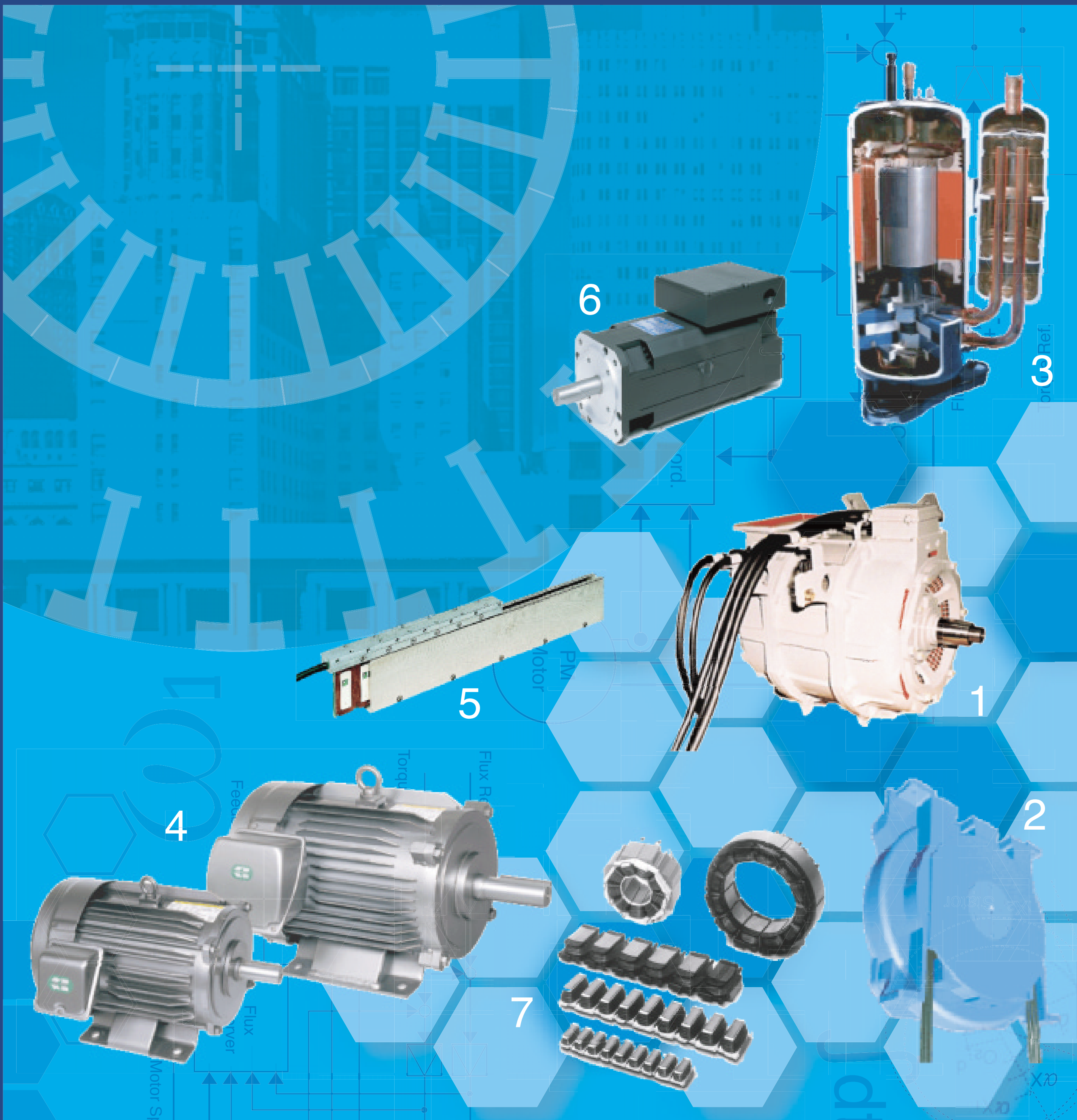
ISSN 1345-3041

VOL. 103/SEP. 2003

MITSUBISHI ELECTRIC ADVANCE

Motor Technologies for Industry and Daily Life Edition



MITSUBISHI ELECTRIC

Changes for the Better

A Quarterly Survey of New Products, Systems, and Technology
●Vol. 103/September 2003 Mitsubishi Electric **ADVANCE**

Motor Technologies for Industry and Daily Life Edition

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Cover Story

Motors support our affluent lifestyle. Mitsubishi Electric's motors serve in all sectors of industry: examples include the motors that power Japan's "bullet" trains (1), elevator motors that make high-rise buildings more pleasant and comfortable (2), high-efficiency motor for air-conditioners in our cars (3), motive power for our factories (4), and motors for factory automation that, by their high precision, support advances in information technology (5 and 6). Advances in the corporation's motor design and manufacturing technology (including the "Poki-poki" core shown in (7), and in control technology, have significant new contributions to make to quality of life in the 21st century.

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Mitsubishi Electric Advance is published on line quarterly (in March, June, September, and December) by Mitsubishi Electric Corporation.

Overview

How Diverse Technologies Contribute to New, Improved Motors.

*by Mahito Unno**

The electric motor has a history of 170 years, but increasingly stringent demands for environmental compatibility and market-based requirements for better performance are forcing the pace of motor evolution using revolutionary developments in a broad range of technologies from design through materials to manufacturing and control. Specific market requirements vary according to the type of motor, and include higher efficiencies, greater controllability, lower vibration and noise, higher reliability and smaller size. Mitsubishi Electric Corporation is tackling these diversified requirements by advancing a wide spectrum of technologies, including electrical design that takes into account upper harmonic frequencies, the revolutionary manufacturing technology we call the "*Poki-poki* core," and control technologies that minimize torque ripple. We also seek to combine these technologies synergistically, investigating at the very earliest conceptual stages the overall integration of factors in the design, manufacture, control, performance and cost of our motors.

The results of our development work are as diversified as the applications in which our motors are used, and include everything from machine room-less elevators that make high-rise buildings more pleasant places to live and work, to automobile power steering that contributes significantly to greater fuel economy. Many of our motor-product lineups are leaders in their class. The articles of this issue of *Advance* give some examples of our latest motor developments, and the technologies that made them possible. It is my earnest hope that these developments will prove to be of benefit to the reader, and that this will lead to further opportunities for cooperation in the future.

**Mahito Unno is with Nagoya Works.*

Elevator Traction-Machine Motors

By Takanori Komatsu and Akihiro Daikoku*

Elevators are more than just means of vertical transportation in buildings; they must fulfill a variety of other requirements in terms of comfort, energy consumption, space constraints, etc. Mitsubishi Electric Corporation has developed a slim traction machine using a joint-lapped core concentrated-winding motor, dispensing with the usual elevator machine room. This article describes the motor technology responsible for the elevator car's luxurious ride.

State-of-the-Art Traction Machines for Elevators

Elevators can be broadly categorized as either cable type or hydraulic type, depending on the drive principle employed. At present, the cable type is prevalent, in which the elevator car is raised and lowered by cables in the sheave of a traction machine. High-speed elevators, typically used in high-rise buildings, generally use gearless traction machines, where the motor and sheave are connected directly, enabling the passengers to experience a sense of luxury in the ride, free of vibrations and noise. On the other hand, the standard low-speed elevators typically used in apartments and office buildings generally use traction machines with gears between the motor and the sheave.

The corporation made advances in the energy efficiency of drive equipment in the 1980s and 1990s by improving the efficiency of reduction linkages and the creation of inverter-control methods. In the late 1990s, it was the first in the industry to apply gearless traction machines using permanent magnet synchronous motors to high-speed elevators. This simultaneously improved energy efficiency and reduced the size of the traction machines. This technology was extended to low-speed elevators in 1998, producing elevators that dispensed with the machine room. In such elevators, the traction machine is located in the hoist way itself, calling for gearless traction machines that are both compact and superior in terms of reduced noise.

As described above, the Mitsubishi Electric applies the gearless traction machines, using permanent magnet synchronous motors, to a broad range of typical elevators, including both low-speed and high-speed types.

Features and Key Technologies of Traction-Machine Motors

Features of the elevator traction-machine motors include a large torque for accelerating heavy elevator cars, and minimal torque ripple in order to provide a luxurious ride, in addition to having the high reliability critical to a functional component of building facilities. Motors for gearless traction machines require large torque at low rotary speeds. Moreover, in machine roomless elevators, where the traction machines are positioned in the hoist way itself, the compact form factor is especially critical, because it determines the layout.

REDUCED SIZE. The corporation uses concentrated-winding permanent-magnet synchronous motors, which are smaller than induction motors, and has achieved a small, thin motor through the application of proprietary joint-lapped core technology along with high-performance Ne-Fe-B rare-earth magnets and multipole design, and shown in Fig.1.

RELIABILITY. A critical factor in maintaining the reliability of permanent-magnet synchronous motors is their long-term resistance to demag-

Fig. 1 Slim traction machine (3.7kW, 93r/min)

Takanori Komatsu is with Inazawa Works and Akihiro Daikoku is with the Advanced Technology R&D Center.

netization. The temperature characteristics of permanent magnets are taken into consideration at the corporation, and the magnetic-circuit design and evaluation are performed taking into account the usage-temperature regime of the equipment to provide a design with adequate resistance to demagnetization.

RIDE. Because torque ripple influences the ride experienced by the passenger, the torque-ripple characteristics are important determinants of the quality of the elevator. On the other hand, because a smaller motor necessarily experiences relatively higher electric and magnetic loading, reducing the size of the motor tends to increase torque ripple. Detailed magnetic analyses are performed in pursuit of designs that suppress torque ripple arising from various causes.

The slim traction-machine motor technologies that provide passengers with a luxurious ride are as follows.

Design for Torque-Ripple Reduction

Generally, designs that reduce torque ripple in permanent-magnet synchronous motors reduce magnetic-drive resonance in the motor by optimizing the shapes of the permanent magnets.

They also investigate the coil arrangement (including the ratio of the numbers of poles and slots), and take advantage of skew, etc. In distributed winding motors, which are used in high-speed/high-capacity applications, torque-ripple reductions closely matching theoretical values have been archived by these design processes.

However, slim motors use a concentrated winding method, in which the motor is much thinner and the diameter is larger. The resulting effects of magnetic saturation and of manufacturing tolerances have prevented torque ripple from being reduced by the theoretical values. Torque ripple can, however, be reduced by taking magnetic saturation into account when designing the magnetic circuits, and analyzing the manufacturing tolerances and taking appropriate countermeasures.

1. Reducing the Impact of Magnetic Saturation

Since reducing the thickness of the motor inherently increases the electric loading on the concentrated-winding stators, this easily leads to magnetic saturation in the stator teeth when an electric current is applied. This tends to give higher torque ripple than with distributed-winding stators. However, the use of magnetic-field analysis to optimize the various parameters shown in Fig.2, and careful consideration of the

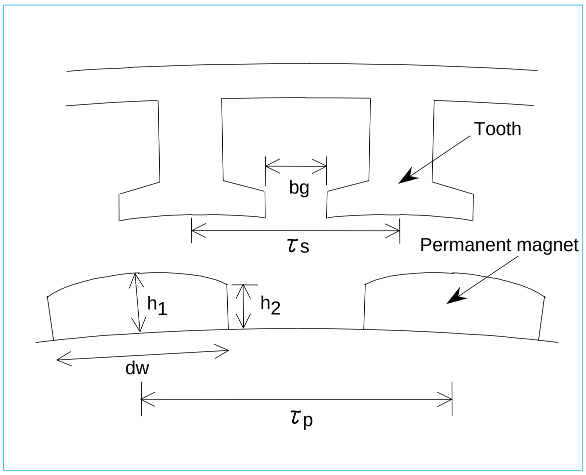

Fig. 2 Typical design parameters for concentrated-winding motors

shapes and dimensions of the stator teeth and the shapes of the permanent magnets, make it possible to combine high electric loading with low torque ripple. Fig.3 shows the effect on torque ripple of changes in the slot opening. Setting the slot opening *bg* and the tooth pitch *rs* to an appropriate ratio (0.25 in the example shown in

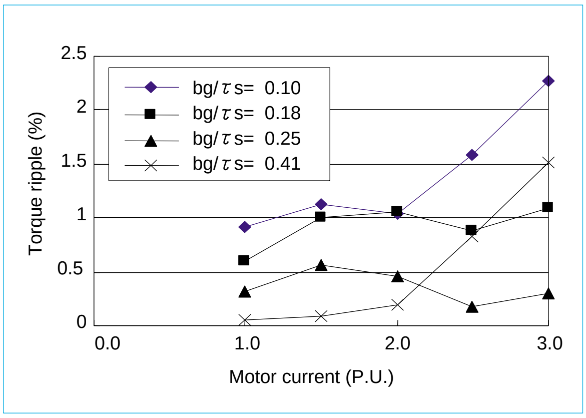

Fig. 3 Electric current-torque ripple characteristics (as a function of the slot opening)

the figure) alleviates magnetic saturation due to the leakage of magnetic flux at the tips of the teeth, reducing the torque ripple over the entire driving range.

2. Analysis and Countermeasures Regarding the Impact of Manufacturing Tolerances

The manufacture of motors will always be subject to manufacturing tolerances that deviate from the ideal design values. This may cause increased torque ripple and variability.

After analyzing manufacturing tolerances for the factors that cause torque ripple, the corporation used magnetic-field analysis to investigate the relationship between torque ripple and manufacturing error. Fig.4 shows an example of this, where the relationship between warp in the stator inner diameter and torque ripple was investigated. While a variety of different modes of warp are possible, individual investigations using magnetic-field analysis established that only certain modes of warping actually contributed to torque ripple. Given this, the relationship between torque ripple and the amount of warping in these specific modes of warping, was investigated at different load currents as shown in Fig. 4(b). The horizontal axis is specified using the *d* and *e* shown in Fig.4(a). The figure shows that the amount of ripple is proportional to the amount of warping, and that, given a specific amount of warping, the torque ripple is essentially proportional to the load current. These results indicate that reductions in torque ripple require the utmost efforts to reduce this warping. The corporation has implemented warping control measures in the manufacturing process base on the analyses described above, making it possible to achieve stable quality levels.

