http://dx.doi.org/10.11142/jicems.2013.2.3.313

Journal of International Conference on Electrical Machines and Systems Vol. 2, No. 3, pp. 313~320, 2013

Study of Winding Method to Reduce Stray Loss and Stator Core Vibration of Synchronous Machine

Daisuke Hiramatsu *, Kadek Fendy Sutrisna *, Hiroaki Ishizuka *, Masashi Okubo * Kazuma Tsujikawa *, Takashi Ueda *, Hideyuki Hachiya *, Junji Mori * Toshiyuki Aso *, and Toru Otaka *

Abstract – The fractional slot windings are widely used in rotating machine in order to increase the flexibility of design and improve the voltage waveform. However, the MMF wave of fractional-slot windings are found to contain unique harmonic component, which are designated as even order space flux harmonics, fractional number flux harmonics ,or both. They may cause stray loss and stator core vibration. This paper proposes new winding methods "novel interspersed windings" and "expanded group windings" to reduce these harmonics. The advantages of two proposed windings are verified by using numerical analysis and measurement test of winding model.

Keywords: Synchronous Machine, Fractional-slot windings, Harmonics, MMF

1. Introduction

For rotating machines, when the number of slots for armature winding is selected, the number of slots per pole per phase is usually made in integer number (hereinafter referred to as "integral-slot windings"). However, there are cases where the number of slots of pole per phase is adopted in fractional number (hereinafter referred to as "fractional-slot windings") for many purposes [1][2].

Fractional-slot windings have the advantage of improving waveform compared to integral-slot windings. However, there are unsymmetrical electromagnetic forces which are caused by space flux harmonics (MMF) resulting from the unequal number of slots per each pole. There are fractional number and/or even order space flux harmonic components. Then in some cases the electromagnetic force produced by these harmonics may cause stray loss and stator core vibration [3]. The authors propose new winding methods that reduce these space flux harmonics. Authors report the review result of two cases.

(1) 4 pole machine for analysis of even order harmonics

(2)10 pole machine and 56 pole machine for analysis of fractional number harmonics

2. Space Flux Harmonics (MMF) Caused by Fractional-slot windings

* Toshiba Corporation, Japan
(First Author e-mail:daisuke.hiramatsu@toshiba.co.jp)
Received 13 July 2013; Accepted 20 August 2013

2.1 Calculation of harmonics components

The armature MMF induced by the distributed windings can be evaluated by superposing the flux distribution of all the coils belonged to the winding. Fig. 1 shows a magnetic flux distribution induced by single coil assuming that the permeability of the iron core is infinity [6].

MMF distribution by 6 coils is shown in Fig. 2. The distribution of Fig. 2 can be expressed as follows.

$$B(x)=\sum_{n=1}^{\infty} A_n \cos\left(n\frac{\pi}{\tau}x\right) \tag{1}$$

$$A_n=\frac{1}{\tau}\int_0^{2\tau} B\cos\left(n\frac{\pi}{\tau}x\right)dx \tag{2}$$

where τ is pole pitch , α is coil pitch, (1) and (2) are obtained.

$$A_n=\frac{2B_C}{\pi n}\sin\left(n\frac{\alpha\pi}{2\tau}\right) \tag{3}$$

$$B(x)=\frac{2B_C}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin\left(n\frac{\alpha\pi}{2\tau}\right)\cos\left(nx\frac{\pi}{\tau}\right) \tag{4}$$

(4) gives the flux density distribution induced by single coil. The total flux distribution can be obtained by superposing by flux distribution of each coil.

By using (5), each harmonic can be calculated respectively. Here, n=1 means fundamental wave component of armature MMF.

