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Influence of Different Frequency Harmonic Generated by Rectifier on High-speed Permanent Magnet Generator

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Abstract – Since the stator winding of High-Speed Permanent Magnet Generator (HSPMG) has few winding turns and low inductance value, it is more prone to be influenced by harmonic current. Moreover, the operation efficiency and the torque stability of HSPMG will be greatly influenced by harmonic current. Taking a 117 kW, 60 000 rpm HSPMG as an example, in order to analyze the effects of harmonic current on HSPMG in this paper, the 2-D finite element electromagnetic field model of the generator was established and the correctness of the model was verified by testing the generator prototype. Based on the model, the losses and torque of the generator under different frequency harmonic current were studied. The change rules of the losses and torque were found out. Based on the analysis of the influence of the harmonic phase angle on torque ripple, it is found that the torque ripple could be weakened through changing the harmonic phase angle. Through the analysis of eddy current density in rotor, the change mechanism of the rotor eddy current loss was revealed. These conclusions can contribute to reduce harmonic loss, prevent demagnetization fault and optimize torque ripple of HSPMG used in distributed power supply system.

Keywords: High-speed permanent magnet generator, Harmonic current, Core loss, Eddy current loss, Torque ripple

1. Introduction

Due to the advantages of small volume, low loss, high efficiency [1-3], the HSPMG has a wide application range [4-6]. Therefore, more and more scholars pay attention to it. HSPMG also has disadvantages of larger loss per unit volume, insufficient heat dissipation, etc. In addition, HSPMG will reach tens of thousands of revolutions per minute in the working process. So even for small torque ripple, it would make a great influence on the steady-state running of the generator. It is of great significance to study the influence of harmonic current on HSPMG.

At present, many experts and scholars have studied high speed permanent magnet machine, including structural design [1-2, 8-9], electromagnetic analysis [3-4, 10-12], thermal optimization [5-7, 13-15], and so on. In addition, the influence of harmonics on induction motor is studied, and a reduced-loss rotor slot design is proposed [20]. Some experts have studied the effect of harmonic generated by various voltage-source inverter modulation techniques on induction motor, and an optimized modulation is proposed [21]. The influences of the harmonics on permanent magnet motor are studied in reference [19, 22-23], and the influence laws of harmonic on torque and loss of motor are determined. These studies focus on the influence of harmonic on the motor running at low speed. There are few studies on the motor operating at high speed condition, and the researches on the influence of harmonic and revealing the influence mechanism are fewer.

In this paper, a 117 kW, 60 000 rpm HSPMG driven by micro gas turbine is taken as an example. The influences of characteristic harmonics generated by rectifier on the loss and torque of HSPMG are studied, and the influence laws of the ratio, order and phase angle of the harmonic on the generator loss and torque ripple are determined. At the same time, the influence mechanism of different harmonics on rotor eddy current loss is revealed. Based on the analysis of the influence of the harmonic phase angle on torque ripple, it is found that the torque ripple could be weakened through changing the harmonic phase angle. This study is helpful to reduce the loss, prevent demagnetization fault and improve the efficiency of HSPMG. It also contributes to reduce torque ripple, improve running stability and prevent mechanical failure of the generator. These conclusions also can provide references for harmonic optimization and electromagnetic structure parameters optimization of HSPMG with rectifier load.

2. Parameters and Models of the Generator

2.1 Parameters and models

The study object of this paper is a HSPMG driven by a

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Table 1. Basic parameters of the HSPMG

Basic parameters	Value
Rated power (kW)	117
Rated voltage (V)	670
Pole number	2
Rotor type	PM
Frequency (Hz)	1000
Stator outer diameter (mm)	135
Stator inner diameter (mm)	72
Rotor outer diameter (mm)	66
Core length (mm)	275
Slot number	36
Amplitude of fundamental current (A)	141.41
Parallel branch number	1
Single conductor diameter (mm)	0.63
Sleeve thickness (mm)	5.5
Sleeve material	50Mn18Cr5C0.4