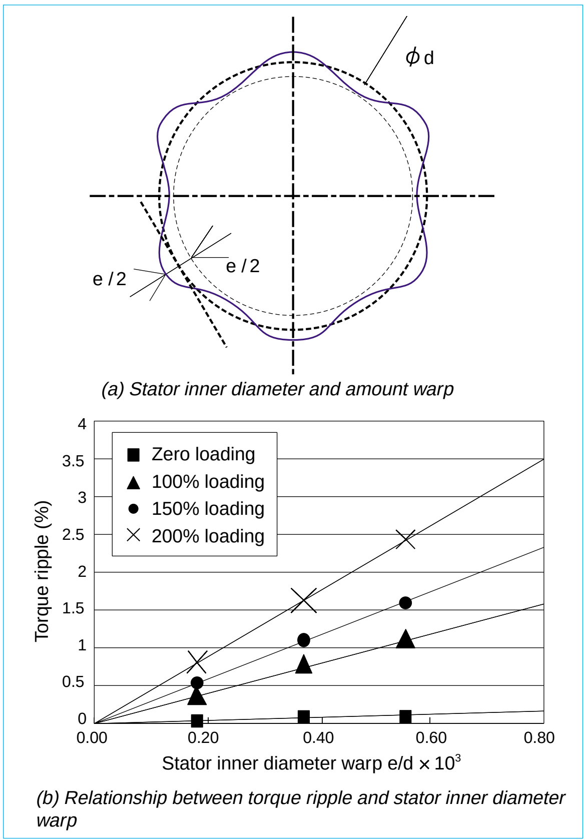

Fig. 4 Effect of stator warp on torque ripple

Mitsubishi Electric has been extending the benefits of its pioneering developments in traction-machine motors to an ever-wider range of elevators, and is developing theoretical and practical techniques to optimize the quality of ride for users. By identifying the critical factors affecting ride quality, both in design and in practical manufacturing, effective and efficient measures will continue to be devised to maintain the corporation's current lead in this important area of vertical transportation. ❑

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High-Efficiency Motors for Air-Conditioner Compressors

*By Hitoshi Kawaguchi and Tomoaki Oikawa**

Although induction motors are used as the source of motive power in a variety of equipment used in the home because of their durability, quietness, and low cost, they are increasingly being replaced by high-efficiency brushless DC motors due to increased environmental concerns. In particular, because the power consumed by air conditioners and refrigerators accounts for some 40 percent of household power consumption, brushless DC motors are being used in both of these appliances.

This article describes the efficiency-enhancing technologies in brushless DC motors for room air-conditioner compressors developed and implemented by Mitsubishi Electric Corporation.

Brushless DC Motors for Room Air-Conditioner Compressors

Beginning in the air-conditioner season of 2001, the corporation completely revised the structure of the 4-pole distributed-winding interior permanent magnet (IPM) motor that had been used until then, successfully improving efficiency through moving to a 6-pole concentrated-winding IPM motor with a jointed separated core structure.

Motor Structures for Compressors

Fig. 1 shows the cross-section of the structure for a room air-conditioner compressor. In the motor for the compressor, the stator is secured (though a thermal-shrinking process) to the inside of the compressor housing, and the rotor and the compressor element are linked by a shaft that transmits the driving force to the rotary compressor section.

Fig. 2 shows lateral cross-sectional diagrams of the new motor for compressors and conventional motors, and Fig. 3 shows the side views. Fig. 3a is a conventional motor, with a structure in which a 3-phase 4-pole 24-slot distributed winding stator is combined with an IPM rotor. Fig. 3b is the new motor, with a structure that combines a 3-phase 6-pole 9-slot concentrated winding stator with an IPM rotor. The stator uses a proprietary jointed-separated core (i.e., a joint-lapped core) invented by the corporation, and the rotor uses an IPM structure with a surface layout in which six double arc-shaped magnets are embedded.

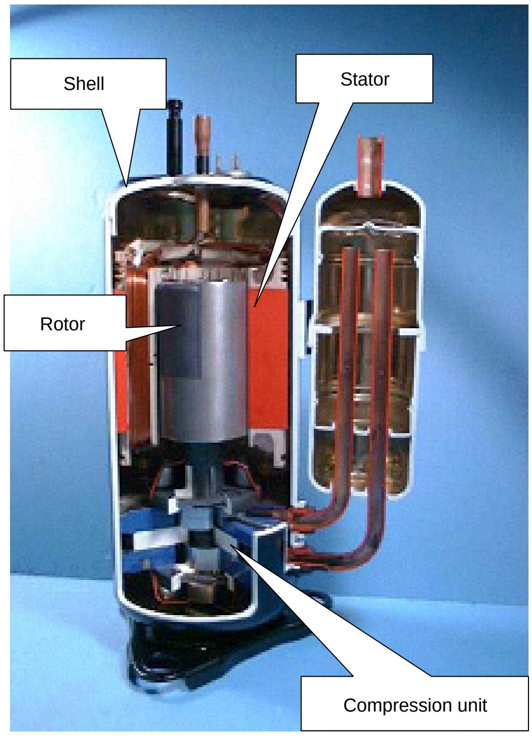

Fig. 1 Cross section of compressor

A Shift to Concentrated Windings Using Jointed-Separated Cores

The new motor dramatically decreases the resistance in the coils through the selection of the concentrated winding approach.

As shown in Fig.2b, concentrated windings, in which the winding is placed directly on each tooth, can reduce the length of the coil windings below that of the distributed winding approach. This reduction in length produces the effect of reducing the copper loss by 22 percent. Furthermore, as shown in Fig. 3a and 3b, the height of the coil end was about halved, also effective in reducing the size of the motor.

In order to fully exploit the benefits of the concentrated windings, a jointed-separated core was used for the first time in a compressor motor. This made it possible to produce perfectly aligned windings, stacked up like drum cans, producing a coil space factor of 95 percent. Fig. 4 shows the

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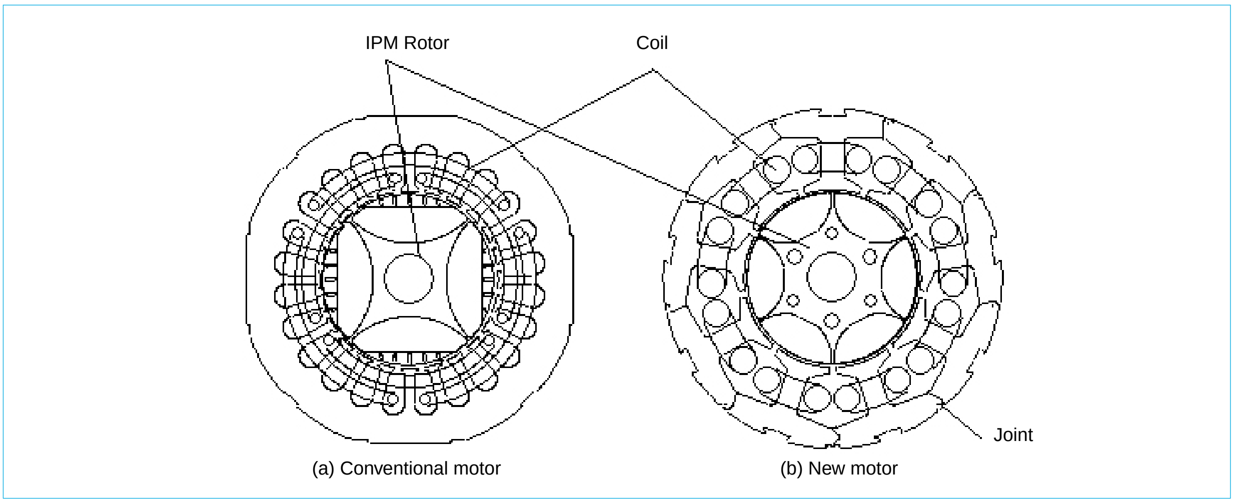

Fig. 2 Cross section of motor

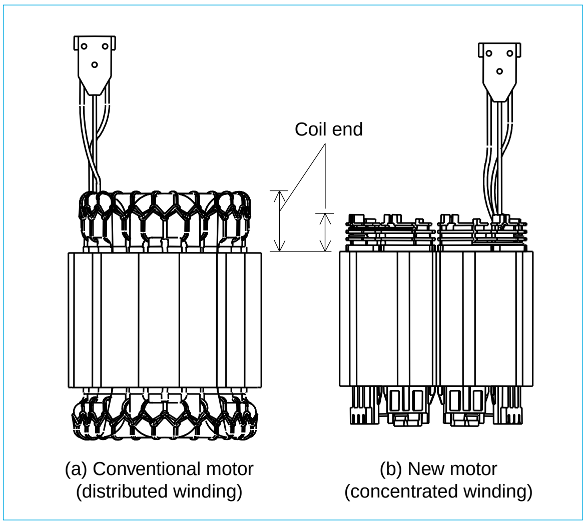

Fig. 3 Side vew of motor

relationship between the coil space factors and the efficiencies achieved by motors at Mitsubishi Electric. The best coil space factor achievable with a conventional one-piece core for the stator was

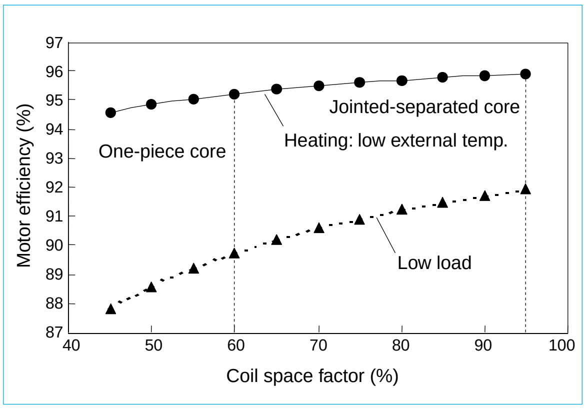

Fig. 4 Relationship between the coil space factor and the motor efficiency

no more than 50 to 60 percent. Conventional motors' copper loss was cut 28 percent by increasing the cross-sectional area of the slots and increasing the coil space factor. When this reduction in copper loss is combined with the reduction in length mentioned above, the copper loss is cut to half that of the conventional motor.

The IPM Structure and the Change to Six Poles

Generally, concentrated windings have tended to suffer from increased iron loss. To reduce iron loss, a change was made from a 4-pole to a 6-pole structure, and the rotor structure was reworked. Moving to six poles from four poles reduced the deviation in the magnetic flux-density distribution in the core, and while the electrical frequency was increased, the iron loss was successfully reduced by 11 percent from the 4-pole concentrated-winding motor under rated conditions (3,180rpm at 1.63N-m). Furthermore, a surface-layout IPM rotor structure was used in which permanent magnets are positioned near to the outer peripheral part of the rotor and electromagnetic steel plate with even lower iron losses was adopted. In addition, the shape of the permanent magnets in the layout on the rotor surface was changed from D-shaped to a double-arc shape in order to increase the thickness of the magnets, thereby increasing the magnetic force. For the orientation of the magnets, a reverse-radial orientation was used to direct the central focus of the orientation towards the outer diameter. Magnetic-field analysis was used to perform optimization so as to maximize the torque constant. Switching to six poles and reworking the rotor structure made it possible to reduce the iron loss by about 20 to 30%, depending on the load conditions.

New Motor Efficiency Performance
Fig.5 compares the efficiency for the output of a 6-pole concentrated-winding jointed-separated core IPM motor, a 4-pole distributed-winding IPM (GD4 rotor) motor, and a 4-pole concentrated-winding one-piece core IPM (GD4 rotor) motor. Motor efficiency was measured at the compressor load points for motor output powers between 200W and 1.2kW. The load points of the compressors are classified broadly into low-power conditions, rated conditions and high-power conditions, and the speed and torques are both adjusted simultaneously for each of these conditions. The results indicate that the efficiency of the 6-pole concentrated-winding jointed-separated core motor was superior throughout the entire range, and

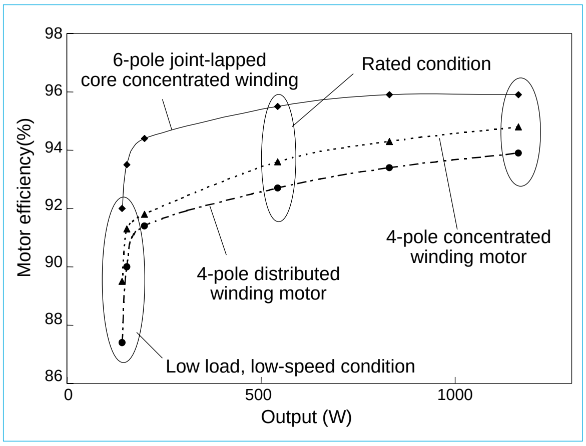

Fig. 5 Comparison of motor efficiencies

there was a particularly dramatic improvement in the efficiency under low-power conditions. The results also indicated efficiency increases of 5% under low-power conditions, 3% under rated conditions, and 2% under high-power conditions. Fig 6 compares the losses in the respective motors when operating under rated conditions. When compared with the 4-pole distributed-winding IPM motor the concentrated-winding IPM motor had a

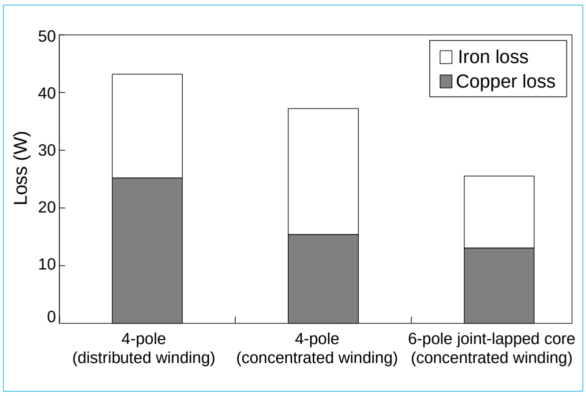

Fig. 6 Comparison of motor losses

40% reduction in copper loss, the iron loss increased by 20 percent, and the improvement in efficiency in the motor was no more than about 1%. In contrast, in the 6-core concentrated-winding jointed-core IPM motor, both the copper loss and the iron loss were reduced, successfully producing dramatic reductions in the copper loss (50%) and the iron loss (20%).

Use of the high-efficiency brushless DC motor is effective in energy conservation and size reductions in equipment for the home. The brushless DC motor, as reported for use in compressors, has produced a dramatic leap in efficiency over conventional motors. However, rapid advances in performance due to joint-lapped cores and new magnetic materials, including electromagnetic steel plate, are being proposed by the corporation, which is planning in this way to continue the development of motors with even higher efficiency levels. ❑

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Motors for Electric Power Steering

*by Toshinori Tanaka**

The use of electric power steering (abbreviated "EPS," below), in which the motor is driven only when the steering wheel is turned, greatly improves fuel performance over conventional hydraulic power steering. EPS is therefore being increasingly adopted. The range of vehicles in which EPS is used is also expanding to include those with larger engines, and so the power required for EPS motors is increasing. This article will describe the development of motors for EPS systems fulfilling these requirements.

