Elemental Technologies to Realize Electrification of High Speed Rotating Machinery

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The stationary type turbomachinery is expected to be more efficient and maintenance free and the turbomachinery mounted in vehicles is expected to be smaller, lighter and more controllable. In recent years, with the rapid advancement of power electronics technology, it has become a mega-trend to realize the electrification of high speed rotating machinery such as turbomachinery driven with direct drive motor system and mounted with oil-free bearings. This article introduces the elemental technologies for high speed rotating machinery: high speed motor technology, gas bearing technology and inverter technology.

1. Introduction

In high speed rotating machinery such as stationary type of turbomachinery, speed increasing gears and sliding and rolling bearings are commonly used. However, they require maintenance because they use lubricating oil and grease, and, in addition, often require gears and rolling bearings to be replaced because these are life-limited parts. Therefore, it is anticipated that higher efficiency and free of maintenance will be achieved by directly driving turbomachinery with a high speed motor instead of gears, and adopting gas or magnetic bearings, which do not use lubricating oil. For turbomachinery mounted in vehicles, it is anticipated that this will be made smaller, lighter, and more controllable by eliminating the lubricating oil system and adopting a motor drive system instead of a turbine drive system, which has low responsiveness.

In recent years, with the rapid advancement of power electronics technology, there has been a mega-trend to realize the electrification of high speed rotating machinery such as turbomachinery driven with direct drive motor system and adopting oil-free bearings.

2. Electrification technologies for high speed rotating machinery

Major elemental technologies for realizing the electrification of high speed rotating machinery, which is required to achieve ultra-high speed and high output, consist of high speed motor technology, gas bearing technology, which is used to support the rotating shaft, and inverter technology, which is used to drive the motor.

Because the machinery needs to be smaller and lighter, the high speed motor also needs to be smaller, and therefore needs to have higher power density. To achieve a smaller motor with higher power density, cooling is important. The magnet and resin for insulation have low heat resistance, and it is therefore necessary to achieve lower loss while achieving higher power density. In addition, the motor rotor is not high in strength, so it is important to optimize electromagnetic and strength design.

Next, a gas bearing, which is a type of oil-free bearings, enables the machinery to be smaller and lighter. In particular, a dynamic pressure gas bearing does not require static pressure to be applied from outside and can support the rotating shaft with the force generated by the gas film through rotation. The gas bearing eliminates the need for oil replacement and provides longer service life, since it supports the rotating shaft in a non-contact manner.

In addition, the inverter, which is used to drive the high speed motor, needs to have a higher switching frequency in order to enable high speed rotation. Because of switching loss and noise increase, the inverter requires to have lower loss. Moreover, the inverter also needs to be smaller and lighter.

2.1 High speed motor technology

2.1.1 High speed motor

Motor output P can be represented by Equation (1).

$$P = KD^2Ln \quad \cdots\cdots (1)$$

K : Output coefficient
D : Outside diameter of rotor
L : Length of rotor
n : Rotational speed

From Equation (1), it can be seen that torque depends on size, and that output is determined by size and rotational speed. Rotational speed is determined by the aerodynamic specifications of the turbomachinery, so size is always determined to be that which is optimal. Hence, the extent to which output coefficient can be increased is an important issue. High speed motors include squirrel cage induction machines (IM) and surface permanent magnet synchronous machines (SPMSM). The SPMSM, for which highly magnetic materials can be used, provides a higher power density than other motor types. However, the SPMSM requires a means of preventing the magnet from bursting, and ultra-high speed is achieved by providing a sleeve around the magnet. In this way, when developing high speed motors, it is necessary to solve not only electrical and magnetic issues but also mechanical issues such as material strength and cooling method.

