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The Structure Optimization of Novel Harmonic Current Excited Brushless Synchronous Machines Based on Open Winding Pattern

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***Abstract*— In an open-winding machine, the three-phase stator currents can be controlled to contain the third harmonic current component, which could generate a third harmonic vibration pulse magnetic field. The brushless harmonic excitation principle is realized by utilizing this field. On the role of producing rotor harmonic winding induced back-EMF, it hopes that the third harmonic vibration pulse magnetic field plays a maximum role, meanwhile, the influence of high harmonic magnetic field and tooth harmonic magnetic field should be minimum. This paper had carried on the theoretical analysis about the influence factors of rotor winding induced back-EMF and concluded that the 4 poles, 18 slots, pitch of 4 structure is best suited for this principle. Finally, the finite element simulation analysis was performed and the simulation results were consistent with theoretical analysis, which validated the correctness of the theory.**

***Keywords*— synchronous machine, open winding, harmonic excitation, finite element analysis**

I. INTRODUCTION

The prices of rare earth permanent magnets with high magnetic energy product values have increased to a very high level, which make the permanent magnet machines become luxury. The long-term and stable supply of rare earth materials are facing challenges with the rapidly production growth of permanent magnet machines. So, a means to realize a high-performance machine without permanent magnets, or with reduced permanent magnet quantities, has become a meaningful research topic to solve.

At present, most of scholars pay attention to the hybrid excitation motor which combines permanent magnet and electrical excitation together. Amara Y etc. has summarized some of these hybrid excitation machines[1]. They have concluded that, compared with permanent magnet machine, the hybrid excitation machines have good flux weakening abilities and good energy saving effect used in vehicle propulsion system. Gaussens B etc. proposed a novel hybrid excitation switched reluctance machine with field winding on the stator[2]. It showed that the structure can adjust the air gap magnetic field conveniently and is suitable for high speed running state. S. Wang etc. proposed a novel hybrid excitation machine with tooth harmonic magnetic field being applied to the excitation system[3]. In all these research efforts, the hybrid excitation machines showed certain attractive performance features, but the permanent magnet remain crucial and un-cancelable. Many shortcomings of the permanent magnet machine still exist, such as the demagnetization problem, the poor control capability of main fields and high price, while all these shortcomings do not exist in purely electric excitation synchronous machines.

However in conventional electrical excitation synchronous machines, the establishment of rotor field requires brushes or an additional exciter. Clearly, the brushes will cause spark and life maintenance problems. An additional exciter substantially increases the volume and the cost of small and medium-sized machine. So the key point is how to realize an electric brushless excitation synchronous machine without using brushes and additional exciters. For this purpose, harmonic excitation technologies may be a solution.

Harmonic excitation mainly refers to the third harmonic excitation technology. Zhejiang University and Hefei University of Technology had carried on considerable work to study this technology[4-6]. The main idea is to utilize the third harmonics of rotor main fields. A specially designed harmonic winding was embedded in the stator slot, when the main magnetic field rotates, there will be electromotive force (EMF) in the harmonic winding. After being rectified, the induced back-EMF was sent to the rotor excitation system through brushes or an additional exciter. This type of

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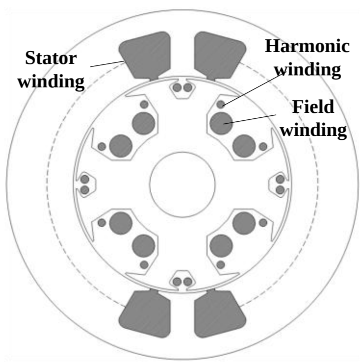
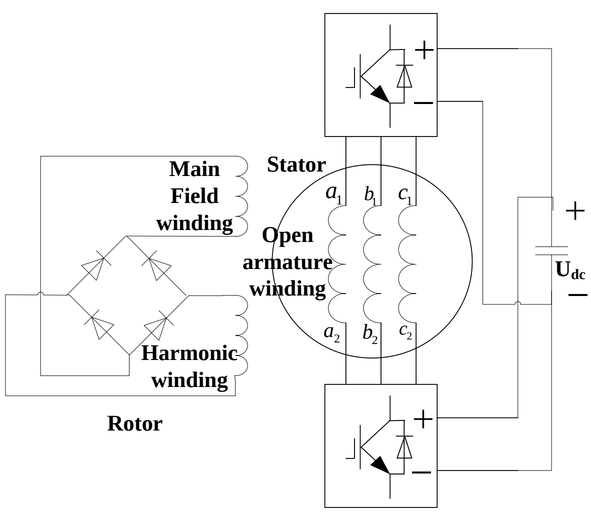
harmonic excitation synchronous generator showed features such as simple structure and certain load capabilities, but it still cannot eliminate brushes and additional exciter together.

With the magnetic field generated by the third harmonic current component of stator current, the EMF could be produced in the specially designed harmonic winding on the rotor, and then the EMF could be applied to the excitation system. This scheme can completely remove the brushes and additional exciter.

