Influence of Die Cast Rotor Fill Factor on the Starting Performance of Induction Machines

Jangho Yun[1,2], Sungho Lee[1], Myung Jeong[2], *Student Member, IEEE*, and Sang Bin Lee[2], *Fellow, IEEE*

[1]Hyundai Electric, Yongin, 16891, Korea, ydh7999@gmail.com
[2]Korea University, Seoul, 02841, Korea, sangbinlee@korea.ac.kr

One of the most important requirements for low voltage induction motor designers is to meet the customer-specified starting characteristics and international regulations on efficiency. Although porosity in die-cast rotors degrade motor performance, the fill factor (FF) of the rotor bar and end ring are usually assumed to be 100% in the design stage. If the influence of FF is not properly taken into account in the design, it results in an inaccurate prediction of the starting performance. In this paper, the influence of die cast rotor FF on the starting torque is investigated based on the porosity and FF distributions measured from actual aluminum die cast rotors. A simplified 3-dimensional finite element analysis (3D FEA) model that accounts for the porosity distribution in bars and end rings for different FFs is presented for predicting the starting characteristics. The effectiveness of the proposed method is verified on a 440 V, 15 kW induction motor prototype with rotors with FF of 93% and 67%. The results show that porosity has a significant influence on the starting torque, and must be taken into account for reliable prediction of motor performance for design optimization.

***Index Terms*—Die-cast Rotor, Fill Factor, Induction Motor, Porosity, 3D Finite Element Analysis.**

I. Introduction

THE most important task for motor designers is to understand the customer's performance requirements, and provide designs that meet their demands, while satisfying the international regulations and minimizing the cost. Since reliable design tools for accurate prediction of performance is critical for design optimization, the imperfections introduced during the manufacturing stage must be taken into account in the design process. Porosity in die-cast rotors is inevitable due to shrinking of aluminum or copper during solidification, insufficient die-cast material or leakage of material during the die-cast process. The fill factor (FF) of die cast rotor cages of induction motors are determined by the type of die cast process and conditions for metal temperature, pressure, etc. However, when motor performance is predicted during the design stage, it is usually assumed that the FF is 100%.

The starting performance of induction motors is an important criterion for the motor end user considering its impact on motor performance and reliability. With the international regulations on premium efficiency induction motors, it has become more difficult to meet the demands on starting performance due to contradicting design requirements. Accurate prediction of the impact of rotor bar/slot geometry on the starting performance is a challenging task, as deep bar/skin effects and magnetic saturation on the rotor bar/end ring parameters must be considered. Non-ideal FF is also expected to have a negative influence on prediction of the starting performance. Considering that majority of low voltage induction motors employ cost-effective die-cast rotor cages, it is very important to investigate the influence of porosity on starting performance.

Although there have been research efforts on improving FF through adjustments in the die-cast process, the influence of die cast rotor FF on motor performance has not been properly investigated. In this paper, the influence of die cast rotor FF and porosity distribution on the starting performance is investigated. The statistical distribution of FF is measured, and an X-ray scan is performed on rotor bars and end rings to study the porosity distribution. A simplified 3-dimensional finite elements analysis (3D FEA) that includes the influence of FF and porosity distribution is performed for the study. To verify the FEA results, an experimental study on 440 V, 15 kW induction motor prototypes is performed. It is shown that die cast rotor FF has a significant influence on the starting torque, and needs to be considered in the design process for reliable prediction of performance and design optimization.

II. 3D FE Modeling based on FF & Porosity Distribution

To obtain the FF distribution, the weight of 64 aluminum die-cast rotors of a 440 V, 15 kW motor were measured and compared to that of an ideal 3D CAD model rotor. According to the normal distribution obtained from the data, shown in Fig. 1, the average FF and standard deviation were 96.7% and 0.76. To observe how porosity is actuallly distributed inside the bars and end rings, an X-ray scan was performed in the axial direction on 7 different rotors from motors rated between 1.5 and 22 kW (5 different manufctaurers). The scan for all the rotors showed that porosity in the bars were concentrated in the outer and center portion of the slot, as shown in Fig. 2(a)-(b). In the end rings, porosity was concentrated at the rotor slot area close to the rotor bars and core, as shown in Figs. 2(c)-(d). The FF calculated from the X-ray scan for end rings from 7 different rotors are summarized in Table I (average FF: 95.3%).

