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IE4-class 2.2-kW Induction Motor Design and Performance Evaluation

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ABSTRACT

In this study, a 2.2 kW super-premium (IE4) class 4-pole three-phase induction motor was designed and developed. We compared this prototype motor with the industrial induction motors sold by leading international companies. We designed and fabricated a stator, an Al rotor, housing, bearing front and rear covers made of Al 6061, a shaft, and a cooling fan. The cooling fan produced with 3D printing technology was assembled on the unload shaft. Following motor assembly, its mechanical performance, such as noise, vibration, wind speed, and efficiency, was analyzed. Compared with the considered international-standard motors, our proposed motor showed superior performance in terms of noise, vibration, and efficiency but not in terms of air gap and wind speed.

1. Introduction

For conserving energy and reducing greenhouse gas emissions, policies on minimum energy performance standards (MEPS) have been implemented, and the distribution of high-efficiency motors have been promoted worldwide. In accordance with the global trend of enhancing the minimum efficiency standard from IE2 to IE3, the standard was enhanced to IE3 in South Korea as well in 2015, and it is expected that the motor-efficiency standard will be enhanced to IE4 and IE5 by 2030. With the continuous development of motor control technology and power semiconductor devices, the utilization ranges of various motors, including induction motors, are continuously expanding. With the increase in industrial rotary-machine size, technologies to reduce the driving motor noise are being continuously developed. Compared to advanced overseas companies that dominate the motor market, the research and development infrastructure and personnel available in South Korea are not competitive. Moreover, latecomers, such as China, are rapidly catching-up; therefore, the development of this technology is urgently required domestically. Motor losses can be reduced, and motor efficiency can be improved by replacing the existing die-cast aluminum (Al) rotors with die-cast copper (Cu) rotors. In induction motors with die-cast Cu rotors, the temperature increase can be reduced by 2-5℃ compared to those with die-cast Al rotors because of the reduced rotor heating caused by low copper loss in the rotors [1-3]. Currently, Al die casting is mainly used because Cu die casting is difficult due to the high melting temperature of Cu. Although Al rotors are used for IE3-class induction motors, the use of rotor materials with high electrical conductivity is required to achieve IE4-class efficiency levels. Therefore, it is necessary to design and develop hybrid rotors that combine the advantages of Al rotors, and the low copper loss of Cu rotors during initial motor operation and the high efficiency during operation under rated load. In this study, the products of advanced companies leading the domestic and overseas

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induction motor markets are compared with a prototype induction motor designed and developed in this study to construct a database for the noise, vibration, balancing, and air gap. In addition, the key components of the developed 2.2-kW IE4 (super premium)-class 4-pole 3-phase induction motor, such as the stator, shafting, Al alloy housing, bearing front and rear covers, three-dimensional (3D) printing cooling fan, and die-cast Al/Cu rotors, are assembled to evaluate the mechanical performance of the motor. A precision machined shaft with shaft oscillations less than 10 μm is shrink-fitted with the bearings and Al/Cu rotors; the balancing at the drive end (DE) and nondrive end (NDE) of the shaft are less than 0.4 g. A cooling fan fabricated with 3D printing technology is assembled at the NDE to complete the shafting. A stator with a 43.7% space factor and 0.68 Ω (@ 25℃) resistance that meets the $(0.80 \times 2 + 0.85 \times 2) \times 28$ turn winding specification is developed and shrink-fitted with the housing. The mechanical and electrical performances of the assembled motor, such as the noise, vibration, wind speed, temperature increase, power factor, and efficiency, are analyzed.

The rest of this paper is organized as follows. Section 2 analyzes the mechanical performance of commercial induction motors developed by leading international companies. Section 3 focuses on the design, development, and evaluation of the proposed 2.2-kW induction motor. Finally, Section 4 summarizes the results of the study.

2. Analysis of the mechanical performances of domestic and overseas commercial induction motors

2.1 Noise

The IE3/IE4 class 2.2-kW 4-pole 3-phase commercial induction motor model was utilized in this study. As per the KS C IEC 60034-9 standard, when the rated output of the motor was 1 kW or more, the average value was derived by measuring five times at a distance of 1-m per direction in the front, right, left, and rear directions of the induction motor, as shown in Fig. 1 [4].

The initial noise level of the noise measurement room was 42.0 dB. The sound level meter was calibrated in conformance with the KS C IEC 60034-9 standard. The rotational speed of the induction motor during no-load operation was measured at 1,800 rpm, after 30 min of warm-up; the measurements were performed in the forward and reverse directions. The measured noise values of the motors manufactured by companies A, B, C and Z were 55.9 dB, 65.2 dB, 66.3 dB and 61.3 dB, respectively. When the rotation direction of the motor was opposite, the left-side exhibited the highest noise value; the noise generated by the cooling fan moved in the direction of the load axis. Thus, low noise was measured at the rear of the fan.