Market Requirements and the Response by Mitsubishi Electric Corporation

Increasing the power of the EPS motors leads to larger motors, causing more noise, torque ripple, frictional loss torque, higher moments of inertia, etc. This negatively impacts the experience of the driver and degrades the way the vehicle maneuvers. The corporation was quick to address these problems, the first manufacturer to do so. Taking advantage of proprietary electromagnetic-field analysis techniques, the corporation developed high-powered brush-type motors with low noise and low vibration, even at high loading currents. The "New Motor Series," as they are known, can be used in cars up to the two-liter engine class. A brushless motor has also been developed to handle even higher output-power requirements and this will also be described.

Requirements for EPS Motors and the Corporation's Response

COMPARISON OF SYSTEM REQUIREMENTS. The requirements for EPS motors vary depending on the type of EPS system, or in other words, with the location at which the motor is installed. In general, there are three types of EPS systems, as shown in Fig.1 (a) column-axis EPS, where the motor is mounted on the column axis, (b) pinion-axis EPS, where the motor is mounted on the pinion axis,(c) the rack-axis EPS, where the motor is mounted on the rack axis. Table 1 shows a comparison of the characteristics required of these motors, depending on the type of system.

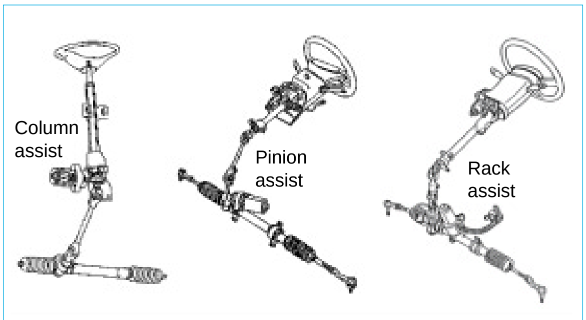

Fig. 1 Structures of various power-steering systems

Issues Affecting Increases in EPS Power

The motor is mounted near the driver in column-axis EPS systems, and vibrations from around the dashboard are transmitted directly to the ears and hands of the driver through the steering-column system. This means that motor noise, torque ripple, etc., are very likely to cause driver dissatisfaction.

Issues Affecting Motors with Brushes, and the Corporation's Response

REDUCING ELECTROMAGNETIC NOISE. Detailed electromagnetic analyses, taking into account brush coverings and commutation switching motors, and taking into account also the changes in the electric current in the commutating zone, reveal that the vibrational forces in the radial direction of the rotors depend on the electromagnetic design specifications. These include the winding method, the number of slots, and the number of brushes. The electromagnetic noise of the motor was reduced substantially through innovations in the windings and by selecting the optimal specifications to minimize vibrations in the radial direction. Fig 2 shows an example of a mesh-partitioned diagram using the finite-element method used in the analysis.

These results made it possible to provide a brush-type motor up to the 75A, 500W class, in which noise is essentially independent of electronic current. This type of motor was dubbed the "New"(Noise Erase Winding) motor, and a series of motors with rated currents ranging from 45A to 75A has been established.

Reducing Mechanical Noise

A motor combining the "New" windings and

**Toshinori Tanaka is with Himeji Works*

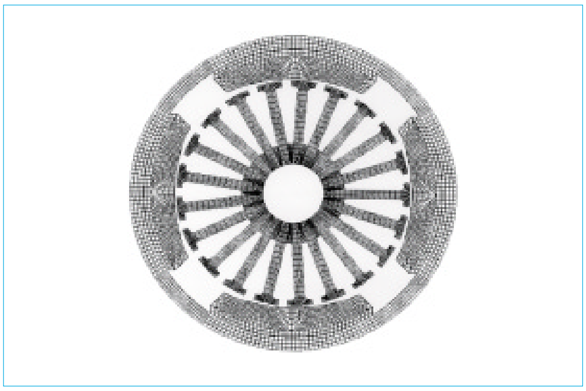

Fig. 2 Mesh-partitioning diagram (critical parts only)

Table 1 Requirements for the Motor for the Various Systems

System	Column	Pinion	Rack
Maneuverability			
Noise/vibration	Major	Intermediate	Minor
Torque ripple	Intermediate	Intermediate	Intermediate
Cogging torque	Minor	Minor	Minor
Frictional loss torque	Intermediate	Intermediate	Intermediate
Moment of inertia	Intermediate	Intermediate	Intermediate
Environment of use			
Temperature (thermal durability)	Minor	Major	Major
Water resistance	Minor	Major	Major
Power (required output)			
Power level	Minor	Intermediate	Major

an elastic support structure was termed the "Super silent motor," and was designed specifically for column axis EPS systems.

Effects of Motor Noise Reduction

Fig. 3 and Fig. 4 show the effects of the noise reduction strategies described above. Fig. 3 shows the relationship between the rated currents of the motor and the overall noise pressure level for each motor series. Fig. 4 shows the effects, comparing the sizes of the noise components, broken down by noise frequencies, for each motor series.

Development Targets for Brushless Motors

Although the series now runs up to the 75A, 500W-class for brush-type motors, when EPS is to be used in vehicles with still larger engines, more powerful motors will be required. The use of brush-type motors for these higher power motors (in excess of 500W) would require the motors to be unacceptably large, and with moments of inertia, torque losses, etc., unsuitable for motors in EPS systems. The corporation responded to market requirements by developing a brushless motor, combining the low torque ripple, low cogging torque, and low noise characteristics required of an EPS motor, while achieving the compact size, low moment of inertia, and low frictional loss torque required of a high-power motor.

Fig.5 shows the corporation's plans for the various types of motors and their corresponding power levels.

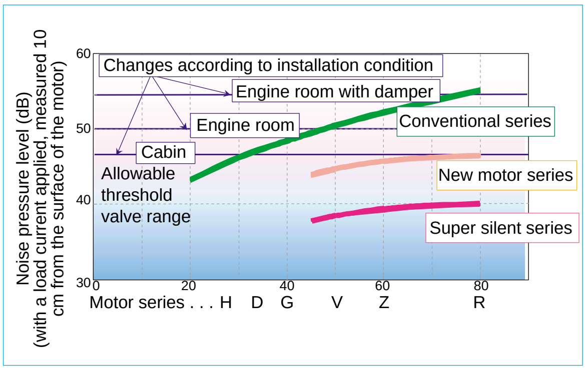

Fig 3 Rated currents and noise pressure levels of various motors

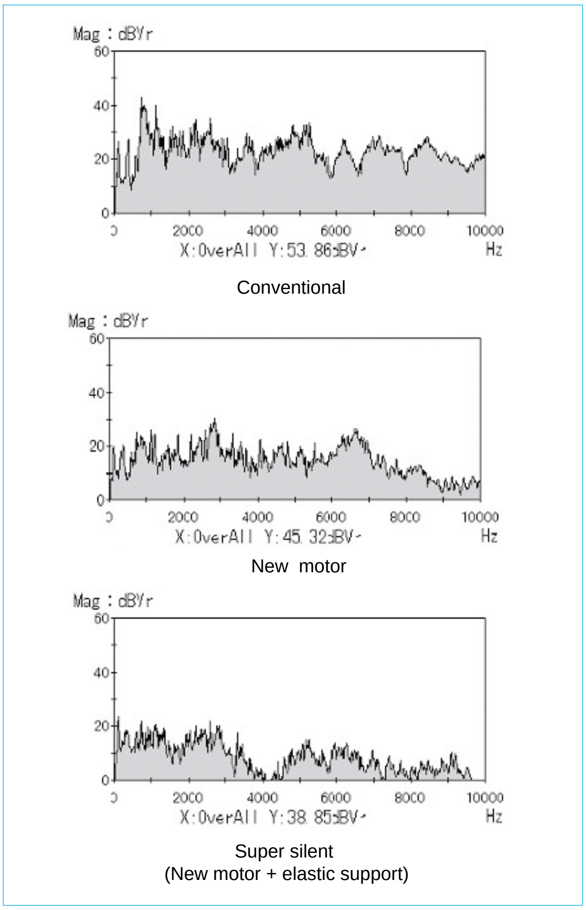

Fig. 4 Effects of noise reduction (frequency analysis)

Elemental Technologies for the Brushless Motors

The corporation has developed high-powered EPS motors using the elemental technologies described below:

1. Low moment of inertia: The motor and the rotor were both reduced in size through the use of a field-magnet rotor and a high-energy magnetic material.

2. Low loss torque: In addition to reducing mechanical torque losses by eliminating the springs applying pressure to the brushes, the magnetic iron losses were reduced as well.

3. Low torque ripple: Brushless motors can be driven by the classical square-wave method or the sine-wave method (where the later provides more precise control). Here, the design was optimized using the sine-wave method and a skewed air-gap and selected magnetic circuit. Table 2 compares the square-wave method and the sine-wave method. Overall, the sine-wave method is evidently better suited to the EPS system.

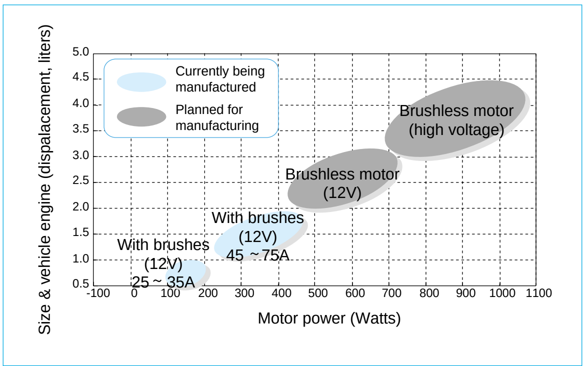

Fig. 5 Motor power in corresponding motors

4. Low cogging torque: As described above, the design was optimized using a skewed air-gap and selected magnetic circuit, while at the same time providing a low torque ripple.

5. Reduced noise: With no sliding brushes, the noise produced by friction with them and the noise produced by commutation were eliminated, reducing dramatically the sources of noise.

Other Features

1. Use of linear-bridged (snap) cores: By extending the application of this type of core, which is used broadly in the corporation's other brushless motors, to brushless motors for EPS, the motors could be made smaller (thanks to the increased stator-coil-space factor).

2. Use of ring magnets: Ring magnets, unlike segment magnets, make it possible to have a skewed magnetic field. The ring magnets not only contribute to the reduction of the cogging torque as described above but also improve the anti-overrun characteristics by simplifying the rotor structure.

Table 2 Comparison of the Square-Wave Method and the Sine-Wave Method

	Square wave	Sine wave
	Distributed winding	Concentrator winding
Maneuvering (feel and performance)		
Cogging torque countermeasures		○
Torque ripple when conducting		○
Noise + vibration		○
Weakening field	△	○
Cost		
Magnets	○	
Sensors		△
Windings		○
Control circuits	△	
Size		
Small/light		○
Overall evaluation		○

Note: *Triangles indicate advantages, circles indicate even stronger advantages.*

In 1988, Mitsubishi Electric was the first in the world to bring EPS motors/ECUs to mass production. Ever since, the corporation has continued to fulfill the needs of the market for increased power accompanying the broadening range of vehicles in which EPS has been adopted. As a result of its continuous development and marketing of a rapid succession of high-powered motors suitable for use in EPS systems, it has been able to exploit steadily increasing scale benefits in manufacturing. At present, the cumulative manufacturing volume for motors and ECUs is each in excess of 15 million units, a number that is expected to increase rapidly in the future.

To Mitsubishi Electric, this mass-production history, spanning 15 years, with over 15 million units produced is a valuable asset. From the perspective of being in the business of providing solutions, the corporation, as the pioneer for EPS motors and ECUs, plans to continue to rapidly developed and commercialize a succession of EPS motors/ECUs answering the needs of the market, thereby contributing to the increased use of EPS systems. ❑

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High-Efficiency Motors for Rail Traction Engines

by Hideo Terasawa*

Given the major role they play in heavy transportation, railroads are an indispensable part of our lives. With this mode of transportation being reassessed from the perspective of global environmental protection, demand in the electric railway market is as strong as ever. These trains are powered by electric motors; this article will describe electric motors for railway use from the perspective of improved efficiency and reduced maintenance.

Traction Motors for Railcars

Under the railcar body there is the running device known as the "bogie" and the traction motor is installed within the bogie frame. The electrical power supplied is converted into mechanical power (torque), and the railcar is propelled by the adhesion between wheels and rails. Since the traction motor is mounted, with the gear unit and coupling, in the space available within the bogie frame, smaller motors that maintain high power outputs are needed.

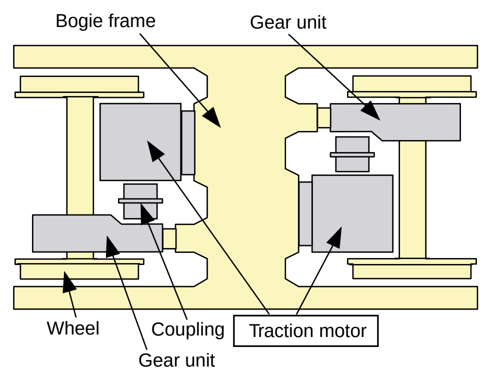

Fig. 1 Layout of the traction motor in the bogie

Shifting Customer Needs and Traction Motors

Although rheostatic control has been used for many years, a variety of customer needs has led to the rise of auxiliary excited-field control, armature-chopper control, field-chopper control, and four-quadrant chopper control. All of these are DC motor systems, and there is a pervasive underlying need to eliminate commutators. The development of power-electronics technologies in the 1980s led to the appearance of inverter trains driven by induction motors, which rapidly became popular. The needs of the railroads in terms of cost reductions contributed to the switch to the use of induction-type traction motors.

Diversification of Customer Needs

Improved railcar performance and high-power outputs taking advantage of improved adhesion performance allowed reduced initial investment through a reduction in the number of traction motors used. Improvements in regeneration performance also increased the amount of regenerated power, essentially decreasing the amount of power consumption.

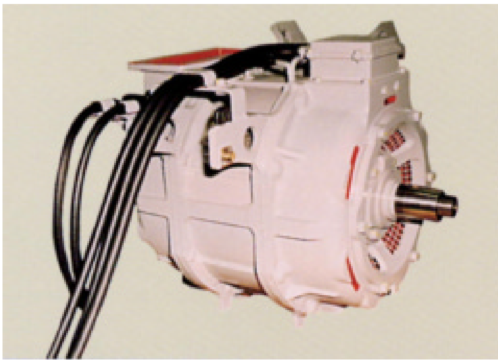

Fig. 2 Induction-type traction motors for Shinkansen trains

Without the need for commutators and brushes it became possible to greatly reduce the size and weight compared with the previously used DC traction motors. The key factor in the decision to use this type of motor in the Japanese Shinkansen train was the great reduction in the weight of the motor, making it possible to maintain stability at high speeds. When compared to the DC traction motors used for the Series 100 in the Tokaido/Sanyo Shinkansen trains, the induction-type traction motors used for Series 300 were approximately 63% smaller in terms of mass per kilowatt, despite the fact that the actual output powers were higher.

