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Design of High-Speed IPM-BLDC Motor with High Efficiency

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Abstract: In recent years, there are many applications that use BLDC (Brushless DC) motors. Ranging from tens to hundreds of watts to several megawatts, from low-speed drive systems to high-speed drive systems. This study describes the design of a BLDC motor for application to a system driven at about 800 W class, 60,000 rpm or more. Particularly discuss IPM (Interior Permanent Magnet) type BLDC rather than SPM (Surfaced Permanent Magnet) structure. An efficiency improvement design method for reducing iron loss and permanent magnet loss due to high-speed rotation will be described.

Key words: Brushless DC Motor (BLDC), Interior Permanent Magnet Synchronous Motor (IPMSM), high-speed, design, applications, megawatts

INTRODUCTION

The demand for BLDC motors has been increasing for not only the high torque power density but also the low cost driving and control. In BLDC motors, the lower cost operating is available by detecting the rotor position from only three cheap hall sensors (Kim *et al*., 2013). In addition, it is available to the severe operation environment. This is the reason why BLDC motors are gaining grounds in industries, especially in the areas of appliances production, computer peripherals, electric vehicles, industrial automation and so on.

Moreover, IPM is attractive for high-speed operation compared with SPM because of absence of guide cans used in SPM to avoid magnets flying away from rotors by a centrifugal force (Jiaxin *et al*., 2006). In addition, IPMs can generate a reluctance torque benefited from the rotor saliency (Shigematsu *et al*., 2004). However, IPM-BLDC drive system is not a common case. Because IPM motors get sinusoidal EMF but BLDC drive have trapezoidal voltage source (Nagorny, 2009). Nevertheless, in high-speed current waveform that is response of voltage source is adaptive to sinusoidal EMF. Additionally, driving regions are only one speed point or small change in speed applications BLDC is better than BLAC drive (Han *et al*., 2010).

MATERIALS AND METHODS

Specification generation: In designing the motor, the first thing is to determine the load characteristics and set the design point showed in Fig. 1 and 2. When the fan rotates at 100% speed, so that, the motor can operate at the point where the performance curve of the applied fan is at the highest efficiency, it operated at the point B which is the point where the efficiency is the best and the load transmitted to the motor is the heavy load. Therefore, in this case made a judgment and decided specification. The input power of the designed motor is 700 W, the system efficiency (motor+inverter) is higher than 87%, the motor output is 609 W, the rated speed is 60,000 rpm and the torque at the rated speed is 0.1 Nm.

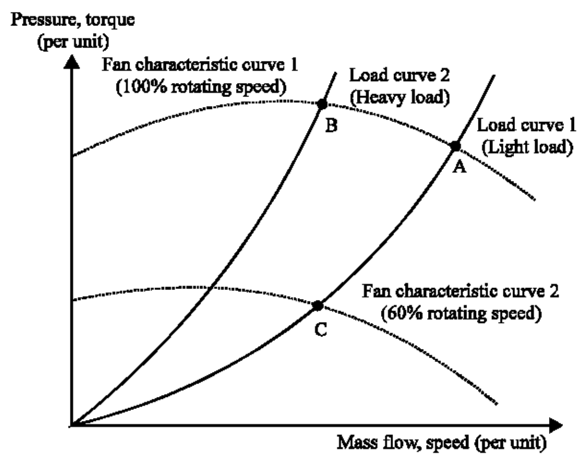

Fig. 1: Fan performance curve and motor load curve

The characteristics of the used battery showed in Fig. 3. One package consists of nine cells, each with a voltage of 2.5-4.2 V. That is, the rated voltage of one

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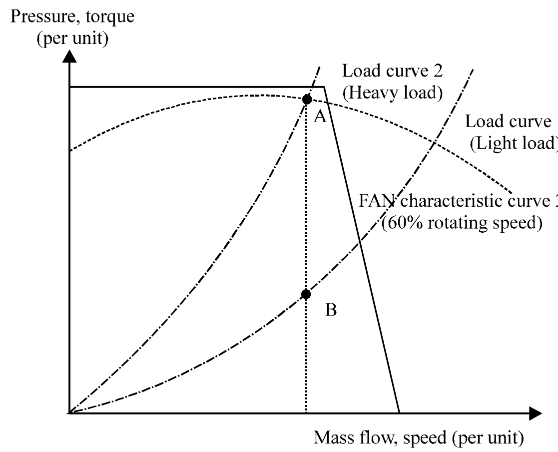

