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Influence of Frequency on Electromagnetic Field of Super High-Speed Permanent Magnet Generator

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Abstract

When compared with traditional power frequency generators, the frequency of a super high-speed permanent magnet generator (SHSPMG) is a lot higher. In order to study the influence of frequency on the electromagnetic field of SHSPMGs, a 60000rpm, 117kW SHSPMG was taken as a research object. The two-dimensional finite element model of the generator was established, and the two-dimensional transient field of the generator was simulated. In addition, a test platform of the generator was set up and tested. The reliability of the simulation was verified by comparing the experiment data with that of the simulation. Then the generator electromagnetic field under different frequencies was studied, and the influence mechanism of frequency on the generator electromagnetic field was revealed. The generator loss, voltage regulation rate, torque and torque ripple were analyzed under the rated active power load and different frequencies. The influences of frequency on the eddy current density, loss, voltage regulation rate and torque ripple of the generator were obtained. These conclusions can provide some reference for the design and optimization of SHSPMGs.

Key words: Electromagnetic field, Frequency, Losses, Torque, Voltage regulation rate, Super high-speed permanent magnet generator

I. INTRODUCTION

In recent years, because of its advantages of small size, large power density and high efficiency, SHSPMG has received increased public attention [1]-[6]. In addition, it is the key part of the distributed systems. The frequency of a SHSPMG can be up to 1000Hz, and its speed can reach tens of thousands of revolutions per minute. SHSPMGs usually have a small volume, high power density and poor heat dissipation. The generator loss increases the generator temperature, and this temperature rise can result in serious consequences in terms of demagnetization especially in rotors. At the same time, different frequencies have different effects on the harmonic magnetic field of a generator. When the generator operates at different frequencies, the parameters of the generator include the reactance and leakage reactance change. These parameters directly determine the generator voltage regulation rate. Other generator characteristics are affected by the change of parameters caused by changes of the frequency. It is important to study the influence of frequency on generators. Therefore, it is conducive to improve generator performance to study the influence mechanisms of generator loss, voltage regulation rate and torque ripple on the generator electromagnetic field under different frequencies. Then the high-speed generator can operate in a better running state.

In recent years, the magnetic circuit method and analytical method have been frequently used for the electromagnetic analysis and design of conventional motors. However, with the development of modern industry, special motors with a special structure or application have been used more and more widely, such as some high-speed motors. Because the distribution of the magnetic field of these motors is complex, it is difficult to obtain accurate results through magnetic circuit methods. Therefore, the finite element method (FEM)

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based on Maxwell equations has attracted the attention of more and more researchers. Based on FEM, some studies on high-speed permanent magnet generators with different frequencies have been carried out. The authors of [7], [8] studied the iron losses of different high-speed generators with frequencies of 1333Hz and 1666Hz when adopting different stator core materials. Some optimized structures and methods for a high-speed generator were obtained through an analysis of the loss distribution and temperature field under three different speeds in [9]. The electromagnetic fields of generators have not been researched further. The rotor loss of generators with frequencies of 300Hz and 600Hz was studied in [3], [10]. Arfakhshand Ali Qazalbash et al. calculated the rotor eddy current loss in permanent magnet machines with frequencies of 3000Hz and on-load condition [11]. However, these studies only focus on the rotor loss of the generator. They lack a complete comparative analysis of one generator operating under different frequencies. Although F. Martin et al. studied the eddy current loss of a high speed generator and the magnet loss when the generator operated under frequencies of 900Hz and 1800Hz [12], there was no comparative analysis of the voltage regulation rate, the torque ripple of high speed generators and other generator electromagnetic field parameters were not involved, and the influence of the external circuit was not taken into consideration.

Therefore, in this paper, in order to make the analysis of the influence of frequency on SHSPMGs under the rated power more accurate, the field-circuit coupled time-stepping finite element method is used. Taking a 117kW, 60000rpm SHSPMG as an example, the influence of different frequencies on the performance of a SHSPMG under the rated output power is studied. Firstly, based on the calculation and analysis of the eddy current density, the losses in the SHSPMG are calculated. The change in the regulation of the generator loss under different frequencies is obtained, and the influence mechanism of frequency on the generator losses is revealed. At the same time, the influences of frequency on the generator voltage regulation rate, the torque and the torque ripple are analyzed. In addition, the change mechanism is revealed. The conclusions obtained can serves as a reference for further research on SHSPMGs.