The model diagram and schematic diagram of this novel harmonic excitation brushless synchronous generator were shown in Fig.1. There is only an open three-phase ac winding on the stator armature and the stator current waveform is controlled by dual power converter. The harmonic winding and field winding were installed on the rotor and they were connected through the rotating rectifier directly. The harmonic winding is used to obtain the magnetic field energy generated by the stator third harmonic current and the field winding is used to produce rotor main magnetic field.



(a) The model diagram



(b) The schematic diagram

Fig.1 A new type of brushless harmonic excitation synchronous machine

The first important problem on the implementation of harmonic excitation system was generating stable and controllable excitation current, it means that the harmonic winding EMF was stable and controllable and the field winding EMF should be small as far as possible. There were high harmonics like the 5th and 7th harmonics in the armature magnetic motive force (MMF) and tooth harmonics caused by stator slotting in the air gap, both of which could cause interference. Therefore, the influence of high order harmonic magnetic field and tooth harmonic magnetic field should be tried to eliminate by considering various aspects in order to achieve the goal of stable and controllable exciting current.

Firstly, this paper briefly introduced the generating mechanism of rotor winding EMF and its influencing factors. Then the finite element analysis was carried on by optimizing the structure. Finally, it is concluded that 4poles, 18 slots and pitch of 4 was the most suitable structure for this principle.

II. THE GENERATING MECHANISM OF ROTOR WINDING EMF

The MMF generated in the single-phase coil is periodic rectangular wave, which could be expressed by Fourier series, so the MMF of each phase stator winding can be expressed as

$$\begin{aligned} f_a &= N_\varphi i_a \sum_{v=1}^{\infty} \frac{k_{wv}}{v} \cdot \cos v\theta_s \\ f_b &= N_\varphi i_b \sum_{v=1}^{\infty} \frac{k_{wv}}{v} \cdot \cos v\left(\theta_s - \frac{2}{3}\pi\right) \\ f_c &= N_\varphi i_c \sum_{v=1}^{\infty} \frac{k_{wv}}{v} \cdot \cos v\left(\theta_s + \frac{2}{3}\pi\right) \end{aligned} \tag{1}$$

Where $N_\varphi = \frac{4}{\pi}\frac{N}{2p}$, N is each phase series winding number of turns, p is the number of pole pairs, θ_s is the space electric angle, i_a, i_b, i_c, are the stator three phase currents, k_{wv} is winding factor of v harmonic, v=1,3,5…

For harmonic excitation brushless synchronous machine, the stator winding adopted open structure that is opening the stator winding neutral point and protruding all six terminals. This kind of structure is not restricted by KCL, thus the stator current could contain third harmonic current component. Supposing the stator current expression is

$$\begin{aligned} i_a &= I_1 \cos\omega t + I_3 \cos 3\omega t \\ i_b &= I_1 \cos\left(\omega t - \frac{2\pi}{3}\right) + I_3 \cos 3\omega t \\ i_c &= I_1 \cos\left(\omega t + \frac{2\pi}{3}\right) + I_3 \cos 3\omega t \end{aligned} \tag{2}$$

Where I_1 is the fundamental wave current amplitude, I_3 is the third harmonic current amplitude, ω is electrical angular frequency, t is time.

Bring Eq. (2) to Eq. (1), and add the MMF of three phase windings, then the synthesized MMF is

$$F_{abc}(\theta_s,i)= \frac{N_\varphi I_1}{2}\sum_{v=1}^{\infty}\frac{k_{wv}}{v}\begin{pmatrix} \cos(v\theta_s+\omega t)+ \\ \cos\left(v\theta_s+\omega t-v\frac{2\pi}{3}-\frac{2\pi}{3}\right)+ \\ \cos\left(v\theta_s+\omega t+v\frac{2\pi}{3}+\frac{2\pi}{3}\right)+ \\ \cos(v\theta_s-\omega t)+ \\ \cos\left(v\theta_s-\omega t-v\frac{2\pi}{3}+\frac{2\pi}{3}\right)+ \\ \cos\left(v\theta_s-\omega t+v\frac{2\pi}{3}-\frac{2\pi}{3}\right) \end{pmatrix}+ N_\varphi I_3\cos 3\omega t\sum_{v=1}^{\infty}\frac{k_{wv}}{v}\begin{pmatrix} \cos v\theta_s+\cos\left(v\theta_s-v\frac{2\pi}{3}\right)+ \\ \cos\left(v\theta_s+v\frac{2\pi}{3}\right) \end{pmatrix} \tag{3}$$

Because v was odd number 1, 3, 5…, it can be expressed as four groups of numbers: v=1, v=6n-3, v=6n-1, v=6n+1, in which n=1, 2, 3… So the Eq. (3) can be simplified as

$$F_{abc}= \frac{3N_\varphi I_1}{2}\begin{pmatrix} k_{w1}\cos(\omega t-\theta_s)+ \\ \sum_{n=1}^{\infty}\begin{pmatrix} \frac{k_{w(6n-1)}}{6n-1}\cos\left(\omega t+(6n-1)\theta_s\right) \\ +\frac{k_{w(6n+1)}}{6n+1}\cos\left(\omega t-(6n+1)\theta_s\right) \end{pmatrix} \end{pmatrix}+ N_\varphi I_3\cos 3\omega t\sum_{n=1}^{\infty}\frac{k_{w(6n-3)}}{2n-1}\cos(6n-3)\theta_s \tag{4}$$