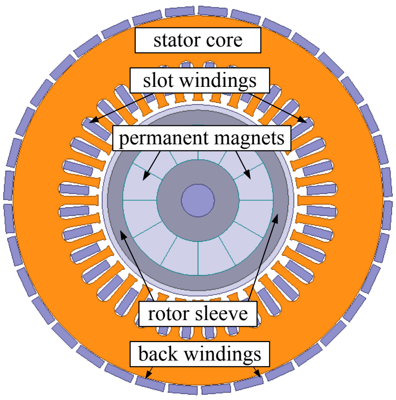

Fig. 1. 2-D finite element model of the HSPMG

micro gas turbine. The cooling system of the generator stator adopts the oil cooling system. The back rounded structure of generator stator windings is adopted to reduce the axial length of the rotor and enhance the mechanical strength of the generator rotor [9]. The magnetic pole structure adopts the cylinder style, and it is made up of 12 pieces of permanent magnets to reduce the eddy current losses. The basic parameters of the generator are shown in Table 1. According to the actual structure and parameter, the 2-D finite element model is built, as shown in Fig. 1.

During the analysis of the electromagnetic fields in this paper, in order to simplify the calculation and analysis, the following assumptions are presented [16]:

(1) The displacement current and the end leakage flux of the generator are ignored, and the electromagnetic field in the generator is quasi-stationary electromagnetic field.

(2) During the calculation of the generator 2D transient field, only the z-axis component of the magnetic vector potential is considered.

Based on the electromagnetic field theory and the above assumptions, the boundary value equation can be used to analysis the electromagnetic field of the generator, and the associated boundary conditions are given as shown in formula (1) [16, 24].

$$\begin{cases} \Omega : \dfrac{\partial}{\partial x}\left(\dfrac{1}{\mu}\dfrac{\partial A_z}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\dfrac{1}{\mu}\dfrac{\partial A_z}{\partial y}\right)=-\left(J_z-\sigma\dfrac{dA_z}{dt}\right) \\ S_1 : A_z = 0 \\ S_2 : \dfrac{1}{\mu_1}\dfrac{\partial A_z}{\partial n}-\dfrac{1}{\mu_2}\dfrac{\partial A_z}{\partial n}=J_s \end{cases} \tag{1}$$

where Ω is the boundary value equation of the current density and magnetic vector potential in 2d cross-section solution region. S_1 is the Dirichlet boundary condition or the first boundary condition. Because the electromagnetic field is mainly concentrated in the interior of the generator, the first boundary conditions are attached to the stator outer boundary. S_2 is the Neumann boundary condition or the second boundary condition, and contains equivalent face current of PM, so S_2 is attached to the PM boundary. J_S is the PM equivalent face current density. A_Z is the magnetic vector potential. J_Z is the source current density in the z-axial component. σ is the conductivity. μ_1 and μ_2 are relative permeability values. n is the normal direction of permanent magnet boundary.

2.2 Experimental testing and data comparison

To verify the correctness of the HSPMG finite element model, the terminal voltage and the armature current of the HSPMG are obtained through testing the generator prototype under 6000, 8000 and 10000 rpm. The terminal voltage and the armature current of the finite element model are also obtained, and then the results are compared with the test results.

The test platform and the experimental equipment are shown in Fig. 2.

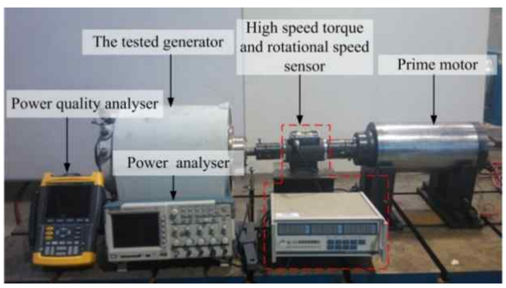

Fig. 2. The test platform

Table 2. Comparison of the test data and the calculated result

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

The test data of the generator and the calculated results of the finite element model are shown in Table 2.

The error between the test data and the calculated results is less than 1.5%. The calculated results show good agreement with the test data by comparative analysis. So the finite element model could be validated.