II. Model Establishment and Experimental Verification

A. Generator Model and Basic Parameters

A 117kW, 60000rpm SHSPMG driven by a micro gas turbine has been studied in this paper. The material of the sleeve is high strength austenitic steel (50Mn18Cr5), and its relative permeability is 1 and bulk conductivity is 1.31×10^{6} S/m [13]. The main components of the generator structure include the stator core, the rotor core, the windings, the permanent magnets (PM), the sleeve, the rotating shaft and so on. The most obvious difference between the prototype and the traditional generator is the installation of the windings. The back-winding structure is used to shorten the length of the stator end windings, as shown in Fig. 1. Due to the high frequency of the SHSPMG in the operation and that fact that it is limited by strength, the rotor is designed to be slender. In the conventional stator winding structure, the windings are only in the stator slot. If this structure is used, the end length of the generator increases. By adopting the back-winding structure, the end length can be effectively reduced, which can reduce the axial length of the stator and the volume of the generator. To reduce the eddy current loss, PMs are axially segmented and attached to the rotor surface of the SHSPMG [14]-[17]. The axial segmentation can effectively cut off the eddy current path. Then the eddy current loss can be effectively reduced. At high frequencies, the permanent magnet material must be contained so that it does not break apart under its own inertia. This is the reason for the metallic sleeve wrapped around the rotor. The sleeve is fixed on the surface of PM, which provides pre-stress for PM [18]. Table I shows the basic parameters of the SHSPMG. Fig. 1 shows the stator end

TABLE I
Basic Parameters of the SHSPMG Prototype

Basic parameters	Value
Rated power	117kW
Rated voltage	670V
Rated speed	60000rpm
Number of pole-pairs	1
Rotor type	PM
Stator outer diameter	135mm
Stator inner diameter	72mm
Rotor outer diameter	66mm
Core length	275mm
Slot number	36

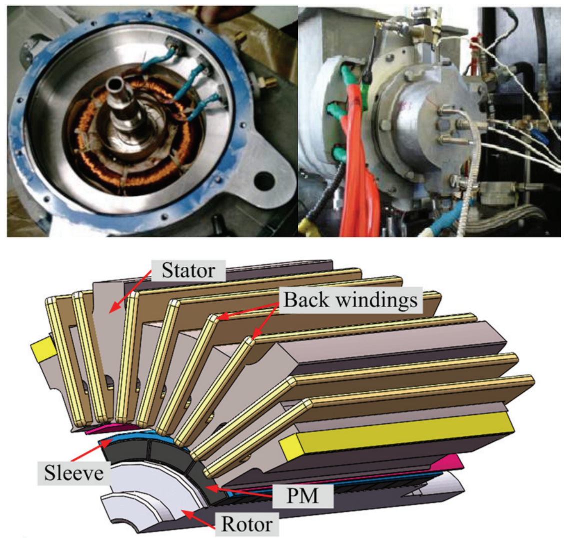

Fig. 1. Prototype and 3D model of the generator.

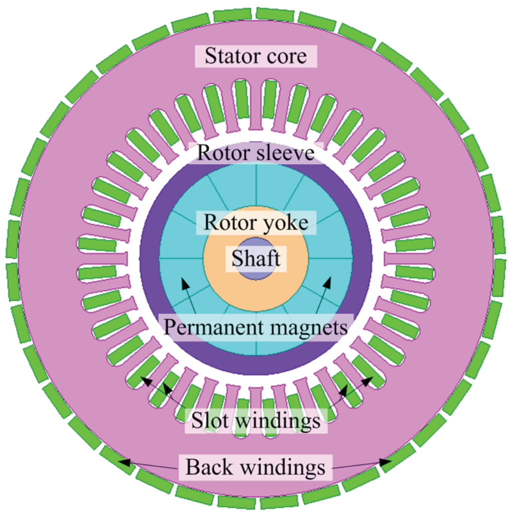

Fig. 2. Finite element model.

of the generator and the prototype.