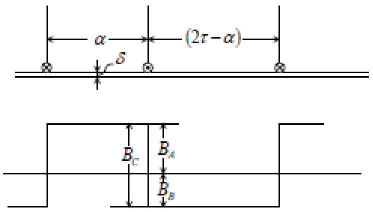


Fig. 1. Flux distribution of single coil

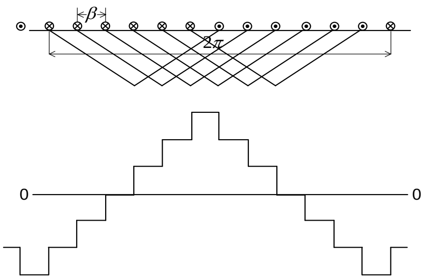


Fig. 2. MMF distribution of 6 coils

$$\boldsymbol{B} = \boldsymbol{B}(\boldsymbol{x}) + \boldsymbol{B}(\boldsymbol{x}+\boldsymbol{\beta}) + \boldsymbol{B}(\boldsymbol{x}+2\boldsymbol{\beta}) + \cdots + \boldsymbol{B}(\boldsymbol{x}+(\boldsymbol{q}-1)\boldsymbol{\beta})$$
$$= \frac{2\boldsymbol{B}_C}{\boldsymbol{\pi}} \sum_{n=1}^{\infty} \frac{1}{\boldsymbol{n}} \sin\left(\boldsymbol{n}\frac{\boldsymbol{\alpha\pi}}{2\boldsymbol{\tau}}\right) \frac{\sin\left(\boldsymbol{nq}\frac{\boldsymbol{\beta\pi}}{2\boldsymbol{\tau}}\right)}{\sin\left(\boldsymbol{n}\frac{\boldsymbol{\beta\pi}}{2\boldsymbol{\tau}}\right)} \cos \boldsymbol{n}\left(\boldsymbol{x} + \left(\frac{\boldsymbol{q}-1}{2}\right)\boldsymbol{\beta}\right)\frac{\boldsymbol{\pi}}{\boldsymbol{\tau}} \tag{5}$$

where q : coil number, β : slot pitch , δ : gap length

2.2 Fractional-slot windings

When the number of armature winding slots of a rotating machine is *Ns*, the number of slots per pole per phase *Nspp* is:

$$N_{spp} = \frac{N_s}{P\,m} \tag{6}$$

where P is number of poles, m is number of phases, Ns is total number of armature winding slots.

In many cases, Nspp is selected as integer number (integral-slot windings). However, the number of slots is limited, depending on the machine size. Nspp becomes smaller as the number of poles increases. As the result, the voltage waveform is getting worse. Therefore to avoid this drawback, Nspp is often selected in fractional number (fractional-slot windings) [6].

2.3 Space flux harmonics

In synchronous machine, the space flux density in the air gap can be shown by (7).

$$B_g(\theta_m, \omega t) = B_{gf}(\theta_m, \omega t) + B_{ga}(\theta_m, \omega t) \tag{7}$$

$\boldsymbol{\theta_m}$: mechanical angle, $\boldsymbol{\omega}$: angular frequency,

$\boldsymbol{B_{gf}(\theta_m, \omega t)}$: Flux density by excitation MMF

$\boldsymbol{B_{ga}(\theta_m, \omega t)}$: Flux density by armature MMF

Here, as the excitation MMF of each pole is equal, fractional number and even order harmonics are not present in $B_{gf}(\theta_m, \omega t)$. Flux density by excitation MMF in the air gap is shown by (8).

$$B_{gf}(\theta_m, \omega t) = B_{gf1}\cos(p\theta_m - \omega t) + B_{gf3}\cos(3p\theta_m - 3\omega t) + B_{gf5}\cos(5p\theta_m - 5\omega t) \tag{8}$$

where p : number of pole pairs

The flux density by armature MMF is as follows.

(1) If *Nspp* is integral

Fractional number and even order harmonics are not generated because MMF per pole is equal.

(2) If *Nspp* is fractional

Armature MMF per pole is unequal in each pole.

(2a)Case A, *Nspp* is fractional and denominator is 2

Even order space flux harmonics are contained in some cases.

(2b)Case B,*Nspp* is fractional and denominator is not 2

Fractional number space flux harmonics are contained.

Case A and B will be explained as follows:

(i) Case A; Nspp is fractional and denominator is 2

In case A, authors will explain 4-pole three-phase generator with 54 slots (4P-54slots) case as example. The number of slots per pole per phase is represented by (9).

$$N_{spp} = \frac{54}{4 \times 3} = 4\frac{1}{2} \tag{9}$$

In three-phase machine, *3n* order harmonics of armature MMF are zero by superposed three phases consequently. Moreover, when the rotating direction is considered. The magnetic flux density in the air gap by armature MMF of fractional-slot windings can be expressed as follows.

$$B_{ga}(\theta_m, \omega t) = B_{ga1}\cos(p\theta_m - \omega t) + B_{ga2}\cos(2p\theta_m + \omega t) + B_{ga4}\cos(4p\theta_m - \omega t) + B_{ga5}\cos(5p\theta_m + \omega t) + B_{ga7}\cos(7p\theta_m - \omega t) \ldots \tag{10}$$