Table 1 lists the measured values of the noise, wind speed, and the cooling-fan size of the induction motor for each manufacturer. The larger the wind speed and cooling-fan size, the higher was the noise level.

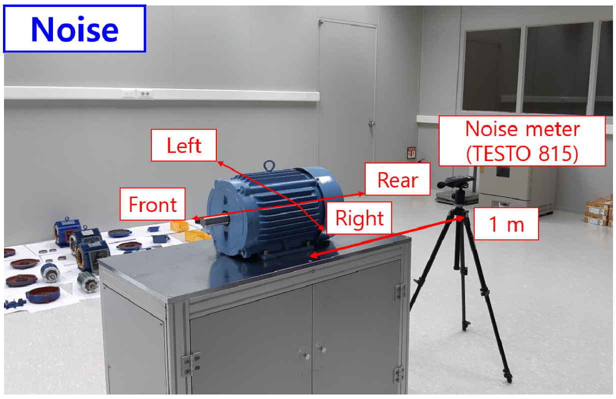


Fig. 1 Induction motor noise measurement setup

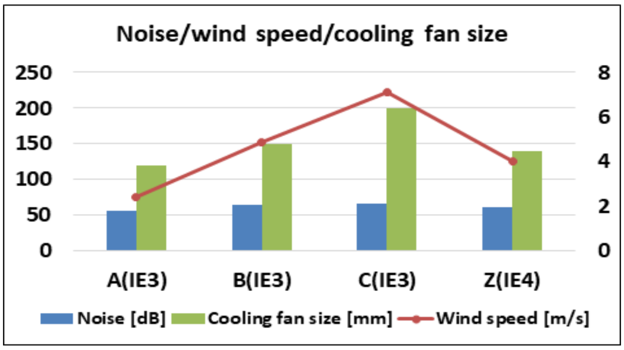


Fig. 2 Measurement results for induction motor noise/cooling fan size/wind speed

Table 1 Noise/wind speed/cooling fan size for each manufacturer

Manufacturer	Domestic			International
	A (IE3)	B (IE3)	C (IE3)	Z (IE4)
Noise [dB]	55.9	65.2	66.3	61.3
Wind speed [m/s]	2.4	4.9	7.1	4.0
Fan size [mm]	Ø 120	Ø 150	Ø 200	Ø 140

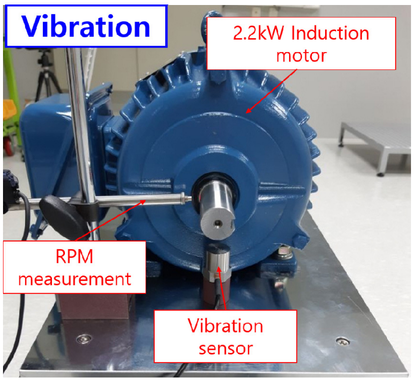


Fig. 3 Induction motor vibration measurement setup

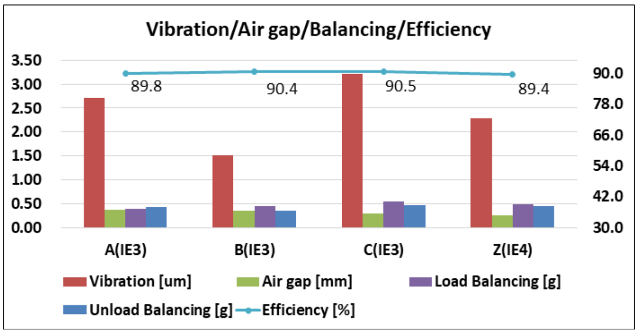


Fig. 4 Measurement results for induction motor vibration/air gap/balancing/efficiency

2.2 Vibration

Vibrations of induction motors result from various sources. Most vibration sources are extrinsic anomalies such as unbalance and misalignment; some sources are intrinsic factors such as bearing or shaft asymmetries. As these vibration sources exist unavoidably in rotating bodies as vibrating systems, it is important to obtain the natural vibration characteristics when designing rotating shafts [5-7]. To measure the vibration of the induction motor shaft, a dedicated table (1,000 × 500 × 15 T) was fabricated, and the external vibration was blocked to a maximum. The vibrations of the motor body were measured using a field balancer (Sigma) as shown in Fig. 3. 14 points were set on the table and the motor vibration was measured by attaching the sensor to a certain position. The motor vibration for companies A, B, C and Z were 2.715 μm, 1.511 μm, 3.206 μm and 2.290 μm, respectively, at 1,800 rpm.

