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General Characteristic of Fractional Slot Double Layer Concentrated Winding Synchronous Machine

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Abstract – The concentrated winding configurations offer significant advantage for reducing end windings. These machines are generally used in low speed high torque application due to relatively low copper loss. However, numbers of fractional slot construction make the designer hard to properly choose pole and slot numbers for the certain application. This paper provides the general information of possible fractional slot concentrated double layer winding machine.

Keywords: Fractional slot, Concentrated winding, SPMSM, Saturation

1. Introduction

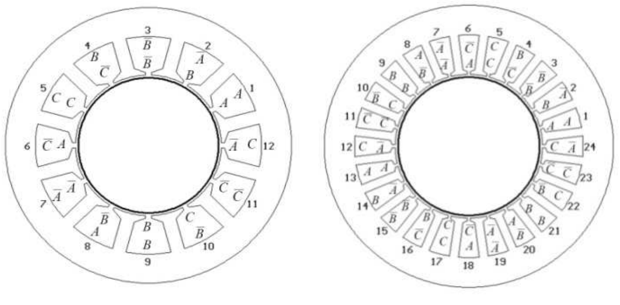
Fractional-slot concentrated winding (FSCW) machines are very attractive solution in several applications. These advantages include high efficiency, short end turn, high slot fill factor especially used with segmented stator core. The drawbacks of fraction-slot configurations are a slightly lower winding factor and a high harmonic content in the MMF distribution compared to the integral slot machine. The undesirable low order vibrations, local saturations are occurred due to these harmonic contents. Especially, there are sub-harmonics which have harmonic order lower than pole pair of the machine. These sub-harmonics produce significant rotor losses when the machine operates in high speed [1]. Therefore, the designer has to properly choose poles and slot combination by the applications of the machine. In this paper, the general characteristics of FSCW machines for poles and slots combination are compared and the design information to select the proper combination will be provided for the better performance of the machine.

2. Characteristic

A fractional-slot winding is represented by non overlapped coils wounded around a single tooth. There are numberless poles/slot combinations in fractional slot machines. To simplify the problems, only a 3 phase common double layer concentrated winding is considered.

A. Balanced concentrated winding configuration

There are certain winding configurations to maximize winding factors of the machine. It means that electrical fundamental harmonic of ampere-conductor distribution can reach its maximum in particular poles/slots combination. In FSCW machine, the fundamental winding factor can be maximized when numbers of poles are closed to number of slots in unit period. Fig. 1(a) shows the double layer concentrated winding configuration of 10p/12s (poles/slots) and 20p/24s machine respectively. The period of the 20p/24s is 2 as the greatest common divider between pole pair and number of slots and is same as multiplier from 10p/12s. Note that the winding configuration between 10p/12s and 20p/24s is symmetrical. Therefore, one can also easily notice the winding configuration of the 30p/36s, and 40p/48s machine. It is due to that their *Q/t* values are same where *Q* is number of slots and *t* is the period of the machine. By using above relationship, most of possible fractional slot machine can be categorized by *Q/t* value as presented in Table 1. In case of *Q/t*=18, the basic combination (*t*=1) should be 16p/18s and 20p/18s. However, they are already members of *Q/t=9* group when *t*=2. Therefore, 14p/18s and 22p/18s becomes basic combination of *Q/t*=18 group. Note that, the combinations in another group are independent with each other. The remains of paper deal with the explanations of the table.



(a) 10 pole 12slot (b) 20 pole 24slot

Fig. 1. Double layer concentrated winding configuration

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Table 1. Characteristic of FSCW double layer winding machine

Q/t	3		9		12		15		18		21		24	
K_w	0.866		0.9452		0.933		0.9514		0.9019		0.9531		0.9495	
Lcm (2p,Q)	6·t	12·t	72·t	90·t	60·t	84·t	210·t	240·t	126·t	198·t	420·t	462·t	264·t	312·t
t	2p / Q													
1	2/3	4/3	8/9	10/9	10/12	14/12	14/15	16/15	14/18	22/18	20/21	22/21	22/24	26/24
2	4/6	8/6	16/18	20/18	20/24	28/24	28/30	32/30	28/36	44/36	40/42	44/42	44/48	52/48
3	6/9	12/9	24/27	30/27	30/36	42/36	42/45	48/45	42/54	66/54	60/63	66/63	66/72	78/72

