

Study on a High Torque Density Motor for an Electric Traction Vehicle

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ABSTRACT

A compact and high performance electric motor, called the 3D motor and designed to achieve output torque density of 100 Nm/L, was developed for use on electric vehicles and hybrid electric vehicles. The motor adopts an axial flux configuration, consisting of a disk-shaped stator sandwiched between two disk-shaped rotors with permanent magnets. It also adopts 9-phase current with a fractional slot combination, both of which increase the torque density. The rated torque output of this high power-density motor is achieved by applying a hybrid cooling system comprising a water jacket on the outer case of the stator and oil dispersion into the air gaps. The mechanical strength of the rotors against centrifugal force and that of the stator against torque exertion were confirmed in mechanical experiments. Several measures such as flux barriers, a chamfered rotor rim, parallel windings, and radially laminated cores were adopted to suppress losses. As a result, the motor achieves maximum efficiency of 97%.

INTRODUCTION

Global warming and the increasing cost of fossil fuels in recent years have challenged automobile manufacturers to produce low-emission vehicles that reduce the level of carbon dioxide (CO₂) emissions. Electric-powered vehicles such as hybrid electric vehicles (HEVs) and electric vehicles (EVs) are considered to be among the possible effective solutions to meet the requirements for reducing emissions and fuel consumption. For the electric motor that is used on such electric-powered

vehicles, there are multiple demands. Firstly, whether it is installed between the internal-combustion engine and the transmission to function as a traction motor for HEVs or installed inside the wheels to function as an in-wheel motor for EVs, the motor is often required to be thin in its axial direction compared with its radius. Secondly, high torque output is always required to improve the drivability of the vehicle. Thirdly, high efficiency is required to increase the rated power output and decrease the consumption of electricity, thereby directly lowering the operating cost of the vehicle.

The 3D motor described here was developed to meet such demands for the traction motor. It is able to generate a high level of torque output from a small motor volume while achieving high efficiency.

This paper discusses the technologies employed in the development of the 3D motor with respect to its output performance, mechanical strength and efficiency.

OVERVIEW OF 3D MOTOR

MOTOR CONFIGURATION

Table 1 lists the general specifications of the 3D motor and Figures 1 and 2 show schematic diagrams of its structure. The motor adopts a double-sided configuration with an internal stator. It is constructed of a disk-shaped stator sandwiched between two disk-shaped rotors which are connected to the motor shaft that penetrates the hollow located inside the stator disk. The rotors employ fan-shaped Nd-Fe-B magnets aligned in the

tangential direction with a back core consisting of radially laminated magnetic steel rolled up in a thin layer. The magnets are located in slots formed by the back core that hooks the magnets in the axial direction. The back core is held by a baseplate that holds the back core and magnets against centrifugal force and transmits the torque they generate to the motor shaft. The stator is composed of fan-shaped cores made of radially laminated steel. Each core is wound by rectangular magnetic wires to give the motor its concentrated winding design and is aligned in the tangential direction. The assembled stator is molded of unsaturated polyester resin and fixed inside the motor case.

Table 2 shows the performance characteristics of the 3D motor. The motor is able to achieve a high level of output with high efficiency from its compact volume. Furthermore, its cogging torque is suppressed to a low level.

