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Fractional Slot Permanent Magnet Brushless Machines and Drives for Electric and Hybrid Propulsion Systems

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Abstract: *Fractional slot permanent magnet brushless machines having concentrated non-overlapping windings have been the subject of research over last few years. They have already been employed in the commercial HEVs due to high torque density, high efficiency, low torque ripple, good flux-weakening and fault-tolerance performance. However, due to rich mmf harmonics, such machines exhibit relatively high rotor eddy current loss, potentially high unbalanced magnetic force and acoustic noise and vibration, while the reluctance torque component is relatively low or even negligible when an interior PM rotor is employed. This paper summarizes their various structural and design features for EV/HEV applications.*

Keywords: acoustic noise, cogging torque, fault tolerance, flux weakening, fractional slot, iron loss, magnet loss, modular structure, permanent magnet machines, unbalanced magnetic force, vibration, winding inductance.

1. Introduction

Electrical machines and drives are a key enabling technology for electric (EV) and hybrid electric (HEV) vehicles. For such applications the basic required characteristics include [1]-[3]: (a) High torque density and power density; (b) High torque for starting, at low speeds and hill climbing, and high power for high speed cruising; (c) Wide operating speed range; (d) High efficiency over wide speed and torque ranges, particularly at low torque operation; (e) Intermittent overload capability for short durations.

Due to the permanent magnet (PM) excitation, PM brushless machines are inherently efficient and hence have been extensively used for EV/HEV applications. They can be generally classified as either brushless DC (BLDC) in which the back-emf waveform is desirable to be trapezoidal and the current waveform is controlled to be rectangular, or brushless AC (BLAC) in which the back-emf waveform is desirable to be sinusoidal and the current waveform is controlled to be sinusoidal, in order to maximize the torque density and minimize the torque pulsation. However, it is usually preferable to employ BLAC drives in EV/HEV applications [4][5] due to their advantages in terms of torque density, efficiency, as well as controllability.

Surface-mounted PM (SPM) brushless machines which have a fractional number of slots per pole and a concentrated non-overlapping winding have been the subject of recent research [6]-[66]. The stator coils may be wound either on all the teeth (double-layer winding) or only on alternate teeth (single-layer winding). They have an inherently low cogging torque [46]-[51], short end-windings and, hence, a low copper loss, a high efficiency, and a high power density, as well as better flux-weakening and fault-tolerance performance [35]-[45]. However, the torque is developed by the interaction of a high stator space harmonic mmf with the permanent magnets. The fundamental and low order space