A single slot pitch 3D FE model [1] that best represents actual FF and porosity distribution was created based on the Fig. 2 measurements. The procedure for calculating the rotor impedance and starting performance can be summarized as:

- The porosity in the bar is assumed to be close to the outer surface, where the radial length is increased inwards with decrease in FF. For the end ring, FF is fixed at 95.3%, and an air ring similar in proportion to what was observed in Fig. 2(b)-(c) is inserted in the end ring, as shown in Fig. 3(a).
- The FF in the bar is calcualted from the FF of the rotor and assuming a fixed FF = 95.3% in the end ring.

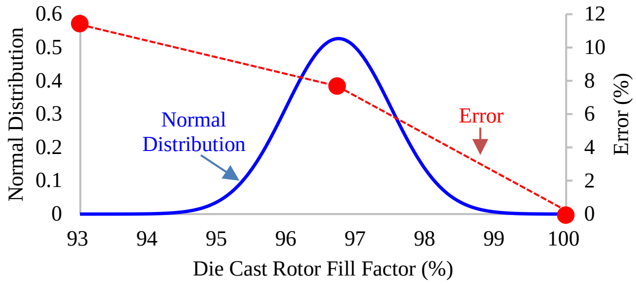

Fig. 1 Normal distribution of aluminum die cast rotor FF and error in starting torque prediction for FF=93%, 96.7%

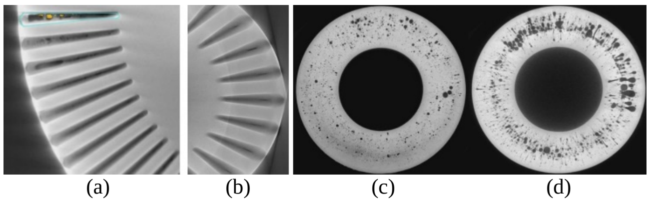

Fig. 2 X-ray scan of porosity distribution in (a) rotor bar of 440 V, 22 kW motor, and in (b) rotor bar, (c)-(d) end ring of 440 V, 1.5 kW motor ((c) 98.8% and (d) 68% of end ring width from outer surface)

TABLE I
FF CALCULATED FROM X-RAY SCAN PERFOREMD ON 7 DIFFERENT ROTORS

Motors (kW)	1.5	1.5	11	18.5	22	22	22
FF (%)	95.3	95.7	98.0	95.9	92.0	95.7	94.8

- The rotor parameters are calculated from a half axial length, single slot pitch rotor model with 3D FEA, where the *R* and *X* components of the bar and end ring are obtained separately assuming the FF and porosity distribution assumptions above.

III. FEA & EXPERIMENTAL STUDY

An FEA and experimental study were performed for rotors with FF of 67% and 93% to investigate the influence of porosity on starting performance. The FFs were selected since a defective rotor produced due to insufficient aluminum (67%) and a normal rotor (93%) were available for a 440 V, 15 kW induction motor. The FFs of the rotors were obtained by measuring the rotor weight before and after die-casting, as shown in Fig. 4. The no-load and locked rotor tests were performed according to IEEE 112-2004 [2] for obtaining the rotor resistance, R_r, and starting torque, T_s, and current, I_s.

