"GNS Series" & "GNP Series" of High-Efficiency IPM Motors

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ABSTRACT

Attempting to reduce energy use, as well as rapid resource demands rise, has been a problem worldwide in recent years. To solve this problem, Fuji Electric developed the "GNS Series" and "GNP Series" of high-efficiency interior permanent magnet (IPM) motors, which quest the ultimate reduction of generated loss.

In addition to increased efficiency of electric motors, these motors can greatly reduce power consumption in fan and pump applications through implementing revolution speed control by combining with power electronic devices such as inverters. In addition, their design considers ease of replacement from electric motors already in use and ease of exchanging bearings, arousing demands for energy reduction.

1. Introduction

The electric motor is a key component indispensable for life in society and industrial activity. Electric motors are used in a variety of devices and systems including infrastructure equipment such as air-conditioning fans and compressors, blower fans, water pumps and elevators, and as a motive power supply for various industrial machines such as machining tools, printing machines and cranes. Environmental protection measures for increasing energy savings, curbing CO_2 emissions and the like are being carried out worldwide, and increasing the efficiency of electric motors has become an important matter.

The interior permanent magnet (IPM) motor, a type of permanent magnet motor, has outstanding motor efficiency characteristics. Unlike a typical electric motor, however, the IPM motor cannot be simply connected to a commercial power supply and driven, and instead can only be driven in conjunction with the power electronics equipment known as an inverter. As will be described later, if a high efficiency IPM motor is used in a suitable application, a further energy-savings effect can be obtained as a result of a reduction in energy consumption of the electric motor by itself and by the variable speed control enabled by the inverter. The accurate identification of applications that will exhibit large energy-saving effects as a result of the introduction of a high-efficiency IPM motor and power electronics equipment is extremely important.

This paper introduces representative technologies for increasing the efficiency of electric motors, and describes features of the "GNS Series" and "GNP Series" of high efficiency IPM motors.

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2. Electric Motors and Amount of Power Consumption

In 1997, the "Kyoto Protocol" for preventing global warning was adopted, and the curbing of greenhouse gas emissions became a global commitment. Thereafter, efforts to reduce power consumption in the industrial equipment field began in earnest. In particular, in Japan, the "Act on the Rational Use of Energy" (Energy Conservation Law) was amended in 2010, the "standards of judgment for factories etc. on rational use of energy" was announced, and businesses have been mandated to work toward the rationalization of energy usage.

Twenty trillion kWh of power is consumed worldwide, approximately 40% of which is consumed by electric motors[1] (see Fig. 1). A 1% improvement in electric motor efficiency would reduce the worldwide power consumption by 80 billion kWh, and curb CO_2 emissions by 32 million tons. At factories, the power consumption by electric motors used to drive fans and pumps, and to move equipment and the like accounts for a significant proportion of the total power consump-

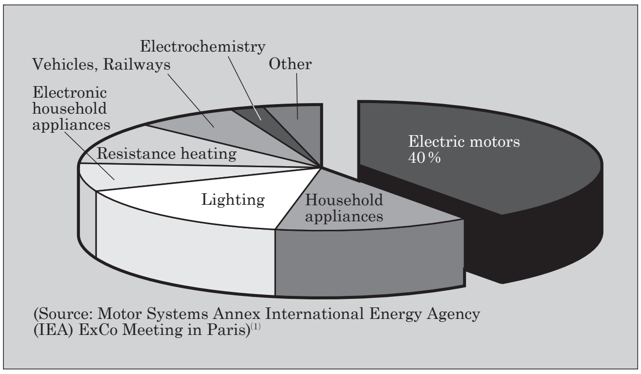


Fig.1 Breakdown of worldwide power consumption

tion.

To reduce the consumption of power by electric motors, the usage of IE3 premium efficiency motors was made mandatory in the USA as of December 19, 2010, while in Europe, mandatory usage has been set for 2015. Various countries, including Japan, are considering or are planning mandating such usage, and efforts to regulate the efficiency of electric motors themselves are being advanced.

3. Techniques for Increasing the Efficiency of Electric Motors

Figure 2 shows a structural cross-section of an IPM motor. Loss occurs in each part of the electric motor, and techniques for reducing these losses are introduced below.