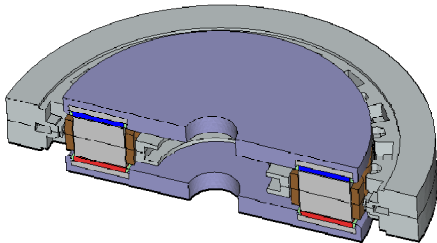


Figure 1 Schematic diagram of 3D motor

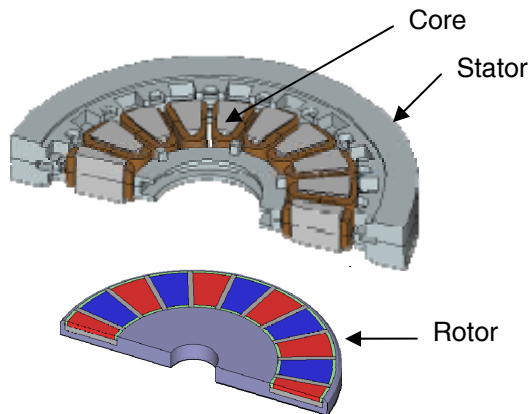


Figure 2 Schematic diagram of stator and rotor

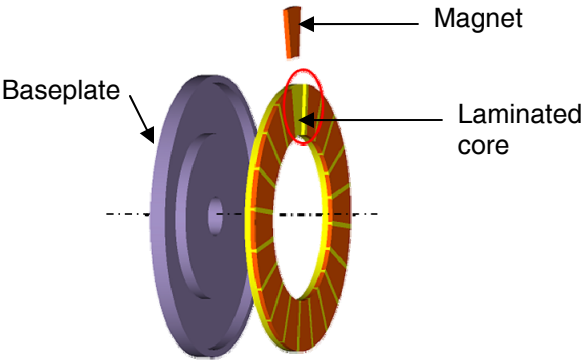


Figure 3 Structure of rotor

Table 1 Motor specifications

Type		Axial flux PMSM
Structure		2 rotors, 1 stator
Outer diameter	Do	280 mm
Inner diameter	Di	150 mm
Axial length	L	82 mm
Phase		9-phase, 2 parallel connections
Number of slots		18
Number of poles		20

Table 2 Motor characteristics

Maximum current	246 Arms
DC voltage	300 V
Maximum torque	537 Nm
Maximum power	135 kW
Maximum efficiency	97%
Cogging torque	2.5 Nm p-p

TECHNOLOGIES FOR HIGH TORQUE DENSITY

AXIAL FLUX DESIGN

The 3D motor is required to achieve high torque output from a limited volume, especially in the axial direction. Under such layout conditions, an axial flux motor is able to generate higher torque output than a conventional radial flux motor. The relationship of the torque output with respect to the airgap magnetic flux density B_{mg} , average magnetic flux density B_{avg} , line current density A , rotor outer diameter D_o , rotor inner diameter D_{in} , armature stack length L_i , and winding factor k_w is shown in Equation (1) for the axial flux type^{[1] [3]} and in Equation (3) for the radial flux type.^[3]

$$T_{axial} = \frac{1}{4} \alpha_i m_1 N_1 k_w B_{mg} D_o^2 (1 - k_d^2) I_a \quad (1)$$

$$= \frac{\pi}{4} \frac{1}{4\sqrt{2}} \alpha_i k_w D_o^3 (1 + k_d)(1 - k_d^2) B_{mg} A_{axial} \quad (2)$$

$$T_{radial} = \frac{\pi}{4} k_w D_o^2 L_i B_{mg} A_{radial} \quad (3)$$

where $\alpha_i = \frac{B_{avg}}{B_{mg}}$ $A_{radial} = \frac{2m\sqrt{2}NI_a}{\pi D_o}$

$$A_{axial} = \frac{2m\sqrt{2}NI_a}{\pi \left(\frac{D_{in} + D_o}{2} \right)} \quad k_d = \frac{D_{in}}{D_o}$$

The notations m , N , and I_a represent the number of phases, number of turns, and stator current, respectively.

The torque output of the axial flux type is related approximately to the cube of the motor diameter, while that of the radial flux type is related approximately to the square of the diameter multiplied by the axial length. Therefore, the performance of the axial flux motor becomes superior to that of the radial flux motor as the aspect ratio, i.e., the outer diameter relative to the axial length, increases. Figure 4 shows the typical torque output of the radial flux motor and axial flux motor as a function of their outer diameter when the axial length is fixed.