The following is an example of the motor that we developed. **Figure 1** shows the cross section of a 1.2-kW high speed motor with a rated speed of 100 000 rpm. The electromagnetic steel sheet used as the stator core was made thinner than those for home appliances so as to reduce the loss caused by high speed rotation. In addition, the stator geometry and winding method were improved so that the magnetic flux density fluctuates less in the circumferential direction, thereby reducing eddy current loss on the rotor surface. The rotor consists of a shaft made of magnetic material, a ring-shaped neodymium magnet and a retaining sleeve. A high specific strength material was used for the sleeve, thereby achieving high circumferential velocity. High speed motors tend to have low inductance, and the stray load loss tends to increase due to driving current ripple[1]. Air cooling was adopted for cooling of the motor, and a self-excited fan was built in to cool the inside of the machinery. As shown in **Fig. 2**, cooling air is sucked in from the opposite side to the impeller, passed between the stator and rotor, and discharged from the impeller side. The heat generated on the stator side is cooled by cooling air, and also radiates from the casing.

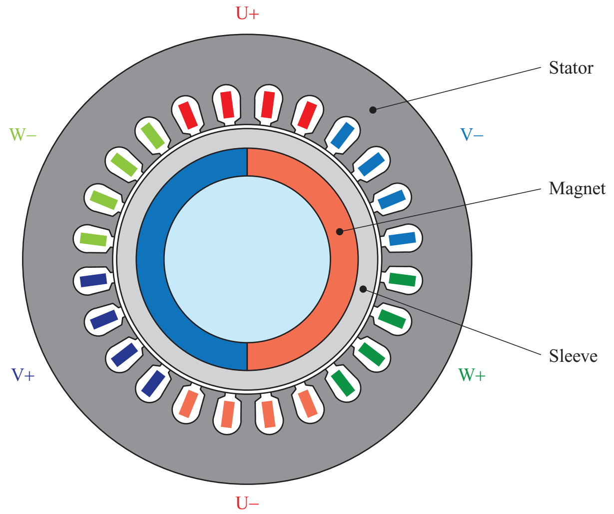

Fig. 1 Schematic cross sectional view of the high speed motor

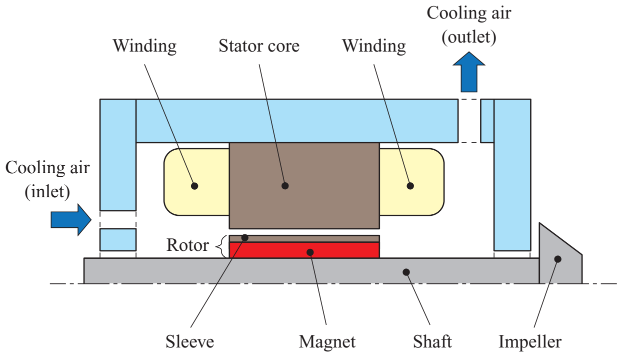

Fig. 2 Schematic cross sectional view of high speed rotating machinery

2.1.2 Analysis and evaluation of high speed motors

In general, performance evaluation of the drive motor, which is measured via a torque meter, is performed with load motor opposing each other. However, when the rotational speed is high, torque measurement is difficult due to coupling and machinery restrictions. Therefore, the high speed motor that we developed was evaluated with a fluid load.

In this evaluation, the loss obtained by electromagnetic field analysis was input and the temperature distribution was calculated by thermal analysis. This was then compared to the measured temperature of each part. **Figure 3** shows the test rig. Several temperature sensors located around the rig were used to measure temperature distribution.

At the rated point (100 000 rpm/1.2 kW), a motor efficiency (including machine loss) of 89.5% and power density of 20 kW/*l* (electromagnetic parts only) were achieved[2]. Currently, we are working to further increase power density and reduce size and weight.