3.1 General techniques

(1) Reduction of copper loss

Copper loss is Joule loss caused by electrical resistance and current in the motor windings, and is proportional to the resistance value. By optimizing the shape of the stator slots, improving the filling rate and enlarging the cross-sectional area of the conductor, the electrical resistance is decreased and copper loss is reduced.

(2) Reduction of iron loss

Iron loss is the sum of eddy current losses caused by changes in the magnetic flux in the core and hysteresis loss. To reduce the change in magnetic flux in the core, the magnetic flux density is designed to be low, and to reduce iron loss in the material itself, high-grade electromagnetic thin steel sheets that exhibit low iron loss are used.

Additionally, because loss increases if stress is applied to parts of the iron core, it is also important to relieve the stress. For example, when punching an electromagnetic steel sheet in a press mold, loss in the material increases due to the punching strain, but strain-relieving annealing can be performed to prevent an increase in loss and to restore the original magnetic properties.

Iron loss accounts for approximately 40% of the loss in an electric motor, and it is important that the power loss be computed accurately at the time of design. Iron loss had conventionally been calculated numerically based on the assumption of an alternating magnetic field. Inside an actual electric motor, however, a rotating magnetic field is generated in addition to an alternating magnetic field, and the conventional method did not account for the effect of the rotating magnetic field. Therefore, in order to improve the calculation accuracy, highly accurate computations are presently being implemented using the finite element method or the like to account for the loss due to the rotating magnetic field. In consideration of the balance with copper loss, the number of poles, winding method, number of slots and core shape are optimized to realize higher efficiency.

(3) Use of permanent magnet

An induction motor generates magnetic flux on the rotor side by flowing an induction current in a secondary conductor of aluminum, copper or the like, but a permanent magnet type electric motor uses a permanent magnet as the rotor to create magnetic flux and therefore does not require current flow and has extremely low loss on the rotor side. Accordingly, a permanent magnet motor can achieve higher efficiency than an induction motor.

Moreover, because a permanent magnet motor generates little heat, the area for heat dissipation can be made smaller, allowing permanent magnet motors to be made smaller and lighter in weight.

(4) Reduction of eddy current loss generated in various parts

When driven by a pulse width modulation (PWM) inverter, the carrier frequency component of the current in an electric motor contains harmonic current, and as a result, unnecessary eddy currents generated inside the electric motor may result in loss.

In a permanent magnet motor, neodymium magnets capable of generating a strong magnetic field are often used. Neodymium magnets have the characteristic of high conductivity, and eddy currents flowing inside the magnet result in loss. One countermeasure is to reduce the interlinking harmonic flux in the permanent magnet. Also, the magnetic flux generated in the coil leaks to the frame shield and other members of the electric motor, causing eddy currents to be generated that result in loss. As a countermeasure, the parts that configure the electric motor must maintain a proper distance from the stator coil.

(5) Reduction of loss with an electric motor cooling fan

An electric motor is equipped with a cooling fan, and the mechanical loss caused by the rotation of the cooling fan is included in the loss of the motor. Accordingly, to make fan-based cooling a minimum requirement, the motor temperature must be computed with high accuracy at the design state.

