Research on Topology of Axial Flux Permanent Magnet Synchronous Generator

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***Abstract* –** Through the comparative study of the TORUS-NN and TORUS-NS topologies for the axial flux permanent magnet synchronous generator (AFPMSG), it is shown that the AFG with single stator double rotors topology is suitable for vertical axis wind turbines (VAWT). The basic parameters are designed and their 3D finite element models are established for the two topologies, which are compared and analyzed respectively on the same amount of magnets and windings, the magnetic density, THD value, torque ripple and efficiency. The research shows that the efficiency of TORUS-NN structure is only 0.22% higher than that of TORUS-NS structure with the same amount of magnetic steel, but the torque ripple of TORUS-NN structure is much greater than that of TORUS-NS structure, when the amount of magnet steel and the winding are the same, the efficiency of TORUS-NS structure is 8.5% higher than TORUS-NN structure. Considering their performance and economy, the TORUS-NS structure is superior to TORUS-NN topology structure for VAWT in starting torque and low wind speed. The experimental results and finite element analysis results are within the allowable error range, which verifies the feasibility and superiority of TORUS-NS topology for VAWT.

***Index Terms* –** Efficiency, finite element analysis, TORUS topology, vertical axis wind turbines.

I. INTRODUCTION

Wind power generation is one of the most mature, scalable and commercialized power generation methods in the field of renewable energy besides water energy [1]. Disc permanent magnet motors have been widely used in electric vehicles, wind power generation, ship driving, heart pumps and so on, because of their compact structure, high efficiency and high power density [2,3].

In view of the special working conditions of wind power generation, single stator and double rotors (also known as TORUS structure) have larger moment of inertia, and have better effect on suppressing the EMF fluctuation caused by wind fluctuation [4]. For structures with one or more pairs of axial rotors, their structures can be divided into three categories: TORUS-NS structure, TORUS-NN structure and hybrid structure, among which TORUS-NS structure and TORUS-NN structure are more common. Axial flux generator can be divided into fan-shaped, ring-shaped and fan-ring hybrid windings according to different winding forms [5-7]. The topology structure studied in this paper is applied to small vertical axis wind turbine. It is widely favored because of its simple structure, low starting wind speed, low noise and large moment of inertia [8]. In [9], by comparing the topological structure of single stator and double rotor generator with iron core or coreless, it is showed that the performance of coreless structure is better than the iron core structure though the comprehensive analysis of torque ripple, efficiency and THD value and other parameters. In [10], a permanent magnet synchronous motor (PMSM) with wedge-shaped air gap and no iron core based on Halbach array is proposed. The FEM method is used to model the 16-pole disk permanent magnet synchronous motor. The optimal solution region is obtained by comparing the sizes of different air caps. Then the static magnetic field of uniform air gap and wedge air gap is compared. In [11], three kinds of special axial flux permanent magnet motors are designed and their important dimensions are optimized. At the same time, the electromagnetic performance and stator vibration modes are compared and studied. Reference [12] compares the traditional stator toothed and stator toothless structures of axial permanent magnet motors. Quasi three dimensional finite element method is used to analyze the effect of stator structure change on the copper and iron losses of armature windings. In [13], the efficiency and temperature of coreless permanent magnet generator are taken as optimization objectives, and single variable parametric analysis and multi-dimensional optimization method are adopted. The corresponding parameterized model is established and programmed. The loss of each part of the motor is analyzed by using Matlab. After comprehensive analysis, the optimal values of efficiency and temperature are found in the spatial distribution of multidimensional design. In [14], a kind of Halbach array coreless axial

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permanent magnet motor with combined magnetic poles is proposed. The pole arc coefficients of permanent magnets and soft magnetic materials are determined by using three-dimensional finite element analysis method under the condition that the air gap magnetic density is guaranteed. In [15], a disk permanent magnet generator is designed to be used in the power generation system of weapon platform. According to the basic electromagnetic relationship and the special requirements of the generator, the basic parameters of the generator are obtained and the magnetic field is simulated in Maxwell. Reference [16] presents a multi-objective optimization design method for axial permanent magnet generator based on Taguchi response surface method. The main characteristics such as generator efficiency, power quality and induction induced voltage are optimized. The validity of the optimization method is verified by finite element analysis and prototype test. In [17], the different cogging torque values of the magnet pole-arc are studied for triangle type, oval and fan type magnets. Thereby, a rotor structure with a small cogging torque is obtained. In [18], two torque optimization methods are proposed, and a three-dimensional finite element model is established to verify the analytical results of multi-objective genetic algorithm. Compared with the skew technique to verify the superiority for the two methods.