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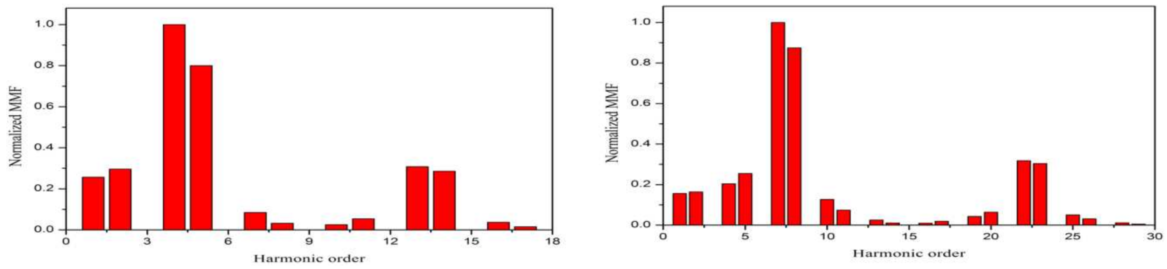
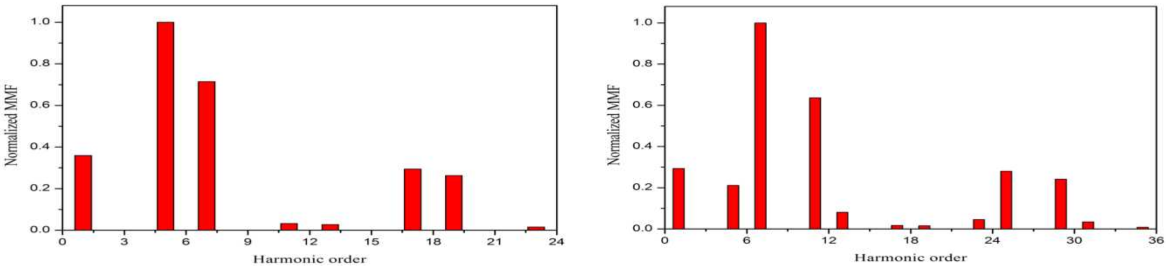


(a) Q/t=9 (b) Q/t=12



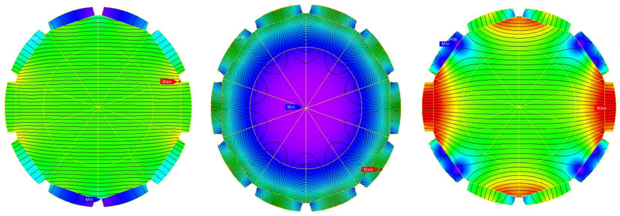
(c) Q/t=15 (d) Q/t=18

Fig. 2. Normalized MMF of each Q/t when t=1.

B. MMF

Due to the symmetric winding configuration in same *Q/t* group, the only difference is the harmonic order multiplied by *t* from MMF of the basic combination. Therefore, one can know MMF distribution in any of the combinations if the basic combination with same *Q/t* value is known. Fig. 2 shows MMF of the some basic combinations within third electrical periods. Note that *Q/t*=odd groups have more sub-harmonic components compared to *Q/t*=even. It also can be seen that higher value of *Q/t* groups have more sub-harmonic contents.

The effects of those sub-harmonics are shown in Fig. 3. The rotor configuration is chosen as bread-loaf type with 10 poles. The permanent magnets are considered as air-gap to only observe the effects of armature reactions. If the machine has 12 slots with double layer concentrated winding, the harmonics of idle armature reaction filed is identical with those of MMF itself as shown in Fig. 2(b). Fig. 3(a) shows the effects of the 1st mechanical order harmonic. The flux is concentrated along the horizontal axis. Fig. 3(b) presents the fundamental (5th) harmonic. The saturated condition of rotor core is identical with each rotor pole. Fig. 3(c) considers the effect of above two harmonics. This causes the local saturation of the machine which decreases average torque and increases torque ripple. The number of *Q/t* over the 24 is not recommended especially when *Q/t* is odd.