The air gap between the rotor and stator was measured using a three-dimensional coordinate measuring machine. The resulting values for companies A, B, C, and Z were 0.371 mm, 0.354 mm, 0.297 mm, and 0.255 mm, respectively.

Table 2 depicts the measured values of the vibration, air gap, balancing, and efficiency of the induction motor for each manufacturer. The motor efficiency was measured through a dynamo test. The larger the balancing and air-gap size, the larger was the vibration data value. Fig. 4 shows measurement results for induction motor vibration, air gap, balancing and efficiency.

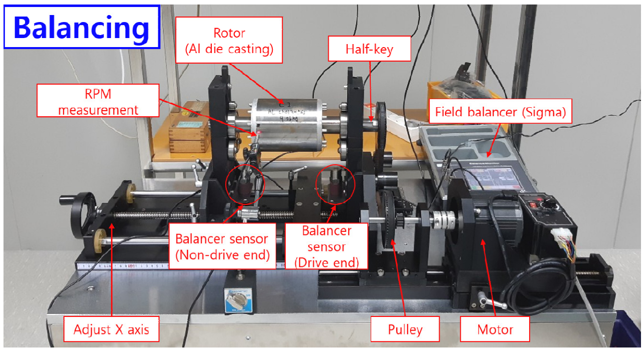


Fig. 5 Induction motor balancing measurement setup

Table 2 Vibration/air gap/balancing/efficiency by manufacturer

Manufacturer		A	B	C	Z
Vibration [μm]		2.715	1.511	3.206	2.290
Air gap [mm]		0.371	0.354	0.297	0.255
Balancing [g]	Load	0.40	0.45	0.55	0.49
	Unload	0.43	0.35	0.46	0.44
Efficiency [%]		89.8	90.4	90.5	89.4

For the balancing measurement of the rotor, a balancing machine was designed and manufactured, as shown in Fig. 5. For precise measurement, the height references for both ends of the rotor were aligned within 10 μm using a height gauge. In addition, a fabricated half-key was inserted in the load shaft. The measurement results of balancing at 1,800 rpm with the bearing engaged are listed in Table 2.

3. Design/assembly of the developed 2.2-kW induction motor and mechanical performance evaluation

3.1 Design and assembly of the developed 2.2-kW induction motor

The developed 2.2-kW IE4-class induction motor mainly comprised a stator, rotor, shafting, and frame. In detail, it was composed of approximately 23 components. For the stator, heat treatment techniques to remove stress, and techniques to measure the impact of magnetic losses are required to minimize the magnetic losses of the electrical steel sheets. A stator with a 43.7% space factor and 0.68 Ω (@ 25℃) resistance that meets the $(0.80 \times 2 + 0.85 \times 2) \times 28$ turn winding specification was fabricated, as shown in Fig. 6. The press welding method was applied, and stress was removed through the heat treatment process.

50PN470 was used as the rotor core material, and an interlocking technique was applied. An Al skew rotor and a Cu non-skew rotor without heat treatment were developed, as shown in Fig. 7.

Shrink fitting was used for the assembly of the shaft and rotor bearings. The weight of the die-cast Al rotor was 9.26 kg, whereas that of the die-cast Cu rotor was 11.46 kg. Industrial induction motors shafts are mostly composed of S45C steel. However, application of the general grade among the shaft oscillation standards, bearing burnout caused by cooling-fan noise/vibration, and shaft corrosion, may reduce the motor service life. After the shafts were subjected to precision machining, a shaft with less than 10-μm shaft oscillations was selected, using a shaft-oscillation measuring instrument, for shrink fitting with the bearings. The general

