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Development of Highly Efficient Compressor Series Driven by IPM Motors

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ABSTRACT

Due to the recent environmental concerns, the demand for highly efficient compressors with inverter speed control is escalating as well as those with HFC refrigerants. Accordingly, we have developed highly efficient compressor series with inverter speed control.

The series consists of five models with its system capacity ranging from 2.2kW to 16kW. The Interior Permanent Magnet (hereinafter referred to as IPM) synchronous motors using rare-earth permanent magnets are adopted for all the compressors of this series. Swing compressors are adopted for small range from 2.2kW to 8kW and scroll compressor is adopted for large range up to 16kW. As a result, the efficiency improved by 17 to 32% in the low speed range and 12 to 18% in the high speed range.

In conclusion, we were successful in developing highly efficient compressor series. All the models are designed for R410A, R407C and R22.

1. INTRODUCTION

Though the conventional inverter controlled air conditioners are fairly efficient under the standard load conditions, they are not efficient under the partial load conditions. Therefore, in order to improve the efficiency of the inverter controlled air conditions, it is essential to operate compressors at high efficiency in the range from low to high speed.

For development of such compressors, we needed to solve two problems. The first one was to develop compressors which can operate at high efficiency from low to high speed. The second one was to select the optimum compressor type for corresponding capacity.

This paper explains about development of highly efficient inverter controlled compressor series.
2. DESIGN CONCEPT AND TEST RESULTS

2-1. Outline of the series

Fig.1 diagrammatically shows the basic design concept of the compressor series. All the models adopt the IPM motors using rare-earth permanent magnets. The structure of compressors is classified according to the corresponding capacity. The small range from 2.2kW to 8kW adopts the swing type and the large range up to 16kW adopts the scroll type. The swing type is a kind of rotary compressor of which vane and roller are structured in monobloc. In order to minimize the leak from the clearance, the smallest model adopts one cylinder structure. In order to improve the efficiency, the scroll compressor has a discharge chamber and its passage with a valve for short circuiting the refrigerant under the partial load. As for the refrigerants, all the models are designed for R410A, R407C and R22.

2-2. Assessment conditions

Unlike the standard air conditioner, the compressor of an inverter controlled air conditioner changes the operating speed according to the required load. The basic design concept for development of inverter controlled compressors is to obtain high efficiency under various temperature conditions to meet the actual operating conditions in the field. The assessment condition is made on the basis of investigated relations between the temperature conditions and the compressor speed of inverter controlled air conditioners normally used in the field.

2-3. IPM motor

It is essential for compressor motors to operate at high efficiency from low to high speed for wide application range.

With the conventional induction motors used for inverter controlled compressors, there is a limitation in reduction of copper loss created by the current generated through the aluminum conductor. This copper loss is called the exciting loss. Unless the exciting loss is reduced, there is no way to improve the efficiency.

On the other hand, since the ferrite permanent magnets mounted on the SPM (surface permanent magnet) synchronous motor generates magnetic flux which is required for torque, the motor gives high efficiency without the exciting loss. However, since there is a limitation in magnetic flux density, large size motors cannot output high efficiency performance. In addition, the efficiency of the SPM motor reaches the highest point at the maximum speed and is unsatisfactory in the range of low to medium speed.

Fig.2(C) shows the configuration of a rotor of the Interior Permanent Magnet (IPM) synchronous motor we developed. By using the rare-earth permanent magnets of which the magnetic energy density is approximately 10 times of the conventional ferrite magnets, the magnet pieces to be inserted can be made thinner and mount inside of the rotor. This IPM motor generates not only magnetic torque but also the reluctance torque. Fig.3 shows the motor torque versus the current phase.
The sum of the magnetic alignment torque and reluctance torque can reach approximately 35% larger than that in the case of only the magnetic alignment torque being 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 that of the SPM motor. In addition, flux weakening control enables the IPM motor to operate at higher speed without reducing the efficiency in the range from low to medium speed. Fig.4 shows that the efficiency greatly improves. Therefore, we decided to adopt the IPM motor using the rare-earth permanent magnets for this compressor series.

