Abstract

This dissertation focuses on advanced modeling and torque control of Electrically Excited Synchronous Machines (EESMs) for high-performance automotive traction applications. Driven by the necessity to reduce reliance on rare-earth-based Permanent Magnet Synchronous Machines (PMSMs), this research investigates EESMs as a competitive, sustainable, and high-efficiency alternative for traction electric powertrains. The work addresses the inherent challenges introduced by the traction EESMs, focusing on nonlinear magnetic saturation, significant armature reaction, and the dynamic cross-coupling between stator and rotor circuits.

The scientific contribution is structured around four fundamental pillars. First, a robust three-stage experimental identification procedure is proposed to accurately characterize the stator and rotor flux linkage maps. This methodology identifies both stator and rotor flux linkages across the complete operating envelope by: time-domain integration of the rotor back-EMF during continuous sinusoidal excitation; implementation of a Particle Swarm Optimization (PSO) routine to eliminate fictitious hysteresis loops caused by thermal resistance drifts and inverter non-linearities; and determination of the integration constant through magnetic symmetry during open-rotor stator current reversals.

Second, a novel Full-Voltage-Behind-Reactance (Full-VBR) model is developed to provide a circuital digital twin capable of accurately replicating electromagnetic transients and nonlinear saturation effects. Unlike traditional models, this formulation partitions the machine into a dq-frame stator subsystem and explicit rotor state-space equations, allowing for the analytical identification of stator leakage inductance and the effective current ratio under deep saturation conditions.

Third, a Unified Torque Controller (UTC) architecture is introduced, providing a modular platform that integrates different Torque Control Approaches (TCAs), including Current Vector Control (CVC), Direct Torque Control (DTC), Direct

Flux Vector Control (DFVC), Flux Polar Control (FPC), and Flux Vector Control (FVC). The UTC employs a dual-torque reference strategy (T^* and T_f^*) to decouple stator and rotor regulation paths, optimizing global Joule losses while incorporating dynamic thermal derating to protect the powertrain components across all operating regimes.

Finally, a self-calibrated Dead-Beat Direct Flux Control (DB-DFC) methodology is proposed to be integrated in the UTC framework with minor control modules changes. By directly regulating the stator and rotor flux linkages in discrete-time, this "plug-and-play" approach eliminates the need for extensive inner-loop calibration and gain scheduling. The DB-DFC is rigorously derived in stationary $\alpha\beta$, rotor dq, and stator dqs coordinates, demonstrating superior performance and stability even at low sampling-to-fundamental frequency ratios.

Experimental validation, conducted on a 100 kW commercial traction EESM using a dSPACE MicroLabBox platform, confirms the high-fidelity of the identified maps and the robustness of the proposed control schemes. The results demonstrate a competitive torque regulation dynamic and accuracy across the entire speed range. However, different behavior are highlighted according to the different TCA implemented. This dissertation establishes a comprehensive methodological approach that enables the full performance exploitation of EESMs, providing a definitive benchmark for the next generation of electrified automotive powertrains.