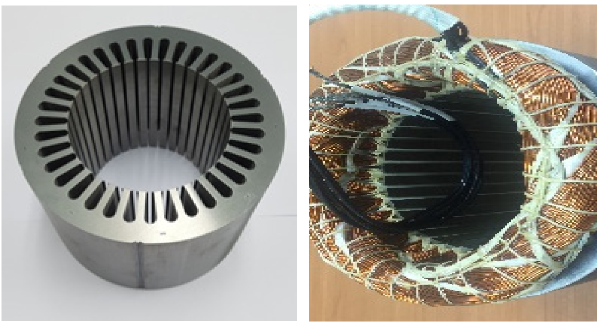


Fig. 6 2.2-kW induction motor stator

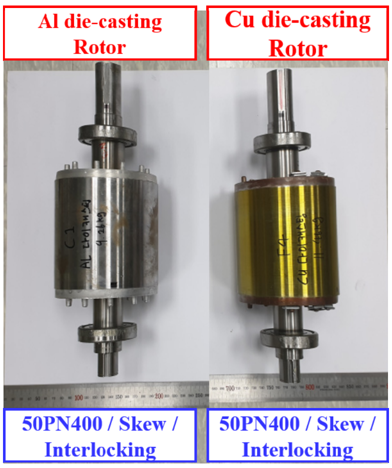


Fig. 7 2.2-kW induction motor rotor

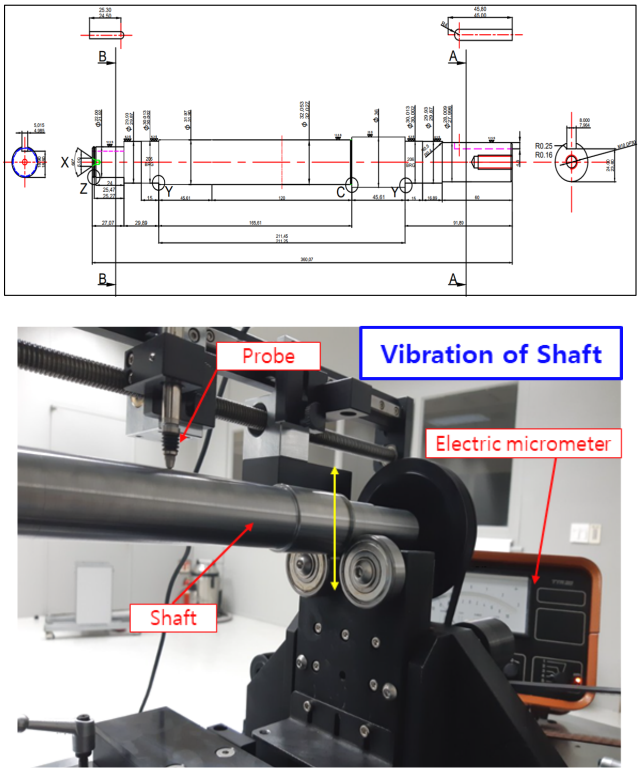


Fig. 8 Shaft design drawing and vibration of shaft measurement setup

shaft run-out standard is 40 μm or less, and if it is managed in a precision grade, it has a management standard of 25 μm or less. Shaft shaft run-out standards follow IEC 60072-1 [8]. Shaft-oscillation measurement is performed by rotating the shaft at a constant speed of 50 rpm as shown in Fig. 8, while the probe detects shaft-oscillation and measures the degree of oscillation with an electric micrometer. The resolution of the electric micrometer is 0.1 μm.

The cooling-fan size was minimized to improve the efficiency of the induction motor. When the cooling fan size was reduced to 75%, the temperature rise of the motor was stable and the most ideal size was able to reduce noise. The size was reduced by 75% and 50%, compared to the original size; prototypes of the cooling fan were fabricated using two different materials and a 3D printer as shown in Fig. 9. Testing using acrylonitile + poly-butadiene + styrene (ABS), which is the most common and extensively used plastic resin, indicated a reduction in the impact strength. Therefore, the material was replaced by M2G-CL, and the cooling fans were fabricated using 3D printing technology with shrinkage compensation.

The housing frame was fabricated using lightweight

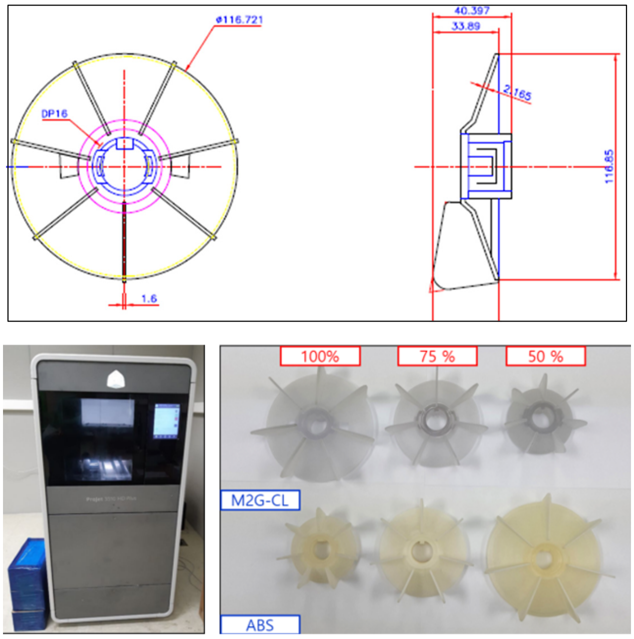
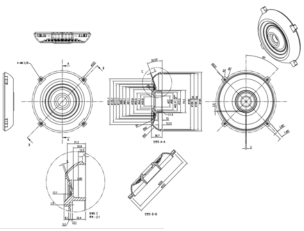
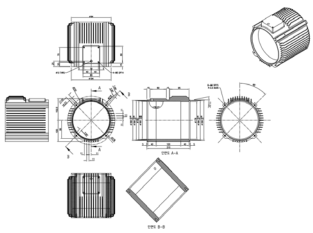


