Increasing the Operating Speed of a Consequent Pole Axial Gap Motor for Higher Output Power Density

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In this study, we examine how to increase the operating speed of a consequent pole axial gap motor to achieve higher output density. Our research group has been developing a consequent pole axial gap motor with field windings as the traction motor for electric vehicles. A smaller and lighter traction motor is required for better fuel economy and layout of such vehicles, and it is profitable to manufacture a smaller motor with an increased operating speed. To achieve high-speed operation, it is necessary to suppress the line-to-line voltage, and to that end, we examine the slot/pole combination. Moreover, because the rotor outer diameter of an axial gap motor is larger than that of a radial gap motor, the rotor strength should also be considered. We study the use of non-magnetic high-tensile-strength steel for the component that supports the rotor. We present the motor design and the results of spin burst tests, and we confirm that the motor can operate at the target maximum speed and output power density.

Keywords: motor, consequent pole, ferrite permanent magnet, axial gap, variable flux

1. Introduction

The regulations against vehicles with internal combustion engines are becoming stricter. Electric vehicles (EVs) are gaining attention as one solution to reduce CO₂ emissions, and many car and component manufacturers are developing traction motors^{(1)–(3)}. There are many necessary attributes for traction motors for EVs, for example variable flux capability and a flat shape; the latter is needed regarding the layout of the motor in the EV. Another necessary attribute is the ability to achieve simultaneously (i) high torque at low speed, (ii) high efficiency at low load, and (iii) a wide constant output. Generally, high magnetic flux is necessary for high torque, but if the magnetic flux in a motor is too large it is difficult to reduce the iron loss at low load. Moreover, high induced voltage when operating at high speed makes it difficult to achieve constant output over a wide speed range. Consequently, there is a trade-off relation between high torque and high efficiency or wide constant output characteristics.

In the study for variable flux capability, many types of motor have been developed^{(4)–(7)}. To achieve variable flux capability and a flat shape simultaneously, our research group has proposed and has been developing an axial gap motor of the consequent-pole type with a ferrite permanent magnet (PM) with field windings^{(8)–(11)}, overmore higher output

density is also needed. Many research groups are investigating motors that operate at higher speed to increase the output density^{(12)–(13)}. Regarding the axial gap motor that we are proposing, it is profitable to increase the outer diameter of the rotor and decrease the motor length. Therefore, the radius and centrifugal force of an axial gap motor are generally larger than those of a radial-gap motor. This makes it necessary to attend to the larger centrifugal force when seeking to increase the operating speed of an axial gap motor. It is also necessary to suppress the line-to-line voltage to increase the operating speed.

Herein, we examine a design that increases the operating speed, and we show by three-dimensional (3D) finite-element analysis (FEA) that this design achieves the target output power density. To facilitate operation at maximum speed, we also examine the choice of material and structure for the rotor. Through burst tests on the rotor, we confirm its ability to operate at maximum speed. We assemble a proto sample and present test results.

2. Proposed Motor

2.1 Structure Figure 1 shows the proposed motor schematically, comprising an internal rotor and external stators. The rotor comprises PMs and rotor cores (SMCs). The SMCs are made of magnetic material and form the consequent poles. All the PMs are magnetized axially in the same direction. The PMs and SMCs are arranged circumferentially and alternately on the supporting component, which is made of non-magnetic material. There is not a back yoke on the rotor, and the magnetic flux passes through the rotor only axially. There is a stator on either side of the rotor with concentrated windings on each tooth. We choose concentrated

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Fig. 1. Outline of proposed motor

Fig. 2. Magnetic flux due to field winding current

windings so as not to increase the stator outer diameter, and we place field windings at the inner space of stator cores to utilize the dead space.

2.2 Variable Flux Capability We explain here how the proposed motor achieves variable flux capability. Figure 2 shows the proposed motor in cross section. A direct current (DC) is applied to each field winding to generate a magnetic flux; the DC currents are in the same direction. In Fig. 2, the arrows indicate the path of the magnetic flux generated by the DC winding current (also known as the field current). The magnetic flux due to the field current goes around the magnetic path that is formed by the motor shaft, motor case, stator core, rotor, stator core, and motor case on the other side.

Next, we show how the magnetic flux in the motor is altered. Figure 3 shows how the magnetic flux due to the field current goes through around the rotor. When no field current is applied (Fig. 3(a)), the magnetic flux comes from the PMs only and goes around the magnetic circuit formed by the teeth and back yoke of the stator core and the SMCs, teeth, and back yoke of the other stator. Consequently, magnetic poles appear on the SMCs with a direction that is opposite to that of the PMs. When a field current is applied in a direction chosen to generate a magnetic flux that opposes that of the PMs (Fig. 3(b)), that of the SMCs is strengthened. Thus, the magnetic flux density in the air gap (a fundamental component in the present case) increases. We refer to the direction of this field current as the strengthening direction. By contrast, if the field-current direction is chosen to generate a magnetic flux in the same direction as that of the PMs (Fig. 3(c)), the magnetic flux of the SMCs is weakened, thereby reducing the magnetic flux density; we refer to that direction as the

Fig. 3. The path of magnetic flux due to the field current around the rotor

weakening direction. Therefore, as explained, the proposed motor has variable magnetic flux capability.

