Featured Articles

Amorphous Motor with IE5 Efficiency Class

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OVERVIEW: Improving the efficiency of electric motors has become a subject of interest amid growing concern about energy efficiency throughout the world. There have been ongoing improvements in the efficiency of industrial motors prompted by national regulations, with international standards having been formulated to define levels of efficiency. Hitachi has developed axial-gap electric motors that comply with the IE5, the most stringent of these efficiency classes, by utilizing amorphous alloys and drawing on Hitachi's own design and manufacturing technologies. By developing techniques for reducing losses relative to motors in the IE4 efficiency class that involved assessing the motor's internal magnetic characteristics and performing precise analysis and design, Hitachi came up with a motor design that significantly reduces the losses in the amorphous core and succeeded in achieving the IE5 efficiency class.

INTRODUCTION

ELECTRIC motors have long been an essential part of our lives through their use in a wide range of products as a means of converting electrical energy into mechanical energy. Although it is more than 200 years since their principle of operation was first discovered, uses have continued to expand in recent years, including as a source of motive power in vehicles and aircraft, and the development of technologies for improving their performance continues[1]. In the case of industrial motors, efficiency improvement has become a matter of urgency since 2000. Reducing motor power consumption has become a subject of interest against a background of international moves to prevent global warming. Fig. 1 shows a breakdown of power use in Japan[2]. Of total annual power use in Japan of approximately 1 trillion kWh, electric motors account for more than half. In the case of factories and other industrial users, this proportion rises to around 75%. This demonstrates how important it is to improve the efficiency of motors used in industry.

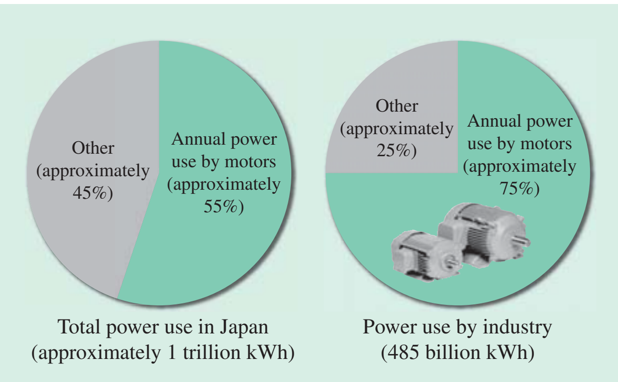


Fig. 1—Power Use in Japan (2009).
As motors account for a large proportion of power consumption in industry, a 1% improvement in motor efficiency in this sector would save the equivalent of the power generated by a major 1-GW power plant.

Countries have responded to this situation by adopting regulations for motor efficiency. The International Electrotechnical Commission (IEC), meanwhile, has defined an international standard for the efficiency of industrial motors, the International Efficiency (IE) code. Internationally, countries have begun introducing requirements that motors satisfy the IE3 efficiency class, with Japan having introduced regulations that stipulate industrial motor efficiency through its Top Runner scheme that came into force from April 2015. This obliges industrial motor vendors to sell motors that achieve an IE3 or better efficiency class.

Following the development in 2008 of the basic technology for an axial-gap motor that achieves superior efficiency through the use of an amorphous alloy core, Hitachi has continued with product developments to increase motor size and further improve efficiency, and to make the technology available in a series of models. A prototype of an 11-kW amorphous motor was successfully completed in 2012 with an efficiency of 93% (high enough to comply with the IE4 efficiency class).

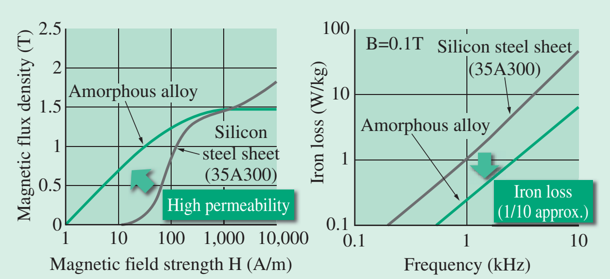
This article describes the development of techniques for further improving efficiency to comply with the more demanding IE5 efficiency class.

