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Topology Optimization of Single-Phase Induction Motor of Rotary Compressor for Reducing OCR

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ABSTRACT

The oil circulation rate (OCR) of the rotary compressor is a crucial factor affecting the performance and reliability of air-conditioning systems. In this paper, topology optimization of the single-phase induction motor of rotary compressor is carried out for reducing the OCR. The nonlinear transient characteristic of single-phase induction motor for rotary compressor is analyzed by using FLUX2D. The topology optimization for electromagnetic systems is developed using the finite element method (FEM). The proposed method is applied to a single-phase induction motor for reducing the OCR. For validation, optimized induction motors are manufactured and tested.

NOMENCLATURE

\[ A \]: Vector potential
\[ \mu \]: Permeability
\[ \tilde{A} \]: Space of virtual vector potential
\[ H \]: Magnetic field intensity
\[ P \]: Penalization factor
\[ J \]: Current density
\[ \lambda \]: Adjoint vector potential
\[ \tilde{\lambda} \]: Virtual adjoint vector potential
\[ B \]: Magnetic flux density
\[ \rho \]: Density function

INTRODUCTION

The oil circulation rate (OCR) of the rotary compressor is a crucial factor affecting the performance and reliability of air-conditioning systems. The flow circulating in refrigeration systems is a mixture of the refrigerant and lubricating oil. The primary function of the lubricating oil is reducing friction to minimize wear at the journal bearing of the compressor. The oil pumped out of the compressor causes problems both in the unit and the compressor. The oil concentration in the unit may have significant effects on the hydrodynamic and heat transfer performance of the condenser and the evaporator, because of changes in the thermodynamic and transport properties [1]. So it negatively affects the unit efficiency by lowering effectiveness of coil heat transfer. And high OCR may lead the compressor to bearing failure in split, multi-evaporator split and heat pump. Recognizing these important effects of oil in a refrigeration system, the OCR must be kept at minimum level.
Stator core cut area and rotor vent hole, which are related with pressure drop across motor, are major factors to reduce OCR as paths are related with gas velocity as shown in Figure 1 [1].

In this paper, the topology optimization of the single-phase induction motor is obtained to reduce the OCR and the results of the topology optimization are validated by the experimental tests.

The study of the topology optimization on the electromagnetic systems began few years ago [2-3]. The principle of the topology optimization on electromagnetic systems is the same with that of structural systems. Researchers applied the topology optimization methodology into the electromagnetic system using the density method.

Hence, this paper aimed on the development of theory and the application into the single-phase induction motor for the rotary compressor. In this paper, the torque properties of the single-phase induction motor are calculated by using a commercial finite element analysis (FEA) program, FLUX2D, because FLUX2D can easily express the effect of the squirrel cage in the induction motor.

However, the topology optimization is obtained by using a different FEA program, ANSYS, because the access and change of ANSYS files for reanalysis and optimization are much easier than those of FLUX2D. To obtain the meaningful topology optimization, the magnetostatic analysis of ANSYS uses all information calculated from the magneto-transient analysis of FLUX2D.

The sensitivity equation is derived using the continuum method [4], and the sensitivity is calculated by using the software of topology optimization for electromagnetic systems [5]. In the optimization program, the optimization routine is implemented using SLP in DOT [6].

A single-phase induction motor is optimized to reduce the OCR while maintaining the current torque. The optimized design shows improved OCR without losing the torque after they are manufactured and tested.

**TOPOLOGY OPTIMIZATION**

**Sizing Design Sensitivity Analysis of Electromagnetic Systems**

Design sensitivity analysis (DSA) [4] is widely used in structural systems. Mostly DSA for electromagnetic systems are related with shape design variable [6] because sizing variable case like thickness was rare in electromagnetic devices.

Consider a measure of electromagnetic performance that may be written in integral form as

$$\psi = \iiint_{\Omega} g(A, \nabla A, u) d\Omega$$

where $A$ is the vector potential, $u = [J_s, \mu]^T$ is the design vector of current density and permeability.

Using the variational form of objective function of (1) and direct differentiation result [4], the sizing design sensitivity equation is [5]

$$\psi' = \iiint_{\Omega} [g_A A' + g_{vA} \nabla A' + g_u \delta u] d\Omega$$

$$= \iiint_{\Omega} g_u \delta u d\Omega + \iiint_{\Omega} [g_A A' + g_{vA} \nabla A'] d\Omega$$

$$= \iiint_{\Omega} g_u \delta u d\Omega + \lambda' \alpha (A, \lambda) - a' \alpha (A, \lambda)$$

The adjoint equation for the adjoint variable $\lambda$ is

$$\alpha_u (\lambda, \overline{A}) = \iiint_{\Omega} [g_A \overline{A} + g_{vA} \nabla \overline{A}] d\Omega$$

where $\overline{A}$ is the virtual adjoint vector potential, $\overline{A}$ is the space of virtual vector potential, And the adjoint equation must hold for all admissible virtual vector potential $\overline{A} \in \overline{A}$.  