3. Harmonic Current of HSPMG with Rectifier Load

Since the frequency of the power generated by HSPMG can reach hundreds Hertz, or even thousands Hertz, the electrical equipment cannot connect to the generator directly [3]. The high-frequency power has to be converted to DC power by rectifiers. Some part of the power is supplied to DC power users or DC energy storage equipment, the other is converted to 50Hz AC power for the users by inverters. Because the rectifier is nonlinear load, it is inevitable that harmonic current will be generated during the running process, which could increase current harmonics in the generator stator armature windings.

3.1 Uncontrolled rectifier load

When the generator is running with uncontrolled rectifier load, the harmonic order is:

$$\textit{harmonic order} = 6k \pm 1 \tag{2}$$

where k=1, 2, 3...

So when k=1, the harmonic order is 5th and 7th; when k=2, the harmonic order is 11th and 13th.

3.2 Full-controlled rectifier load

Due to the influence of switching frequency, harmonic is produced in the AC side of rectifier which frequency is near to the integer switching frequency but not include multiples frequencies of the switching frequency. The harmonic current frequency is [17]:

$$\textit{harmonic frequency} = nf_2 \pm kf_1 \tag{3}$$

where f_2 is switching frequency, f_1 is fundamental frequency of the generator.

When n is odd number, k is positive even number which is non-3 integer multiples; When n is even number, k is positive odd number which is non-3 integer multiples.

The fundamental frequency of the generator is 1 kHz. Based on formula (3), the harmonic frequency can be obtained. When the carrier frequency is 21 kHz, the harmonic frequencies of the largest harmonic amplitude are 19 kHz and 23 kHz. When the carrier frequency is 51 kHz, the harmonic frequencies of the largest harmonic amplitude are 49 kHz and 53 kHz.

In order to study the influence of the each harmonic generated by different rectifier, the lower harmonics such as 5th, 7th, 11th and 13th, the effects of higher harmonics such as 19th, 23th, 49th and 53th were analyzed in this paper.

4. Influence of Harmonic Currents on the Generator

When the generator is running at rated power, the fundamental current amplitude of the generator is 141.41A. In this study, the current of the stator windings includes fundamental current and different order and ratio harmonic current.

4.1 Influence of harmonic current on the generator stator core loss

Based on finite element method, the stator core loss is obtained and shown in Table 3 by adding harmonic current in the stator winding.

Through the analysis of Table 3, the following conclusions can be drawn from the data analysis. With the increase (1%~5% of fundamental current) of the harmonic current ratio, the change of core loss is less than 1.5%. With the increase of the current harmonics order under the same ratio, the core loss is unchanged.

4.2 Influence of harmonic current on the generator rotor eddy current loss

Because the permanent magnetic material is conductive, there will be eddy current in permanent magnet when the external magnetic is changing. So the eddy current loss will be also generated. Due to the poor heat dissipation capacity of the rotor and the influence of the eddy current loss, the too high permanent magnet temperature will cause the permanent magnet irreversibly demagnetized and affect the safe operation of the generator. Especially for HSPMG, the rotor frequency is 1000Hz, and the eddy current loss is more prominent due to the skin effect. Therefore, the study on eddy current loss is very necessary.

During the analysis, the rotor eddy current loss is

Table 3. The generator stator core loss of different harmonic current (Partial Data)

Harmonic Ratio	The Stator Core Loss (W)					
	5th	11th	13th	23th	49th	53th
Fundamental current	1269.2	1269.2	1269.2	1269.2	1269.2	1269.2
1%	1269.6	1269.1	1269.4	1269.5	1270.2	1270.0
2%	1270.1	1269.5	1269.9	1271.0	1272.1	1272.3
3%	1270.7	1270.1	1270.9	1273.7	1276.0	1276.0
4%	1271.3	1271.0	1272.2	1277.2	1281.1	1281.3
5%	1272.1	1272.2	1274.0	1281.9	1287.7	1287.9

