New Type of Harmonic Current Excited Brushless Synchronous Machine Based on an Open Winding Pattern

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Abstract—In an open-winding machine, the three-phase stator currents can be controlled to contain the same harmonic current components like the third harmonics. This paper introduces a new harmonic current excitation principle in synchronous machines based on open winding controls. Unlike existing harmonic excitation technologies which utilizing the third harmonic components of rotor magnetic fields, this brushless harmonic excitation principle is realized by injecting the third harmonic current component or high frequency single-phase current component or DC component into the three phase stator open windings, to generate a time pulsating magnetic field which can induce back-EMFs in the specially designed rotor harmonic coils. Through rectification, the induced back-EMFs are used to supply DC current to the rotor excitation winding. To verify the above principle, theoretical analysis, magnetic field calculations by FEA and experiments were carried out. The significance of this harmonic excitation principle is to provide a new brushless machine option in place of increasingly expensive permanent magnet machines in some applications.

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

I. INTRODUCTION

In recent years, in contrast to the wide application and rapid production growth of permanent magnet machines, the prices of rare earth permanent magnets with high magnetic energy product values have increased to a very high level, which make such permanent magnet machines become almost a luxury. Moreover, when taking a look at rare-earth material industries, the long-term and stable supply of rare earth materials are facing challenges such as environmental pollution problems which have caused great concern.

As a result of these problems, 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 and have attracted considerable attention worldwide.

Besides conventional induction machines and reluctance machines, a variety of new machines with different excitation principles have been investigated. Most of them are remain hybrid excitation machines. That is, permanent magnet and electrical excitation are combined together in these machines. Amara 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. Sulaiman etc. investigated a novel hybrid excitation switched reluctance synchronous machine with permanent magnet and field winding on the stator [2]. The machine showed the same power density with average interior permanent magnet synchronous machines. S. Wang etc. proposed a novel hybrid excitation machine utilizing tooth harmonics [3-4]. Besides permanent magnet poles on the rotor, there are some tooth-harmonic coils installed on the rotor, which generates back-EMFs induced by the inherent tooth harmonic magnetic fields as a result of slots, then after rectification, the tooth-harmonic coils will supply DC field currents to the excitation windings on the rotor. In all these research efforts, the hybrid excitation machines showed certain attractive performance features, but the permanent magnet poles remain crucial and un-cancelable. Many shortcomings of a permanent magnet machine still exist, such as the demagnetization problem, and the poor control capability of main fields, 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 and slip rings or an additional exciter.
Clearly, traditional mechanical contact device such as brushes and slip rings will cause spark and life maintenance problems. An additional exciter substantially increases the volume and the cost of small and medium-sized machine. These factors limit the application of small and medium-sized electrical excitation synchronous machine. The key point is how to realize an electric brushless excitation synchronous machine without using brushes or additional exciters. For this purpose, harmonic excitation technologies may be a solution.

Harmonic excitation mainly refers to the third harmonic excitation technology which is not a new concept. In the early 1970s considerable work was carried on to study utilizing the third harmonics of rotor main fields to excite small synchronous generators [5-7]. In these small synchronous generators, brushes and slip rings were still adopted, and one harmonic winding about one third of main pole pitch was embedded in the stator slot. With specially designed rotor pole shapes, the third harmonics in rotor magnetic fields were strengthened, and will induce the third harmonic back-EMF in the harmonic winding when the main magnetic field rotates. As an excitation source, the induced back-EMF in the harmonic winding was sent to the rotor field winding through a rectifier and slip rings as well as brushes.

The basic principle is shown in Fig. 1. This type of harmonic excitation synchronous generator showed features such as simple structure and certain load capabilities, and have gained acceptance in small power generators for low cost farming machines.

Based on the above principle, brushless harmonic excitation generators were implemented by adding an additional rotating armature ac exciter to eliminate the brushes and slip rings. As shown in Fig. 2, the harmonic EMF produced in the stator harmonic winding was sent to an exciter stator winding via rectification. The armature winding of exciter rotor supplied the main rotor field winding current via rotating rectifier, thus can eliminate the brushes. The technology of brushless harmonic excitation could eliminate many problems caused by the existence of brushes. However, a rotating armature excitation increased the volume of generator and made the structure considerably more complicated.

