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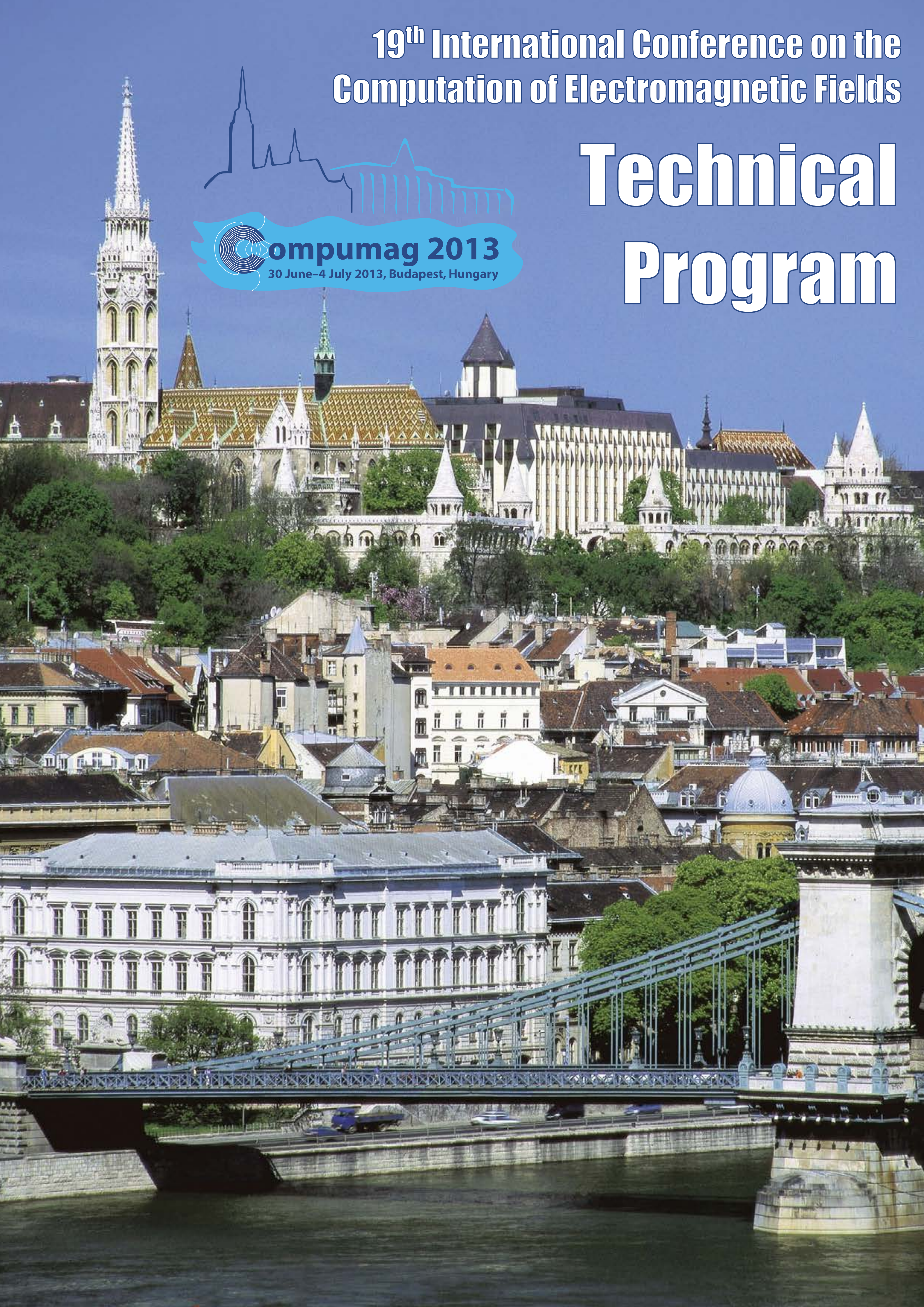
30 June–4 July 2013, Budapest, Hungary