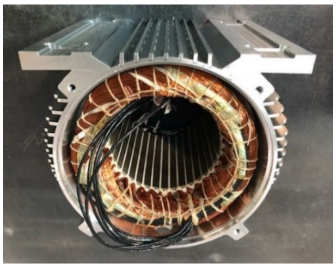
Fig. 9 Fan design drawing and fabrication of fan using 3D printing



(a) Bearing cover design



(b) Housing frame design



(c) Assembly stator with housing frame

Fig. 10 2.2-kW induction motor stator with frame

material with high thermal conductivity and an extrusion process to reduce the weight of the motor and secure its cooling performance as shown in Fig. 10. The average service life of a motor is 30 years, when operated within the allowed temperature range; however, this is reduced by half, when the temperature range exceeds 10℃ under the influence of overload operation or the surrounding environment. Hence, the heat release of a motor is directly related to its service life. Therefore, the application of lightweight material with high thermal conductivity can improve the motor efficiency.

3.2 Noise and vibration

Shafting was constructed using a high-precision shaft with less than 21-μm shaft oscillations and a 3D-printed cooling fan whose size was reduced by 75%. The shafting combined with the rotor exhibited less than 0.4 g balancing at the DE and NDE. When the shafting was finally assembled with the stator after the balancing process, the vibration, noise, and wind speed were measured.

Table 3 lists the balancing, vibration, noise, and air gap characteristics of the developed 2.2-kW IE4-class induction motor according to the rotor type. The rotor noise was 58.4 dB for the die-cast Al rotor and 66.3 dB for the die-cast Cu rotor, indicating that the noise increased with the increase in rotor weight. The measured vibrations were 1.845 μm and 2.464 μm for the for the die-cast Al and Cu rotors, respectively, showing that the vibration decreased with the decrease in balancing and shaft oscillations. Also, as the weight of the rotor increases, the vibration of the motor becomes larger. The upper left corner of the motor exhibited the highest wind speed, which ranged from 3.1-3.3 m/s. The power factor was 80% (criterion for the IE4 class is 77.0% or higher). Both rotors exhibited stable results in terms of the ambient temperature increase; they achieved IE4-class efficiency levels because the criterion for the 2.2-kW IE4 class is 91% or higher.

Table 3 Mechanical characteristics of the developed 2.2-kW inductor motor according to rotor type

Division		International Al/Cu hybrid (IE4)	Al die casting	Cu die casting
Air gap [mm]		0.255	0.302	0.289
Balancing [g]	Load	0.49	0.38	0.38
	Unload	0.44	0.30	0.37
Rotor weight [kg]		11.02	9.26	11.46
Noise [dB]		61.3	58.4	66.3
Maximum wind speed [m/s]		4.0 (Top left)	3.1~3.3 (Top left)	
Power factor [%]		75	80	80
Max ambient temperature [℃]		23.86	22.86	21.33
Efficiency [%]		89.4	91.0	91.6

4. Conclusions

A mechanical performance analysis based on noise/vibration/balancing/wind velocity measurements was conducted for IE4 grade 2.2-kW induction motors manufactured by different international companies. Precision grade shaft manufacturing technology was used for shaft optimization and a fine cutting process was used to minimize shaft-oscillation. The shaft micro-cutting technology improved the existing shaft-oscillation level (40 μm) to < 25 μm and procured > 60% superiority. IE4 grade 2.2-kW induction motors noise standard is 68 dB, shaft-oscillation standard is 21 μm and efficiency is 91%. Promotion of this technology can help improve IE4 class induction motor efficiency through shrinkage of the motor and stator. On comparing the performances of the developed 2.2-kW IE4-class induction motor in this study with those of the products of advanced overseas companies, the developed motor exhibited higher performances in terms of the noise, vibration, and efficiency, except the air gap and wind speed. If Al/Cu hybrid rotors are developed in the future, in addition to the improvement in the shaft oscillations and air gap (to less than 0.25 mm), it will be possible to develop ultra-premium efficiency (IE5) motors that exceed the developed IE4-class motor.

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