High-Torque Low-Speed Machines for In-Wheel Application: Comparative Study of Radial, Axial, and Transverse Flux Machines

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***Abstract*—For the in-wheel motor development, three different types of electric motor were designed and compared the performance. The radial-flux machine with surface-mounted permanent-magnet on the rotor, the three-phase transverse-flux machine with flux-concentrated permanent-magnets in the rotor, and the axial-flux permanent-magnet machine with single-stator single-rotor were selected. The three motors were about 15 kW output power at 300 rpm. The radial-flux machine had good performances except the heavy weight. The transverse-flux machine had the best torque density but had bad torque quality. Based on the performance comparisons, the axial-flux machine was recommended for in-wheel application only if compactness and/or lightness were imperative.**

***Index Terms*—Electric machines, electric vehicles, performance evaluation, permanent magnet machines, wheels.**

I. Introduction

Since electrical vehicles are cheaper than gasoline vehicles to operate, it is increasingly interesting for automotive industries to develop electric motor for electric vehicle propulsion system. In-wheel motors, mounting the motors directly to the wheels, are more efficient than gear motor system due to the removal of the gear-box with the related mechanical loss. For the in-wheel motor development, the important things of motor design are high torque density, high torque quality, high efficiency, compactness, and lightness except mechanical and thermal problems. Several papers have already presented to evaluate the performance of the different design types such as radial-flux, axial-flux, and trasverse-flux topologies. In 2004, Rahman [1] evaluates radial, axial, and transverse flux motor, but rotor diameter, pole-pair, and number of phase are not fixed. In 2005, Andriollo *et al.* [2] focus on urban buses with large wheel diameter. In 2010, Chen *et al.* [3] compare three machine prototypes for downhole applications. In 2012, Lee *et al.* [4] investigate longitudinal flux and transverse flux machine with large diameter and short axial length.

This paper compared the performance of radial-flux, transverse-flux, and axial-flux electric motors for in-wheel applications. The three in-wheel motor was designed for 14 inch tire rim and design optimization had not been considered further in this paper. The most important things, from the above, are the volume and the weight. Thus, the axial-flux machine was chosen for in-wheel motor.

II. Electromagnetic Design

For the in-wheel three-phase electric motor development, three machine prototypes were selected without considering mechanical and thermal problems. First, the radial-flux machine with the surface-mounted permanent-magnet on the inner rotor (RFPM) shown in Fig. 1 was selected due to the conventional type. Second, the transverse-flux machine with the flux-concentrated permanent-magnet in the inner rotor (TFPM) represented in Fig. 2 was selected due to the high torque density. Finally, the single-stator single-rotor axial-flux permanent-magnet (AFPM) machine depicted in Fig. 3 was chosen due to the simple geometry. The RFPM rotor diameter and axial length are the same as the TFPM. The AFPM axial length is smaller than the other machines. The proposed TFPM machine has the single-sided air-gap, flux-concentrating cores with permanent-magnets in the rotor, and the C-cores with single-winding in the stator [5]. The TFPM machine consists of three single-phase machines with shifting the stators by 120 electrical degrees among the phases. In the proposed AFPM machine, the concentrated windings are inserted in the slotted stator core. The silicon steel and the NdFeB materials are applicable for the three machines. The three machine diameters are fixed at 270 mm without housing due to the restrictions on the tire rim. Some constraints, rotation speed, air-gap, pole-pairs, are fixed, as listed in Table I. The number of turns is freely chosen, but the back electromotiveforces are similar in root-mean-square value.

III. Performance Comparisons

3-D FEM simulations have been performed for the three machines and simulated results are listed in Table I. The three machines are about 15 kW output power at 300rpm. Both the RFPM and the TFPM machines have higher efficiencies than the AFPM. Due to the high rated current, the AFPM machine has high current density and low efficiency. However, the AFPM machine has higher torque density than the RFPM machine. Since the mass of the machine is quite light, the TFPM machine has better torque density compared to the RFPM and AFPM machines. However, the TFPM machine has higher torque ripple due to high cogging torque. The RFPM machine has good performances except the heavy weight of the machine.

The mass and the volume of the machine are of critical factor in the in-wheel electric motor. Hence, the AFPM machine is recommended for in-wheel application despite its poor efficiency. However, the TFPM machine is possible for in-wheel to select only if cogging torque and torque ripple are reduced significantly.