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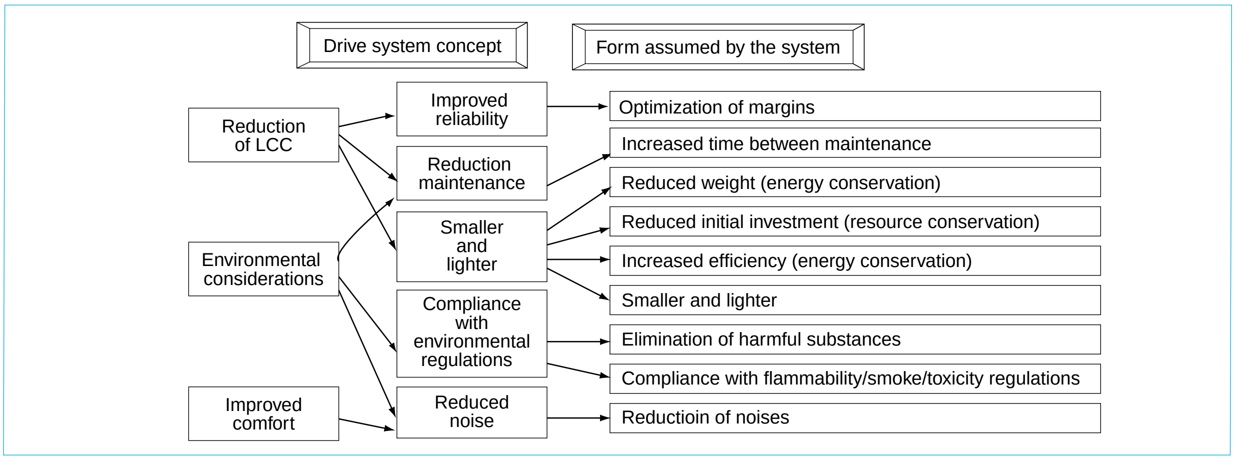

Fig. 3 Traction-motor design concepts

A reduction in maintenance work is the greatest benefit from using induction-type traction motors. According to a user survey, both labor and costs were reduced to less than 10% of those for DC traction motors. The majority of maintenance activities have to do with the bearings, and this maintenance was reduced through the use of optimal bearings and long-life grease in order to increase the length of time between overhauls.

There has been a change in attitude towards railcars. From being seen as just a means of transportation they are coming to be seen as an extended living space. This has increased the need for quiet operation. The noise in the traction motors includes the magnetorestrictive noise associated with the high-frequency components of the inverter currents, and the sporadic flapping sound from collisions in the coooling ventilation. Reductions to these noises require improvements in the inverter output waveforms (to reduce magnetorestriction) and the design of longer gaps, smoothness, and reduced airflow (to reduce the flapping sound).

Diversification of Customer Needs, and Future Approaches to Traction Motors

DESIGN CONCEPTS IN TRACTION MOTORS. There is a shift in customer needs when it comes to traction motors, and so the design concept is now as shown in Fig. 3, based on these needs.

REDUCED LIFE CYCLE COST (LCC). Because the customers perform maintenance on the traction motors for the railcars, the motor design must reduce the maintenance costs. Customers are demanding that reliability data such as MTBF and MDBF be applied to scheduled maintenance, and the design must provide high reliability levels, with appropriate margins.

Because the work involved in maintaining induction-type traction motors mostly involves the bearings, the need to increase the interval between maintenance makes it necessary to reduce the operating temperatures within the bearings. The design must also reduce temperature rises in rotors, e.g., by the use of low-resistance materials.Furthermore, in order to eliminate dust accumulation within the traction motors either a forced-draft fan (centrifugal separation) or an enclosed-type motor must be used. A structure that makes it possible to reduce the temperature of the bearings in enclosed-type motors has yet to be developed, and work is needed on the permanent-magnet synchronous motor and the reluctance motor.

Environmental Considerations

Increased efficiency in traction motors implies a reduction in electrical power consumption. This, as well as being effective in energy and resource conservation, will also be increasingly important in the future as a means of reducing the size of the traction motors themselves. The use of low-resistance materials in the rotor conductors is useful in increasing efficiency, and permanent-magnet type synchronous electric motors and reluctance motors are also useful.

It is essential to investigate and use structures that reduce high-frequency iron loss, based on analytical techniques. Furthermore, the use of toxic materials is regulated, and thus it is important to encourage the use of materials that do not contain specific toxic chemical materials, and also necessary to use materials that are in compliance with regulations for flammability, smoke emission and toxicity to ensure fire safety.

Improved Comfort

In order to ensure that railcars are comfortable moving spaces, noise must be reduced below past levels. It is useful to use a silencer, where sound-absorbing material is attached to the inner surfaces of the silencer. Although this is very effective in reducing noise, it also hinders ventilation, and calls for in-depth studies of cooling performance. Furthermore, in order to reduce the amount of noise inside the railcar, it will be necessary to damp the propagation of oscillations through the entire mechanical system, including the railcar body and the bogie, in order to reduce solid-phase propagated noise resulting from the transmission of vibrations.

Advances in induction-type traction motors are based on the needs of the customers. Mitsubishi Electric is well able to respond to the current needs of users, and is committed to continuing to do so in the future, where there is still much room for progress. ❑

References:

[1] Yokonishi, et al.: Reduced weight in the 300-series Shinkansen train electric motors. National conference of the Institute of Electrical Engineers of Japan, No. 1082, (1993-4)

[2] Iida, et al.; VVVF Inverter Control Railcar - 1-, Railroad Cars and Technologies, Vo. 3-12, No. 29 (1997-12)

High-Efficiency Industrial Motors

*by Hiromitsu Tatsumi and Hitoshi Yoshino**

Since the operating principle for induction motors was discovered in the 19th century, induction motors have been the principal source of motive power in industry, and have undergone continual refinement, becoming smaller, lighter, and better in many ways, with higher performance. However, the requirements for improved efficiency in motors have become even more stringent in recent years, given accelerating movements in energy conservation in order to protect the environment (including the avoidance of global warming) and concerns regarding the depletion of petrochemical energy resources.

Mitsubishi Electric Corporation has developed a series of high-efficiency motors fulfilling the efficiency requirements of both the JIS standards in Japan and the Energy Policy Act of 1992 in the United States, and was the first Japanese manufacturer to earn a conformance certificate number from the United States Department of Energy. This article discusses trends in three-phase motors and describes the high-efficiency motors at the corporation and technologies used to achieve these efficiencies.

Smaller and Lighter

Advances in technologies for design, cooling, materials, and manufacturing have enabled the production of smaller and lighter three-phase motors. Trends in the reductions in size and weight of these motors are shown in Fig.1. They are particularly linked to advances in insulating materials and it is evident from the figure that changes in the class of thermal durability have been accompanied by increases in power for motors of the same size.

As shown in Fig.1, the output power of a typical open-type 250-frame four-pole motor has increased about sevenfold, from 25 horsepower (18.5 kW) to 175 horsepower (132kW). Comparing motors with identical output powers, the volume and weight has been reduced by about 75%.

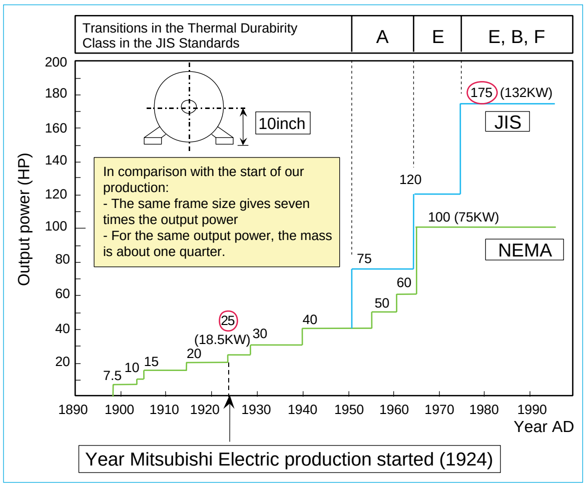

Fig. 1 The history of miniaturization (power capacity of 250 frame/NEMA 404 frame)

Regulations and Standards

Energy conservation policies have been enacted globally in recent years, including measures against global warming (i.e., reductions in CO_2 emissions). In Japan , the "Law for Rational Use of Energy " has been enacted, and new policies by the Japanese Ministry of Economy, Trade and Industry have resulted in tighter regulations in specific industries targeting stricter control of energy conservation and dramatically increasing the requirements for high-efficiency motors. This is because electric motors account for an estimated 70% of the electricity consumed in factories, so more efficient electric motors will dramatically reduce overall energy consumption.

In the United States, which is aggressively addressing energy conservation, the Energy Policy Act of 1992 mandates the use of high-efficiency motors, not only putting restrictions on the sale and use of motors other than high-efficiency motors (with a few exceptions), but also requiring that a compliance certification number be displayed on all eligible motors. Japanese Industrial Standard JIS C4212 came into effect in July 2000, establishing standards for high-efficiency motors within Japan.

Super Line Eco Series

To respond to these trends in regulations and standards for high-efficiency motors, the corporation has introduced a line of high-efficiency

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motors, the “Super Line Eco Series”, shown in Fig.2, that fulfill the efficiency criteria in both the JIS standards and the Energy Policy Act of 1992. These will be described below.

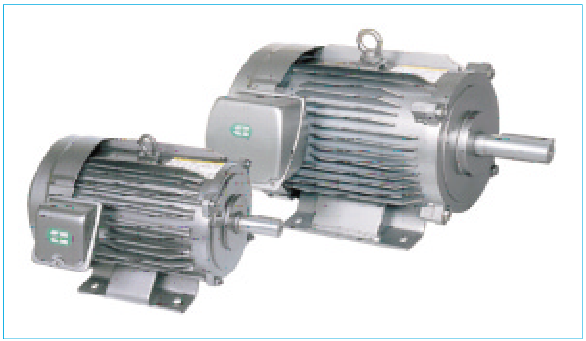

Fig. 2 Examples of the Super Line Eco series (totally enclosed, fan-cooled, 02.~55kW 2~6P)

Table 1 Features of the Super Line Eco Series

(1) Fulfills both the Japanese JIS criteria and the American EPAct criteria - Best-in-industry class high-efficiency/low-energy motors. - Received the “Directors Award for Superior Energy Equipment” from the Japan Machinery Federation in 1999. - Received conformance certificate no.CC0012A from the US Dept. of Energy, the first such Japanese company.
(2) A 1:10 constant torque linked drive is enabled through advanced vector control operation using the Mitsubishi Electric Corporation inverter FR-A500.
(3) The weather resistant standard specifications are able to handle 100% humidity (non-condensing), operation in the tropics, and a range of ambient temperatures from -30 to 40°C. A long-term maintenance-free bearing is used. (Comparison to other companies: Calculated life expectancy of the bearing grease more than doubled, with approximately four times the anti-creep performance.)
(4) On the average, 3dB(A) quieter than the corporation’s standard motors.

FEATURES AND EFFICIENCY STANDARDS. The features of the Super Line Eco Series are shown in Table 1. Table 2 provides a comparison of the efficiency criteria for four-pole high-efficiency motors in the JIS standards and in the Energy Policy Act of 1992, and although their voltages are different, the efficiency criteria values at 60Hz are essentially identical. The Super Line Eco Series fulfills both of these criteria in its standard specifications.

EFFICIENCY-ENHANCING TECHNOLOGIES. Energy losses in three-phase motors can be categorized primarily as primary-copper losses, secondary-copper losses, iron losses, mechanical losses, and stray-flux losses. High-efficiency motors must have totals for these losses that are 20 to 30% less than standard motors. As shown in Table 3, the technologies used in the Super Line Eco Series have succeeded in reducing these losses and increasing efficiency. The use of electrical design that takes advantage of the effects of magnetic-field analysis (taking the magnetic permeability of the steel frame into account) has succeeded in further increasing the efficiency of conventional high-efficiency motors, with identical or smaller stator sizes.

Issues in High-Efficiency Motors

Because high-efficiency motors are 20 to 30% more expensive than conventional motors, they have so far only achieved a market penetration of a few percent in Japan. Consequently, one issue facing these motors today is the need to develop low-cost products while further increasing efficiency.

REDUCED COPPER LOSSES. In order to reduce primary-copper losses further, it will be necessary to develop winding technologies that further increase the stator-slot coil-occupancy rate, further shortening the so-called “coil ends”, i.e., the parts of the coils that extend beyond the coil slots. Although many new winding technologies have been developed and major advances have been made in high-density winding methods, there is still a need to develop and implement new coil-fabrication-and-insertion technologies for distributed coils that can be used in three-

Table 2 A Comparison of Efficiencies (totally enclosed, fan-cooled, 4P)

Efficiency criterion		US EP Act	JIS C 4212	
Voltage		230V	200V	220V
Frequency		60Hz	50Hz	60Hz
Output power (kW)	0.2	-	72.0	74.0
	0.4	-	76.0	78.0
	0.75	82.5	80.5	82.5
	1.5	84.0	82.5	84.0
	2.2	87.5	85.5	87.0
	3.7	87.5	86.0	87.5
	5.5	89.5	88.5	89.5
	7.5	89.5	88.5	89.5
	11	91.0	90.2	91.0
	15	91.0	90.6	91.0
	18.5	92.4	91.7	92.4
	22	92.4	91.7	92.4
	30	93.0	92.4	93.0
	37	93.0	92.4	93.0
	45	93.6	92.7	93.0
	55	94.1	93.3	93.6
Efficiency test method		IEEE Std 112 method B (actual load)	JIS C 4212 Actual load method, using brake or dynamometer.	