Fig. 2: Determine design point

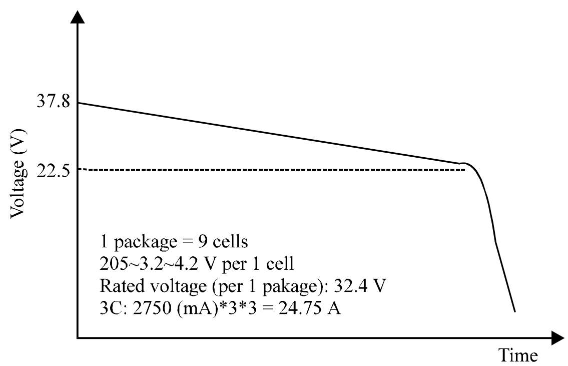

Fig. 3: Battery characteristics package

is 32.4 V on the average. By connecting three of these packages in parallel, we increased the amount of peak current we could draw. Since, the output current of the battery is <25 A, this has served as the current limit of the DC current stage at design time. Addition to, the permanent magnet used is N38 UH and the Br value is 1.05 at 120°C. In case of knee point, it exists in <0.1 T, so, it has strong potato characteristics.

Designed for efficiency improvement: Shape optimization was done to improve efficiency. Adjusts the input power by changing the stack length while keeping the counter electromotive force constant when the motor output changes due to the change of the back electromotive force value as the shape parameter value changes. The geometry parameters were chosen for slot opening, tip length, web width, rib thickness and electrical steel plate. A description of each parameter is shown in Fig. 4. As a result, the final model was selected by selecting the parameters with the lowest iron loss and permanent magnet loss.

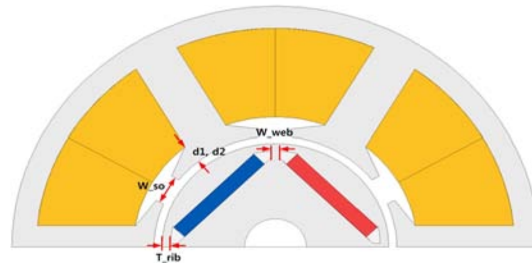

Fig. 4: Optimization parameter

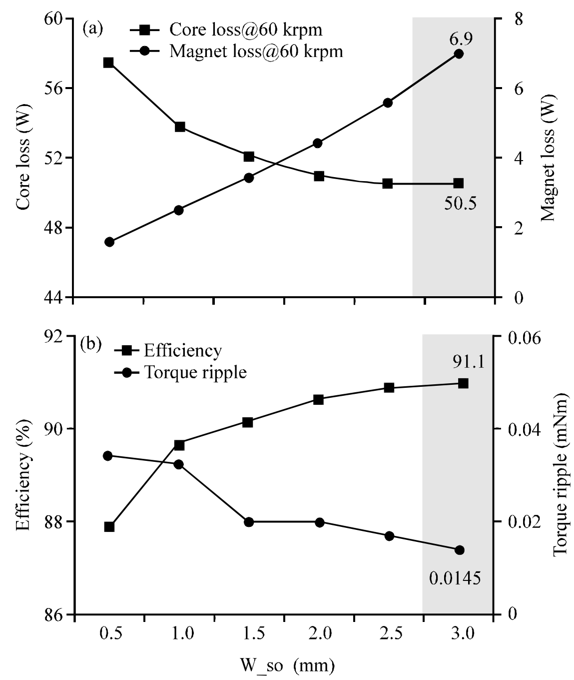

Fig. 5: a) Core loss and magnet loss due to slot opening and b) Efficiency and torque ripple due to slot opening

If the slot opening is small, many fluxes saturate the teeth, resulting in harmonics and torque ripple. In addition, the iron loss is large and the efficiency of the saturated portion is low. Therefore, we found a point where iron loss is minimized and efficiency is maximized by widening the slot opening showed in Fig. 5.