3. Examination for Higher Output Density

3.1 Slot/pole Combination We studied to increase output power density by 1.3 times compared to first type motor from 3.7 kW/L to 4.8 kW/L. Table 1 compares the targeted design conditions between a motor of the first type⁽¹⁰⁾⁽¹¹⁾ and one of the new design. The target output density of the latter is 4.8 kW/L. This higher output density is achieved by increasing the operating speed from 5,000 rpm to 12,000 rpm. The armature and field current densities of the new motor are

Table 1. Targeted properties of studied motors

	First type	New design
Maximum armature current	74.8 A _{rms}	74.8 A _{rms}
Maximum armature current density	11.9 A _{rms} /mm ²	11.9 A _{rms} /mm ²
Maximum field current	5.5 A	4.3 A
Maximum field current density	6.95 A/mm ²	5.5 A/mm ²
Base speed	1,600 rpm	3,360 rpm
Maximum speed	5,000 rpm	12,000 rpm
Output power density	3.7 kW/L	4.8 kW/L

Table 2. Winding factors of studied motors

Pole number	10	14		
Slot number	12	12	15	18
Fundamental	0.933	0.933	0.951	0.902
2nd order	0	0	0.100	0
4th order	0	0	0.100	0
5th order	0.067	0.067	0.173	0.038
7th order	0.067	0.067	0.111	0.136
8th order	0	0	0.165	0
10th order	0	0	0.100	0
11th order	0.933	0.171	0.044	0.136
13th order	0.933	0.210	0.021	0.038

either the same as or less than those of the motor of the first type. To increase operating speed of hybrid excitation consequent pole axial gap motor and achieve higher output power density, it is necessary to take following points into consideration, (i) suppress operating frequency as high as 1.5 kHz, (ii) suppress iron loss which increases under high frequency operation and keep high efficiency, (iii) make slot number and pole number as high as possible to reduce magnetic saturation in iron core, and (iv) suppress the influence of even-order harmonic components by selecting appropriate slot/pole combination. We choose 24 slots and 20 poles for the motor of the first type. With 20 poles, it is difficult to suppress the operating frequency under 1.5 kHz when the maximum speed is increased to 12,000 rpm. Therefore, to suppress the operating frequency, it is necessary to have fewer poles. Our group has shown that the slot/pole combination of 12 slots and 10 poles is suitable for a motor with a consequent-pole rotor⁽⁹⁾⁽¹⁰⁾. Because the winding factors of even harmonic orders are zero, the influence of an asymmetrically distributed air-gap magnetic flux density can be canceled. However, because it is difficult to miniaturize a 10-pole motor we investigate changing the number of poles from 20 to 14.

Table 2 lists the winding factors of a 14-pole motor along with those of a 12-slot/10-pole motor. Although the fundamental winding factor of the 15-slot/14-pole motor is the largest, the winding factors of even orders are not zero, and the even-order harmonic component of the rotor's magnetomotive force cannot be canceled. The even-order winding factors of the 12-slot and 18-slot motors are zero, making 12 or 18 slots suitable for the 14-pole motor. Comparing the magnetic fluxes between 12-slot motor and 18-slot motor, that of the 12-slot motor is larger. Optimizing the thickness of the back yoke for the 18-slot motor makes the magnetic flux density at the back yoke of the 12-slot motor excessively large, causing magnetic flux to leak to the cover, which is made of magnetic material. However, the cover is not made of laminated material, and very large iron loss occurs when operating at high speed. Consequently, we choose the 18-slot motor, which is suitable for miniaturization.

3.2 Rotor Strength Next, we consider the outer diameter of the rotor. Figure 4 shows the rotor structure of the proposed motor. The PMs and SMCs are glued to the rotor's supporting component, which is made of non-magnetic material. To avoid closing the circuit around the PMs and rotor cores, there are slits in the outer part of the rotor's supporting component to decrease the eddy current loss that is generated

Fig. 4. Top view of rotor

Fig. 5. Rotor displacement at maximum rotation speed (new design)

therein. The rotor's supporting component is reinforced with 3-mm-thick carbon fiber reinforced polymer (CFRP). We use SUS304 for the rotor's supporting component of the motor of the first type, the von Mises stress of which is 109.2 MPa at the maximum speed of 5,000 rpm; we use a yield stress of 206 MPa for SUS304. The von Mises stress is proportional to the square of the rotation speed and would exceed 600 MPa at 12,000 rpm, making it clearly impossible to drive the motor up to 12,000 rpm without countermeasures. Because the von Mises stress is generally proportional to the outer diameter of the rotor, we reduce the outer diameter of from 250 mm to 210 mm.