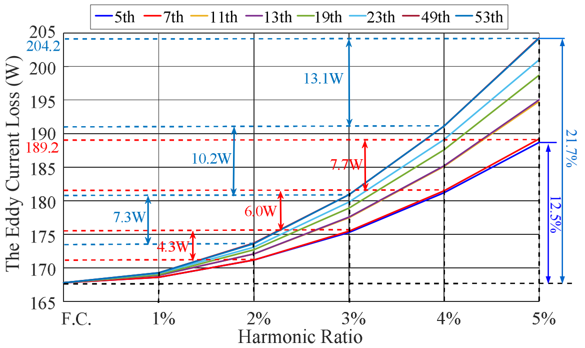

Fig. 3. The rotor eddy current loss of the HSPMG

calculated in a cycle as the following formula (4) [12]:

$$P_e = \frac{1}{T_e} \int_{T_e} \sum_{i=1}^{k} J_e^2 \Delta_e \sigma_r^{-1} l_t dt \tag{4}$$

where P_e is the rotor eddy current loss; J_e is the current density in each element; Δ_e is the element area; l_t is the rotor axial length; σ_r is the conductivity of the eddy current zone, and T_e is the cycle of time.

Through attaching different harmonic current in the stator windings respectively, the rotor eddy current loss could be obtained by finite element method, as shown in Fig. 3.

In Fig. 3, F.C. represents the Fundamental Current amplitude, whose value is 141.41A. The eddy current loss is 167.8W when only fundamental current is contained. It could be known from Fig. 3 that the eddy current loss is increased with the harmonic current ratio increasing in the same harmonic order, and the increment of eddy current loss is bigger and bigger.

Using the eddy current loss when only fundamental current is contained as reference, when the harmonic ratio is 5%, the eddy current loss increment could be calculated, and the calculation is shown in Table 4.

From Table 4, it can be obtained that the current harmonic order also has a great influence on the eddy current loss of the generator rotor. With the increase of harmonic order, the increment rate of eddy current loss is from 12.5% to 21.8%.

In order to explain the changing mechanism of the eddy current loss, the fundamental current and harmonic ratio 5% of each harmonic current are added in the stator winding, the eddy current density distribution of the generator rotor is obtained by the finite element method, as shown in Fig. 4.

The same scale is adopted in Fig. 4. It could be known from Fig. 4 that eddy current is mainly distributed on the rotor surface and the maximum of the eddy current density appears on the sleeve due to the skin effect. In addition, it could be found that the eddy current density of rotor surface increases obviously with the increase of harmonic order. By the finite element method, the maximum eddy

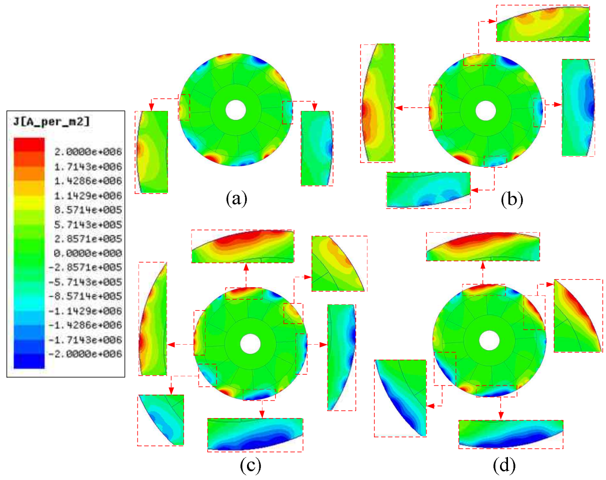

Fig. 4. The rotor eddy current density distribution when the harmonic ratio is 5%: (a) when only fundamental current is added in the stator windings; (b) when fundamental current and the 13th harmonic current are added in the stator windings; (c) when fundamental current and the 19th harmonic current are added in the stator windings; (d) when fundamental current and the 49th harmonic current are added in the stator windings

Table 4. The increment rate of eddy current loss and the maximum eddy current density of the rotor when the harmonic ratio is 5%

Harmonic order	The increment rate of eddy current loss (%)	The maximum eddy current density ($\times 10^6$ A/m^2)
Fundamental current	——	4.34
5th	12.5	5.04
7th	12.8	4.74
11th	16.1	5.20
13th	16.2	5.01
19th	18.4	5.21
23th	19.8	5.48
49th	21.8	5.49
53th	21.7	5.56

current density of the rotor could be calculated and shown in Table 4.