Not much progress concerning these third harmonic technologies have appeared in recent years though there are still papers being published. Most of the recent research has focused on the improvement of harmonic excitation regulator and the magnetic saturation, especially the analysis about the influence of harmonic excitation generator characteristics on the saturation of magnetic pole tips [8-10].

From above description, it can be concluded that the existing third harmonic excitation technology requires brushes and slip rings in the same manner as conventional electrical excitation synchronous machines. In this paper a new harmonic excitation principle for synchronous machines is described which can eliminate brushes and slip rings inherently since the harmonic excitation currents are generated in stator open windings.

II. PRINCIPLE OF THE NEW HARMONIC EXCITATION BRUSHLESS MACHINE

The brushless harmonic excitation technology studied in this paper is different from the existing harmonic excitation technologies summarized above, which utilizes the third harmonic components of rotor magnetic fields. This brushless harmonic excitation principle is realized by injecting a third harmonic current component or other high
frequency single-phase current component or even a DC component into the three phase stator open windings. With an open-winding machine, the three-phase stator currents can be controlled to each contain the same harmonic current components such as the third harmonics, to generate a time pulsating magnetic field which can induce back-EMFs in the specially designed rotor harmonic coils. Through rectification, the induced back-EMFs are used to supply DC current to the rotor excitation winding.

The basic principle diagram of machine system is shown in Fig.3. Different from existing harmonic excitation technology, the harmonic winding is installed directly on the machine rotor, and connects the main field winding directly via rotating rectifier. There is only an open three-phase ac winding on the stator armature. With dual power converter controlling stator current waveform, the third harmonic current or high frequency single-phase current or dc current can be generated to produce induced back-EMF in the rotor harmonic winding.

[Diagram of machine system]

As stated above, the three-phase stator currents in a set of open winding can be controlled to contain the same harmonic current component. The three-phase stator currents can be controlled to be:

\[ i_a = I_1 \sin \omega t + I_n \]
\[ i_b = I_1 \sin(\omega t - \frac{2\pi}{3}) + I_n \]
\[ i_c = I_1 \sin(\omega t + \frac{2\pi}{3}) + I_n \]

Where \( I_1 \) is the amplitude of fundamental current, \( I_n \) is the single phase current component contained, \( \omega \) is the electrical angular frequency.

Bring Eq.(2) to Eq.(1), and add the magneto-motive force of three phase windings. Then the synthesized armature magneto-motive force (MMF) can be expressed as:

\[ F_{abc}(\theta, i) = F_a + F_b + F_c \]
\[ = N_{pl} \left( \sin \theta + \frac{1}{3} \sin 3\theta \right) (I_1 \sin \omega t + I_n) \]
\[ + N_{pl} \left( \sin(\theta - \frac{2\pi}{3}) + \frac{1}{3} \sin 3\theta \right) (I_1 \sin(\omega t - \frac{2\pi}{3}) + I_n) \]
\[ + N_{pl} \left( \sin(\theta + \frac{2\pi}{3}) + \frac{1}{3} \sin 3\theta \right) (I_1 \sin(\omega t + \frac{2\pi}{3}) + I_n) \]

\[ = N_{pl} \begin{bmatrix} I_1 \sin \omega t \sin \theta + \sin(\omega t - \frac{2\pi}{3}) \sin(\theta - \frac{2\pi}{3}) \\ + I_1 \sin(\omega t - \frac{2\pi}{3}) \sin(\theta + \frac{2\pi}{3}) \\ + 3 \times I_n \sin 3\theta \end{bmatrix} \]

\[ = \frac{3}{2} I_n N_{pl} \cos(\omega t - \theta) + I_n N_{pl} \sin 3\theta \]

It can be seen from Eq.(3) that the synthesized armature MMF consists of two parts: the usual fundamental rotating MMF and the spatial-location-fixed pulsating MMF induced by the additional single phase component. These two magnetic fields are not coupled, and the pole pitch of the third harmonic magnetic field is one third of that of stator winding. It can be shown in Fig.4.


