Fuji Electric's Top Runner Motor— Loss-Reduction Technology of "Premium Efficiency Motor"

TACHI, Norihiro* KOIBUCHI, Hirobumi* TAKAHASHI, Kazutoshi*

ABSTRACT

Motors are a key component indispensable for social and industrial activities. They consume electric power that accounts for nearly 40% of the global energy consumption. Consequently, improving motor efficiency is a challenge for the major countries of the world. In Japan, the Top Runner Program was introduced in April 2015 to regulate motor efficiency. The "Premium Efficiency Motor" that Fuji Electric has developed satisfies the efficiency regulation value through various loss-reduction technologies including an optimized slot shape and the adoption of magnetic steel that dissipates less power. This is an environmentally friendly product achieving low noise as well as high efficiency.

1. Introduction

Three-phase induction motors ("motors"*1) are a key component indispensable to life in society and industrial activities. They are used in large numbers as sources of power for infrastructure facilities such as air-conditioning fans/compressors, blower fans, water service pumps and elevators; and in various industrial machines including machine tools, printers and cranes. Accordingly, it is essential to improve the efficiency of motors in order to conserve energy on a global scale.

While major countries outside Japan have moved forward with efficiency regulations, in Japan, the focus has been to save energy of entire systems and there has been no regulation for motors alone. However, the amended "Act on the Rational Use of Energy" (Energy Conservation Act) was enforced in November 2013, and it stipulates the start of efficiency regulation in April 2015 as the Top Runner Program for motors.

This paper describes the loss-reduction technologies of Fuji Electric's top runner motor "Premium Efficiency Motor."

2. Amount of Power Consumption and Efficiency Classes of Motors

The global electric power consumption is 20 trillion kWh a year,approximately 40% of which is consumed by motors[(1)] (see Fig. 1).

In 1997, the "Kyoto Protocol"*2 for prevention of global warming was adopted, which made reduction of greenhouse gas emissions a global commitment. If motor efficiency is improved by 1%, the global power consumption can be reduced by 80 billion kWh and CO_2 emissions by 32 million tonnes.

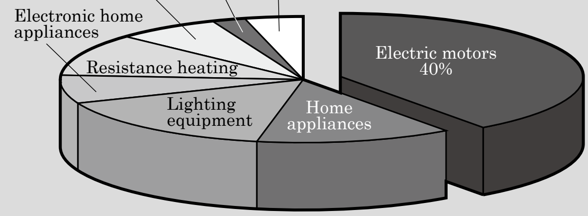

Fig.1 Breakdown of global electric power consumption

Table 1 IE code and efficiency classes

IE code	Efficiency class	JIS
IE3	Premium efficiency	JIS C 4213
IE2	High efficiency	Equivalent to JIS C 4212
IE1	Standard efficiency	Equivalent to JIS C 4210

For major energy consuming nations including Western advanced nations, improvement of motor efficiency is positioned as a very effective measure for reducing CO_2 emissions, and this has created a trend toward improving the efficiency of the motors themselves. One international standard in relation to efficiency is IEC 60034-30 [Rotating electrical machines - Part 30: Energy-efficiency classes for single-speed, 3-phase, cage-induction motors (IE code)] of the International Electrotechnical Commission (IEC) (see

*1: Motors: Although motors generally refer to all types of electric motors, 3-phase induction motor is referred in this paper.

*2: Kyoto Protocol: Officially called the "Kyoto Protocol to the United Nations Framework Convention on Climate Change."

* Power Electronics Business Group, Fuji Electric Co., Ltd.

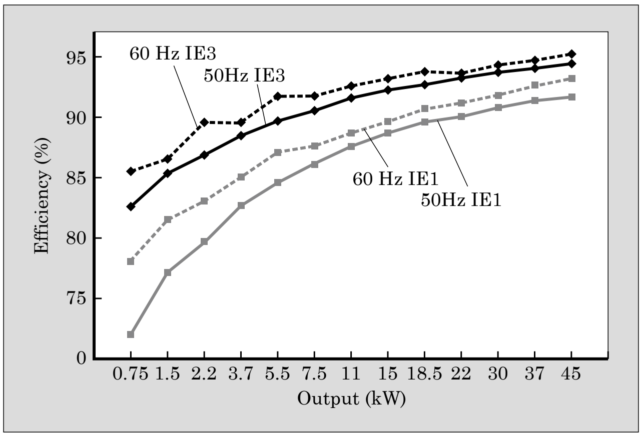

Fig.2 Efficiency comparison among Fuji Electric's representative types

Table 1). In the U.S., the total number of high efficiency (IE2) and premium efficiency (IE3) models produced and shipped accounts for approximately 70% of all motors. In Europe, IE2 accounts for over 50% and legislative regulation with IE3 started in January 2015.

