Study on mechanical proportion and anti-demagnetization characteristic of 15 kW, 150,000 r/min PM motor

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Abstract. This paper describes a relationship and compatibility between the mechanical proportion and anti-demagnetization characteristic of an ultra-high-speed permanent magnet (PM) motor of which rated output power is 15 kW and rated speed is 150,000 r/min. The ultra-high-speed motor must be designed to achieve outstanding electromagnetic characteristics under various server mechanical constraints. In the paper, three motor models having different characteristics of 15 kW, 150,000 r/min are investigated from the viewpoints of electromagnetic and mechanical compatibility. all the motor models designed here achieve high efficiency over 95 %, but it is found that anti-demagnetization characteristics are different among the three. In addition, rotor shaft material is discussed for anti-demagnetization. As a result, stainless steel is found to be a better material than carbon steel for anti-demagnetization.

1. Introduction

Recently, electrification of mechanically systems is widely and intensively spread to various industry sectors and it is required that motor in the center of the trend has not only high-power but also high power density and high efficiency. Permanent magnet synchronous motors (PMSMs) using rare earth PM is intensively developed and spread to various industry sectors from the viewpoint of the above [1][2]. In order to enhance the motor output power, it is definitely necessary to deliver as high electromagnetic torque as possible and to rotate at a higher speed as possible under some electrical and mechanical design constraints. But, in general, the former tends to cause an increase in motor volume. So, the action of ultra-high-speed (ultra-high-frequency) of motor is valid for decreasing motor volume. But, in the case of ultra-high-speed motor, many various problems such as electrical restriction (e.g. voltage and current), mechanical restriction (e.g. axis vibration and centrifugal force) exist. In the paper, three motor models have different characteristics of 15 kW, 150,000 r/min is investigated. As a result, it is found that anti-demagnetization is very important on ultra-high-speed PM motor. So, rotor shaft material is discussed for anti-demagnetization. As a result, stainless steel is better than carbon steel for anti-demagnetization.

2. Design specifications and design characteristics of 15 kW, 150,000 r/min PM motor

2.1. Design specifications and Simulation methods

Table 1 indicates design specifications of 15 kW, 150,000 r/min PM motor. Figure 1 indicates mechanical constraints of 15 kW, 150,000 r/min PM motor. About design, specifications are shown in Table 1, compatible design with restricted DC bus voltage and rated current is theoretically impossible.

And so, while one of the two restrictions is kept, some models were designed in restricted conditions. Then three motor models were picked up from them. The major specifications of those motor models are shown in Table 2. In addition, in the ultra-high-speed motor, the rotor rotating speed comes up to the sound of speed when the rotor diameter is 37.3 mm. So, motor models are selected in this restriction. In order to investigate losses and demagnetizing characteristics, JMAG-Designer 17.0TM, electromagnetic simulation software is used.

2.2. Fundamental design policy

Figure 2 indicates cross-section of 15 kW, 150,000 r/min PM motor. All motors are adopted surface permanent magnet synchronous motor (SPMSM). The reason is SPMSM doesn't need field magnetizing current like induction motor and reluctance motor. And it is difficult that interior permanent magnet synchronous motor (IPMSM) is adopted from restrictions of the rotor diameter and shaft diameter, so SPMSM which has simple rotor structure is adopted. Rotor pole pair is two poles so that decrease operating frequency. The permanent magnet which has $BH_{max} = 350$ kJ/m^3 is used. This enables wide air gap structure and decreases permeance drifting and synchronous reluctance. And so, the more permeance coefficient is small, losses are lower in ultra-high-speed motor. So, permeance coefficient is integrated 1.1. In regard to stator, concentrated winding is adopted so that leakage flux is decreased and magnet eddy-current that causes heat demagnetization is decreased. Solid copper wires are used stator winding, stator brim is equipped 3 mm on the tip of the Stator teeth.

