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Design and Experimental Investigation of High-Speed Three-Phase Induction Motor for Turbo Blower

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Abstract

High-speed electrical motor has been studied for several applications, i.e. for direct-drive systems of centrifugal compressors and turbo blowers. This paper deals with a design consideration of electromagnetic, mechanical and thermal limits of high-speed induction motor for turbo blower. Basic design concept of high-speed motor was proposed. As the motor is to be operated at high speed, the losses are quite different from conventional low-speed machines.

Especially,the increases of rotor eddy current and friction losses could lead to an overheated motor. So, we suggested a special cooling system to reduce temperature rise. And, based upon this design concept, the prototype induction motor (37[kW], 45,000[rpm]) for high-speed turbo blower was designed and 2-D electromagnetic field analysis was implemented. Finally, criteria to evaluate the characteristics of high-speed induction motor have been proposed and tested.

Key Words : High-Speed, Design, Induction Motor, Turbo Blower

1. Introduction

In the recent years, with the aid of development of voltage and frequency converters, there has been an increasing interest on high-speed, variable speed drive systems for the waste-water treatment system and pneumatic conveying system. Therefore, the electric drive can be reach to the power range of 10~1000[HP] and speed range of 10,000~200,000[rpm]. In general, there are lots of possible candidates for the high-speed for previously mentioned power and speed ranges.

Some researchers reported the operation speed and power ranges of several high-speed motors, i.e. laminated cage type rotor and solid rotor induction motors and cylindrical permanent magnet synchronous motor[1]. Wen L. Soong et al.[2] have reported some papers on squirrel cage type induction motors of 28[HP], 47,000[rpm] for centrifugal compressor. Juha Saari[3] published a thermal analysis of solid rotor induction motor power range of 30~500[kW] and rotation speed range up to 200,000[rpm].

In the above mentioned works, it has been presented the comparison of electromagnetic, mechanical characteristic of each machine. Thepermanent magnet motor shows a high

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efficiency and high power weight ratio, but the highest cost and thermal constraints of rotor magnet is a main problem to solve. The solid rotor induction motor can stand very high speed operation over the rotor peripheral speed 400[m/sec]. So, it is being employed in applications such as large power and super high speed turbo compressors. But, its low efficiency caused from large rotor eddy-current losses and low power factor are the main problems to solve.

This paper reports the development of a laminated squirrel cage induction motor for turbo blower which is an industrial fan that supplies large air flow and medium pressure ratio. The targeted motor rating is a 37[kW], 45,000[rpm]. This capacity can supply an air flow 30[m^3/min] and pressure ratio 1.6.

Fig. 1 shows the basic construction of turbo blower. Turbo blower consists mainly of high-speed induction motor, air-foil bearings and 3-dimensional two impellers installed at both ends of the shaft. Two kinds of air-foil bearings were used to increase the reliability of rotor, one is radial bearing and the other is thrust bearing. This type of air-foil bearing means oil-free drive and its application for high-speed machines is very wide for their high reliability and low cost.

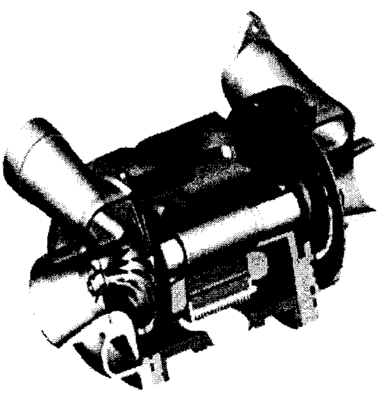


Fig. 1. Turbo Blower Model

In this work, some design considerations of laminated squirrel cage type high speed induction motor were dealt with and based upon this design concept, the prototype induction motor for high-speed turbo blower was designed and 2-D electromagnetic field analysis was implemented. Finally, criteria to evaluate the characteristics of high-speed induction motor have been proposed and tested.

2. Design of High-Speed Motor

2.1 Design process of high-speed induction motor

The design process of high-speed induction motor is quite different from conventional general purpose three-phase induction motor. And, it must be included careful considerations of electrical, mechanical and thermal (machine cooling problem) design point and can not be ignored the empirical design parameters comes from test results. The Fig. 2 shows the flow of design process for high-speed cage type induction motor. The first stage of design process begins to understand the load characteristics of turbo blower. Once the detailed load characteristics such as operation speed, air flow, and pressure ratio are known, we can estimate the motor output power and can design the rough rotor volume. Secondly, structural and electromagnetic aspects are considered in the design of the motors. And, the stability of rotor will checked from therotor dynamic analysis of motor. If the critical speed range of first bending mode is close to the operation speed, it is necessary to raise the critical speed to much higher than the operation speed. In that case, rotor dimensions (stack length, rotor outer diameter and shaft diameter) are modified to raise natural frequency. As a result, the design of high-speed motor is an iterative process to meet a required load characteristic. From the electromagnetic characteristics, the inverter power can be determined

The main factors to be considered at preliminary design stage for high-speed induction motor are as follows.