IMPROVEMENT IN MOTOR EFFICIENCY FROM USING AMORPHOUS ALLOY

Amorphous alloys are magnetic alloys manufactured by ultra-fast quenching such that the molten metal is solidified at a faster rate than it takes for crystallization to occur (1,000°C in less than 0.001 s, for example). Because of their excellent magnetic properties, amorphous alloys are widely used in applications such as reactors or transformers, and Hitachi has built up know-how in the design and manufacture of such devices. The objective of the current work was to utilize these superior technologies of Hitachi to satisfy the need for energy efficiency in electric motors.

Properties of Amorphous Alloy

An "amorphous metal" means a metal that does not have a crystalline structure. In this article, the term "amorphous alloy" refers to alloys of iron that exhibit excellent soft magnetic properties that include high permeability and low losses due to their



Parameter	Silicon steel sheet	Amorphous iron alloy
Material	35A300 (JIS)	2605SA1 (Hitachi Metals)
Photograph	 Rolled sheet	 Ribbon foil
Density	7.7 g/cm^3	7.2 g/cm^3
Thickness	0.35 mm	0.025 mm
B_1 (100 A/m)	0.95 T	1.26 T
Specific resistance	0.52 μΩ・m	1.3 μΩ・m
Losses $W_{10/400}$	18 W/kg	1.5 W/kg
Hardness (HV)	100 to 200	900

JIS: Japanese Industrial Standards

Fig. 2—Properties of Amorphous Iron Alloy.
Although the permeability and iron loss characteristics of amorphous alloy are significantly better than those of the silicon steel sheet typically used in motors, the thin and hard properties of the material have previously prevented it from use in motors.

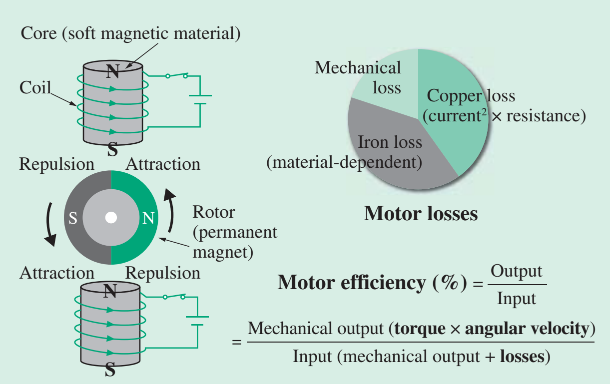


Fig. 3—Principle of Operation of Permanent Magnet Motor, Breakdown of Losses, and Definition of Motor Efficiency.
To improve motor efficiency, it is necessary either to increase mechanical output or reduce losses. Use of amorphous alloy can achieve both these goals.

non-crystalline (amorphous) structure (see Fig. 2). Amorphous alloy is recognized as a way of improving the energy efficiency of electrical machinery because its iron loss is only one-tenth that of the silicon steel sheet typically used in motor cores[3].

In 1960, it was discovered that metals could exist in amorphous form, and amorphous alloy intended for use as a soft magnetic material became commercially available from the late 1970s. It has primarily been used as core material for distribution transformers, with a variety of highly efficient models being developed. The volume of amorphous alloy production is currently rising in response to strong demand from markets such as China and India. In contrast, there has been no progress on the use of amorphous alloy in motors despite these being another product that depends on magnetism. This is because the complex shapes of motor cores are difficult to fabricate using thin and hard amorphous alloy.

Techniques for Improving Motor Efficiency

Fig. 3 shows a simplified model that provides a definition of motor efficiency together with a breakdown of the losses that determine this efficiency. The principle by which a motor turns involves passing a current through the coil wound around the core so that the magnetic polarity of the coil flips between north (N) and south (S), thereby inducing a force of attraction or repulsion on the permanent magnet in the rotor. The associated losses include copper losses (Joule losses) due to the current in the coil, iron losses due to the magnetization of the soft magnetic material, and mechanical friction losses. The efficiency of a motor is expressed in terms of the ratio of its output to