Table 1. Design specifications of 15 kW, 150,000 r/min PM motor

Rated output power	**15 kW**
Rated speed	150000 r/min
Rated torque	0.955 Nm
Rated efficiency	Over 92 %
DC bus voltage	Less than 259.2 V
Rated current	75A (Overload 200%)
Maximum current	150 A
Rotor diameter	Less than 37.3 mm
Demagnetization rate	Within 1 %

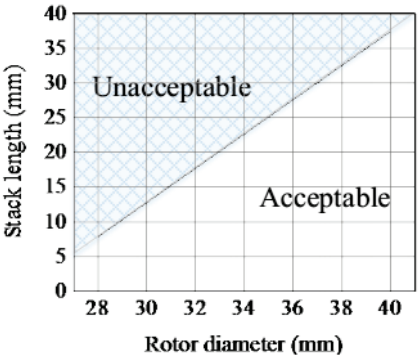

Figure 1. Mechanical constrains of 15 kW, 150,000 r/min 150,000 PM motor.

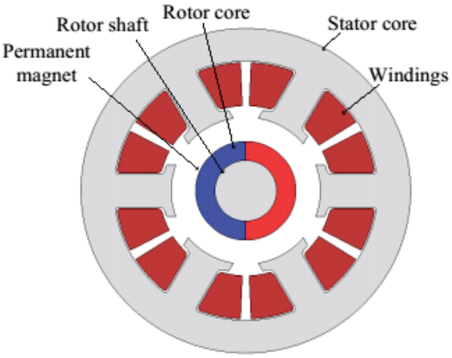

Figure 2. Cross-section of 15 kW, 150,000 r/min PM motor

3. Electromagnetic simulation conditions and comparison of simulation results

The electrical characteristics of studied three motor models are compared. When a motor is evaluated, losses and demagnetizing characteristics are important. In regard to the former, it is important not only total power losses are low but also motor efficiency is maximum at the rated operating point. Regarding the latter, it is desired that the demagnetizing rate is low.

Table 2. Major specifications of ultra-high-speed motor models.

	#1	**#2**	**#3**
DC voltage	358.8 V	258.4 V	243.4 V
Rated current	75 A	107.2 A	107.2 A
Rotor diameter	35.1 mm	34.2 mm	37.2 mm
Stack length	25.2 mm	23.0 mm	30.3 mm
Windings	37	29	21
Shaft diameter	21 mm	21 mm	21 mm

From those backgrounds, in the paper, simulation results are compared from the viewpoint of losses, operating point in maximum efficiency and demagnetizing characteristics. It is assumed that temperatures of magnet and stator winding are 70 °C about losses. On the other hand, the maximum efficiency can be obtained when the equation below is satisfied :

$$Wi + Wmag = Wc \tag{1}$$

Where :
Wi : Stator iron core loss
Wmag : Magnet eddy-current loss, and
Wc: Stator winding copper loss.

From this equation, It is found that the maximum efficiency can be obtained if the iron losses and the copper loss is almost the same. The maximum efficiency operating point is evaluated from the viewpoint of this condition. About demagnetizing conditions, it is assumed when magnet temperature is 200 °C and maximum current flows negative direction of d-axis, and the magnet before demagnetization is compared with the one after demagnetization. Figure 3 shows comparison of total power losses. Figure 4 shows comparison of iron loss and copper loss rate. Figure 5 shows a comparison of the demagnetizing characteristic. In regard to losses, #1 has the best characteristic. The reasons are # 1 needs smallest a current of three motor models and an area of rotor side face is smaller than #3. #1 has smallest total loss for those reasons. #2 is the model that operates the point of nearest to the maximum efficiency operating point. It is because #2 is the most copper machine of three motor models. Regarding, #3 has the best demagnetizing characteristic. It is because the magnet of #3 is thickest and stator windings are smallest of three motor models. However, as shown in Figure 5, because the smallest demagnetizing rate is 17.2 %, it is found that it is important demagnetizing characteristics is improved.

4. Study on anti-demagnetization

4.1. Study on anti-demagnetization

Above described above, three motor models of 15 kW, 150,00 r/min are studied. As a result, it is found that anti-demagnetization characteristic is the most important problem. Although #3 has the best demagnetizing characteristic, the demagnetizing rate is 17.2 %. The value doesn't possibly come close to under 1 % described in design specification. The method to improve a demagnetizing characteristic are indicated below.

1. Increasing permeance coefficient
2. Decreasing negative magnetic field to a magnet.
3. Changing stator slot combination

It is difficult that 1 is adapted to the motor because rotor diameter and rotor shaft diameter has restriction and magnet eddy-current is expected. In regard to 3, It is expected the number of slots is decreased, magnet eddy-current is increased, if not because of wide air gap, the flux that flows between stator tooth increases. In the paper, from the above, 2 is adopted.

