MH loop Modeling of NdFeB Anisotropic Bonded Magnet

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1. Introduction

The NdFeB anisotropic bonded magnet is one of the most important permanent magnets. It enables the achievement of complex shapes and is superior in strength to other magnets[1]. Therefore, it is useful for motors of hybrid vehicles (HV) and electric vehicles (EV), which are in demand because of their smaller size and higher-speed rotation. However, we are concerned about its demagnetization, which is called "magnetic fatigue"[2]. We expect that the magnetic fatigue is caused by a high frequency field of 0.5 kOe at 10 kHz, a DC reverse field from 3 to 4 kOe, and a high temperature over 400 K. In our previous study, we showed that when the anisotropy field (H_k) of a grain-surface is lower than that of a main phase, the coercivtiy field H_c is much lower than H_k. However, the MH loop did not fit an experimental value.

In this study, the standard deviations of c-axis orientation distribution ($\sigma_{C\text{-}axis}$) and H_k distribution (σ_{Hk}) were investigated to fit the experimental MH loop of an NdFeB anisotropic bonded magnet.

2. Micromagnetic simulator

In this simulation, a one-grain model was assumed for the MH loop modeling of an NdFeB anisotropic bonded magnet[1]. A dynamic magnetic reversal process was calculated by using the Landau-Lifshitz-Gilbert equation as follows.

$$\frac{dM}{dt} = -\gamma(M \times H_{eff}) + \frac{\alpha}{M_s}\left(M \times \frac{dM}{dt}\right) \tag{1}$$

M is the magnetization, and M_s is the saturation magnetization. H_{eff} is the effective field, which is summed up as an external field, a static field, an anisotropy field, and an exchange field. γ is the gyromagnetic ratio, and α is the damping factor.

The one-grain model is shown in Fig. 1. The grain was divided into 16×16×16 hexagonal prism cells, and each cell was 2 nm in diameter and 2 nm high. The grain was assumed to have a low H_k surface, which was painted grey in Fig. 1. The surface layer was 2 nm wide. The M_s was 1.61 T, the intercell exchange energy was assumed to be 0.5×11^{-11} J/m, and the damping constant was 1.0 at room temperature. The c-axis represented the perpendicular direction (z-axis direction) and changed from 0 to 3° every 1°, and the anisotropy constant K_u changed from 0.8 to 7.0 MJ/m^3 every 0.2 MJ/m^3 to fit the experimental MH loop of the NdFeB anisotropic bonded magnet. First, MH loops were calculated with every combinations of c-axes and K_u values. Next, each magnetization was multiplied by the constant in accordance with a statistical probability. Last, all magnetizations were summed up, and the MH loop modeling was completed.

3. Results and discussions

Fig. 2 shows the comparison of MH loops between simulations and the experiment. The experimental data was for magnetic particles of the NdFeB bonded magnet[3]. For the simulation, the $\sigma H_k/\langle H_k\rangle$ was 10 and 30 % when the $\sigma_{C\text{-}axis}$ was 1°.　Here, H_k is defined as $2K_u/M_s$. $\langle H_k\rangle$ was the average H_k, and the main phase $\langle H_k\rangle$ was 6077 kA/m. The H_k of the surface layer was 0.135 times lower than the main phase. From this result, the experimental MH loop fit the simulation loop for $\sigma H_k/\langle H_k\rangle$ of 30 %. Therefore, the NdFeB bonded magnet is predicted to have a large distribution of H_k and a low distribution of c-axes.

Acknowledgments

We thank Dr. Mishima of Aichi Steel Corporation for his advice on the experimental bonded magnet. We also thank Hitachi Corp. for providing us with the use of this simulator.

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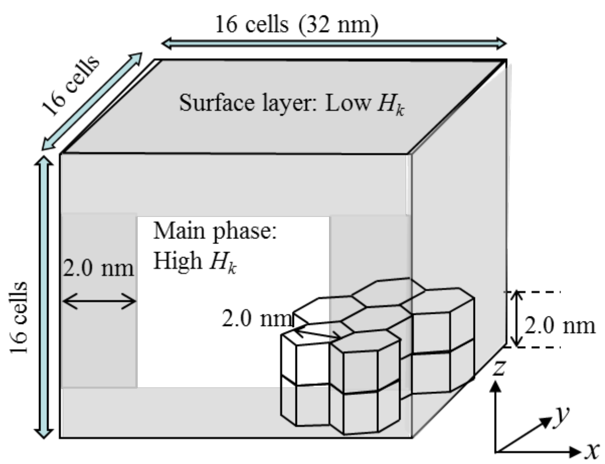

Fig. 1 Structural model of one grain.