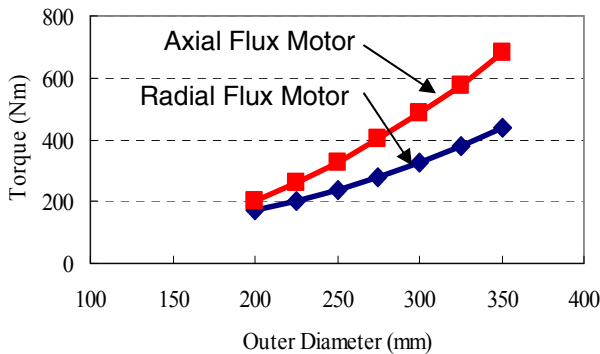


Figure 4 Torque characteristics of axial flux and radial flux motors

FRACTIONAL SLOT CONFIGURATION

The 3D motor adopts a fractional slot configuration with concentrated windings. A conventional motor with concentrated windings usually has a configuration such that the ratio of the number of slots to the number of poles is 3:2, whereas the 3D motor has 18 slots with 20 poles, for a ratio of slots to poles of 9:10. This configuration was adopted to increase the winding factor,

which represents the effectiveness of the motor's use of magnets, and to reduce cogging torque.

Maximizing the winding factor

The linear relationship between torque output and the winding factor is expressed as^[1]

$$T = 2 \frac{p}{\pi} m N k_w \Phi I_a \quad (4)$$

where p is the number of pole pairs, k_w is the winding factor, and Φ is the magnetic flux excited by the number of permanent magnets per pole. The winding factor is expressed as the distribution factor multiplied by the pitch factor. The distribution factor is defined as "the ratio of the phasor sum to arithmetic sum of EMFs induced in each coil"^[1] and it represents the phase offsets between the electromotive force (EMF) phasor and the magnetomotive force (MMF) phasor of the coils. The induced EMF phase in the k_{th} core of the stator can be expressed as

$$\theta_{sl}(k) = \text{rem} \left((k-1) \frac{N_m}{N_{sl}} \pi, 2\pi \right) \quad (5)$$

for $k = 1, 2, \dots, N_{sl}$

where $\text{rem}(x, y)$ returns the remainder of the division x/y , N_m and N_{sl} represent the number of poles and the number of slots, and k represents the core number.^[2] The MMF phase in each core can be expressed as

$$\theta_m(n_m) = \frac{2\pi}{m} (n_m - 1) \quad (6)$$

for $n_m = 1, 2, \dots, N_{sl}$

where m represents the number of phases and n_m is an arbitrary number. Given a certain core having an EMF phase of $\theta_{sl}(k)$, an MMF phase $\theta_m(n_m)$ is assigned such that the phase offsets between the EMF phase and the MMF phase, $\theta_{sl}(k) - \theta_m(n_m)$, will be minimized. The distribution factor can then be expressed by

$$k_d = \frac{\sum_{k, n_m=1}^{N_{sl}} \cos(\theta_{sl}(k) - \theta_m(n_m))}{N_{sl}} \quad (7)$$

In the case of the 3D motor, the EMF phase of adjacent cores is offset by 200 degE and the greatest common divisor (GCD) of the EMF phases of all the cores is 40

degE. Therefore, 9-phase current, of which the phase offset of adjacent phases is 40 degE apart, was adopted in order to eliminate the unwanted phase offset between the EMF and MMF phases. As a result, the 3D motor is able to achieve a distribution factor of 1.

The pitch factor is defined as “the ratio of the phasor sum to arithmetic sum of the EMFs per coil side”^[1] and is expressed by following equation:

$$k_p = \sin\left(\beta \frac{\pi}{2}\right) \quad (8)$$

where β is the ratio of the coil pitch to the pole pitch. The 3D motor has a pitch factor is 0.985.

