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# High Efficiency Hermetic Compressor Operated by IPM Motor and Inverter System

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## ABSTRACT

A high efficient Interior Permanent Magnet (IPM) synchronous motor used in a compressor for air conditioners, which we have developed and is now commercially produced, is presented in this paper. This IPM motor fed by an inverter is more efficient than any other type of motor at any rotational speed. There are two key factors to get such high efficiency, one is rare-earth permanent magnets placed inside of the rotor, and the other is appropriate control of the motor current vector by the inverter. These are explained in detail with the help of the equivalent circuit of PM motors. Machine parameters and efficiency of commercially produced motors are also given.

This type of motor is actually used in a commercial 3/4HP swing compressor for home-use air conditioners and in a 5HP scroll compressor for commercial-use air conditioners which we are manufacturing. It has been actually proved in the market that these compressors have desirable characteristics such as high efficiency and wide operating range.

## 1. INTRODUCTION

As public awareness of environmental issues is heightened, the requirement to reduce power consumption of air conditioning equipment is growing. Since the power is mainly consumed by a motor used in the compressor for air conditioners, it is most effective to use the high efficient motor to save energy. On the other hand, in order to reach comfortable room temperature quickly, increasing of heating and cooling capability is also required. Therefore it is desired to develop a variable speed motor to operate at higher rotational speed than conventional motors.

Inverter driven induction motors, which has moderate efficiency, are widely used for compressor application. Fig.1(a) shows the cross section of the rotor of an induction motor. Magnetic flux-induced currents passing through an aluminum conductor and armature winding currents produce torque in this motor. Then there is a limitation of efficiency in induction motors, because of the copper loss generated by the current through an aluminum conductor, which is unnecessary power consumption.

On the other hand, for a small capacity compressor, adopting of inverter driven permanent magnet motors is increasing rapidly. The rotor configuration of a Surface Permanent Magnet (SPM) synchronous motor known as a high efficient motor is shown in Fig.2(b). In this type of motor, magnetic flux necessary to produce torque are generated by permanent magnets, and then we can expect high efficiency without unnecessary power consumption. However, since there is a limitation in magnetic flux density by permanent

magnets, it is difficult to get higher efficiency in the case of a large capacity motor. Although the SPM motor is most efficient at maximum rotational speed, it is not sufficiently efficient at low to middle rotational speed where a compressor for air conditioners is mainly operated. In addition to that, if it is designed to make the maximum rotational speed even higher, it tends to make the efficiency even lower at low to middle rotational speed.

In order to cope with these problems, we focused attention to the configuration to place permanent magnets inside of the rotor instead of the SPM configuration. <sup>(1)(2)</sup> Fig.1(C) shows the configuration of a rotor of the Interior Permanent Magnet (IPM) synchronous motor we have developed. By appropriate control of the motor current vector by the inverter, we can utilize the reluctance torque effectively added to the magnetic alignment torque to realize the high efficient motors superior to other type of motor. Flux weakening control enables the motor to operate at higher rotational speed without reducing the efficiency.

In chapter 2, these features are explained with the help of the equivalent circuit of PM motors. In chapter 3, the characteristics of developed motors and the performance of commercially produced 3/4HP swing compressors and 5HP scroll compressors using IPM motors are introduced. And the capability of IPM motors to save energy, which meets the social needs, is also described.

## 2.CHARACTERISTICS OF IPM MOTOR AND INVERTER SYSTEM

### 2.1 Model of PM motor

The d-q axis equivalent circuits of PM motors are shown in Fig.2. The voltage and torque equations in the d-q coordinates are expressed as follows.<sup>(3)</sup>

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_a + pL_d & -\omega L_q \\ \omega L_d & R_a + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \dots\dots\dots(1)$$

$$T = P_n \psi_a i_q + P_n (L_q - L_d) i_d i_q \dots\dots\dots(2)$$

The first term in (2) represents the magnetic alignment torque produced by the magnetic flux of permanent magnets, and the second term represents the reluctance torque produced by the magnetic flux of the motor current.

### 2.2 Torque Characteristics of IPM motor

Since permanent magnets are placed on the surface of the rotor in the case of SPM motor in Fig.1(b), the motor inductance in d- and q- axis,  $L_d$  and  $L_q$  respectively, become equal, which means that the second term in (2) is nearly zero. Therefore, only the magnetic alignment torque can be produced.

On the other hand, in the case of IPM motors, since we place permanent magnets inside of the rotor and silicon steel laminations on the surface of that, the motor inductance in d- and q- axis can be designed to be different. The IPM motor shown in Fig.1(C) has a saliency as  $L_d < L_q$ . Consequently we can utilize the reluctance torque represented by the second term in (2) added to the magnetic alignment torque.

