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Feature

Development of High-Speed AC Servo Motor

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1. Introduction

Higher speed and higher acceleration are required for driving the spindle of a machine tool, and motors for spindles must achieve both faster rotation and torque. These days, demand is rising even further for faster and higher-torque motors (i.e., motors with a larger range of operation).

This paper presents the features of internal magnet type synchronous servo motor (IPM motors) developed to meet these demands.

The paper will first present the main specifications of the newly developed IPM motor. Next, the paper will compare it with conventional surface magnet type synchronous motors (SPM motors) in terms of torque characteristics and will demonstrate that the newly developed IPM motor can achieve higher speed and torque while having the same motor structure and servo amplifier capacity as conventional SPM motors.

The paper will then compare the new motor with SPM motors in efficiency in a steady operation state and will demonstrate that the newly developed IPM motor is more efficient and a greater contributor to the energy-saving of host equipment than SPM motors.

The newly developed IPM motor achieves a maximum rotating speed of 16,000min^{-1} and a rated output of 6kW.

2. Main specifications of the newly developed IPM motor

Table 1 shows the main specifications of the internal magnet type synchronous servo motor (IPM motor) designed as the spindle of machine tools. Fig. 1 is an external view of the newly developed motor.

The newly developed IPM motor is a fully closed, external fan type spindle-purpose synchronous servo motor. The motor has a flange measuring 155mm each side and an overall length of 357mm.

This servo motor is given larger outputs (torque and rotating speed) while having the same structure and the same maximum current as a conventional surface magnet type synchronous servo motor (IPM motor), as will be described later. As opposed to conventional SPM motors having a rated output of 4kW, rated speed of 3,000min^{-1}, and maximum speed of 12,000min^{-1}, the new motor achieves a rated output of 6kW, rated speed of 6,000min^{-1}, and maximum speed of 16,000min^{-1}.

Table 1 Main specifications of the newly-developed IPM motor

Rated output	6kW	Detector	Optical incremental encoder
Rated torque	9.8N･m	Protection type	IP44 (except for shaft-penetrating portion and external fan)
Rated speed	$6000 min^{-1}$	Cooling system	Fully closed, external fan
Instantaneous maximum torque	44N･m	Vibration grade	V3
Maximum speed	$16000 min^{-1}$	Flange dimension	155mm
Rotor inertia	$19.6x10^{-4}$ kgm^2	Overall length of motor	357mm

3. Torque characteristics

3.1 Torque generated by PM motor

The torque, T, generated by a permanent magnet type synchronous motor (PM motor) can be expressed as follows:

$$T = 3p\{(E_m/\omega)I_q + (L_d-L_q)I_qI_d\} \quad (1)$$

$$I_q = I_a sin\Phi \quad (2)$$

$$I_d = I_a cos\Phi \quad (3)$$

Where p: number of pole pairs, E_m: electromotive force by the permanent magnet, ω : power supply angular frequency, L_d, L_q: motor armature inductance on the d axis and q axis,Φ: angle difference of magnetomotive force (the phase difference between the d axis and the center of motor armature magnetomotive force), I_d, I_q: motor armature current on the d axis and the q axis, I_a: motor armature current.

The first term on the right side of Equation (1) is a magnet torque component, while the second term is a reluctance torque component. In the case of a surface magnet type synchronous motor (SPM motor), $L_d = L_q$ so that no reluctance torque component occurs. Therefore, increasing torque with an SPM motor requires such a design that achieves a high bach-emf (BEMF)(E_m). However, increasing BEMF results in voltage saturation in the high-speed range, thus generating torque. In addition, the SPM motor can naturally be alleviated in voltage saturation by setting it to$\Phi > \pi/2$ and effecting equivalent field weakening control. However, this reduces torque and generates a harmonic eddy current loss on the magnet, resulting in lower efficiency [(1)].

On the other hand, internal magnet type synchronous motors (IPM motors) are subjected to $L_d < L_q$. Therefore, its current can be controlled in the range of $\Phi > \pi/2$ to effect equivalent field weakening control with the current of the d-axis motor armature and suppressing voltage, while adding it to the magnet torque component and using the reluctance torque component as an effective torque. The operation range can be expanded without reducing torque in the high-speed range.