Technical Program



10:45am - 12:25pm Corvina	**PB3: Electrical Machines & Drives 2** **Session Chairs:** Markus Clemens, Johan Gyselinck
	PB3-1 **Characteristic Analysis Method of Irreversible Demagnetization in Single-phase LSPM Motor** Byeong-Hwa Lee, Jae-Woo Jung, Kyu-Sub Kim, Jung-Pyo Hong Hanyang University, Republic of Korea (South Korea) **PB3-2** **Development of Electric Machine for Robot Eyes by Using Analytical Electromagnetic Field Computation Method** Dongwoo Kang[1], Sunghong Won[2], Ho-Joon Lee[1], Ju Lee[1] [1]Hanyang University, Republic of Korea (South Korea); [2]Dong Yang Mirae University, Republic of Korea (South Korea) **PB3-3** **Optimum Design of a Switched Reluctance Motor Fed by Asymmetric Bridge Converter Using Experimental Design Method** Takeo Ishikawa, Yoshinori Hashimoto, Nobuyuki Kurita Gunma University, Japan **PB3-4** **A Novel Stator and Rotor Dual Permanent Magnet Vernier Motor with Space Vector Pulse Width Modulation** Shuangxia Niu, S. L. Ho, W. N. Fu The Hong Kong Polytechnic University, Hong Kong S.A.R. (China) **PB3-5** **Design and Analysis of Electric Controlled Permanent Magnet Excited Synchronous Machine** Ryszard Palka, Piotr Paplicki, Marcin Wardach West Pomeranian University of Technology, Poland **PB3-6** **A Noble Method for Minimization of Cogging Torque and Torque Ripple for Interior Permanent Magnet Synchronous Motor** Ki-Chan Kim Hanbat National University, Republic of Korea (South Korea) **PB3-7** **Characteristic Analysis for Concentrated Multiple-layer Winding Machine with Optimum Turn Ratio** Hae-Joong Kim[1], Do-Jin Kim[2], Joong-Pyo Hong[3] [1]Hanyang University, Republic of Korea (South Korea); [2]Hanyang University, Republic of Korea (South Korea); [3]Hanyang University, Republic of Korea (South Korea) **PB3-8** **Air-gap Magnetic Field Analysis of Wind Generator with PM Embedded Salient Poles by Analytical and Finite Element Combination Technique** Yujing Guo, Heyun Lin, Yunkai Huang, Shuhua Fang, Hui Yang, Kang Wang Engineering Research Center for Motion Control of Ministry of Education, Southeast University, Nanjin, People's Republic of China

Characteristic analysis for Concentrated Multiple-layer Winding Machine with Optimum Turn ratio

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Three-phase fractional slot concentrated winding synchronous machines (FCSM) has excellent electrical properties of high torque density, low cogging torque and torque ripple, yet in armature, as vibration / noise characteristics are not good due to asymmetric magnetomotive force (MMF), and due to the presence of sub-space harmonics in MMF, eddy current loss of permanent magnet is increased. . If Multiple-layer winding with optimum turns ratio is applied to three-phase FCSM, this can improve these problems. In this paper, the turns ratio in concentrated multiple-layer winding machine is proposed to be applied. Taken the turns ratio into consideration, a general formula is derived in order to calculate the winding factor. Using the induced formula, the winding factor changes according to changes in the turns ratio is calculated, and the turns ratio to remove the harmonic components that the MMF has is determined. To verify improvement in the motor characteristics for the proposed method, turns ratio is applied to motors of 16pole 18slot and 10pole 12slot. For the two models, MMF distribution in the air-gap using Finite Elements Method (FEM) is calculated, and through harmonic analysis, reduction or removal of a particular harmonic is verified. In addition, through FEM transient analysis, reduced eddy current loss in permanent magnet is to be identified, and improvements in vibration / noise are to be verified by deformation / acoustic noise analysis of stator.