Through the above analysis of the eddy current density distribution, the conclusions can be obtained that the eddy current distribution area becomes larger remarkably with the harmonic order increasing, and the eddy current density maximum also becomes bigger. According to the formula (4), when other parameters are the same, the eddy current loss will increase with the eddy current density and distribution area increasing in a cycle, and its distribution area is mainly located on the sleeve surface.

4.3 Influence of harmonic current on the generator copper loss

In this paper, the generator copper loss is also researched.

Table 5. The generator copper loss of different harmonic current (Partial Data)

Harmonic Ratio	The Copper Loss (W)					
	5th	11th	13th	23th	49th	53th
Fundamental current	755.88	755.88	755.88	755.88	755.88	755.88
1%	755.95	755.81	756.1	756.04	755.95	755.96
2%	756.17	755.9	756.46	756.34	756.18	756.19
3%	756.54	756.13	756.98	756.80	756.56	756.57
4%	757.06	756.52	757.65	757.41	757.09	757.10
5%	757.74	757.06	758.48	758.17	757.77	757.78

For the HSPMG, since the rotor has no winding, the copper loss is concentrated in the stator winding. Because the single conductor diameter of the stator winding is small (0.63mm), the influences of the skin effect and proximity effect can be ignored. The stator winding copper loss can be calculated by the following formula (5).

$$P_{cu} = R_s \sum I_i^2 \tag{5}$$

where R_S is the armature resistance, I_i is the phase current.

Based on formula (5), the generator copper loss could be obtained, as shown in Table 5.

The following conclusion could be drawn that with the change of the harmonic current, the generator copper loss is unchanged.

4.4 Influence of harmonic current on the generator torque

The torque ripple reflects the stability of the generator running. It causes generator vibration and noise, and even causes generator to be damaged. The generator efficiency will be also degraded. So the study of torque is of great significance. The effect of harmonic current on the generator torque (In this paper, the generator torque is the electromagnetic torque) is analyzed emphatically.

By using the finite element method, the torque waveform can be obtained by adding the fundamental current and attaching different harmonic current in stator winding. The harmonic current ratio is 5% during the analysis process.

It could be seen from Fig. 5 that the frequency of fluctuation of the torque is markedly increased with the additional harmonic order increasing during the same period of time. High-frequency vibration may also cause parts of the generator to be damaged because of resonance.

The generator average torque could be calculated by:

$$T_{em} = \frac{P_{em}}{\Omega_s} = \frac{P_1 - P_{mec} - P_{Fe}}{\Omega_s} = \frac{mE_0 I \cos\psi_0}{\Omega_s} \tag{6}$$

where P_1 is the input mechanical power; P_{mec} is the mechanical loss; P_{Fe} is the stator core loss; Ω_S is synchronous angular speed.

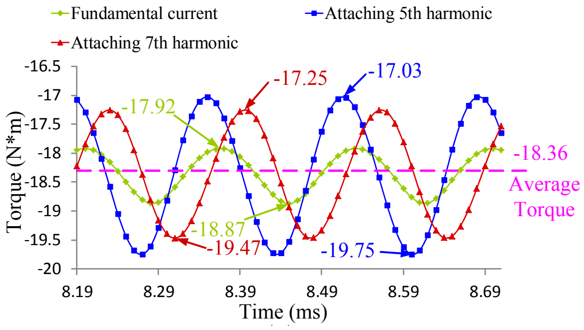

Fig. 5(a). The generator torques when only fundamental current is added and 5th, 7th harmonic of 5% ratio is attached respectively in the stator windings

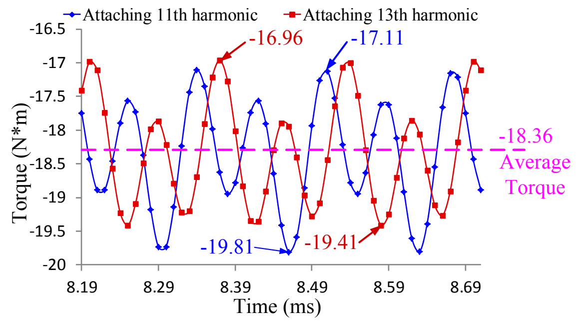

Fig. 5(b). The generator torques when 11th, 13th harmonic of 5% ratio is attached respectively in the stator windings