As an improvement in the efficiency of motors makes progress in Europe in this way, regulation on efficiency using the Top Runner Standards is starting in April 2015 in Japan as well.

The Top Runner Standards provide regulation in view of the 3 rated voltage and frequency types, which is Japan's peculiar power supply situation, while being based on IE3. That is, while IE3 is used as the efficiency regulation values for 200 V 50 Hz and 220 V 60 Hz, IE3 value multiplied by a coefficient is used as the regulation value for 200 V 60 Hz; and the judgment of achievement of regulation values is defined by 36 categories. Figure 2 shows an efficiency comparison between IE1 and IE3 of Fuji Electric's representative types.

3. Features of "Premium Efficiency Motor"

The external appearance and specifications of the Premium Efficiency Motor are shown in Fig. 3 and Table 2 respectively. The features are:

Fig.3 "Premium Efficiency Motor"

Table 2 Specifications of "Premium Efficiency Motor"

Item		Specification
Series name		MLU (cast iron frame 100L or larger) MLK (steel frame 90L or smaller)
Protection rating		IP44 (indoor) IP55 (outdoor)
Rated voltage/ frequency		Frame number 160 L or smaller: 200/200 to 220 V and 400/400 to 440 V 50/60 Hz Frame number 180M or larger and outdoor type: 200 to 400 V 50 Hz and 200 to 400/220 to 440 V 60 Hz
Time rating		S1 (continuous)
Starting method		3.7 kW or smaller: direct-on-line starting 5.5 kW or larger: star-delta starting
Thermal class		155 (F)
Terminal box (Foot mounting)	Mounting position	Frame number 200L or smaller: left side as seen from load Frame number 225S or larger: top side as seen from load
	Port orientation	Frame number 200L or smaller: Downward (indoor) Opposite operation side (outdoor) Frame number 225S or larger: leftward as seen from load
Lead wire	System	Frame number 160L or smaller: terminal block system Frame number 180M or larger and outdoor type: lug system
	Number of wires	Output 3.7 kW or smaller: 3 (indoor), 9 (outdoor) Output 5.5 kW or larger: 6 (indoor), 12 (outdoor)
Vibration resistance		6.8 m/s^2 (0.7 G)
Color of coating		Munsell N1.2 (black matte)
Nameplate Badge Emblem	Specification nameplate	Frame number 200L or smaller: stuck on frame (steel plate) nailed on frame nameplate mounting seat (cast iron) Frame number 225S or larger: nailed on fan cover
Standard	Application	JIS C 4213
	Efficiency	JIS C 4034-30:2011*
Motor efficiency class		2P-45 kW or smaller, 4/6P-7.5 kW or smaller (except 6P-1.5 kW): IE3/IE3-IE3 at 200/200 to 220 V, 400/400 to 440 V 50/60 Hz, dual voltage 2P-55 kW or larger, 4/6P-11 kW or larger and 6P-1.5 kW: IE3/IE2-IE3 at 200/200 to 220 V, 400/400 to 440 V 50/60 Hz, dual voltage

*Motor efficiency testing is carried out according to "low uncertainty" of JIS C 4034-2-1 "Methods for determining losses and efficiency from tests of single-speed, three-phase, cage-induction motors" provision.

(1) Motor efficiency of Top Runner Standards

Motor efficiency of the Top Runner Standards is achieved in all output specifications (0.75 to 375 kW). In addition, efficiency class IE3 (premium efficiency of JIS C 4034-30:2011) is achieved at the 3 ratings[*3] and the 6 ratings[*4] of voltage and frequency.

(2) Easy replacement with standard motors

The design makes it possible to smoothly replace motors since it adopts the same frame[*5] size and mounting dimensions as those of the conventional standard motors of Fuji Electric. The foot mounted models with a frame number of 160M or smaller have the same total lengths and diameter.