***Index Terms*—Concentrated winding, electrical machine, fractional-slot, multiple-layer, turns ratio**

I. Introduction

RECENTLY, FCSM has been used in many fields including consumer electronics, industrial and aerospace fields and many studies are being done on improvement in performance. As FCSM is high in winding factor and short in end winding length, it is high in Torque density. Many studies have been carried out for decades. The combination of the number of poles and slots, and single-layer and double-layer characteristics of the motor has been studied [2-5]. Multilayer m-phase windings theory has been studied, and rule for winding placement was proposed [6-7]. Some methods for controlling turns in multilayer 3-phase windings and combinations of the number of poles and slots have also been studied [8]. In this paper, turns ratio was applied for the FCSM multilayer (4-layer) winding. Turns ratio is the ratio of the number of turns to coil of a phase winding on the slot of each winding layer. By adjusting the turns ratio, the MMF harmonic order can be reduced or eliminated. Among the MMF's harmonic orders, if the most influential harmonic order on eddy current loss is reduced, the eddy current loss may be reduced and if another harmonic order with a significant impact on vibration or noise, the vibration/noise can decrease. In this paper, the general formulas are derived considering the FCSM winding factor and using a derived formula, change in winding factor according to change in turns ratio are identified. In order to verify the proposed method, analytical models of 10pole 12slot and 16pole 18pole are chosen. Turns ratio is determined to eliminate certain harmonic order of the chosen model. Finite Element Method (FEM) is used to analysis MMF in the air-gap, and through harmonic analysis, removal of a particular harmonic order is checked. In addition, by performing transient analysis using FEM, its effects on eddy current loss in permanent magnets are studied. Radial force is calculated by interacting with stators based on FEM, and improvements in vibration/noise are analyzed through the deformation / acoustic noise analysis.

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II. Turns ratio in a multiple-layer windings

Double (two)-layer winding

The winding is called fractional slot winding if q (slots per pole and per phase) is not an integer number. In a Double-layer winding a slot can be divided into two different parts in which the coils may belong to different phases. The following formula represents q as it does below.

$$q = \frac{S}{2pm} = \frac{z}{n} \tag{1}$$

where S is the number of slots, m is the number of phases, z is the numerator of q and n is the denominator of q reduced to the lowest terms [9] [10]. The following graphs represent electromotive force (EMF) phasor vector on a phase of each coil.

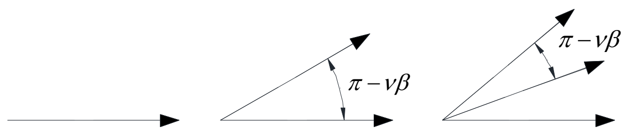

Fig. 1. The EMF phasor vector (β=2$\pi p/S$) (a) z = 1 (b) z = 2 (b) z = 3

In Figure 1., ν is harmonic order, and β is electrical angle between neighboring two slots. p represents pole pair; S represents the number of slot. Examples of a combination of pole and slot in case that z is 2 include 10pole 12slot and 14pole 12slot, etc, whereas in case that z is 4, they are 22pole 24 slot, etc. As z increases, so does the number of voltage vector on a phase and the angle between the voltage vectors will be different. Therefore, a distribution factor may be changed depending on z. If z is 2, the phase angle of each EMF phasor vector will be 0*deg*. and 30*deg*., whereas if z is 4, it the 0*deg*., 15*deg*., 30*deg*., 45*deg*. Using Gaussian function, this relationship can be expressed as in the following formula.

$$\theta_{v,i} = z\left(\frac{i}{z} - \left[\frac{i}{z}\right]_{Gauss}\right)\alpha_v, \qquad \alpha_v = \pi - v\beta \tag{2}$$

Where θ_v represents phase angle of EMF phasor vector for v^{th} harmonic order, while v means harmonic order, i meaning integer number of phasor vector element and α meaning angle between the two EMF phasor vectors.

The resulting phase EMF phasor is the sum of the element phasors assigned to that phase, as given by

$$\vec{E}_{phase,v(pu)} = \sum_{i=0}^{z-1} e^{j\theta_{v,i}} \tag{3}$$

The winding factor can be written

$$k_{v,w} = k_{v,d}k_{v,p}, \quad k_{v,d} = \frac{\left|\vec{E}_{phase,v(pu)}\right|}{z}, \quad k_{v,p} = \sin\left(\frac{v\beta}{2}\right) \tag{4}$$

where k_{vp} represents short pitch factor for v^{th} harmonic order, and short pitch factor is influenced by the β.