**Topology Sensitivity of Linear Magnetostatic Fields**

The magnetostatic field can be described using the set of Maxwell’s equations.

\[ \nabla \times H = J_s , \quad H = \frac{1}{\mu} (B - \mu_0 M) , \quad \nabla \cdot B = 0 \]  \( (4) \)

where \( H , J_s , B , \mu , \mu_0 \) is the magnetic field intensity vector, the current density vector, the magnetic flux density vector, the permeability of material, and the permeability of free space \((4\pi \times 10^{-7})\), respectively.

By introducing a vector potential, \( A \), such that \( B = \nabla \times A \) and eliminating \( H \) in \( (4) \), we have a single governing equation

\[ \nabla \times \left( \frac{1}{\mu} \nabla \times A \right) = J_s + \nabla \times \left( \frac{\mu_0}{\mu} M \right) \]  \( (5) \)

To obtain the variational equation, multiplying both sides of \( (5) \) with the virtual vector potential \( \lambda \) and integrating over the domain and applying boundary condition \([4-5]\), then the variational equation becomes

\[ a_\Omega (A, A) = l_\Omega (A) \quad \text{for all} \quad A \in \tilde{A} \]  \( (6) \)

where \( a_\Omega (A, A) \) is the energy bilinear form and \( l_\Omega (A) \) is the load linear form. Those are functions of permeability \( \mu \) and system output \( A \).

The adjoint equation of \( (3) \) may be defined, which in this case is

\[ a_u (\lambda, \lambda) = \iint_\Omega \left[ g_A \lambda \right] d\Omega \]  \( (7) \)

because of the gradient of virtual vector potential \( \nabla \lambda \) becomes zero.

If the equivalent source current is \( J_{eq} = g_A \), then the adjoint response \( \lambda \) is the response of \( (5) \) but the right side of \( (5) \) is replaced with equivalent source current.

\[ \nabla \times \left( \frac{1}{\mu} \nabla \times \lambda \right) = J_{eq} = g_A \]  \( (8) \)

Using design sensitivity formula of \( (2) \) and variations of the energy bilinear form and load linear form from \( (6) \), the sensitivity about permeability is \([5]\)

\[ \frac{\partial \psi}{\partial \mu} = \iint_\Omega \left[ g_{\rho} + \frac{1}{\mu^2} (\nabla \times A) \cdot (\nabla \times \lambda) d\Omega - \frac{\mu_0}{\mu^2} M \cdot (\nabla \times \lambda) \right] d\Omega \]  \( (9) \)

In order to represent the porous material, suppose a fictitious material whose properties like permeability \( \mu \) can be represented as a \( p \)-powered function of \( \rho \), that is \([5]\),

\[ \mu = (\mu_0 \mu, - \mu_0) \rho^p + \mu_0 , \quad p > 1 \]

\[ \int_\Omega \rho(x) d\Omega \leq V , \quad 0 \leq \rho(x) \leq 1 , \quad x \in \Omega \]  \( (10) \)

where \( P \) is a penalization factor, \( \rho \) is a density function.
FEA OF INDUCTION MOTOR

In this paper, the single-phase induction motor of the rotary compressor is analyzed by using the 2D FEA. The FE model and the boundary conditions are shown in Figure 2 and 3, respectively.

The input voltage and frequency are 115 [V] and 60 [Hz]. The outer radius of stator is 52.6 [mm], the outer radius of rotor is 27.5 [mm], and the stacked height of motor in the vertical direction is 76 [mm]. And this motor has the 33 slots of rotor and the 24 slots of stator.

For the non-linearity of stator and rotor, the saturation point of magnetic density is defined as 1.79 [T] as shown in Figure 4. And also, for driving the motor, the external circuit is designed by FLUX2D.

In this paper, through the non-linear transient FEA, the torque properties of induction motor are studied at 3509, 3482, 3472, and 3000 RPM. At 3509 RPM, the plot of torque vs. time is shown in Figure 5. These results are validated with the experimental data as shown in Table 1. The error is below 3%.

TOPOLOGY OPTIMIZATION OF SINGLE-PHASE INDUCTION MOTOR

For the topology optimization, another FE model is made by using ANSYS as shown in Figure 6 because the access and change of ANSYS files for the reanalysis and the optimization are much easier than those of FLUX2D.

All material properties and applied loads of ANSYS model are obtained from the verified FLUX2D model (3509 RPM). However, differently from FEA, in the topology optimization, the linear material properties are used such as the relative permeability of stator is about 4000.

The single-phase induction motor has only one current input. It is impossible to make rotating magnetic fields since it has only one source current. Thus the single-phase induction motor uses a condenser to make another current that has 90º phases delay as shown in Figure 7.

The induction motor is put in the middle of the rotary compressor as shown in Figure 1. And for the cooling and lubricant effect, the lubricating oils flow under the motor. However, some of lubricating oils flow into the upper side through the stator core cut area and rotor vent hole due to the difference of the pressure between upper and lower side of motor. The amount of loss for total oils is called as OCR.

For reducing the difference of the pressure, the new holes or more cut areas in the stator and rotor are required in the induction motor. Therefore, the topology optimization of the single-phase induction motor is needed to reduce the OCR while maintaining the torque and the efficiency of motor.