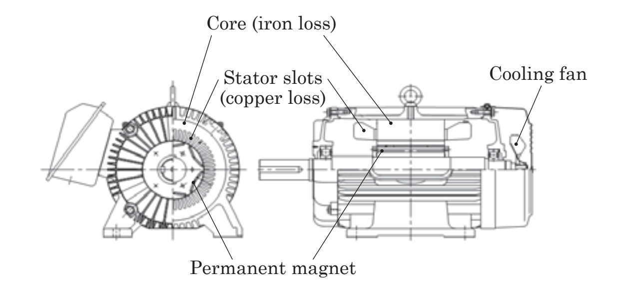


Fig.2 Structural cross-section of IPM motor

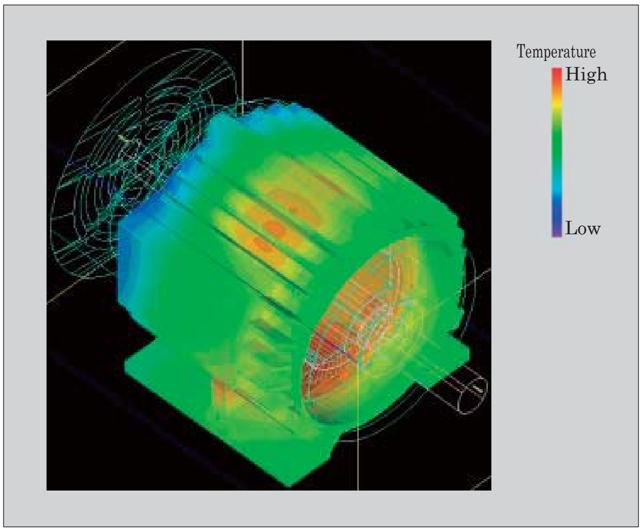


Fig.3 Example of thermo-fluid analysis of electric motor

3.2 Fuji Electric's efforts

At Fuji Electric, highly accurate thermal design for typical electric motors such as a totally enclosed fan-ventilated motors is carried out using a fluid circuit network calculation to compute the wind speed and then using a thermo-fluid circuit network method to compute the temperature of each part of the motor.

Additionally, thermo-fluid analysis may also be used when consideration of natural convection and the like is necessary (see Fig. 3). For both the thermo-fluid circuit network method and thermo-fluid analysis, the way in which elements that cannot be analyzed simply, such as the contact resistance of different components, are defined as thermal resistances is important and it is extremely important that basic data be accumulated through experimentation and the like.

4. Characteristics of High Efficiency IPM Motors

In addition to applying the various techniques for increasing efficiency described in Chapter 3, high-efficiency IPM motors have also been specially developed for higher efficiency, and realize extremely high efficiency. Fuji Electric provides a lineup of its "GNS Series" of IPM motors featuring higher efficiency than the IE4 level and standard output power in the range of 11 to 160 kW, and a lineup of its "GNP Series" of IPM motors featuring an IE4 level of efficiency and standard output power in the range of 5.5 to 90 kW.

In particular, the GNP Series has a multi-rated specification for voltage, and have been designed so that a single motor is compatible with a domestic 200 V power supply or a 400 V power supply. Standard stocking of all models in the 5.5 to 90 kW output range enables instant delivery.

Additionally, IPM motors are smaller than induction motors and naturally had different mounting dimensions than induction motors in the past. The GNS Series and the GNP Series both have the same mounting dimensions, however, facilitating the replacement of induction motors already in use.

4.1 Realization of effect of higher efficiency

Electric motor efficiency is prescribed by IEC 60034-30 (see Fig. 4). The IE1 standard value is at the level of a general-purpose induction motor, and the IE2 standard value is at the level of a high-efficiency induction motor and is the same as the EPAct level.

Furthermore, IE3 and IE4 standard values that are higher than those of the prior EPAct have been enacted. The GNS Series has the highest level of efficiency standards, surpassing the IE4 standard values, and is 8.5 to 3 points above the level of commonly used induction motors (IE1 level) and 2 to 1 points above the IE3 level.

As for the measured results of efficiency of the GNS Series motor of 75 kW rated output and the induction motor, the reduction effect at the rated load is shown in Table 1(a) and the reduction effect at a 50% load factor, which is close to actual usage, is shown in Table 1(b). The efficiency is improved 4.1 percentage points at the rated load and is improved 5 percentage points at the 50% load factor.

The reduction effect in terms of power consumption, electricity price and CO_2 emissions is as shown in Table 1.

4.2 Maintainability

In electric motors, the bearings are consumable parts and will need to be replaced. In the case of an induction motor, on-site replacement is possible since the bearings can be replaced by removing brackets on the directly coupled side and on the non-directly coupled side and pulling out the rotor.