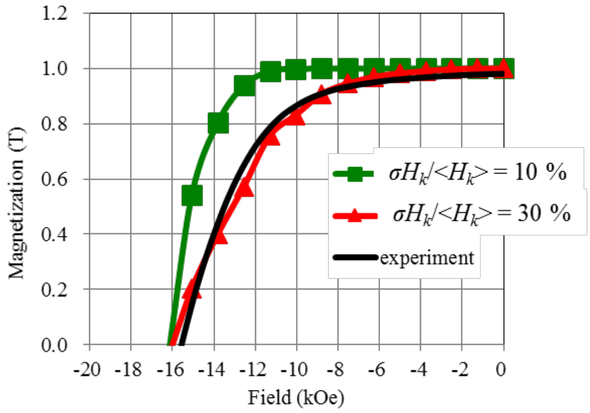

Fig. 2 Comparison of MH loops between experiment and simulations.

Behavior of a permanent magnet used for the high efficiency motor under the high frequency magnetic field

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The development of high efficiency motors is accelerating as energy problems become more serious. Many magnetic materials are used in high efficiency motors, and the demands on the properties of the magnetic materials are changing greatly by the use of power electronics[1).

For example, in soft magnetic materials such as electrical steel, increases in iron losses of 20% to 60% caused by the inverter excitation have been reported[1)].

On the other hand, with hard magnets such as permanent magnets, the eddy current loss on the surface of the magnet cannot be neglected as the electric resistivity of rare earth sintered magnets is very low in comparison with ferrite sintered magnets.

As a result, the measurement and numerical analysis of losses under AC magnetic fields based on NdFeB sintered magnets has been studied[2)、3)].

With recent high speed motors, larger magnetic fields are applied to the magnet and the frequencies of those fields are higher, and as a result the problem of magnet losses will become more important.

We have manufactured a device to study the magnetic properties in a high AC magnetic field. With the device, we studied the magnetic properties of Nd sintered magnets, anisotropic bonded magnets and ferrite magnets.

The results show that while there is a large delay in the magnetization of Nd sintered magnets, this delay was small in Nd bonded magnets and the ferrite magnets.
This may be attributed to electrical resistivity.

However, it was difficult to perform the comparison of magnetic properties in high AC field with the normal BH tracer, because it was not possible to express the AC hysteresis with a magnetic unit.
This time, we have succeeded in expressing hysteresis with a magnetic unit.

Furthermore, we are remodeling the device to allow high frequency measurements while applying a static magnetic field to the magnet.

In this report, we report the outline of the device and results of a measurement.

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Fig.1 Experimental Apparatus

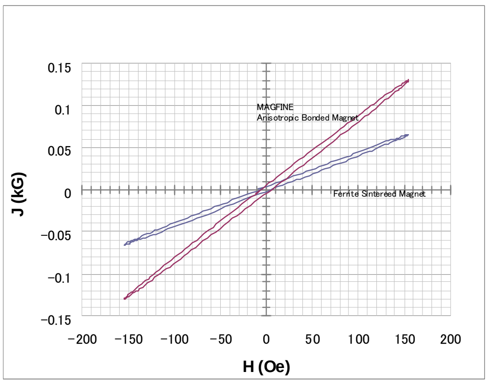

Fig.2 Minor loops in a high frequency magnetic field

Future Trend of Electrical Motor Drive System

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Electrical motors are used more than one-hundred years ago. At first DC motor was used because of battery power source [1]. After electrical power network was distributed as AC, AC electrical motors were driven by constant frequency and constant voltage such as 50 Hz or 60 Hz. So they were mainly used in fan, blower and compressor to give some force to water or air in water and sewage plant or so. They are considered to support the industrial revolution in modern society. However, the applications were limited in almost constant force or constant rotation speed condition, and the rotational speed control is difficult to be realized in high efficiency because of electrical power source problem.

