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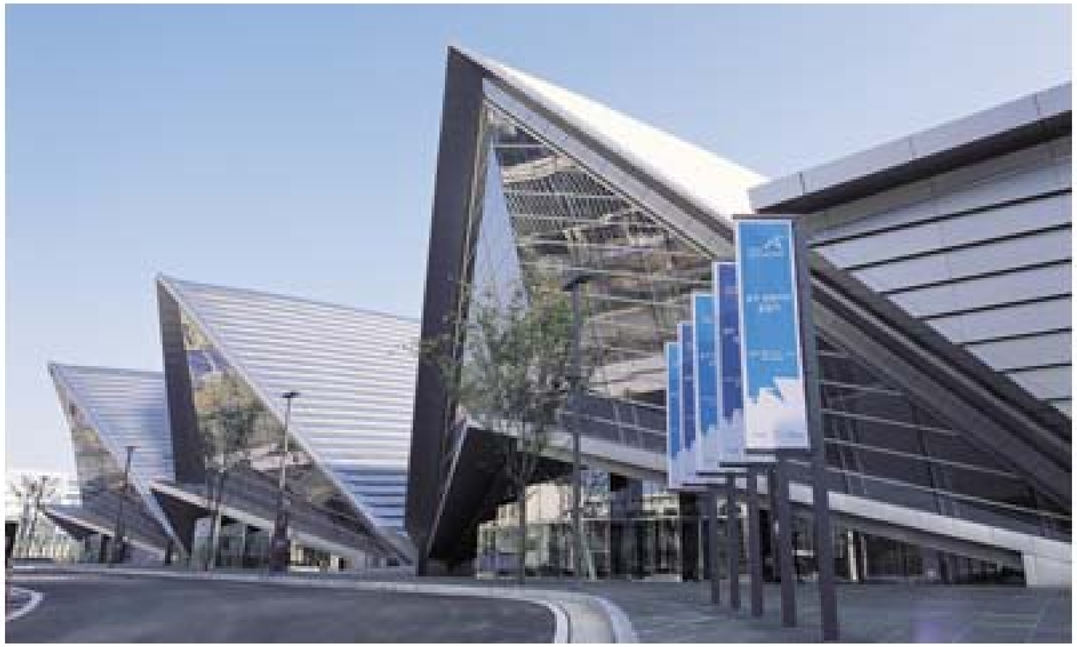

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- The Effect of Silicon Steel Sheet on Core Loss in Induction Motor

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- Effect of Vibration and Noise on IPMSM Type Integrated Starter and Generator According to Number of Slots

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- Reduction Design of Eddy Current Loss in IPMSM using Response Surface Methodology

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- A Study on the Relation Between Rotor Rib and Maximum Power of IPMSM in Flux Weakening Region

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- Reduction Eddy Current Loss Design and Analysis of In-Wheel Type Vehicle Traction Motor

Design of an Interior Permanent Magnet Synchronous In-Wheel for Electric Vehicles

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Abstract — This paper deals with a design approach to an interior permanent magnet synchronous motor (IPMSM) used in in-wheel motor drive systems of electric vehicles. Interior Permanent Magnet (IPM) type motor which has high efficiency and high durability is selected. To apply for the electric vehicles, a form, a tire and a wheel of vehicles are considered when calculating the motor performance. So, the constant power region of IPMSM and gear ratio are investigated in order to meet the specifications of the in-wheel motor system. After calculating a motor performance, space harmonic analysis and finite element analysis in consideration of magnetic saturation is used for designing in-wheel motor, and designed motor is verified by experiments.

I. Introduction

These days, the representative one of environment-friendly technologies is a technology of electric vehicle (HEV, FCEV, etc). A great interest is focused on more efficient and reliable propulsion systems of electric vehicles because of an exhaustion of petroleum resources and environmental problems. In-Wheel motor receives a lot of favorable attention as a new structure which satisfies this environment-friendly technology. In general, the propulsion system for electric vehicles consists of batteries, electric motors with drives, and transmission gears to wheels. However, if an in-wheel motor system is applied as the power system of electric vehicles, the transmission composed of many components can be eliminated. Thus, the transmission losses are minimized, and the operation efficiency and reliability is improved [1]. Moreover, more batteries can be installed in the space that would be occupied by the transmission, which help to increase the driving range per charge. On the contrary, due to the elimination of gears, the system needs to produce the total torque directly into the wheel shaft. Consequently, the size of the system tends to grow [2], [3]. Accordingly, for the miniaturization, a planetary gear system is applied in the in-wheel motor system treated in this paper.