Four-layer winding

In order to design a 4–layer winding, the sectors are doubled. Therefore each phase has sector A and sector B. Then, the sector B is shifted on EMF phasor vector of the angle α_{sh}. The selection of the shift angle α_{sh} between the two sectors is an additional degree of freedom in the winding design [4]. Figure 2. shows EMF phasor vector for a combination of the number of pole and slot if z = 3. As the shift angle α_{sh} increases, Sector B moves to the CCW direction.

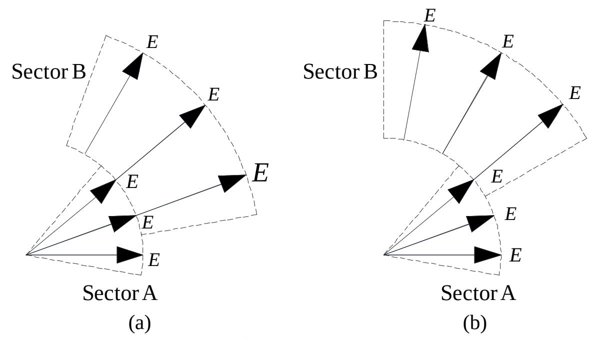

Fig. 2. The EMF phasor vector for four-layer winding(z=3) (a) $\alpha_{sh} = \alpha$ (b) $\alpha_{sh} = 2\alpha$

As shown in Figure 2., each EMF phasor vector is the same in size. When turns-ratio is applied to each EMF phasor voctor, this can more effectively remove or reduce MMF harmonic components. Figure 3. shows turns ratio-applied EMF phasor voctor in case of a combination of the number of pole and slot if z = 3. In Figure 3., R is the turns ratio. According to a combination of the number of poles and slots, the number of turns ratio is z-1. In other words, the combination of the number of slots and poles if z = 2 has one turns ratio, for z = 4, it has 3 turns ratios. The turns ratio can be expressed as follows.

$$R_i = \frac{N_i}{N_0} \qquad (i = 0,\ 1 \ldots z-1) \tag{5}$$

where N_0 is the number of turn for the standard EMF phasor vector.

In Sector A, the subscript notation of turns ratio is in the CW direction and, the subscript notation of Sector B in the CCW direction. The case if z=3, phase difference from E' of sactor A and E' of sactor B is 0*deg*., while phase difference of R_1E' is 2α, and for R_2E' is the phase difference 4α. These rules are reflected in the winding factor formula. By doing so, a more sinusoidal MMF waveform can be designed. In Figure 2. and Figure 3., the number of turns on a phase has to be the same, and thus the EMF phasor vector E indicated in Figure 2. and E' indicated in Figure 3. should be different in terms of amplitude.

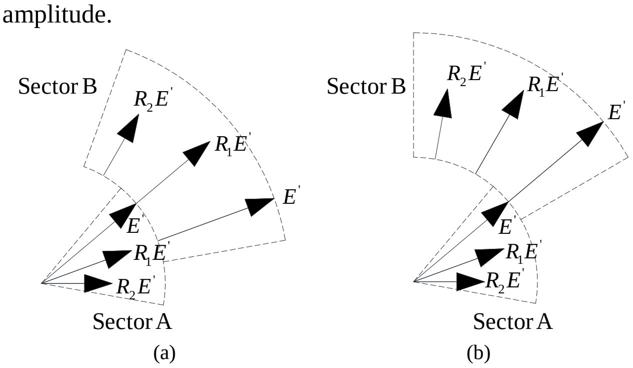

Fig. 3. Applying turns ratio(z=3) (a) $\alpha_{sh} = \alpha$ (b) $\alpha_{sh} = 2\alpha$