Power electronics technology [2] solves the problem. It makes it possible to realize the variable rotational speed efficiently [3, 4]. The variable speed requires the change of voltage and frequency of supplied electrical power source because of the electrical motor theory. The rotating speed should be controlled to be the same as the traveling speed of magnetic field in the stator core, which is decided by supplied frequency. When the frequency increases, supplied voltage should increase because of the Faraday's law of induction. By means of the power electronics technology, variable voltage and frequency are possible to be realized efficiently, and then electrical energy is used widely [5].

Power device is used in it as a switching operation, which makes a high efficient electrical power conversion because voltage or current becomes zero and then the power loss becomes almost zero. Figure 1 shows the inverter circuit, a kind of power electronics technology, and IPM motor. The variable voltage is realized by changing the pulse-width and the variable frequency is realized by changing the pulse-timing in the output voltage as shown in Fig. 2. Then the electrical motor drive system is realized in transportation system such as electrical vehicle, hybrid ship or electrical airplane. Now is considered to be the second stage of electrical motor application. The closed connection between the electrical motor and the power electronics technology is indispensable. So their total system design is required as shown in Fig. 3 because each technology in the motor drive system is usually based on the different background [6-8].

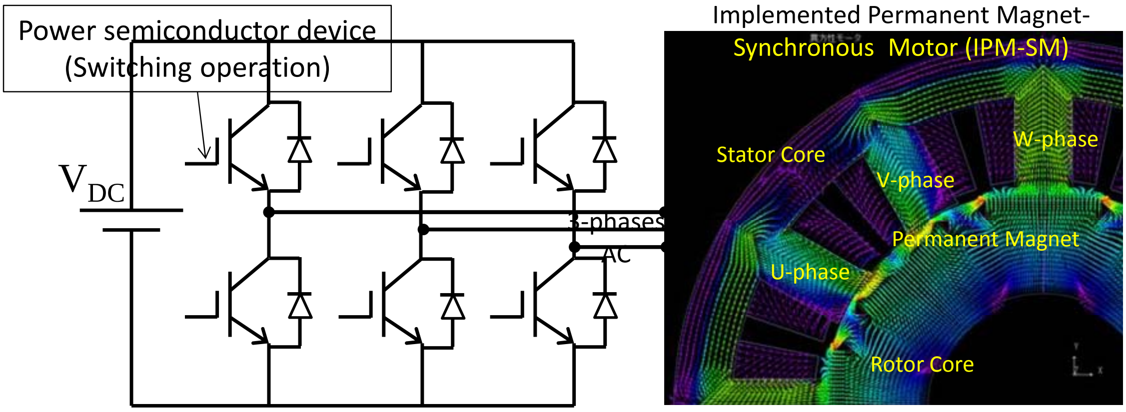

Fig. 1 Electrical motor drive system for speed control of electrical motor by power electronics technology.

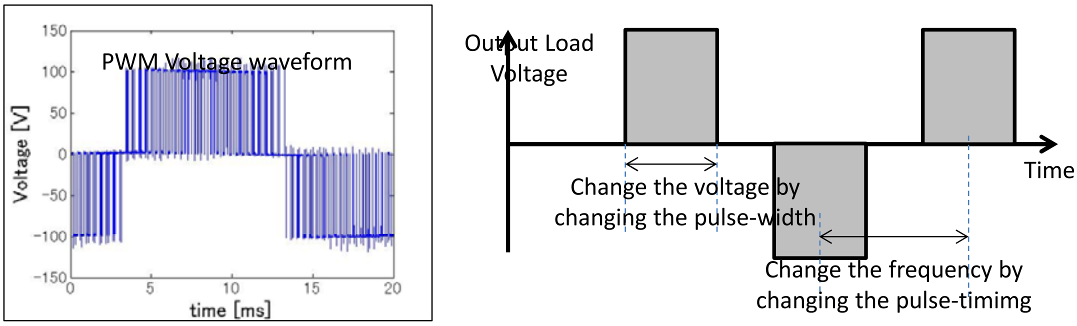

Fig. 2 Variable voltage and variable frequency realization by switching operation of power semiconductor device.