In summary, the single stator and double rotor structure of disk-type axial permanent magnet generator has a wide range of applications. The TORUS-NS and the TORUS-NN are named according to the distribution of its magnetic circuit and magnetic pole. The magnetization direction of the two relative magnetic poles is opposite for the TORUS-NN structure, and the magnetic circuit formed is shown in Fig. 1 (a). The magnetization direction of the two relative magnetic poles is same for the TORUS-NS structure and the magnetic circuit formed is shown in Fig. 1 (b).

In this paper, the structures of TORUS-NN and TORUS-NS are compared and analyzed, and a suitable topology for low-power wind turbines is selected by comparing the air gap magnetic density, efficiency, torque ripple and power quality. In this paper, TORUS-NN can only use fan-shaped windings with stator core due to the limitation of its topological structure. The magnetic path starts from N pole and passes through air gap, coil and stator core to S pole to form a magnetic path. The magnetic path at left and right ends is symmetrical, so the direction of induced current generated by the coils on both sides is opposite. The TORUS-NS structure adopts a coreless fan-shaped winding. The 3D FEA analysis was performed by Magnet software. In the 3D model, the magnetic field is unsaturated. The magnetic path passes through the winding and the uniform air gap on both sides formed a closed loop, as shown in Fig. 1.

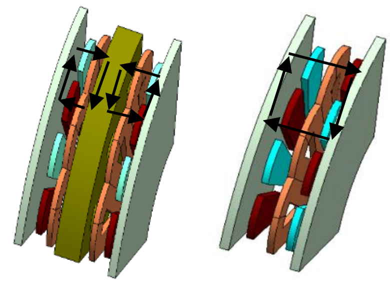


Fig. 1. Three-dimensional finite element model of generator: (a) structure of TORUS-NN, and (b) structure of TORUS-NS.

II. DESIGN OF AXIAL FLUX GENERATOR

A. Basic electromagnetic relations

For disc generator, if a single conductor is considered, the position of the plane is expressed by radius and polar angle. The air gap flux density is represented by the magnetic flux density at the average radius, which can be written as B_δ. The maximum induced voltage produced by a single conductor can be obtained:

$$e(\theta)=\Omega\int_{Di/2}^{D_o/2}B_\delta(\theta)rdr=\frac{1}{8}\Omega(D_o{}^2-D_i{}^2)B_\delta(\theta). \quad (1)$$

The average induced voltage produced by a single conductor is:

$$E_{av}=\frac{p}{\pi}\int_0^{\pi/p}e(\theta)d\theta=\frac{1}{8}\Omega(D_o{}^2-D_i{}^2)B_{\delta av}. \quad (2)$$

Where Ω is the mechanical angular velocity, D_o is generator's magnetic pole outer diameter, D_i is generator's magnetic pole inner diameter, $B_{\delta av}$ is average air gap magnetic density.

Armature induced voltage of generator:

$$E=\frac{NE_{av}}{2a}=C_e\Phi n, \quad (3)$$

where

$$\begin{cases} C_e=\dfrac{pN}{60a} \\ \Phi=\dfrac{\pi}{8p}B_{\delta v}(D_o{}^2-D_i{}^2), \end{cases} \quad (4)$$

a is the pairs of parallel branches of winding, N is the number of total conductors, p is number of pole pairs, n is rated speed, C_e is electromotive force constant, Φ is magnetic flux.

The effective conductor of the winding of disc generator radiates radially in space, and the electric load at the inner end of the winding is the largest. If the electric load at the minimum diameter of the generator is taken into account, its electromagnetic power can be obtained from equation (5):

$$p_{em}=EI=\frac{\pi^2}{240}nB_{\delta av}A_{\max}(D_o{}^2-D_i{}^2)D_i, \quad (5)$$

where A_{max} is maximum electric load.

