

Method of Magnetizing Rotor with Wide Air Gap Using Magnetic Circuit that Concentrates Magnetic Flux

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ABSTRACT

A post-assembly magnetization method was developed to increase magnetic field strength by concentrating magnetic flux in the pulse-type magnetization of small-diameter multipole high-speed rotors with wide air gaps. By concentrating the magnetic flux generated by two sets of magnetizing coils located on the outer periphery of the rotor, a Y-shaped magnetic circuit that passes through one set of magnetizing coils can be created that applies a high magnetic field locally. Magnetizing coils were placed at locations $\pm 135^\circ$ from the one set of magnetizing coils through which the concentrated magnetic flux passes. This magnetizing coil arrangement can form a large magnetic circuit that passes around the inner periphery of the rotor. The magnetic flux that is not concentrated by this magnetic circuit flows in the direction opposite to the magnetization of the magnet. Therefore, the similar placement of auxiliary coils at the $\pm 67.5^\circ$ locations suppressed the magnetic flux that leaked from the magnetic circuit. This technology created a high magnetic field in a rotor with a wide air gap and realized the target magnetization ratio of 99.0% or higher in single magnets.

1. Introduction

Environmental awareness on a global scale is bringing increasing calls for the reduction of CO₂ emissions from the operation of mobility devices and enhancement of fuel economy. As a result, the spread of electrification is tending to accelerate in all fields of mobility. To achieve more widespread electrification, motors that are more compact or that have more poles for higher torque are being installed in various types of mobility devices. Motors are also appearing that achieve higher speeds in order to realize high power with a small diameter. These include Surface Permanent Magnetic (SPM)-type motors that have permanent magnets affixed to the rotor surface in a Halbach array⁽¹⁾. In these motors, the rotor periphery is made of resin material parts in order to keep the centrifugal force at high speeds⁽²⁾. For that reason, the air gap between the stator and rotor is 8 to 12 times wider than in conventional motors. The method of generating pulse magnetic fields by using a jig called a magnetizing yoke is extensively employed as a method for post-assembly magnetization of permanent magnets built into the rotor. Magnetizing yokes are fabricated with specially designed coil arrangements to generate magnetizing fields in the magnet arrangement of the target rotor⁽³⁾. The closer the air gap between the magnetizing yoke and the rotor, the more efficiently magnetization can be carried out. This means that greater

energy is needed to magnetize rotors with wide air gaps, such as high-speed SPM rotors, than for conventional rotors. In order to strengthen the pulse magnetic fields to be applied, it is necessary to establish production conditions with increased electrostatic energy. However, increasing the device capability to provide adequate electrostatic energy calls for increased investment in production equipment, and results in decreased productivity for various reasons such as increased heat generation of the magnetizing coil due to higher current values, and lower coil insulation durability and coil deformation due to electromagnetic force. As an approach to reducing electrostatic energy, methods of partially magnetizing the permanent magnets assembled on the rotors are also known^{(4), (5)}. However, when partial magnetization is performed on a small-diameter, multipole SPM rotor, the magnets next to the magnetization targets are magnetized in the opposite direction. It is no simple matter to establish post-assembly magnetization methods that maintain electrostatic energy levels for rotors with wide air gaps using conventional magnetization methods. Conventionally, increasing magnetic field strength under conditions of the same or lower electrostatic energy was an issue. In order to address this issue, it is necessary to efficiently apply the effective magnetization components of the magnetic field generated from the coils to the permanent magnets. The coil arrangement is of great importance in achieving this. In addition, if the magnetic field strength

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can be increased by the coil arrangement alone, there will be no great impact on production equipment and other such facilities, enabling minimizing of the impact on production of new products.

With a conventional coil arrangement that applies a magnetic field from the outer periphery of a rotor, the magnetic field strength is limited. Attention was therefore focused on a coil arrangement that also considers the magnetic paths including the rotor interior. A coil arrangement that enables concentration of the magnetic field and suppresses the demagnetizing field paths was investigated, a magnetizing yoke was fabricated, and the permanent magnet magnetization ratio was evaluated.

This paper introduces a technology that combines a magnetizing coil arrangement that realizes a high magnetic field in pulse-type magnetization together with an auxiliary coil arrangement that suppresses the demagnetizing fields occurring in partial magnetization.

2. Magnetization Principles and Issues

2.1. Post-assembly Magnetization Method

Post-assembly magnetization is a manufacturing method that uses a device called a magnetizing yoke to magnetize materials that become magnets during rotor production. Dedicated magnetizing yokes are designed according to the number of poles and the diameter of the rotor. When fabricating anisotropic magnets, since the direction of magnetization is determined by applying a magnetic field, the degree of magnetization is determined by the magnetization direction and strength on the magnet through which magnetic flux from the magnetizing coil passes⁽⁶⁾.