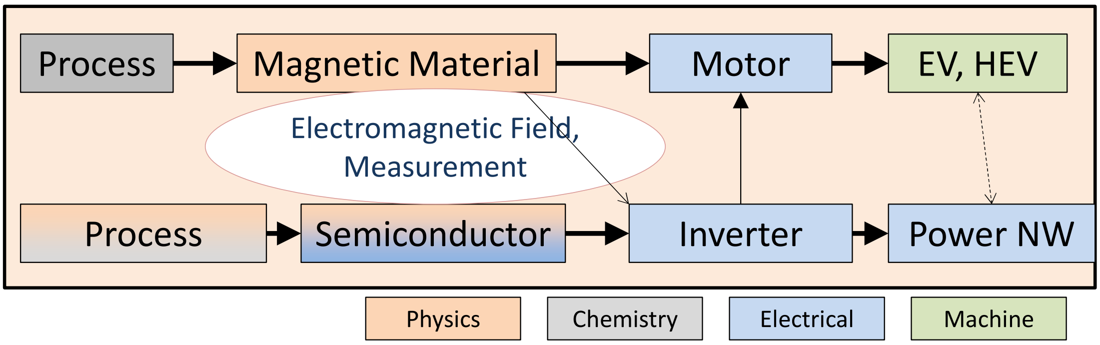

Fig. 3. Elementary technologies of motor drive system in electrical motor and power electronics.

The motor drive system usually moves with the vehicle in the transportation system. So there is a requirement for the downsizing and weight reduction of drive system. Because of electrical motor theory, the high rotational speed and then the high frequency operation are demanded in motor drive system as well as magnetic material [8)]. Usually electrical power of motor (P) is shown as

$$P=\omega T$$

Here, ω is rotational angle velocity, and T is electrical torque. Since magnetic saturation of magnetic material is usually limited as 2 [T] or so, the torque per unit volume is said to be almost constant. Maxwell stress's law shows that electrical force is proportion to the square of magnetic flux density. So in order to increase the electrical power, the increase of rotational speed is required.

However, the high frequency demand derives some new problems to be solved; 1.Increase of supplied voltage (extra step-up converter is required), 2. Increase of mechanical gear, 3.Bearing problem for high rotation, 4.Increase of iron loss of the motor, 5. Increase of centrifugal force of the rotor (high tensile strength steel superior to magnetic property is required).

Direct drive system is considered to be another trend for high rotational speed and high frequency. Electrical motor directly rotates the wheels. So it has superior characteristics as; 1.Low voltage, 2.Gear less or so, 3.No bearing problem, 4.Iron loss reduction, 5.Centrifugal force reduction. Vehicle weight is reported to deduce more than 30 %. Which system is better is not now decided. But magnetic material is considered to be a key technology for future vehicle, because it is used not only in electrical motor but also in power electronics circuit [9)].

Table 1 EV comparison of high speed and direct drive

	High Speed	Direct Drive
Electrical motor size	Small	Large
Supplied voltage	Large	Small
Mechanical gear	Large	Small
Mechanical bearing	Difficult	Easy
Iron loss	Large	Small
Centrifugal force	Large	Small
Drive shaft	Large	Small

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Hysteresis Model and Eddy Currents in FEM Analysis

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Highly accurate analysis of magnetic fields requires faithful reproduction of the magnetization characteristics of magnetic materials. In the thermodynamic hysteresis model found in our last proposal to achieve such an analysis, the magnetization characteristics in three dimensions are determined by free energy and their history dependence is assumed to be associated with friction and other irreversible processes. The hysteretic magnetic field corresponding to friction determines the coercivity of a magnetic material. Application of the variational method to the thermodynamic potential not only enables us to formulate finite elements for numerical analysis, but also offers the advantage of simpler handling of spontaneous magnetization and hysteresis as compared to the conventional FEM analysis based on the weighted residual method.

This model assumes a static nature of magnetic materials. The validation was made by extrapolating the static behavior of hysteresis based on the frequency characteristics of the measured data. However, in reality magnetic materials are generally subject to dynamic magnetic fields. Such dynamic elements must be introduced to the model in order to express the dynamic nature of the hysteresis.