\[ e_h = 6 \times \frac{d\psi_h}{dt} \]
\[ = 6n_p P_s N_{\phi} (0 + 3I_n \omega \cos (3\omega t + 3\theta_0)) \]  \hspace{1cm} (5)

Should \( I_n \) be a dc current, \( I_n = I_0 \), the back-EMF of the harmonic winding is expressed by Eq. (6).

\[ e_h = 6 \times \frac{d\psi_h}{dt} \]
\[ = 6n_p P_s N_{\phi} (0 + 3I_n \omega \cos (3\omega t + 3\theta_0)) \]  \hspace{1cm} (6)

When \( I_n \) is a high frequency single-phase current, \( I_n = I_m \sin m \omega t \), the back-EMF is shown in Eq.(7), where \( m>3 \).

\[ e_h = 6 \times \frac{d\psi_h}{dt} \]
\[ = 6n_p P_s N_{\phi} (0 + mI_n \omega \cos m \omega t \sin(3\omega t + 3\theta_0)) \]
\[ + 3I_n \omega \sin m \omega t \cos(3\omega t + 3\theta_0) \]
\[ = 3n_p P_s N_{\phi} I_m \omega \left( \frac{(m+3)}{2} \sin \left( \frac{(m+3)}{2} \omega t + 3\theta_0 \right) \right) \]
\[ - \left( \frac{(m-3)}{2} \sin \left( \frac{(m-3)}{2} \omega t - 3\theta_0 \right) \right) \]  \hspace{1cm} (7)

It can be seen from Eq.(5) to Eq.(7), the harmonic back-EMF is only related to \( I_n \). When it is a dc current, the back-EMF is three times as much as synchronous angular frequency. When it is a third harmonic current, the back-EMF of harmonic winding is six times as much as synchronous angular frequency. When it is a high frequency single-phase current, the back-EMF of harmonic winding is \( (m+3) \) and \( (m-3) \) times that of the synchronous angular frequency. The back-EMF of the harmonic winding can supply the main field winding dc current by rotating rectifier to realize the brushless excitation.

III.  FINITE ELEMENT ANALYSIS OF THE HARMONIC EXCITATION

According to the principle mentioned above, a machine calculation model was implemented. A set of three phase symmetrical full-pitch, concentrated windings were mounted on the stator, which maximized the winding coefficient of three harmonics. The field winding and harmonic winding were located on the rotor, while the rotor pole shape changed to be salient, the pole arc equals 2 times of the harmonic winding pitch. As shown in Fig.5, the machine structure adopted has 4 poles and 12 stator slots.
To calculate the back-EMFs generated in the harmonic winding under different current supplies, the stator windings were supplied with different types of currents as shown in Fig.7.(a). The sinusoidal current is \( I_a = 2\sin(100\pi t) \), the dc current is \( I_n = 2 \), the third harmonic current is \( I_n = 2\sin(300\pi t) \), the high frequency single-phase current is \( I_n = 2\sin(1000\pi t) \). The results for the back EMF are shown in Fig.7.(b).

It can be seen that when the stator current is sinusoidal only, there is still some back-EMF induced in the harmonic windings, which is mainly 6th and 12th harmonics, corresponding to the stator numbers per pole pair and suggests that this harmonic back-EMF is caused by stator slotting etc.

With the stator current is selected to be a third harmonic current, the back-EMF’s frequency is six times of synchronous frequency, corresponding with the above theoretical analysis.

In dc current supply case, the harmonic back-EMF’s frequency is mainly three times of synchronous frequency and the waveform shows a flat top like that of a DC machine. Fourier analysis shows the back-EMF also contains 9 times, 15 times harmonics, etc.

In high frequency single-phase current case, the back-EMF frequency is different from that of the stator current. In
the Fourier analysis diagram of the harmonic winding EMF shown in Fig.8. It can be seen that the harmonic winding EMF’s frequency is 7 times and 13 times the synchronous angular frequency, when single phase current of 10 times synchronous angular frequency was supplied. This result verifies the theoretical analysis.

Fig.8. The Fourier analysis diagram of the harmonic EMF

Further FEM analyses were carried on with different synthetic current supplied, as shown in Fig.9(a). The synthetic current means, certain percentage of excitation components were injected into the sinusoidal stator current. In the calculations the percentage is fixed to be 15% of the rated stator current.