TABLE I
MACHINE PARAMETERS AND SIMULATED RESULTS

Parameters	RFPM	TFPM	AFPM
Stator outer diameter [mm]		270	
Rotor outer diameter [mm]	189	189	270
Axial length [mm]	120	120	84.8
Rotation speed [rpm]		300	
Air-gap [mm]		0.8	
Total weight [kg]	32	24.7	26.2
Pole-pair		10	
Number of stator slots	24	3	24
Number of turns / slot	11	36	15
Fill factor [%]	58.1	74.6	67.7
Self-inductance [mH]	1.042	2.689	1.353
Back-EMF / phase [Vrms]	41.5	42	40.2
Cogging torque [Nm]	13.0	58.4	3.0
Output power [kW]	15.1	15.4	15.0
Rated Torque [Nm]	481.2	491	478.5
Torque ripple [%]	3.99	14.82	1.04
Rated Current [Arms]	117.0	92.0	146.0
Current density [A/mm^2]	11.25	14.96	18.85
Iron loss [W]	45.5	42.0	71.0
Copper loss [kW]	3.487	3.368	5.972
Efficiency [%]	81.1	81.9	71.3
Torque density [Nm/kg]	15.0	19.9	18.3

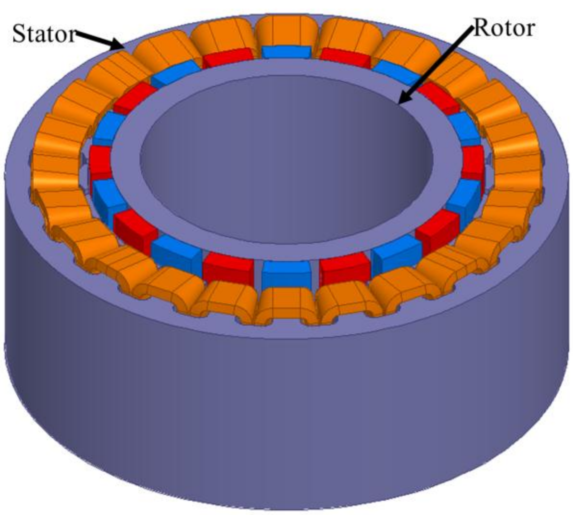

Fig. 1. Radial-flux machine.

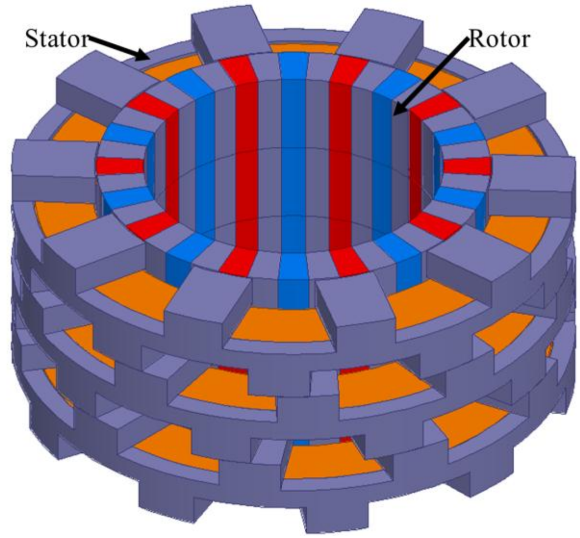

Fig. 2. Transverse-flux machine.

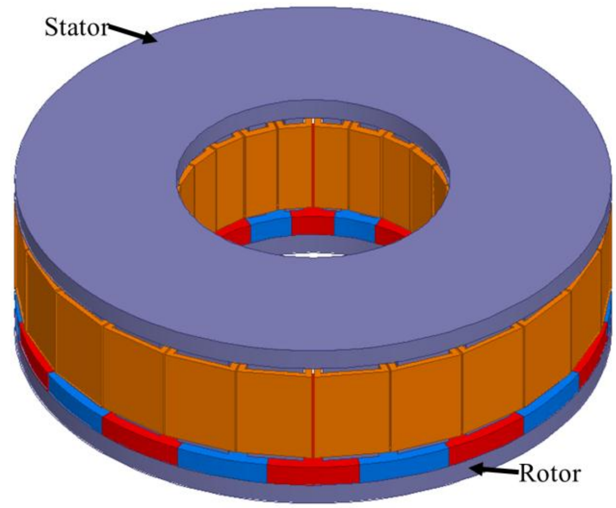

Fig. 3. Axial-flux machine.

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