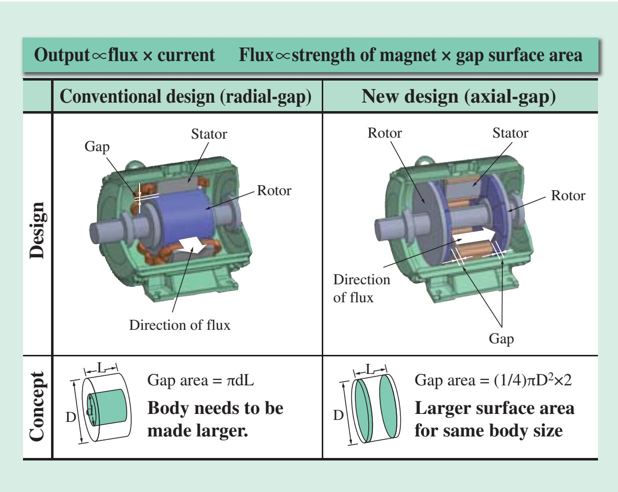


Fig. 4—Comparison of Motor Designs.
Because of its larger rotor diameter, an axial-gap motor has a larger gap area (surface area of the gap region between rotor and stator) relative to volume than a radial-gap motor.

its input. This means that increasing motor efficiency requires either an increase in motor output (torque or speed, etc.) or a reduction in losses.

Because the high permeability of an amorphous alloy means it can generate a high magnetic flux density from a low current, as shown in the graph in Fig. 2, it can increase output torque while also reducing copper losses due to the lower current. Furthermore, because losses are low at high frequency, iron losses can also be kept low even when the motor speed is increased. These features make it an effective way to improve motor efficiency.

Axial-gap Motor Design

Using amorphous alloy for the motor core requires that the core be fabricated without the need for machining it into complex shapes. This led Hitachi to look at using an axial-gap motor with two rotors and to consider a motor design that used amorphous alloy for the stator core. Fig. 4 shows the structural differences between an axial-gap motor and a conventional radial-gap motor. The stator core of an axial-gap motor is a cylinder with a uniform cross-section shape in the axial direction, meaning it is comparatively easy to fabricate using amorphous alloy. Furthermore, a study of the characteristics of axial-gap motors found that they deliver more torque than radial-gap motors when the length in the axial direction is short. This is a result of the rotor diameter being smaller in a radial-gap motor because the rotor is located inside the stator, and also because the rotor is shorter in the axial direction due to the "coil-end" crossover wires of the stator coil that run in the axial direction and therefore take up space in that direction, leaving less area able to contribute to generating torque. The study found that, for typical industrial motors of the same volume, there is an approximately three-fold difference in the torque produced by radial and axial motors (difference in surface area of the gap region between rotor and stator).

Put another way, being able to increase the surface area of the rotor magnet by a factor of around three is equivalent to being able to make the magnetism of the magnet only about one-third as great. The magnets used in motors are expensive because they use large amounts of rare elements, with especially scarce elements such as dysprosium being subject to heightened procurement risk due to reliance on China as a source of supply. Because motors used in industry require security of supply and need to help improve energy efficiency, they need to be made from materials that are low-cost and readily available. Accordingly, Hitachi built an axial-gap motor using very low-cost ferrite magnets with magnetism exactly one-third that of rare earth magnets and conducted performance testing. The results indicated that a motor built with the same volume as existing motors but with an amorphous alloy stator core was able to achieve the IE4 efficiency class (see Fig. 5)(4).

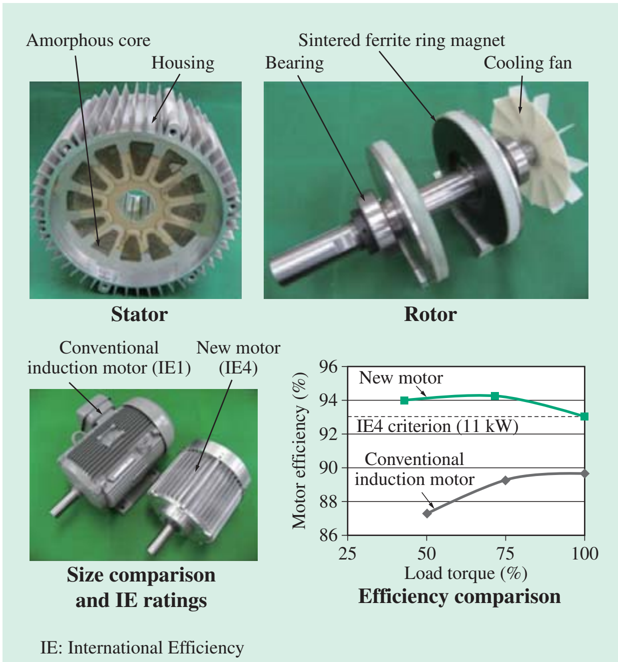


Fig. 5—Design of 11-kW Amorphous Motor, Comparison of Size and Efficiency.
The newly developed motor with an amorphous core and a low-cost ferrite permanent magnet complies with the IE4 efficiency class despite being the same size or smaller than previous models.