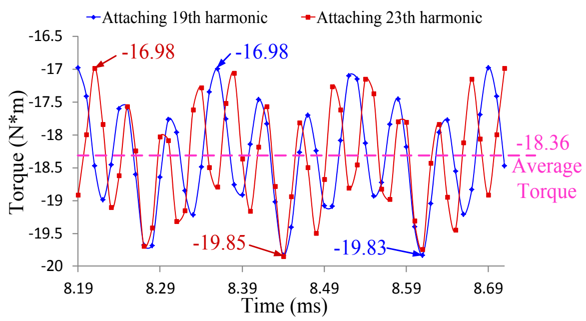

Fig. 5(c). The generator torque when 19th, 23th harmonic of 5% ratio is attached respectively in the stator windings

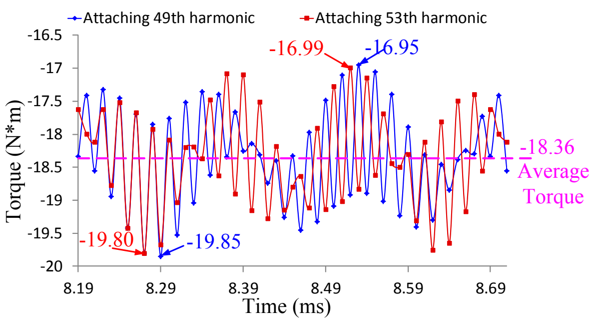

Fig. 5(d). The generator torque when 49th, 53th harmonic of 5% ratio is attached respectively in the stator windings

Table 6. The generator average torque (Partial Data)

Harmonic Ratio	The Average Torque (Nm)					
	5th	11th	13th	23th	49th	53th
Fundamental current	-18.36	-18.36	-18.36	-18.36	-18.36	-18.36
1%	-18.37	-18.36	-18.36	-18.36	-18.36	-18.36
2%	-18.37	-18.37	-18.36	-18.36	-18.36	-18.36
3%	-18.37	-18.37	-18.36	-18.36	-18.36	-18.36
4%	-18.37	-18.37	-18.36	-18.37	-18.36	-18.36
5%	-18.38	-18.37	-18.36	-18.37	-18.36	-18.36

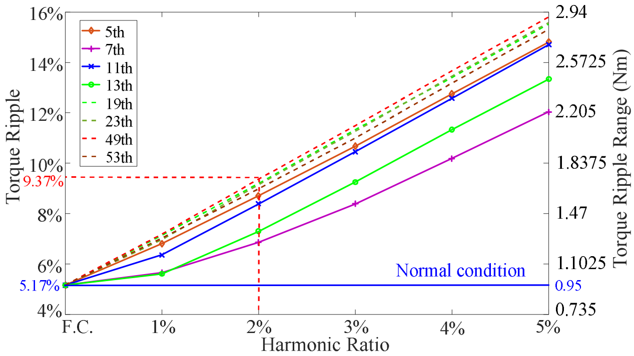

Fig. 6. Torque ripple and torque ripple range

The average torque of the generator under different conditions is obtained, as shown in Table 6.

The conclusion could be known from Table 6 that the change of the generator average torque is less than 1% with the influence of different harmonic current. Thus the generator average torque is basically unchanged.

4.5 Influence of harmonic current on the generator torque ripple

To analyze the torque accurately, the torque ripple in this paper is defined as (7-8) [18].

$$T_{rip} = \frac{T_{\max} - T_{\min}}{T_{av}} \tag{7}$$

$$T_{range} = T_{\max} - T_{\min} \tag{8}$$

where T_{rip} is torque ripple; T_{range} is the torque ripple range; T_{av} is the average torque; $T_{\max}$ is maximum torque and $T_{\min}$ is minimum torque.

Thus, the torque ripple could be calculated based on formula (7-8), the torque ripple can be drawn in Fig. 6.

