Development of Traction Unit for 2-motor Driven Electric Vehicle

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Abstract

This paper describes a development of traction unit for 2-motor driven electric vehicle (EV). The traction unit is consisted with an interior permanent magnet synchronous motor (IPMSM), a reduction gear and an inverter for electric vehicle that is driven by 2 motors without differential gear. For traction unit, prototype IPMSM and inverter have been developed. The IPMSM was designed by CAD program that was developed with both equivalent circuit method and FEM. Also the inverter was developed to drive 2 motors with 6 legs IGBT switches in a control board. The vector control algorithm was implemented with maximum torque control method in the constant torque region and field weakening control method in the constant power region considering inverter capacity.

To verify that the traction unit is more high efficiency and has more high power density than a traction unit with induction motor with the same power, we would like to show the results about the design and analysis of the IPMSM and the experiment results about the traction unit.

1. Introduction

EVs are likely to become increasing important to our society with regard to the negative aspects of internal combustion engines such as pollution, noise, and smell. And many countries are aiming to commercialize EVs in early 21st century. So many automobile manufacturers are introducing prototype EVs and sharing markets of automobiles.

A technology incorporated in the IZA was a direct drive method in which one motor called the "in-wheel motor" was installed in each wheel.

With this system, transmission and differential gears are no longer required and the efficiency of the entire drive system is improved. However, with the direct drive motor, the percentage of copper losses to the total losses is becoming large and causing the efficiency to drop remarkably especially when a large torque is required [1]. To improve this problem, it is recommended that using a high-speed motor and inserting one step of reduction gear between the rotor and wheel. And it is necessary that a motor with advanced dynamic characteristics about power density, efficiency, and thermal increasing.

So this paper proposes a high performance traction unit configured of an IPMSM, a reduction gear, and an inverter. The motor and reduction gear is installed on the wheel. Details about the traction unit of 2-motor driven EV are given as followings.

2. Two-motor Driven Electric Vehicle

The traction unit has a structure built on the drum of a wheel. The shaft output of the IPMSM with a maximum speed of 7500 rpm is transmitted to the wheel via one step reduction gear that is planetary gear with a gear ratio of 6:1. Each component such as the motor, reduction gear, and configuring the unit has each been developed to target downsizing optimum positions and high efficiency. By installing this drive unit in the two rear wheels or two front wheels and using the torque split method, a two-motor drive system of EV can be configured [2].

The desired torque of 2-motor is calculated to achieve the acceleration time of under 21 seconds from 0 to 100km/h when two drive units are installed in a compact passenger vehicle with total weight of approximately 1656Kg. Rated speed of the EV is set to 60 km/h. And rated current per a motor is set to 80A. Also height from bottom should be larger than 150mm.

3. Development of IPMSM

A. Design of IPMSM

It is very difficult to determine precisely the design parameter of an IPMSM using equivalent magnetic circuit, especially for a heavily saturated system. For precise design we have applied to CAD system, which have a program using hybrid method of equivalent magnetic circuit with numerical method [3,4,5]. CAD system process is summarized in below Fig. 1. Cross section and specification of IPMSM are shown in Fig.2 and Table 1.