Here case A $\boldsymbol{p} = 2$

$$B_{ga}(\theta_m, \omega t) = B_{ga1}\cos(2\theta_m - \omega t) + B_{ga2}\cos(4\theta_m + \omega t) + B_{ga4}\cos(8\theta_m - \omega t) + B_{ga5}\cos(10\theta_m + \omega t) + B_{ga7}\cos(14\theta_m - \omega t) \ \ldots \tag{11}$$

If only fundamental time frequency components are considered, by substituting (8), (10), and (11) to (7), the following result are obtained.

$$B_g(\theta_m, \omega t) = (B_{gf1} + B_{ga1})\cos(p\theta_m - \omega t) + B_{ga2}\cos(2p\theta_m + \omega t) + B_{ga4}\cos(4p\theta_m - \omega t) + B_{ga5}\cos(5p\theta_m + \omega t) + B_{ga7}\cos(7p\theta_m - \omega t) \cdots$$

Here $\boldsymbol{B}_1 = \boldsymbol{B}_{gf1} + \boldsymbol{B}_{ga1}$

$$B_g(\theta_m, \omega t) = B_1\cos(2\theta_m - \omega t) + B_{ga2}\cos(4\theta_m + \omega t) + B_{ga4}\cos(8\theta_m - \omega t) + B_{ga5}\cos(10\theta_m + \omega t) + B_{ga7}\cos(14\theta_m - \omega t) \ldots \tag{12}$$

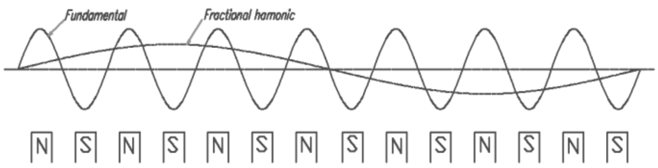


Fig. 3. Example of fractional harmonics (Case B' 56P-552slots)

where B_{ga2} and B_{ga4} are unique space flux densities when fractional-slot winding is adopted and may be related to an increase in additional stray losses and cause of core vibration.

(ii)Case B;Nspp is fractional and denominator is not 2

Authors will explain fractional number harmonics generated by fractional-slot windings using by 10P-54slots (Case B) and 56P-552slots (Case B'). *Nspp* of both cases are as follows.

$$\text{Case B} \quad \boldsymbol{N}_{spp} = \frac{54}{10 \times 3} = 1\frac{4}{5} \tag{13}$$

$$\text{Case B'} \quad \boldsymbol{N}_{spp} = \frac{552}{56 \times 3} = 3\frac{2}{7} \tag{14}$$

As the denominators calculated in (6), flux wave changes periodically per 5 or 7 poles each case. Fig.3 shows flux wave shape of case B'. It can be seen that *1/7th* harmonic occurred. In case B', the fractional number harmonic flux is shown:

$$B_g(\theta_m, \omega t) = B_1\cos(7\theta_m - \omega t) + B_{ga\frac{1}{7}}\cos(\theta_m - \omega t) + B_{ga\frac{5}{7}}\cos(5\theta_m + \omega t) + B_{ga\frac{11}{7}}\cos(11\theta_m + \omega t) + B_{ga\frac{13}{7}}\cos(13\theta_m - \omega t) \cdots\cdots \tag{15}$$

2.4 Electromagnetic force

Electromagnetic force per unit area caused by space flux in air gap is described in (16).

$$F(\theta_m, \omega t) = \frac{1}{2\mu_0} B_g^{\,2}(\theta_m, \omega t) \tag{16}$$

The above equation shows energy in the air gap and the relation between the coupling force of the stator (armature) and rotor (field).

(i) Case A; Nspp is fractional and denominator is 2

The AC component of magnetic force *Fac* is proportional to the AC component of the square of flux density. Here, as B_1 is larger than other amplitude ($B_1 >> Bga_2$, Bga_4, Bga_5, and Bga_7), the terms which is not containing B_1 can be neglected. The (16) can be rewritten as follows:

$$\begin{aligned} F_{ac}(\theta_m, \omega t) &= \frac{B_1^{\,2}}{4\mu_0}\cos(4\theta_m - 2\omega t) + \frac{B_1 B_{ga2}}{2\mu_0}\cos(2\theta_m + 2\omega t) \\ &\quad + \frac{B_1 B_{ga4}}{2\mu_0}\cos(10\theta_m - 2\omega t) + \frac{B_1 B_{ga5}}{2\mu_0}\cos(8\theta_m + 2\omega t) \\ &\quad + \frac{B_1 B_{ga7}}{2\mu_0}\cos(16\theta_m - 2\omega t) + \cdots \\ &= F_{a2}\cos(4\theta_m - 2\omega t) + F_{a1}\cos(2\theta_m + 2\omega t) \\ &\quad + F_{a5}\cos(10\theta_m - 2\omega t) + F_{a4}\cos(8\theta_m + 2\omega t) \\ &\quad + F_{a8}\cos(16\theta_m - 2\omega t) + \cdots \end{aligned} \tag{17}$$

