A Novel Rotor Configuration and Experimental Verification of Interior PM Synchronous Motor for High-speed Applications

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Abstract — On account of high efficiency and high power density, permanent magnet synchronous motors (PMSMs) are mainly applied to a high-speed machine. Especially, because of relatively easy magnetic circuit design and control, a surface-mounted PMSM of them is adopted in almost the whole high-speed applications. However, the surface-mounted PMSM has some weak points due to a sleeve, which is non-magnetic steel used in order to maintain the mechanical integrity of a rotor assembly in high-speed rotation. The sleeve causes additional eddy current loss in the rotor besides permanent magnet and increases not only magnetic air-gap length but manufacturing costs by raw material purchase and shrink fitting. Thus, in this paper, a new rotor shape for a high-speed interior permanent magnet synchronous motor (IPMSM) is presented in order to resolve the faults of the surface-mounted PMSM. Moreover, the amount of permanent magnet employed in the IPMSM is decreased approximate 53% than that of the surface-mounted PMSM. Except the rotor configuration, all design conditions of the IPMSM are identical compared with the surface-mounted PMSM. Finally, the IPMSM is fabricated, and its superiority and reliability in high-speed operation are verified by test.

I. INTRODUCTION

Recently, in a variety of industrial applications such as machine tools, vacuum pumps, and centrifugal compressors, the case applied to high-speed machines for miniaturization and weight reduction is growing more and more [1]. In particular, they are fitted for automotive applications where space and energy savings are critical. The application of gearless directly coupled high-speed machines can avoid problems such as oil leakage, maintenance costs, and gear losses and increase the system reliability by simplifying the structure. Moreover, noise can also be considerably reduced by eliminating an additional transmission system.

A permanent magnet synchronous motor (PMSM) of varied motors such as an induction motor and a reluctance motor are becoming more and more favored to the high-speed machine. On account of the non-electric excitation, rotor losses are very small, leading to minor thermal rotor expansion and to improved efficiency [2]. Particularly, due to relatively simple magnetic circuit and control, a surface-mounted PMSM is applied in almost the whole high-speed machines. Nevertheless, in the surface-mounted PMSM, a sleeve, non-magnetic steel, existing in order to maintain the mechanical integrity of a rotor assembly in high rotational speed is a critical fault, because the eddy current loss by slot harmonics is produced in that with conductivity, and a large amount of permanent magnet is consumed for compensating the magneto-motive force reduced by the increase of magnetic air-gap. Consequently, this paper presents a new rotor shape of a high-speed interior permanent magnet synchronous motor (IPMSM) as the alternative of the surface-mounted PMSM.

The IPMSM does not fundamentally need the sleeve, because permanent magnet is inserted inside the rotor. Moreover, the IPMSM has higher power density than the surface-mounted PMSM, because it can employ both a magnetic and a reluctance torque with a proper current vector control. However, due to the rotor complexity and the electrical and mechanical characteristics conflicted in high-speed rotation, there are very few technical papers investigated on the rotor structure of the IPMSM for high-speed applications. Thus, the 2-pole IPMSM considering electrical and mechanical characteristics is designed and fabricated as the driving motor of a 8kW, 40000rpm class air-blower. In the end, the superiority and reliability of the IPMSM in high-speed operation is verified by the results obtained by test.

II. CONFIGURATION AND DESIGN SPECIFICATIONS OF HIGH-SPEED SURFACE-MOUNTED PMSM

The rotor shape of a surface-mounted PMSM is shown in Fig. 1. The permanent magnet magnetized in the parallel direction is retained within a sleeve, which has been pressed on the rotor to withstand the centrifugal stress under high-speed operation. In particular, the permanent magnet and sleeve are divided as two parts in order to reduce eddy current loss. Fig. 2 displays the manufactured stator with 3-phase coils, and it is employed for both the surface-mounted PMSM and IPMSM. Also, main design specifications given in Table I are equally applied for them.