According to the actual structure of the SHSPMG prototype, the finite element model of the generator is built, as shown in Fig. 2.

During the analysis of the generator electromagnetic field, some assumptions are made to simplify the calculations [13], [19].

(1) Because the stator core is elongated, the electromagnetic field of the generator varies very little in the axial direction. The magnetic flux leakage at the end of the generator is neglected. When analyzing the two-dimensional transient field, the vector magnetic potential only has the Z axis component A_z.

(2) The materials are isotropic. The permeability and conductivity of the materials are constant except for the stator core and the rotor yoke.

(3) The displacement current is ignored.

During the analysis, the two-dimensional electromagnetic field boundary equations are [13], [20].

$$\begin{cases} \Omega: \dfrac{\partial}{\partial x}\left(\dfrac{1}{\mu}\dfrac{\partial A_z}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\dfrac{1}{\mu}\dfrac{\partial A_z}{\partial y}\right)=-\left(J_z-\sigma\dfrac{dA_z}{dt}\right) \\ \Gamma_1:\ A_z=0 \\ \Gamma_2: \dfrac{1}{\mu_1}\dfrac{\partial A_z}{\partial n}-\dfrac{1}{\mu_2}\dfrac{\partial A_z}{\partial n}=J_s \end{cases} \tag{1}$$

where Ω is the calculation region, A_z and J_z are the magnetic vector potential and the source current density in the z-axial component, J_s is the PM equivalent face current density, σ is the conductivity, Γ_1 is the stator outer boundary condition, Γ_2 is the PM boundary condition, and μ_1 and μ_2 are the relative permeability values [13], [20].

In this paper, the field circuit coupling method [21]-[23] is adopted to analyze the electromagnetic field of the SHSPMG. This method strikes a balance between calculation efficiency and calculation accuracy. The external circuit is shown in Fig. 3.

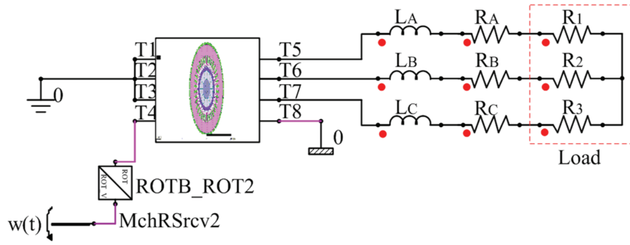

Fig. 3. External circuit of the SHSPMG.

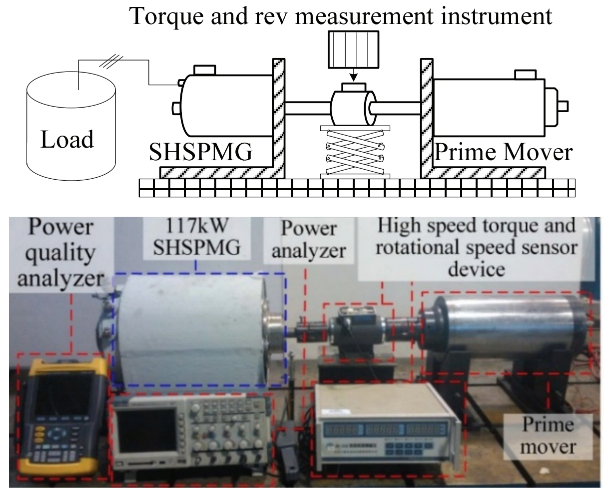

Fig. 4. Test platform.

TABLE II
COMPARISON OF THE TEST DATA AND THE CALCULATED RESULTS

Speed (rpm)		6000	8000	10000
Calculated results	Terminal voltage (V)	39.9	53.1	65.8
	Armature current (A)	14.5	18.3	22.4
Test data	Terminal voltage (V)	39.6	53.7	65.1
	Armature current (A)	14.4	18.5	22.1

where L_A, L_B and L_C are the end leakage inductances; R_A, R_B and R_C are the winding resistances; and R_1, R_2 and R_3 are the load resistances.