B. Design of structural parameters

Firstly, the inner and outer diameters of disc generator are determined. According to the output power and operating speed of the axial flux permanent magnet generator selected in this paper, the electric load is 1000A/m. This paper designs a small generator with rated power of 300W and rated speed of 300rpm. Derivative of power ratio between inner and outer diameter is obtained, when $\gamma = \sqrt{3}$, the output power of the generator is the largest, then the outer diameter of the permanent magnet can be obtained from equation (6) [19]:

$$D_o = \sqrt[3]{\frac{\gamma^3 P}{\frac{\pi^2}{120} mn\alpha_i k_w B_\delta A_{av}(\gamma^2 - 1)(\gamma + 1)}} . \quad (6)$$

Where m is armature winding phase number, α_i is the calculation of pole arc coefficient, k_w is the coefficient of armature winding, A_{av} is average electric load, P is generator power.

The length of permanent magnet can be expressed as [20]:

$$L_{\mathrm{PM}} = \frac{\mu_r B_g}{B_{\mathrm{r}} - B_g K_f / K_d}(g + W_{\mathrm{cu}}) . \quad (7)$$

Where K_f is the disc generator air gap flux density in the radial direction of the maximum correction coefficient, K_d is the magnetic leakage coefficient, W_{cu} is armature winding end extension length, B_g is air gap flux density, g is air gap length, μ_r is relative permeability.

When the speed is constant, the number of pole pairs is 10 can be obtained according to p=60f/n. In this paper, the number of coils can be determined to be 15 when the span electric angle of armature winding is 240 degrees. Polar arc coefficient has an effect on the amplitude of air gap magnetic density. When the pole arc coefficient is too small, the magnitude of magnetic density is low, if the pole arc coefficient is too large, the economy cannot be guaranteed, so pole arc coefficient is 0.78.

Table 1: Structural parameters of two prototype

Parameters	Value
Rated power	300 W
Rated speed	300 rpm
Rated line voltage	30 V
Inner diameter of permanent magnet	140 mm
Outer diameter of permanent magnet	240 mm
Back iron inner diameter	110 mm
Back iron outer diameter	270 mm
Pole arc coefficient	0.78
Permanent magnet thickness	4.5 mm
One side air gap length	1 mm

The above design parameters are suitable for two different topologies, but the stator core structure is adopted in the TORUS-NN structure, so the influence of the saturation and thickness of the core on the output power quality should also be considered. Magnet software can get all kinds of data needed in this paper. These analyses are completed with a computer with 2.3GHz Intel Core i5-8300H and 7.86 GB of RAM. The CPU processing time is 37 minutes.

The optimum core thickness is selected by comparing different core thickness, as shown in Fig. 2.

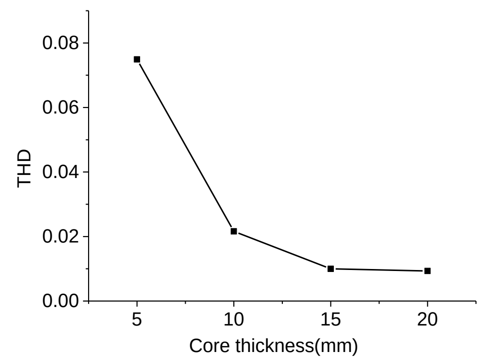


Fig. 2. THD with different core thickness.

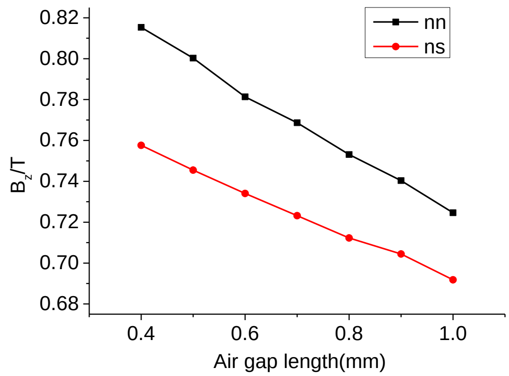
As shown in Fig. 2, the THD (total harmonic distortion) value decreases with the increase of core thickness. The output power of the two kinds of topological junctions should be compared quantitatively, and the THD of the TORUS-NS structure is also low. Therefore, the thickness of stator core is 20 mm.