As an example, Fig. 1 shows the composition of a magnetizing yoke for use on an eight-pole rotor. The numbers of rotor poles and magnetizing coils are the same, and the coils are firmly fixed in place with resin. In consideration of productivity, the magnetizing yoke and rotor have an air gap of about 0.25 to 0.3 mm. The design elements for magnetization are the wire diameter, number of turns, and coil arrangement of the magnetizing coils. The magnetization conditions include the source voltage, which is electrostatic energy, and the electrostatic capacity. An

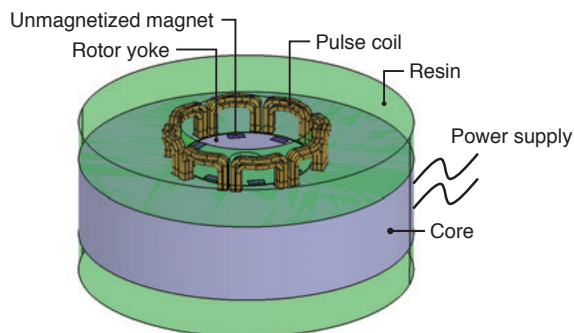


Fig. 1 Composition of magnetizing yoke

appropriate magnetizing yoke is designed according to the rotor specifications.

2.2. Principles of Magnetization

Magnetization is carried out by a magnetic field generated from a magnetizing coil when a high current is momentarily passed through the coil. At this time, the magnetic field H is as shown in Eq. (1), where I is the magnitude of the current and r is the distance from the magnetic field source.

$$H = \frac{I}{2\pi r} \quad (1)$$

Consequently, when the magnetizing coil and the target magnet are close together in the magnetization field, a strong magnetic field is applied.

2.3. Magnetization Target

Figure 2 shows the composition and magnetization direction of the target SPM Halbach array rotor. The target rotor has an outermost diameter of 67 mm, a cumulative thickness of 33 mm, and uses Nd-Fe-B-based sintered magnets as the magnet material. Since the design assumes a high rotation speed in order to achieve the target output, and a resin ring is mounted to help prevent magnet scattering due to centrifugal force.

Figure 3 shows the magnetization characteristics. A

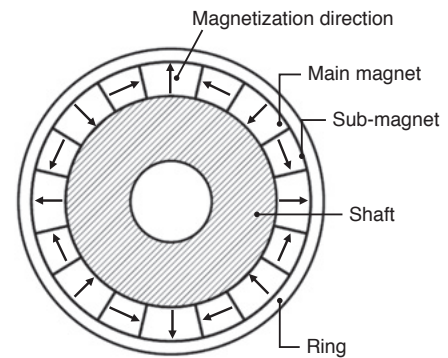


Fig. 2 Small-diameter, multipole, and high-speed rotor

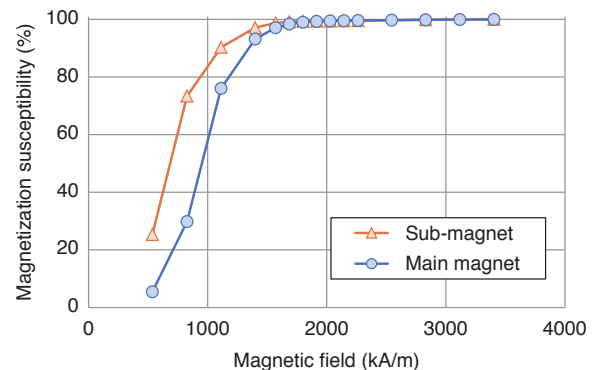


Fig. 3 Magnetization characteristics of magnets

magnetization ratio of 99.0% or more can be obtained by applying a magnetic field strength of 1800 kA/m or more in the main magnets and 1635 kA/m or more in the sub-magnets. Therefore, these values were used as the respective target magnetic field strength values in the single magnets.

2.4. Issues in Magnetization of High-speed Rotors with Wide Air Gaps

The first issue is that mounting a resin ring on the outer periphery of the magnets to help prevent magnet scattering increases the distance between the magnetizing coil and the target magnet, which greatly reduces the magnetizing field. Figure 4 shows that magnetic field strength decreases according to the distance from the magnetic field source.

The second issue is that reducing the diameter of the target rotor narrows the magnetic circuit between the poles, and an adequate magnetizing field cannot be applied to the inner periphery of the magnets. This is because the spacing between the poles of the magnetizing coil becomes narrower and the magnetic circuit becomes smaller⁽⁷⁾.