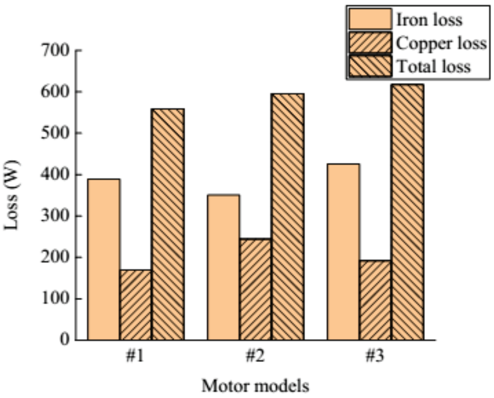

Figure 3. Comparison of total power losses.

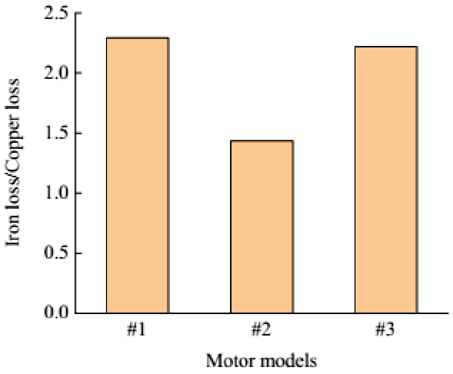

Figure 4. Comparison of iron and copper loss rate

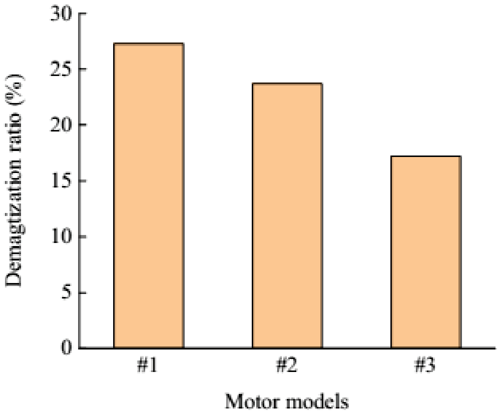

Figure 5. Comparison of demagnetization characteristics.

4.2. Investigating a material of the shaft.

Figure 6 indicates a route of Armature flux by Shaft permeability. Permeability of Rotor shaft is deeply concerned with an amount of negative magnetic field to a magnet. As shown in Figure 6, because of changing permeability of rotor shaft cause changing magnetic resistance of rotor. As a result, the amount of magnetic field to magnet is changed. Thus, because of changing permeability of rotor shaft, magnetic circuit route of rotor is changed. The above influences a demagnetizing characteristic.

In the paper, demagnetization characteristics of #A that is used S45C and #B that is used SUS304 on rotor shaft are compared within the mechanical restriction. Table 3 indicates Major specifications and simulation conditions of motor models. The former is about 880 times as much as the latter. On the other hand, because SUS304 has lower rigidity than S45C, mechanical restriction gets too strict in the case of SUS304.

From the above, under the mechanical constraints of 15 kW, 150,000 r/min PM motor in the case SUS304 is used on Shaft. shown in Figure 7, # A and # B are designed. The next topic is the simulation conditions. In both # A and # B, output power is 15 kW and Rotor dimension is same. In regard to stator,

stator teeth width and coil space factor are not changed, stator diameter and number of windings are only changed. Figure 8 indicates a comparison of the demagnetization rate. Figure 9

Table 3. *Major specifications and simulation conditions of motor models*

Motor model	**# A**	**# B**
Shaft material	s45c	SUS304
Relative permeability	1846.2	2.1
Young’s modulus	202000 MPa	192000 Mpa
Rated output power	15 kW	15 kW
Phase current amplitude	150 A	150 A
Rotor outer diameter	37.2 mm	37.2 mm
Rotor length	25.5 mm	25.5 mm
Magnet thickness	8.1 mm	8.1 mm
Airgap length	10.7 mm	10.7 mm
Permeance coefficient	1.1	1.1
Stator diameter	112.3 mm	113.8 mm
Stator stack length	25.5 mm	25.5 mm
Number of Winding turns	25	28
Winding space factor	54.6 %	54.6 %