III. COMPARATIVE STUDY OF TWO TOPOLOGICAL STRUCTURES

A. Contrastive study for isomagnetic steel consumption

Because the core of TORUS-NN structure is used as the conducting medium of the magnetic path for the generator, which is stronger than the air conductivity of TORUS-NS structure, it is necessary to adjust the number of coil turns for the TORUS-NN structure so that the output power of the two topological structures is the same. After optimization, the turn number of TORUS-NN coil is 60, and the thickness of one side coil is 4.2 mm. When the amount of permanent magnets used in the two topologies is the same, the efficiency, magnetic density amplitude and total harmonic distortion (THD) of the two topologies are compared under different air gaps.

According to the detailed analysis of Fig. 3 (a), the average magnetic density of TORUS-NN structure is 6.03% higher than that of TORUS-NS structure. From Fig. 3 (b), the efficiency of TORUS-NN structure is 0.22% higher than that of TORUS-NS structure except that the efficiency of TORUS-NN structure is lower when the air gap is 0.7. The maximum THD value of TORUS-NN structure is much lower than that of TORUS-NS structure, as shown in Fig. 3 (c), but both of them meet the requirement of national standard THD not exceeding 5%.



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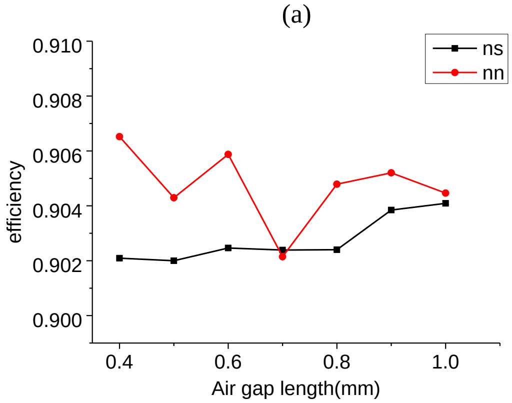

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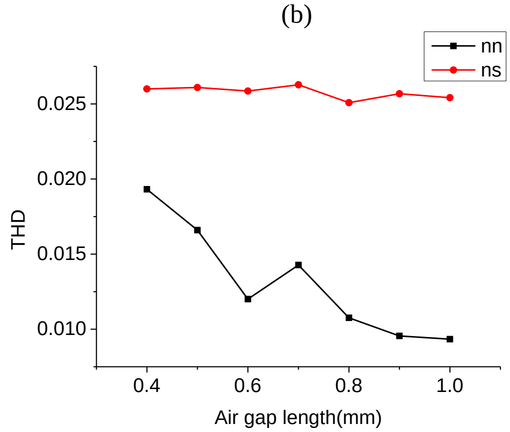
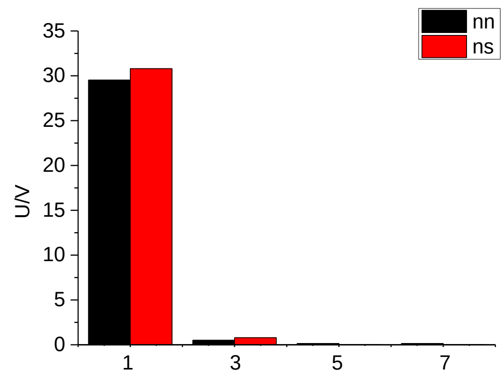


(c)

Fig. 3. (a) Comparison of magnetic density, (b) comparison of efficiency, and (c) comparison of THD values.

In the case of 0.4mm air gap and 1mm air gap, the difference between them in the magnitude, efficiency and THD of magnetic density is the smallest and the largest, respectively, and then the fundamental wave and each harmonic wave of the two are compared. According to Fig. 4, the fundamental wave, fifth and seventh harmonics of TORUS-NN structure are higher than those of TORUS-NS structure under two kinds of air gap, but the third harmonic is lower than that of TORUS-NS structure. Because of the factors of topological structure, the cogging torque will be produced in the TORUS-NN structure, then the electromagnetic torque of the generator will fluctuate, so the torque ripple of the TORUS -NS structure will be smaller than that of the TORUS-NN structure. In this paper, two structures with 1 mm air gap are selected to compare the torque ripple, as shown in Fig. 5. The TORUS-NS torque is basically stable at - 11N·m, while the TORUS-NN structure's torque ripple amplification diagram is jagged, and the torque ripple is large.