It can be seen from Eq. (4) that the armature synthetic MMF contains the MMF produced by fundamental current and the MMF produced by the third harmonic current and they are decoupled. As shown in Fig.1, the MMF generated by fundamental current contains fundamental rotating MMF and 5times, 7times etc harmonic rotating MMF, while the MMF generated by the third harmonic current is spatial location fixed 3times, 9times etc harmonic pulsating MMF. Then, the harmonic winding whose pole pitch is equal to the 3rd harmonic pulsating MMF was installed on the rotor and the pole pitch of field winding is 2 times that of harmonic winding. It is shown in Fig.2.

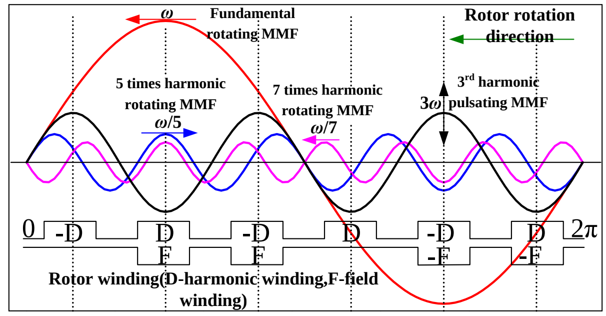


Fig.2 The armature magnetic field and rotor winding structure

Assume that the initial position angle of rotor winding is θ_0, the rotor rotates at synchronous speed. Then the spatial position of rotor winding is $\theta_s=\omega t+\theta_0$. The stator and rotor slot effect was ignored temporarily, namely the air gap permeance is constant. Then the back-EMF of one rotor winding is shown in Eq. (5).

$$e_h=-9n_r\Lambda_0\omega N_\varphi I_1\sum_{n=1}^{\infty}\begin{pmatrix} \frac{nk_{w(6n-1)}}{6n-1}\sin\begin{pmatrix}6n\omega t+ \\ (6n-1)\theta_0\end{pmatrix}+ \\ \frac{nk_{w(6n+1)}}{6n+1}\sin\begin{pmatrix}6n\omega t+ \\ (6n+1)\theta_0\end{pmatrix} \end{pmatrix}- 3n_r\Lambda_0\omega N_\varphi I_3\sum_{n=1}^{\infty}\frac{k_{w(6n-3)}}{2n-1}\begin{pmatrix} n\sin\begin{pmatrix}6n\omega t+ \\ (6n-3)\theta_0\end{pmatrix}+ \\ (n-1)\sin\begin{pmatrix}(6n-6)\omega t+ \\ (6n-3)\theta_0\end{pmatrix} \end{pmatrix} \tag{5}$$

Where n_r is the turns of one rotor winding, Λ_0 is the average air gap permeance.

It can be seen from Eq. (5) that the fundamental rotating magnetic field will not generate EMF in the rotor winding. While the 5 times, 7times etc harmonic rotating magnetic field and 3rd harmonic pulsating magnetic field could generate EMF in the rotor winding. Due to the rotor pole arc being designed to be 2 times that of the harmonic winding pitch, the EMF generated by 3rd harmonic pulsating magnetic field in field winding will counteract with each other completely.

Because of stator and rotor slot, there is the tooth harmonic magnetic field in air gap, which is mainly caused by stator slot. Only considering the stator slot, the permeance is[7]:

$$\lambda(\theta_s,t)=\Lambda_0+\sum_{v_s=1}^{\infty}\Lambda_{sv_s}\cos v_s\frac{Z}{p}(\theta_s+\omega t) \tag{6}$$

Where v_s is the order of stator tooth harmonic permeance, when v_s=1, it is called first-order stator tooth harmonic permeance, Λ_{sv_s} is the amplitude of each-order tooth harmonic permeance, Z is the number of stator slots.

From Eq. (4) and Eq. (6), the tooth harmonic magnetic density can be expressed as Eq. (7).