Table 3 Technologies for Reducing Losses

Type of loss		Loss reduction technology
Primary and secondary copper loss	I^2R loss occur due to the electrical current in the primary (the stators) in the secondary (the rotors) where I is a current and R is the Resistance	The key point is to reduce the resistance in the primary and the secondary to reduce the copper loss, reducing the conductor resistance as follows: Reducing the number of coils and increasing the cross-sectional area of the coils Increasing the cross-sectional area of the secondary conductor through optimizing the rotor slot configuration Increasing the end ring cross-sectional area (Reduction in copper loss when compared to the standard motors by the corporation : 10 to 30%)
Iron loss	Loss occurring due to the application of the rotating magnetic field to the stator core	Development and use of high magnetic flux density, low iron loss isotro-pically electromagnetic steel plate materials Optimization of the design of the magnetic circuit using the electromagnetic steel plate materials described above. (Reduction in iron loss when compared to the standard motors by the cor-poration : 20 to 40%)
Stray flux loss	Total of losses such as the eddy-current loss between the bars due to inadequate rotor slot installation, high-frequency copper losses when loaded, iron losses due to high-frequency flux, conductivity losses due to inadequate installation between layered cores, etc..	Use of magnetic field analysis to analyze the high-frequency losses by analyzing the high-frequency iron losses and high-frequency copper losses separately, and experimentally validating the quantitative value for the stray flux loss. Optimization of the length between the stators and rotors, the amount of rotor skew, the rotor slot bridge thickness, and other factors pertaining to the magnetic circuit constant
Mechanical loss	Losses due to bearing fiction, fan power, etc.	Development and use of a grease with reduced frictional loss Use of a fan with less air losses than the standard Mitsubishi fan

phase motors to further reduce primary-copper loss. Reductions in secondary-copper losses will require efforts to increase the cross-sectional area of the motor slots and to decrease the resistance inherent in the conductive materials. The development and application of aluminum melt-forging technology instead of cast aluminum conductors in order to obtain higher density conductors with fewer voids, and the development of manufacturing technologies for copper conductors, which have lower inherent resistances than aluminum conductors, are two viable approaches.

STRAY-FLUX LOSSES. Stray-flux losses account for about 10% of all motor losses. These losses increase with the motor load, and have been difficult to analyze quantitatively in the past, because it has been difficult to analyze quantitatively, through considering the fundamental frequency copper alone, the high-frequency components that increase with the load. Recent advances in magnetic-field analysis technologies have made it possible to separate the high-frequency losses into iron-related and copper-related losses, making it possible to analyze with high precision the losses that occur at the stators, the rotors, the gaps, etc. When combined with high-precision losses-measurement technologies, this makes it possible to analyze stray-flux losses quantitatively and to validate the analytical results experimentally, producing major reductions in stray-flux losses that previously relied exclusively on empirical methods. This offers good prospects of further cost reductions.

OTHERS. Apart from the need to increase efficiency, other issues facing motors include energy and resource conservation in the motor-manufacturing process, manufacturing methods that reduce materials harmful to the environment, product design that takes recycling and disposal into account, and other methods by which to reduce the environmental impact over the entire product lifecycle.

Motors are made of iron, aluminum, and a small amount of organic materials, but it is usually the life expectancy of the small amount of organic insulating material that determines the life expectancy of the motor as a whole. The life expectancies of the bearings, which determine the mechanical life expectancy of the motor, can be extended by changing the bearings. Consequently, it is imperative to increase the useful life of the insulators and the coils, and to facilitate maintenance.

In addition to three-phase motors, products targeting high-efficiency and smaller size using advanced methods have also been produced in, for example, IPM motors, reactance motors, and DC brushless motors. However, in most applications, three-phase motors are expected to remain the dominant high-durability/low-cost commercial option, due in part to their ease of use. The corporation will continue to pursue the development of three-phase motors with even higher performance and further improved efficiency, contributing to improved energy conservation. ❑

Spindle Motors for Machine Tools

*By Kazuyuki Kawashima and Akihiro Shimada**

Spindle motors for machine tools are a type of servo motor characterized by emphasis on high-speed performance. With the increases in speed needed to support advances in high-speed machining centers, spindle motors for machine tools with a maximum speed of up to 70,000rpm have been marketed. From the perspective of high-precision machining, there have been advances in technologies developed to reduce the amount of heat produced. Also, with increases in the efficiency of induction motors, long used as conventional AC spindle motors, the advent of internal permanent-magnet motors has expanded the range of options for increased efficiency.

This article discusses (1) spindle motors that use ultrahigh-speed induction motors to reach speeds of 70,000rpm, (2) spindle motors that use high-speed/high-efficiency induction motors to reduce electrical losses in the high-speed domain by 50%, and (3) spindle motors that use internal permanent-magnet motors to achieve high efficiencies in the high-torque domain.

Ultrahigh-Speed Built-In Induction-Type Spindle Motors

In recent years, a focus on increasing the efficiency of machine tools has seen rapid advances in technologies to speed up the spindles in, for example, machining centers. Mitsubishi Electric Corporation has been developing ultra high-speed built-in induction-type spindle motors since 1995, and has marketed a spindle motor with a maximum speed of 70,000rpm.

The mechanical strength of the rotor becomes an issue when the spindle motor rotates at ultrahigh speeds. Generally, a squirrel-cage rotor, made as a single piece integrated with an aluminum conductor, is used for its durability under high-speed rotation. However, even with this structure, the mechanical strength of the various parts of the rotor, particularly the fatigue strength of the rotor end rings, becomes an issue. These problems stem from casting defects during rotor manufacture, and the corporation has developed a new and proprietary manufacturing technology known as “floating die squeeze casting” to avoid these defects, enabling ultrahigh-speed rotors whose outer edges move at 180 meters per second, see Fig. 1.

The specifications for the series of high-speed built-in induction-motor spindle rotor products are shown in Table 1. In all the products, the inner diameter of the rotor has been increased by about 20 to 30 % over the existing series of spindle motors, while the overall length has been reduced as much as possible, contributing to increased stiffness of the spindle itself.

High-speed/High Efficiency Built-In Induction-Type Spindle Motors

Typically, spindle motors in high-speed machining centers operate at their maximum speeds for considerable periods of time, and high-speed machining technologies have focused in recent years on having a small bite but a rapid feed. Thus, the load when cutting is comparatively small. When there is minimal loading on the induction motor, or none at all, the electrical losses should also be low. However, given the effects of factors such as the increase in the power-supply frequency at the higher rpm used, and the inflow of the high-frequency electric current accompanying inverter switching operations, heating of the motor in the high-speed domain is unavoidable. The corporation has therefore used its proprietary motor-design and

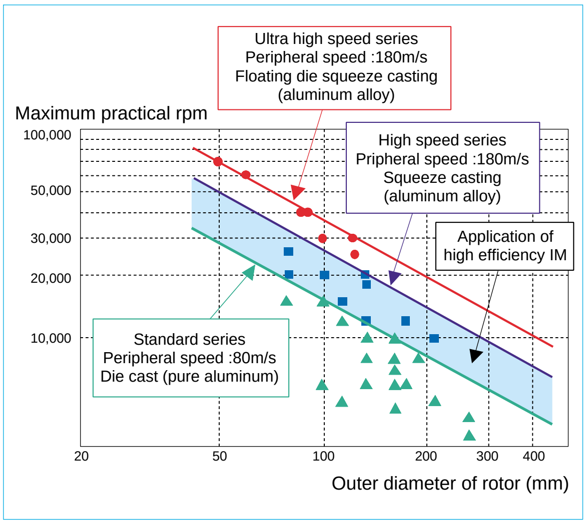

Fig. 1 Structure of the built-in induction-type spindle motor series

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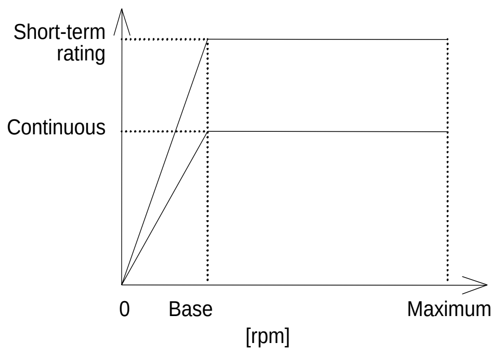
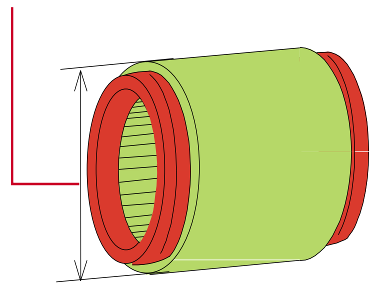
Table 1 Specifications of the Ultrahigh-Speed Built-In Induction Motor Series

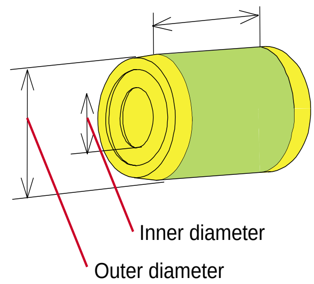
Model	Frame size	Output power (kW) (cont./30-min. rating	Speed of rotation (base/max. rpm)	Principal dimensions (mm)			
				Stator outer diam.	Rotor outer diam.	Rotor inner diam.	Core length
SJ-2B2A04Y	50-50	7.5/11	40,000/70,000	89.5	49.1	28	50
SJ-2B2009Y	63-70	5.5/7.5	30,000/60,000	109.5	57.1	35	70
SJ-2B2210Y	100-60	11/15	30,000/40,000	159.5	86	55	60
SJ-2B2307Y	112-60	15/22	30,000/30,000	179.5	98.9	70	60
SJ-2B2402Y	132-90	22/30	20,000/25,000	209.5	122.8	85	90



Output Power - Speed Characteristics



Principal dimensions of stator



Principal dimensions of rotor

manufacturing processes to develop a high-efficiency induction-type spindle motor, where the electrical losses in the high-speed domain are half those of a conventional high-speed spindle motor. Because the main motors for today's high-speed machining form a series of high-speed motors, the corporation has increased the speed and the efficiency of this entire series, see Fig. 1.

The key changes to specifications are as follows:

1. A higher grade of magnetic steel sheets
2. Optimized dimensions of the air gaps between the stators and the motors
3. Optimized rotor-core specifications (the number of slots, etc.)

Fig. 2 compares the losses of the 100-frame, 4-pole, 1500rpm (max.) high-speed/high efficiency

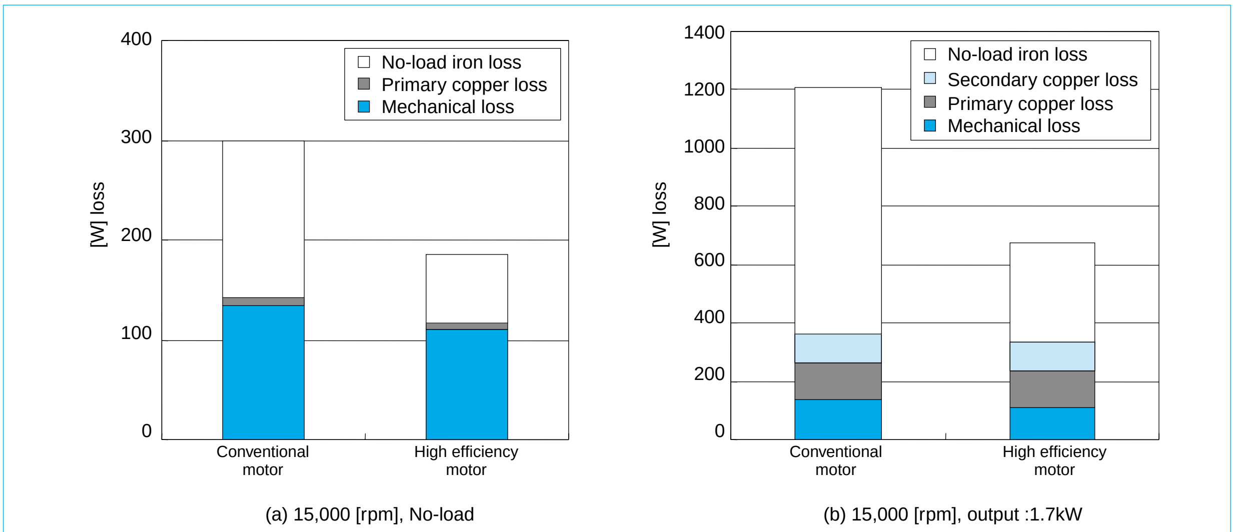


Fig. 2 Comparative losses in the high-rpm domain

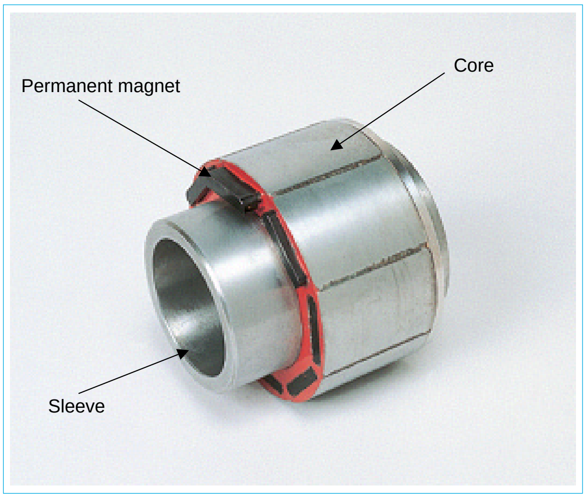


Fig. 3 Rotor cut model of internal permanent magnet-type spindle motor

series product (or more simply, the "high-efficiency product, ") that has a continuous rated power of 2.2kW and a 30-minute rated power of 3.7kW, with those of a conventional motor with similar specifications. The electrical losses in the motor when operating at its maximum unloaded speed of 15,000rpm were 54 percent less than those of the conventional product. Furthermore, the electrical losses in the motor at 15,000rpm and 1.7kW power were found to be 47 percent less. These effects were primarily due to reduced iron losses, where the effects of the increased efficiency were verified quantitatively.

The high-efficiency product also has the following features:
1. The standard use of a squeeze-cast rotor, and
2. A reduction in the total length of the stator (20 % shorter than the conventional product).

Internal Permanent-Magnet Type Spindle Motors

The application of internal permanent-magnet type motors to spindle motors for machine tools is primarily in the built-in specifications for lathes. This application fully exploits the increased efficiency in the high-torque domain, making it possible to reduce the size of the spindle units and to simplify the cooling structures, taking advantage of the lower heat generation.

Fig. 3 shows a rotor cut model of an internal permanent-magnet spindle motor. The structure features permanent magnets embedded within the rotor, making it possible to take advantage both of the magnetic torque and the reluctance torque.

