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Limitations/capabilities of electric machine technologies and modeling approaches for electric motor design and analysis in plug-in electric vehicle applications

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ABSTRACT

The electrical machine (EM) is a key component in plug-in electric and hybrid vehicle (PEV) propulsion systems. It must be designed for high torque/power densities, wide speed range, over load capability, high efficiency at all speeds, low cost and weight, fast acceleration and deceleration, while meeting performance and reliability expectations. This paper overviews various EM technologies that are the best candidates for use in PEVs. Their basic operational characteristics, design features and relative advantages and disadvantages are discussed and compared for PEV propulsion systems. The latest and future research directions of EMs for PEVs are identified and discussed. Literature concerned with limitations and capabilities of finite element analysis and magnetic equivalent circuit analysis for EM design and analysis in PEVs is presented. Unfortunately, few papers give thorough comparisons between experimental measurements and simulation tools for EMs; even fewer compare torque. Those that report on torque show errors of 10% or more between tests and simulations. Saturation and losses appear to be the likely culprits. When nonlinear magnetic effects are taken into account, including magnetic saturation, eddy currents losses, and modeled with care, differences between simulations and tests typically are on the order of 5%.

Contents

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1. Introduction

In recent years, concerns about energy security and costs, global warming and environmental issues, fossil fuel availability, and consumer expectations have motivated research in plug-in electric and hybrid vehicles (PEVs). The PEV electric drive system of consists of four key components: electric machine (EM), battery, power electronic converter and controllers, as shown in Fig. 1. The challenges are to achieve high efficiency, reliability, ruggedness, small size and volume, and low cost in EMs, as well as in associated power electronics [1,2]. Improvements to the PEV electric drive system increase overall efficiency and driving range, and reduce greenhouse emissions and fuel dependence [3,4].

The EM is a key enabling technology for PEV drive system and is highly efficient in a wide operational area, emits no tailpipe pollutants and offers faster acceleration and quieter operation than internal combustion engines (ICEs) [5–7]. Thus research on EMs in the PEV has been intense over the past decade [2,8]. EM requirements for traction applications place a premium on a high power/weight ratio, efficiency, reliability and fault tolerance, overload capability, a wide speed range, robustness, low cost, and small size and volume [9–13]. These requirements make EM design and analysis a particular challenge. Selecting the most appropriate and efficient electric propulsion system for PEV is also a challenging task. The major types of EM technologies for PEVs include dc, induction (IM), permanent magnet (PM) and switched reluctance (SRM) machines, each with its own specific advantages and disadvantages [14–16]. IMs and PM machines are in the main stream in today's PEV propulsion. IMs provide a magnet-less motor design because they rotate with induction MMF. The IM is one of the main candidates for the PEV powertrain due to its simplicity, low cost, wide speed range, ruggedness, reliability and good dynamic performance [17–119]. The superior performance of the PM machine, including high efficiency and torque density, small volume, light weight, is the most important reason that it is claimed to be the ideal EM choice [13,20–22]. Although PM machines currently dominate, IMs, the hybrid excited and non-magnet or less rare-earth magnet EM topologies, such as synchronous reluctance machine (SynRM) [23] and PM assisted SynRM [24], are expected to see a significant increase in their share over the next decade, due to the limitation of resources and fluctuation in the price of the PM materials [25,26]. SRMs can be strong competitive candidates and are gaining interest, since they have simple and robust rotor structure and exhibit inherent capability for fault tolerance. However, SRMs have disadvantages, including large torque ripple, high noise and vibration, and relatively low torque density compared with PM machines. Therefore, SRMs are being extensively investigated to overcome these drawbacks [9,23,27,28] (Table 1).

Electric machines for PEVs may operate at higher current density than more conventional EMs of the same power rating, either because liquid cooling is employed or because short-term rating requirements are much different. Effective EM analysis must address unusual operating regimes. Modeling of saturation, end-effects, eddy currents, and hysteresis effects are difficult but essential for accurate models. If a user simply neglects saturation and other nonlinear magnetic effects, a machine can only be modeled up to a limited fraction of its operating capability, and substantial errors are likely over the full operating range. Traditional EM design methods focus on single-point performance optimization. They are based on empirical design formulations and rules gathered from standard designs. In general, EM design considerations for PEVs significantly differ from conventional design and require a series of iterative computations based on the selection of different configurations. They involve several fields of physics, such as electromagnetic, thermal, and mechanical (multiphysics) [29,30]. The propulsion system performance is strongly constrained by thermal limits. It is essential to accurately predict thermal behavior of the traction motor in the design stage. And an efficient cooling system design plays an important role in successful EM design [31]. The temperature rise computation in various EM parts can proceed in parallel with the electromagnetic performance computation [32]. Therefore, a coupled electromagnetic and thermal model is needed for more accurate prediction of the machine's performance limits. Mechanical designs are also challenging in EMs due to the high operating speeds used to achieve high power density in PEVs [14].

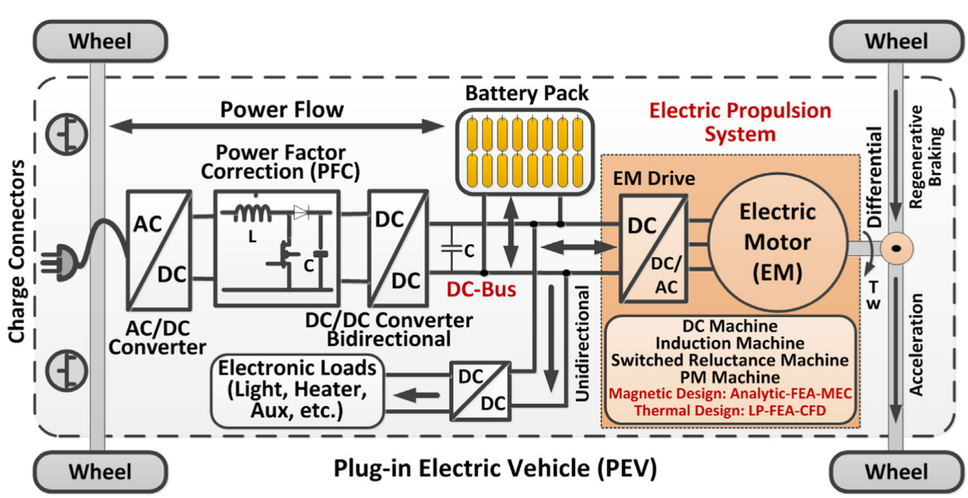

Fig. 1. Electric propulsion system of PEV.