$$
\begin{aligned}
b_t = {} & \frac{3\Lambda_{sv_s} N_\varphi I_1}{4} \bullet \\
& \left(\begin{aligned}
& \sum_{v_s=1}^{\infty} k_{w1} \left(\begin{aligned} & \cos\left(\left(v_s \frac{Z}{p} - 1 \right)\theta_s + \left(v_s \frac{Z}{p} + 1 \right)\omega t \right) + \\ & \cos\left(\left(v_s \frac{Z}{p} + 1 \right)\theta_s + \left(v_s \frac{Z}{p} - 1 \right)\omega t \right) \end{aligned} \right) + \\
& \sum_{v_s=1}^{\infty}\sum_{n=1}^{\infty} \left(\begin{aligned}
& \frac{k_{w(6n-1)}}{6n-1} \left(\begin{aligned} & \cos\left(\begin{aligned} & \left(v_s \frac{Z}{p} - 6n + 1 \right)\theta_s + \\ & \left(v_s \frac{Z}{p} - 1 \right)\omega t \end{aligned} \right) + \\ & \cos\left(\begin{aligned} & \left(v_s \frac{Z}{p} + 6n - 1 \right)\theta_s + \\ & \left(v_s \frac{Z}{p} + 1 \right)\omega t \end{aligned} \right) \end{aligned} \right) + \\
& \frac{k_{w(6n+1)}}{6n+1} \left(\begin{aligned} & \cos\left(\begin{aligned} & \left(v_s \frac{Z}{p} + 6n + 1 \right)\theta_s + \\ & \left(v_s \frac{Z}{p} - 1 \right)\omega t \end{aligned} \right) + \\ & \cos\left(\begin{aligned} & \left(v_s \frac{Z}{p} - 6n - 1 \right)\theta_s + \\ & \left(v_s \frac{Z}{p} + 1 \right)\omega t \end{aligned} \right) \end{aligned} \right)
\end{aligned} \right)
\end{aligned} \right) + \\
& \frac{N_\varphi I_3}{4} \sum_{v_s=1}^{\infty}\sum_{n=1}^{\infty} \frac{\Lambda_{sv_s} k_{w(6n-3)}}{2n-1} \bullet \\
& \left(\begin{aligned}
& \cos\left(\left(v_s \frac{Z}{p} + 6n - 3 \right)\theta_s + \left(v_s \frac{Z}{p} + 3 \right)\omega t \right) + \\
& \cos\left(\left(v_s \frac{Z}{p} - 6n + 3 \right)\theta_s + \left(v_s \frac{Z}{p} + 3 \right)\omega t \right) + \\
& \cos\left(\left(v_s \frac{Z}{p} + 6n - 3 \right)\theta_s + \left(v_s \frac{Z}{p} - 3 \right)\omega t \right) + \\
& \cos\left(\left(v_s \frac{Z}{p} - 6n + 3 \right)\theta_s + \left(v_s \frac{Z}{p} - 3 \right)\omega t \right)
\end{aligned} \right)
\end{aligned}
\tag{7}
$$

It can be seen that the tooth harmonic magnetic field is constant amplitude and rotating magnetic field from Eq.(7). Relative to the rotor, it has a certain speed, and thus produce EMF in the rotor winding, namely the tooth harmonic EMF.

It can be analyzed that the angular frequency of tooth harmonic EMF generated by the fundamental current is $2\omega v_s Z/p$, $(2v_s Z/p \pm 6n)\omega$, and the angular frequency of tooth harmonic EMF generated by the 3rd harmonic current is $(2v_s Z/p \pm 6n)\omega$, $[2v_s Z/p \pm 6(n\text{-}1)]\omega$.

III. THE INFLUENCE FACTORS OF ROTOR WINDING EMF

The first-order tooth harmonic magnetic field in the tooth harmonic magnetic field and the fundamental, 3rd, 5 times, 7 times harmonic magnetic field are mainly considered. The back-EMF of one rotor winding can be expressed as

$$
\begin{aligned}
e = {} & -9n_r \omega N_\varphi I_1 3\Lambda_0 \left(\begin{aligned} & \frac{k_{w5}}{5}\sin\left(6\omega t + 5\theta_0\right) + \\ & \frac{k_{w7}}{7}\sin\left(6\omega t + 7\theta_0\right) \end{aligned} \right) - \\
& 3n_r \omega N_\varphi I_1 \frac{\Lambda_{sv_1}}{2} \bullet \\
& \left(\begin{aligned}
& k_{w1} \left(\begin{aligned} & \frac{Z}{p}\sin\left(\left(2\frac{Z}{p} \right)\omega t + \left(\frac{Z}{p} - 1 \right)\theta_0 \right) + \\ & \frac{Z}{p}\sin\left(\left(2\frac{Z}{p} \right)\omega t + \left(\frac{Z}{p} + 1 \right)\theta_0 \right) \end{aligned} \right) + \\
& \frac{k_{w5}}{5} \left(\begin{aligned} & \left(\frac{Z}{p} - 3 \right)\sin\left(\left(2\frac{Z}{p} - 6 \right)\omega t + \left(\frac{Z}{p} - 5 \right)\theta_0 \right) + \\ & \left(\frac{Z}{p} + 3 \right)\sin\left(\left(2\frac{Z}{p} + 6 \right)\omega t + \left(\frac{Z}{p} + 5 \right)\theta_0 \right) \end{aligned} \right) + \\
& \frac{k_{w7}}{7} \left(\begin{aligned} & \left(\frac{Z}{p} + 3 \right)\sin\left(\left(2\frac{Z}{p} + 6 \right)\omega t + \left(\frac{Z}{p} + 7 \right)\theta_0 \right) + \\ & \left(\frac{Z}{p} - 3 \right)\sin\left(\left(2\frac{Z}{p} - 6 \right)\omega t + \left(\frac{Z}{p} - 7 \right)\theta_0 \right) \end{aligned} \right)
\end{aligned} \right) - \\
& 3n_r \omega N_\varphi I_3 k_{w3} \Lambda_0 \sin\left(6\omega t + 3\theta_0\right) - \\
& n_r \omega N_\varphi I_3 k_{w3} \frac{\Lambda_{sv_1}}{2} \bullet \\
& \left(\begin{aligned}
& \left(\frac{Z}{p} + 3 \right)\sin\left(\left(2\frac{Z}{p} + 6 \right)\omega t + \left(\frac{Z}{p} + 3 \right)\theta_0 \right) + \\
& \left(\frac{Z}{p} \right)\sin\left(\left(2\frac{Z}{p} \right)\omega t + \left(\frac{Z}{p} - 3 \right)\theta_0 \right) + \\
& \left(\frac{Z}{p} \right)\sin\left(\left(2\frac{Z}{p} \right)\omega t + \left(\frac{Z}{p} + 3 \right)\theta_0 \right) + \\
& \left(\frac{Z}{p} - 3 \right)\sin\left(\left(2\frac{Z}{p} - 6 \right)\omega t + \left(\frac{Z}{p} - 3 \right)\theta_0 \right)
\end{aligned} \right)
\end{aligned}
\tag{8}
$$