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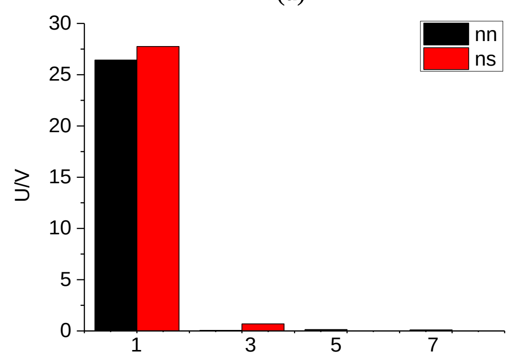


(b)

Fig. 4. Comparison of harmonic contents of two topological structures in different air gaps: (a) in 0.4mm air gap and (b) in 1 mm air gap.

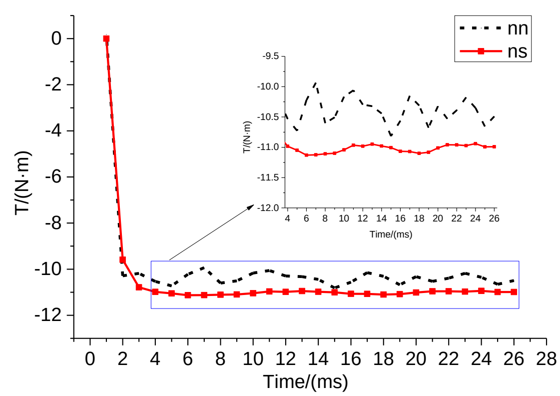
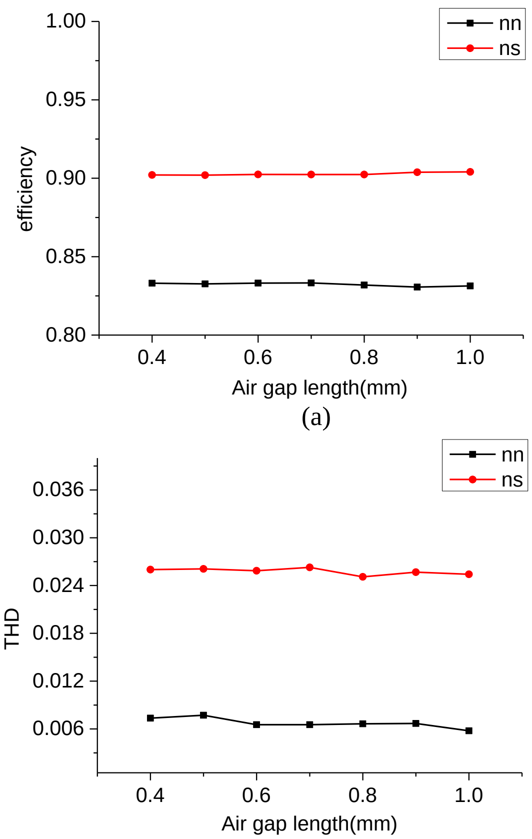


Fig. 5. Comparison of torque ripple of two structures in 1 mm air gap.

B. Contrastive study for equal turns of equal winding thickness with equal magnet steel dosage

The thickness of permanent magnet is set to 4.5mm for the two topological structures. Because the coil of TORUS-NS structure is single layer and the coil thickness is 4.2mm, in order to compare the winding thickness as a fixed value, the thickness of windings on both sides is set to 2.1mm for the TORUS-NN structure. The coil turns of the two structures are set to 155. Change the air gap of the two topologies, and compare the efficiency and THD value of the two topologies under the same air gap, as shown in Fig. 6.



(b)

Fig. 6. (a) Comparison of efficiency, and (b) comparison of THD values.

According to the analysis of Fig. 6 (a), when the thickness of permanent magnet, winding turns and thickness are the same, the efficiency of TORUS-NS structure is 8.5% higher than that of TORUS-NN structure on average. As shown in Fig. 6 (b), the THD value of TORUS-NN structure is lower and its harmonic content is less than that of TORUS-NS structure. Although the total harmonic content of the TORUS-NN structure is low and the sinusoidal waveform is good, the cogging torque of the TORUS-NN structure affects the magnitude and the torque stability. And eddy current loss will occur in the stator core, which reduces the efficiency of the motor. In this case, the performance of TORUS-NS structure is better than that of TORUS-NN structure.