Therefore, a higher phasor sum of EMF induced in the coils is achieved with a higher winding factor, which translates into higher motor torque output. Applying these equations to the 3D motor, it achieves a winding factor as high as 0.985, due to its distribution factor of 1 and pitch factor of 0.985. In contrast, the winding factor of a conventional motor with a slot-to-pole ratio of 3:2 is 0.866, due to its distribution factor of 1 and pitch factor of 0.866. The 3D motor is able to produce approximately 10% more torque output.

Table 3 Characteristics of 3D motor compared with a conventional motor

	Slots/Poles	Winding factor	Cogging harmonics
Conventional motor	18 slots 12 poles	0.866	36
3D motor	18 slots 20 poles	0.985	180

Minimizing cogging torque

It is desirable to reduce cogging torque in the traction motor of an electric-powered vehicle, because it degrades passenger comfort. Several methods such as skewing the stator or the rotor and utilizing unique core shapes are known to reduce cogging torque, but they often result in lower torque output and poorer efficiency. The fractional slot configuration is able to suppress cogging torque without sacrificing torque output.

Cogging torque can be expressed as

$$T_{cog} \propto \frac{1}{2} \phi^2 \frac{d\mathcal{R}_e}{d\theta} \quad (9)$$

where ϕ is magnetic flux, $\mathcal{R}_e$ is the reluctance of the electromagnetic circuit, and θ is the tangential angle.^[2] The equation shows that cogging torque is produced as

a magnet passes by the stator core where the reluctance of the electromagnetic circuit changes as the rotor rotates in the tangential direction. In conventional motors, with a ratio of slots to poles of 3:2, each pole pair appears in the same position relative to the stator core. As a result, the cogging torque produced by each pole pair is in-phase to the other pole pairs. The net cogging torque becomes larger as that produced by one pole pair is added to the cogging torque of other pole pairs. In contrast, the 3D motor suppresses cogging torque to a low level because most of the magnets appear in different positions relative to the stator cores; only 2 of the 20 poles appear in the same position. As a result, the cogging torque produced by the magnets is mostly mutually out of phase. The net cogging torque is the sum of the cogging torque produced by a set of 10 poles, in which some of the cogging components are cancelled out, multiplied only by 2.

Another way of considering cogging torque is to count the number of net reluctance changes. Reluctance is the lowest when a stator core is facing the q-axis of the rotor core and the highest when a stator core is facing the d-axis. The changes in net reluctance occur as many times as the least common multiple (LCM) of the number of slots and poles per mechanical rotation of the rotor. If this number shows high harmonics, cogging torque decreases and vice versa. Figure 5 shows this tendency in which the cogging torques of several sample motors having different slot combinations were calculated. The number of cogging harmonics, i.e., LCM of slots and poles, is shown along the x-axis and cogging torque is shown along the y-axis. Because the 3D motor has 18 slots and 20 poles, it has a 180th cogging harmonic, which gives the motor a very smooth output torque with its cogging torque as small as 2.5 Nm peak to peak.

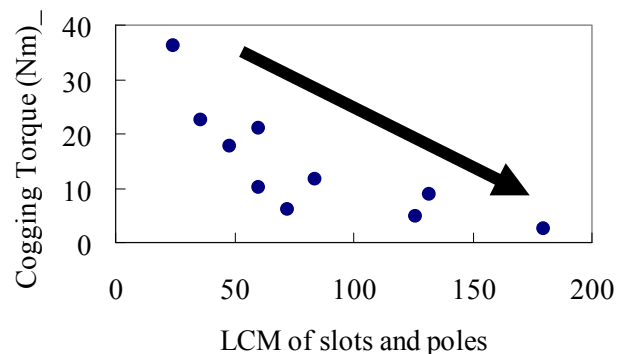


Figure 5 Relationship between cogging harmonics and cogging torque

COOLING SYSTEM

Since the 3D motor is a highly power-dense motor with maximum output power of 135 kW from a volume of 5 liters, its heat generation due to the copper and iron losses is dense as well. In order to ensure high continuous rated power, heat must be effectively