2.2 Gas bearing technology

2.2.1 Gas bearing

Gas bearings use gas as a lubricating fluid. When the shaft rotates, the gas around the shaft is trapped in a thin gap between the shaft and bearing, so that a thin pressurized gas film forms in the gap. The shaft floats due to the load-supporting pressures in the gas film, and, as a result, can rotate at high speed in a non-contact manner. Since they use only gas as the lubricating fluid, gas bearings can be used where oil cannot, and have excellent maintainability. In

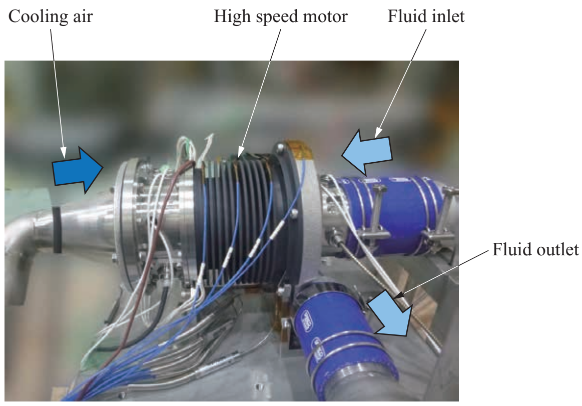

Fig. 3 Test rig

addition, gas bearings do not require an oil supply device, and this contributes to reducing the overall size and weight of the machinery.

However, compared to sliding bearings which use lubricating oil, gas bearings require a thin bearing gap, and are therefore sensitive to temperature changes. In addition, the low damping value of gas bearings causes instability.

To overcome these challenges, IHI has been working on the development of foil-type gas bearings, for which the effect of temperature changes on the gap is low, and which have excellent vibration stability.

(1) Radial gas bearing

Figure 4 shows a schematic cross section of a typical foil-type dynamic radial gas bearing. A foil-type dynamic radial gas bearing consists mainly of a thin corrugated plate spring (bump foil) and thin metallic foil (top foil), the latter coming into direct contact with the rotating shaft at low speed. Both the bump foil and top foil are made from one sheet covering the entire circumference, and, for each foil, only one edge is welded to the bearing housing. When the shaft rotates, pressure is generated in the thin gap between the shaft and top foil by the gas film, and the shaft is supported by this pressure and does not come into contact with the bearing.

As previously mentioned, ensuring vibration stability is a challenge that needs to be resolved. As the shaft rotates, the gas swirls inside the bearing in the rotational direction of the shaft and generates an exciting force, causing stability to decrease. This may generate large self-excited vibration that hinders the operation of the machinery. In addition, the shaft thermally expands due to shear force generated inside the bearing, and, as a result, the gap between the shaft and bearing decreases, resulting in seizure.

Figure 5 shows a cross section of the foil-type dynamic radial gas bearing that IHI specially designed[3] to solve these challenges. The bump foil is circumferentially divided into three segments and secured to the housing at the center of each segment by fixing metal fitting. Dividing the bump foil into three segments allows each part to deform individually according to the behavior of the rotating shaft, thereby reducing the destabilizing force generated when the lubricating gas feed flow inside the bearing in the rotational direction is sufficiently large. In addition, changing the securing method so as to increase the range of movement of the bump foil allows the sliding motion to provide frictional damping, resulting in further enhanced vibration stability. With regard to thermal expansion, the bump foil deforms in a radial direction as the shaft expands, thereby ensuring a gap between the shaft and bearing.