The following eq.(3) is derived by replacing  $I_d, I_q$  to the current to armature windings  $I_a$  to (2).

$$T = P_n \psi_a (I_a \cos \beta) + P_n \frac{L_q - L_d}{2} (I_a^2 \sin 2\beta) \dots\dots\dots(3)$$

where  $I_a$  : armature current [A]

$\beta$  : phase of armature current[deg]

Fig.3 shows the magnetic alignment torque and the reluctance torque with respect to the current phase in the case of IPM motors having the inductance  $L_d=10.7$ [mH] and  $L_q=27.6$ [mH]. Apparently from Fig.3, by controlling the current phase  $\beta$  appropriately with the inverter, the sum of the magnetic alignment torque and the reluctance torque can reach approximately 35% larger compared with the case only the magnetic alignment torque is produced. In other words, in order to produce the torque necessary to rotate the same compressor, the IPM motor needs 35% less motor current than the SPM motor, which means that the IPM motor is significantly efficient.

### 2.3 Flux Weakening Control of IPM Motor

From (1) the terminal voltage  $V_a$  of PM motors is expressed as follows

$$V_a = \sqrt{V_d^2 + V_q^2} \\ = \sqrt{(R_a i_d - \omega L_q i_{oq})^2 + \{R_a i_q + \omega(\psi_a + L_d i_{od})\}^2} \dots\dots\dots(4)$$

Since there is a limitation of the output voltage of the inverter, the terminal voltage must be less than the maximum inverter voltage. As rotational speed is increased, the voltage expressed by the underlined term in (4) becomes inevitably high.

Placing the silicon steel laminations on the surface of the rotor of IPM motors enables to design the d-axis inductance  $L_d$  to be large. Then, by putting the d-axis current  $i_d < 0$  the voltage, which cause problems at high rotational speed as mentioned above, can be effectively reduced. This becomes possible by the phase control of the motor current vector just as mentioned for the reluctance torque. Then it is generally called the flux weakening control because it is equivalent to reducing(i.e. weakening)  $\psi_a$ . With this control, we can relieve the limitation of rotational speed which is the inherent issue of PM motors. As a result, we can make the extremely high efficient motor at low to high rotational speed without sacrificing efficiency, which meets the needs to increase the air conditioner's performance.

## 3. PERFORMANCE EVALUATION

### 3.1 Motor Performance Characteristics

Machine parameters of the IPM motor used in an commercially produced 3/4Hp swing compressor are shown in Table 1, and the cross section and appearance of it are shown in Fig.4. In the rotor of this motor, rare-earth permanent magnets(Neodymium-Iron-Boron) are used, which have the magnetic energy density ( $BH_{max}$ ) approximately 10 times as high as conventional ferrite magnets. Using this high performance permanent magnets enables us to make the inserted magnet pieces thin and place them inside of the rotor. As a result, salient coefficient  $L_q/L_d=2.58$  and large d-axis inductance 27.6mH are obtained in this particular case, which show that the features of IPM motors are utilized.

Rotational speed versus efficiency characteristics of the IPM motor, the SPM motor and the induction motor are compared in Fig.6 under the condition of the rated-load torque and room ambient temperature. The IPM motor achieves significant high efficiency reaching 95% at its peak, which is about 40% higher at low rotational speed and more than 10% higher at the rated rotational speed compared with the induction motor used commonly so far.

### 3.2 Compressor Performance

From rotational speed versus COP characteristics of a 3/4HP swing compressor<sup>(4)</sup> using IPM motor under the load condition in actual operation shown in Fig.7-a, it is obvious that the compressor with IPM motor can significantly improve the performance compared with the compressor using conventional induction motors. By adopting the IPM motor first in the HVAC industry, we achieved the top-level energy saving performance since the IPM motor can improve the efficiency especially at low to middle rotational speed where a compressor for air conditioners is mainly operated.

Fig.7-a shows the rotational speed versus COP characteristics of a 5HP scroll compressor using IPM motor under the same load condition as above. You can also see the significant improvement at low to middle rotational speed. By using the IPM motor first in the world in this category of air conditioners, this newly introduced compressor would become the world leading compressor in energy saving performance.

### 4.CONCLUSION

At present there are two major issues in the compressor system for air conditioners. One is to handle alternative refrigerants corresponding to total abolition of refrigerants using HCFCs in order to prevent ozone layer depletion, and the other is to achieve further energy saving to cope with the global warming. Newly developed swing and scroll compressors can handle the alternative refrigerants. And by adopting the IPM motor and inverter to the compressor, we can provide one solution to the energy saving of air conditioners.