(3) Wide-ranging voltage classes

With outdoor motors, versatility has been pursued and the 6 ratings of voltage and frequency adopted in order to reduce the quantity of stock at Fuji Electric and its customers.

(4) Improved environmental endurance

The insulation performance has been improved while reducing temperature rise and the scope of adoption of cast iron frames has been expanded for improvement of corrosion resistance and noise reduction. These have made it easier to use the motors in various environmental conditions.

(a) Protection rating

The protection rating of conventional motors was IP44*6 with no distinction between indoor and outdoor models but the Premium Eefficiency Motor has been designed in conformity to the global standard to offer IP44 with the indoor model and IP55 with the outdoor model.

(b) Ambient temperature

While the ambient temperature specification was generally −20 °C to +40 °C, the range has been expanded with Fuji Electric's Premium Efficiency Motor to −30 °C to +50 °C.

(c) Maximum starting current

The reduction of resistance from that of conventional standard motors for better efficiency has caused the maximum starting efficiency to increase but the increase has been kept to approximately 20% by revising the rotor slot shape.

(5) Adaptation to inverter operation

The range of use for inverter operation has been expanded. At the base frequency of 60 Hz, constant torque operation in the range of 15 to 60 Hz was possible with conventional motors. The Premium Efficiency Motor allows constant torque operation in the range of 3 to 60 Hz. The wider range of use has improved convenience.

4. Loss-Reduction Technologies

4.1 Method of loss reduction

Figure 4 shows measures for reducing the loss of motors. Loss occurs in various parts of the motor, and in order to satisfy the efficiency regulation values, loss must be reduced everywhere it occurs. Loss can be classified into copper loss (stator copper loss and rotor copper loss), iron loss, mechanical loss and stray load loss, of which a reduction of copper loss and iron loss, accounting for approximately 50% and 30% of the total loss respectively, is particularly important.

(1) Reduction of copper loss

The stator copper loss, which is joule loss due to the electrical resistance and current in the motor windings, increases in proportion to the resistance when the current is constant. In order to reduce the resistance, revisions have been made including optimization of the number and shape of the stator slots to make the slot shape larger and increase the cross-sectional area of the conductors from those of conventional motors. As shown by equation (1), there is an inverse proportional relationship between the resistance and the conductor cross-sectional area and the resistance has been decreased by increasing the cross-sectional area of the conductors to reduce the loss.

$$R = \rho \frac{L}{S} \qquad (1)$$

R : Resistance (Ω)
ρ : Electrical resistivity (Ω·m)
L : Conductor length (m)
S : Conductor cross-sectional area (m^2)

The number and shape of the slots were studied by using the finite element method to choose the optimum ones in consideration of the balance between the magnetic flux distribution of the stator and rotor and the generated loss. In addition, increasing the conductor cross-sectional area by improving the filling factor of the windings to be inserted in the slots and reducing the conductor length by making the coil end shorter reduced the resistance of the windings and thus decreasing the stator copper loss.

The rotor copper loss generated in the rotor is generated by an induced current flowing to rotor bars such as aluminum or copper. As with for the stator copper

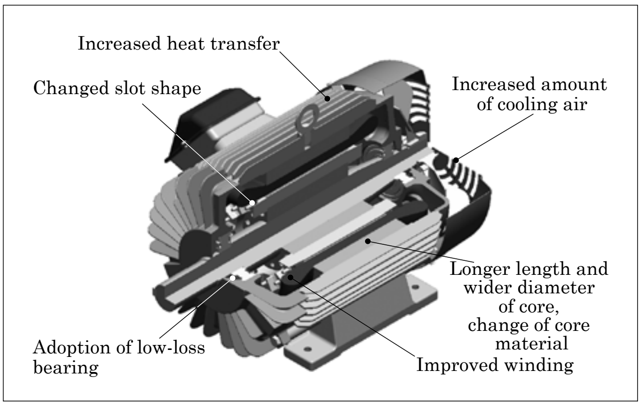

Fig.4 Measures for motor loss reduction

*3: 3 ratings: Refers to 200 V 50 Hz, 200 V 60 Hz and 220 V 60 Hz.
*4: 6 ratings: Refers to 200 V 50 Hz, 400 V 50 Hz, 200 V 60 Hz, 400 V 60 Hz, 220 V 60 Hz and 440 V 60 Hz. To achieve 6 ratings, a design in consideration of voltage and current increase based on 3 ratings is required.
*5: Frame: A series of motors often has a standardized size as a "frame" that collectively refers to 2 or 3 capacity specifications.
*6: IP: See "Supplemental explanation 4" on page 69.

loss, the slot shape has been optimized for reducing the resistance to decrease the rotor copper loss. Because the motor torque and current characteristics may greatly vary depending on the shape of the rotor slots, the shape has been optimized for each motor output and by number of poles in order to achieve the efficiency while satisfying the respective characteristics.