Additional efficiency improvement is obtained by selecting the sine wave Pulse Width Modulation (hereinafter referred to as PWM) inverter for speed control. The compressor motor transmits the signal of 6 pulse per one rotation to the microcomputer in the PWM inverter. Based on this signal, the microcomputer generates the sine wave signal and returns the result to the compressor motor. The sine wave reduces the harmonic loss from the rectangular wave. As a result, the efficiency improves by 0.9% in the low speed range and 2.3% in the high speed.

As shown above, the motor efficiencies of all the models improved by approximately 13% in the low speed range and 8% in the high speed range.

2-4-1. Selection of compressor type

In this range, the scroll type and the swing or rotary type are the most suitable type. We selected the type according to the capacities in consideration of each characteristics. The comparison of characteristics of each type are shown as follows:

Since the swing or rotary type has a structure of discharging the gas by operating the valve utilizing the inlet and outlet pressure difference, the efficiency is uniformly high regardless of operating conditions. However, due to its load characteristics which constantly fluctuate during one rotation, the bearing design for large capacity models is difficult.

Therefore, the swing type shows more advantageous characteristics for smaller capacity models and also in the low speed range when the compression ratio is small.

On the other hand, since the scroll type has a structure of discharging the gas according to the initially designed fixed compression ratio without using a valve, the efficiency is high at a certain point. Due to its characteristics of uniform load during one rotation, the bearing design for larger capacity models is not difficult.

Therefore, the scroll type shows more advantageous characteristics for larger capacity models.
Fig. 5 shows the total compressor efficiency by each compressor type of the equivalent capacity. It shows that though the efficiency of scroll type is higher than that of the swing type at a certain point, it is smaller than that of the swing type in the low speed range and under low compression ratio.

Fig. 6 shows efficiencies of various simulated compressors. The swing type is highly efficient in the small capacity range and the scroll type is highly efficient in the large capacity range and their boundary lies somewhere around 8kW. In addition, the swing type has a simple structure and cost efficient. Therefore, we decided to set the boundary at 8kW. However, we selected one cylinder type for the smallest model which has structurally less leakage.

2-4-2. Improvement of swing type efficiency

The swing compressor is a rotary compressor of which sliding vane and roller are designed in monobloc structure. Therefore, the swing type has no contact between the roller and the vane and, as a result, the mechanical loss between the roller and the vane is eliminated and results in less oil deterioration and less generation of sludge, which means HFC refrigerants are applicable. In addition, the monobloc structure has an advantage of less gas leakage from high to low pressure side.

Since optimization of lubricating oil leakage amount from high to low pressure side is a theoretically important factor, we added this subject for improvement of efficiency.

The test analysis of the swing type and the rotary type is as follows:

The monobloc structure reduces leakage from high pressure side to low pressure side and, as a result, the volumetric efficiency improves by 3% in the low speed range.

We conducted the test by changing the clearance between the cylinder and the piston (which is the name of roller and vane in monobloc), and checked the relation between the clearance and the efficiency instead of measuring the leakage amount. Fig. 10 shows the results. It shows that for improvement of efficiency the clearance must be optimized. If the clearance is too small, the sealing effect is insufficient and the capacity drops. On the other hand, if the clearance is too large, the sealing effect is sufficient but unnecessary oil is compressed and the power loss is created. As a result, the optimized clearance contributes to improvement of efficiency by 1% in the low speed range.

The monobloc structure also contributes to improvement of mechanical efficiency in the high speed range by 5%.

Other improvements include optimization of discharge valve lift height, increase of crank shaft rigidity and addition of streamlined cover for balance weight. In conclusion, the efficiency totally improved by 4% in the low speed range and 7% in the high speed range without the effect of IPM motor.
2-4-3. Efficiency improvement of scroll type

All the improvements applied to the standard non-inverter controlled compressors are applied to the IPM motor mounted inverter control compressors. These improvements are as follows:

(1) volumetric efficiency improvement by eliminating superheat of suction gas by adoption of high pressure casing.

(2) indicated efficiency improvement by reducing leakage inside the scroll. For reduction of leakage, we adopted non-uniform thickness scroll wrap and improved compliance between fix scroll and orbiting scroll.