It can be seen from Eq. (8) that the main influence factors are winding coefficient, winding turns, the amplitude of fundamental current and 3rd harmonic current, stator slots and the tooth harmonic permeance. The stator current is controlled by dual power inverter, and the winding turns are constant, and the tooth harmonic permeance is caused by stator slots. So the winding factor and stator slots are mainly analyzed. It hopes that the rotor winding EMF is controlled by the 3rd harmonic current and is influenced by high harmonic MMF and tooth harmonic MMF minimally. So the k_{w3} should be bigger and the k_{w5}, k_{w7} should be smaller. To k_{w1}, it should be bigger in order to generate enough back-EMF in the stator winding, when the field winding is supplied DC current.

The basic structure of the machine is 4 poles, 12 slots and pitch 3. Then on the basis of the basic structure, the structure of 4 poles, 12 slots, pitch 2, 3, 4 and 4 poles, 18 slots, pitch 2, 3, 4 were studied.

For the structure of 4 poles, 12 slots, the winding coefficient of v times harmonic is expressed as

$$k_{wv} = \sin(\frac{\pi}{6} yv) \tag{8}$$

Where y is the pitch of winding.

For the structure of 4 poles, 18 slots, the winding coefficient of v times harmonic is expressed as

$$k_{wv} = \frac{\sin(vy\pi/9)\sin(v\pi/6)}{3\sin(v\pi/18)} \tag{9}$$

Then the winding coefficients of the above several structures are shown in Tab.1.

Tab.1 Winding factors

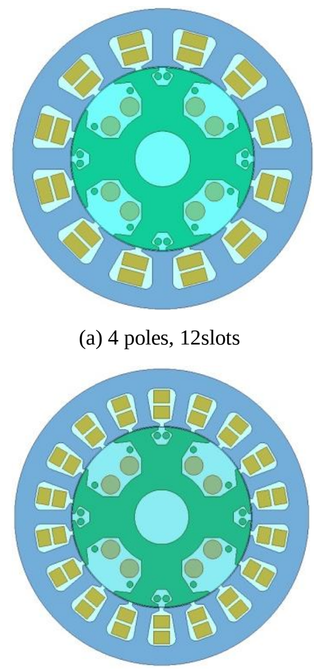
	12slots pitch2	12slots pitch3	12slots pitch4	18slots pitch2	18slots pitch3	18slots pitch4
k_{w1}	0.8660	1	0.8660	0.6169	0.8312	0.9452
k_{w3}	0	-1	0	0.5774	0	-0.5774
k_{w5}	-0.8660	1	-0.8660	-0.0744	-0.1884	0.1398
k_{w7}	0.8660	-1	0.8660	0.1747	-0.1536	0.0607

From Tab.1 and Eq. (8), it can be concluded that the k_{w3} of 12 slots, pitch 2, 4 and 18 slots, pitch 3 are zero, so the rotor winding EMF will not exist with the 3rd harmonic current was supplied. For the structure of 12 slots, pitch 3, the winding coefficient amplitude of each harmonic is 1, so the rotor winding EMF generated by the 3rd harmonic current is large, but it is also greatly influenced by high harmonic MMF and tooth harmonic MMF, which increased the uncontrollability of harmonic winding EMF. For the structure of 18 slots, pitch 2, 4, the k_{w3} amplitude is same, namely the consistent harmonic winding EMF in 3rd harmonic current, while the k_{w1} of pitch 4 is bigger than that of pitch 2, which indicates that the structure of pitch 4 could generate larger back-EMF in the stator winding. The k_{w5}, k_{w7} of them are both small which could better eliminate the influence of high harmonic MMF and tooth harmonic MMF.

From the above analysis, it can be concluded that compared with other structures the structure of 4 poles, 18 slots, pitch 4 is best suited for realizing the principle of harmonic excitation brushless synchronous machine.

IV. THE VERIFICATION OF FINITE ELEMENT ANALYSIS

In order to verify the theoretical analysis, the finite element analysis (FEA) model of 4 poles, 12 slots and 4 poles, 18 slots were established in the ANSOFT MAXWELL, as shown in Fig.3.