B. Experimental Test and Data Comparison

To verify the accuracy of the generator finite element model, the generator prototype is tested, as shown in Fig. 4. In the experiment, the load is resistance. A high-speed torque and rotational speed sensor device is placed between the prime motor and the generator. The electromagnetic parameters of the generator are measured by a 3193 frequency conversion electric energy quality analyzer. The terminal voltage and armature current of the generator running at different speed conditions (6000 rpm, 8000 rpm and 10000 rpm) are experimentally obtained. The experimental data and the model calculated results are compared, as shown in Table II.

Through the data comparison of Table II, it could be found that the experimental results have a good agreement with the calculated results. Therefore, in this paper, the analysis of the generator electromagnetic field based on this model is reliability.

III. Influence of Frequency on the Generator Loss

For SHSPMGs, due to the high frequency, the space harmonic components in the air gap magnetic field caused by the time harmonic currents of the windings seriously affect the generator losses. This cannot be ignored. Due to the high speed, the harmonic frequency caused by the cogging harmonics is high, which results in increases of the generator loss and torque ripple [24].

In addition, the power generated by a SHSPMG is high-frequency, which cannot be directly used. Therefore, the power should be converted into direct current through an AC/DC converter. Then it should be converted to alternating current through a DC/AC converter. Due to the high frequency, high power and the large harmonic components in current when converters are used in the frequency conversion process, there are a lot of harmonic components in the current, which results in large time harmonic loss [25]. At the same time, the interaction between the time harmonic currents and the space harmonic magnetic field also causes loss.

Furthermore, high-speed permanent magnet generators usually have a small volume, a high power density and a difficult heat dissipation. The loss caused by harmonics increases the generator temperature, which can result in the serious consequences of demagnetization, especially in the rotor. Combined with the above analysis, the harmonic loss of a high-speed generator cannot be ignored.

A. Influence of Frequency on the Generator Rotor Eddy Current Density and Rotor Eddy Current Loss

In the operation of a SHSPMG, the space harmonic magnetic fields generated by the time harmonic currents of the windings rotate with respect to the rotor at integer multiples of the rotor speed. In addition, the space harmonic magnetic fields generated by the fundamental currents do not rotate synchronously with the rotor. These harmonic magnetic fields can result in changes of the rotor flux density. Therefore, the eddy currents are induced in the rotor PM and sleeve. Then the eddy current loss is generated. However, due to the high power density, small volume and poor rotor heat dissipation, the heat generated by the eddy current loss produces a higher temperature rise in the rotor. If the heat cannot be released in time, it causes partial demagnetization of PMs, which seriously threatens the stable operation of the SHSPMG. Therefore, it is critical to calculate the eddy current loss accurately [11]. The loss of the SHSPMG is closely related to the frequency. Under high frequency operation conditions, the temperature rise generated by the eddy current has a more serious impact on the SHSPMG under high frequency operation when compared with ordinary

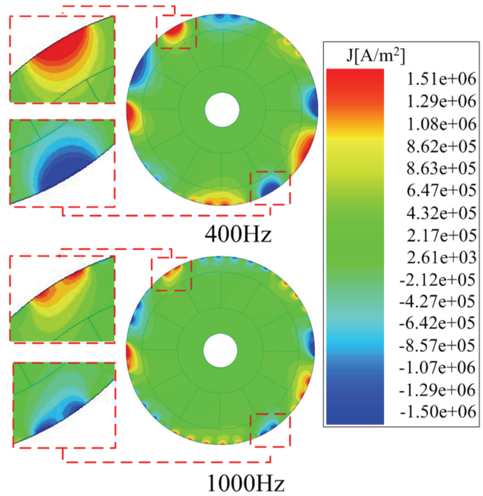

Fig. 5. Eddy current density under different frequencies.

generators. Therefore, it is necessary to study the eddy current losses of the generator under different frequencies. During the analysis, it is found that the output active power cannot reach the rated value of 117kW when the frequency is below 400Hz due to the magnetic saturation. Thus, in this paper, the electromagnetic field of the generator is studied when the frequency is from 400Hz to 1400Hz. Based on FEM, the eddy current densities and eddy current losses of the generator rotor under different frequencies are calculated when the output active power is 117kW. The rotor eddy current densities under frequencies of 400Hz and 1000Hz are shown in Fig. 5. For ease of comparison, the same scale is used.