The objective function for this example is the magnetic energy (magnetic energy is used since torque is generated by the derivative of energy) and the constraint is volume (80% is remained) of stator or rotor.

\[
\text{Maximize } W_m = \int_{\Omega_1} \frac{1}{2\mu_0} \left[ B_x^2 + B_y^2 \right] d\Omega_1
\]

Subject to

\[
g_i = \int_{\Omega_2} \frac{\rho A d \Omega_2}{0.8V_0} - 1 \leq 0, \text{ Bounded to } 0 \leq \rho \leq 1 \text{ for all } \rho \in \Omega_2
\]

where \(A\) is the area, \(t\) is the thickness, and \(V_0\) is the initial volume.

There are many possible optimal topologies depending on time. Among them, optimal topologies are obtained only at \(t_1\) to \(t_4\) in Figure 7. Two topology results (at \(t_1\) and \(t_2\) in Figure 7) of them are shown in Figure 8 and 9. Therefore, it is needed to find an optimal topology that could be global optimum in whole time. The final optimized topology can be obtained by summing of topology results at each time as shown in Figure 10 and 11.

EXPERIMENTAL RESULTS

From the topology optimization, the improved models of induction motor can be designed. There are some cuts in the outer part of stator and holes in rotor for reducing the difference of pressure. The torque test of motor and the OCR test of rotary compressor are performed as shown in Tables 2 and 3. In the Tables, MRT and LRT mean the
variation rate (%) of maximum torque and starting torque, respectively. EER means the energy efficiency of compressor.

From topology optimization, the starting torque of induction motor looks like slightly increased and the efficiency of compressor is nearly maintained, and the OCR of Stator is decreased about 35 % due to reconfiguration in outer parts of stator and the OCR of Rotor about 33 % by means of rotor vent hole.

The gas passage area was increased twice as original area. It was expected that in our motor design’s experience the efficiency would be dropped 2 or 3 %. In spite of the big loss of steel amount, actual drop in motor shows much less than expected and the efficiency of compressor is found to be equal to original one. Particularly the effect of rotor vent hole looks like better than that of the stator reconfigured. The approach seems to be hopefully applicable to optimize the motor design.

CONCLUSIONS

In this paper, the topology optimization of induction motor for rotary compressor is carried out for reducing OCR. The topology sensitivity equation is derived using continuum approach. FLUX2D is used for nonlinear transient electromagnetic analysis and ANSYS is used for topology optimization for magnetostatic field. Optimal topology suggests cuts in outside of stator and new holes in side of rotor. New design is validated by test of manufactured ones.

ACKNOWLEDGEMENTS

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REFERENCES

Figure 1: Oil Discharge Mechanism in Rotary Compressor.

Figure 2. FE Model for FLUX2D

Figure 3. Boundary Condition

Figure 4. B-H Curve of Stator and Rotor

Figure 5. Torque in Transient FEA [3509 rpm]

Table 1. Comparison between Transient FEA and Experiment

<table>
<thead>
<tr>
<th>RPM</th>
<th>Slip</th>
<th>Torque [Nm]</th>
<th>Error (%)</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td>FEA</td>
<td>Experiment</td>
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<tr>
<td>3509</td>
<td>0.2528</td>
<td>1.5155</td>
<td>1.5344</td>
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<tr>
<td>3482</td>
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<td>1.8826</td>
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<td>3472</td>
<td>0.03556</td>
<td>2.0260</td>
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<td>3000</td>
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<td>4.8067</td>
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Table 2. Ratio Between Original and New in Stator

<table>
<thead>
<tr>
<th>*Motor Models</th>
<th>Motor (%)</th>
<th>Compressor (%)</th>
<th>Total Sample Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MRT (oz-ft)</td>
<td>LRT (oz-ft)</td>
<td>Efficiency (%)</td>
</tr>
<tr>
<td># 1</td>
<td>+0.3</td>
<td>+13.3</td>
<td>-0.23</td>
</tr>
<tr>
<td># 2</td>
<td>-0.9</td>
<td>+4.9</td>
<td>-0.50</td>
</tr>
</tbody>
</table>

Note 1. ‘*’ : Selected Representative Models in Same Motor Frame.
2. All data were calculated in proportion with original performance

Table 3. Ratio Between Original and New in Rotor

<table>
<thead>
<tr>
<th>* Motor Models</th>
<th>Motor (%)</th>
<th>Compressor (%)</th>
<th>Total Sample Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MRT (oz-ft)</td>
<td>LRT (oz-ft)</td>
<td>Efficiency (%)</td>
</tr>
<tr>
<td># 1</td>
<td>+ 0.7</td>
<td>+ 1.48</td>
<td>- 0.12</td>
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<tr>
<td># 2</td>
<td>- 1.1</td>
<td>+ 0.24</td>
<td>- 0.03</td>
</tr>
</tbody>
</table>

Note 1. ‘*’: Selected Representative Models in Same Motor Frame.
2. All data were evaluated in proportion with original performance.