(a) 4 poles, 12slots

(b) 4poles, 18 slots

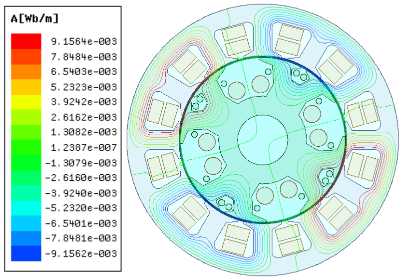
Fig.3 Finite element model of machine

The two stators adopt double-layer winding form. To ensure that the two machines have the same serial number of turns per phase, for 12 slots, each layer of the stator winding turns' number is 135, for 18 slots, each layer of the stator winding turns' number is 90. The other parameters are the same, as shown in Tab.2.

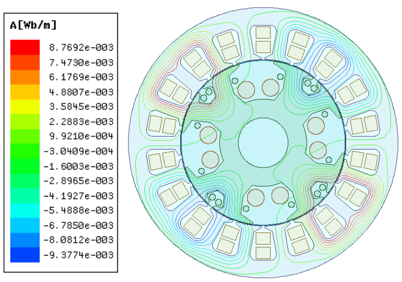
Tab.2 Machine Prototype parameters

Rated power/KW	1
Rated voltage/V	380
Rated frequency/HZ	50
Phase numbers	3
Harmonic winding turns	15
Field winding turns	150
Stator outer diameter D_1/mm	130
Rotor outer diameter D_2/mm	79
Airgap length δ/mm	0.5
Stack length L/mm	120

The flux distributions are shown in Fig.4 in the case of only stator 50Hz sinusoidal current existing.



(a) 4 poles, 12slots



(b) 4poles, 18 slots

Fig.4 Flux distributions

For the two structures, it is researched by supplying fundamental current, 3rd harmonic current and the synthesis of them respectively.

When the amplitude 0.3, frequency 150 Hz third harmonic current is supplied, the harmonic winding EMFs and field winding EMFs are shown in Fig.5 and Fig.7. It can be seen that the harmonic winding EMFs of 12 slots, pitch 2, 4 and 18 slots, pitch 3 are almost zero, which is mainly determined by the third harmonic winding coefficient. The harmonic winding EMFs of 18 slots, pitch 2, 4 are about 0.55 times of that of 12 slots, pitch 3, which is consistent with the theory on the consideration of tooth harmonic MMF. For the field winding EMF, the EMFs of 18 slots, pitch 2, 4 are similar, so the Fourier analysis is carried on for the structures of 12 slots, pitch 3 and 18 slots, pitch 4. As shown in Fig.6 and Fig.8, compared with the harmonic winding EMF, the six times harmonic content in the field winding EMF decreased significantly, which is caused by that the pole pitch of field winding is 2 times that of harmonic winding. The field winding EMF is mainly generated by the tooth harmonic magnetic field.

With supplying the amplitude 2, frequency 50 Hz fundamental stator current, the harmonic winding EMFs are shown in Fig.9. The EMFs of 12slots are very big, and mainly generated by the high harmonic magnetic field and the tooth harmonic magnetic field. The EMFs of 18 slots are relatively small, and slightly affected by the high harmonic magnetic field and the tooth harmonic magnetic field, which is consistent with theoretical analysis.

With supplying the synthetic current, namely, the sum of the amplitude 2, frequency 50 Hz fundamental current and the amplitude 0.3, frequency 150 Hz third harmonic current, the harmonic winding EMFs are shown in Fig.10. It can be analyzed that the EMFs of Fig.10 are consistent with the addition of that of Fig.5 and Fig.9, which means that the effects of fundamental current and third harmonic current are decoupled. It can also be seen that the existence of high harmonic magnetic field and tooth harmonic magnetic field play a negative role in the generation of harmonic winding EMF.

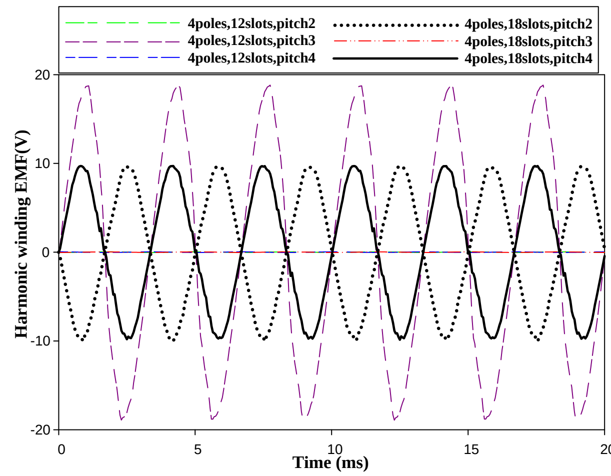
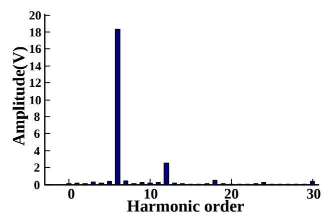
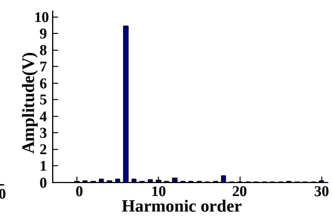