In Fig. 6 and 7, D1 and 2 are interpreted such that the sum is 2. As a result, it was found that the maximum efficiency was obtained when D1 was 0.8 and D2 was 1.2.

Theoretically, the smaller the web width, the more magnetic torque is used without using the reluctance torque. Therefore, it is expected that the effect of the present invention becomes narrower and the gain becomes larger in Fig. 8 and 9.

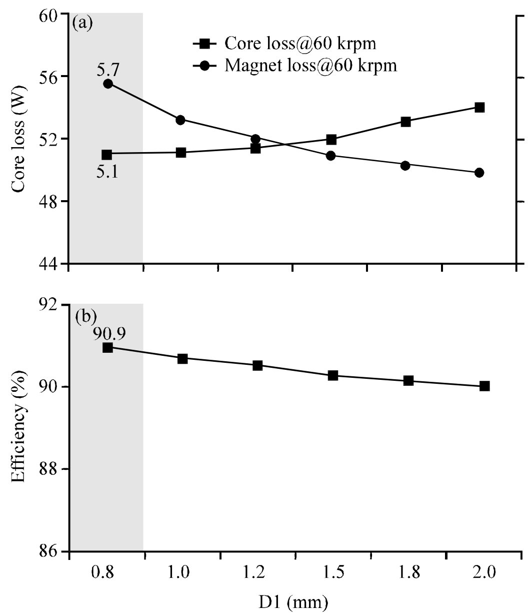

Fig. 6: a) Core loss and magnet loss due to D1 and b) Efficiency and torque ripple due to D1

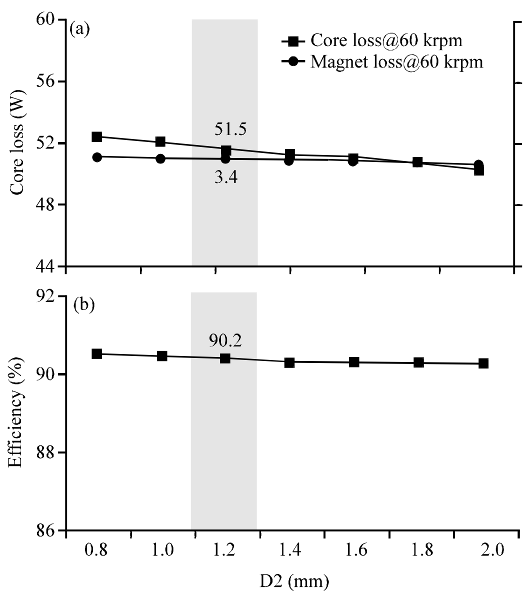

Fig. 7: a) Core loss and magnet loss due to D2 and b) Efficiency and torque ripple due to D2

The thinner the rib thickness, the thinner the leakage flux, the better the characteristics in Fig. 10.

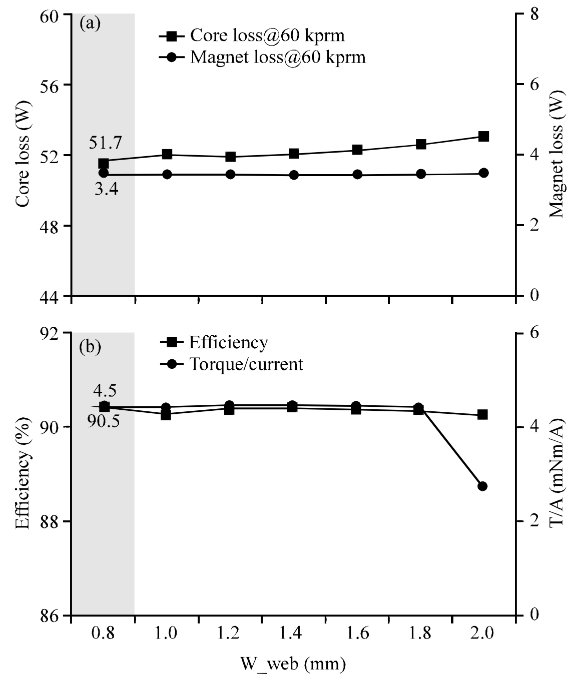

Fig. 8: a) Core loss and magnet loss due to W_web and b) Efficiency and torque ripple due W_web