In Figure 3., in case of $\alpha_{sh} = \alpha$=20*deg*., the phase angle of EMF phasor vector for sector A is 0*deg*., 20*deg*. and 40*deg*., and the phase angle of EMF phasor vector for sector B is 20*deg*., 40*deg*. 60*deg*. If $\alpha_{sh} = 2\alpha$ = 40*deg*., the phase angle of EMF phasor vector for sector B is 40*deg*., 60*deg*., 80*deg*. These rules reflect the generalized EMF phasor of each harmonic order can be expressed as follows.

$$\vec{E}_{phase,v(pu)} = \sum_{i=0}^{z-1} R_i\left[e^{j\theta_{v,i}} + e^{j\{\theta_{v,i}+(z-i)\alpha_v\}-v\alpha_{sh}}\right], \quad (R_0 = 1) \tag{6}$$

where α_{sh} represents the shift angle.

For short pitch factor and winding factor, each formula is respectively as shown in formula (4). Figure 4. shows the winding factor according to the change in turns ratio for 8pole 9slot model. The 4^{th} harmonic for 8pole 9slot model is of fundamental harmonic. The 8pole 9slot is the case if z=3 (the numerator of q), and according to the turns ratio of R_1 and R_2, the winding factor changes. Figure 4. (a), (b), shows 1^{st} and 2^{nd} harmonic respectively. The black line on a curved surface in Figure 4. (a) and (b) is the point at which each harmonic order is zero. R_1 and R_2 are selected to this point, it would be easier to remove a specific harmonic order.

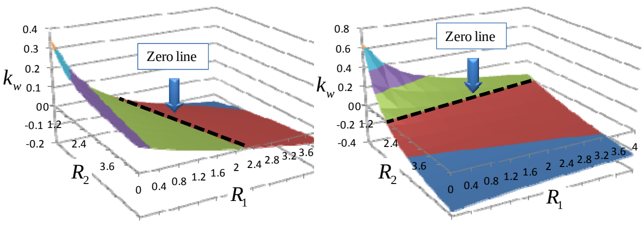

Fig. 4. Winding factor(8pole 9slot, z=3, $\alpha_{sh} = 2\alpha$) (a) v=1 (b) v=2

III. EXAMPLES OF APPLICATION

In order to verify an impact of turns ratio on motor performance, the two models of 16pole 18slot and 10pole 12slot were under MMF analysis and eddy current loss analysis using FEM. MMF analysis is used to verified whether the harmonic order was removed, whereas eddy current loss analysis and noise analysis are used to confirm whether the motor performance is improved. In order to verify the proposed method, analytical models of 10pole 12slot and 16pole 18pole are chosen. Each models has different power and size. Input current is the 200A_{rms}, and current angle is the 0*deg*. Operating speed is the 1000rpm. 10pole 12slot (z = 2) has one turns ratio and turns ratio R = 1.15. 16pole 18slot (z = 3) has two turns ratio and R_1=1.43, R_2=0.57 for turns ratio.

A. MMF Analysis

MMF of 10pole 12slot and 16pole 18slot are analyzed by 2D FEM. The amplitude of harmonic order of MMF is computed by harmonic analysis where permanent magnet is considered as air. MMF spectrums of double layer and four layer applied by turns ratio are shown in figure 5. In 10pole 12slot model, values of slot harmonic in the order 5th, 7th components are great and the value of the first order is also great. The order 1st and 11th components of turns ratio-applied four layer model appeared to disappear. In 16pole 18slot, slot harmonic of the order 4th, 5th components have the greatest value. It was found that Order 1st, 8th, 10th components of the turns ratio-applied four layer model were disappeared. Any harmonic component except slot harmonic component can be removed by applying turns ratio in motor design.

