Design and Control of a Novel Axial Flux Permanent Magnet In-Wheel Machine for HEVs

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***Abstract* —For hybrid electric vehicles with in-wheel drive, it is important for the motor to operate with constant power over a wide speed range and with the possibility of being operated with high flux weakening. It is however difficult for traditional surface mounted PM machines to produce constant-power for wide speed range, since the inductances of these machines are generally too small and hence cannot be adjusted readily to allow the motors to operate at constant power. In this paper, an axial flux Vernier PM direct-drive machine for in-wheel applications is proposed and analyzed. The stator windings have a fractional slot concentrated distribution with relatively high phase inductance. Its steady-state and transient performance is simulated using three-dimensional (3-D) finite-element methods (FEM) and the results are used to showcase the design validity of the proposed machine.**

***Index Terms*—Electric machine, electric vehicle, finite element method, hybrid electric vehicle.**

I. Introduction

Axial flux permanent magnet (PM) machines have compact structures, high torque density, high efficiency, short axial length and hence are very suitable as in-wheel direct drives in electric vehicles or hybrid electric vehicles [1-2]. Recently, magnetic flux-modulated PM machines with a low stator armature pole pair and a high rotor PM pole pair for direct-drive operation have received increasing interests [3-6]. The idea of flux-modulated machines is initially derived from magnetic gears (MG). By exploiting flux modulation through the magnetic segments in the airgap, the high-speed rotary field of MG is transformed to a low-speed rotary field, and the rotor can then be driven at a low speed to produce high torque [7-8]. By replacing the rotary PMs with stationary armature windings, flux modulation are obtained and the magnetic gear effect is realized within PM machines. In this paper the concept of flux-modulated machines is generalized and further extended. If the number of modulation segments is chosen to be a multiple of the stator tooth number, a Vernier PM machine (which is a special type of flux-modulated machines) is obtained. In this paper, the Vernier structure is integrated with an axial flux PM machine to include the magnetic gear effect to produce high torque for in-wheel drives of electric vehicles.

For in-wheel drivers, a high flux weakening capability and a wide speed range of constant-power operation are important. It is difficult for traditional surface mounted PM machines to produce constant-power for wide speed range operation, since the inductances of such machines are small and hence cannot be adjusted readily. In this paper, the proposed axial flux Vernier PM direct-drive machines for in-wheel applications are analyzed. The stator windings have a fractional slot concentrated distribution with relatively high phase inductance. As inductance is an important parameter to realize good dynamic performance, it is necessary to calculate the inductance precisely in order to estimate the flux weakening capability of machine. Previous inductance calculation method with finite element method is time consuming. In this paper, the machine d-axis and q-axis inductance can be calculated at two specific positions and the flux weakening control method is applied to this novel in-wheel machine to realize constant power over a wide speed range.

II. Analysis of the Flux Modulated Machine

As shown in Fig. 1 (a), the proposed machine has two airgaps and 23 pole-pairs of surface mounted PMs on the outer rotor. The winding armatures with 4 pole-pair are housed in a stator which has 9 slots and 27 teeth. The static and transient performances of the machines are analyzed using three-dimensional time-stepping finite element method (3D-TS-FEM) [9].

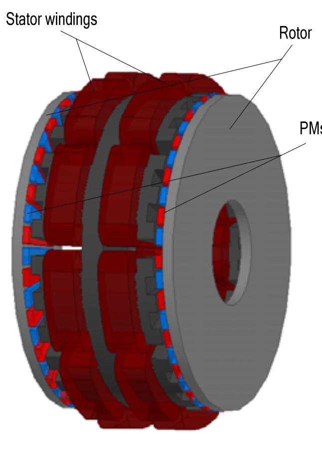


Fig. 1. Configuration of the machine.

The rated speed of the machine is 800 rpm and its rated power is 900 W. The back emf waveform is basically sinusoidal at rated speed as shown in Fig. 2. The cogging torque is very small, as shown in Fig. 3. Torques on stator and rotor during locked-rotor are shown in Fig. 4(a) and the rated torque waveform is depicted in Fig. 4(b). By aligning the center of phase A with the d-axis, the d-axis and q-axis inductances are calculated using the 3/2 phase transformation. The detailed inductance calculation, flux weakening control strategy and experimental results will be given in the full page paper.