In (17), the most effective component is, $F_{a2}\cos(4\theta_m - 2\omega t)$, that is the same as the pole number mode. On the other hand, there are unique space electromagnetic force components such as $F_{a1}\cos(2\theta_m + 2\omega t)$ and $F_{a5}\cos(10\theta_m - 2\omega t)$, those terms are caused by even order of space flux harmonic component. $F_{a1}\cos(2\theta_m + 2\omega t)$ may be related to increase vibration of stator core and noise.

(ii) Case B;Nspp is fractional and denominator is not 2

Calculation of electromagnetic force ia the same as case A and the result is shown below.

$$F_{ac}(\theta_m,\omega t)=F_{a2}\cos(14\theta_m-2\omega t)+F_{a\frac{1}{7}}\cos(8\theta_m-2\omega t)+F_{a\frac{5}{7}}\cos(2\theta_m-2\omega t)+F_{a\frac{11}{7}}\cos(4\theta_m+2\omega t)+F_{a\frac{13}{7}}\cos(20\theta_m-2\omega t)+\cdots \quad (18)$$

As to the stator core vibration, the mode of electromagnetic force is getting higher, stiffness of core becomes higher. Now the most noteworthy frequency is the ones close to fundamental frequency wave such as case B *7/5*th , case B' *5/7*th

In case B', *5/7* th and fundamental wave interact with each other, electromotive force of double frequency power supply is occurred. If this frequency were close to natural frequency of stator core, the core resonation may occur.

3. Comparison of Integral-slot Windings and Fractional–slot Windings

In this part, two cases of four pole machine are considered to compare integral-slot windings and fractional-slot windings. Fig. 4 (a) and Fig. 4 (b) show the slot arrangement of both cases.

Here case A-1 (4pole-54slots machine), the number of slots per pole is 13.5. This means that the number of slots per pole is 13 or 14, and the armature MMF differs for eachpole. From this winding arrangement, the armature MMF contains even order harmonics. Fig. 5 (a) and Fig. 5 (b) showthe wave form of both cases.

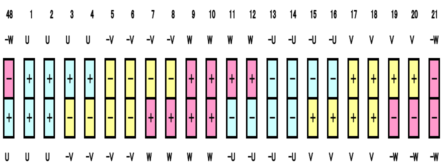


Fig. 4. (a) Example arrangement of armature winding of three-phase, 4-pole, and 48 slots machine (integral-slot windings).

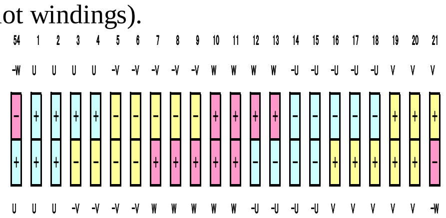


Fig. 4. (b) Example arrangement of armature winding of three-phase, 4-pole, 54slots machine (fractional-slot windings: caseA-1)

As described in the previous section, the *3n* order space flux harmonic components of armature MMF become zero by superposition of three phases consequently. The fundamental, *2*nd, *4*th, *5*th,and *7*th order harmonic components of the space flux by armature MMF are shown in Table 1.

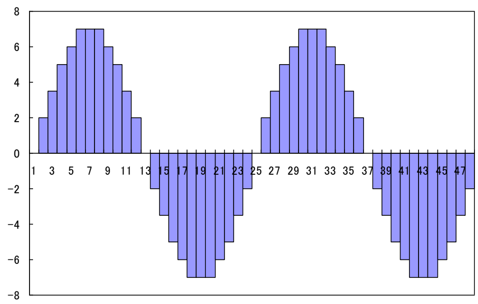


Fig. 5. (a) Wave form of integral-slot windings (4pole-48slots machine)