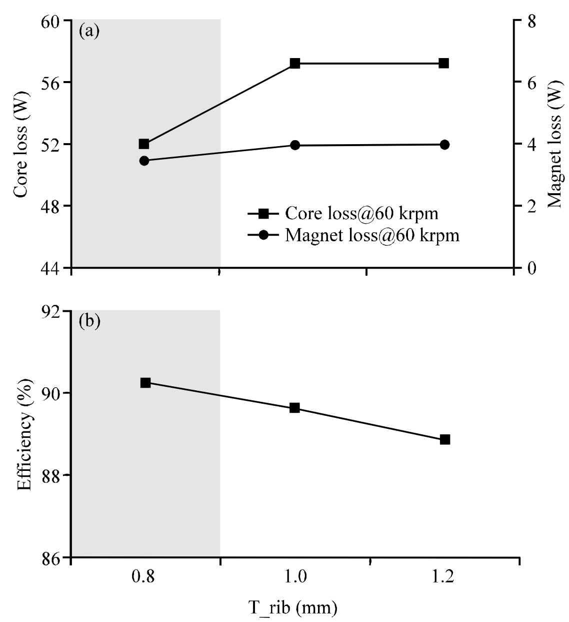

Fig. 9: a) Core loss and magnet loss due to T_rib and b) Efficiency and torque ripple due T_rib

Final designed model: For the final model, the outer diameter is 51.2 mm which is much smaller than the 60 mm constraint and the stack length is designed to save money with a lot of space in mind. The rib length which has the greatest influence on the stiffness of the rotor is designed with rigidity in mind. Detailed dimensions of the final model are shown in Table 1. Table 2 shows the performance characteristics of the final model. However,

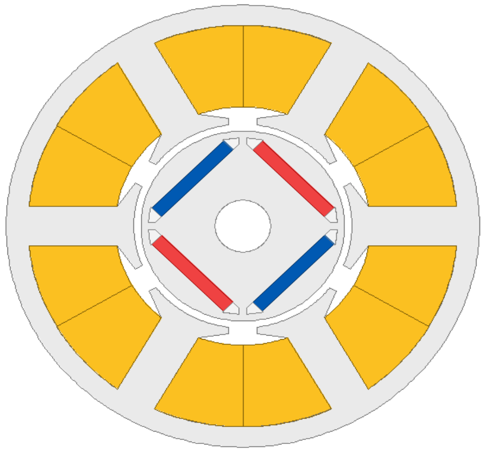

Fig. 10: Final designed model

Table 1: Detailed dimensions of the final model

Contents	Values
Input voltage	32.4 V
Rib length	0.8 mm
Rotating speed	60,000 rpm
Air-gap	0.8 mm
Outer diameter	51.2 mm
Turns per teeth	15
Rotor diameter	22 mm
Parallel branch	2
Stack length	16 mm
Fill factor	33%
Magnet size	11/1.5 mm
Coil diameter	1.4 mm
Slot area	140 mm^2
Phase resistance	0.007 Ω
Slot opening	3 mm
Advance angle	0°E
Web width	0.8 mm
On-time angle	120°

Table 2: Performance characteristics of final model

Contents	22.5 V	32.4 V	37.8 V
Input power (W)	513	680	730
Inverter efficiency (%)	94.76	95.74	95.05
Motor efficiency (%)	93.9	93.32	92.96
System efficiency (%)	88.98	89.34	88.36
Motor power (W)	456.8	607	645
Average torque (Nm)	0.11	0.1	0.11
Motor loss (Pr/Pc/Pe) (W)	10.9, 18.1, 0.64	9, 33.2, 1.3	10.3, 36.5, 2.1

even when the minimum nominal voltage and the maximum nominal voltage of the battery voltage are designed to be 32.4 V, the input current Id_c is controlled to control the speed to 60,000 rpm. The results for each voltage system are shown in Table 2.

CONCLUSION

This study presented the design of a BLDC motor for application to a system driven at about 800 W class, 60,000 rpm or more. In particular, an improved design method for reducing iron loss and permanent magnet loss due to high-speed rotation has been described. Therefore, this study shows the possibility of performance improvement of IPM-BLDC motor by the optimization of design parameters.

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