(2) Reduction of iron loss

Iron loss is the sum of the eddy current loss and hysteresis loss generated by the change in magnetic flux inside the iron core. In order to reduce the iron loss of the material itself, a low-loss electromagnetic steel sheet has been adopted.

Added stress on various part of the iron core strains the magnetic characteristics of the material, thus increasing the loss. Therefore, reducing the stress is also important. For example, the amount of interference between the core and the frame has been decreased in order to minimize core deformation and prevent loss from increasing. With conventional motors, the back of the core is welded in order to laminate on electromagnetic steel sheets, and this was assumed to cause an increase in the stress on the core due to welding, resulting in increased iron loss. Accordingly, the core lamination method has been changed to avoid welding and thereby prevent any increase in iron loss.

To reduce the iron loss, various parameters must be taken into account such as the number of slots of the stator and the rotor (slot combinations) and the shape and dimensions of slots. Increasing the size of slots to reduce the copper loss increases the magnetic flux density of the motor, which causes an increase in the iron loss, leading to decreased efficiency. This means that the iron loss must be reduced while considering the balance with the copper loss and the electrical characteristics, and we have used our original calculation program to decide on a rough specification and increased design accuracy by means of electromagnetic field analysis to achieve optimization.

This paragraph describes electromagnetic field analysis of the stator iron core (see Fig. 5). Figure 6 shows an example of the magnetic flux density distribution of the iron core. It represents the magnetic flux density at a certain point during rotation. Figure 7 shows an example of the iron loss density distribution of the iron core. It shows the average iron loss density observed as the voltage varies sinusoidally over one cycle.

In Fig. 6, the magnetic flux density was estimated to increase locally by increasing the size of the slots, which proved to be generally 1.4 to 1.6 T (green to yellow) and it was found that, even in the area with a high magnetic flux density, indicated by the circle in the figure, the magnetic flux density did not saturate but was about the same as that of conventional motors. Figure 7 shows that the iron loss does not increase in the area with high magnetic flux density in Fig. 6 and the slot shape was confirmed to be balanced between the copper loss and iron loss.

(3) Reduction of mechanical loss

The motor has a fan for cooling the housing and the windage loss generated by its rotation is included in the mechanical loss. Taking into account that the top runner motor features a lower loss than conventional motors and a decrease in the temperature rise resulting from heat generation, we carried out thermal design by using the thermal fluid network method in the design phase to compute the motor tempera-

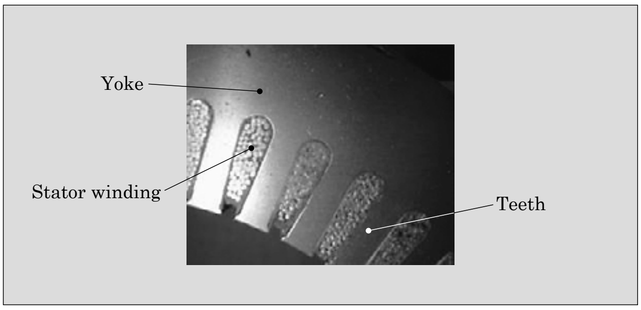

Fig.5 Cross section of stator iron core (part)

