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Conference Title

Comparison of Concentrated and Distributed Winding in an IPMSM for Vehicle Traction

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Abstract

There are two winding methods for the interior permanent-magnet synchronous motor for vehicle traction: concentrated winding and distributed winding. Both have merits and demerits, and both influences the motor's performance. In this paper, designs of concentrated- and distributed-winding motors with the same capacities are presented, and each motor's characteristics were analyzed using the finite-element method.

Keywords: IPMSM; distributed winding; concentrated winding;

1. Introduction

The interior permanent-magnet synchronous motor (IPMSM) produces not only the magnetic torque through the permanent magnet but also the reluctance torque, due to the difference between the d- and q-axis inductances. Thus, IPMSM has a high power density and can be driven at a high speed using flux-weakening control. Therefore, the IPMSM for vehicle traction is widely used because of its constant torque at low speeds and its extensive constant power at high speeds [1].

IPMSM's winding can be distributed or concentrated depending on the combination of the numbers of slots and poles. The IPMSM with a concentrated winding is small and lightweight and has higher productivity than the IPMSM with a distributed winding, thus having a short end coil and an easy winding

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operation. The IPMSM with a distributed winding, on the other hand, can have high efficiency by producing a higher reluctance torque than the concentrated winding, and having low eddy current loss in the permanent magnet at a high speed.

In this paper, the initial design of IPMSM for the selection of the appropriate winding type was proposed through the comparative analysis of the characteristics of 110kW IPMSMs designed with concentrated and distributed windings, respectively.

Nomenclature

V	Phase voltage
E	Electromotive force
r	Motor-winding resistance
I_a	Armature current amplitude
P_n	No. of pole pairs
Ψ_a	Linkage flux by the permanent magnets in the armature winding
i_d	D-axis current
i_q	Q-axis current
L_d	D-axis inductance
L_q	Q-axis inductance

2. Design of the Traction Motor

Traction motors need a constant torque at low speeds and a widely constant power at high speeds. Therefore, the speed-torque curve for the traction motor is shown in Fig. 1. The 110kW IPMSM has a rated speed at 2,400 rpm and a maximum speed at 6,000 rpm. The torque of IPMSM is 433 Nm at a rated speed and 133 Nm at a maximum speed.

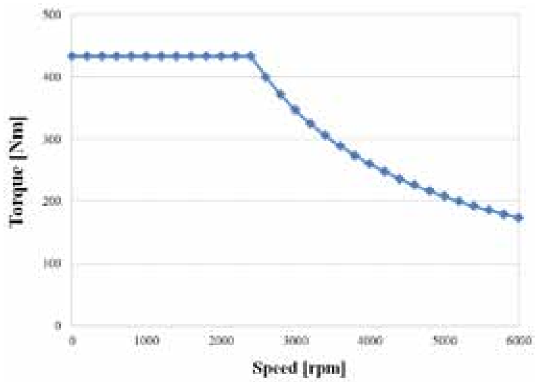

Fig. 1. Speed-torque curve for IPMSM.

The traction motor for a vehicle should be designed considering the switching device's withstanding voltage because it uses regenerative braking. In other words, the motor should not be designed in such a way that the no-load induced electromotive force exceeds the switching device's withstanding voltage. When the withstanding voltage of IGBT is 1200 V (line-line), the phase voltage is 692 V peak. Therefore, the motor's no-load induced electromotive force should be lesser than 692 V. At the base speed (2400 rpm), the phase voltage should be less than 277.1 V.

The inverter has a DC link voltage of 750 V and was operated by SVPWM (space vector pulse-width modulation). As such, the maximum phase voltage from the inverter is 433 V. If IPMSM's speed increases, the back EMF also increases. As such, the back EMF should not exceed the voltage limit value 428 V. This value is attained by subtracting the voltage drop in the winding resistance from the input voltage. This is intended to satisfy equation (1).

$$V = E + rI \qquad (1)$$

The current density of IPMSM winding is 4.5 A/mm^2 because this IPMSM is used for the air-cooling system. The number of poles is selected with respect to the inverter, using a carrier frequency of 10 kHz. As such, six poles (6p) were selected, considering stable control. The number of slots (s) needed to have concentrated windings was determined to be nine, and that needed to have distributed winding was 36. The motors' rotor diameter and lamination stack length were designed to be the same. Fig. 2 shows the resulting geometry of the IPMSM design, and Table 1 lists the detailed specifications of the design model.