(a) 1st harmonic (b) 5th harmonic (c) combined

Fig. 3. Effects of sub-harmonic in 10p/12s machine

C. Torque ripple

The torque ripple expressed by Lorentz force is the results from interaction between $6n\pm1^{th}$ electrical harmonics of air-gap flux density and ampere-conductor distribution where ampere-conductor distribution is,

$$A(\theta)=\frac{i\cdot C(\theta)}{R} \tag{1}$$

The function $C(\theta)$ is conductor distribution and i, R denote phase current, stator bore radius respectively. The so-called MMF distribution $f(\theta)$ is the integral of the ampere-conductor distribution

$$f(\theta)=\int A(\theta)\cdot R d\theta=\sum_{n=1}^{\infty}F_n\cos(n\theta+\phi_n) \tag{2}$$

Considering ideal air gap flux density distribution produced by PM that there exists only odd electrical harmonics,

$$B_g=\sum_{h:odd}B_h\cos(h\theta) \tag{3}$$

where h is electrical harmonic order. Neglect non electrical order harmonics of MMF in 3 phase FSCW machine and consider rotating synchronously reference frame with rotor, (2) and (3) can be modified as

$$B_g=\sum_{h:odd}B_h\cos(h\theta-h\omega_e t) \tag{4}$$

$$f=\sum_{h\neq3,6,9...}F_h\cos(h\theta\mp h\omega_e t\mp\phi_h) \tag{5}$$

The instantaneous torque is,

$$T_e=\frac{P}{2}r_g l_{stk}\int_{2\pi}B_g\frac{df_s}{d\theta}\,d\theta \tag{6}$$

leads to

$$Average\,Torque=\frac{P}{2}r_g l_{stk}\pi f_1 B_1 \tag{7}$$

$$Torque\,Ripple=-\frac{P}{2}r_g l_{stk}\pi \times\sum_{\substack{h=6m\mp1\\ m=1,2,3..}}\{hf_h B_h\sin((h\pm1)\omega_e t\pm\phi_h)\} \tag{8}$$

Where ω_e, r_g, l_{stk} is the electrical rotor angular velocity, radius of air gap, stack length respectively.

Seok-Hee Han *et al.* have studied the reduction of torque ripple in interior permanent magnet machine with distributed winding by choosing odd numbers of slots per pole pair [2]. The Fig. 4 can help to understand the idea. It can be seen that period is 15 which is the same as *Q/t* value. Because of the mechanical symmetry, the electrical harmonic spectra of any poles/slots combinations in same *Q/t* group are identical. The main idea is that $6m\pm1^{th}$ order harmonics of hF_h having its peak amplitude should be positioned at high order. Since the harmonics of hF_h have its peak in electrical order at every $Q/t\cdot n\pm1^{th}$, the idea can be adopted in FSCW machine as

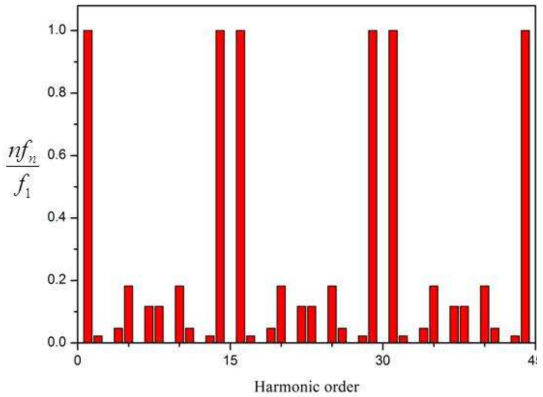


Fig. 4. Normalized electrical order MMF of Q/t=15 multiplied by harmonic index

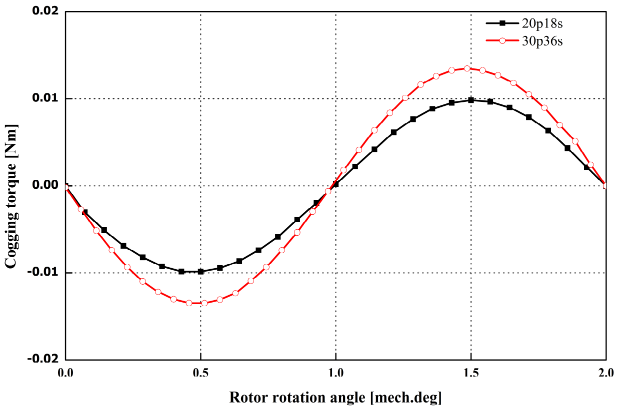
$$\text{Maximize}\ \{N_{6h}=LCM(6,\tfrac{Q}{t})\}$$