Fig.5 The harmonic winding EMF under third harmonic current



(a) 4poles,12slots,pitch3



(b) 4poles,18slots,pitch4

Fig.6 The Fourier analysis diagram of harmonic winding EMF

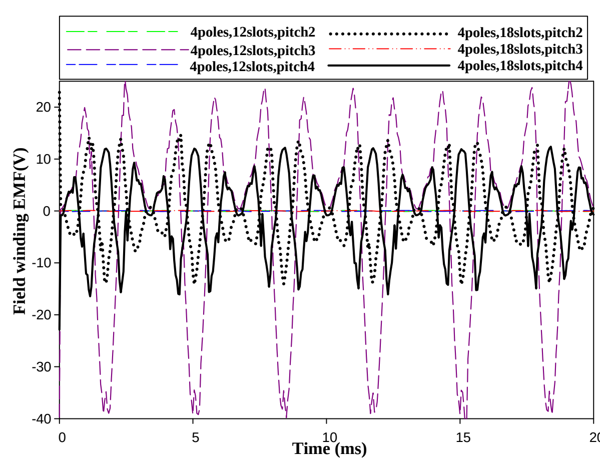
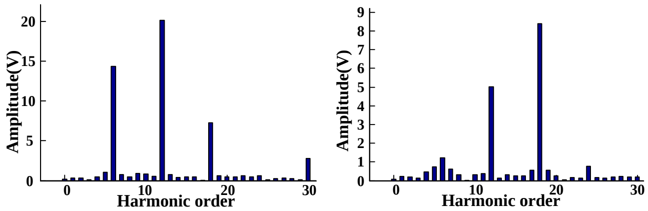


Fig.7 The field winding EMF under third harmonic current



(a) 4poles,12slots,pitch3 (b) 4poles,18slots,pitch4

Fig.8 The Fourier analysis diagram of field winding EMF

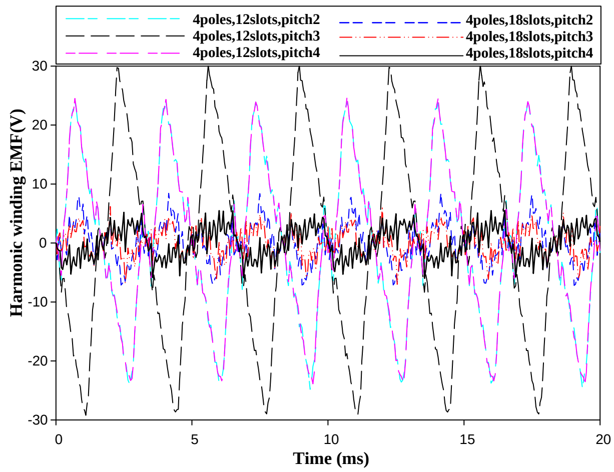


Fig.9 The harmonic winding EMF under fundamental current

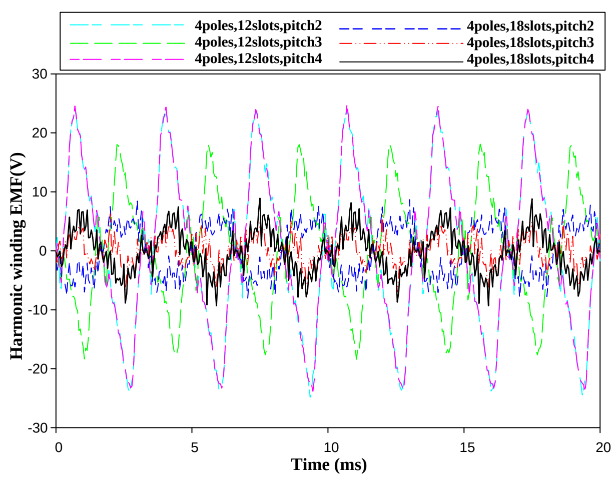


Fig.10 The harmonic winding EMF under synthetic current

It can be known from the above analysis that the structures of 12 slots, pitch 2, 4 and 18 slots, pitch 3 cannot be adopted. The other structures would be researched with supplying 1A DC current to the field winding. When the rotor rotated at synchronous speed, the EMF of stator phase A winding and its Fourier analysis are shown in Fig.11 and Fig.12. It can be seen that the fundamental content of the EMF of 12 slots, pitch 3 is the biggest, but other times harmonic content is bigger also. The fundamental content of the EMF of 18 slots, pitch 2 is the smallest, which made the output voltage too low. For the structure of 18 slots, pitch 4, the fundamental content is enough large to reach the rated output voltage, the 3rd harmonic content is also large to be helpful for the control, which complies with the requirements of this principle.