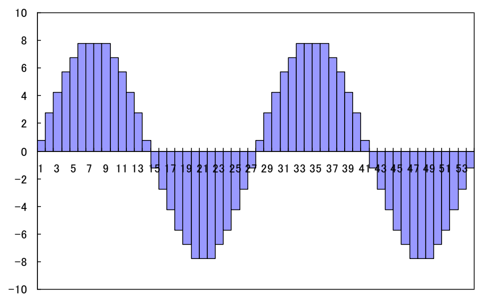


Fig. 5. (b) Wave form of fractional-slot windings (4pole-54slots machine case A-1)

Table 1. Analysis result of armature MMF

	Slot no.	Coil pitch	Harmonic component [pu]				
			1	2	4	5	7
Integral-slot windings	48	#1～#11	1.0	0	0	0.0015	0.0063
Fractional-slot windings (Case A-1)	54	#1～#12	1.0	0.0168	0.0143	0.0049	0.0098

4. Proposal of New Winding Method and Verification Test

4.1 Novel interspersed windings

As mentioned before, on the fractional-slot windings, there exists fractional number and/or even order harmonics. These harmonics cause the increase of stray loss and resonance with stator core. To avoid those problems, authors proposed two new winding methods.

The armature winding is arranged in three-phase, 60-degree phase belt. To reduce the space flux harmonics the method that one coil is interchanged with adjacent phase coil has been adopted. This method had been called as "interspersed one coil windings". The proposal method is based on interspersed one coil windings, however either top or bottom bar is individually interchanged with adjacent phase group. We call the new method as "novel interspersed windings". Conventional interspersed one coil windings method is adopted in integral-slot windings to reduce space flux harmonics of 5^{th} and 7^{th} [7]. In contrast, novel interspersed windings can reduce the specified flux harmonics of fractional-slot winding. Fig. 6 shows the fractional-slot windings, interspersed one coil windings, and novel interspersed windings.

The analysis results on harmonic components of armature MMF in fractional-slot windings (case A-1) and novel interspersed windings (case A-3) are shown in Table 2. As shown in Table II, it is clear that the adoption of the proposed winding (Case A-3) can reduce the even order harmonics (2^{nd}, 4^{th} order harmonics) of armature MMF in comparison with those in case A-1. Table 3 and IV show that the comparison fractional-slot windings, interspersed one coil windings and novel interspersed windings by using 10P-54slots (case B) and 56P-552slots (case B').

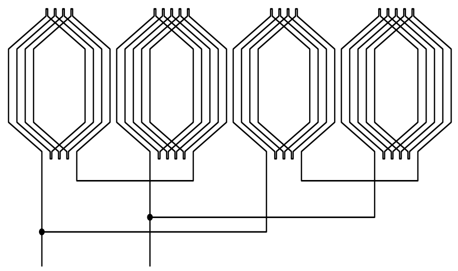


Fig. 6. (a) Fractional-slot windings (Case A-1)

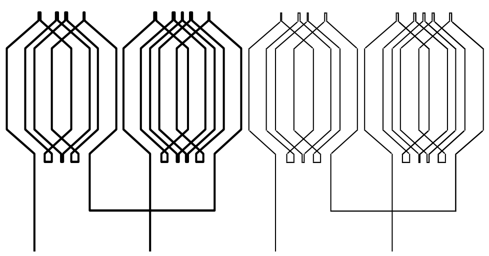


Fig. 6. (b) Interspersed one coil windings (Case A-2)

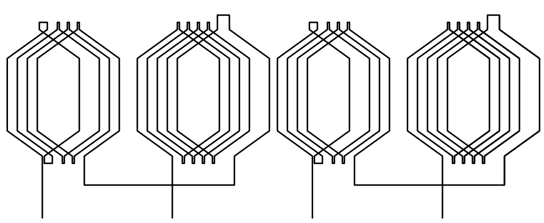


Fig. 6. (c) Novel interspersed windings (CaseA-3)

Table 2. Analysis result of armature MMF (Case A)

	Slot no.	Winding method	Harmonic component [pu]				
			1	2	4	5	7
Case A-1	54	Fractional-slot windings	1.0	0.0168	0.0143	0.0049	0.0098
Case A-3	54	Novel interspersed windings	1.0	0.0045	0.0064	0.0174	0.0091
Ratio (Case A-3/Case A-1)				0.266	0.447	3.553	0.931

Table 3. Analysis result of armature MMF (Case B)

	Slot no.		Harmonic component [pu]		
			1/5	1	7/5
Case B-1	54	Fractional−slot windings	0.1073	0.8773	0.0407
Case B-2	54	Interspersed one coil windings	0.1222	0.8188	0.0221
Case B-3	54	Novel interspersed windings	0.1180	0.8482	0.0095