2.5. Initial Investigation by Magnetic Field Analysis

Figure 5 shows the model initially investigated using the electromagnetic field analysis software JMAG in magnetization of this rotor. The same number of magnetizing coils were arranged as the number of main magnet poles. This is the magnetizing coil arrangement used

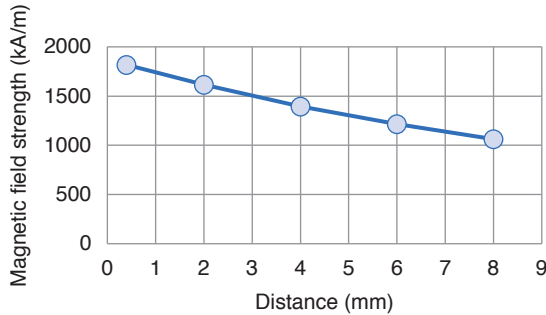


Fig. 4 Relationship between magnetic field and distance

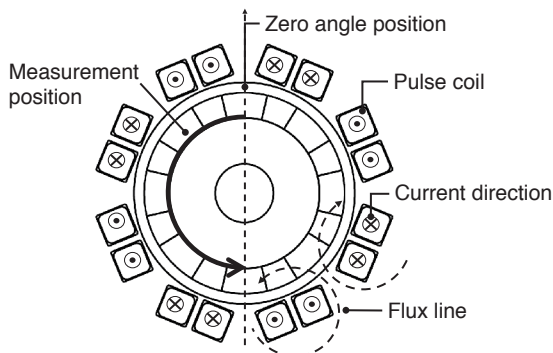


Fig. 5 Pulse coil position and measurement position

by the conventional post-assembly magnetization method. The conditions for magnetic field analysis were current of 12,000 A and nine coil turns.

Figure 6 shows the results of the magnetic field analysis of the initial investigation at the measurement positions (magnetic field strength at the innermost periphery of the magnets) in Fig. 5. The results show that the magnetic field strength is lowest at the center of the innermost periphery of the sub-magnets and does not reach the target value needed for magnetization.

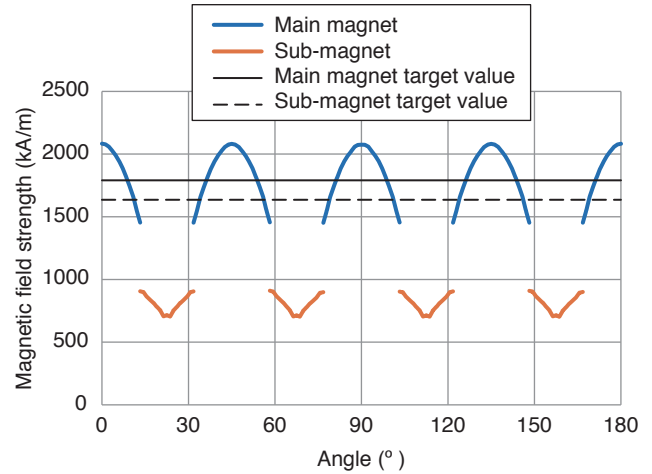


Fig. 6 Magnetic field on inner periphery of magnet

3. Magnetic Circuit of Magnetizing Field by Concentration of Magnetic Flux

3.1. Magnetic Circuit Passing Through Rotor Inner Periphery

As the magnetic fields of the magnetizing coils need to efficiently apply the magnetic flux component that contributes to the magnetization direction of the magnets, the wire diameter, number of turns, arrangement, and other characteristics of the magnetizing coils were investigated. Figure 7 shows the models of magnetizing coil arrangements (coil spacing) and uses contour diagrams to express the distribution of magnetic flux density obtained by analyzing those models. The magnetic field strength can be seen to shift to the inner periphery side as the coil spacing widens. Figure 8 shows a graph of magnetic field strength for different spacings between the main magnet and sub-magnet magnetizing coils. The magnetic field strength was measured in the innermost periphery of the magnets. This graph also shows that, compared to the narrow coil spacing, the magnetic field strength with a wide coil spacing is approximately 1.5 times stronger at the main magnets and approximately 2.5 times stronger at the sub-magnets. In addition, the rotor magnetic poles alternate between N and S poles. For this reason, maximization of the spacing between the N-pole magnetization and S-pole magnetization

of the corresponding magnetizing coil was investigated. Figure 9 shows a diagram with the small magnetic circuits produced by adjacent magnetizing coils removed to expand the coil spacing up to the position of magnetizing coil B. The solid line indicates the predicted magnetic circuit for the expanded coil spacing, and the dashed lines indicate the flow of magnetic flux before removal of the magnetizing coils. The motor has periodicity, so a large magnetic circuit was proposed that passes around the inner periphery of the rotor where the magnetic flux from magnetizing coils B and C is concentrated, by similarly expanding the coil spacing up to the magnetizing coil C.