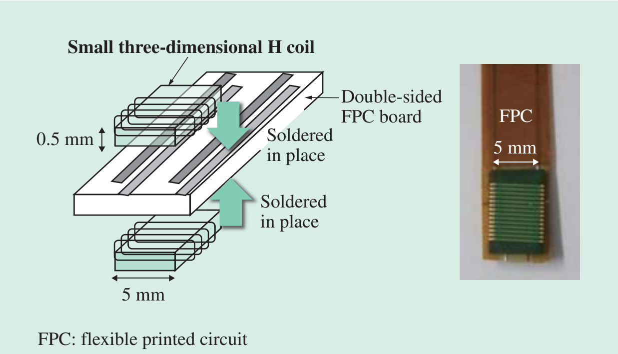


Fig. 6—H Coil Micro-sensor for Measuring Magnetism.
The micro-sensor is able to measure magnetic properties accurately due to improvements in the dimensional and positional accuracy of the two H coils that enable it to be installed in the narrow space next to the magnets.

To achieve an even higher efficiency class, Hitachi then went on to develop techniques for obtaining the best performance from amorphous characteristics. The following section describes these in detail.

LOSS-REDUCTION TECHNIQUES TO ACHIEVE IE5

Technique for Assessing Magnetic Properties of Amorphous Alloy Cores

Achieving the IE5 efficiency class requires a further reduction in motor losses of 20% relative to IE4. Hitachi conducted a study that looked at magnetic properties degradation in amorphous alloy cores as one potential means of reducing losses. While amorphous alloy has exceptionally low-loss characteristics, as shown in Fig. 2, it is known that these characteristics deteriorate in the presence of external disturbances such as applied stress. It was anticipated that the amorphous alloy core used in the new motor would be subject to stress due to the housing design. However, because it had not previously been possible to obtain an accurate determination of the magnetic properties of an amorphous alloy core after it had been fitted in an assembled motor, the design used empirically obtained coefficients to take account of core degradation. This meant that determining the actual degradation would enable an improvement in motor efficiency by allowing the design to use smaller coefficients. Accordingly, Hitachi developed a technique for accurately assessing the magnetic properties of amorphous alloy cores fitted inside assembled motors.

To perform accurate measurement of magnetism, Hitachi developed a very small micro-sensor comprised of two pairs of coils (called “H coils”) in precise dimensional alignment. Fig. 6 shows a diagram. It consists of two pairs of very small three-dimensional coils printed in precise alignment on a double-sided substrate and mounted on both sides of a

