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eMotor advanced fault-tolerant torque control for automotive applications

By

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Abstract

In the automotive industry, emerging technologies are rapidly advancing, with a strong potential to become disruptive in the near future. These innovations are mainly centered around electric traction systems, which can function either alongside traditional internal combustion engines or independently. These technologies are pushed by the global shift towards Electric Vehicles (EVs) that continues to accelerate, and so, the need for advanced and precise torque control strategies for electric motors has become increasingly crucial.

The primary objective of all control techniques is to ensure that the electrical machine's torque regulation remains stable and accurate across all possible operating conditions. Not only is the transportation sector transitioning towards electrification, but the industry is also following suit, subjecting electric motors to increasingly stringent performance requirements. This heightened demand, particularly in high-performance applications, such as automotive and motorsport, results in accelerated wear and degradation due to electric motor parameter variations and components aging. These variations, caused by environmental conditions such as temperature changes, overload and prolonged operation, lead to reduced efficiency, torque ripple and system instability.

In light of these challenges, this thesis proposes an advanced torque control strategy for electric motors that is robust against motor parameter variations due to environmental influences and components aging. To address these challenges, the proposed strategy employs multidimensional LookUp Tables (LUTs) to dynamically generate accurate current references for a Current Vector Control (CVC) system. By integrating multidimensional LUTs, the control system can account for real-time variations in motor resistance, inductance, and magnetic flux, providing improved torque accuracy, reduced energy losses, and enhanced overall performance. A detailed investigation is conducted on the impact of motor parameter variations on traditional torque control methods, such as Field-Oriented Control (FOC).

The study demonstrates the limitations of conventional approaches in handling parameter deviations, which often result in compromised torque precision and reduced efficiency. In contrast, the proposed robust control strategy consistently delivers more

accurate torque output, even under varying environmental and aging conditions. To further enhance reliability, the control system incorporates fault-tolerant properties to handle potential cooling system faults and encoder faults.

In the event of a cooling fault, the system can detect rising temperatures and adjust the motor's current limits accordingly, preventing overheating and ensuring continued operation under safe conditions. Similarly, the control system addresses encoder faults by implementing estimation algorithms that allow it to maintain stable torque control, even when encoder signals become unreliable or fail entirely. These fault-tolerant features improve the system's resilience and reliability, particularly in high-performance applications where any downtime can be critical.

The validation, carried out in a simulation environment and experimentally in laboratory, is performed on a range of electric motor platforms subjected to diverse operating conditions. The motors considered in the treatment are: an Internal Permanent Magnet (IPM) motor for high-voltage hypercar applications, an IPM motor for low-voltage micromobility applications, a Surface Permanent Magnet (SPM) In-Wheel motor and an IPM motor for automotive applications with motor onboard. The control algorithm has been tested with dSPACE environment and with an automotive microcontroller ensuring the control compatibility with automotive hardware of the final application.

The results highlight the high performance of the proposed control strategy in maintaining stable and efficient operation, especially in demanding applications such as electric vehicles, motorsport, and industrial automation. In conclusion, this thesis presents a significant advancement in electric motor control by offering a robust and adaptive solution to address the challenges posed by parameter variations and fault conditions in an electric vehicle and the proposed strategy ensures enhanced motor and vehicle longevity, reduced maintenance costs, and improved torque control precision in different conditions, making it an ideal choice for high-performance electrified systems.

Future step will explore the validation process in the final environment to validate the proposed control in a real vehicle prototype addressing real driving cycles and testing the control flexibility in high demanding applications.

Introduction and thesis goals

The automotive industry is undergoing a fundamental transformation driven by the global push towards electrification. As the world grapples with the challenges of climate change and the depletion of fossil fuels, the shift from conventional Internal Combustion Engine (ICE) vehicles to Electric Vehicles (EVs) has gained significant momentum. This transition is motivated by the need to reduce greenhouse gas emissions, improve energy efficiency and meet stringent regulatory standards that govern vehicle emissions. As a result, electric mobility (e-mobility) is becoming an increasingly viable and attractive solution for both consumers and manufacturers. Electrification in the automotive sector encompasses not only the complete replacement of ICEs with electric motors but also the proliferation of hybrid systems, where electric motors work in conjunction with traditional engines. Electric motors, known for their high efficiency, almost instant torque, and lower environmental impact, play a central role in this paradigm shift. However, as the automotive industry continues to evolve, so do the performance demands placed on electric powertrains. Motors must now meet stringent requirements for power density, efficiency, durability and cost-effectiveness, all while maintaining high reliability in different and harsh operating environments.

One of the key challenges in the widespread adoption of electric vehicles lies in optimizing the control strategies used to manage electric motors. The dynamic and varying operating conditions encountered in automotive applications demand robust and adaptive control systems, that can ensure the precise regulation of motor torque, speed and efficiency. The accuracy and stability of these control systems are critical for ensuring smooth vehicle operation, extending battery life and enhancing overall vehicle performance. Traditional control methods, such as Field-Oriented Control (FOC), have proven effective in managing motor performance, but they face limitations in high-performance and high-efficiency applications, particularly when subjected to parameter variations due to temperature fluctuations, component aging or unpredictable environmental conditions. As electrification advances, so does the need for more sophisticated and intelligent control strategies. Modern control algorithms must not only improve upon existing techniques but also address the growing complexity of electric powertrains. Advanced strategies, such as model predictive control, machine learning-based control and the use of multidimensional lookup tables, offer the potential to enhance motor performance, increase robustness to parameter variations and improve energy efficiency under varying loads and operational conditions.