This paper deals with a design approach to an interior permanent magnet synchronous motor (IPMSM) used in in-wheel motor drive systems of electric vehicles. Interior Permanent Magnet (IPM) type motor which has high efficiency and high durability is selected. To apply for the electric vehicles, a form, a tire and a wheel of vehicles are considered when calculating the motor performance. So, the constant power region of IPMSM and gear ratio are investigated in order to meet the specifications of the in-wheel motor system. After calculating a motor performance, space harmonic analysis and finite element analysis in consideration of magnetic saturation and operating temperature is used for designing in-wheel motor, and designed motor is verified by experiments.

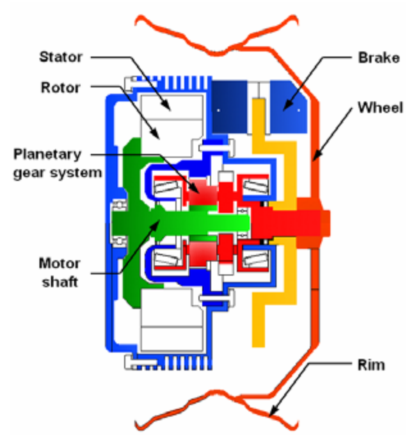


Fig. 2. Assembly configuration of in-wheel motor drive system

II. Specifications of In-Wheel Motor Drive System

The assembly configuration of in-wheel motor system is shown in Fig. 1. It consists of four parts: motor, reduction gear, brake, and wheel. The specifications of an EV are illustrated in Table I. The road load on the vehicle is composed of three components: aerodynamic drag force F_{ad}, rolling resistance force F_{rr}, and climbing force F_c, which are expressed as follow:

$$F_{ad} = 0.5\rho AC_d v^2 \quad (1)$$

$$F_{rr} = \mu_r mg \quad (2)$$

$$F_c = mg\sin\theta \quad (3)$$

where ρ: the air density; A: the frontal area of the car; C_d: the aerodynamic drag coefficient; v: the relative vehicle velocity to the head wind; μ_r: the rolling friction coefficient; m: the curb mass; θ :angle of the road.

The force required to reach the prescribed acceleration a by overcoming the road load is as follow:

$$F = ma + F_{ad} + F_{rr} + F_c = \frac{G}{r} \cdot T \quad (4)$$

where G: the gear ratio; r: the effective radius of the tire; T: motor torque.

Fig. 2 shows the process for selecting in-wheel motor in electric vehicle. The motor specification and reduction ratio are chosen after enough vehicle information is checked. At the maximum speed, performance of acceleration and climbing is tested, then motor size could be decided through the result if the test result satisfies required condition. However, the motor specification and reduction ratio should be changed after altering Constant Power Speed Range (CPSR) if the test result does not satisfy required condition. In case decided motor size fits to the in-wheel size, the process for selecting in-wheel motor ends. Otherwise this process should be repeated.

Based on the specifications, the required motor torque and the corresponding speed under various operation conditions of the vehicle are shown in Fig. 3 and Fig. 4 [4]. At this time, the maximum output power of the motor is 25kW.

TABLE I
SPECIFICATIONS OF AN ELECTRIC VEHICLE

Items	Value
Curb mass	1000kg
Cruising and max. speed	40/60 km/h
Acceleration 0-40km/h	Within 5 sec.
Max. climbing slope	30%(16.7°)
Aerodynamic drag coefficient	0.35
Rolling friction coefficient	0.013
Frontal area	2.5m2
Air density ρ	1.1774
Gear efficiency	0.95
Effective radius of tire	0.3262

