Abstract

The growing environmental concerns have led to extensive research on Hybrid and Battery Electric Vehicles (HEVs/BEVs) due to their potential as a promising solution for reducing emissions and improving fuel efficiency in the automotive industry. Furthermore, enhanced electrification and transformed mobility are translating to a demand for higher power and more efficient Electric Drive Units (EDUs) that are compact, reliable, affordable and provides better range for a given battery charge. To realize these targets, the Electric Machine (EM) should be designed and optimized as an integrated system with transmission rather than an isolated unit to achieve high power density, high efficiency with minimum cost and volume. However, most of the existing literature on EM design optimization focuses solely on the component level and does not consider system-level requirements and integration with other components of the EDU, such as the transmission. Furthermore, few efforts are dedicated to a systematic approach to design and optimize EM starting from the vehicle performance requirements. Moreover, design choices such as EM winding configurations, skew topologies and manufacturing aspects exert a significant influence on the overall performance of the EDU and requires more attention due to lack of detailed literature on this subject.

In this context, this doctoral thesis first focuses on the development of a methodology for system level optimization of EM and transmission, starting from the vehicle performance requirements. To this end, a multi-objective optimization methodology based on Particle Swarm Optimization (PSO) within the MATLAB environment has been developed to achieve optimal operating points for the EM and transmission over a target driving cycle in traction applications, resulting in reduced energy consumption at the vehicle level. Proposed design optimization method considers the entire range of operation instead of enhancing the rated performance. The optimization has been carried out on three different pole-slot combination of V-type Interior Permanent Magnet (IPM) synchronous machine combined with eight different transmission gear ratios to shed light on the trade-offs and trends related to drive-cycle losses, power density, torque ripple, weight and material cost of the IPM machine. The developed design algorithm is applicable to any configuration of sine-wave-driven IPM and synchronous reluctance motors over any target driving cycle.

The present work introduces a system-level design optimization methodology that establishes specific steps for designing the EM for a given vehicle. The methodology starts from the calculation of EM design requirements in terms of maximum torque based on gradeability and maximum speed to reach the top vehicle speed, as a function of transmission gear ratio to fulfill the vehicle performance targets. Subsequently, the torque-speed operating profile of the EM in a target driving cycle is determined using a backward simulation model of the BEV. A range split clustering method is then employed to identify representative points (RPs) in the torque-speed plane. FEMM is used to set-up a parametric 2D Finite Element Model of the EM containing eight independent design variables on stator and rotor. Then a high-fidelity Finite Element Method (FEM) is employed for the full characterization of each EM design candidate over the entire range of current excitation in first stage. While, performance parameters such as weight, material cost, EM losses, and torque ripple are calculated over the previously obtained RPs in the second stage. Finally, the effectiveness of the methodology is demonstrated by optimizing the well-established EM design represented by the Nissan Leaf IPM motor over a WLTP driving cycle. The average efficiency over the WLTP cycle was increased by 1.2% and also the weight of the Permanent magnet was reduced to achieve lower cost with the developed design algorithm.

While the second part emphasizes the impact of design choices on EM performance to facilitate a faster design. It presents a qualitative and quantitative comparison between concentrated and distributed winding configurations for HEVs, and analyzes their effect on energy consumption in a P2 HEV for a WLTP driving cycle. Additionally, 3D finite element modeling and simulation are employed to assess the influence of rotor skew on the performance of the V-type IPM and flat type IPM motors. It has been demonstrated that the maximum torque reduction in V-type IPM can go upto 18.5%, instead in Flat IPM it can be until 12% based on the type of skew. The validity of the simulation is experimentally validated using an EM prototype. Furthermore, the impact of air-gaps between modular teeth and yoke on the performance of an IPM machine is highlighted at the end. It has been observed that the air-gaps can result in a decrease of 4-5% in BEMF.