3.2 Comparing the torque speed (T-N) characteristics

Fig. 2 compares Sanyo Denki's conventional SPM motor with the newly developed IPM motor in torque speed characteristics (instantaneous region). These SPM and IPM motors have a stator core with the same armatur length and inner diameter, and almost the same outside diameter. Drive-purpose servo amplifiers have the same specifications as well. However, servo amplifiers for driving IPM motors can control the reluctance torque component.

As is evident from Fig. 2, the newly developed IPM motor achieves a maximum torque in the low-speed range about 13% higher, and a maximum speed about 30% higher than conventional SPM motors. Thus, it is demonstrated that the newly developed IPM motor achieves higher torque and speed with the same servo amplifier (the same current) and the same motor structure as conventional motors.

The newly developed IPM motor is designed with optimal BEMF and reluctance torque with a magnet so as to combine high torque with high speed. For example, the motor is so designed as to achieve a lower BEMF with a magnetic flux than a typical SPM motor, thus suppressing speed electromotive force in the high-speed range and optimizing the shape of the rotor core to expand the reluctance torque component.

Here, let us think of an embodiment of the characteristics of an IPM motor shown in Fig. 2 in the form of an SPM motor.

Increasing the maximum speed from 12,000min^{-1} to 16,000min^{-1} requires reducing the torque constant (BEMF force constant) to avoid voltage saturation during fast rotation. To obtain the same torque, therefore, requires an increased current. The result is a rise (about 1.5-fold) in the current capacity of the servo amplifier, thus requiring a major cost increase.

A 10% rise in the maximum torque in the low-speed range requires a longer armature length in the motor core. However, a longer armature length increases the loss (iron loss) during fast rotation, resulting in an excessive heatup in the high-speed range.

Thus, on SPM motors, it is difficult to combine high torque with high speed in an economical design. As described above, in the newly developed IPM motor, higher torque and speed (i.e., a larger operable range) has been achieved with the same servo amplifier current capacity and the same motor structure.

On the newly developed IPM motor, the shape of its rotor core and the arrangement of its magnet are so specified as to maximize its resistance to strength to centrifugal force.

4. Efficiency and heatup during steady-state operation

4.1 Motor efficiency during steady-state operation

As described before, on the IPM motor, the magnet torque component and reluctance torque component can be used, resulting in a rise in torque generated per unit current and a lower copper loss in the motor armature at the same torque than SPM motor. Another point to be noted is a lower harmonic eddy current loss generated on the surface of the rotor, which results in higher operation efficiency than that of SPM motor.

Table 2 compares conventional SPM motors with IPM motors in terms of efficiency during a rated output. Motor efficiency is 86% for SPM motor, and as high as 90% for IPM motor. Compared with SPM motor, IPM motor suffer an armature copper loss of about 13% lower, and a sum of copper loss and machine loss of about 45% lower than IPM motor. The newly developed IPM motor is designed with a lower flux density with a magnet, resulting in a decline in the fundamental wave iron loss generated in the armature core. The non-exposure of the magnet into the clearance results in a decline in the harmonic eddy current loss generated in the magnet. Thus, the newly developed IPM motor is highly efficient, so that it will presumably be of sufficient help in the energy-saving of machinery incorporating such a motor.

Table 2 Comparison of efficiency during a continued rated operation (actual measurements)

Motor type	Number of poles	Flange (mm)	Overall length of motor (mm)	Rotating speed (min^{-1})	Torque (N・m)	Output (kW)	Efficiency (%)
Conventional SPM motor	4	155	364	3000	12.7	4	86
Newly developed IPM motor	4	155	357	3000	12.7	4	90

4.2 Motor heatup

Table 3 compares heatup results during steady-state operation. The heatup values in the table are expressed in relative values with regard to a typical SPM motor. This SPM motor achieves a rated speed of 3,000min^{-1} and a rated output of 4kW. The table indicates relative heatup values on the basis that the surface temperature of the frame of the SPM motor at this rating is 1.