Where *LCM*(*a*, *b*) is the least common multiplier between *a* and *b*. This can be simplified,

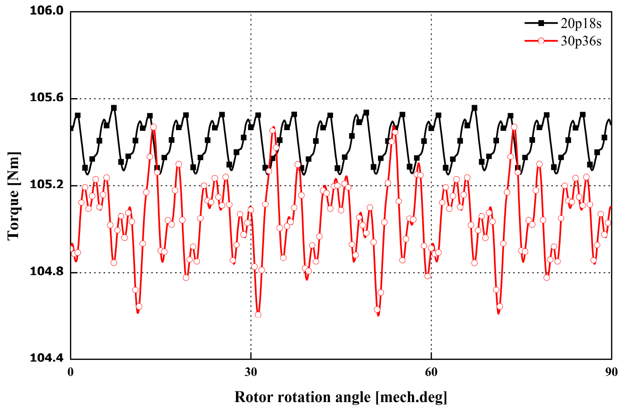
If Q/t=odd, $N_{6h}=Q/t\times2$
If Q/t=even, $N_{6h}=Q/t$

The comparative study has been conducted for above discussion. Cogging torque of 20p/18s and 30p/36s bread-loaf type surface permanent magnet machines are presented in Fig. 5(a). The permanent magnet is radially magnetized with 150 electrical degree pole arc and 0.5 slot/tooth width ratio with the open slot structure. They both have same cogging torque periods, however, those of 20p/18s machine have slightly lower peak to peak value. Fig. 5(b) shows the waveforms of torque in the loaded state. Both machines can reach very low torque pulsations. However, since N_{6h} value of the 20p/18s machine is more higher compared to 30p/36s machine, the torque ripple becomes lower.

Table 2 presents the torque ripple data from [3]. The high number of *LCM*(2p, Q) can generally reduce cogging torque. Therefore, more Higher N_{6h} with similar *LCM*(2p,Q) value FSCW machine have the lower torque ripple characteristics. However, the higher values of *Q/t* machines have more sub-harmonic contents and it can lead to undesirable torque ripple due to the local saturation.



(a) Cogging torque



(b) Torque wave forms

Fig. 5. Comparison of torque characteristics

D. Radial forces density

The harmonic orders of radial force density are the differences between any harmonic orders of armature reaction fields and permanent magnet flux density fields. The harmonic orders of radial force density in FSCW machine can be simplified as

If Q/t=odd : $t \times n$ ($n = 1,2,3 \ldots$)
If Q/t=even : $2 \times t \times n$

Fig. 6 shows radial force density of 44p/48s (*Q/t*=even, *t*=2) compared by the finite element analysis.
In general, *Q/t*=odd, and *t*=1 combination is not recommended due to unbalanced magnetic forces. One have to choose *Q/t*=even combination or *t* should be larger than 1 in case of *Q/t*=odd to avoid fatal vibration and noise. It is also worth to note that between two combinations with same *t* in same *Q/t* groups, the machines with higher pole number than slot number have more larger amplitude of the lowest order vibration [4].

Table 2. Torque ripple of FSCW machine, 96page of [3]

2p/Q	N_{6h}	LCM(2p,Q)	T ripple %
8/12	6	24	13
16/12	6	48	3.5
16/24	6	48	3.82
24/36	6	72	2
10/12	12	60	2.5
14/12	12	84	1.5
20/24	12	120	1.7
28/24	12	168	0.8
30/36	12	180	1.5
42/36	12	252	0.6
14/18	18	126	1.2
22/24	24	264	0.25
26/24	24	312	0.3

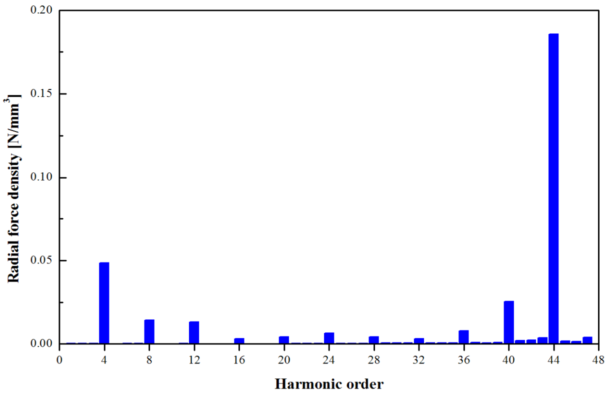


Fig. 6. Radial force distribution of 44pole/48slot, double layer winding.