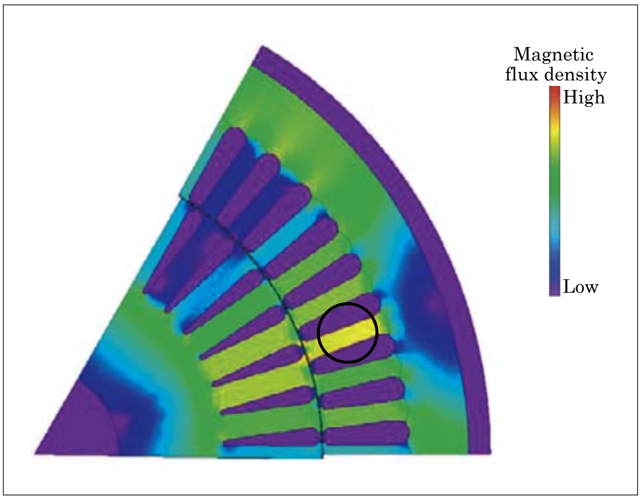

Fig.6 Example of magnetic flux density distribution of iron core

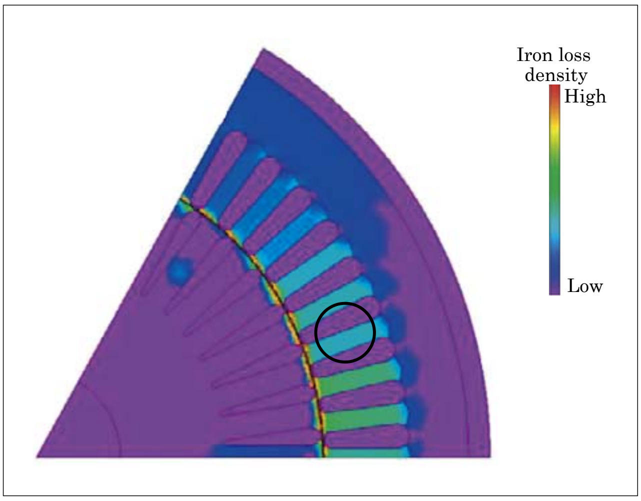

Fig.7 Example of iron loss density distribution of iron core

ture with high accuracy to minimize the windage loss caused by the cooling fan. The thermal fluid network method is a technique in which the wind speed is computed using fluid network calculations, and then the temperatures of various parts are computedusing thermal network calculations.

The loss generated in the motor bearing is also included in the mechanical loss, so we changed the bearing size and improved the grease used to further reduce the mechanical loss.

(4) Reduction of efficiency variation between products

The Top Runner Standards define 36 categories to represent the judgment on the achievement of regulation values and the efficiency value must be satisfied by the weighted average of each category. For this reason, it is also important to reduce efficiency variations between products, and this has been realized by applying strict processing accuracy and management during manufacturing.

4.2 Future issues with loss reduction

In the future, we must work on further loss reduction assuming that stricter efficiency regulation values will be enforced.

As described in Section 4.1, the loss generated in the motor can be classified into copper loss, iron loss, mechanical loss and stray load loss. These losses have trade-off relationships with each other and a significant decrease of one of them causes another to increase. Accordingly, all types of loss must be reduced while maintaining a good balance between them. To reduce loss and improve from IE1 to IE3, the loss must be reduced by 20 to 40%. In order to further reduce the loss to improve efficiency in the future, it is necessary to reduce stray load loss.

There are 2 major factors causing stray load loss:

(a) Eddy current loss generated in stator windings due to leakage magnetic flux in the stator slots
(b) Loss caused by harmonic magnetic flux in the air gaps

Stray load loss is difficult to compute with high accuracy and is generally considered as loss not included in copper loss, iron loss or mechanical loss. While the percentage of stray load loss is small enough to be negligible with types of motor having small outputs, the percentage is large with large output types, and it constitutes a factor for increased loss. In order to reduce stray load loss, the cause of loss generation must be identified and a technique allowing high-accuracy computation of the loss in the design phase must be adopted.

In addition, high-efficiency motors are inclined to have lower starting torque performance and current characteristics. With the "MLU/MLK Series," the slot shape has been optimized to achieve reduced loss and good starting characteristics at the same time, but establishing both will likely be harder as loss is decreased further. For further loss reduction, study of new low-loss core materials is necessary in conjunction with making changes to shapes and other considerations. Iron loss of the material is also increased by punching distortion generated when electromagnetic steel sheets are punched with a press, which makes it necessary to study how to eliminate the distortion.

5. Postscript

This paper has described the loss-reduction technologies of Fuji Electric's top runner motor "Premium Efficiency Motor." As efficiency regulations are enforced in major countries including Japan, Fuji Electric has been moving ahead with development in order to realize high-efficiency motors that satisfy the regulations.

In the future, motors will be required to save energy and power continuously in order to reduce greenhouse gases. We intend to keep working on development to further improve efficiency.

References

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