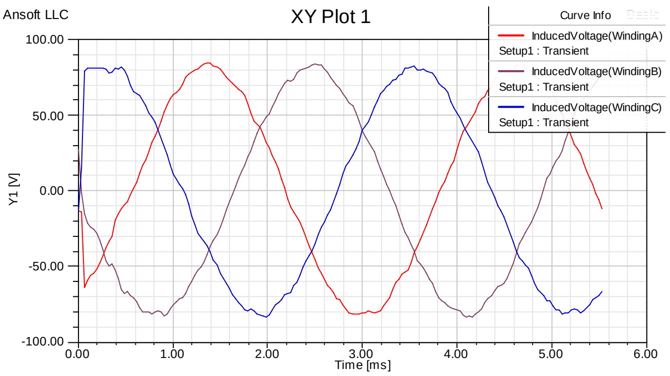


Fig. 2. Back emf.

In this paper the concept of flux-modulated machines is further extended. If the machine has a similar slot and pole number, such as in fractional slot concentrated winding design, the slot/pole combination of such machine can be classified as one special case of flux-modulation machines in which the number of modulation segments is equal to the stator tooth number, and no additional flux modulating poles are needed. Fractional slot concentrated windings have the beauty of having reduced copper losses and high copper fill factor. The multi-pole structure also contributes to a very thin stator yoke with reduced machine volume. The synchronous effect and gear effect can be effectively integrated and utilized to produce a steady and positive torque output at a relatively low speed within one machine.

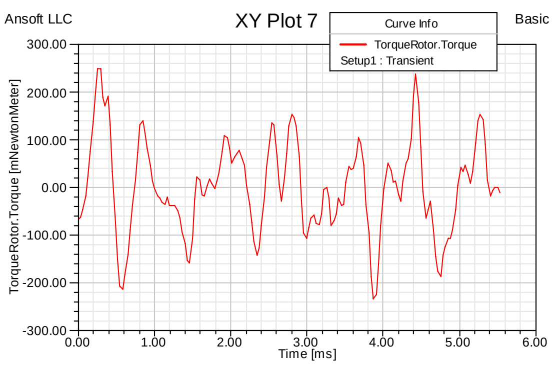
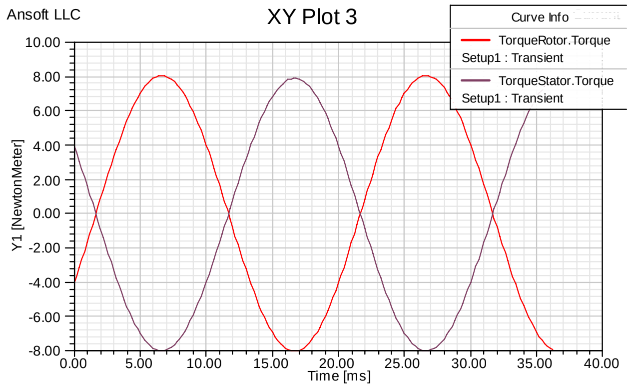
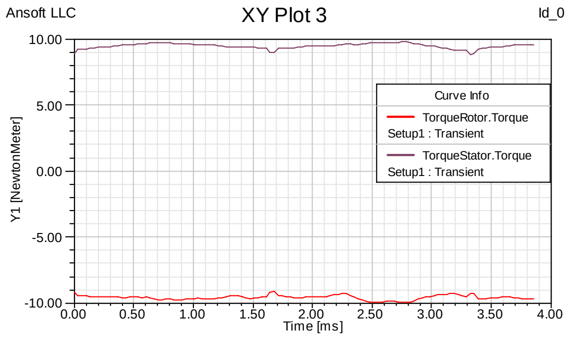


Fig. 3. Cogging torque.



(a)



(b)

Fig. 4. Torques on stator and rotor. (a) Static. (b) Rated torque.

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