3.2. Analysis of Magnetic Field of Magnetic Circuit that Concentrates Magnetic Flux

Figure 10 shows the composition and magnetic circuit of the high magnetic field-magnetizing yoke. Magnetizing coils B and C were placed at locations $\pm 135^\circ$ from magnetizing coil A. The magnetic flux generated from

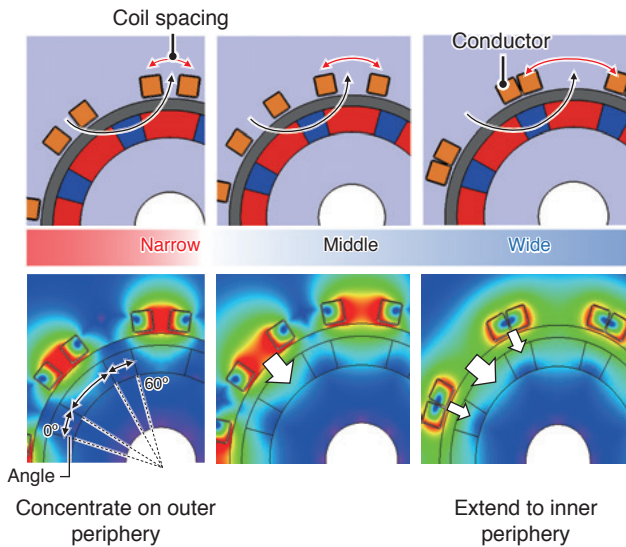


Fig. 7 Coil spacing and magnetic flux density

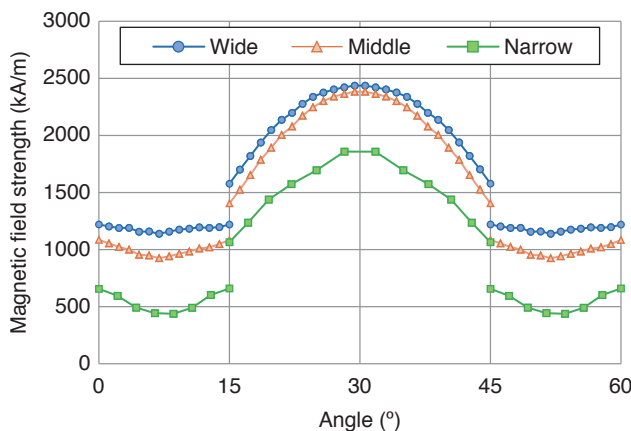


Fig. 8 Comparison of magnetic flux density of magnets

B and C is concentrated and flows to A, creating a large magnetic circuit that passes around the inner periphery of the rotor. Figure 11 shows the results of magnetic field analysis (due to model symmetry, these are the results for the half-circumference from 1 to 9). At the poles where the magnetic fields of 1 and 7 are strengthened, the magnetic field strength at the innermost periphery of the main