1) electromagnetic design considerations : additional high frequency losses, current density and magnetic flux density and iron losses.
2) mechanical design considerations : centrifugal forces acting on rotor surface, critical speed, rotor slot shape and end-ring shape of rotor and losses of windage and friction.
3) system cooling considerations : coolant passage on stator core, rotor cooling topology and temperature rise of stator coil.

Table 1. Required Load and Motor rating

Item	Value	Item	Value
Pr	1.6	Air flow	30[m³/min]
Phase	3	Poles	2
Power	37[kW]	Speed	45,000[rpm]

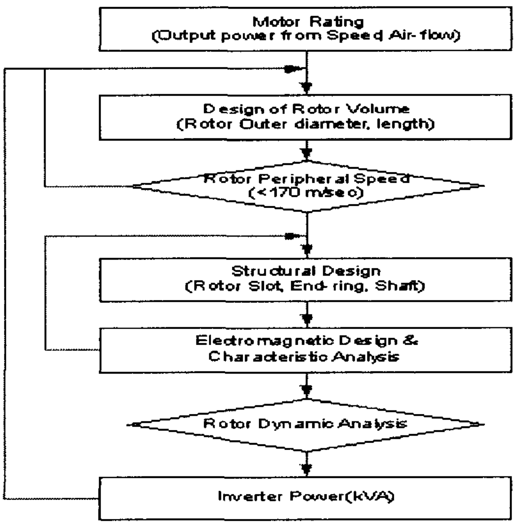


Fig. 2. High-speed motor design process

2.2 Required load characteristics and motor ratings

The required load characteristics of turbo blower and calculated motor ratings are shown in table I. The pressure ratio Pr (discharge pressure/suction pressure) is 1.6 and air flow is 30[m³/min]. From these conditions, the calculated motor output power is 37[kW] and operation speed is 45,000[rpm].

2.3 Electromagnetic Design

In high-speed induction motor, the power equation of m-phase winding motor can be expressed as[4],

$$P_o = mEI_s = C_o D_r^2 L_i n_o \quad (1)$$

C_o is output constant and D_r, L_i, n_o is rotor diameter, effective stack length, and synchronous speed respectively. Therefore, rotor volume can be written from equation (1).

$$V_r = \frac{\pi}{4} D_r^2 L_i = \frac{\pi}{4} \frac{P_o}{C_o n_o} \quad (2)$$

The output constant is related to stator current density and machine flux. By using these equations, the basic size of high-speed induction motor, when the output power and rotation speed is specified, rotor diameter and stack length can be calculated.

And, it is important to check the peripheral speed of rotor in order to prevent the mechanical deformation of rotor slots. Generally, a peripheral speed of silicon steel is limited to 200[m/sec]. But, in case of complicated shape like squirrel cage rotor, the peripheral speed is lowered to the range of 180[m/sec]. In this paper, its value is limited below 170[m/sec]. The stator of high-speed induction motor is the same shape of conventional low-speed motor. But, current density of stator conductor, rotor cage bar and end-ring is quite different.It is necessary to lower than that of general purpose motor due to its high power density per volume. The stator conductor would be better to use the round wire with several strands and it can be reduce the high-frequency copper loss. And, several considerations must be followed in electromagnetic design to reduce additional high frequency losses:

- arge stator slot number to improve the magneto motive force waveform.
- 2 layer winding with 5/6 chorded short pitch to minimize higher harmonic losses on rotor surface.
- modify the slot opening width to smooth the air-gap flux density.
- increase the air-gap length to reduce higher harmonic losses on rotor surface.

And, 2-dimensional magnetic field analysis is also calculated by time-stepping techniques to verify the field distributions and calculate rotor joule losses.