Fig. 4 shows the temperature rise during continuous load operation of spindle motors at an

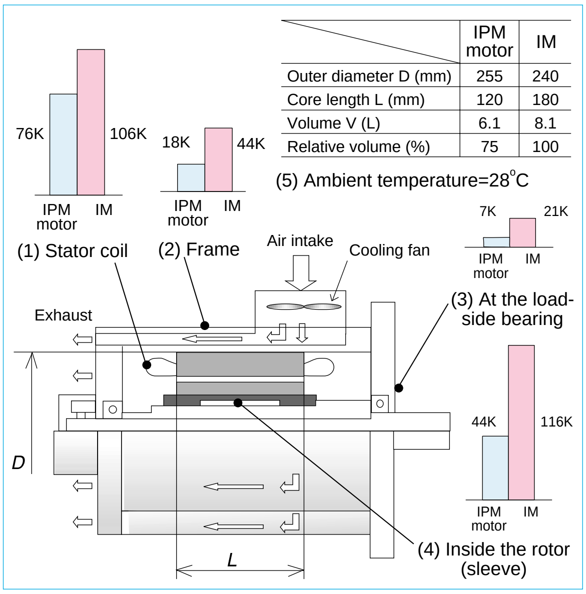


Fig. 4 Comparison of temperature rises for internal permanent magnet-type spindle motor with those for an induction motor under continuous operation under load (output power: 5kW; speed 445rpm)

output power of 5kW and a speed of 445rpm, for an internal permanent-magnet type and an induction type each having an output power of 5.5/7.5kW(continuous/30-minute rating) at a maximum speed of 6000rpm. These experimental results clearly show the high-efficiency/load heating of the internal permanent-magnet type spindle motor in the high-torque domain. Note particularly that, although the stator core of the internal permanent-magnet type spindle motor is 25% smaller than the induction-type spindle motor, the temperature increases in the various parts remained small for the same output power.

Despite the numerous advantages of the internal permanent-magnet type spindle motor cited above, the rotor structure of the induction-type spindle motor allows higher speed operation than standard surface magnet-type servo motors, giving it an advantage in terms of maximum speed. In view of the limitations on efficiency under high-speed, no-load conditions, motors should always be selected to suit the conditions in which they will be used for speeds up to 20,000rpm.

Further increases in the speeds of feed systems and of spindles in machine tools are anticipated, and work is underway to further increase the speeds and reduce the heat generated in induction-type spindle motors. The scope of applications of internal permanent-magnet type spindle motors is also expected to expand, taking advantage of their high efficiencies in the low-speed/high-torque domain. ❑

New Motor Electromagnetic Design Technologies

*by Haruyuki Kometani and Masaya Inoue**

Field design has recently come to play an essential role in achieving both improved performance and lower costs in electromagnetic design for motors. It is therefore essential to establish design methodologies that use previously unavailable computer capabilities in addition to conventional design technologies.

Design Technologies Relating to Harmonics

BASIC THEORY OF HARMONICS IN MOTORS. Harmonics within motors can be divided into spatial harmonics and temporal harmonics, where physical phenomena can be inferred through harmonic analyses of gap flux density.[1]

The magnetic vibrational force **F** [N/m²] is expressed in terms of the gap flux density $\mathbf{B}_g$[T] by the following formula:

$$\mathbf{F} = \frac{\mathbf{B}_g^{\,2}}{2\mu_0} \quad \text{Eq.1}$$

Here, μ_0 represents the permeability of free space. Thus, the order of the space harmonics is given by the following formula:

$$N_sK_s + N_rK_r + 6K_{ps}p + 4K_Bp + \begin{cases} 2p \\ 0 \\ -2p \end{cases} \quad \text{Eq.2}$$

The order of the time harmonics is given by the following formula:

$$\frac{N_rK_r(1-s)}{p} + 4K_B + \begin{cases} 2p \\ 0 \\ -2p \end{cases} \quad \text{Eq.3}$$

and so on, in that order, where N_s is the stator slot number, N_r is the rotor slot number, s the slip factor, p the pole pair and K_s, K_r, K_{ps} and K_B are arbitrary integers.

Here the first term is the stator-slot harmonics, the second term is the rotor-slot harmonics, the third term is the stator magnetic motive-force harmonics, and the fourth term is the harmonics from magnetic saturation.

This theoretical treatment can be extended to optimize physical shapes in permanent-magnet motors so as to reduce torque ripple, and to optimize the slot combinations in induction motors.

ELECTROMAGNETIC VIBRATIONAL-FORCE ANALYSIS IN SMALL INDUCTION MOTORS. Quantification using electromagnetic field analysis is required when investigating the size of the harmonics. In this section, we will analyze the changes in the electromagnetic vibrational force resulting from skew in small induction motors as an effect of the harmonics. The analytical model uses the three-phase induction motor model K of the Institute of Electrical Engineers of Japan found in Reference[2].

In this section we investigate the electromagnetic vibrational force, using mode 2 (the mode for second-order space harmonics) as an example. Fig. 1 shows a harmonic analysis of the mode 2 electromagnetic vibrational force when there is no skew, when there is rotor-slot pitch skew, and when there is stator slot-pitch skew.

According to the above treatment, the -13.6 order interacts with the stator-slot harmonics, the rotor-slot harmonics, and the

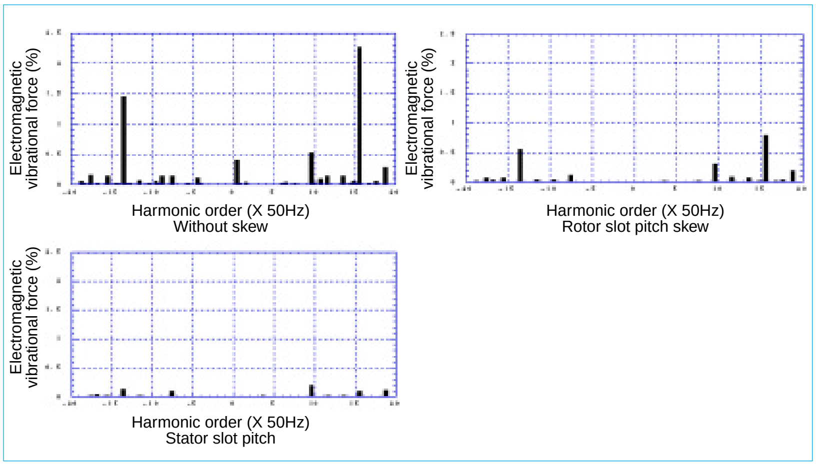


Fig 1 Changes in the mode 2 electromagnetic vibrational force depending on skew

**Haruyuki Kometani and Masaya Inoue are with the Advanced Technology R&D Center.*

5th and 7th stator magnetic motive-force harmonics. The 15.6 order has a primary interaction with the stator-slot harmonics, the rotor-slot harmonics, and the 5th stator magnetic motive-force harmonics. This figure shows that the electromagnetic vibrational forces can be reduced substanitally by skew.

Design Technologies for Iron Loss and Stray Loss

METHODS OF INVESTIGATING IRON LOSS AND STRAY LOSS. The magnetic flux density in the iron core can be calculated using the finite-element method, making it possible to calculate the iron loss. If the maximum value for the magnetic-flux density for each element is defined as $|\boldsymbol{B}_m|$ [T] and the maximum value for the n-order harmonic component in the magnetic flux-density frequency analysis results is expressed as $\boldsymbol{B}(n)$ [T], then the hysteresis loss W_h [W] and the eddy-current loss W_e [W] can be expressed by the following formulae:

$$W_h = \sum_{n_e} \sum_{a_x} [K_f \left\{ K_h |B_m|^x f \right\} DV] \quad \text{.......... Eq.4}$$

$$W_h = \sum_{n_e} \sum_{a_x} \sum_{n} [K_c \left\{ K_h B^y(n)(nf)^z \right\} DV] \quad \text{......... Eq.5}$$

Here, f represents the base frequency (Hz), D the density (kg/m^3), V the volume of the element (m^3), K_f the hysteresis-loss multiplier due to residual stress. K_c the eddy-current loss multiplier[3] due to overlapping harmonics or the surface-loss multiplier, a_x is the radial direction and the tangential direction, and n_e the number of elements in the core. Here K_h, x, K_e, y and z are calculated from the iron-loss curves derived experimentally from the materials.

IRON-LOSS ANALYSIS IN AN EMBEDDED MAGNET MOTOR. Iron-loss analysis was performed using an embedded magnet motor as an example.[4] Fig. 2 shows the iron-loss distribution when there is a load. Under load, an inverter driver is used with 120 degrees commutation, and thus the eddy-current loss due to temporal harmonics is dominant. Table 1 shows the losses, identified separately through the analysis. It can seen in this table that the dominant losses are the stator-surface loss (the harmonic loss) and base-frequency hysteresis loss, which includes the effect of residual stresses.

ANALYSIS OF STRAY LOAD LOSS IN INDUCTION MOTORS. The stray load loss in induction motors is defined by Eq. 6.[5]

$$W_{LL} = P_1 - (P_2 + W_{c1} + W_{c2} + W_h + W_m) \quad \text{............................. Eq.6}$$

Table 1 Iron Loss, etc., when Loaded

Measured values		Analytical values	
Average torque	1.63Nm	Average torque	1.63Nm
No-load iron loss	5.6W	Hysteresis loss	7.3W
Other losses	11.3W	Base frequency eddy loss	2.9W
		Harmonic eddy loss	6.6W
Total iron loss	16.9W	Total iron loss	17.0W

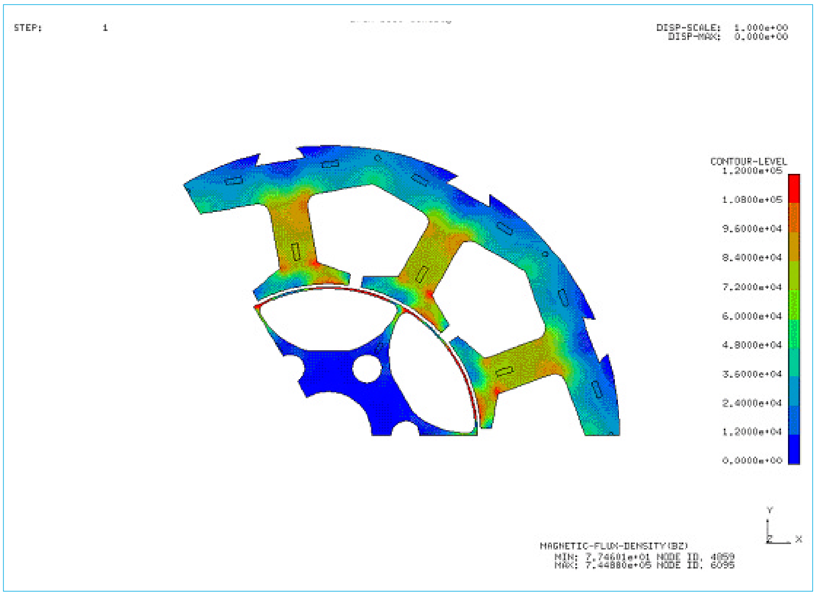


Fig. 2 Distribution of iron loss when loaded

Here, W_{LL} represents the stray load loss, P_1 the input, P_2 the output, W_{c1} the primary copper loss, W_{c2} the secondary copper loss, W_h the no-load iron loss, and W_m the mechanical loss. The stray-load loss is divided primarily into the harmonic secondary copper loss and the harmonic iron loss, which are difficult to measure. However, the use of electromagnetic field analysis makes it possible to calculate them separately. For example, Fig. 3 and and 4 show the analytical results for a 4-pole 75kW induction motor. The figures show that the load increases the harmonic secondary copper loss and the harmonic iron loss.

Conclusions

The article has described the basic theory of harmonic calculations within a motor in order to approximate,using a finite-

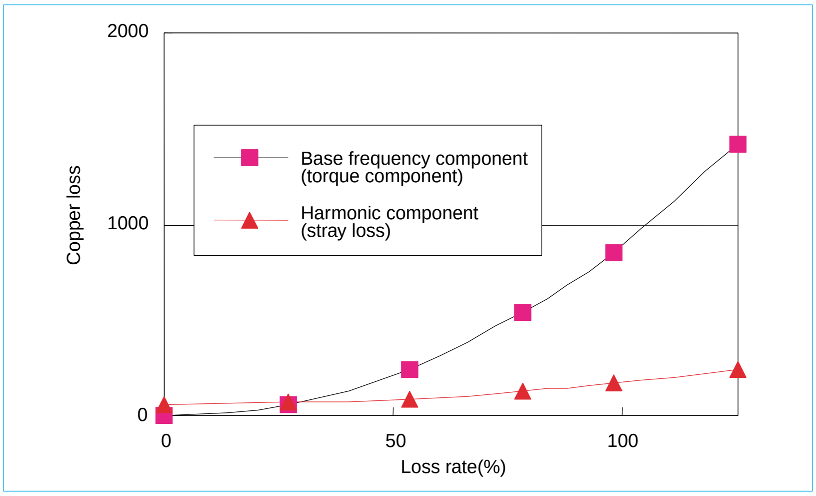


Fig. 3 Secondary copper loss calculated using magnetic field analysuis

field treatment, the electromagnetic design of the motor, and went on to describe examples of analysis using new technologies such as electromagnetic vibrational force analyses, copper-loss and stray-loss analyses, etc., using sophisticated computers.

In the electromagnetic vibrational force calculations,the relationship with the skew of the induction motor was shown, demonstrating how it is possible to select an optimal skew angle.The article also discussed an iron-loss analysis taking into consideration temporal harmonics, such as inverter harmonics, in an embedded permanent magnet motor. Analytical results are in good agreement with actual measurements. This makes it possible to estimate the iron loss of the product at the design stage.

Finally, the article described an example of stray-loss analysis, usually the most difficult of analyses, showing that it is possible to separate the stray loss into loss values for the individual causes of stray losses and at the same time making it possible to develop designs to reduce them.

These important developments will be reflected in future generations of the corporation's electric motors, providing performance enhancements where the resources of conventional engineering approaches have already been largely exhausted. ❑

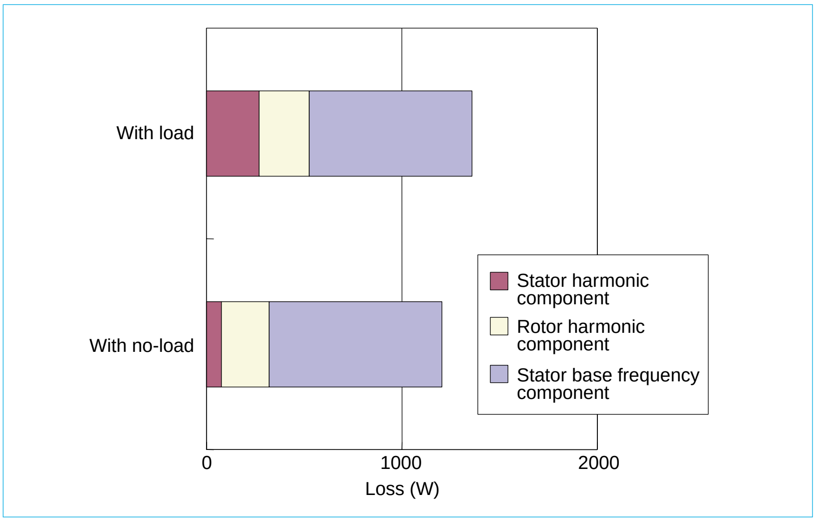


Fig. 4 Iron-loss analysis using magnetic field analysis

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New Motor Manufacturing Technologies

*by Nobuaki Miyake**

Conventional technologies are reaching the limits of what can be achieved in reducing energy consumption and increasing efficiency. This makes "design for manufacturing," which reexamines the basic structural and electromagnetic designs from the point of view of ease in manufacturing, critically important. Mitsubishi Electric Corporation has reviewed the basic structures of its motors, focusing on core-assembly and coil-winding technology, developing the so-called "Poki-poki Motor" since 1993, and so responding to a broad variety of product requirements.