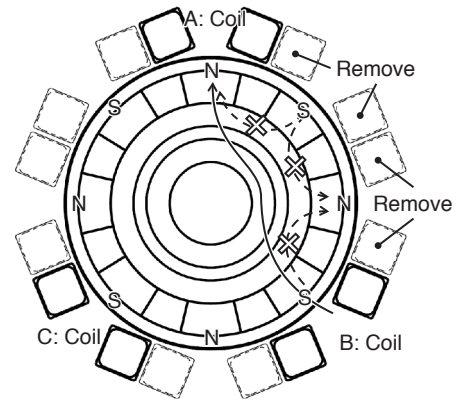


Fig. 9 Investigation of expansion of coil spacing

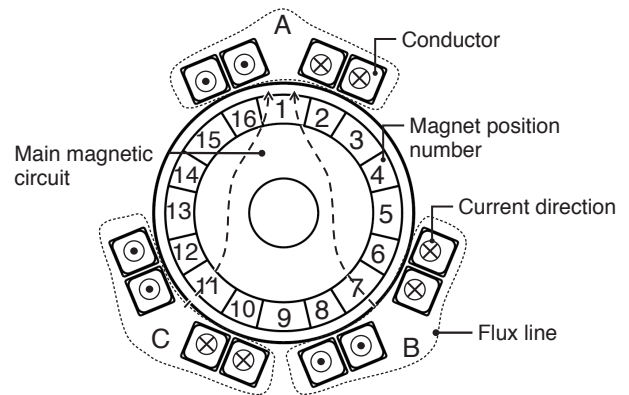


Fig. 10 Magnetic circuit

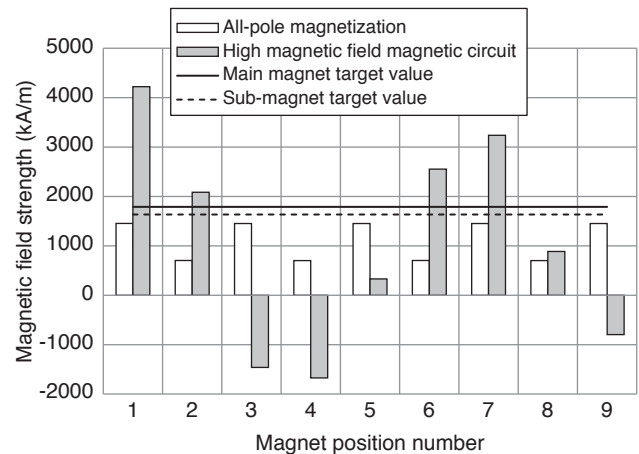


Fig. 11 Magnetic field analysis results

magnets was observed to increase by 290.42% at 1 and by 222.86% at 7. In addition, increases of 296.3% and 363.2% were confirmed at sub-magnets 2 and 6, respectively. These analysis results confirmed the ability to create a magnetic circuit that applies a high magnetic field locally by concentrating the magnetic flux.

3.3. Issue with Magnetic Circuit that Concentrates Magnetic Flux

The issue here is the magnetic flux that is not concentrated. In the magnetic field analysis results in Fig. 11, magnets 3 and 4 have negative magnetic field strength, indicating that they are magnetized in the reverse direction from the original magnetization direction. Figure 12 shows the distribution of the magnetic flux that is not concentrated. It is thought that, due to the magnetic circuit passing around the inner periphery of the rotor, magnetic flux occurred outside of the target magnetic circuit partway along the path. In addition, the magnetic permeability of the magnets is larger than that of the shaft, which indicates that magnetic flux passing through the magnets produced a demagnetizing field.

3.4. Use of Auxiliary Coils to Suppress Leakage Flux

A magnetic circuit with newly placed auxiliary coils was devised and analyzed with the goal of suppressing the magnetic flux generated outside the magnetic circuit. Figure 13 shows the model for suppression of leakage flux. Since the magnetic fields from the coils are formed concentrically, auxiliary coils D and E were respectively placed at locations $\pm 67.5^\circ$ from A, which are the angles at which symmetrical magnetic fields are applied to the main magnets 3 and 5 and sub-magnet 4 when placed on its radial extension. The magnetic fields generated from the auxiliary coils suppress the magnetic flux in the reverse direction that deviates from the main magnetic circuit. In addition, this auxiliary coil placement applies magnetic fields in the correct direction to magnets 3, 4, and 5. Figure 14 shows the results of suppressing leakage flux with auxiliary coils. The magnetic fields of the auxiliary coils interfere with the main magnetic circuit, so the magnetic field strength decreases. The magnetic field strength after

countermeasures decreased to 70.66% for 1, 77.68% for 7, and 77.13% for 2. It was confirmed that the reverse magnetic field due to the magnetic flux that leaked to the outside of the magnetic circuit was enhanced by 78.44% for 3 and by 93.81% for 4.