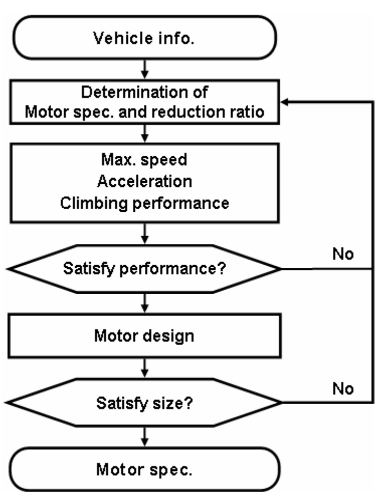
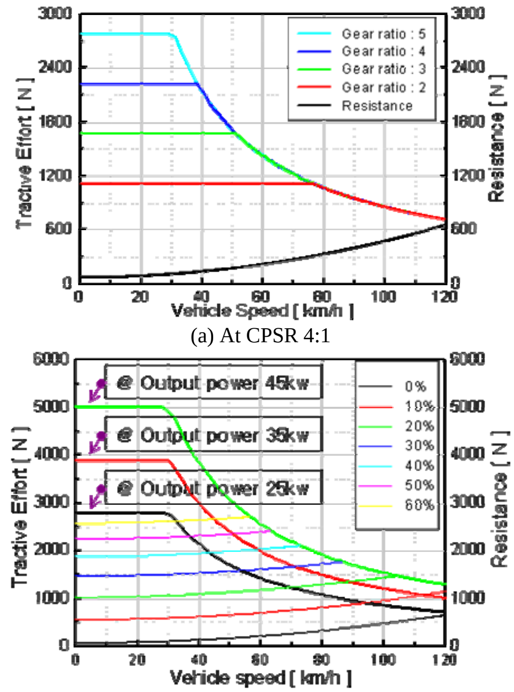


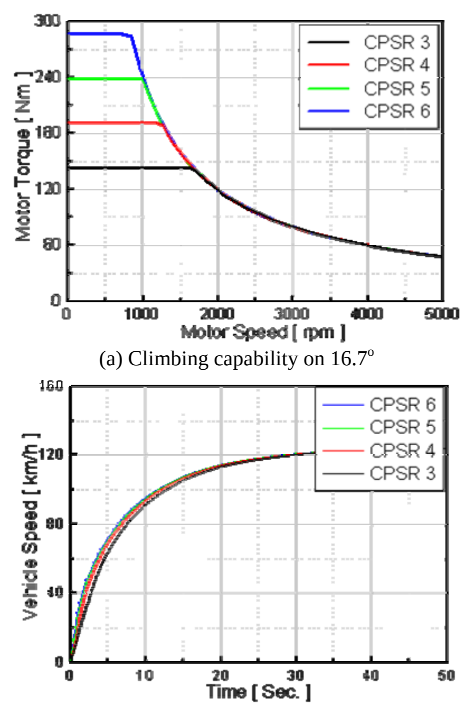
Fig. 2. Process of for selecting in-wheel motor in Electric-Vehicle



(a) At CPSR 4:1

(b) At gear ratio 5:1

Fig. 3. Force and motor torque curve according to gear ratio and CPSR



(a) Climbing capability on 16.7°

(b) Acceleration capability on 0° slope

Fig. 4. Acceleration and climbing capability curve of electric vehicle

III. IN-WHEEL MOTOR DESIGN

A. Analysis theory

The parametric design named in this paper is carried out in order to satisfy the given design conditions of IPMSM applied in the in-wheel driving system. That is, it is to estimate the range of inductance and back-EMF treated as the most critical factors in the initial design of IPMSM. The region is obtained by changing the value of inductance and back-EMF in (5), (6) and (7) expressed as the voltage and torque equation of the IPMSM in the steady-state.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_a \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1+\frac{R_a}{R_c}\right)\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix}\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \quad (6)$$

$$T = P_n[\psi_a i_{oq} + (L_d - L_q) i_{od} i_{oq}] \quad (7)$$

where i_d, i_q: d- and q-axis components of armature current; i_{cd}, i_{cq}: d- and q-axis components of iron loss current; v_d, v_q: d- and q-axis components of terminal voltage; ψ_a: $\sqrt{3/2}\ \psi_f$; ψ_f: maximum flux linkage of permanent magnet; R_a: armature winding resistance; R_c: iron loss resistance; L_d, L_q: inductance along d- and q-axis; P_n: number of pole pairs.