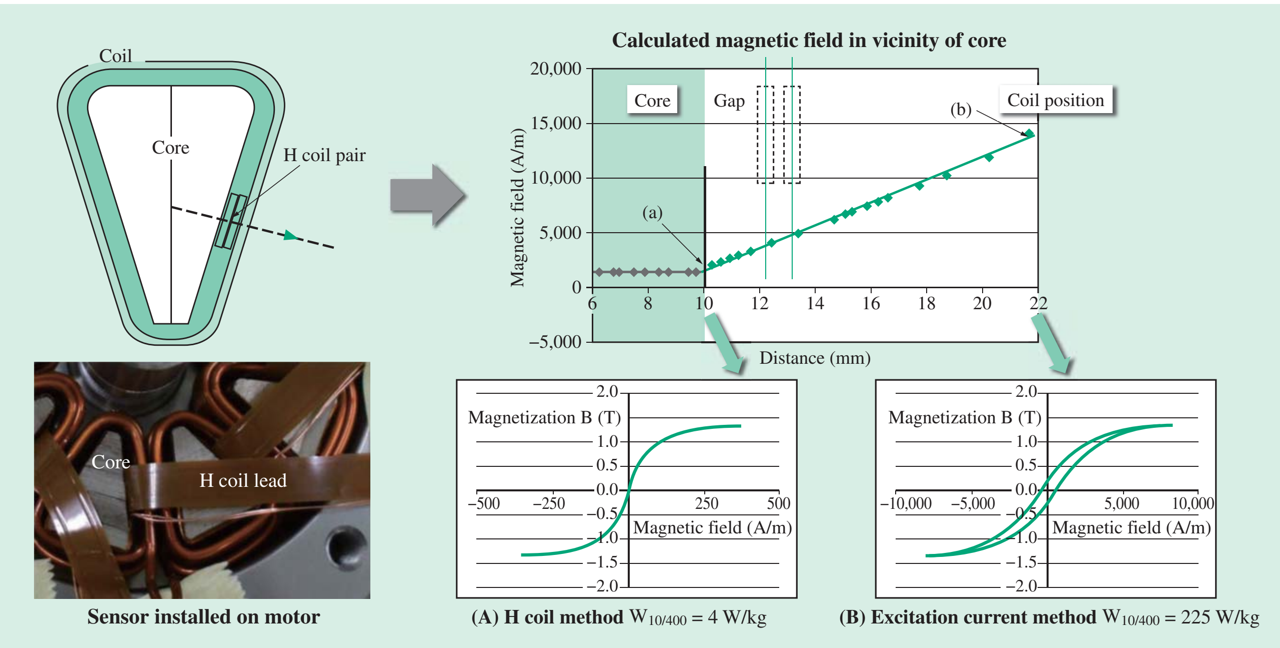


Fig. 7—Overview of Measurement Method for Determining Magnetic Field Applied to Core.
By attaching an H coil on the surface of the motor core (gap between core and coil), it is possible to determine the actual magnetic field applied to the core with high accuracy and obtain the correct magnetic properties.

flexible printed circuit (FPC). Fig. 7 shows an outline of how this micro-sensor was used to make precise measurements of magnetic properties.

Measuring the magnetic properties of a core requires the application of a magnetic field. This applied field is the circumferential magnetic field of the coil (b), and it becomes the weaker field (a) in the vicinity of the core due to the opposing magnetic field of the magnetic core. If the applied magnetic field (b) is strong, a difference appears in the magnetization curve obtained by signal B measured by coil B, as shown by graphs (A) and (B). In (A), both the saturation magnetic field and coercivity are low. The saturation magnetic field is high compared to the magnetic properties of the material and it is subject to mechanical stress. In (B), in contrast, both the saturation magnetic field and coercivity are high. The value of the magnetic field at (b) can be determined easily from the supplied current, in which case the magnetic properties are as shown in (B) and analysis indicates that the core losses make up the bulk of motor losses. On the other hand, if the actual magnetic field

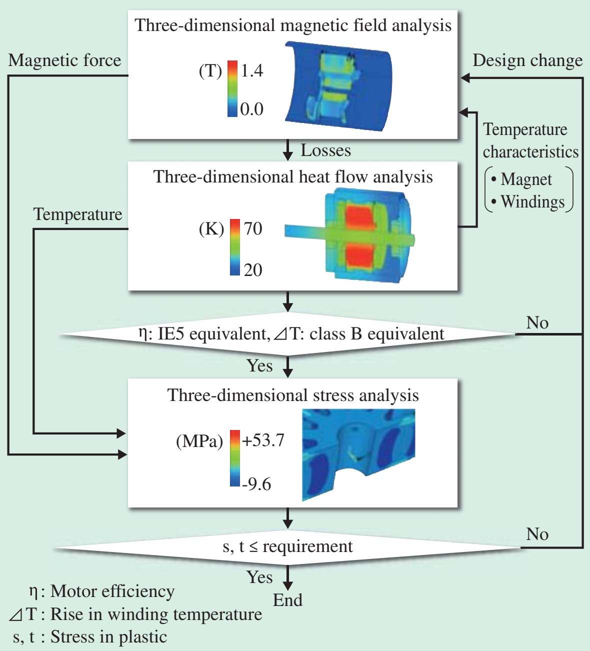


Fig. 8—Flow Chart of Precise Analytical Motor Design.
Parameters such as temperature increase were determined by calculating motor losses with high precision utilizing the losses under actual conditions obtained using three-dimensional magnetic field analysis, and then performing a thermal analysis. The highly accurate prediction of actual conditions allows design margins to be reduced to achieve higher efficiency.

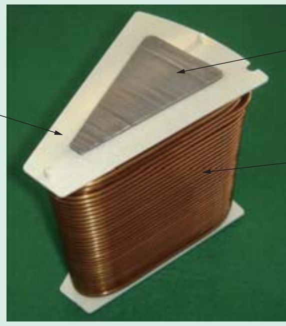


Fig. 9—Design of Amorphous Alloy Core.
The design uses amorphous alloy foil that is first cut and laminated, then inserted into a plastic housing to ensure it holds its shape.

applied to the core (a) and the magnetic properties (A) can be determined, the allocation of losses can be adjusted and the accuracy of motor design enhanced.