E. Torque density

N. Bianchi *et al.* reveals that some of the poles/slots combination can lower the width of stator yoke which satisfy [5]:

$$2p = Q \pm 2t$$

It leads to that the poles/slots combinations in *Q/t*=12, 24, 36 groups have a possibility to reduce dimensions of the machine and increase the power density. It is due to that there are no mutual flux linkages among each phase.

Another point of view for the torque density is the winding factor of the machine. Higher winding factor means that required numbers of turns are smaller with same currents to produce same torque. The slot area can be reduced in higher winding factor poles/slots combinations considering same current density and slot fill factor.

In a high pole machine, the width of permanent magnet has to be reduced on the same rotor dimension, and there is certain leakage flux between edges of the permanent magnet. Table 3 presents pull-out torque when all machines are driven by same input voltage and have same no-load induced voltage in analytical prediction [6]. Note that pull-out torque of higher pole machine is reduced in FEM model.

Table 3. Pull-out torque comparison by FEM, analytical method

2p/Q	Basic combination (2p/Q, t=1)	Q/t	Analytical/FEM Pull-out torque [p.u]
16/12	4/3	3	1.03/1.05
12/18	2/3	3	2.05/2.05
16/24	2/3	3	2.05/2.05
24/36	2/3	3	2.05/1.86
14/12	14/12	12	1.17/1.17
28/24	14/12	12	1.17/1.3
42/36	14/12	12	1.17/1.02
10/12	10/12	12	1.64/1.66
20/24	10/12	12	1.64/1.79
30/36	10/12	12	1.64/1.53
14/18	14/18	18	1.76/1.79
26/24	26/24	24	1.26/1.0
22/24	22/24	24	1.49/1.56

Table 4. FEM results of 45kW motor losses (w), 70 page of [3]

Q/t	3			12				
Poles/ slots	8 /12	16 /24	24 /36	10 /12	20 /24	30 /36	14 /12	28 /24
Rated current (A)	88.0	83.5	95.2	88.4	82.0	90.0	91.5	86.0
Back EMF(V)	180	185	168	179	188	189	180	192
Stator losses	262	350	511	258	374	696	274	507
Rotor losses	19	15	14	22	20	19	37	30
Cupper losses	2881	2364	2936	2344	2017	2430	2512	2219
n %	93.0	93.8	92.4	94.0	94.5	93.0	93.7	93.8

F. Losses

In same *Q/t* value, and *t* combination, the FSCW machines which have more numbers of poles than slot numbers have a tendency to the lower efficiency. The rotor losses increase as pole number increases in the same number of slot. The stator core losses are also larger at the same rotating speed due to higher number of poles.

In another *Q/t* value group, the lower winding factor group needs more currents to produce same torque and generate more copper losses. Table 4 presents the above discussions. Note that, the rotor losses are reduced as increased periods of the machine and lowered number of poles in same number of slots. Since there are no sub-harmonics in Q/t=3 groups, the rotor loss is relatively low [7].

3. Conclusion

The general characteristic of FSCW machine for pole/slot combination is compared. It has been shown that the main advantage of *Q/t*=odd machine is low torque pulsations. However, these solution are vulnerable to noise and vibration compared to *Q/t*=even solutions. High *Q/t* with odd number machine have high winding factor. The drawback of high *Q/t* machine has been taken into account. The high value of *Q/t* machine presents increased sub-harmonic contents, causing undesirable effects. Therefore, an SPM machine is far better solution in high *Q/t* value, or Q/t=odd machine due to lower amplitude of armature reactions compared to IPM machine. The Q/t=3 group can be proper solutions for IPM machine due to low sub harmonic contents.

The *Q/t*=12, 24 groups are characterized by no mutual coupling among the phases. The torque density can be increased by reducing stator yoke width of those solutions. Number of poles is also important for torque density due to the leakage flux of PM.

Examples and simulations are presented to help the reader. Table 1 can help the designer to choose the candidate poles/slots combination depending on the application of machine.

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