We also consider the material of the rotor's supporting component. The Japan Steel Works produces a special material that is a non-magnetic high-tensile steel to which 18% manganese and 18% chromium is added (18%Mn18%Cr steel)⁽¹⁴⁾. The material was developed for the retaining ring of an electric generator that required high yield strength; the yield stress of the material is 1,260 MPa. Figure 5 shows the distribution of rotor displacement at the maximum operating speed. The displacement is emphasized by 30 times. As PMs are designed to be wider than SMCs referring to the former examination⁽¹¹⁾, the weight of PMs are heavier than that of SMCs. Centrifugal force on PMs are greater than that on SMCs. And slit at the PMs widened. The von Mises stress at the maximum operating speed is 586.1 MPa, which is less than the yield stress of the material.

Figure 6 shows the rotor in cross section. The rotor's supporting component comprises three plates that are joined

Fig. 6. Cross-sectional view of rotor

Table 3. Specifications of studied motors

	First type	New design
Number of poles	20	14
Number of slots	24	18
Outer diameter (coil end included)	250 mm	210 mm
Total motor axial length	76.4 mm	77.8 mm
Air gap	1.0 mm	1.0 mm

(a) Waveforms

(b) Harmonic components

Fig. 7. No-load induced line-to-line voltage

using rivets. A part is added to the inner area of the rotor to prevent the PMs and SMCs from lifting under high-speed operation.

3.3 Motor Characteristics Table 3 compares the motor specifications of the motors of the first type and the new design. We confirm the motor characteristics by means of 3D FEA. Figure 7(a) shows waveforms of the no-load induced line-to-line voltage calculated with (i) the maximum field-weakening current, (ii) the maximum field-strengthening current, and (iii) no field current, and Fig. 7(b) shows the harmonic components. Figure 8 shows the no-load induced line-to-line voltage versus the field winding current. The no-load induced line-to-line voltage is increased by 85.3% with the maximum field-strengthening current compared to that with no field winding current, and it is decreased

Fig. 8. No-load line-to-line voltage vs. field current

Fig. 9. Field-current-torque characteristic

by 57.7% with the maximum field-weakening current. Figure 9 shows the calculated output torque upon changing the field current from the maximum field-weakening current to the maximum field-strengthening current. The armature current is set to a maximum value of 74.8 A_{rms}. When no field current is applied, the average torque is 22.6 Nm. By applying the maximum field-strengthening current of +4.3 A, the torque is increased by 81.9% compared to that with no field current. The torque ripple is 11.9% under the maximum field-strengthening condition, whereas the torque with the maximum field-weakening current is reduced by 65.2%. As expected, these results indicate that the magnetic flux can be controlled over a wide range by changing the field current.

When the motor is driven under high speed, eddy current loss should be considered. In the case of such motor as PMs and SMCs are supported by non-magnetic steel rotor supporting component, eddy current loss occurs in it. It is confirmed that eddy current loss could be suppressed by making slits at outer area of the rotor supporting component in (15). Eddy current losses with and without slits are compared under 3360 r/min. Figure 10 shows eddy current loss density of rotor support component with and without slits. Without adding slits, eddy current loss of rotor supporting component around SMC is extremely large. By adding slits at outer area, eddy current loss can be suppressed. Table 4 shows 3D-FEA results of eddy current losses and Eddy current loss of proposing motor can be reduced with adding slits at outer area of rotor supporting component from 1450 W to 36.8 W. It is confirmed that there is an effect with the proposing motor to suppress eddy current loss by adding slits. Figure 11 shows the motor torque–speed characteristic. The torque at the base speed of 3,360 rpm is 41.7 Nm, and the output power is 14.7 kW. The output power density is 5.4 kW/L, meaning that the newly designed motor can achieve higher than

Fig. 10. No-load induced line-to-line voltage

Table 4. Eddy current loss at rotor supporting component

Without slits	With slit
1450.0 W	36.8 W

Fig. 11. Speed-torque characteristic

1.4 times output power density compared to first type motor and achieve the target output power density. The torque at the maximum speed of 12,000 rpm is 11.9 Nm, and the output power is 14.9 kW. It is confirmed that the motor can be driven at constant output power over a wide range of rotation speed from 3,360 rpm to 12,000 rpm. It is also confirmed that the proposed motor can achieve higher output density by increasing its operating speed by using non-magnetic high-tensile stainless steel for the rotor's supporting component and CFRP for reinforcement.