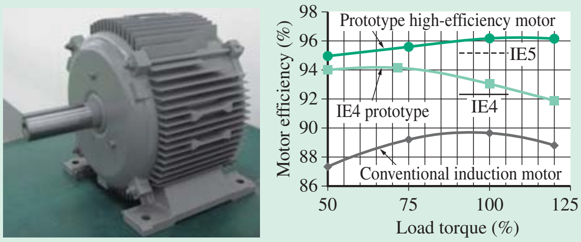
Precise Analytical Design Technique

Fig. 8 shows a flow chart of motor design. To obtain accurate predictions for the three-dimensional magnetic field distribution, temperature distribution, and stress distribution of the axial-gap motor with a double-rotor configuration, the process includes three-dimensional magnetic field analysis, heat flow analysis, and stress analysis. First, the magnetic field analysis is used to calculate the motor losses, output torque, and the magnetic forces on the stator and rotor. Next, heat flow analysis uses these calculated losses as input to calculate the temperature distribution. The magnet and winding temperatures calculated by heat flow analysis are fed back into the physical properties used in magnetic field analysis. From these two analyses, the motor efficiency and temperature rise in the windings are then calculated. If the outcomes satisfy the target performance, the stress analysis is then performed to calculate the stresses on the plastic parts using the electromagnetic force, temperature distribution, and other parameters as inputs. If these stresses are within the permitted limit, the design is complete. The limits are determined based on consideration of how plastic strength varies with temperature and degrades with extended use.

The losses (W_i) in the amorphous core are given by the following equation.

$$W_i = K_h f B^{1.6} + K_e f^2 B^2$$

Here, f is the frequency, B is the maximum magnetic flux density, K_h is the hysteresis loss



Prototype high-efficiency motor Efficiency comparison

Fig. 10—Prototype Amorphous Motor with IE5 Efficiency.
Because lower losses mean less increase in temperature, the motor temperature remains within the specification despite not using a cooling fan. The motor also has a much thinner and flatter profile than previous models.

coefficient, and K_e is the eddy current loss coefficient. As the amorphous core losses can be predicted with greater accuracy by using the H coil method for measuring magnetic properties described earlier to determine the actual values of each type of loss in the core, the margins incorporated into the design can be made smaller to produce a design that minimizes motor losses.

AMORPHOUS MOTOR WITH IE5 EFFICIENCY

Low-loss Amorphous Core Design

The IEC is currently considering adding a new efficiency class above IE4. This IE5 class efficiency will stipulate losses 20% lower than IE4. To satisfy this new standard, Hitachi has been utilizing the loss reduction techniques described above to make further efficiency improvements to its amorphous motors. The work has involved investigating the assembly process and looking at core designs that reduce losses based on performance assessments of the amorphous alloy core in an actual motor. This has indicated that the losses in a core that has been fitted in an assembled motor are significantly different depending on the core shape and how it is housed. The use of housings and assembly techniques that do not impose excessive stress on the amorphous alloy can reduce losses by a large margin. Fig. 9 shows the design of the amorphous alloy core. The amorphous alloy foil is cut and laminated and then fitted into a plastic housing that ensures the core keeps its shape. This keeps losses low by insulating the amorphous alloy core from external disturbance such as stress.

Amorphous Motor with IE5 Efficiency

Reducing core losses also has the effect of reducing the amount of heat generated by these losses. Higher efficiency can be achieved through optimal design that takes account of how temperature affects things like electrical resistance and magnet performance. Fig. 10 shows a photograph of the motor with enhanced efficiency. This motor has a flatter profile than the prototype described above that achieved IE4 efficiency, and testing demonstrated that the efficiency improvements have enabled it to remain within the specification for temperature increase even without the presence of a cooling fan. As a result, the motor significantly surpasses the IE5 requirements, thanks in part to the benefits of eliminating the mechanical losses due to the fan[5].