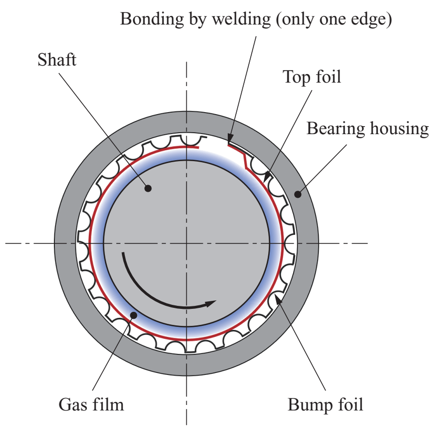

Fig. 4 Schematic cross sectional view of foil-type dynamic radial gas bearing

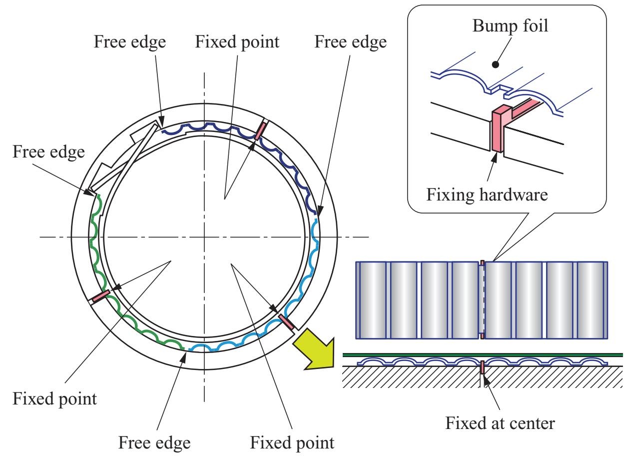

Fig. 5 Schematic cross sectional view of foil-type dynamic radial gas bearing designed to have bump foil with three segmental structure

(2) Thrust gas bearing

Like the radial gas bearing, the foil-type dynamic thrust gas bearing is subject to the axial load caused by uneven pressure distribution between front and back side of the impeller as well as acceleration originating from the outside environment. The foil-type dynamic thrust gas bearing was designed to have adequate load capacity and minimum bearing loss even when it is subject to these loads.

2.2.2 Rotor-bearing dynamics design

To achieve stable rotation at the rated rotational speed, there must be no critical speeds, at which critical vibration is generated, within the operating speed range. There are two modes of vibration that are excited while the shaft is rotating: the rigid body mode, in which the bearing mainly vibrates, and the bending mode, in which the rotor mainly vibrates. **Figure 6** illustrates critical speed analysis of the bending mode. The rotor-bearing dynamics was designed so that the critical speed is significantly higher than the rated rotational speed.

2.3 Inverter technology

2.3.1 SiC power devices

High expectations have been placed on the development of technologies enabling practical use of wide band gap semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) as next-generation semiconductor materials that will replace silicon (Si). With regard to the

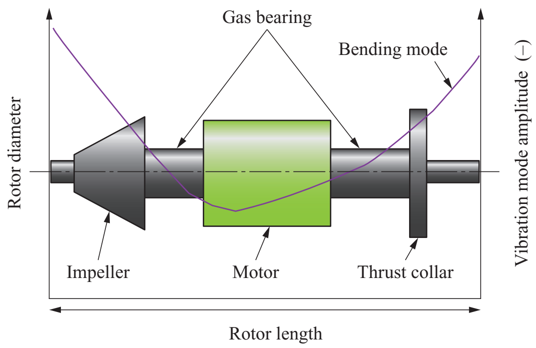

Fig. 6 Illustration of critical speed analysis

electrification of mobility, such as hybrid vehicles and electric vehicles (EV), fuel economy and emission performance are greatly affected by the mass of mounted components, and there is therefore a strong requirement for downsizing and lightening. It is expected that next-generation power devices, which can operate with lower loss than Si power devices, will enable further reductions in size and weight than were possible with conventional Si power devices.

High speed motors for driving high speed rotating machinery are likely to have larger current distortion and higher loss than general-purpose motors. In addition, smaller and lighter motors are likely to have a higher loss density, and it has been an important challenge to develop technologies to decrease the loss and temperature of high speed motors. An effective way of achieving this is to increase the switching frequency of the power device and decrease its current distortion(4). Next-generation SiC power devices, which enable switching at higher frequency than conventional Si power devices, can reduce the loss and temperature of a high speed motor by increasing the switching frequency. For this reason, in order to accelerate the electrification of high speed rotating machinery, vehicle and marine systems, and aircraft through power electronics technology, IHI has been working on the development of application technology in next-generation SiC power devices to reduce the size and weight of the inverter(5).

A metal-oxide semiconductor field-effect transistor (MOSFET) and an insulated gate bipolar transistor (IGBT) are representative power devices. **Figure 7** shows schematic cross sections of the structure of an IGBT and MOSFET. In the case of Si power devices, the MOSFET is a unipolar device, and therefore operates at high speed, but the MOSFET does not have high voltage resistance. Conversely, the IGBT has high voltage resistance, but also has high switching loss because it is a bipolar device.