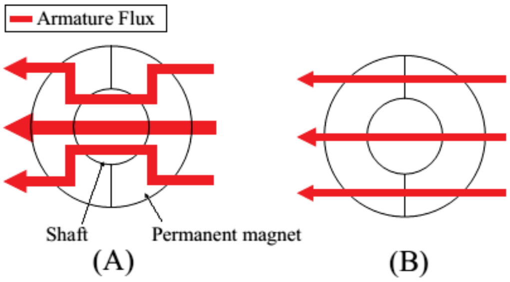

Figure 6. *Route of Armature flux by Shaft permeability.*

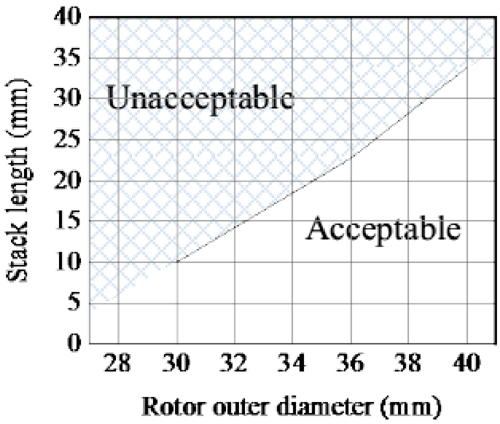

Figure 7. Mechanical constraints of 15 kW, 150,000 r/min PM motor in the case SUS304 is used on Shaft.

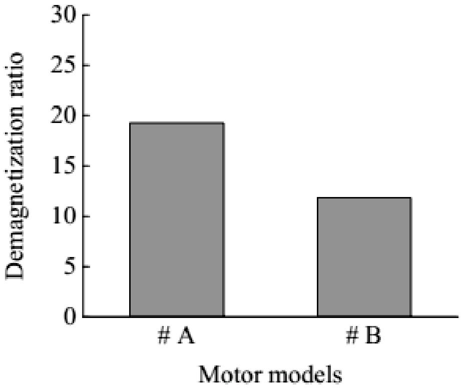

Figure 8. Comparison of demagnetization rate

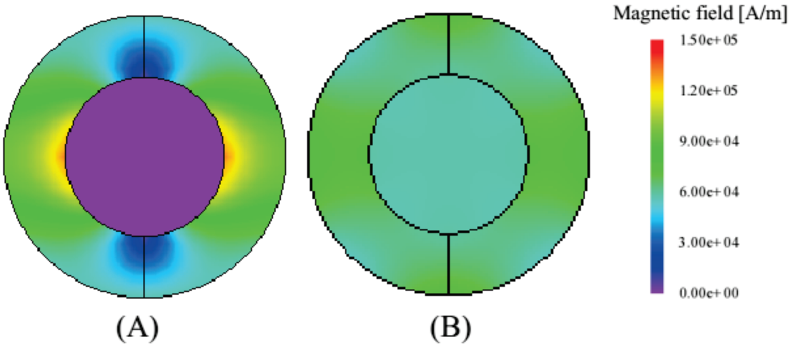

Figure 9. Rotor flux density distribution of the motor model.

indicates rotor flux density distribution of the motor model. As shown in Figure 8, demagnetization rate of # A and # B are 19.3 % and 11.8 %. It is found that the demagnetization rate when SUS304 is used on rotor shaft is lower than that when S45C is used. Thus, as shown in Figure 9, because it is found that # A has more magnetic field near Shaft than # B, magnetic field of #A is gathered intensively. That causes the deterioration of demagnetizing characteristics. From the above, SUS304 is adopted on the rotor shaft.

5. Conclusion

In the paper, proportions of 15 kW, 150,000 r/min PM motor, three motor models have different characteristics are investigated from the viewpoint of loss characteristics, the operating point of maximum efficiency operating point, demagnetizing characteristics. From the simulation result, three motor models have relationships of trade-off, and it is difficult that all design specifications are achieved. Thus, it is the most important investigated problem in ultra-high-speed motor. Therefore, rotor shaft material is discussed for anti-demagnetization. As a result, stainless steel is better than carbon steel for anti- demagnetization. However, the demagnetization rate is about 11.8 %. For future work, it is required to reduce the demagnetization rate and a real machine is created.

6. References

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