B. Specification

Table II shows motor specification through process for selecting In-Wheel motor that already performed. 12 pole 18 slots are determined for pole and slots. DC link voltage is 320[V] and modulation ratio is about 90[%]. In addition, max. power and torque are relatively 25[kW] and 195[Nm], also base rpm and max rpm are relatively 1250[rpm] and 5000[rpm]. Fig.5 shows characteristic curve of in-wheel motor.

TABLE II
THE REQUIREMENTS FOR IPMSM DESIGN

Items	Value
Stator outer diameter	Less than 280 mm
Stack length	Less than 67 mm
Efficiency @ 3500rpm	More than 90 %
DC link voltage	320 V
Max. and rated output power	25 / 10 kW
Base and Max. speed	1250 / 5000 rpm

C. In-Wheel motor design and test results

In this section, the procedure for preliminary geometry design of IPMSM is illustrated. Above all, in the process, torque per rotor volume (TRV) according to PM type is estimated within the dimension displayed in Table II. Second, the number of series turns, air-gap length, and PM shape such as pole arc and thickness are determined with an analytical method used for the design of PM synchronous motor. Third, the coil diameter considering current density is selected. At this time, the current is obtained by the parametric design. Finally, the shape of stator is roughly decided by the number of series turns and fill factor.

Fig. 6 shows initial designed configuration of in-wheel motor.

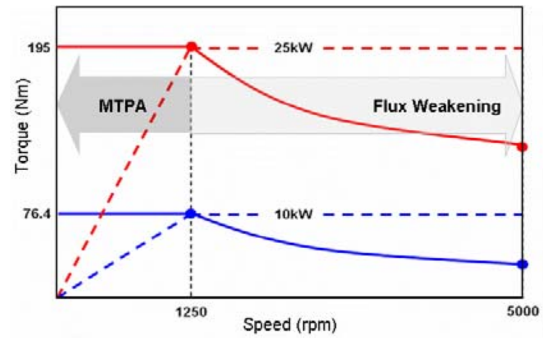


Fig. 5. Characteristic curve of in-wheel motor

The parametric design named in this paper is carried out in order to satisfy the given design conditions of IPMSM applied in the in-wheel driving system. That is, it is to estimate the range of inductance and back-EMF treated as the most critical factors in the initial design of IPMSM. The region is obtained by changing the value of inductance and back-EMF. At that time, some parameters are greatly influenced by past experimental data or designer's experience, and there are assumptions. First of all, the iron loss is neglected. Second, the winding resistance is assumed at the operating temperature. Third, the ratio between Ld and Lq is 1.5. Finally, mechanical loss is 0.1% of maximum output power at 1000 rpm, and the loss is proportional to the square of speed. The requirements of IPMSM are shown in Fig. 7 display the results obtained by the parametric design [5].

Designed in-wheel motor is fabricated. Max. and rated power speed are 25kW and 10kW respectively. The in-wheel motor obtained by FEA and test a load condition is compared in Fig. 8 which is compared with voltage, input current and efficiency according to speed at max., rated power. And Fig. 9and Fig. 10 are test setup for load test and fabricated in-wheel motor system.

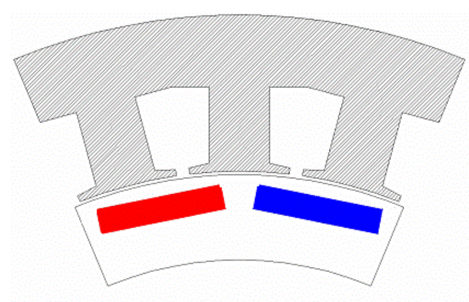
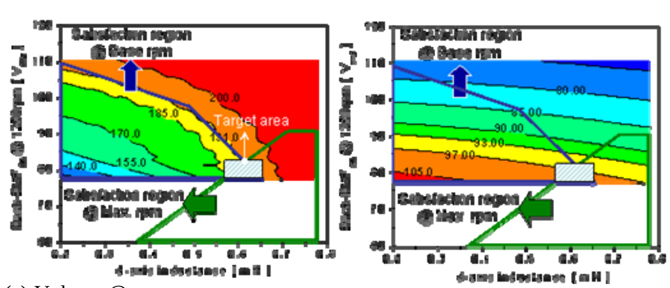
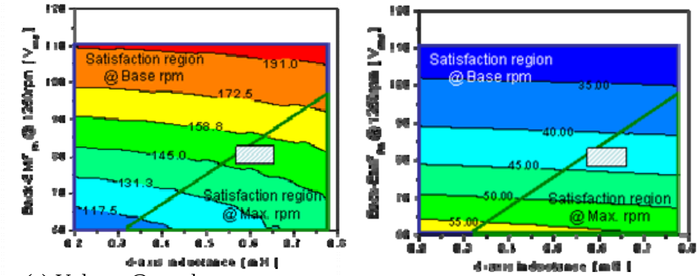