It can be found from Fig. 5 that the eddy current density is concentrated on the sleeve of the rotor surface. This is due to the skin effect principle. At the same time, the eddy current in the rotor is decreased along the rotor radial direction. The distance from the surface to the place where the current value is reduced to 1/e (about 0.3679) of the surface is referred to as the penetration depth. The penetration depth can be calculated [13], [26]:

$$\Delta = \sqrt{\frac{2}{\omega\mu\sigma}} \tag{2}$$

where Δ is the penetration depth, ω is the angular frequency of the harmonic magnetic field, μ is the permeability of the material, and σ is the conductivity of the material [13], [26].

When the frequency is 400Hz, the maximum eddy current density value is 3.25×10^6A/m^2. When the frequency is 1000Hz, the maximum eddy current density value is 2.59×10^6A/m^2, which is a decrease of 20.3% when compared with that when the frequency is 400Hz. When the generator output active power is constant, the value of the eddy current density shows a decreasing trend with the increase in the frequency.

The value of the eddy current density is closely related to the eddy current loss value. With a decrease of the eddy current density, the eddy current loss also decreases. Based on FEM, the eddy current loss of the generator is calculated

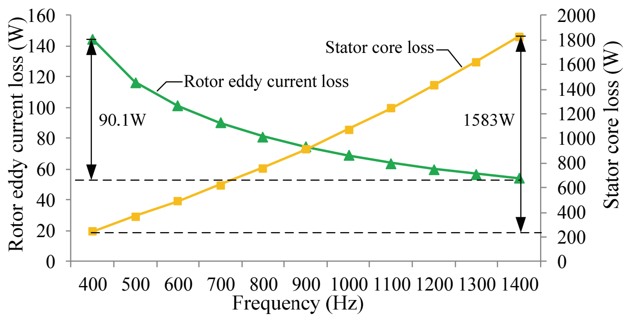

Fig. 6. Rotor eddy current loss and stator core loss under different frequencies.

TABLE III
WINDING CURRENTS AND ROTOR EDDY CURRENT DENSITY UNDER DIFFERENT FREQUENCIES

Frequency (Hz)	Fundamental current (A)	5th harmonic current (A)	7th harmonic current (A)	Rotor eddy current density maximum (A/m^2)
400	233.1	3.12	0.87	3.25×10^6
900	91.3	1.56	0.50	2.64×10^6
1000	82	1.43	0.46	2.59×10^6
1400	57.9	1.07	0.32	2.58×10^6

under different frequencies. During the analysis, the rotor eddy current loss can be calculated in a cycle [27]:

$$P_e = \frac{1}{T_e}\int_{T_e}\sum_{i=1}^{k} J_e^2 \Delta_e \sigma_r^{-1} l_t dt \tag{3}$$

where P_e is the rotor eddy current loss (W), J_e is the current density in each element (A/m^2), Δ_e is the element area (m^2), l_t is the rotor axial length (m), σ_r is the conductivity of the eddy current zone (S/m), and T_e is a cycle of time.

By the finite element calculation, the eddy current loss of the SHSPMG under different frequencies is shown in Fig. 6.

It can be observed that when the frequency is 400Hz, the eddy current loss is 144.4W. When the frequency is 900Hz, the eddy current loss is decreased by 48.4 % when compared with that of 400Hz. When the frequency is 1400Hz, the eddy current loss is only 54.3W, which is a decrease of 62.4% when compared with that of 400Hz. Based on the above data analysis, it can be found that with increases in the generator frequency, the eddy current loss decreases nonlinearly. In addition, with increases of the frequency, the decreasing trend is even more subdued. The reason why the loss decreased with an increase in the frequency is analyzed in the following. Although the generator voltage and current increase with an increase in the frequency, in order to make the output power reach 117kW, the armature current is decreased, and the amplitudes of the harmonic currents and the rotor eddy current density maximum are also decreased, as shown in Table III.

With an increase in the frequency, the penetration depth of the eddy current also decreases. Therefore, according to formula (3), the eddy current loss gradually decreases with an increase of the frequency. From Table III, it can be found that the decrease of the winding currents is an important reason for the decrease of the generator rotor eddy current loss.