The actual dynamic characteristics of a magnetic material are largely influenced by eddy currents, which are divided into two types. The first are macroscopic eddy currents by induced electromotive force from variable magnetic fields. The second are eddy currents caused by displacement of a domain wall (i.e., an interface separating domains), which does not affect the magnetic field at the macro level while contributing to the loss of the magnetic material.

Similar to the ordinary analysis of dynamic magnetic fields, the effects of the former type of eddy currents can be taken into account in FEM or other numerical methods designed for analyzing macroscopic phenomena when the electric conductivity of a target magnetic material is given.

Nevertheless, the latter type of eddy currents occurs within one domain at most. It is difficult for FEM to take these effects into account without any modification. For this reason, a model needs to be devised for expressing such a phenomenon on a macro scale.

Accordingly, an attempt was made to devise a necessary macro model by performing theoretical calculation of domain wall displacement in a simple one-dimensional model. The study proved that eddy currents do not manifest themselves on a macro scale and only negligibly influence the field distribution in a small domain as most of them cancel out each other.

Therefore, in a small domain the loss associated with this type of eddy currents can be evaluated by post-processing of the results of an analysis that ignores these currents. In a larger domain toward more macro scale, effects of these eddy currents are no longer negligible and must be taken into account during the analysis.

In some cases, conducting FEM analysis with macroscopic eddy currents is met with difficulties, as is the case with laminated electrical steel sheets. In order to make such an analysis possible, preliminary research was carried out as a part of necessary systematic research.

High density soft magnetic composite core of nanocrystalline FeSiBPCu alloys

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Recently, growing concern about the global environmental and energy issues, the next generation vehicles (HEV, EV and FCV) and renewable energy (solar photovoltaic and wind generation) have been developed and become popular throughout the world. Therefore, down-sizing, high efficiency, and high power are demanded for those motor and power supply parts. As one of the candidate to meet the demand is a soft magnetic composite core manufactured by press forming process using soft magnetic alloy powder coated with insulating resin. There are several advantages of these cores, such as 3-dimensional magnetic isotropy, high flexibility of core design, high efficiency by reduction of eddy current loss and, low cost by a near net shape manufacture process. So, we have developed a composite core with high packing density and low loss using new high B_s nanocrystalline alloy powder produced by a high packing density forming method. In this paper, we have investigated magnetic properties of toroidal soft magnetic nanocrystalline composite cores and clarified the possibility of using high packing density nanocrystalline composite cores for high performance applications.

The base powder consists of FeSiBPCu nanocrystalline alloy powder with nearly 50 μm in median particle diameter and silicone resin of 2 wt% for electrical insulator and binder between the particles. The toroidal cores were formed by our method. Core loss at 400 Hz was evaluated by AC-BH curve tracer. Nanocrystalline structures were examined by X-ray Diffraction (XRD) with Cu-K_α radiation and analyzed by whole-powder-pattern decomposition method (WPPD).

Fig.1 shows the photo image of a nanocrystalline toroidal composite core of 56 mm in outer diameter 36 mm in inner diameter and 7 mm in thickness. In general, nanocrystalline alloy shows high hardness and it is difficult to high packing density forming. On the other hand, this composite core has high packing density of 83.4 %, as compared with normal press core of about 70 % in packing density.

Fig.2 shows the core loss at 400Hz of the nanocrystalline composite core as a function of maximum induction (B_m). The data of an Fe-Si composite core and non-oriented magnetic steel are also shown for comparison. The core loss at 400 Hz-1.0 T of the nanocrystalline composite core is 9.8 W/kg, corresponding to one-fourth of that of Fe-Si composite core, and superior to non-oriented magnetic steel[2].

Fig.3 shows the XRD patterns of the nanocrystalline composite core. The core consists of α-Fe grains of about 30 nm in diameter estimated by WPPD. As a result, the magnetocrystalline anisotropy [3] and magnetostriction[4] of this alloy are reduced, and the nanocrystalline core exhibits excellent magnetic properties.

In conclusion, the soft magnetic composite core with high packing density and nanocrystalline structure shows low core loss and large core B_s and is suitable for high performance next generation magnetic devices.