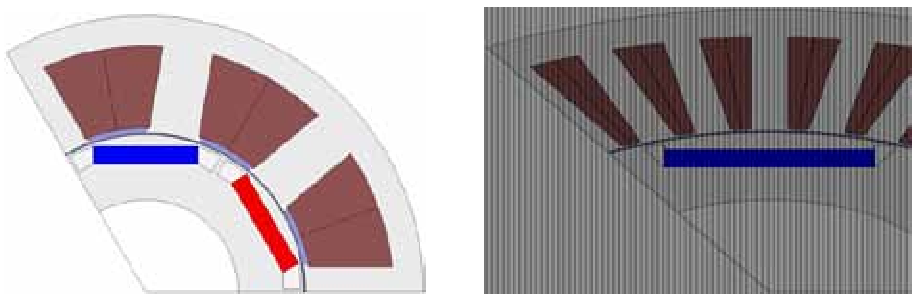

Fig. 2. Design model of IPMSM: (a) concentrated-winding model (6p9s); and (b) distributed-winding model (6p36s).

Table 1. Specifications of the Motor

Model	Specifications
Phases and poles	3 phases, 6 poles
DC voltage of the inverter	750 V
Carrier frequency of the inverter	10 kHz
Maximum output	110 kW
Diameters of the stator and rotor	318 mm, 180 mm
Core length	280 mm
Magnet type, magnetization	Nd-Fe-B, 1.15T
Conductivity of the magnet	909090 S/m
Thickness of the steel plate for the core	0.35 mm

3. Analysis of the Traction Motor's Characteristics

3.1. Comparison of the components of the torques and the d- and q-axis inductances

As in equation (2), IPMSM can obtain the magnetic torque through the use of a permanent magnet, and the reluctance torque based on the difference between the d- and q-axis inductances.

$$T = P_n \Psi_a i_q + P_n (L_d - L_q) i_d i_q \qquad (2)$$

If the salient ratio (Lq/Ld) is large, the reluctance torque can be used even more because of the large difference between the d- and q-axis inductances. In the case of the concentrated-winding motor, the current phase angle that can generate maximum torque at the base speed (2400 rpm) is 18˚, and the salient ratio is about 1.2. That is, the torque mainly has magnetic-torque components. On the other hand, in the case of the distributed-winding motor, the current phase angle that can generate maximum torque at the base speed is 40˚, and the salient ratio is about 2.1. As such, about 29.5% of the total torque is the reluctance torque.

In the comparison of the concentrated- and distributed-winding motors at the maximum speed of IPMSM (6000 rpm), the back EMF of IPMSM was found to be over the voltage limit when driving at a certain high speed. At this point, field-weakening control must be carried out by increasing the current phase angle. In the case of the concentrated-winding motor, the current phase angle that can be performed within the voltage limit at the maximum speed is 75˚. At this point, the back EMF is 366.7 V, which is not over the voltage limit of 428 V, and the salient ratio is about 1.8. It shows a higher increase compared to the salient ratio, at the base speed. On the other hand, in the case of the distributed-winding motor, the current phase angle that can be performed within the voltage limit at the maximum speed is 80˚. At this point, the back EMF is 419.1 V, which is also not over the voltage limit of 428 V.