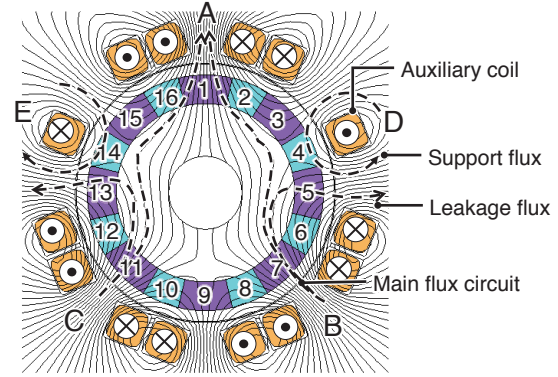


Fig. 13 Suppression of leakage flux

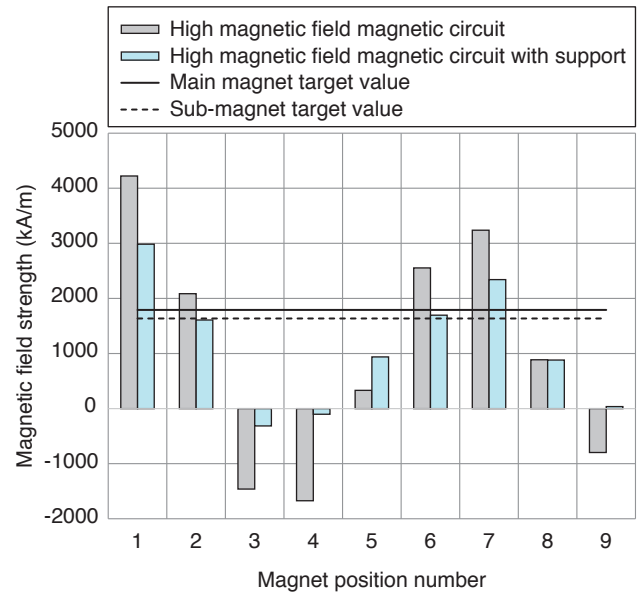


Fig. 14 Results of reverse magnetic field suppression

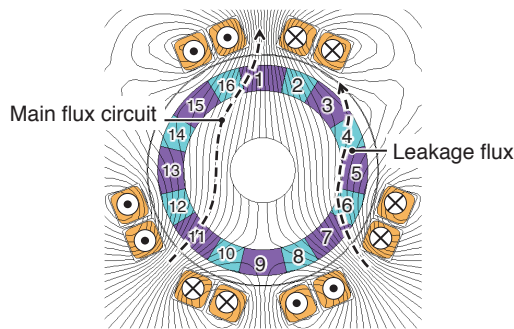


Fig. 12 Leakage flux analysis

4. Experimental Results

4.1. High Magnetic Field-Magnetizing Yoke

A magnetizing yoke with a high magnetic field-magnetic circuit was fabricated that enables post-assembly magnetization of rotors with wide air gaps. Figure 15 shows the developed high magnetic field-magnetizing yoke. The structure is divided into two sets of coils that concentrate the magnetic flux and one set of coils through which the concentrated magnetic flux passes, and the auxiliary coils are placed in the divided gap. The magnetic circuit is also indicated by the dotted lines.

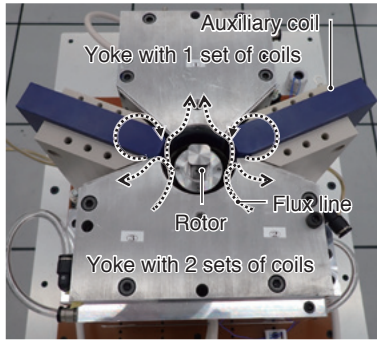


Fig. 15 High magnetic field magnetizing yoke

4.2. Measurement of Magnetic Field Strength

The strength of the magnetic field generated from the magnetizing yoke was measured in order to set the magnetizing conditions. Measurement used a so-called search coil consisting of copper wire wound in multiple circular turns. The measurement component used a search coil (20 turns; compensation value: $T = 142.9 \times 10^{-9}$) made by OP DENSHI KOGYO CO., LTD. The voltage induced by the magnetic flux passing through this search coil is obtained⁽⁸⁾. Figure 16 shows the method for acquiring the magnetic field and a photo of placement at the measurement point. The search coil is placed at the measurement point perpendicular to the magnetization direction of the magnet and acquires the magnetic field. Equation (2) shows the formula for calculating the magnetic field strength from the voltage.

$$H = T \times \int v \, dt \times \frac{4 \times \pi}{1000} \quad (2)$$

Magnetic field strength: H [kA/m] Voltage: v [V]

Figure 17 shows graphs of (a) the voltage waveform acquired by the search coil and (b) the magnetic field strength. The magnetic field strength was calculated from the acquired induced voltage waveform using Eq. (2).