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Fig. 1 Photo image of nanocrystalline composite core.

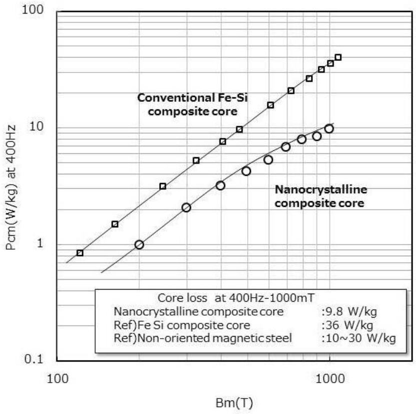

Fig. 2 Core loss at 400Hz of nanocrystalline composite core.

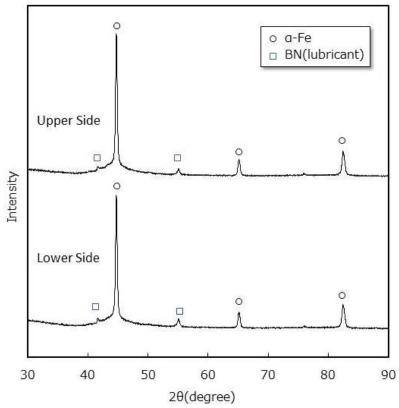

Fig. 3 XRD patterns of nanocrystalline composite core.

High-efficiency IPM motor design and iron loss evaluation

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The expectation for higher-efficiency motors has been increased because the demand for the motorized vehicles and the energy-saving consumer electrical appliances has been grown. For that reason, Motors and Magnetic Materials R&D Center, which is a branch of Technology Research Association of Magnetic Materials for High-Efficiency Motors (MagHEM), develops the design technology of high-efficiency interior permanent magnet synchronous motors (IPMSMs) applying the newly developed magnetic materials and the magnetic material evaluation technology. It is important to develop the design technology of high-efficiency IPMSMs to utilize the newly developed magnetic materials (i.e. high-remanence permanent magnets). High-remanence permanent magnets tend to be adopted as the motor structure is the same, because it is thought that the high efficiency motors can be obtained by using the high-performance materials. However, as shown in Table I, the efficiency of this motor decreases due to increase in the iron loss by using high-remanence permanent magnets in order to reduce the copper loss. Furthermore, the motor structures have a significant influence on the efficiency of the motor if the same magnets are adopted. Therefore, in order to increase the motor efficiency, it is necessary to evaluate the iron loss generated by the magnetic flux including the fundamental components and the harmonic components.

First, the authors developed an ultra-high-precision motor loss analysis system equipped with magnetic bearing in which there is no mechanical friction loss because the rotor is levitated. It enables to reduce the variation in the mechanical friction loss that is a cause of an error of motor loss evaluations, because the iron loss is estimated by subtracting obtained losses, such as the copper loss and the mechanical loss, from the total loss.

Second, because the iron loss density is distributed in the motor, it is necessary to develop a technique for evaluating local iron loss in order to design motors. Therefore, by using search coils and sensors (H coil) for measuring the magnetic field strength, we have developed a technique for evaluating local iron loss under excitation by an inverter. As measurement examples, we report the comparison result of the loss of the ring core using conventional electromagnetic steel sheets and FeBPCu nanocrystalline alloy ribbon.

Acknowledgments

The work is based on results obtained from the future pioneering program "Development of magnetic material technology for high-efficiency motors" commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

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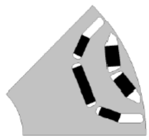
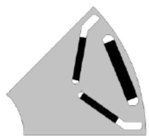
Table I Influences of remanence and rotor structures on motor losses (City-driving evaluation point)

Model	Type 1V-1	Type 1V-2	Type 1V-3	Type 2D	Type ▽
Rotor structure					
Remanence Br[p.u.]	1	1.143	1.268	1	
Current [p.u.]	1	0.892	0.813	1.054	0.973
Copper loss [p.u.]	1	0.796	0.660	1.110	0.947
Iron loss [p.u.]	1	1.152	1.327	0786	0.914
Total loss [p.u.]	1	0.984	1.016	0.938	0.929