Table 4. Analysis result of armature MMF(Case B)

	Slot no.		Harmonic component [pu]				
			1/7	5/7	1	5	7
Case B'-1	552	Fractional-slot windings	0.0318	0.0620	0.9461	0.0297	0.0113
Case B'-2	552	Interspersed one coil windings	0.0315	0.0435	0.9188	0.0109	0.0024
Case B'-3	552	Novel interspersed windings	0.0287	0.0496	0.9325	0.0228	0.0118

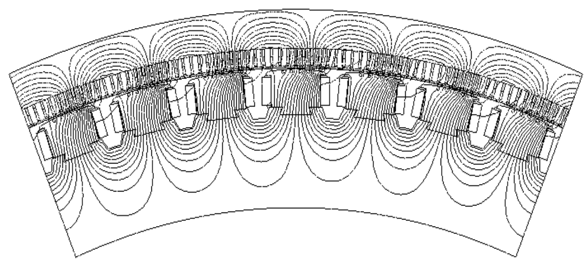


Fig. 7. Flux distribution of Case B' model

Table 5. Analysis result of armature MMF using FEM (Case B')

	Slot no.		Harmonic component [pu]				
			1/7	5/7	1	5	7
Case B'-1	552	Fractional-slot windings	0.0035	0.0343	1.00	0.0258	0.0293
Case B'-3	552	Novel interspersed windings	0.0032	0.0278	1.00	0.0323	0.0227

As shown in Table 3 and 4, in multi poles case, if both top and bottom coils were interchanged adjacent phase group as interspersed one coil windings, the fundamental component becomes small. In this case, it might be required to redesign larger core size to prevent saturation of flux. However if the novel interspersed windings is adopted, it could reduce the amplitude of the specified harmonics without reducing fundamental component.

Fig.7 and Table 5 show the results of analysis of Case B' using FEM. The reduction of specified harmonics by using novel interspersed windings is confirmed.

4.2 Expanded Group Windings

In fractional slot-windings, the coils are arranged some group. For 10Pole-54Slots case, *Nspp* is 1+4/5, so the distribution of coil is 1 2 2 2 2, repeatedly. In this case, the group consists of 9 coils. However, in the proposed method 18 coils are arranged in one group.

Table 6. Analysis result of armature MMF (Case B 10P-54 slots expanded group winding case)

	Slot no.		Harmonic component [pu]				
			1	2	5	7	7/5
Case B-1	54	Fractional-slot windings	1.00	0.00	0.0198	0.0219	0.0464
Case B-3	54	Novel interspersed windings	1.00	0.00	0.0249	0.0082	0.0112
Case B-4	54	Expanded group windings	1.00	0.0231	0.0190	0.0201	0.0107

Table 6 Analysis result of armature MMF harmonics component This method is called as "expanded group windings", it can reduce the unbalance of MMF. Table VI shows the harmonics component 10pole-54slot machine

(Case B). According to this table, specified harmonics can be reduced.

4.3 Effect of harmonics

As described in the previous section, for the fractional-slot winding machines, stray loss may increase due to even order harmonics. When *2nd* and/or *4th* even order harmonics are included, eddy currents by such harmonics will cause heating of rotor surface in solid rotor machines such as turbine generators and salient 4pole machines. The effect of the non-synchronous component of armature MMF components is evaluated by the equivalent negative phase sequence current. (19) shows the equivalent negative phase sequence current.

$$I_{2eq} = \sqrt{\sum_{n} \sqrt{\frac{n}{2}\left(I_{n-1}^{2} + I_{n+1}^{2}\right)}} \tag{19}$$

Where: I_2eq : equivalent negative phase sequence current
I_k : current of k^{th} harmonic

The evaluation results of equivalent negative phase sequence component for case A-1 and A-3 are shown in Table 7.

In the evaluation of the effect of negative phase sequence current, such as pole surface loss, MMF harmonics on the rotor surface should be considered. The armature MMF on the rotor surface can be expressed as (20) considering the decay in the air gap [9].