Moreover, this new sophisticated motor and inverter technology can be adopted to the compressor of even large capacity more than 5HP, which would contribute to significant energy saving and comfortable air conditioning capability. Since high efficiency, high torque and high maximum rotational speed performance of this motor are also desirable for electric vehicles and refrigerator compressors for example, IPM motor will be paid more attention to as the significant energy saving motor which meet the social needs.

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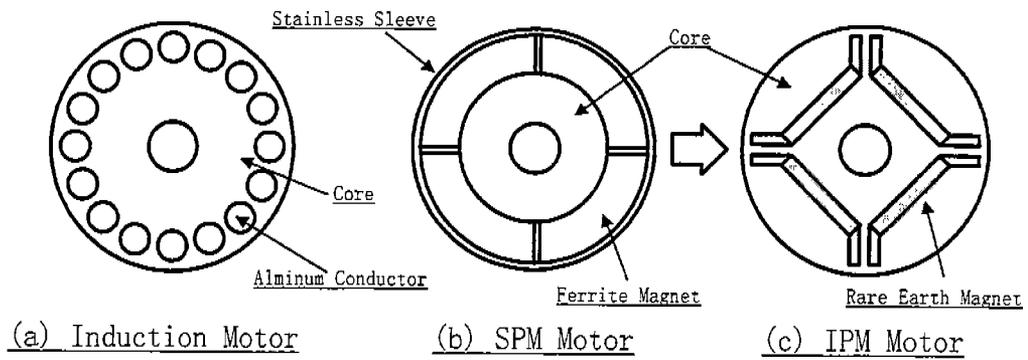
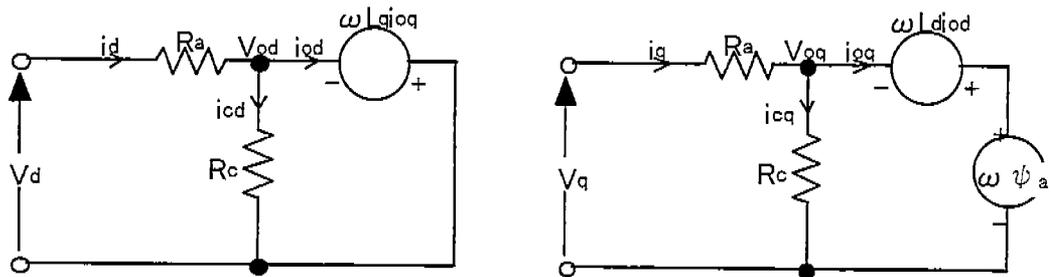


Fig.1 Rotor Configuration



(a) d-axis equivalent circuit

(b) q-axis equivalent circuit

$V_d, V_q$ : d-q axis Motor Voltage

$R_a$ : Winding Resistance of each phase

$i_d, i_q$ : d-q axis Motor Current

$R_c$ : Equivalent Ferro Loss Resistance

$L_d, L_q$ : d-q axis Inductance

$P_n$ : Pole Pair

$\omega$ : angular velocity

$\psi_a$ : Magnetic Flux-Linkage

Fig2. Equivalent Circuits of PM Motor

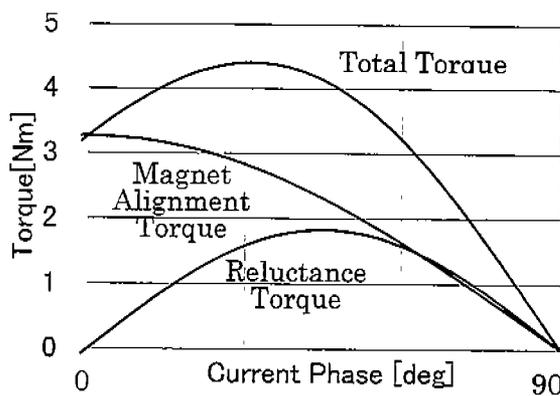


Fig3. Torque-Phase characteristic for IPM

Table1. Electrical motor parameters

Maximum speed	7,200(r/min)
Maximum torque	4.5(Nm)
Magnet flux-linkage	0.157(Wb)
d-axis inductance	10.7(mH)
q-axis inductance	27.6(mH)
winding resistance for a phase	0.81(ohm)
pole-pair	2