4. Experimental Results

4.1 High-speed Burst Tests To confirm the strength of the rotor, we performed high-speed burst tests. For these,

Fig. 12. Overview of high-speed burst tests

Fig. 13. Shaft runout versus rotation speed

(a) Without CFRP

(b) With CFRP

Fig. 14. Rotor deformation with rotation speed

we used parts made of SUS304 instead of the actual PMs and SMCs because the specific gravities are almost the same. Figure 12 shows an overview of the high-speed burst tests. The shaft runout is measured with an induced-displacement sensor near the fixing point. Figure 13 shows the shaft runout versus the rotation speed. The tests were performed without CFRP. The rotation speed at which the runout increases rapidly ($\sim 21,800$ rpm) is that at which the rotor disintegrated.

Figure 14 shows how the rotor's supporting component deformed with rotation speed. We measured the outer diameter

Fig. 15. Deformation of rotor's supporting component near slits

Fig. 16. Photograph of proto machine

Fig. 17. Waveforms of no-load line-to-line voltage

after increasing the rotation speed using caliper. Figure 14(a) shows the results measured without CFRP. Even without CFRP, no irreversible deformation occurred at the maximum operating speed of 12,000 rpm, but irreversible deformation did occur once the speed exceeded 14,000 rpm. Figure 14(b) shows the deformation measured with CFRP; adding CFRP reduced the rotor deformation to a quarter of that without CFRP. Figure 15 shows a test rotor without CFRP after it had been rotated at 19,000 rpm. Because the PMs were heavier than the SMCs, the centrifugal force on the former was greater than that on the latter. Consequently, the slits at the PMs widened and those at the SMCs narrowed.

4.2 Test of Motor Characteristics Figure 16 shows a photograph of a proto machine that was assembled based on the specifications given in Table 3. Figure 17 shows waveforms of the no-load line-to-line voltage measured with (i) the maximum field-strengthening current, (ii) the maximum field-weakening current, and (iii) with no field winding current. The waveform distortion is small and the waveforms are close to sine waves.

Figure 18 shows the no-load induced line-to-line voltage

Fig. 18. No-load line-to-line voltage vs. field winding current

Fig. 19. Torque vs. field winding current

Fig. 20. Measured speed-torque characteristic

versus the field current measured at a base speed of 3,360 rpm; FEA results are also plotted. The test results coincide well with the FEA results. The induced line-to-line voltage is increased by 74.7% with the maximum field-strengthening current and decreased by 50.8% with the maximum field-weakening current. The total harmonic distortions of the no-load line-to-line induced voltage with the maximum field-strengthening field current, with no field current, and with the maximum field-weakening current are 0.9%, 0.5%, and 2.5%, respectively. This test indicates that the proposed motor has variable flux capability by controlling the field winding current. Figure 19 shows torque versus the field winding current measured at the base speed. Torque also indicates the same trend as no load induced line-to-line voltage. Figure 20 shows measured speed-torque characteristic. Test was operated up to 7000 r/min due to ability of test bench. It is confirmed that under rotation speed of higher than the base speed, 3,360 r/min, motor output power is more than 13.3 kW, which output power density (4.9 kW/L) is larger by more than 1.3 times compared to first type motor (3.7 kW/L),

although test results are smaller than 3D-FEA results due to magnetic saturation in iron core. The target, 1.3 times larger output power density, can be achieved. It is considered that slot pole combination of 18 slots and 14 poles is suitable for hybrid excitation consequent pole axial gap motor to increase operation speed.

5. Conclusion

In this paper, we have presented an examination of increasing the operating speed of a consequent pole axial gap motor to achieve higher output density. For the countermeasure against centrifugal force of axial gap motor, a non-magnetic high-tensile stainless steel is applied as the rotor's supporting component and it is confirmed that the proposed motor could be operated at 12,000 rpm by means of burst tests of the rotor. We designed the proposed motor using 3D FEA to achieve the target output power density higher than first type motor by 1.3 times. By selecting slot combination of 18 slots and 14 poles, operating frequency can be suppressed less than 1.5 kHz at the maximum speed of 12,000 r/min and the influence of even-order harmonic due to the asymmetric air gap magnetic flux density distribution can be canceled with test of proto sample. A wide variable magnetic flux capability is also confirmed. Moreover, output power under higher than the base speed is more than 13.3 kW and output power density is 4.9 kW/L, which is more than the target, higher than first type motor by 1.3 times. It is considered that the slot-pole combination of 18 slots and 14 poles is profitable for motor whose maximum speed is high and the combination of 24 slots and 20 poles is suitable for motor whose maximum speed is low or middle.

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