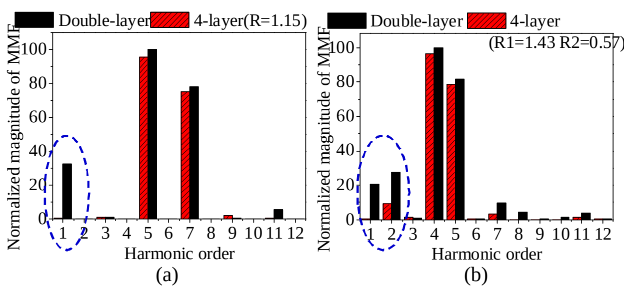

Fig. 5. MMF Spectrum(2D-FEM) (a) 10 pole 12slot(R=1.15) (b) 16pole 18slot(R_1=1.43, R_2=0.57)

B. Eddy current loss analysis

Eddy current loss of permanent magnet in rotor is generated by harmonic orders which are not synchronous speed components. In FCSM, sub-harmonic components are the greatest among harmonic components except slot harmonic which has bad influence on eddy current loss. Therefore eddy current loss can be reduced by applying turns ratio in motor design. Eddy current loss of each model is analyzed by 2D FEM. Figure 7. shows analysis results on eddy current loss in permanent magnet for each model. In 10pole 12slot mode, the four layer model applying the turns ratio showed about 45% of improvement in eddy current loss, while in 16pole 18slot mode, the four layer model applying the turns ratio showed about 16% of improvement in eddy current loss. In other words, compared to double layer winding, the four layer winding in which turns ratio was applied showed the result of reduction in eddy current loss.

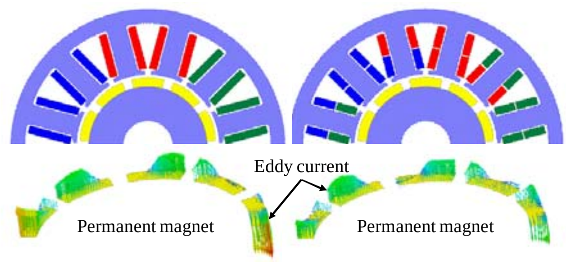

Fig. 6. Eddy current loss analysis(2D-FEM) (a) Double layer (b) four layer

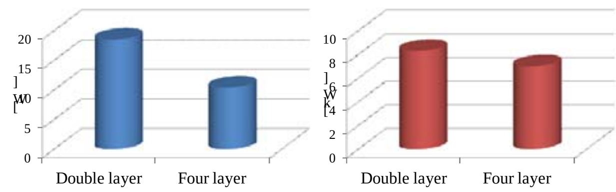

Fig. 7. Eddy current loss (a) 10 pole 12slot(R=1.15) (b) 16pole 18slot (R_1=1.43, R_2=0.57)

C. Vibration & Acoustic noise analysis

Radial force analysis and deformation analysis are performed using FEM and the double layer winding and the turns ratio-applied four layer winding are reviewed for their vibration / noise characteristics. Figure 8. shows vibration / noise analysis process. Radial force acting on the stator varies depending on time and place. Therefore, radial force acting on the stator depending on time and place should be analyzed. The amplitude of each harmonic order is calculated for time-dependent deformation. The harmonic order component with large amplitude of deformation will greatly affect vibration. Calculated deformation of each harmonic order is used to get sound pressure level in calculation. After A-weighting dB gain applied, the results can obtain that of Acoustic noise.

Figure 9. shows results of deformation analysis on Double layer and four layer, which is applied by the turns ratio, for the two models (10pole 12slot and 16pole 18slot analysis model). 10pole 12slot four layer model in which R = 1.15 is applied, compared with Double layer model, was shown to have the harmonic components of the biggest deformation order 10th, 50th, 80th all reduced. In particular, more than 60% of order 50th decreased in amplitude. Deformation of 16th, 32th and 64th harmonic order is great and reduced by applying by R