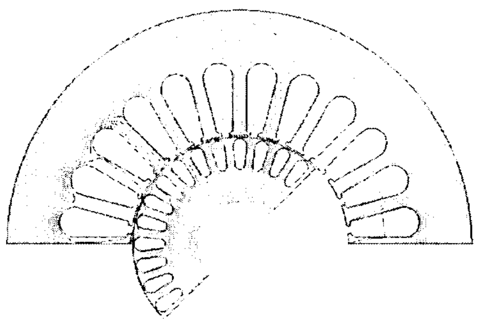
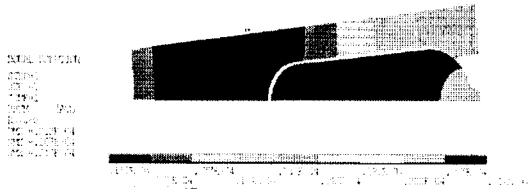


Fig. 3. Field distribution of high-speed induction motor

2.4 Structural analysis of rotor

The rotor slot shape must be designed to minimize stress caused by excessive centrifugal forces in high-speed operation. Fig. 4 shows the results of equivalent stress and displacement of rotor slots at 70,000[rpm] operation. It is a common concept to design rotor slot shape as a closed slot type to reduce windage loss in air gap area in high-speed operation.



(a) Displacement

(b) Equivalent stress

Fig. 4. Structural analysis of rotor

Especially, rotor slot tip height is important factor in high-speed induction motor mechanical design. It is closely related to maximum power and performance of motor, so its value must be within the allowable limit of material property. Considering operation speed and yield strength of silicon steel (250 Mpa), radial displacement of rotor slots and equivalent stress is permissible in this work.

The Fig. 5 shows mode shape of rotor assembly. And Table II is the natural frequency of rotor. The 1st bending mode appears at 856[Hz], and it means that critical speed of this rotor will be about 51,000[rpm]. According to this result, the normal load speed is lower than critical speed of turbo blower.

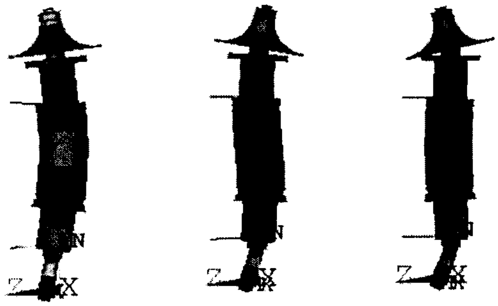


Fig. 5. Mode shape of rotor

Table 2. Natural frequency

Order	1	2	3	4
Frequency(Hz)	926	2,238	2,342	3,248

3. System Construction

3.1 Cooling System

The most important issues of turbo blower are efficiency of total blower system and thermal stability. The construction of turbo blower shows in Fig. 6. In order to achieve a thermal stability of motor, cooling system consists of stator cooling pin installed on stator frame and special rotor cooling fans that are installed on end-ring. The stator core and end windings are effectively cooled by suctioned and passed through the cooling pins which are made of aluminum and high heat conductivity. Additional special cooling fans reduce temperature rise below temperature rise limit.

3.2 Stator and rotor

Fig. 7 shows stator and rotor assembly for high-speed induction motor. The stator was manufactured to withstand a high temperature up to 180[℃] on the continuous normal load operation. And, rotor core is fabricated using aluminum die-casting process. The lamination of stator and rotor core was chosen 0.35[mm] thickness silicon steels to reduce iron losses. The bearings consist of two types: journal bearings which sustain a radial load and thrust bearing which sustain a thrust load acting axially on shaft.

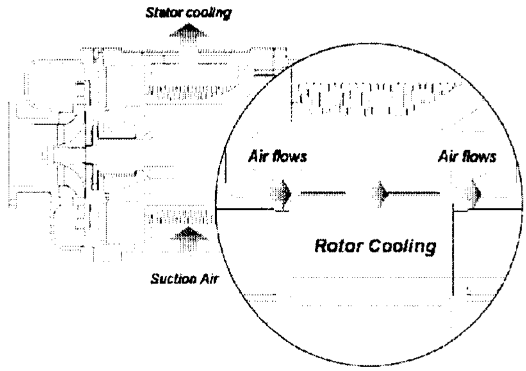


Fig. 6. Cooling system of motor

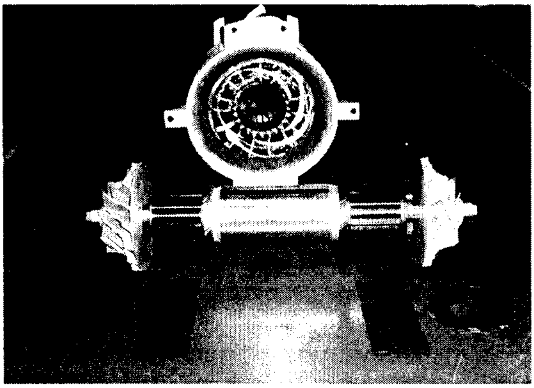


Fig. 7. High speed induction motor for turbo blower

4. Test Result

4.1 Mechanical loss

No load test of high-speed induction motor is carried out to measure the windage and friction loss of rotor without installation of impeller. Because of the presence of cooling fans on rotor, mechanical loss at no load is increased compared to low-speed machine.