Table 2. Analysis Results of the IPMSM Models

	2400 rpm		6000 rpm	
	6p9s (CW)	6p36s (DW)	6p9s (CW)	6p36s (DW)
Phase current [A peak]	400	400	400	400
Current phase angle [deg]	18	40	75	80
EMF [V peak]	215.7	222.1	366.7	419.1
Ld [mH]	0.3012	0.3614	0.2835	0.3330
Lq [mH]	0.3578	0.7450	0.5073	1.1555
Magnetic torque [Nm]	424.0	325.5	103.0	73.8
Reluctance torque [Nm]	12.0	136.0	40.3	101.3
Total torque [Nm]	436.0	461.6	143.3	175.1
Copper loss [W]	592.8	2932.8	592.8	2932.8
Core loss [W]	630.1	832.2	1032.1	3594.4
Magnet eddy current loss [W]	4412.4	45.6	7925.1	26.7
Efficiency [%]	94.89	97.24	89.46	94.20

3.2. Comparison of the losses and efficiency

Fig. 3 shows the calculated losses. The copper loss was calculated based on the phase current and winding resistance of the motors. The copper loss of the concentrated-winding motor, which has a low winding resistance due to the short winding length, is smaller than that of the distributed-winding motor, which has a high winding resistance due to its long end coil.

The core losses of both motors are similar at the base speed, but they have a big difference at the maximum speed. The core loss of the distributed-winding motor increased rapidly with the increase in rotational speed. This can be explained by the harmonic flux of the permanent magnet. In the case of the concentrated-winding motor, this harmonic flux exists only at the top of the teeth because the teeth width is nearly the same as the wavelength of the harmonic field. On the other hand, in the case of the distributed-winding motor, the flux deeply enters into the yoke because of the narrow teeth. As a result, the core loss is generated at the whole part of the stator [2].

Fig. 3 shows the calculated losses of the motors. The distributed-winding motor has a very small magnet eddy current loss. On the other hand, for the concentrated-winding motor, much of the loss is magnet eddy current loss.

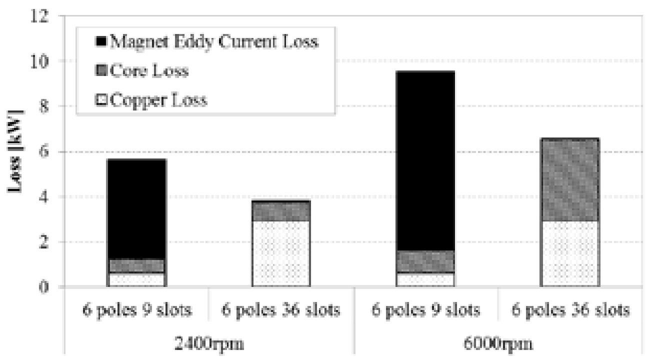

Fig. 3. Calculated losses of the motors.

The losses of the IPMSM are the copper, core, and permanent-magnet eddy current losses. The IPMSM also has mechanical and stray losses, but these were not considered in this study.

The efficiency of the distributed-winding motor was found to be better than that of the concentrated-winding motor, as can be seen in Table 2. In particular, the efficiency largely decreases at high speeds. The permanent-magnet eddy current loss of the concentrated-winding motor was very large. This caused a difference in efficiency between the distributed- and concentrated-winding motors. In addition, the difference in efficiency between low and high speeds is attributed to the fact that the core losses and the permanent-magnet eddy current losses are proportional to the square of the speed

4. Conclusion

In this paper, a concentrated-winding IPMSM and a distributed-winding IPMSM for vehicle traction, with the same capacities, were designed, and their characteristics were analyzed. The concentrated-winding motor was found to be advantageous in terms of copper and core losses, but it was found to have a major disadvantage. That is, it has a large permanent-magnet eddy current loss at a high speed, which is very critical. On the other hand, the distributed-winding motor was found to have disadvantages in terms of copper and core losses, but it was found to have the advantage of low permanent-magnet eddy current loss. Therefore, the distributed-winding IPMSM should be selected for frequent high-speed operation and for an environment where rotor cooling is difficult. If the permanent-magnet eddy current loss of the concentrated-winding motor can be reduced, however, such motor will obtain the advantages of copper and core losses as well as spatial benefits. Thus, the future related researches must aim at reducing the permanent-magnet eddy current loss.

Acknowledgements

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