reducing fuel consumption.

The second part of the thesis shifts focus to the battery management system (BMS), a critical component of hybrid and electric vehicles. The BMS plays a key role in ensuring battery safety, optimizing performance, and prolonging battery life. Accurate estimation of the SOC and SOH is fundamental to these objectives. While SOC estimation provides insights into the remaining driving range and affects power management, SOH estimation quantifies battery degradation and is closely related to the vehicle's remaining life.

This thesis introduces a data-driven SOH estimation method that relies on the extraction of degradation features during fast-charging events. This method is validated using experimental data from various fast-charging protocols, showcasing its applicability to real-world scenarios. Furthermore, this work proposes a hybrid SOC and SOH estimation method that combines model-based and data-driven techniques. This hybrid approach overcomes key limitations of traditional methods, such as the dual extended Kalman filter, by incorporating capacity information derived from data-driven algorithms. The result is a more accurate and robust estimation process, enhancing battery management in both hybrid and fully electric vehicles.

In conclusion, this dissertation provides a comprehensive framework for enhancing HEV energy management and battery diagnostics through innovative control strategies and estimation algorithms. By addressing key challenges in hybrid and electric vehicle technology, this research contributes to the advancement of sustainable transportation solutions, contributing to achieving a cleaner automotive future.