Fig. 6. Initial designed configuration of in-wheel motor

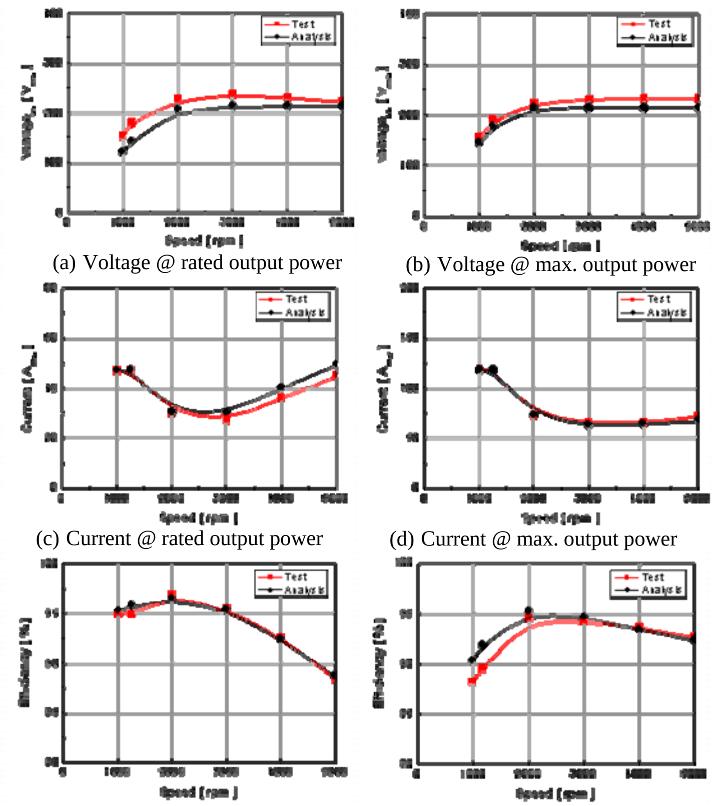


(a) Voltage @ max. output power (b) Current @ max. output power



(c) Voltage @ rated output power (d) Current @ rated output power

Fig. 7. Design region of IPMSM according to back-EMF and inductance



(a) Voltage @ rated output power (b) Voltage @ max. output power

(c) Current @ rated output power (d) Current @ max. output power

(e) Efficiency @ rated output power (f) Efficiency@ max. output power

Fig. 8. Comparison of test and analysis results

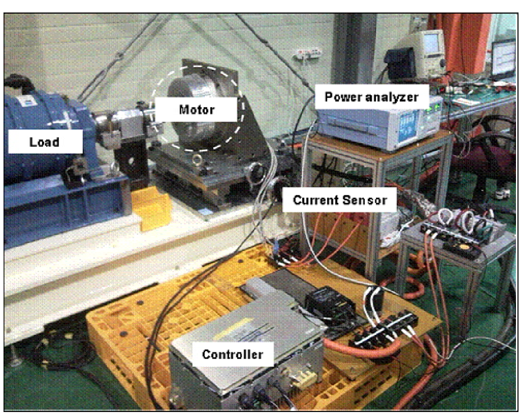


Fig. 9. Test setup for load test

Fig. 10. Fabricated rotor and stator of in-wheel motor

IV. CONCLUSION

In this paper, a design approach to IPMSM for an in-wheel motor driving system was presented. Even if some parameters are assumed in the parametric design stage, the approach is effective for the design of IPMSM. Finally, designing In-Wheel motor, and designed motor is verified by experiments.

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