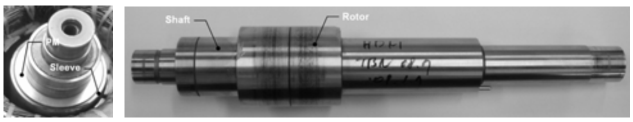


Fig. 1. Rotor configuration of high-speed surface-mounted PMSM

(a) Top view (b) Side view

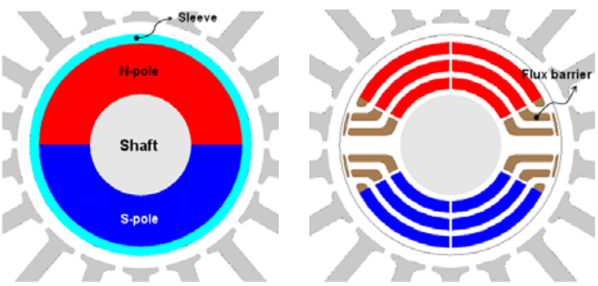
Fig. 2. Manufactured stator with 3-phase coils

TABLE I
MAIN DESIGN SPECIFICATIONS

Specifications	Items	Value (unit)
Structural	Stator outer diameter	88.0 mm
	Rotor outer diameter including sleeve	35.2 mm
	Mechanical air-gap length	2.0 mm
	Stack length	35.0 mm
	Number of poles / slots	2 / 18
	Residual magnetic flux density of PM	1.81 T
	Number of series turns per phase	33
Electrical	DC link voltage	240 V
	Input voltage	88.2 V_{rms}
	Input current	40.0 A_{rms}
	Output power	8.0 kW
	Maximum speed	40000 rpm

III. Rotor Configuration of High-speed IPMSM

In this section, on the basis of specifications given in Table I, the optimal rotor configuration of an IPMSM is designed in order to obtain better performance than the surface-mounted PMSM, which is currently used for driving the air-blower of a fuel cell electric vehicle (FCEV). The design procedure is divided into four parts overall. First, the characteristics of the surface-mounted PMSM are analyzed in order to decide design criteria such as target efficiency and electrical parameters of the IPMSM. Next, a parametric design is carried out in order to reduce the iteration of the rotor design [3]. The parametric design is to determine the range of back-EMF and d-q axis inductance to accomplish the characteristics required in the IPMSM. Third, the initial rotor shapes of the IPMSM fitted for high-speed operation are investigated. Finally, design of experiment (DOE) and response surface methodology (RMS) are employed as a method for the rotor optimization to meet required electrical performances and mechanical stress. Characteristic analysis by an equivalent circuit and structural analysis are carried out in order to the results. The more detailed explanation on the design process will be given in a full paper. Fig. 3 shows the rotor configuration of the surface-mounted PMSM and optimized IPMSM. As appears by the figure, the amount of permanent magnet used in the IPMSM is much smaller than the surface-mounted PMSM.



(a) Surface-mounted PMSM (b) IPMSM

Fig. 3. Rotor configuration comparison

IV. Test Results and Discussion

In order to verify the performance of the fabricated IPMSM, three types of tests are carried out, and one of them displayed in Fig. 4. The results obtained in the test are shown in Fig. 5. The analysis of them will be presented in final paper. In the end, the fabricated configurations of the IPMSM are exhibited in Fig. 6.

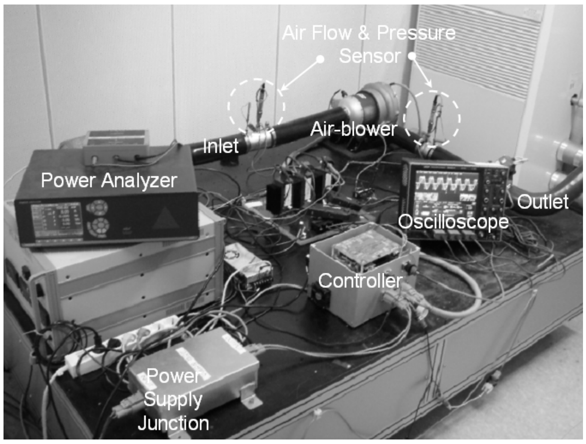
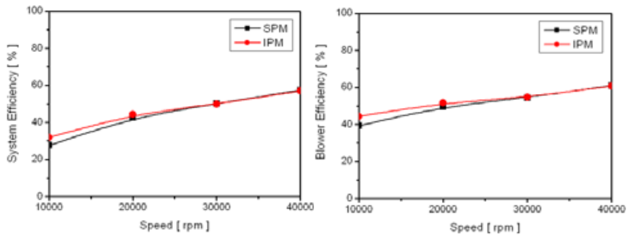


Fig. 4. Testing apparatus for air-blower system test



(a) Air-blower system (b) Air-blower

Fig. 5. Efficiency comparison of surface-mounted PMSM and IPMSM

(a) Rotor (b) Rotor assembly (c) Air-blower

Fig. 6. Configurations of fabricated IPMSM

V. Conclusion

This paper will be good reference for the rotor design of a high-speed IPMSM.

VI. References

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