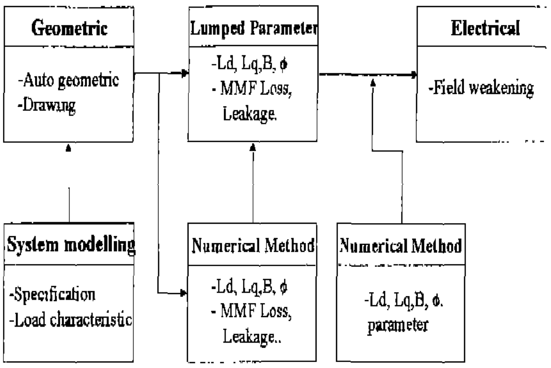


Fig .1 CAD System Flow Chart

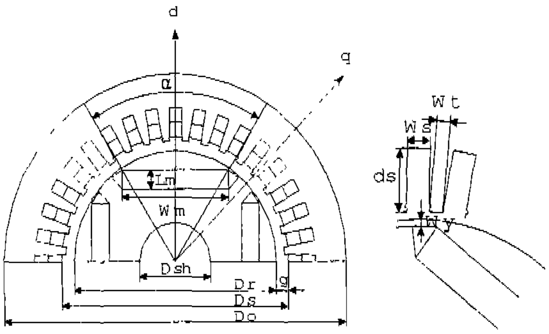


Fig .2 Cross section of analysis model

Table. 1 The specification of analysis model

Output / pole number	15[kW]-4P	**Stator**	[mm]
Phase voltage	98[V]	Do	171
Rated current	85[A]	Ds	91
Base speed	3000[rpm]	Stack length	87
Number of slot	36	Ws	5 8
Chording	8/9	Wt	2 1405
Airgap length	2.2[mm]	Ds	30
Residual flux density	1.12[T]	**Rotor**	
Coercive force	21[Koe]	Dr	87
Pole arc coefficient	0 75	Dsh	40
Magnet width	47[mm]	Wy(link width)	1
Magnet length	91[mm]	Lm	9

B. Characteristics analysis of IPMSM

Interior type Permanent Magnet Synchronous Motor (IPMSM) in which the reluctance torque is generated because of its saliency by structural characteristic of rotor, so its speed versus torque and power characteristics should analyze to precise.

The results of analysis by Equivalent Magnetic Circuit (EMC) about inductance, airgap flux and electromotive force (E_0) due to magnet are shown in Table 2. Saliency ratio of analysis model is 1:2.94.

Table 2. Calculating parameters by using EMC

X_d	0.3585[Ω]	ψ_f	0.0027294[wb]
X_q	1.0555[Ω]	E_0	55.02[V]

The characteristics of Torque to current angle characteristics of IPMSM at base speed are shown in Fig. 3 as estimated from an EMC. Magnetic torque is 44[N.m] at zero degree and reluctance torque is generating 15[N.m] at 45 degree of current angle. Reluctance torque is generating about 1/3 of magnetic torque, so total torque which is generating 52[N.m] at 24 degree has enhanced 18.2[%] relate to magnetic torque. This is due mainly to the saturation effect of rotor. A more accurate inductance calculation method is therefore necessary to improve the accuracy of analysis, especially for inductance evaluation.

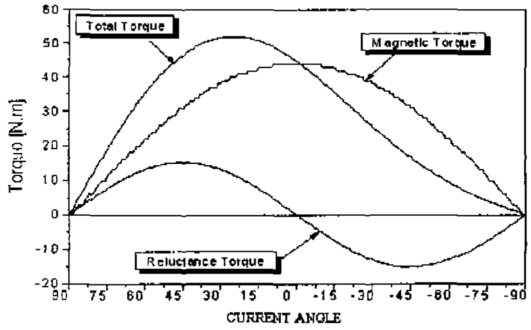
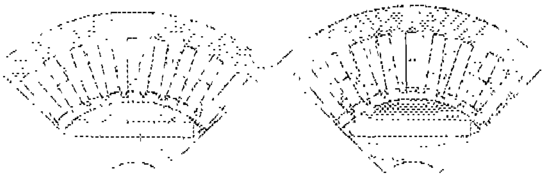


Fig.3 Torque characteristics according to current angle

Fig. 4 shows flux distribution of the d-q axis. D-axis flux varies linearly with respect to phase angle. But q-axis flux largely varies according to phage angle because of nonlinear region by saturation in the link.

Fig.5 shows variation of inductance according to current angle.



(a) d-axis (b) q-axis

Fig. 4 d-axis, q-axis Equivalent potential distribution.

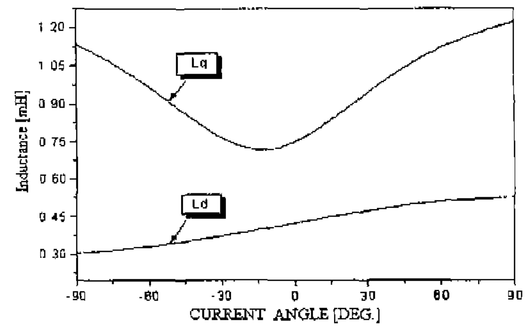


Fig.5 Current angle versus Inductance

C. Field-weakening analysis

Fig.6 and Fig.7 shows speed-power characteristics in field weakening region when calculated nonlinear d-q inductance is considered. The constant-torque operation at which maximum torque per unit current is produced is carried out until the base speed where supply voltage completely is saturated. In addition, the field-weakening operation is introduced in the constant-output region above the base speed to extend the operating speed region.

