Effect of Pole and Slot Combination on Noise and Vibration in Induction Motor

Su-Jin Lee, Jae-Han Sim, Jae-Woo Jung, Hyeon-Jin Park, Jung-Pyo Hong
Department of Automotive Engineering, Hanyang University
222 Wangsimni-ro, Seoul 133-791, Korea
hongjp@hanyang.ac.kr

***Abstract*—The electromagnetic force due to slot combination has a strong influence on acoustic noise from induction motor. This paper investigates the effect of the number of pole and slot combination on noise and vibration according to various operating point (degree of saturation). The magnetic noise characterizations are studied. Firstly, production of radial magnetic pressure waveform is introduced. Additionally, the analytical characterization of Maxwell radial vibration due to saturation effect in induction motor is derived. Furthermore, the method for prediction of the degree on the noise and vibration is presented. Finally, an experiment process is established to test the vibration and noise of analysis model, and verify the proposed analysis process. The effect of the number of pole and slot combination on the noise and vibration are revealed.**

***Index Terms*— Electromagnetic noise, induction machine, Maxwell forces, resonance, slot number.**

I. INTRODUCTION

Induction motor is applied to operate in many different fields from a small fan to large automobile engine. Recently, Electric Vehicle and Hybrid Electric Vehicle needed the various operation region makes good use of the induction motor [1]. Because of the demanding requirement on the environment of human life and useful life of integral systems, the reduction of the noise and vibration of squirrel-cage induction motors have become an important issue.

As progress is being made in mechanical and aerodynamic noise reduction, the full understanding of magnetic noise generation becomes crucial. Electromagnetic noise has two specific features as follows:

(1) Its frequency range is from 700 to 4000 Hz, where the human ear has peak sensitivity.
(2) Sometimes it results in a terrible sound (= resonance) at a certain frequency

One of the most important sources of the electromagnetic noise is vibration of the stator core caused by the radial electromagnetic force in the air gap [2]. Consequently, some researchers started to look for some general rules to decrease motor noise and vibrations that mainly come from Maxwell air-gap magnetic forces. T. Kobayashi et al [3] analyzed the effect of three different kinds of slot combinations on electromagnetic noise reduction by Finite Element Method (FEM) and harmonic analysis. J. L. Besnerais et al [4] present a fast simulation tool for the variable-speed magnetic noise emitted by induction machine, based on fully analytical models. J. L. Besnerais et al [5] derives the analytical characterization of Maxwell radial vibrations due to saturation effects in induction machines. These papers only describe the analytical results of noise and do not justify the validity. Moreover, each paper displays the effect of pole and slots combination considering a property only. However, since electric machines are driven at various region of speed, a ratio of pole and slots considering complex and multiple influences should be presented. Therefore, in this paper, the optimal number of pole and slot combination on the noise and vibration for induction motors are suggests. Furthermore, this paper presents a method for prediction of the degree on the noise and vibration, and the validity of the analysis results is verified by test.

II. MAGNETIC NOISE CHARACTERIZATION

A. Production of radial magnetic pressure waveform

As the component of total force, the radial force can be well calculated in the Maxwell stress tensor method [6]. The force density of the radial component can be obtained as

$$\boldsymbol{p}_r = \frac{\boldsymbol{B}_r^{\,2} - \boldsymbol{B}_t^{\,2}}{2\mu_0}. \qquad (1)$$

where μ_0 is the permeability of air, $\boldsymbol{B}_r$ and $\boldsymbol{B}_t$ are the flux densities of the radial and tangential components, respectively.

$$\begin{aligned}\boldsymbol{p}_r(\alpha,t) &= \frac{1}{2\mu_0}\left[b_r^{\,2}(\alpha,t) - b_t^{\,2}(\alpha,t)\right] \approx \frac{b_r^{\,2}(\alpha,t)}{2\mu_0} \\ &= \frac{\left[b_1(\alpha,t)\right]^2 + 2b_1(\alpha,t)b_2(\alpha,t) + \left[b_2(\alpha,t)\right]^2}{2\mu_0}.\end{aligned} \qquad (2)$$

The radial force waves consist of three groups: the product of the stator harmonics (ν), the rotor harmonics (μ) and the mixed product. A magnetic noise resonance occurs at two conditions:

(1) The order (r) of the force harmonic must be the same as the circumferential mode number of the stator.
(2) The frequency of the force harmonic must be the same as the natural frequency of the stator mode.

Considering only the pure circumferential vibration modes of the stator core, the deflection Δd of the stator core is an inverse function of the fourth power of the force order r. Consequently, in order to reduce some specific electro-magnetic noise, The pole and slot combination that the force order become smaller have to be selected.

Angular frequencies and orders of radial magnetic force result excited by the stator and rotor harmonics can be obtained as

$$\omega_r = \omega + \omega_\mu;\;\; f_r = f \pm f_\mu;\; r = (\nu \pm \mu)p. \qquad (3)$$

For the fundamental time harmonic the field of each stator winding harmonic at a given point with the coordinate α

pulsates with the angular frequency $\omega=2\pi f$, where f is the fundamental frequency. For an induction motor the angular frequency of the rotor slot harmonics is $\omega_\mu = \omega \pm ks_2\Omega_m$ (Ω_m is the mechanical angular speed of the rotor).

The orders are also determined by

$$r = (\nu \pm \mu)p = ks_1 \pm ks_2 \pm 2p \, . \quad (4)$$

where s_1 and s_2 is the number of stator slot and rotor slot respectively and p is the number of pole pairs.