3D FEA was performed in two different ways. Porosity was assumed to be distributed uniformly, and FF was changed by adjusting with the resistivity of the rotor conductor (method I). The FE performed with the 3D model described in II refers to method II. A comparison of the R_r and T_s values calculated from test results, and 3D FE methods I and II are summarized in Table II. The equivalent R_r obtained assuming uniform porosity distribution (method I) is noticeably lower (6.0%, 15.3%) than the R_r values measured from the tests for both rotors with 93% and 67% FF. Incorrect estimates of R_r results in an error in the T_s calculations (11.3%, 12.0%). When porosity distribution is taken into account (method II), the values of R_r and T_s are in good agreement with the test results. This is expected since current distribution in the rotor cage during startup is significantly influenced by the porosity distribution, especially in the bar, as shown in Fig. 3(b)-(c). The values of R_r and T_s obtained with method II for additional data points between 67% and 100% FF are shown in Fig. 5. The results also show 11.4% and 7.7% error in the T_s prediction with FF of 93% and 96.7%, which is lower than the assumed 100% FF, as shown in Fig. 1.

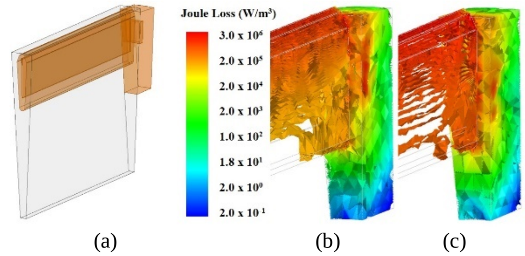

Fig. 3 (a) 3D FEA model with FF and porosity distribution taken into account; distribution of the joule loss in the bar and end ring with ac current excitation (60 Hz) for (b) FF 93% and (c) FF 67%

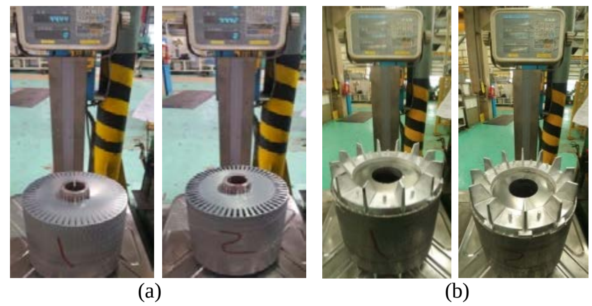

Fig. 4 Weight measurements of (a) rotor core, dummy sharft, and (b) rotor assembly for die cast rotor FF estimation

TABLE II
ROTOR RESISTANCE, R_R, AND TORQUE, T_S, OBTAINED FROM TESTING, ANALYTIC SOLUTION WITH DIE CAST ROTOR (FF 93%, 67%)

FF		Testing	Method I	% error	Method II	% error
93%	R_r	1.00 Ω	0.94 Ω	-6.0%	1.02 Ω	+2.0%
	T_s	336 N.m	298 N.m	-11.3%	326 N.m	-3.0%
67%	R_r	1.31 Ω	1.11 Ω	-15.3%	1.29 Ω	-1.5%
	T_s	374 N.m	329 N.m	-12.0%	381 N.m	+1.9%

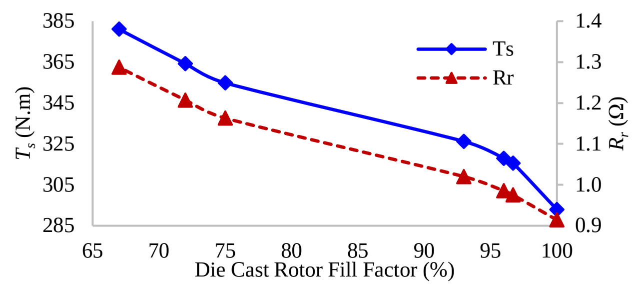

Fig. 5 T_s and R_r estimates (method II) as a function of FF

IV. CONCLUSION

The results summarized in Table II and Fig. 5 show that it is important to include the influence of FF and porosity distribution in the design for accurate prediction of T_s. Considering that many fabricated rotors are being replaced with die cast rotors, and that reliable T_s prediction is critical for design optimization, it is important to understand and account for the influence of porosity on the starting performance.

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