Table 7 also includes the results calculated by (19). From this table, it can be concluded that the novel interspersed windings are able to reduce the equivalent negative phase sequence component.

$$I'_{2n} = I_{2n} \frac{1}{\cosh \frac{\pi g}{\tau_n}} \tag{20}$$

where g : gap length n : wave length of nth harmonics

Table 7. Analysis result of equivalent negative phase sequence current

	Slot no.	Winding method	Harmonic component [pu]					I_{2eq}	I'_{2eq}
			1	2	4	5	7		
Case A-1	54	Fractional-slot windings	1.0	0.0168	0.0143	0.0049	0.0098	0.0284	0.0239
Case A-3	54	Novel interspersed windings	1.0	0.0045	0.0064	0.0174	0.0091	0.0277	0.0203

4.4 Experimental verification of space flux (armature MMF)

To verify above theory, two winding models were prepared for fractional-slot windings (Case B-1) and novel interspersed windings (Case B-3) shown in Fig.8. Table VIII shows the detail specification of two models. To measure the flux density of the air gap, a dummy inner core was installed in the inner side of the stator core. According to flux measurement results (Table IX), the effective of novel interspersed windings can be confirmed.

4.5 Vibration caused by even order or fractional number harmonics

As shown in Table III and Table IV, fractional harmonics of case B (10P-54slots) and case B' (56P-552slots) is not large compared with the fundamental component. However, there is on case that electromagnetic force by these fractional harmonics causes vibration to the stator depending on the natural frequency of stator core.

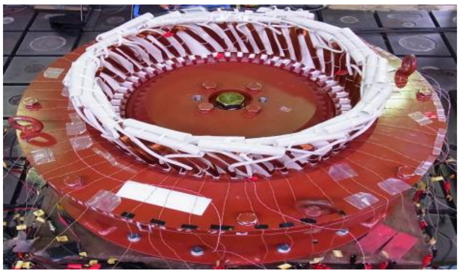


Fig. 8. Verification model

To verify this matter, a resonator model made of steel with similar natural frequency of electromagnetic force was manufactured. In advance, the natural frequency of resonator was adjusted close to 100Hz. 100Hz MMF is made by 7/5th harmonics excited by 50Hz power source.

Vibration measurement test by using case B-1 and B-3 model were conducted. Figs. 9 and 10 show the resonator model used.

Table 8. Specification of the verification model

	Case B-1	Case B-3
core outer diameter	ϕ800	
core inner diameter	ϕ450	
core length	30	
pole No.	10	
phase No	3	
slot No	54	
N_{spp}	1+4/5	
parallel No	Y*1	
coil connection	Fractional-slot windings	Novel interspersed windings

Table 9. Experimental results of armature MMF

	Slot no.		Harmonic component [pu]		
			1/5	1	7/5
Case B-1	54	Fractional-slot Windings	0.0950	1.00	0.0630
Case B-3	54	Novel interspersed Windings	0.1250	1.00	0.0130

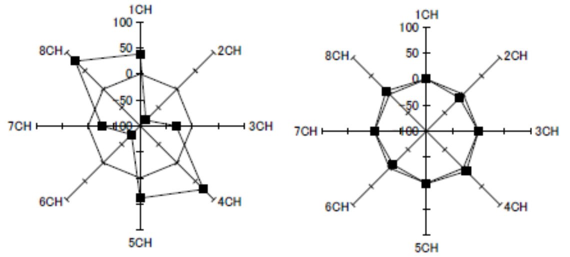
Fig. 9. Vibration measuring on the resonator


Fig. 10. Verification model with vibration measurement test

Table 10. Reduction ratio of vibration

	Slot no.		Vibration Value [m/s2/N]							
			CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
Case B-1	54	Fractional-slot windings	42.7	84.7	35.3	72.7	42.6	76.8	30.7	76.4
Case B-3	54	Novel intespersed windings	5.1	9.9	4.2	8.5	4.8	9.6	3.9	9.3
Ratio (CaseB-3/CaseB-1)			0.12	0.12	0.12	0.12	0.11	0.13	0.13	0.12

In the vibration test, the models as shown in Fig.9 were excited to measure acceleration response at each measurement point as shown in Fig.10. The measurement results were frequency decomposed using the FFT analyzer to get the amplitude of electromagnetic vibration components of 100 Hz. Table 10 and Fig.11 show the vibration measurement results, it is clear that vibration was reduced by adopting the novel interspersed windings.



(a) Case B-1 (Fractional-slot windings)   (b) Case B-3 (Novel interspersed windings)

Fig. 11. Vibration measurement results

5. Conclusion

Conventionally, fractional-slot windings are widely used in rotating machine in order to improve waveform and flexibility of design. However, the fractional number and/or even order harmonics caused by fractional-slot winding is responsible for vibration in stator core and additional stray losses.