Conventionally, in order to wind coils onto inner-rotor type stators, it has been necessary to thread a winding nozzle from a narrow space on the inside of the stators through a slot opening, and then to drive the winding nozzle around the pole teeth, as show in Fig. 1a. This imposes constraints on the tightness of the coils and on the speed of the winding operations. Although the method illustrated in Fig. 1b is available, in which the cores are divided, this approach raises other issues, including a higher component count and more coil-terminal connections.

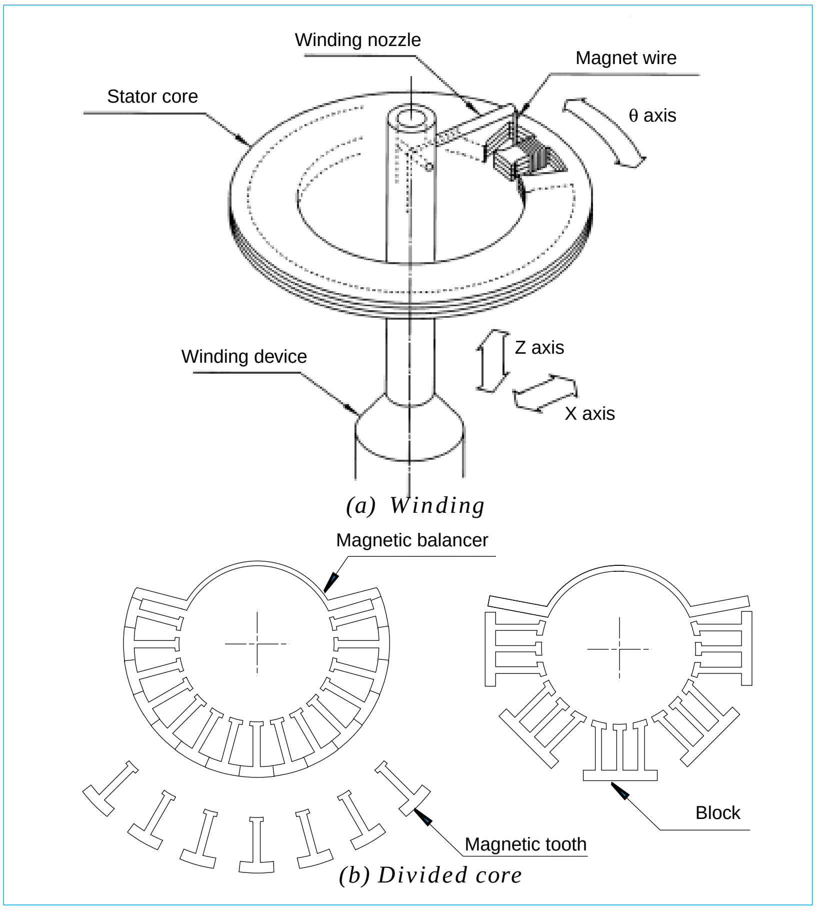

Fig. 1 Conventional motor manufacturing technology

The corporation's proprietary structure makes it possible to solve the problems of divided cores, securing the same amount of space for the winding operations as in the divided-core approach, but without impacting ease of assembly and connectivity.

There is a great need for thin-spindle motors to drive recording media in data-processing equipment. Fig. 2 shows a block-type "Poki-poki" core in which three pole "teeth" form a single block. Five such blocks and the magnetic balancer that is provided in the stator gap are laid out using thin-bridge portions in a straight line. During the winding operations, three winding nozzles, for the U, V and W phases, are driven simultaneously, winding continuously without having to cut the leads when connecting between blocks. After winding has been completed, the thin bridge portions of the iron core are bent, thereby forming a conventional cylindrical stator.

This structure makes it possible to wind orderly coils at high speed using a simple mechanism, because the multiple core "teeth" face multiple winding nozzles. This helps to make these devices thinner. It also improves ease of assembly by greatly reducing both the number of connections at the end of the coils and the number of components parts.

The chain-type "Poki-poki" core is used in several AC servo motors and in the small high-power brushless DC motors widely used in automotive equipment. The structure features a separate back yoke for each of the

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pole teeth, where these back yokes are connected by a thin-bridge portion into a straight line.

The use of this type of core opens up the space between the magnetic pole teeth during the winding operations, not only making it possible to maximize the density of the orderly coil windings within the slots but also making it possible to narrow the slot openings (after the cores are bent) to the optical design values.

The specifications for the stators of fan motors used in home appliances such as air conditioners require fine coil-winding diameters and a large number of coils. When higher-speed winding operations are necessary, a reverse bow-type "Poki-poki" core is effective. In this, the chain-type "Poki-poki" core is bent backwards during the winding operations. This makes it possible to double the opening angle compared to a straight line. When the thickness of the layered iron core is small compared to the spacing between the magnetic pole teeth, the winding nozzle can follow a circular orbit, facilitating high-speed winding.

If the thickness of the layered core is large compared to the spacing between the magnetic pole teeth, then a joint-lap type "Poki-poki" core in which the core can be bent freely for each magnetic pole tooth is appropriate, making it possible to open up the area immediately around the magnetic pole tooth to be wound. Each layer of the core material is lapped at the joint, and dimples are formed at each of the lapped parts, forming hinges when the plates are stacked. The core layers are stacked concentrically at about the same speed as for conventional monolithic cores, using a stacking punch die. The photograph in Fig. 3 shows a stator for motors in air-conditioning units. After the coils have been wound in an orderly "rice-bag" pattern, the stator is again formed into a cylindrical shape and is press fitted into a frame. In this state, the contact stresses are applied uniformly over the divided surfaces of the core, forming a core with the same stiffness and true circularity as a monolithic core.

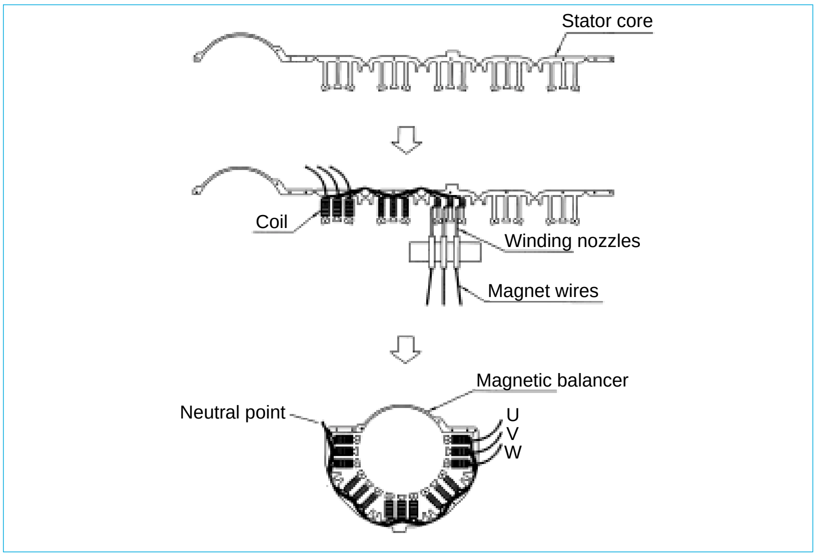

Fig. 2 Block-type "Poki-poki" core

In large motors, typically for elevator hoists, or generators, the arc-joint type "Poki-poki" core is used. With the joint-lapped "Poki-poki" core in large-diameter motors, arc-shaped layers are used. These have lengths that can be handled in standard presses, increasing the yield of steel plates in the punching process and improving the efficiency of material handling. After the winding operations, the arc-shaped segments are arranged in the form of a cylinder, and welded together at the butt portion to form an integrated unit. After a varnishing process, a shrink-fit assembly process is used to attach the stator to the frame, thereby ensuring the required stator precision and strength. This method makes it possible to change the number of segments according to the diameter of the stator and to maintain an essentially uniform length in the core segments, making it possible also to handle multi-variant small-lot manufacturing.

An alternative, spiral-type "Poki-poki" core has been proposed to the block-type core in the stator-manufacturing process to further improve productivity. The core is fabricated with block-type cores for multiple stators in the form of a continuously connected cylindrical spiral, layered by a stacking punch die. After insulation coating, winding is performed when

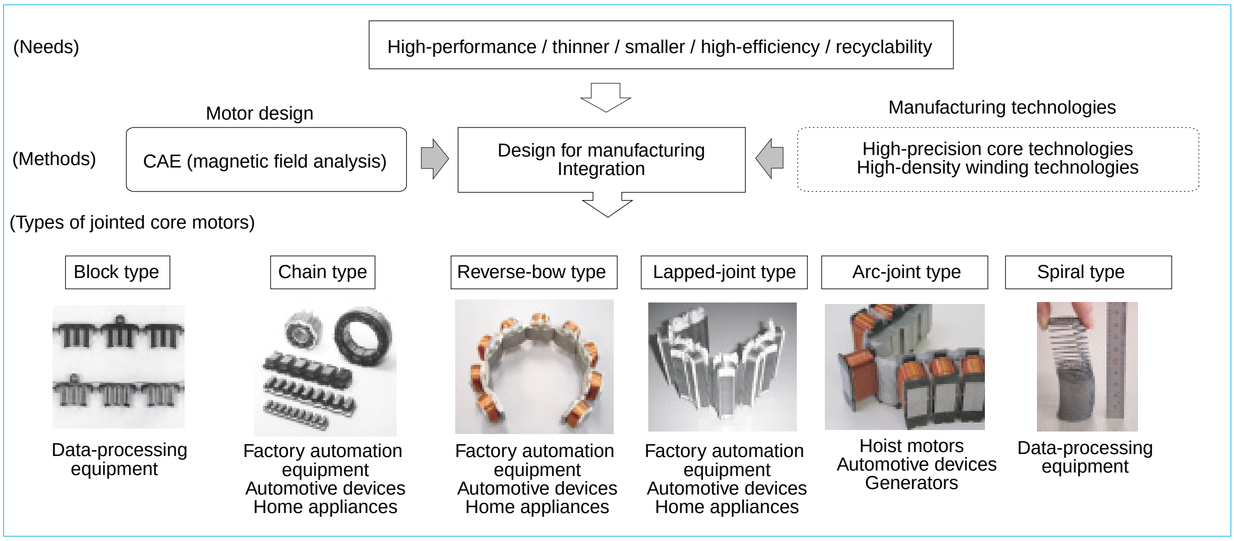

Fig. 3 Types and typical applications of jointed cores

the cores are opened up to form a straight line and then, after dividing off enough for a single stator, the core is bent into a circle for a cylindrical stator. This makes it possible to send cores for multiple stators (for example, 50-units worth) as a batch from the core press, and to improve productivity in the processes from coating through winding.

In the future, product designs will be examined from other perspectives, e.g., their disassembly characteristics and the recyclability of the motors, and undoubtedly "Poki-poki" motors will be deployed even more extensively. ❑

Leading-Edge Motor Control Technologies

*by Akira Satake and Toshiyuki Kaitani**

This article reports on the status of the development of leading-edge motor-control technologies at Mitsubishi Electric Corporation and describes a sensorless control method that provides high-performance drive for permanent-magnet synchronous motors without using rotor-position sensors. It goes on to describe the vector-control method for high-precision control of the temperature-dependent torques generated by induction motors.

Sensorless Control of Permanent-Magnet Synchronous Motors

Permanent-magnet synchronous motors generate magnetic flux using permanent magnets in the rotors, which are driven by the stators applying a synchronous rotational field. On the other hand, the flux that is applied by the stators (the armature-reaction flux) generates torque most effectively when it is perpendicular to flux generated by the rotors. One way to maintain near perpendicularity is to keep constant the sum of the fluxes described above, that is, the stator fluxes. When the control axis is coincident with the stator flux, the stator flux in the load angle can be calculated from the stator current and the motor constants. When attempts are made to control this calculated stator flux at the same magnitude as the permanent magnet flux, the error in the flux can be calculated from the stator flux and the load angle.

This makes it possible to construct a high-speed control system by feeding back the flux error obtained from the above calculation to the stator voltages for the various axes of the permanent magnet synchronous motor, with the control axis coincident with the stator flux, so as to produce a control voltage command. This voltage command is applied to the permanent-magnet synchronous motor at the described frequency. Fig.1 shows a sensorless control system for a permanent-magnet synchronous motor, configured as above. In this figure, a frequency compensator is added to adjust the primary frequency ω_1, using a load current, relative to the command frequency ω_m* in order to maintain the stability of the control system when the changes in the load, etc., are too great.

As an example of the performance of a system using the permanent-magnet synchronous motor sensorless control described above, Fig. 2 shows the

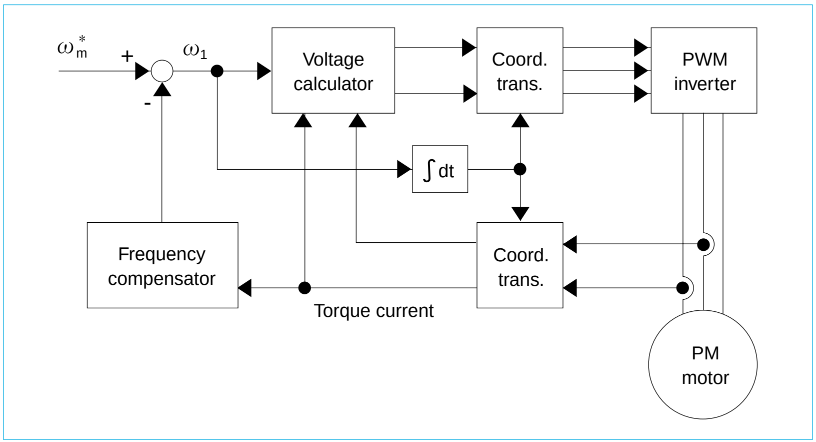

Fig. 1 PMSM sensorless control system

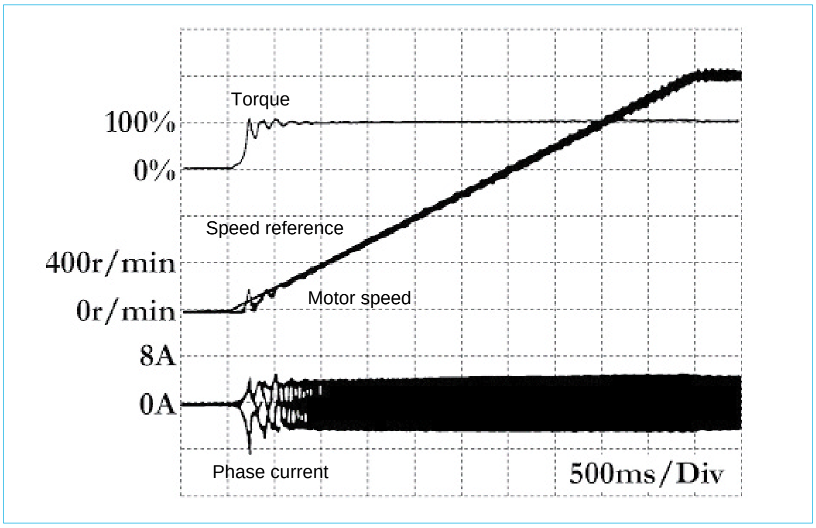

Fig. 2 An example of performance using PMSM sensorless control

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operating waveform when starting up and accelerating from a full stop with a 100% load. It was confirmed that excellent control characteristics can be obtained.