F.C. represents the Fundamental Current amplitude. From Fig.6, the torque ripple range and torque ripple are 0.95 Nm and 5.17% when only fundamental current in the stator windings. Using that as reference value, the torque ripples and the percentages of the torque ripple range increment of the generator are shown in Table 7 when the harmonic ratio is 2%.

Thus it could be seen that the harmonic current has a great influence on the generator torque ripple range.

Table 7. The torque ripple and the increment percentage of the generator with the harmonic ratio is 2%.

Harmonic order	The torque ripple (%)	The percentage of the increment of torque ripple range (%)
Fundamental current	5.17	————
5th	8.71	68.43
7th	6.86	32.63
11th	8.39	62.11
13th	7.30	41.05
19th	9.20	77.89
23th	9.15	76.84
49th	9.37	81.05
53th	8.99	73.68

It could be known that the torque ripple obviously increases under the influence of harmonic current. The torque ripple increases with the harmonic ratio increasing. Another conclusion about the influence of the harmonic order on torque ripple could be obtained that the torque ripple shows an increasing trend as a whole with the harmonic order increasing. When harmonic ratio is only 2% and the order is 53th, the torque ripple is 8.99% and increase by 73.9% compared with the torque ripple when only fundamental current is contained.

5. Influence of Harmonic Current on the Generator with Different Phase Angle

In the analysis of this section, the 5th, 7th, 11th, 13th, 19th, 23th, 49th and 53th harmonic current are attached respectively in the stator windings, and the value of fundamental current amplitude is 141.41A and the harmonic ratio is 2%. The influence of harmonic phase angle on the generator is researched through changing the harmonic current phase angle.

5.1 Influence of harmonic current on the generator stator core loss

Based on the finite element method, the generator stator core loss and eddy current loss can be obtained as shown in Table 8.

Table 8. The stator core loss and rotor eddy current loss (W) when the harmonic ratio is 2% (Partial Data)

Phase Angle	5th		19th		49th	
	Core loss	Eddy current loss	Core loss	Eddy current loss	Core loss	Eddy current loss
0°	1270.1	171.2	1270.6	172.7	1272.1	173.7
60°	1270.1	171.2	1270.3	172.8	1272.2	173.7
120°	1269.3	171.1	1270.3	172.8	1272.3	173.7
180°	1268.4	171.1	1270.7	172.8	1272.2	173.6
240°	1268.4	171.1	1271.1	172.8	1272.3	173.7
300°	1269.2	171.1	1271.0	172.7	1272.3	173.6
360°	1270.1	171.2	1270.6	172.8	1272.1	173.7