From an operating result, the base speed where supply voltage is saturated is increased to 4500 rpm because field weakening is, in some degree, induced by the effect of reluctance in constant-torque region. Therefore, the speed-output region satisfying the desired output, over 15 [kW], can be extended to 9500 rpm by using field-weakening control.

Fig. 8 and 9 show the speed -output characteristics at maximum current.

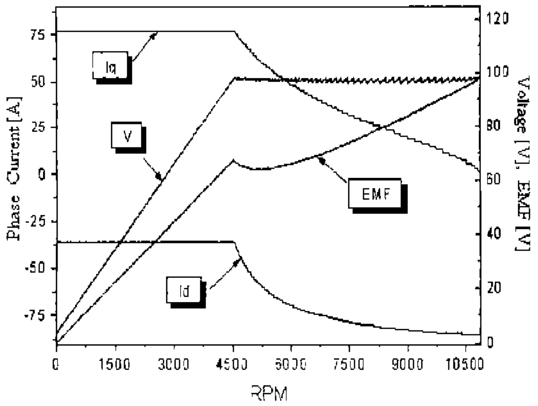


Fig. 6 Voltage versus current characteristics according to velocity

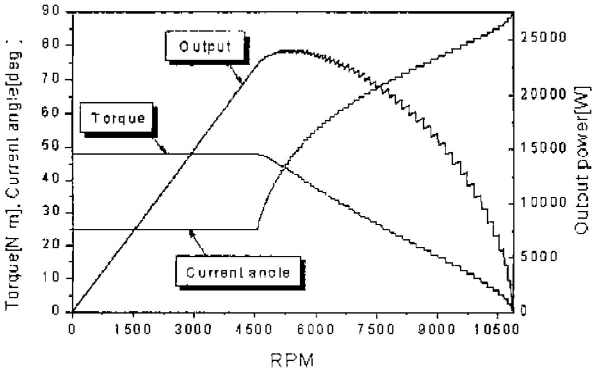


Fig.7 Speed versus output characteristics by Field-weakening

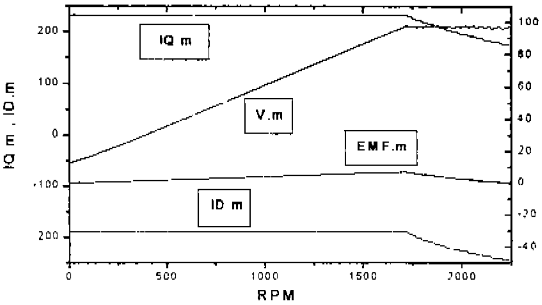


Fig. 8 Voltage versus current characteristic at maximum current (300 A)

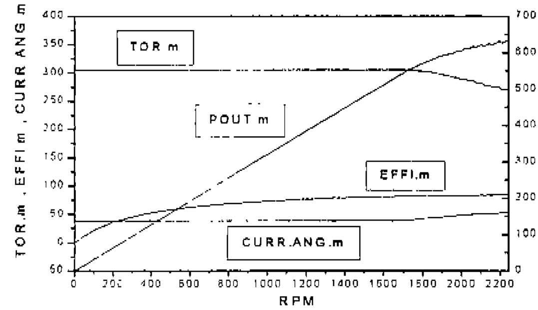


Fig. 9 Speed versus output characteristic at maximum current(300 A)

The Designed motor parameter is shown in the Table 3. And the prototype IPMSM is shown on the Fig. 10.

4. Development of Inverter

The two motors are controlled in an inverter unit. The inverter unit is configured of the inverter main circuit, main contactor and control unit. The inverter is a controlled voltage source inverter that controls the motor armature current using maximum torque control in the constant torque region and flux weakening control considering inverter capacity in the constant power region.

IPMSMs are suitable for constant power operation by flux-weakening control because the IPMSM has a relatively large armature inductance, and as a result, enough flux-weakening effect due to the d-axis armature reaction is expected [6]. The effects of the d- and q-axis armature reactions on the performance of current control are dominant, especially at high speeds and in transient operations [7]. In the flux-weakening region, the terminal voltage is nearly the maximum available voltage of the inverter, and as a result, the commanded voltage vector sometimes exceeds the maximum available voltage in transient operations. In this case, the d- and q-axis current regulators are saturated and affect each other.

So, to solve this problem, we apply to control method of maximum torque per armature current ampere[6].