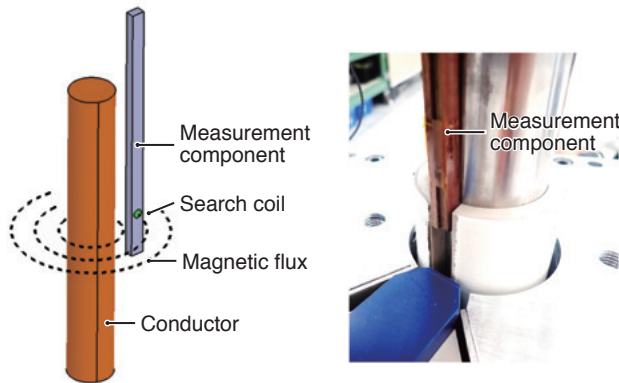


Fig. 16 Measurement method by search coil

Measurement was performed at the measurement points i (main magnet) and ii (sub-magnet) shown in Fig. 18, with the electrostatic capacitance set to 5000 μ F and the source voltage set to 1, 2, and 3 kV. In addition, for reasons of measurement device size, the voltage waveform cannot be acquired at the point with the lowest magnetic field strength in the innermost periphery of the magnets at measurement position ii. Therefore, the magnetic field strength in the innermost periphery of the magnets obtained by CAE was used as the magnetizing condition. Figure 19 compares the measurement results (average value of five measurement times) and the analysis results. In the main magnets, the difference between the measured and CAE values is 13.6% at 9 kA, whereas this difference is 0.89% in the sub-magnets. Compared to the measured magnetic field strength of the main magnets, the CAE results are lower. However, a magnetic field strength of 1800 kA/m or more is adequately achieved in the measurements, so focus was placed on the magnetic field strength of the sub-magnets. The difference between the measured and CAE

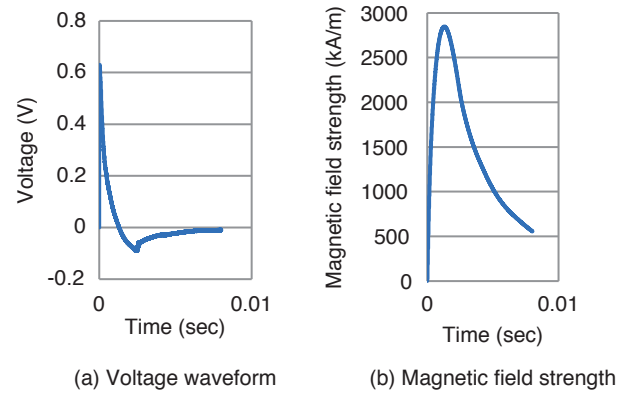


Fig. 17 Conversion of voltage to magnetic field strength

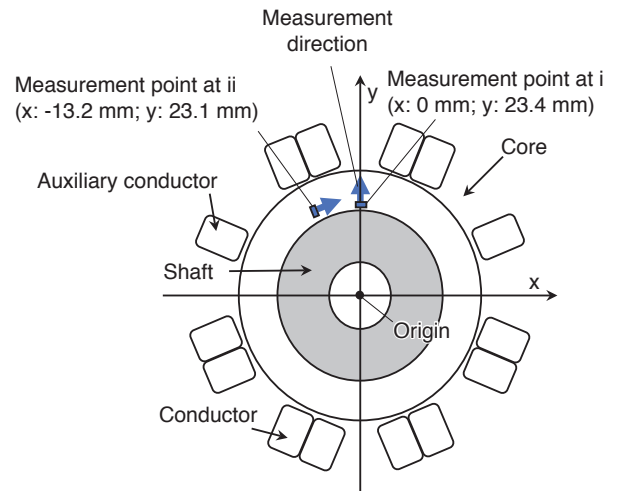


Fig. 18 Measurement points

values of the magnetic field strength of the sub-magnets is within 1%, indicating that the value of the magnetic field strength in the innermost periphery where it is the weakest can be accurately predicted. A magnetic field strength in the innermost periphery of the sub-magnets of 1635 kA/m or more can be obtained at 12,700 A, so this was set as a magnetizing condition.

4.3. Evaluation of Magnetization Ratio

The target magnets used Nd-Fe-B-based sintered magnets (equivalent to N44Z-SGR made by Shin-Etsu Chemical Co., Ltd.) as the material. The total magnetic flux of the magnetized magnets was measured with a search coil. The total magnetic flux is used to assess the degree to which the magnet is magnetized. Figure 20 shows the measurement method. The magnet can be measured by integrating the voltage induced by the change in magnetic flux when the magnet is set in the center of a search coil with multiple turns and then pulled out in the direction of magnetization. The magnetized magnet is saturation magnetized by an air core coil (a device that uniformly generates a 4376 kA/m magnetic field in a $\phi 100 \text{ mm} \times 100 \text{ mm}$ range). The magnetization ratio was calculated by comparing the magnetization level of the magnets magnetized in the experiment and the magnetization level