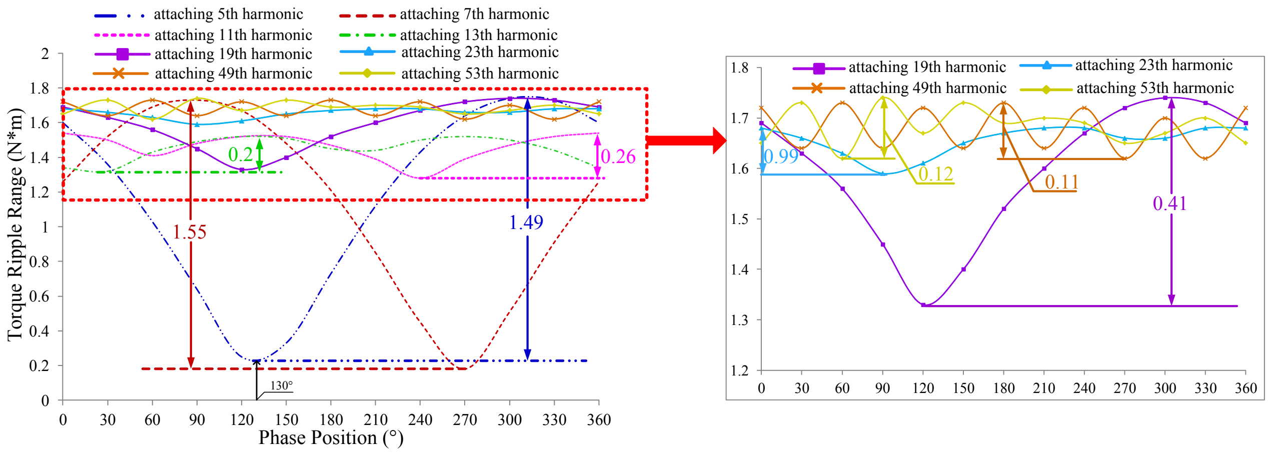

Fig. 7. The torque ripple range

Table 9. The generator average torque when the harmonic ratio is 2%

Phase Angle	The Average Torque (Nm)				
	5th	11th	19th	49th	53th
0°	-18.37	-18.37	-18.36	-18.36	-18.36
60°	-18.36	-18.36	-18.36	-18.36	-18.36
120°	-18.36	-18.36	-18.36	-18.36	-18.36
180°	-18.36	-18.36	-18.36	-18.36	-18.36
240°	-18.37	-18.36	-18.36	-18.36	-18.36
300°	-18.37	-18.36	-18.36	-18.36	-18.36
360°	-18.37	-18.37	-18.36	-18.36	-18.36

Through analyzing the core loss in the above table, it is obtained that the generator stator core loss is unchanged only when the harmonic current phase angle changed. The change of the generator stator core loss is less than 1% only when the harmonic order changes.

Through analyzing the eddy current loss data in the above table, the generator eddy current loss is unchanged only when the phase changed, and the change of the generator eddy current loss is less than 1.5% only when the harmonic order changes.

5.2 Influence of harmonic current on the generator average torque

Based on the finite element method, the generator average torque can be obtained as shown in Table 9.

Through analyzing the data in the above table, the conclusion could be obtained that the generator average torque is unchanged when the harmonic order and phase angle change.

5.3 Influence of harmonic current on the generator torque ripple

According to formula (7-8) and the data, the torque ripple range could be obtained. Its change trend is shown in Fig. 7. The range of the torque ripple range of Table 10 could be obtained by calculation.

Table 10. The range of the torque ripple range (Nm) when the harmonic ratio is 2%

Harmonic order	5th	7th	11th	13th	19th	23th	49th	53th
Minimum range	0.25	0.18	1.28	1.32	1.33	1.59	1.62	1.62
Maximum range	1.74	1.73	1.54	1.52	1.74	1.68	1.73	1.74
Δ	1.49	1.55	0.26	0.2	0.41	0.09	0.11	0.12

where Δ is the difference between the torque ripple maximum range and the torque ripple minimum range.

It could be known from Fig. 7 and Table 10 that the range of torque ripple range (Δ) is gradually reduced with the harmonic order increasing. When the harmonic current order is lower, the torque ripple range could reach the minimum in an appropriate harmonic phase angle. Taking the 2% and 5th harmonic for example, the torque ripple range is 0.25Nm - minimum value when the harmonic phase angle is about 130°. According to this conclusion, the generator torque ripple can be reduced through changing the harmonic current phase angle in the system of HSPMG with rectifier load.

6. Conclusions

In this paper, taking a HSPMG driven by micro gas turbine as an example, the influences of different harmonic current on the loss and torque of the generator were studied. The following conclusions could be drawn.

1) The eddy current loss increases markedly when harmonic current ratio or order increases. The eddy current loss is 167.8W when only fundamental current is contained. However, the eddy current loss increases by 21.7% when harmonic ratio is 5% and the order is 53th. The cause of the increase of eddy current loss is that the maximum eddy current density increases from 4.3×10^6 A/m^2 to 5.56×10^6 A/m^2.

2) The torque ripple obviously increases with the harmonic ratio and order increase. The torque ripple is 5.17% when only fundamental current in the stator

windings. When harmonic ratio is only 2% and the order is 53th, the torque ripple is 8.99% and increase by 73.9%. So the torque ripple is influenced seriously by the harmonic current.

3) With the phase angle of harmonic current changing, the change of the torque ripple range is cyclical. Taking the 2% and 5th harmonic for example, the torque ripple range is 0.25Nm - minimum value when the harmonic phase angle is about 130°. When the harmonic order is low, the torque ripple can be reduced through changing the phase angle of the harmonic current.

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