SiC-MOSFET power devices provide higher voltage resistance, higher heat resistance and lower loss than conventional Si power devices, thereby overcoming the two problems stated above.

Figure 8 shows schematic cross sections of MOSFETs. The voltage resistance of the MOSFET depends on the drift layer, and so a thicker drift layer is required in order to increase it. For conventional Si power devices, the continuity

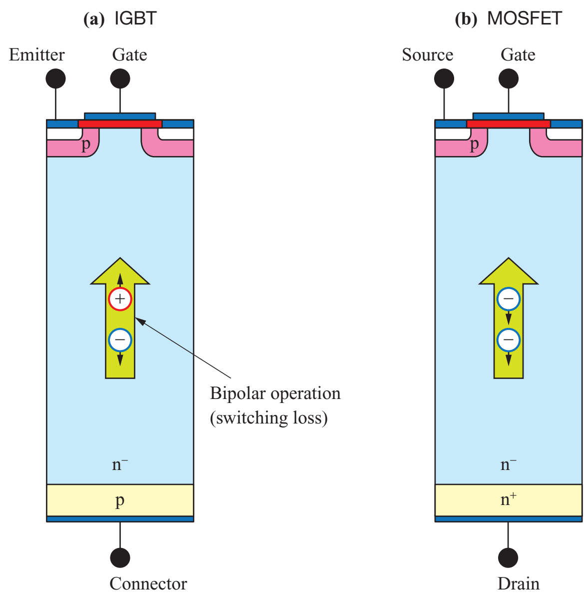

Fig. 7 Schematic cross sectional view of IGBT and MOSFET structures

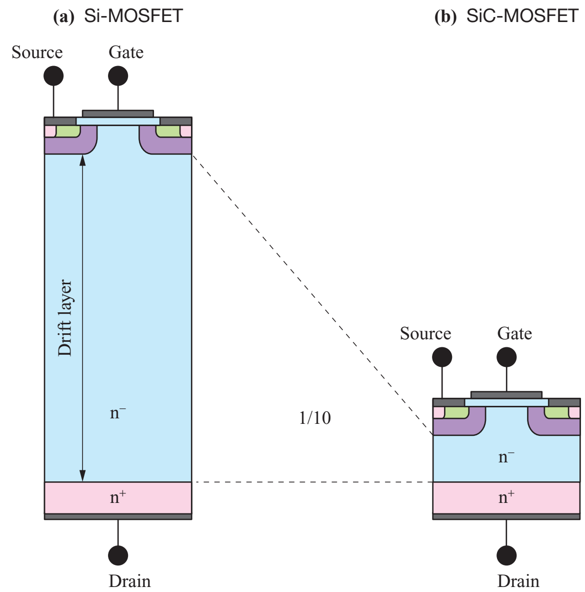

Fig. 8 Schematic cross sectional view of MOSFETs

resistance increases with increasing thickness of the drift layer, so it is difficult to materialize a MOSFET with a voltage resistance of above 200 V.

SiC-MOSFET power devices have high voltage resistance, and can therefore have a thinner drift layer than Si power devices. Since SiC-MOSFET power devices can have the same level of voltage resistance with a drift layer of one-tenth the thickness, conduction resistance can be reduced. High voltage resistance of above 200 V, which are unattainable with Si power devices, can be materialized by SiC-MOSFET power devices.

SiC-MOSFET power devices do not have an IGBT structure, and so do not suffer from high switching loss. IHI's goal of electrifying high speed rotating machinery can be achieved by understanding the switching characteristics of SiC-MOSFET power devices, and developing corresponding drive circuit technology.

2.3.2 Drive circuit technology of SiC-MOSFET power devices

Figure 9 shows the trade-offs that exist for power device switching. With respect to switching characteristics, there is a trade-off relationship between switching loss/speed and switching noise. If switching noise is reduced, then switching loss increases and switching speed decreases. If switching loss is reduced, then switching speed increases, and, as a result, switching noise increases. With respect to size and weight reduction of the inverter, the switching trade-off appears as one between size reduction of the cooling systems and size reduction of the noise filters. Cooling system size can be reduced by decreasing switching loss, but larger noise filters may then be required to decrease switching noise. Conversely, if switching noise is reduced, the noise filters can be made smaller and lighter, but a larger cooling systems will be required due to increased switching loss.