A. Current and Voltage constraints

In the d-q coordinates which rotate synchronously with an electrical angular velocity ω , the voltage equation and the torque equation of IPMSMs are expressed as follows:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -\omega L_q \\ \omega L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} O \\ \omega\phi_f \end{bmatrix} \quad (1)$$

$$T = P_n \phi_f i_q + P_n(L_d - L_q) i_d i_q \quad (2)$$

Considering the voltage and current constraints, the armature current I_a and the terminal V_a are limited as follows:

$$I_a = \sqrt{i_d^2 + i_q^2} \le I_{am} \quad (3)$$

$$V_a = \sqrt{V_d^2 + V_q^2} \le V_{am} \quad (4)$$

The maximum current I_{am} is a continuous armature current rating in continuous operation or a maximum available current of the inverter in limited short-time operation. The maximum voltage V_{am} is the maximum available output voltage of the inverter depending on the dc-link voltage.

B. Control in Constant Torque Region

As the IPM motor has a saliency (L_d > L_q) and, as a result, the reluctance torque is available, the armature current vector is controlled in order to produce the maximum torque per armature current ampere. From (2), the relationship between i_d and i_q for the maximum torque-per-amp control is derived as

$$i_d = \frac{\phi_f}{2(L_q - L_d)} - \sqrt{\frac{\phi_f^2}{4(L_q - L_d)^2} + i_q^2} \quad (5)$$

or

$$i_d = \frac{\phi_f}{4(L_q - L_d)} - \sqrt{\frac{\phi_f^2}{16(L_q - L_d)^2} + \frac{I_{am}^2}{2}} \quad (6)$$

$$i_q = \sqrt{I_{am} - i_d^2} \quad (7)$$

C. Control in Constant Power region

The d- and q-axis components of armature current are controlled in order to keep V_o equal to V_{om} in the flux-weakening constant power region. The relationship between i_d and i_q of the flux-weakening control is derived from (8) and V_o=V_{om}:

$$V_o = \sqrt{V_{do}^2 - V_{qo}^2} \le V_{om} \quad (8)$$

$$V_{do} = -\omega L_q i_q \text{ , } V_{qo} = \omega\phi_f + \omega L_d i_d$$

$$V_{om} = V_{am} - R I_{am}$$

$$i_d = -\frac{\phi_f}{L_d} + \frac{1}{L_d}\sqrt{\frac{V_{om}^2}{\omega^2} - (L_q i_q)^2} \quad (9)$$

A block diagram of the vector control algorithm for the IPMSM is shown in Figure 11. Also current locus and the prototype inverter are shown in Fig. 12 and 13 each other.

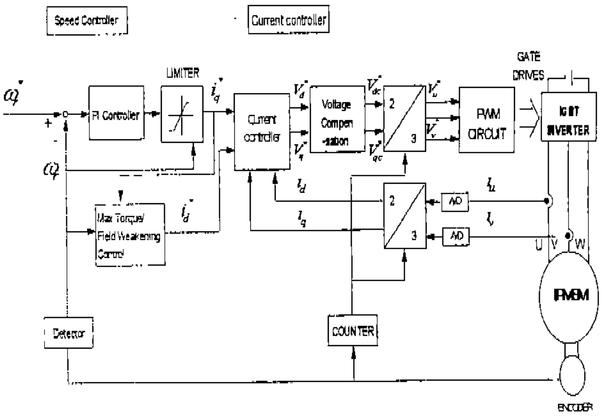


Fig. 11 Block Diagram of the Vector Control Algorithm

5. Conclusion

Prototypes IPMSM for 2-motor driven EV have been developed. Through the analysis of the motor using developed CAD system, the efficiency of the IPMSM is 95%. Maximum power is 63kW. Power density is 1.76kW/kg. Cooling method of the motor and driver are water cooling. And reduction gear ratio is 6:1 of the type of planetary gear. And driver for 2-IPMSM is developed in a control board using control method of maximum torque per armature current ampere and field weakening.

By comparing the characteristics about the torque, power, and efficiency with those of induction motor, we are clarified that with this traction unit, downsizing and weight reduction are possible.

So, it is anticipated that the EV fitted with the IPMSM, planetary gear, wheel and driver will take a longer driving distance per a full charge than EV with various one motor or 2-induction motor.

References

[1] Takayuki Mizuno,Yasuo Yanagibashi, etc, "New Drive System for Electric Vehicle", EVS-13, 1996.