This thesis focuses on the development and implementation of advanced motor control strategies for automotive electric drives. Specifically, it explores unified torque control techniques that aim to improve the efficiency and reliability of electric motors in the demanding automotive environment. The research leverages innovative control methodologies, including the use of pre-calculated multidimensional lookup tables and fault-tolerant control designs, to address the challenges posed by motor parameter variation and environmental factors. The thesis not only contributes to the ongoing electrification of the automotive sector but also lays the foundation for future advancements in motor control, by developing robust, efficient, and adaptive control strategies, this research supports the broader goal of creating more sustainable, high-performance electric vehicles that meet the evolving demands of the automotive industry.

Thesis contents

This PhD thesis contains the research carried out during the three years of PhD at Politecnico di Torino in the Innovative Electric and Hybrid Vehicles (IEHV) Research Group in the DIMEAS department in collaboration with the Power Electronics Innovation Centre (PEIC) of the DENERG department and during the visiting PhD period at Vrije Universiteit Brussels (VUB) university. The main focus of the thesis has been the investigation of different electric motor control strategies for optimal torque control in automotive applications.

- **Silk Faw IPM motor for hypercar applications**

The first developed control, FOC 4D, represents the state of the art in high-performance and high-precision motor control, ensuring accurate torque regulation under varying torque requests, rotor speed, DC-link voltage, and magnet temperature conditions. Designed to enhance motor control accuracy, the FOC 4D dynamically adapts to changes in operating conditions, maintaining stable performance across different speed ranges while compensating for fluctuations in voltage and temperature to prevent saturation and performance degradation.

To validate the control strategy, a hypercar motor simulation was carried out using Finite Element Method (FEM) flux maps provided by Silk Faw. This simulation allowed for an accurate representation of real-world operating conditions, including high-speed and high-torque scenarios. By analyzing motor behavior under varying electrical and thermal conditions, the validation process confirmed the robustness and adaptability of the FOC 4D. The control strategy successfully maintained high torque accuracy, effectively compensating for voltage and temperature variations to prevent deviations.

The results demonstrated that FOC 4D is a highly effective solution for high-performance electric powertrains, providing precise and reliable motor control. Successful validation established its feasibility for hypercar applications, where maintaining accuracy and stability under extreme operating conditions is essential. This development set the foundation for further advancements in multi-dimensional motor control.

- **Mavel IPM motor for micromobility applications**

The validation of the FOC 4D control has been further enhanced by expanding the four-dimensional lookup tables (4D LUTs) into five-dimensional lookup tables (5D LUTs). This expansion incorporates the maximum current limit, a critical parameter for implementing derating strategies in automotive applications, ensuring effective management of powertrain component overheating and potential cooling faults. By integrating this additional dimension, the control system can dynamically adjust performance based on thermal constraints, improving both reliability and efficiency.

To assess the effectiveness of this advanced control strategy, the FOC 5D has been validated through simulation using a Mavel electric motor prototype. The validation process included a comprehensive magnetic characterization of the Mavel IPM motor, where flux maps were generated to accurately replicate its electromagnetic behavior. These detailed flux maps provided a precise representation of the motor’s performance under varying conditions, allowing for a realistic and reliable evaluation of the control strategy. The combination of simulation-based validation and experimental data from the characterized motor ensured that the FOC 5D effectively adapts to real-world operational constraints, reinforcing its suitability for micromobility automotive applications.

- **Elaphe In-Wheel SPM motor for direct drive automotive applications**

The FOC 5D fault-tolerant control has been experimentally validated using an Elaphe SPM motor designed for direct-drive automotive applications. The implementation began with the FEM flux maps provided by Elaphe, ensuring an accurate representation of the motor's electromagnetic characteristics. Following the validation of these flux maps, the control strategy was tested under motor temperature variations by developing and verifying a thermal model to predict and manage thermal behavior effectively.

To further assess its robustness, the derating strategy was validated by intentionally heating the motor, allowing the system to adjust torque limits dynamically to prevent overheating. Additionally, the fault tolerance of the control was tested through a cooling fault scenario by switching off the motor's cooling pumps. This experiment confirmed the control's capability to detect the cooling failure, activate current derating, and maintain safe operating conditions without compromising system integrity. The results demonstrated that the FOC 5D effectively manages temperature variations and cooling failures, ensuring reliable performance in demanding automotive applications.

- **Ecomer IPM motor for automotive applications**

The FOC 5D control has been further enhanced to incorporate compensation for motor aging, resulting in the development of the FOC 6D. This advanced control strategy utilizes six-dimensional lookup tables (6D LUTs) to ensure maximum torque precision under all motor operating conditions throughout the vehicle's lifetime. The proposed control has been experimentally validated using an eComer IPM motor for traction applications, beginning with a comprehensive magnetic characterization to generate the necessary 6D LUTs. Since a real aged motor was not available for testing, the aging dimension was validated through an emulation process designed to replicate the effects of motor aging on performance.

To further optimize the control, the voltage-speed dimensions were condensed into a single Available Flux dimension, while the magnet temperature and aging dimensions were merged into a magnet flux estimation dimension. This transformation resulted in a refined version of the control, effectively reducing the computational complexity while maintaining high precision. The final implementation, referred to as an FOC 4D with a low-priority magnet flux observer, was validated using the eComer motor, demonstrating reliable torque control with significantly reduced memory requirements for storing LUTs and lower computational demands for both the motor thermal model and the aging model. The results confirmed that this optimization preserves fault tolerance and precision while improving efficiency, making it a highly effective solution for long-term traction applications.