On the other hand, because a magnetic force exists in the case of a permanent magnet motor, pulling out the rotor would be substantially difficult to accomplish on-site, and typically the motor is returned to the man-

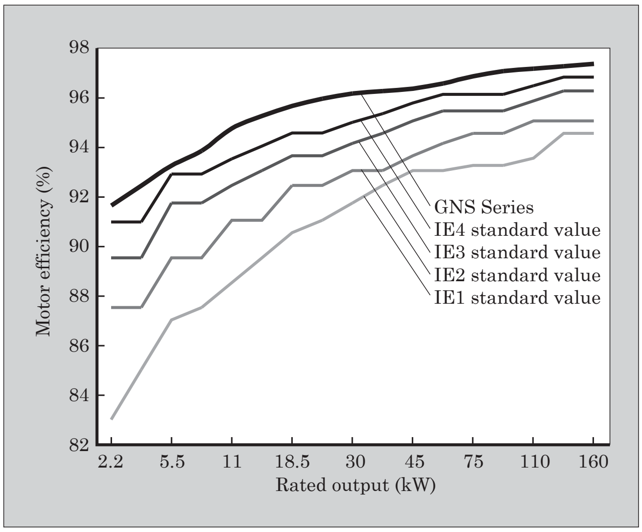


Fig.4 Values of efficiency standards for electric motors

Table 1 Reduction effect due to "GNS"

(a) Rated load, 1,465 min^{-1}

	Induction motor	High-efficiency IPM motor	Reduction effect
Output (kW)	75	75	
Motor efficiency (%)	93.2	97.3	4.1 percentage point improvement
Power consumption (kWh)	704,900	675,200	29,700
Electricity price (1,000s of yen)	8,459	8,103	356
CO_2 emissions (t)	282.0	270.1	11.9

(b) Load factor 50%, 1,480 min^{-1}

	Induction motor	High-efficiency IPM motor	Reduction effect
Output (kW)	37.5	37.5	
Motor efficiency (%)	91.9	96.9	5 percentage point improvement
Power consumption (kWh)	357,400	339,000	18,400
Electricity price (1,000s of yen)	4,289	4,068	221
CO_2 emissions (t)	143.0	135.6	7.4

Computation conditions
Operating time 8,760 hours (continuous for 1 year)
Unit price of electricity 12 yen/kWh
Equivalent CO_2 emissions 0.4 kg/kWh

ufacturer for replacement of the bearings. However, because the GNS Series and the GNP Series have been constructed so as to allow the bearings to be replaced simply by removing the brackets on either side, on-site bearing replacement is possible and maintainability is enhanced.

4.3 Ease of installation

A permanent magnet motor is typically smaller and lighter in weight than an induction motor. However, the GNS Series and the GNP Series are not downsized, but instead maintain compatibility with the mounting dimensions of induction motors. This facilitates the task of motor replacement in existing equipment and stimulates demand for energy conservation.

5. Energy saving Effect of Inverter Driving

Permanent magnet motors do not have a starting winding and must operate in conjunction with an inverter. Therefore, by utilizing the capability of an inverter to freely change the rotational speed of a motor, using the motor in a fan pump of the type that employs the centrifugal force of the rotating blades, and adjusting the flow rate according to the change in rotational speed, further energy savings can be attained.

5.1 Application to fluidic devices that utilize the centrifugal force of the blades

The motive power (W) of the fluid system can be expressed as follows.

Motive power (W) =
Pressure (N/m^2) × Flow rate (m^3/s) ··················· (1)

In the case of a fluidic device that uses the centrifugal force of the blades to deliver water, air or other flow, the pressure is proportional to the centrifugal force of the blades.

Generally, in the case of a fluidic device that uses the centrifugal force of the blades, the centrifugal force can be expressed as $mr\omega^2$ where m is the mass, r is the radius and ω is the angular velocity, and the pressure is proportional to the square of the rotational speed.

Pressure ∝ Rotational speed ^{2} ·························· (2)

Also, since the blades rotate to push out fluid, the flow rate is proportional to the rotational speed

Flow rate ∝ Rotational speed ·························· (3)

As shown in equation (1), motive power is the product of pressure and the flow rate, and in the case of a fluidic device that uses the centrifugal force of the blades, the motive power of the fluidic device, i.e., the power consumption, is proportional to the cube of the rotational speed of the motor.