B. Influence of Frequency on the Generator Stator Core Loss

The frequency of the SHSPMG can be up to thousands of Hertz, which is much higher than that of traditional generators. The stator core loss increases with an increase of the generator frequency. Research on the generator core loss is very important for the stable operation of a SHSPMG.

The main causes of stator core loss are the time harmonics and spatial harmonics in the generator, the change of the magnetic flux density in the stator core caused by the rotor PM magneto motive force, and the effect of the stator slot opening. The harmonic magnetic field rotates relative to the stator, and the magnetic flux density changes continuously in the stator core. This results in the generation of core loss.

In the Bertotti stator core loss discrete model, the stator core loss is divided into three parts. These three parts are the stator hysteresis loss, stator eddy current loss and stator excess loss. The expression is as follow [28]:

$$P = P_h + P_c + P_a = k_h f B_m{}^{\alpha} + k_c (f B_m)^2 + k_a (f B_m)^{1.5} \tag{4}$$

where P_h is the stator hysteresis loss, P_c is the stator classical eddy current loss, P_a is the stator excess loss component, k_h is the hysteresis loss coefficient, k_c is the classical eddy current loss coefficient, k_a is the excess loss coefficient, f is the frequency, B_m is the magnetic density magnitude, and α is a constant of about 2. In the generator, k_h is 305.82, k_c is 0.30, and k_a is 0.64.

The stator core loss mainly includes the stator hysteresis loss and the stator eddy current loss. For the SHSPMG, the stator is laminated with a thin silicon steel sheet. Since the silicon steel sheet is very thin, the flow path of the eddy current is blocked. Therefore, the eddy current loss in the stator core is neglected in the analysis. Due to alternating between the armature magnetic field and the main magnetic field, the flux paths in the stator core are constantly changing. The hysteresis loss of the stator core is larger and cannot be ignored. Therefore, the loss of the stator core is mainly hysteresis loss.

The value of the generator core loss under different frequencies is different. Through finite element calculations, the core loss under different frequencies is obtained, and the change of the core loss with a change of the frequency is shown in Fig. 6. It can be seen from Fig. 6 that with an increase of the frequency, the core loss is greatly increased. When the frequency is 400Hz, the core loss is 247W. When the frequency is 900Hz, the core loss is 914.6W. When compared with that when the frequency is 400Hz, it is increased by 667.6W, which is 3.7 times higher. When the

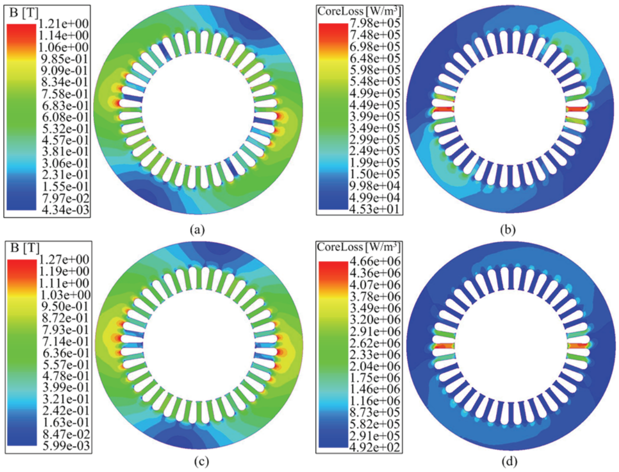

Fig. 7. Stator core loss density and magnetic flux density under different frequencies. (a) 400Hz. (b) 400Hz. (c) 1000Hz. (d) 1000Hz.

frequency is 1400Hz, the core loss is 1830 W. When compared with that when the frequency is 400Hz, it is increased by 1583 W, which is 7.4 times higher. From the above analysis, it can be seen that with an increase of the frequency, the core loss of a SHSPMG is dramatically increased. The frequency of a SHSPMG has a significant influence on the core loss.

The nephograms of the stator core loss density distribution and the stator core magnetic density distribution are shown in Fig. 7 when the generator frequency is 400Hz and 1000Hz, respectively.