[2] H.D.Ha, J.W.Park, J.M.Kim, "Development of Traction Control Algorithm for Two Motor Driven Electric Vehicle", EVS-14, 1997.

[3] J.R. Hendershot Jr. and TJE Miller, "Design of Brushless Permanent-Magnet Motors", Magna Physics Publishing, 1994.

[4] G.H.Kang, J.P.Hong, D.H.Kang, D.H.Koo, and J.W.Park, "CAD system for IPMSM Combined Equivalent Circuit with FEM", IEEE CEFC, Vol.8, pp.267, 1998.

[5]. A. Levran and E. Levi, "Design of Polyphase Motors with PM Excitation", IEEE Transactions on Magnetics, Vol.MAG-20, No.3, 1984.

[6] Shigeo Morimoto, Yoji Takeda, "Expansion of Operating Limits for Permanent Magnet Motor by Current Vector Control Considering Inverter Capacity", IEEE Trans. on Industry Appl., Vol.26, No.5, PP.866~871, 1990.

[7] S.R. Macminn and T. M. Jahns, "Control Techniques for Improved High Speed Performance of IPMSM Drives", IEEE Trans. Ind. Appl., Vol. 27, No.5, pp.997~1004, 1991.

Table 3. Designed Motor Parameters

Parameter	Unit	Value
Back-EMF per phase	[V]	78.876
Resistance per phase	[Ω]	0.042
Synchronous reactance	[Ω]	0.637
d-axis reluctance	[Ω]	0.32327
Q axis reluctance	[Ω]	0.95077
Short circuit current	[A]	123.26
Load angle	[deg.]	46.69
Current phase angle	[deg.]	24.00
Phase current	[A]	85.0
d-axis current	[A]	-34.5
q-axis current	[A]	77.65
d-axis voltage	[V]	-75.28
q-axis voltage	[V]	70.96
Input power	[kW]	24.34
Output power	[kW]	23.43
Efficiency	[%]	96.25
Torque	[N.m]	52.02
Synchronous pull out torque	[N.m]	151.2
Maximum power	[kW]	63.0
Synchronous pull out current	[A]	300.0
Synch. pull out Efficiency	[%]	85.0
Current density	[A/㎟]	7.45

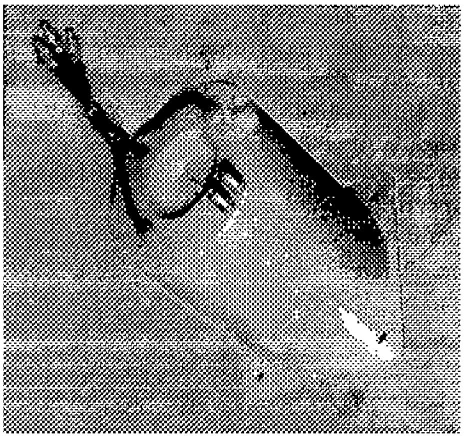


Fig. 10 Interior permanent Magnet Synchronous Motor

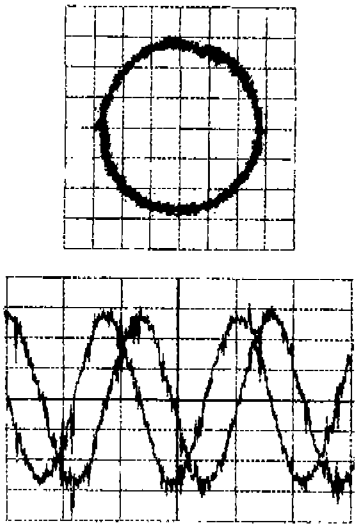


Fig. 12 d-q Current Trajectory (i_{ds} – i_{qs}, 1500rpm)

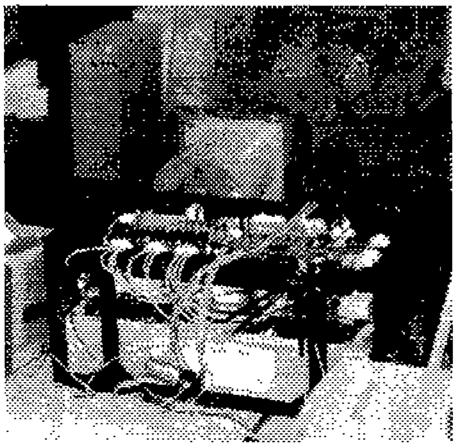


Fig. 13 Inverter (and IPMSM-Gen.)