B. Radial force harmonics due to magnetic saturation

The slot leakage and residual fields of the stator and rotor MMFs are large. Consequently, the tooth tips become highly saturation which is equivalent to the increase in the slot opening. The air gap permeance with respect to the magnetic saturation can be expressed by the following simplified

$$\Lambda(\alpha,t) \approx \Lambda_0 + \Lambda_{sat}(\alpha,t) \, . \quad (5)$$

where $\Lambda_{sat}(\alpha,t) = -\Lambda_{sat}\cos(2p\alpha - 2\omega_1 t - 2\phi_s)$

The saturation magnetic flux density equation is a product of the MMF for ν=1 and the second term of the air gap permeance

$$\begin{aligned} b_{sat}(\alpha,t) &= F_{1,1}(\alpha,t)\Lambda_{sat}(\alpha,t) \\ &= -B_{sat}\left[\cos(p\alpha - \omega t - 2\phi_s) + \cos(3p\alpha - 3\omega t - 2\phi_s)\right] \end{aligned} \, . \quad (6)$$

Assuming that only the harmonic ν=3 in Equation (5) saturates the teeth. The angular frequency and order of radial magnetic forces due to saturation of the magnetic circuit can be represented by

$$\begin{aligned} \omega_{rsat} &= \omega \pm \omega_\mu = \omega \pm 3\omega \pm k\left[2\pi \frac{s_2}{p}(1-s)\right] \\ r &= (\nu \pm \mu)p = \left(k_s \frac{s_1}{p} \pm k_r \frac{s_2}{p} \pm 1 + 3\right)p \end{aligned} \, . \quad (7)$$

III. Analysis Process of the Noise and Vibration

A. Calculation of the noise and vibration

In order to consider mechanical characteristics, the natural frequencies and modes of each component of motor are calculated by using FEM. The natural frequency mode of stator is shown as Fig.2. The measured noise and analysis result of FEM are shown Fig. 3. Calculation process of the noise and vibration will be presented in full paper. Additionally, in order to verify the proposed the number of pole and slot combination, the analysis result and discussion of the noise and vibration will be presented.

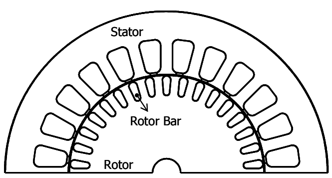


Fig. 1. The half cross-section of the analysis motor

B. Analysis model

The half cross-section of the analysis model is shown in Fig. 1. It has 4 poles and 24 slots with distributed windings arranged in the stator part. In the rotor core, the aluminum conductor bars are inserted into the radial cavity and connected end ring. The detail specification of this motor will be presented in final paper

IV. Conclusion

This paper investigates the effect of pole and slot combination on noise and vibration according to various operating point (degree of saturation). The electromagnetic force due to slot combination has a strong influence on acoustic noise from induction motor. Thus, the proposed the pole and slot combination is very powerful for induction motor. Additionally, an analysis process for predicting the vibration of motor and an experiment verification method are introduced. The validation of the analysis methods on the vibration in this paper is verified by this experiment as well as the effect of radial force (normal local force) on the noise.

References

[1] J. L.Kirtley, R. F. Schiferl, D. T. Peters and E. F. Brush, “The Case for Induction Motors with Die-cast Copper Rotors for Traction Motors,” *SAE International*, 2009

[2] P. L. Alger, “The magnetic noise of induction motors,” *AIEE Trans.*, vol. 73, pp. 118-124, April 1954

[3] T. Kobayashi, F. Tajima, M. Ito and S. Shibukawa, “Effects of slot combination on acoustic noise ,” *IEEE Trans. Magn.*, vol. 33, no. 2, pp. 2101-2104, Mar. 1997

[4] J. L. Besnerais, V. Lanfranchi, “Optimal slot numbers for magnetic noise reduction in variable-speed induction motors,” *IEEE Trans. Magn.*, vol. 45, no. 8, pp. 3131-3135, Mar. 2009

[5] J. L. Besnerais, V. Lanfranchi, , “Characterization and Reduction of Magnetic Noise due to Saturation,”*IEEE Trans. Magn.*, vol. 45, no. 8, pp. 3131-3135, Mar. 2009

[6] J. F. Goeras, C. Wang, J. C. Lai, Noise of polyphase Electric Motors, CRC Press Taulor & Francies Publishing Co., 2006

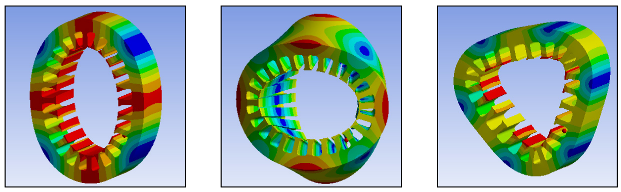
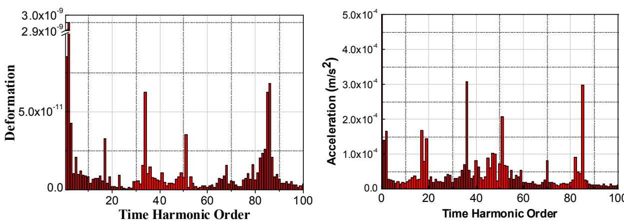


Fig. 2. Natural frequency modes of stator



(a) FEM Simulation (b) Test result

Fig. 3. FFT Analysis for Deformation