Authors studied the MMF harmonics due to fractional-slot windings, and proposed two winding methods "novel interspersed windings" and "expanded group windings"

Authors investigated these effects and the following result has been obtained.

(1)It is possible to reduce the designated fractional number and even order flux harmonics by application of the proposed windings.

(2)The advantage of this proposed winding methods were verified by using analytical calculation and model winding test.

Accordingly, it gives more options on the selection of the number of slot at the designing stage and reducing the probability of stator core vibration and additional losses. Authors are now investigating the other winding methods to reduce the influence of the even order and fractional number harmonics.

References

[1] M. G. Say, "Alternating Current Machines", Pitman Published Ltd., 1976

[2] J. H. Walker, "Large Synchronous Machines", Clarendon Press Oxford, 1981.

[3] A. Gray, "Electrical Machine Design" McGraw-Hill Book Co., 1913

[4] K.Unno, "Synchronous .Generator" Corona Publishing Co. Ltd,1950.

[5] T.Haze, "Synchronous Machine" Shukyosya Shoin Co. Ltd, 1951.
[6] I.Shigyo,"Theory of Electrical Machine Design" Maruzen Publishing Co. 1950
[7] Chalmers, "A.C. machine windings with reduced harmonic content" , Proc. IEE, vol. 111, no. 11, pp. 1859-1863, Nov. 1964
[8] K.Tsujikawa,T.Tokumasu,M.Kakiuchi,D.Hiramatsu,M,Fujita, T.Ueda,K.Ikeda,M.Ichimonji,T.Otaka"Special Winding to Reduce Space Flux Harmonics Caused by Fractional-Slot", International Conference on Electrical Machines and Systems (ICEMS2012)
[9] T. Bratoljic, "Recent studies of stray losses in solid pole-pieces of synchronous machines", The Brown Boveri Review, pp.521-530, Sep., 1966.

Daisuke Hiramatsu received M.A. degree in electrical engineering from Keio University in 1980 and joined Toshiba Corporation, Japan. He was engaged in the design of synchronous generators and motors. He holds a Ph.D. degree in electrical engineering. He is Professional Engineer, First Class Qualified Electrical Engineer and member of IEEE

Kadek Fendy Sutrisna received the B.S. degree in Institute of Technology Bandung, Indonesia, and the M.Eng. degree in engineering from Tokai University, Japan. Since April 2012, he joined Toshiba Corporation, Japan, where he is involved in the research and design of Synchronous Generator.

Hiroaki. Ishizuka received the M.A. degree in electrical engineering from Tokyo Institute of Technology in 1995. He joined Toshiba Corporation, Japan in1995 and engaged in the design of hydro generators. He is now the specialist of the Generator Engineering Group and a member of the Institute of Electrical Engineers of Japan.

Masashi Okubo received M.A. degree in electrical engineering from Utsunomiya University in 2001. He joined Toshiba Corporation, Japan in 2001 and engaged in the design of hydro generators. He is now the specialist of the Generator Engineering Group and a member of the Institute of Electrical Engineers of Japan.

Kazuma Tsujikawa received M.A. degree in electrical engineering from Kyushu Institute of Technology in 2009 and joined Toshiba Corporation, Japan. He was engaged in the design of turbine generators. He is a member of the Institute of Electrical Engineers of Japan.

Takashi Ueda received M.A. degree in electrical engineering from University of Miyazaki in 2006 and joined Toshiba Corporation, Japan as a research engineer and works on the computing analysis of electromagnetic field by the finite element method. He is now the research engineer in the New Energy and Generator Group of the Power and Industrial Systems R&D Center.

Hideyuki Hachiya received B.S. degree in electrical engineering from Yokohama National University in 1980, and joined Toshiba Corporation, Japan. He has been engaged in the engineering of hydroelectric power projects, and is a member of the Institute of Electrical Engineers of Japan.

Junji Mori received M.A. degree in electrical engineering from Nihon University in 1993, and joined Toshiba Corporation, Japan. He has been engaged in the engineering of hydroelectric power.

Toshiyuki Aso received B.S degree in electrical engineering from Niigata University in 1982 and joined Toshiba Corporation, Japan. He has been engaged in the design of hydro generators. He is now the chief specialist of the Generator Department and a member of the Institute of Electrical Engineers of Japan.

Toru Otaka received M.A. degree in elect rical engineering from Waseda University i n 1977. He joined Toshiba Corporation, Ja pan in 1977 and engaged in the design of t urbine generators. He is a member of the I nstitute of Electrical Engineers of Japan.