Abstract

The global shift toward transportation electrification has accelerated in the past decade, driven by growing environmental concerns. Electric motors and their control systems are an essential part of electric vehicle (EV) propulsion. Permanent Magnet (PM) motors currently dominate due to their high torque density, power density, and efficiency. However, drawbacks such as reliance on rare-earth materials, high cost, thermal sensitivity, and limited fault tolerance have prompted exploration of alternatives. Brushless wound-field synchronous motors (WFSMs) present a promising option, offering improved fault tolerance and controllable excitation. The excitation system critically affects WFSM performance, compactness, and reliability. Traditional shaft-mounted auxiliary exciters make the system bulky, while harmonic/sub-harmonic excitation eliminates the exciter but adds control complexity and limits slot utilization. To address these issues, research has been directed towards embedded exciters, integrating exciter windings within the main machine. The Brushless Induction Excited Synchronous Motor (BINSYM) is one such concept. The exciter, which is an induction machine (IM), is embedded inside a power-delivering synchronous motor (SM). Although they share the same magnetic core and slots, the use of different pole numbers ensures magnetic decoupling, enabling independent control. However, a comprehensive study of BINSYM's design, control, and performance across a wide speed range remains unexplored. This thesis aims to fill that gap through a detailed investigation and optimization of BINSYM.

The thesis begins with the mathematical modeling of BINSYM, forming the basis for simulations and control strategy development. It then identifies the suitable operating mode of IM (among plugging, generating, and motoring) for effective field excitation of SM with reduced magnetizing current of IM. The safe operating area of the SM is defined using a circle diagram under voltage and current constraints. Leveraging the wound-field rotor structure, the thesis proposes maximum torque per ampere (MTPA) control using variable field excitation. In the field-weakening (FW)-region, this approach is refined by minimizing the magnitude of d-axis current of SM. A model-based method selects the optimal operating point, enabling efficient torque production with lower current, thereby reducing copper losses and enhancing drive efficiency. Since MTPA with variable excitation is limited to the FW-region and does not guarantee maximum efficiency, an alternative efficiency-maximization strategy is developed. This involves a detailed core loss model derived from experimental prototype data and a new approach to calculate loss based on input voltage and current, eliminating reliance on temperature-dependent resistance. A comparative study confirms the superiority of the efficiency optimization strategy over MTPA control. The proposed strategies are validated through hardware implementation and experimental testing on a lab-scale BINSYM prototype.

The thesis also addresses the unique design challenges of BINSYM for EV applications. As IM and SM share a common magnetic core and slots, a different design approach is adopted to suit this combined structure. A multi-objective optimization framework based on the Pareto front is used to identify the optimal geometry and operating parameters that balance high torque density and efficiency. The final electromagnetic design is validated through finite element analysis (FEA) using ANSYS/Maxwell-2D. Collectively, these contributions offer a rare-earth material (REM)-free, high-performance, brushless synchronous motor for EV applications.

Keywords: Wound-field synchronous motor, BINSYM, embedded exciter, magnetic decoupling principle, MTPA, efficiency optimization, design optimization, finite element analysis