Power consumption ∝ Rotational speed ^{3} ··········· (4)

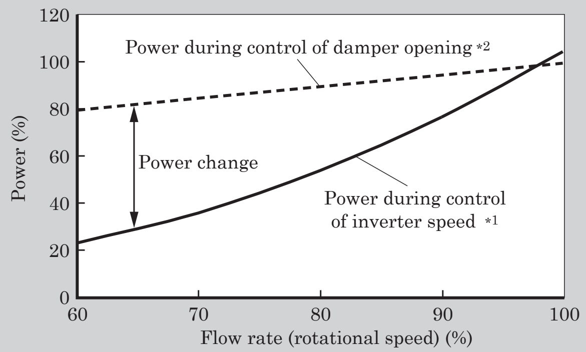
If the rotational speed is halved, the flow rate is halved, the pressure becomes $(1/2)^2 = 1/4$ and the power consumption becomes $(1/2)^3 = 1/8$. However, because the pressure is proportional to the square of the rotational speed, in applications that require pressure such as in pumping water and water jet machines, the rotational speed cannot be reduced by much, and a power-saving effect may not be obtainable. Table 2 and Fig. 5 show these relationships and their effects (theoretical values).

Also, the rotational speed, flow rate, pressure and power are expressed as 100% in the case when the induction motor is driven by a commercial power supply,

Table 2 Energy saving effect with fluidic device utilizing centrifugal force of blades

Rotational speed (%)	Flow rate (%)	Pressure (%)	Power during control of inverter speed *1 (%)	Power change *2 (Point)
100	100	100	105	5
90	90	81	77	−18
80	80	64	54	−36
70	70	49	36	−49
60	60	36	23	−57

*1: Assuming an inverter efficiency of 95%, and assuming a 5% increase in power with the addition of the inverter.
*2: Indicates the power change in response to a flow rate adjustment with a damper opening of 50 to 100%.



*1: Assuming an inverter efficiency of 95%, and assuming a 5% increase in power with the addition of the inverter.
*2: Indicates the power change in response to a flow rate adjustment with a damper opening of 50 to 100%.

Fig.5 Energy saving effect with fluidic device utilizing centrifugal force of blades

without using an inverter.

5.2 Measurement example and effect

A 75 kW induction motor and a 75 kW "GNS" high-efficiency IPM motor were operated side-by-side at the same time at Fuji Electric's Suzuka Factory which has test equipment capable of measuring the input power of the inverter.

Table 3 shows the results of the in-house experiment using that test equipment and assuming an 80% flow rate.

A comparison of the power consumption of the "GNS" high-efficiency IPM motor at a rotational speed of 1,422 min^{-1} (1,778 $min^{-1} \times 0.8$) with the power consumption of an induction motor driven by a commercial power supply, revealed that the power consumption was reduced by 31.9 kW.

Table 3 In-house experimental results assuming an 80% flow rate

	Induction motor *1	High-efficiency IPM motor *2	Reduction effect
Flow rate (%)	80	80	—
Rotational speed (min^{-1})	1,778	1,422	—
Input power (kW)	73.1	41.2	31.9

*1: Assuming that the induction motor runs on a commercial power supply, and that flow rate is adjusted by the degree of valve opening.
*2: In a high-efficiency IPM motor, the flow rate is adjusted by inverter speed control, and the input power indicates the inverter input power.

6. Postscript

This paper has described representative technologies for increasing the efficiency of electric motors, and features of the "GNS Series" and "GNP Series" of high-efficiency IPM motors. In particular, Japan has a history of innovation in permanent magnet technology, and this field is also very advanced throughout the world. Moreover, inverter drive technology is also advanced in this field. Japan is a leader in the technical field of permanent magnet motor systems that combine permanent magnet technology with inverter drive technology, and within this context, Fuji Electric offers solutions with a high level of technical expertise.

In response to the global challenges of increasing energy savings, curbing CO_2 emissions, and protecting the environment, expectations for the higher efficiency of electric motors have increased further, and both as a supplier and as a partner who increases the value of our customers' products, Fuji Electric intends to promote the advancement of technology in order to meet those expectations.

Reference

(1) Rolamd Brüniger. Motor Systems Annex. IEA ExCoMeeting in Paris 14/15 April 2008.

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