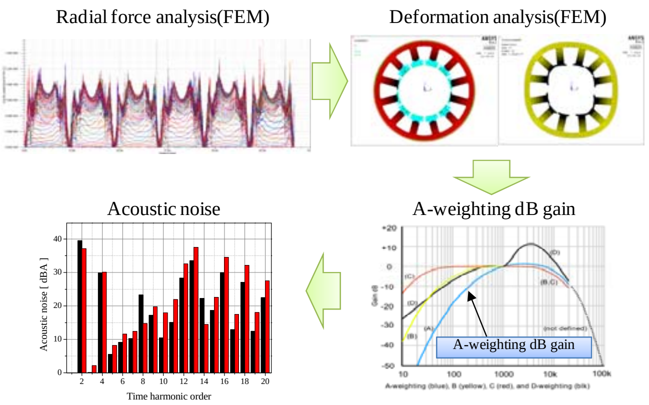

Fig. 8. Vibration & Acoustic noise analysis

= 1.43 and R = 0.57 in 16pole 18slot four layer model. In particular, the amplitude of order 16 was reduced by about 28%. In other words, the turns ratio- applied four layer winding, compared to Double layer winding, improves in the characteristics of vibration.

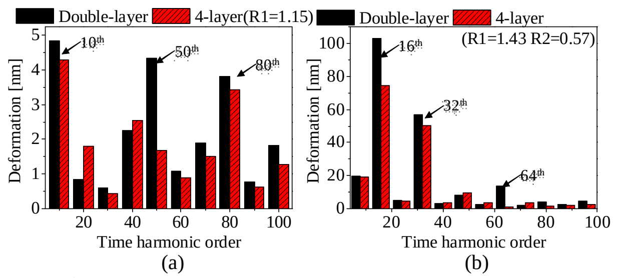

Fig. 9. Deformation analysis(2D-FEM) (a) 10 pole 12slot(R=1.15) (b) 16pole 18slot(R_1=1.43, R_2=0.57)

In order to verified the noise characteristics of this analysis model, using earlier results of deformation analysis, the sound pressure level (SPL) is calculated. With SPL, previously calculated value, the following A-weighting dB gain formulas was applied to get acoustic noise of the analytical model in calculation.

$$A(f) = 2.0 + 20\log(R_A(f)) \quad (7)$$

$$R_A(f) = \frac{12200^2 \cdot f^2}{(f^2+20.6^2)\sqrt{(f^2+107.7^2)(f^2+737.9^2)}(f^2+12200^2)}$$

where f is the sound frequency.

Figure 10. shows results of Acoustic noise analysis on Double layer and the turns ratio-applied four layer for two models.

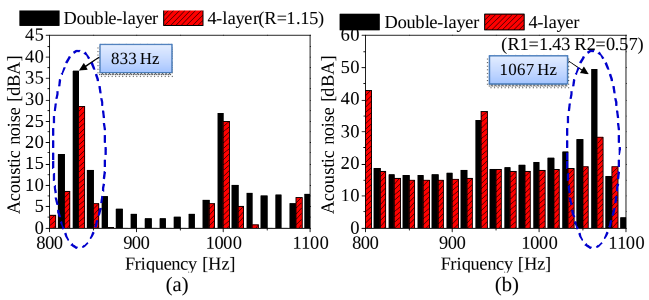

Fig. 10. Acoustic noise analysis (a) 10 pole 12slot(R=1.15) (b) 16pole 18slot(R_1=1.43, R_2=0.57)

Double layer winding of 10pole 12slot model has 833Hz of the highest noise, whereas the turns ratio-applied four layer of the same model see about 23% reduction in acoustic noise. In 16pole 18slot model, the highest noise was 1067Hz, and with turns ratio applied, the four layer model has approximately 43% reduction in 1067Hz acoustic noise. That is, by applying to the motor with turns ratio, it was confirmed to reduce the highest volume acoustic noise.

IV. Conclusion

In this paper, turns ratio for the application to the FCSM multilayer (4-layer) winding is proposed. If the turns ratio applied, this induced the general formula for the FCSM winding factor, and using the formula, a specific MMF harmonic component, except the slot harmonic, can be removed. To evaluate the turns ratio-applied model performance, 16-pole 18-slot model and 10-pole 12-slot model have been selected. Using FEM, MMF in the air gap was analyzed, and through eddy current loss analysis, improvements in eddy current loss of the turns ratio-applied four layer model, compared with double layer winding-applied model, are to be identified. Improvement of vibration and noise in model applied by turns ratio is verified by radial force analysis and deformation analysis.

Acknowledgment

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