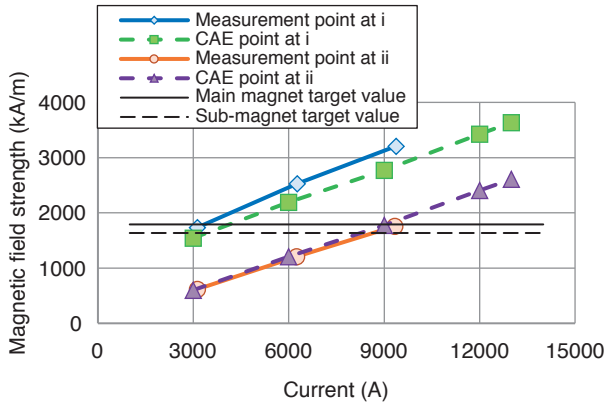


Fig. 19 Measured and analyzed magnetic field strength

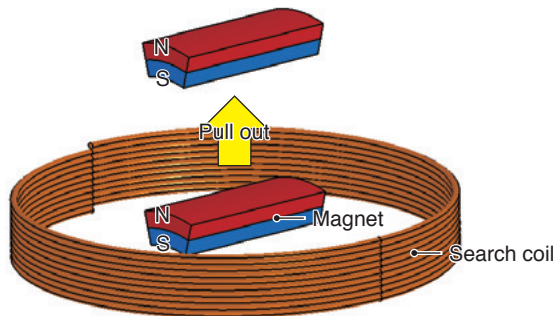


Fig. 20 Measurement of total magnetic flux

when saturation magnetized as shown in Eq. (3).

$$\text{Magnetization ratio} = \frac{\text{Magnetization level after magnetizing experiment}}{\text{Magnetization level after air core coil magnetization}} \times 100 [\%] \quad (3)$$

As the range in which the magnetic field can be strengthened by concentrating the magnetic flux is limited, the phase of the rotor is rotated three times and magnetization is performed a total of four times.

Figure 21 shows the rotor phase rotation procedure with the magnets that could be magnetized to 99.0% or more indicated by shading. All the magnets are magnetized by rotating the rotor so that the magnets can be placed in locations with an intense magnetic field in order of strength.

Figure 22 shows the magnet magnetization ratio results. It can be seen that the magnetization ratio increases when

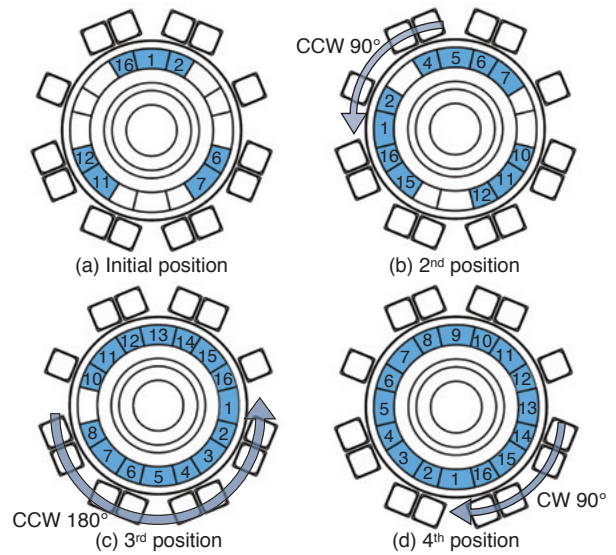


Fig. 21 Rotor phase rotation procedure

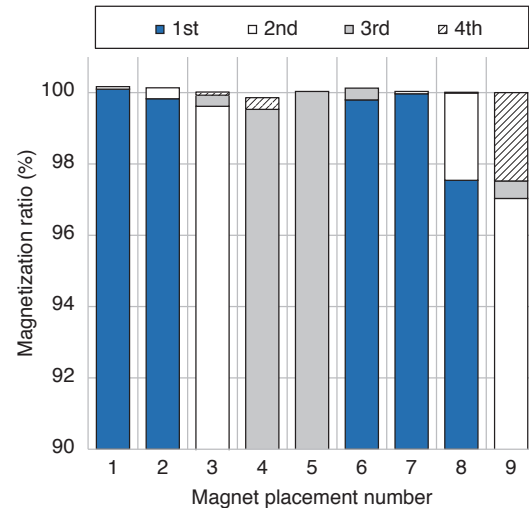


Fig. 22 Magnetization ratio measurement result of 99.0% or more

the magnets are placed in locations where a high magnetic field is locally applied. The target magnetization ratio value of 99.0% or more was achieved in all magnets.

5. Conclusion

A post-assembly magnetization method was developed that increases the magnetic field strength by concentrating the magnetic flux in pulse-type magnetization of small-diameter multipole high-speed rotors with wide air gaps.

- (1) By designing a magnetizing coil arrangement and concentrating the magnetic flux, high magnetic fields could be applied to specific locations.
- (2) Countermeasures were taken to address the issue that demagnetizing fields are produced by the magnetic flux that was not concentrated in the main magnetic circuit. The demagnetizing fields can be suppressed by placing auxiliary coils between the three sets of coils that comprise the main magnetic circuit.
- (3) By rotating the phase of the rotor three times, the high magnetic fields concentrated in specific locations could be applied to magnetize all the magnets.

As a result of the above, the target magnetization ratio of 99.0% or more was achieved.

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