High-Precision Vector Control in Sensored Induction Motors

Generally, in vector control of induction motors, the direction and magnitude of the rotor flux is calculated from the stator current and slip frequency (which is the discrepancy between the rotor speed and the stator voltage frequency). This calculation uses the motor constant, but the coil resistance in the motor stators and rotors will vary with changes in the motor temperature. Because of this, when the motor temperature changes with the operating conditions, the precision of the flux control is reduced, resulting in variations in the torque constant.

A sensored vector-control method using flux observers was investigated as a way to solve the problems noted above. If the feedback gain of the observer is designed so as to minimize the noise in the state variables of the observer relative to the variations in the resistance, it is possible to create a flux that is largely independent of variations in resistance. In this control system a flux observer is used instead of the flux calculator of the conventional slip-frequency vector control. The magnitude and direction of magnetic flux calculated from the rotor flux as a vector, which are state variables, are used in the flux-control system, and in the coordinate transformation.

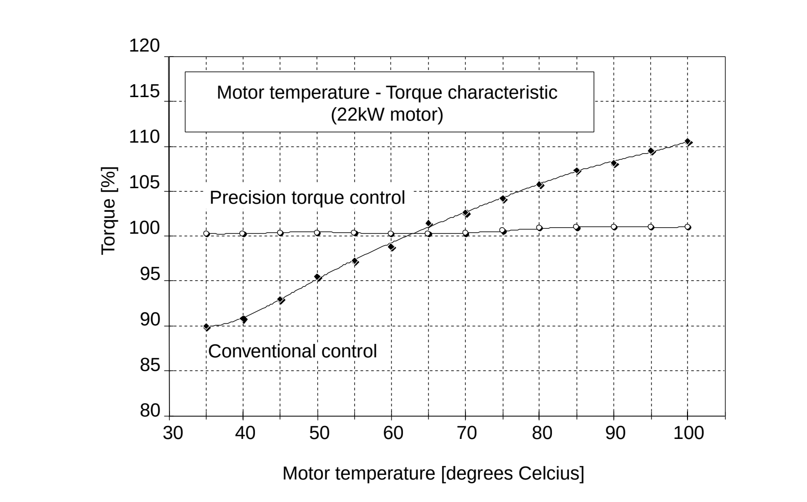

Fig. 3 Example of performance of an IM precision torque-control system

Fig.3 compares the torque-control characteristics of a vector-control system, improved and modified using the above method, with a conventional torque-control system. It shows that this method provides a substantial improvement in the stability of torque control with respect to temperature variations.

The roles played by drive systems using motors as clean, energy-efficient power transducers, will become increasingly important in the future. This is expected to make increasingly severe demands of motor-drive control technologies. Mitsubishi Electric is committed to continuing efforts in technology development that will satisfy these needs. ❑

Noise-Reduction Technology

*by Yoshio Yoshikuwa and Akihiko Imagi**

In small motors of less than 500W, transferred sounds from the motor excitation forces are more of a problem then direct sounds from, for example, the vibration of the motor frame. This article addresses radial excitation forces, which are the most likely sources of transfer excitation forces, and discusses measurement devices and investigation into noise-reduction technologies.

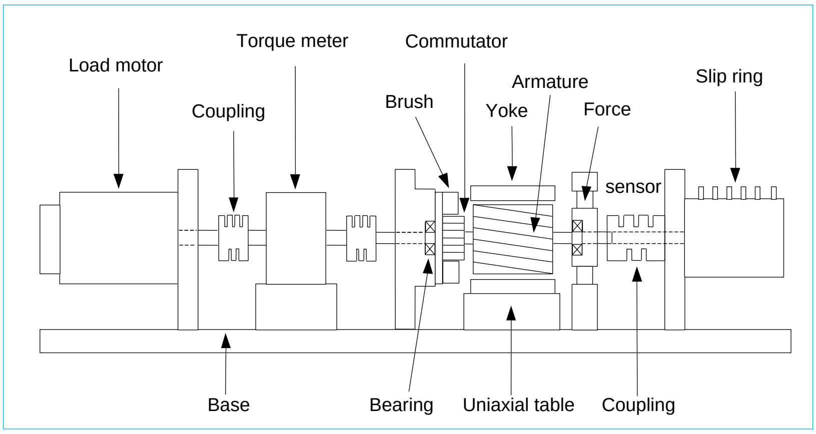

Fig. 1 Apparatus for measuring radial excitation forces

Devices for Measuring Radial Excitation Forces

A test apparatus like that shown in Fig. 1 was created in order to measure this radial component. The stator and the rotor were disassembled and securely fastened. The stator core was attached to a microvibration table, and the static eccentricity with the rotor was measured. The bearing that supports the rotor system was held by a force sensor.

Radial Excitation Forces Due to Eccentricity

We investigated the radial excitation forces caused by eccentricity in capacitor motors for duct fans. The stator was removed and assembled into the equipment shown in Fig. 1. A 5% distortion was applied to the supply voltage.

An investigation was performed into the reduction of radial excitation forces due to eccentricity by varying the numbers of winding coils on opposite poles. The state of the eccentricity can be thought of in terms of the simple model shown in Fig. 2. The magnetic flux ϕ_x induced by the winding coils through a given slot X and the magnetic flux ϕ_y induced by the winding coils through a given slot Y are equal. When the magnetomotive force is *F*, the magnetic resistance is *R*, the number of turns in the winding coils is *n*, and the electric current in the winding coils is *i*, then the following relationships will hold true:

$$F_x/R_x = F_y/R_f \text{ ....Eq.1}$$

$$F_s = n_x \times i_x,\ F_y = n_y \times i_r \text{ ....Eq.2}$$

Considering the air gap length and the magnetic resistance, the condition of eliminating the radial force is derived as follows.

$$(n_x \times i_x)/l_x = (n_y \times i_y)/l_y \text{........Eq.3}$$

Given this, the number of turns in the winding coils *n* and the winding-coil electric current *i* should be adjusted so that the magnetic flux ϕ_x and the magnetic flux ϕ_y will be equal. Here the winding-coil electric current *i* was held constant, and the number of turns in the winding coil n was varied.

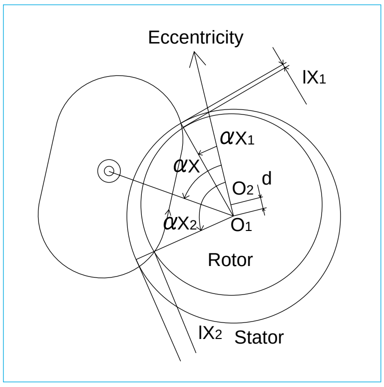

Fig. 2 Motor eccentricity

Experimentally, an unbalanced winding-coil stator for producing a radial damping force was produced for a 15% mechanical eccentricity. Fig. 3 shows the relationship between the eccentricity and the radial excitation force. Although there are components at different frequencies, such as 2*f*, 4*f*, and 6*f*, each of these components was minimized at near 15% eccentricity. The radial excitation forces were successfully reduced by adjusting the winding coils according to the amount of mechanical eccentricity.

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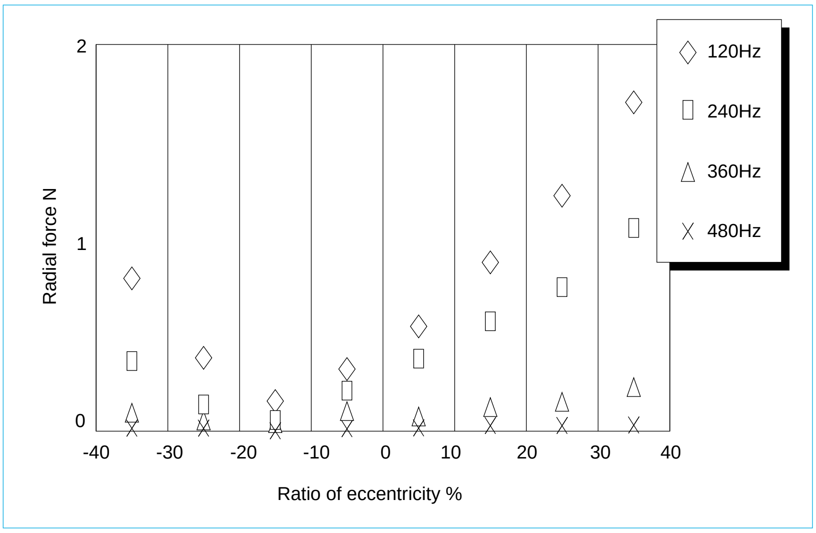

Fig. 3 Radial excitation forces and eccentricity due to winding-coil imbalances

Radial Excitation Forces Due to Brush Commutator Timing

The radial excitation forces generated by brush commutation in a brush-type DC motor for electrical power steering was investigated next.

Because the brush width was designed to have the same dimension as the commutator segment width, each brush was in contact with one or two commutator segments. There are two positive brushes, and if the electric currents flowing into each are not equal, there will be an asymmetry relative to the rotor core in the winding-coil electric current distribution.

Noise reduction was effected through symmetrical short-circuiting wires joining the commutator coils in geometrically symmetrical positions about the center of the rotor core. These short-circuiting wires for symmetrical positions ensured that the commutator segments in symmetrical positions were electrically equivalent to each other when it comes to the state of the brush contact, thereby also insuring symmetry in the electrical current distribution.

Fig. 4 shows the frequency characteristics of the radial excitation force for a conventional motor and for a motor in which this symmetrical-position shorting was employed.

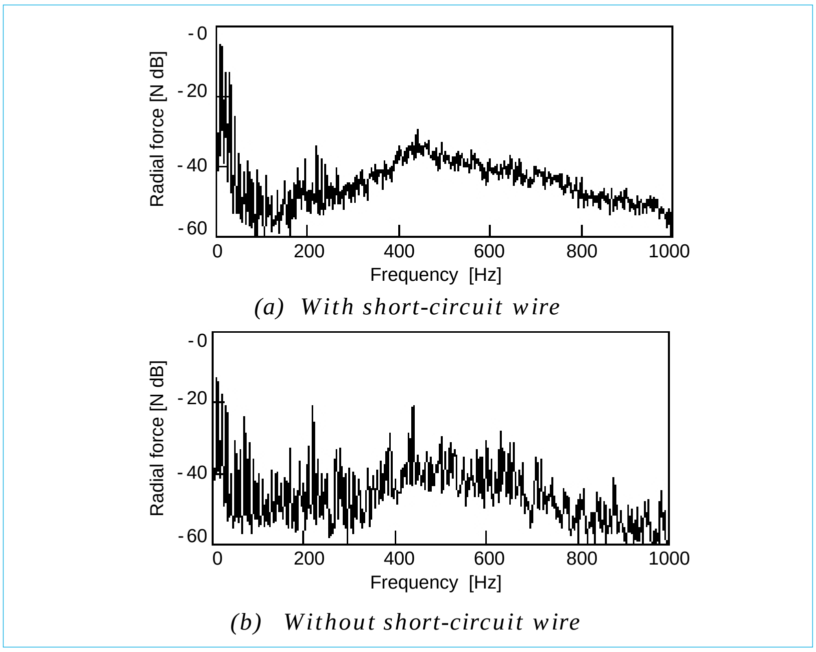

Fig. 4 Frequency characteristics of radial excitation forces

The first-order component of the excitation force with 22 commutator segments was 220Hz. Fig. 4 shows that, even though the radial excitation force components were large at integer multiples of 220Hz, the use of the symmetrical-position shorting dramatically reduces the radial excitation forces. When compared to the 220Hz first-order component of the excitation force, the use of the symmetrical position shorting reduced the excitation force by 14dB, about 20%. The effects of the symmetrical position shorting were confirmed in tests for noise in actual motor cars.

The identification of the major sources of noise in small electric motors and important insights into how it can be minimized have significant potential for the development of new generations of quiet motors. ❑

HF-KP Series Small High-Performance Servo Motors

With the diminishing size and increasing performance of industrial machinery in recent years, there have been demands for smaller servo motors with higher performance to be used in such equipment. Mitsubishi Electric Corporation has responded to these demands by developing and commercializing the "HF-KP Series" AC servo motors, which offer both a smaller form factor and improved performance. Fig. 1 is a photograph of an HF-KP series product.

The HF-KP series pursues high-speed/high-precision performance at 6000rpm. The cogging torque, a factor in torque variability, is reduced to one-half that found in conventional equipment, and the magnetic circuits are optimized through the use of high-density concentrated winding technologies, based on the corporation's proprietary "lapped-joint" jointed cores, and three-dimensional magnetic field simulations. These take into account the variability in the magnetic characteristics produced in the core-punching process. Furthermore, the HF-KP series is equipped with a compact high-resolution optical absolute-value encoder using a newly developed high-density packaging circuit substrate. For the optical method, a new reflective approach is used instead of the conventional transmissive one. Given this, the resolution is improved to 262,144P per revolution, twice the resolution of conventional motors. This, in combination with the reduction of the cogging torque, enables smoother operation.

In terms of the specification, the motors' standard protective structure IP65 is used (excluding the section the shaft passes through). This improves the durability to the environment, increasing the scope of application to food-processing equipment, machining equipment, etc. The connections between the motor and the encoder use connectors provided in the motor itself. Connections can be made in two directions–towards the load side and away from it–by changing the direction in which the connectors are attached. This increases the flexibility with which the power cable and encoder cable are routed. In the HF-KP series, the total length dimensions of the motor are reduced by 20 percent compared with conventional motors, despite the fact that the HF-KP series provides improved performance and functionality. ❑

Fig. 1 The HF-KP Series AC Servomotor