To make the inverters smaller and lighter, it is necessary to develop a drive technology that improves the switching trade-off, and reduces both loss and noise. IHI has developed a drive circuit technology that achieves both low loss and low noise, analyzing the switching behavior of SiC-MOSFET power devices(6).

2.3.3 High power density inverter technology

Figure 10 shows an SiC power module that has higher cooling performance than conventional power modules. A lightweight foil-like cooling fin was soldered directly to the insulated circuit substrate, thereby achieving both high cooling performance, and reduced size and weight. This module also has a built-in noise reduction capacitor.

Figure 11 shows the prototype of the high power density SiC inverter. By utilizing the above-mentioned drive circuit and power module, a continuous output of 35 kW was achieved with a volume of approximately 0.5 *l* and mass of approximately 660 g. In addition, a high power density of 70 kW/*l*, or 50 kW/kg, was also achieved(7). Based on the developed high power density inverter technology, we are currently developing applied technologies such as power electronics integrated high speed electric machines.

3. Conclusion

This paper described elemental technologies for realizing the electrification of high speed rotating machinery. IHI has been aiming to achieve turbomachinery that is smaller, lighter, and maintenance-free with IHI technologies such as high speed motor, gas bearing and inverter technologies and in combination with the accumulated aerodynamic design expertise.

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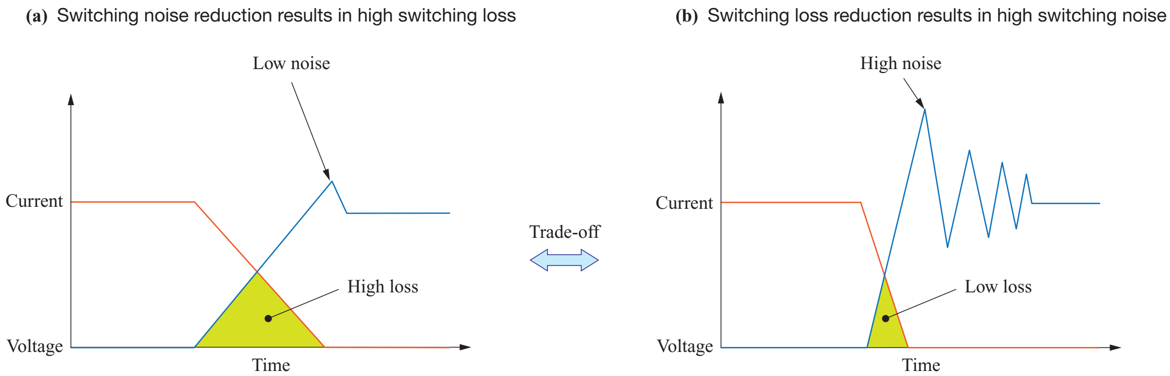

Fig. 9 Trade-off of switching characteristics

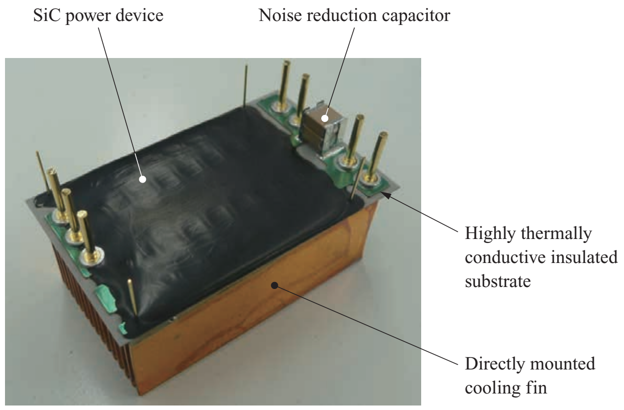

Fig. 10 Prototype of SiC power module

Fig. 11 Prototype of high power-density SiC inverter

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