It can be observed that when the frequency is 400Hz, the difference in the magnetic flux density between 400Hz and 1000Hz is not very obvious. However, the core loss when the frequency is 1000Hz is much higher than that of 400Hz. When the frequency is 400Hz, the maximum magnetic flux density of the stator core is 1.21T. When the frequency is 1000Hz, the maximum magnetic flux density of the stator core is 1.27T. When the frequency increases from 400Hz to 1000Hz, the value of the core loss increases from 43.7W to 823.2W, which is an increase of 19 times when compared with that when the frequency is 400Hz. From the above analysis, it can be found that an increase in the frequency is an important reason for a rapid increase of the generator stator core loss.

IV. Influence of Frequency on the Voltage Regulation Rate

In previous studies, a preliminary investigation of the relationship between frequency and generator external characteristics has been made. This article presents a more detailed study of it.

The voltage regulation rate is one of the most important performance indexes of a SHSPMG. If the generator voltage regulation rate is too high, it results in a high fluctuation of the output voltage, and has a negative influence on the stable

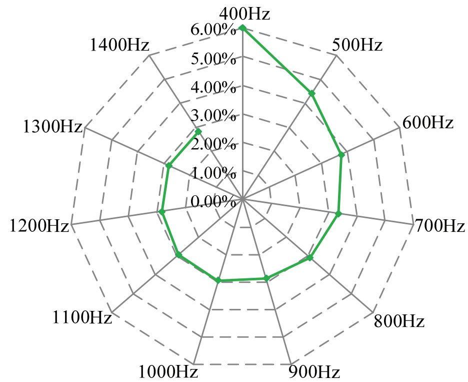

Fig. 8. Voltage regulation rate under different frequencies.

operation of the generator. The voltage regulation rate refers to the ratio of the generator output voltage to the back electromotive force EMF when the speed remains constant. The voltage regulation rate can be expressed as (5) [29].

$$\Delta U = \frac{E_0 - U}{U_N} \times 100\% \tag{5}$$

where E_0 is the generator no-load back EMF, U is the output voltage, and U_N is the rated voltage.

Based on the finite element method, the no-load back EMF and the output voltage of the SHSPMG under different frequencies are calculated. Combined with the voltage regulation rate formula, the voltage regulation rates of the SHSPMG under different frequencies are shown in Fig. 8.

It can be seen that when the frequency is 400Hz, the voltage regulation rate is 6%. When the frequency is 900Hz, the voltage regulation rate is 2.86%. When the frequency is 1400Hz, the voltage regulation rate is 2.82%. From Fig. 8, it can be seen that with an increase of the frequency, the voltage regulation rate shows a nonlinear downward trend, and the change of the voltage regulation rate becomes smaller and smaller. The no-load back EMF of the generator is proportional to the frequency. Therefore, when the output power is constant, the generator no-load back EMF increases with an increase of the frequency. At the same time, the current decreases with an increase of the frequency. Combined with the formula for voltage regulation, it is known that the voltage regulation rate decreases with an increase of the frequency. When the frequency varies from 400Hz to 900Hz, the voltage regulation rate varies by 3.14%. However, when the frequency varies from 900Hz to 1400Hz, the voltage regulation rate only varies by 0.04%. At the same time, it no longer shows an obvious downward trend. When the frequency exceeds 900Hz, the change range of the voltage regulation rate is less than 0.1%, and the value of the voltage regulation rate tends to be stable. It can be seen that when the frequency is lower than 900Hz, the voltage regulation rate is reduced as the frequency increases. However, when the frequency exceeds 900Hz, the increase of the frequency has little effect on reducing the voltage regulation rate.

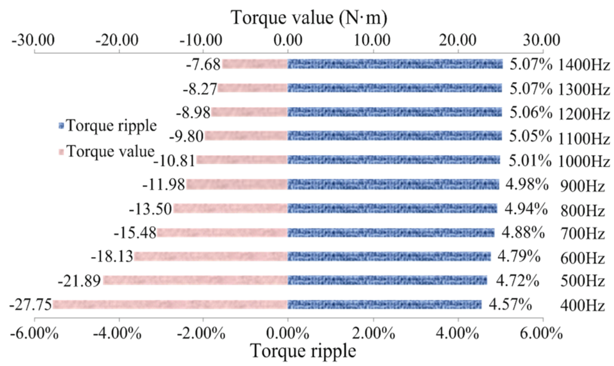

Fig. 9. Torque and the torque ripple under different frequencies.