Commercial Release of Amorphous Motor

In parallel with achieving world-leading efficiency, Hitachi has also been working on preparing the amorphous motor for commercial release. This includes ensuring safety and reliability, and developing a series of models with a range of capacities and at prices that will be acceptable to customers. Because the new motor has no history of commercial use, being significantly different from previous models in terms both of its design and its manufacturing process, Hitachi performed an extensive variety of prototype tests to confirm it satisfied the required specifications and reliability. The product launch announcement for the IE4 range took place at Japan's largest motor trade show in July 2014 (see Fig. 11)[6].

Fig. 12 shows the motor efficiency improvements. An estimate calculated for the replacement of a conventional induction motor with a high-efficiency motor found that, when used to drive a centrifugal pump, an amorphous motor can significantly reduce

Rated output (kW)	3.7 5.5 7.5 11
Speed (min^{-1})	1,500/1,800
Motor efficiency	IE4
Protection	Fully enclosed, external fan (IP44)
Heat-resistant class	Class B
Inverter	WJ200 series

Fig. 11—Commercial Amorphous Motor.
Motors have been released in the high-volume 3.7- to 11-kW capacity range. Models with the same dimensions as IE3 induction motors are available to suit the replacement market.

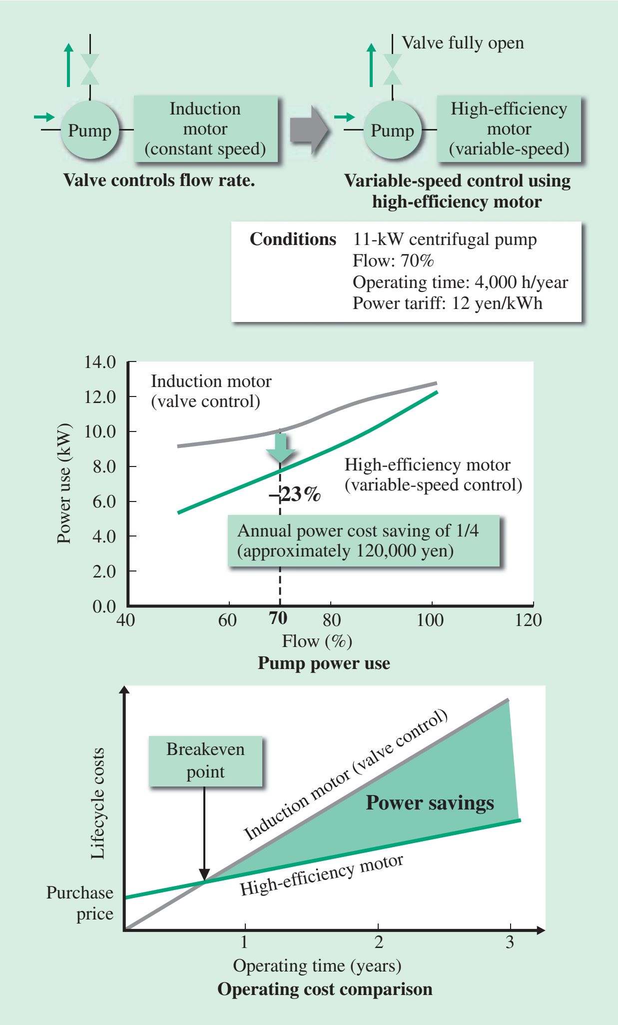


Fig. 12—Benefits of Replacement with High-efficiency Motor. Use of variable-speed drive and a high-efficiency motor significantly reduced power use. The power savings that result from installation of high-efficiency motors reduce running costs.

power use at times when water is not required. This is in contrast to the difficulty of changing power use when operating an induction motor at constant speed and using a valve to control the water flow. Assuming an annual operating time of 4,000 hours, mean flow rate of 70%, and a power tariff of 12 yen/kWh, this saves approximately one-quarter of power costs compared to the previous motor. Because these power savings outweigh the installation cost of the high-efficiency motor, this clearly demonstrates that the breakeven point can be reached quickly.

CONCLUSIONS

This article has described amorphous motor technology that uses low-loss amorphous alloy to improve the efficiency of industrial motors, which are subject to increasingly stringent efficiency standards.

The cost of the motor is also expected to be low because it uses a ferrite magnet as its permanent magnet. This means that another feature of the motor is that it does not use rare earths, which are subject to supply risks. Hitachi anticipates that the motor will enter wider use as an environmentally conscious product that combines energy efficiency with conservation of precious resources.

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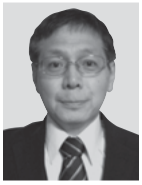

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