(3) reduction of over compression loss by giving time lag between the compression chamber A and B by adoption of asymmetric scroll configuration.

However, these improvements are not sufficient for inverter controlled compressors which are used in the wide operating range. For obtaining high efficiency under wide range of compression ratio, it is necessary to (1) reduce the over compression loss when the compression ratio is small at low speed and (2) reduce the discharge pulsation when the capacity is large at high speed.

For improvement of these disadvantages a discharge chamber and a passage with a valve were added. The discharge chamber is a buffer which is located on the back side of fixed scroll wrap and connected with the discharge port, and functions as a muffler. As a result, the pulsation is reduced. The valve mounted on the passage opens when the compression ratio and the operating speed are low to reduce the over compression loss. As a result, its efficiency improves by 9% in the high speed range and 17% in the low speed range without the effect of IPM motor.

3. CONCLUSION

In conclusion, we were successful in developing high efficiency compressor series by adoption of IPM motors, optimization of compressor model which corresponds to the capacity and other miscellaneous improvements. As a result, the total efficiency is improved by 17% to 32% in the low speed range and 12 to 18% in the high speed range. In addition, we verified that all the models can be used for R410A, R407C and R22.

4. REFERENCES


(3) M.Masuda, et al., "Development of Swing Compressor For Alternative Refrigerants", International Compressor Conference at Purdue, 1996

(4) S.Hagiwara, et al., "Development of Scroll Compressor of Improvement High-Pressure-Housing", International Compressor Conference at Purdue, 1998
<table>
<thead>
<tr>
<th>System Capacity</th>
<th>2.2~3.2kW</th>
<th>~5kW</th>
<th>~6kW</th>
<th>~8kW</th>
<th>~16kW</th>
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</thead>
<tbody>
<tr>
<td>Motor</td>
<td>IPM Motor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor Type</td>
<td>Swing Compressor</td>
<td>Scroll Compressor</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cylinder</td>
<td>1 Cylinder</td>
<td>2 Cylinder</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refrigerants</td>
<td>R410A·R22·R407c</td>
<td></td>
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Fig. 1 Basic Design Concept of Compressor Series

(a) Induction Motor  (b) SPM Motor  (c) IPM Motor

Fig. 2 Rotor Configuration

Fig. 3 Torque-Phase Characteristic for IPM

Fig. 4 Efficient Comparison of each Motor

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Fig. 5 The Total Efficiency by Compressor Type of Equivalent Capacity

Fig. 6 Efficiencies of Various Simulated Compressors (The Temperature Condition is Constant)

Fig. 7 Structures of Compressor

Fig. 8 Comparison of Volume Efficiency in Swing and Rotary Type

Fig. 9 Axial Clearance between Cylinder and Piston

Fig. 10 Relation between The Clearance and The Efficiency

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Table 1. Comparison of Mechanical Loss in Swing and Rotary Compressors

<table>
<thead>
<tr>
<th>Lubrication Parts</th>
<th>Swing Compressor</th>
<th>Rotary Compressor</th>
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<tbody>
<tr>
<td>Main/Sub Bearing</td>
<td>24.1%</td>
<td>24.0%</td>
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<tr>
<td>Crank-pin Bearing</td>
<td>34.5%</td>
<td>31.7%</td>
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<tr>
<td>Vane and Roller</td>
<td>24.0%</td>
<td>12.5%</td>
</tr>
<tr>
<td>Vane Side</td>
<td>6.6%</td>
<td>26.5%</td>
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<tr>
<td>Outside of Swing Bush</td>
<td>6.0%</td>
<td>5.3%</td>
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<tr>
<td>Crank Thrust</td>
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<tr>
<td>Total of Loss</td>
<td>95.3%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Comparison of The Same Design and Same Class of Compressor (~3.2kW Model)

Fig.11 Configuration of Scroll Wrap

Fig.12 Section of Scroll Compressor

Fig.13 Total Efficiency of Swing Compressor (~6kW Model)

Fig.14 Total Efficiency of Scroll Compressor (~16kW Model)