Table 3 Comparison of heatup values (actual measurements)

Output (kW)	Rotating speed (min^{-1})	Torque (N・m)	Surface heatup values of motors	
			IPM motor	SPM motor
4.0	3000	12.7	0.75	1
6.0	6000	9.8	0.61	1.08
6.0	10000	5.7	0.77	1.17
0.0	16000	0	0.87	−

As is evident from Table 3, the heatup values of the newly developed IPM motor are higher than conventional SPM motors by 75% at 4kW/3,000min^{-1}, 61% at 6kW/6,000min^{-1}, and 77% at 6kW/10,000min^{-1}. The heatup values thus declined greatly with a rise in efficiency. The heatup values of the motor surface were no more than 45K.

Thus, the newly developed IPM motor achieves half again as high continuous output as conventional IPM motors, with the same structure and with a lower heatup. Furthermore, reduced heatup increases the service lives of motor constituents.

5. Conclusion

This paper has so far presented the features of internal magnet type synchronous servo motor (IPM motor) designed to meet the demand for higher speed and torque (i.e., a larger operation range) in motors as the spindles of machine tools.

The newly developed fast IPM motor is superior to conventional SPM motors of the same structure in the following aspects:

① The instantaneous maximum torque in the low-speed range (0 to 4,000min^{-1}) is 13% higher.

② The instantaneous maximum output in the high-speed range (5,000min^{-1} to 16,000min^{-1}) is 1.2 to 1.5 times as high.

③ Efficiency during steady-state operation is 4% higher (with a loss 30% lower).

④ The continuous output is half again as high.
The newly developed IPM motor is capable of running at high efficiency in a wide range of speed controls without increasing the servo amplifier capacity and motor size. This servo motor will presumably be of much help in the size reduction, speedup, and energy-saving of machinery.

References

(1)Takahashi, Matsushita, and Onodera: "Consideration of Iron Losses in Permanent Magnet Type Synchronous Motors," A Collection of Lecture Papers Read at the 1997 Congress of the Electric Society, No. 1125 (March 1997)

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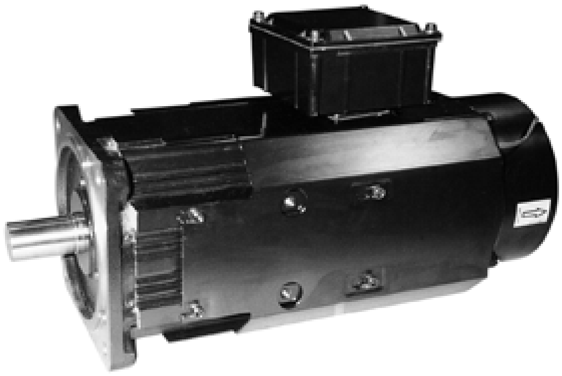

Fig.1 External view of spindle-purpose IPM servo motor

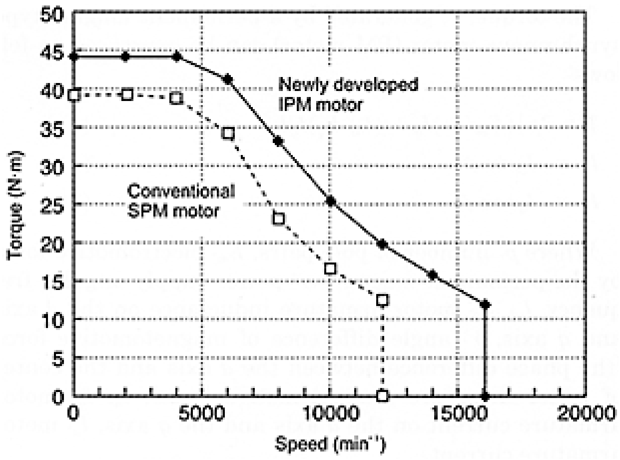

Fig. 2 Torque speed characteristics
(instantaneous range: measurements actually taken)
(input voltage: 3-phase, 200V, motor maximum current: 155Arms)