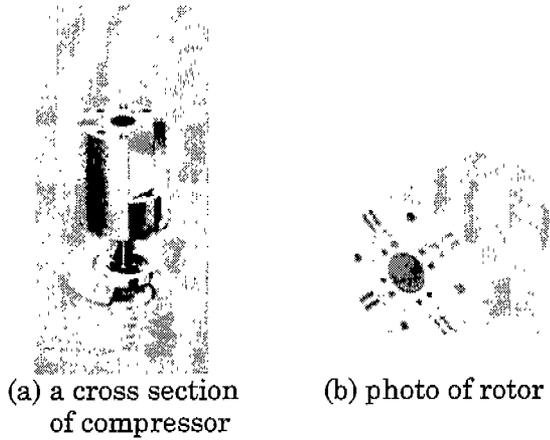


Fig4. Mass produced IPM Motor

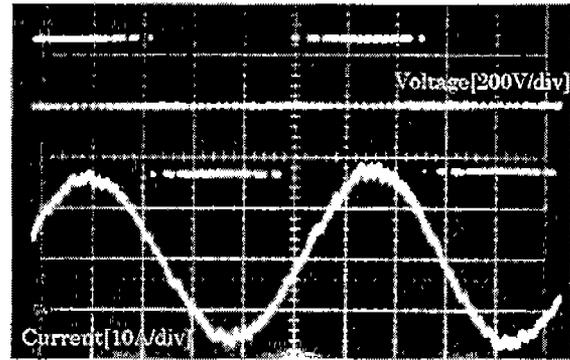


Fig5. Inverter Output Voltage and Current Waveforms

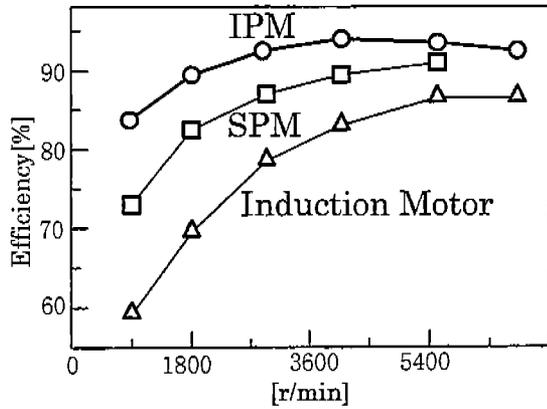


Fig6. Efficient comparison of each Motor

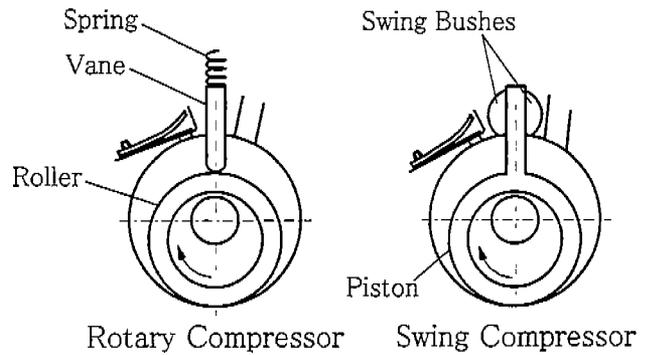


Fig8. Structures of Compressor

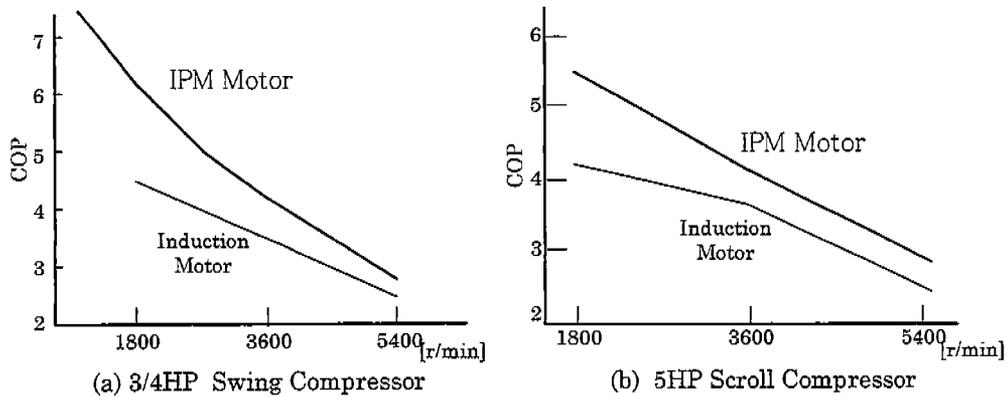


Fig7. Efficiency of Compressors