V. Influence of Frequency on the Generator Torque

The torque of a SHSPMG is generated by the interaction between the rotating magnetic field produced by the three-phase symmetrical sinusoidal current in the stator winding and the magnetic field produced by the permanent magnets. During operation, it makes air gap magnetic field distortion because of the armature reaction, the stator slotting, the generator processing technology and other reasons. In addition, it causes generator torque ripple. Torque ripple is an important index in generator steady operation. The torque ripple value has an obvious influence on generator vibration and noise. Based on the finite element method, the torque and torque ripple of a SHSPMG under different frequencies at the rated output active power are calculated, as shown in Fig. 9. The torque ripple formula is as follows [30]:

$$\text{Torque ripple} = \left|\frac{T_{\max} - T_{\min}}{2 \times T_{avg}}\right| \times 100\% \tag{6}$$

It can be seen that when the frequency is 400Hz, the torque value is -27.75N·m, and the torque ripple is 4.57%. When the frequency is 900Hz, the torque value is -11.98N·m, which is 43.2% of that of 400Hz, and the torque ripple is 4.98%. When the frequency is 1400Hz, the torque value is -7.68N·m, which is 27.7% of that of 400Hz, and the torque ripple is 5.07%. When the frequency increases from 400Hz to 1400Hz, the torque value decreases nonlinearly with the increase of the frequency. At the same time, the torque ripple of the generator has an upward trend with the increase of the frequency. However, the growth rate is not very large. When the frequency increases from 400Hz to 1400Hz, the torque ripple increases by only 0.5%. Thus, the torque ripple can be approximately considered unchanged. The torque of the generator is directly proportional to the output power, and it is inversely proportional to the speed. Therefore, when the output active power is constant, the generator torque shows a downward trend with an increasing speed. The torque ripple is mainly caused by the cogging torque and the stator harmonic magnetic field cutting rotor. The cogging torque of the generator is constant, and it does not change with the frequency. With an increase of the generator frequency, the harmonic current frequency in the stator winding current gradually increases, and the torque ripple increases. Based on the above analysis, it can be concluded that the frequency cannot be increased blindly when the output active power is constant. If the generator frequency is too high, the output torque is reduced, and the advantages of a high power density cannot be fully exploited.

VI. Conclusions

In this paper, taking a 117kW 60000rpm SHSPMG as an example, based on the field circuit coupling theory and FEM, the transient electromagnetic field of the SHSPMG under different frequencies is studied when the output active power is constant. It can be found that frequency has a remarkable influence on the electromagnetic field of the SHSPMG. In addition, the following conclusions have been obtained.

(1) When the generator frequency is lower than 400Hz, the output active power of the generator cannot increase up to the rated condition of 117kW. Therefore, in the design process of a SHSPMG, in order to ensure the rated output active power, the frequency should not be too low.

(2) When the generator output active power is constant, with an increase of the frequency, the eddy current density in the rotor tends to decrease. At the same time, the eddy current loss also presents nonlinear decreasing trend, and this decreasing trend is even more subdued when the frequency increases from 400Hz to 1000Hz.

(3) With an increase of the frequency, the core loss of the SHSPMG increases sharply. When the frequency increases from 400Hz to 1400Hz, the core loss increases by 7.4 times. This increase of the core loss reduces the generator efficiency and increases the heating, which is not conducive to the normal and stable operation of a SHSPMG.

(4) With an increase of the frequency, the voltage regulation rate shows an overall nonlinear decreasing trend, which is caused by the influence of the frequency on the no-load back EMF and the output voltage. When the frequency exceeds 900Hz, the change range of the voltage regulation rate is less than 0.1%, and the voltage regulation rate tends to be stable.

(5) When the output active power is constant, the torque of a SHSPMG decreases and the torque ripple increases with an increase of the frequency, which is caused by an increase of the harmonic current frequency in the stator winding current. In order to guarantee the high power density of the SHSPMG, the frequency should not be too high.

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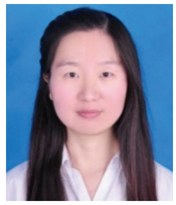

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