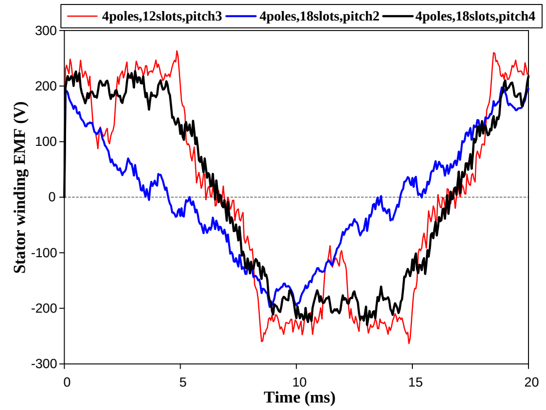
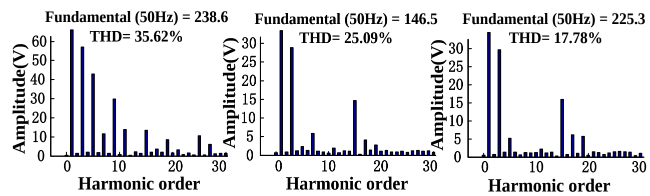


Fig.11 The back-EMFs of stator winding



(a) 4poles,12slots,pitch3 (b) 4poles,18slots,pitch2 (c) 4poles,18slots,pitch4

Fig.12 The Fourier analysis diagram of stator winding EMFs

The principle of harmonic excitation must generate stable and controllable excitation current, so the further study is connecting the harmonic winding and the field winding via rotating rectifier. The third harmonic current content is defined as the ratio of the 3rd harmonic stator current amplitude and the fundamental stator current amplitude. With the structure 4 poles, 18 slots, pitch 4 as an example, when the third harmonic current content is 30%, the field winding current is shown in Fig.13. It can be seen that the field winding current reach the steady-state at around 200ms, and the steady-state value is about 0.36 A.

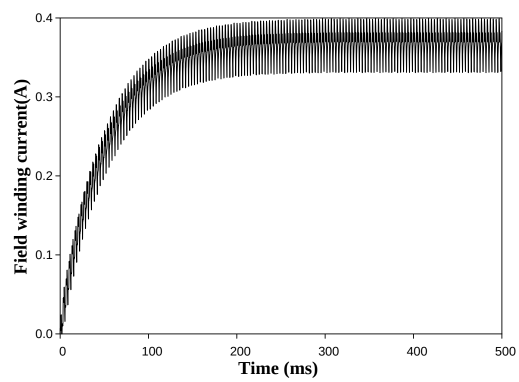


Fig.13 Field winding current

For the structures of 12 slots, pitch 3 and 18 slots pitch 2, 4, as shown in figure 14, the field winding current steady-state value changes with the third harmonic current content. It can be seen that for 12 slots, pitch 3, in the early stage of the third harmonic current content increasing, the field winding current steady-state value decreases on the contrary, the reason of which is that the high harmonic magnetic field and the tooth harmonic magnetic field weakened the effect of the third harmonic pulsating magnetic field. However, for 18 slots, pitch 2, 4, the influence of the high harmonic magnetic field and the tooth harmonic magnetic field is small, so the field winding current steady-state value could increase steadily. Especially for 18 slots, pitch 4, the rising tendency of its field winding current steady-state value is better.

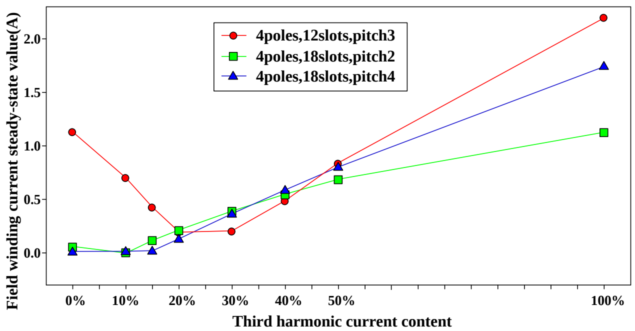


Fig.14 The change of field winding current steady-state value along with the third harmonic current content

From the above analysis, with all kinds of factors be considered, it can be seen that compared with the other structures, the structure of 18 slots, pitch 4 is the most suitable for the principle of this harmonic excitation. Therefore, the further research will adopt this structure.

V. CONCLUSION

When the three-phase stator currents are controlled to contain the fundamental stator current and the third harmonic current component, the machine air-gap magnetic field contains fundamental rotating magnetic field, 5times, 7times etc harmonic rotating magnetic field , the spatial location fixed 3times, 9times etc harmonic pulsating magnetic field and tooth harmonic rotating magnetic field. The paper carried on the theoretical analysis of the influence of these magnetic fields and concluded the expression of a rotor winding EMF. Based on the theoretical analysis, the influence factors of rotor winding EMF are analyzed and several machine structures are discussed in detail. Finally, the FEA was performed and the simulation results were consistent with theoretical analysis, which proves the correctness of the theory. The structure of 4 poles, 18 slots, pitch 4 can strengthen the effect of the third harmonic pulsating magnetic field and weaken the effect of the high harmonic magnetic field and the tooth harmonic magnetic field. Therefore, this structure is best suited for further study with this principle of harmonic excitation.

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