It can be observed that the harmonic back-EMF shown in Fig.9 (b) is still quite same as those shown in Fig.7 (b). This suggests that the exciting current component plays an independent role. That is, the magnetic field generated by the fundamental current and the magnetic field generated by the exciting component in the stator are decoupled from each other. This makes it more easily to control the harmonic winding EMF by controlling the component content of stator exciting current in the stator current.

Through the above analysis, it can be seen that the waveform of harmonic winding EMF accords with theoretical derivation completely. Then a transient simulation was carried out for generator operation, with a circuit model built according to the principle shown in Fig. 3. The harmonic winding and field winding were connected through an uncontrolled diode rectifier. With 15% third harmonic current injected to the stator windings, the simulation results were shown in Fig. 10.

Fig.9. The harmonic EMFs under different imposed current

Fig.10. Simulation results
new type of brushless harmonic excitation synchronous machine.

IV. PROTOTYPING AND STUDY TOPICS

As shown in Fig.11, a prototype machine and a dual-bridge converter have been fabricated to conduct further studies.

The rotor was rotating at synchronous speed and the stator was supplied currents. The initial research results were shown in Fig.12. When the stator current was fundamental current, the back-EMF in the harmonic winding is very small. While supplying the 3rd harmonic current, the back-EMF was high-amplitude and six times of synchronous frequency. When the stator current contained fundamental and 3rd harmonic current, the back-EMF in Fig.12(c) is roughly equivalent to the sum of the back-EMFs in Fig.12(a) and (b). Moreover, as shown in Fig.12(d), when the excitation circuit was switched on, the field winding could generate stable field current in the end. The experimental results are in accord with the calculations of FEA and theoretical analysis, which further proves the feasibility and effectiveness of this machine project.

Further study will include the following topics:

A. Field winding harmonic EMF issues

The machine studied thus far has 4-poles and 12-slots to adopt an integer-slot full-pitch winding to obtain the highest winding coefficient for the 3rd harmonics. However, the integer-slot machine topology leads to high tooth-number harmonics in the MMFs, which also induces high EMFs in
The further study of harmonic excitation

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current via rectification. The brushless harmonic excited

EMF. This EMF may be used to supply the field winding DC

magnetic field to produce a rotor

currents can be controlled to contain harmonic single phase

work.

space vector control strategies will be explored in future

circuit topology is similar t

phase winding of the machine can obtain three levels. It is

completed, it has been determined that this induced field

winding EMF is also very high, and could affect the

establishment of a stable and controllable DC excitation current

There are many factors in machine designs could affect

the EMFs, such as stator tooth numbers per pole per phase,

winding pitches, rotor pole arc, slot skewing etc. Further

studies will deal with this issue and all these related factor

optimizations.

B. Initial machine state issues

In this machine principle, there exist start-up issue for

motor operation and means for obtaining an initial 3rd

harmonic current for generator operation. These issues can

be solved by either designing machine structure with

modified excitation capability especially for motor

operations, or by harmonic current injection control

strategies for generator operation. The establishment of the

initial machine state of will be a key topic for the further

research.

C. Stator current control strategies

The key of the proposed brushless harmonic excitation

synchronous machine is to control the stator current by

injecting the component needed for excitation as part of the

stator current. Both of the excitation and effective power

currents will be controlled at the stator windings. With the

adoption of open winding and double power converter, each

phase winding of the machine can obtain three levels. It is

already known that the space voltage vector control of this

circuit topology is similar to the three-level inverter. Feasible

space vector control strategies will be explored in future

work.

V. CONCLUSION

In an open-winding machine, the three-phase stator

currents can be controlled to contain harmonic single phase

current components to generate an additional pulsating

magnetic field to produce a rotor-based harmonic winding

EMF. This EMF may be used to supply the field winding DC

current via rectification. The brushless harmonic excited

synchronous machine can be realized without using a

separate exciter. To verify the above principle, theoretical

analysis, magnetic field calculations by FEA and

experiments were carried out. The results proved the

feasibility of proposed machine.

The significance of this new harmonic excitation

principle is to provide a new brushless machine option to

increasingly expensive permanent magnet machines in low

and medium power applications.

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