Fig. 8 is a measurement data of no load test. And the mechanical loss of rotor is about 1.36[kW].

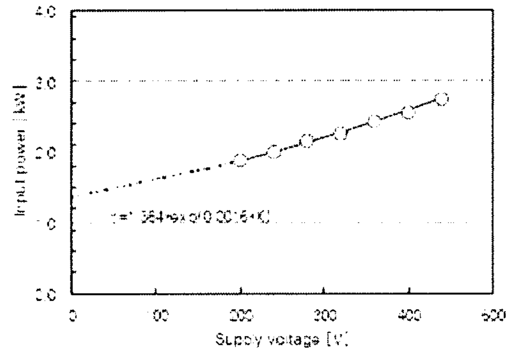


Fig. 8. Mechanical loss measurement test

4.2 Full load test results

In generally, there is several method of determining the motor efficiency, direct torque measurement method and indirect method. In this paper, we adopted alternative indirect method for determining the total efficiency of motor. The total efficiency of motor including mechanical losses of rotor can be expressed as follows.

$$\eta_m = \frac{W_{comp}}{W_{input}} = \frac{\dot{m} c_p \Delta t_{comp}}{\dot{m} c_p \Delta t_{motor}} \tag{3}$$

W_{comp}, W_{motor} are the actual consumption power in compression part(impeller) and the motor input power respectively. As a result, the total efficiency of motor is determined the ratio of temperature rise of compression and motor part. The efficiency test of motor was conducted under full load conditions and estimated efficiency by equation (3) is 91.3[%]. Fig. 9 shows a temperature rise of stator coil and air-gap temperature. From the results it can be seen that the motor has reached steady state temperature and efficiency test method represents a reliable method for high-speed induction motor. Fig. 10 is a measurement data of line-to-line voltage waveform and current waveform.

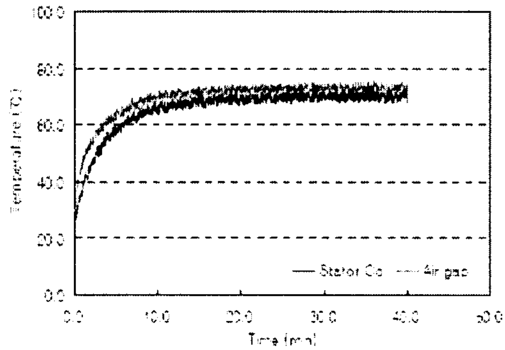


Fig. 9. Temperature rise test results

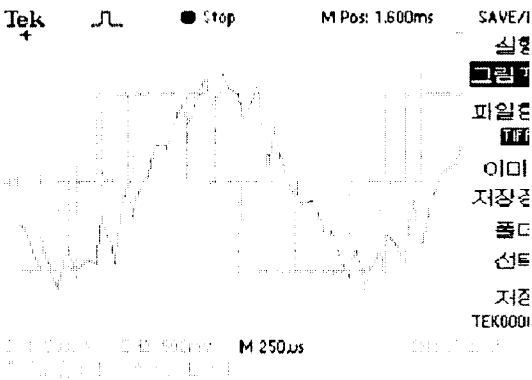


Fig. 10. Temperature rise test results

5. Conclusion

A three-phase squirrel cage induction motor with ratings of 37[kW], 45,000[rpm] for turbo blower has been presented. A design consideration of electromagnetic, mechanical and thermal limits of high-speed induction motor is also presented.

And, based upon this design concept, the prototype induction motor (37[kW], 45,000[rpm]) for high-speed turbo blower was designed and 2-D electromagnetic field analysis was implemented. Finally, criteria to evaluate the characteristics of high-speed induction motor have been proposed and tested.

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Biography

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He received his B.S., MS degree in Electrical Engineering from Hanyang University, Seoul, Korea, in 1990, and 1992, respectively. He is in the Ph.D course in the department of Electrical Engineering, Hanyang University. His research is focused on the analysis and the optimal design with the permanent magnet motor.

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