

Optimal Design and Control of Electric Traction Systems for Efficiency and Handling Enhancement in Battery Electric Vehicles

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Summary

The transition to electric powertrains drives innovation in vehicle design and control, leading to the new generation of sustainable and safe mobility solutions. Electrification offers flexibility in powertrain architectures, from single onboard motor vehicles to multi-actuated systems with in-wheel motors, paving the way to novel modular and reconfigurable architectures. Furthermore, the shift towards electric powertrains has unlocked new possibilities for advanced vehicle control strategies, leveraging the fast and precise torque response of electric motors compared to internal combustion engines, enabling the powertrain to act as a chassis actuator. This doctoral thesis presents efficiency and performance-oriented optimization methodologies for both the design and control of electric traction systems in various powertrain configurations, addressing optimization at the component level and extending to the vehicle-level control. The work is structured into three main research contributions: the optimal design of a multi-phase electric drive module (EDM), the development of a traction control strategy based on road conditions preview, and the design and experimental validation of predictive torque vectoring control for multi-motor electric vehicles.

The first part of the dissertation presents a comprehensive optimal design methodology for a low-voltage reconfigurable EDM, developed within the framework of the MOST National Centre for Sustainable Mobility. The design target is a modular powertrain system that can adapt to multiple driving missions—urban and extra-urban—while complying with the functional and safety constraints of a sub-60 V electric architecture. To this aim, a six-phase interior permanent magnet synchronous machine (IPMSM) is developed, powered by a dual-inverter system and supported by two swappable battery modules. A multi-objective genetic algorithm (MOGA) is employed to optimize the rotor and stator geometry over multiple representative operating points derived from driving cycle analysis. Unlike traditional optimization approaches focused on rated points, the proposed method embeds the full torque–speed envelope for two vehicle modes: the Frugal (single battery module, urban usage) and Dual (two battery modules, extra-urban usage). The optimization loop includes electromagnetic FEA simulations, rotor mechanical stress verification, and thermal performance analysis. The resulting optimal design achieves a peak efficiency of 97.8%, meets torque requirements across both missions, and exhibits reduced torque ripple thanks to the six-phase configuration. The EDM is prototyped and integrated within the original housing of a Fiat 500e, to develop a vehicle demonstrator. Simulation and test bench validation confirm compliance with WLTC performance targets, with urban energy consumption below 8 kWh/100 km in Frugal mode.

Secondly, a preview-based Nonlinear Model Predictive Control (NMPC) is developed to enhance traction control on irregular road surfaces by utilizing data on upcoming road profiles and friction conditions. Simulation analysis and experimental validation on a full-scale vehicle, demonstrate that, thanks to the rapid torque response of electric motors integrated with information from exteroceptive sensors and V2X communication, the proposed control strategy improves tire slip control across various road scenarios. The proposed NMPC uses a novel, detailed prediction model including longitudinal and vertical dynamics of the suspension and tire–road interaction, capturing the effects of road irregularities on wheel load and slip. A soft-constrained optimal control problem is formulated to regulate the tire longitudinal slip ratio within target boundaries adapted to the predicted friction level. Sensitivity analyses on sampling time, prediction horizon, and electric motor dynamics confirm the benefit of the preview-based formulation, which outperforms benchmark sliding mode and non-preview NMPC controllers, achieving up to a 48% reduction in peak slip and improved vehicle stability.

The third contribution investigates torque vectoring control in multi-motor electric vehicle architectures. Two case studies are considered: a rear in-wheel motor B-segment SUV and a four-motor all-wheel-drive electric race car prototype. A novel torque vectoring architecture is developed based on the combination of a feedforward controller, responsible for shaping desired yaw dynamics, and a predictive state-feedback controller, aimed at stabilizing lateral dynamics near handling limits. A sideslip angle estimation algorithm is also implemented, combining a kinematic observer with an extended Kalman filter for integration into the vehicle dynamics controller. The system is designed to operate in real-time without requiring online optimization solvers. Additionally, an energy-efficient torque allocator (ECO-TV) is proposed, which redistributes wheel torques in redundant architectures (e.g., 4WD) to minimize powertrain losses while preserving target yaw moment generation. The complete control scheme is tested in simulation through both open-loop and closed-loop maneuvers, showing improved agility and reduced handling limit violations. The system is also experimentally validated on track using the four-motor prototype, confirming the effectiveness of the torque vectoring controller and the estimator in real-time conditions.

This thesis provides a foundation for the development of a new generation of electric powertrains that combine high efficiency, adaptability, and intelligent control. By integrating optimization techniques into both design and control stages, it demonstrates how electrification not only enables superior torque actuation and energy efficiency but also opens the way to modular and reconfigurable architectures tailored to diverse user needs. These technological advances can foster the growth of novel mobility systems— flexible, safe, performative, and user-centered—which are crucial to accelerate the diffusion of electrified vehicles and overcome current barriers such as cost, range anxiety, and infrastructure limitations. In this perspective, the proposed methods and case studies contribute to shaping more accessible and sustainable electric mobility ecosystems.