Based on the two kinds of comparative analysis above, the TORUS-NS structure does not need to consider the effect of the iron core on the voltage distortion rate. In terms of efficiency, there is little difference between them, and in the second comparison, the TORUS-NS efficiency is all higher than the TORUS-NN efficiency in different air gaps. The efficiency of TORUS-NS is higher than that of TORUS-NN under different air gaps. In terms of electromagnetic torque, the TORUS-NS structure is superior to the TORUS-NN structure in terms of both the stability and size of the torque. At the same time, in the case of similar performance indicators, there is coreless in TORUS-NS structure, which guarantees the economy of manufacturing generators, and provides the possibility for batch production of motors and the manufacture of this prototype.

IV. EXPERIMENT

In order to verify the correctness of theoretical analysis and finite element simulation results, a generator with TORUS-NS structure is designed and manufactured. The rated speed is 300 rpm. The armature winding adopts concentrated winding to reduce end connection length and copper consumption, and the winding is fixed on the stator disc with epoxy resin. The permanent magnet is glued to the back iron with structural adhesive to prevent the permanent magnet from falling off. After the prototype is completed, the experimental platform is built, as shown in Fig. 7 and Fig. 8. The speed of the induction motor is adjusted by the frequency converter. And the three-phase induction motor drives the permanent magnet generator to rotate through the reducer and coupling. The rated power of the three-phase induction motor is 1500W, and the rated phase voltage is 220V. The input line voltage of the frequency converter is 350-450v, and the output line voltage is 0-380V.The required voltage and current are output by the rectifier inverter device.

Fig. 7. Prototype structure of generator.

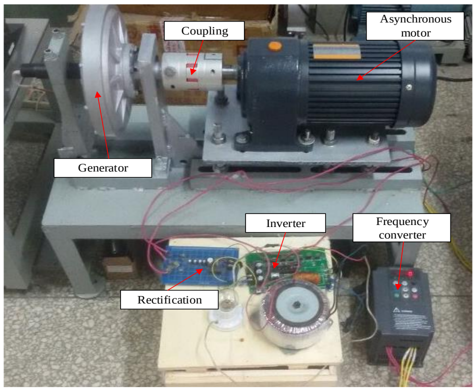
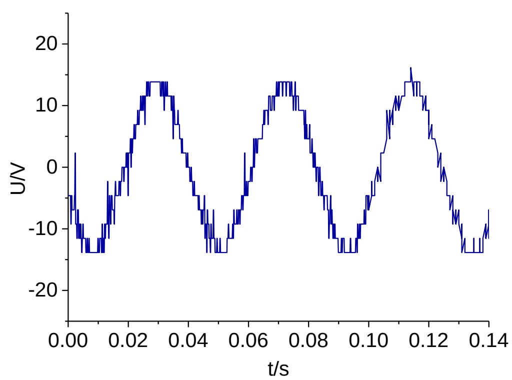
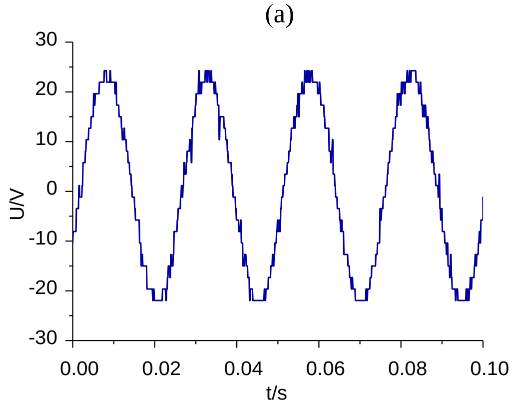


Fig. 8. Experimental platform.

No-load experiments are carried out on the prototype at different rotational speeds. As shown in Fig. 9, the output voltage waveform of the generator at the speed of 150 rpm and 250 rpm contains more harmonics, but the waveform is still sinusoidal. The generator can output relatively smooth sinusoidal waveform when its speed is 300 rpm. The amplitude of the output phase voltage of the prototype is 26.55V, which is similar to 27.2V of the FEM simulation result, as shown in Fig. 10. According to no-load voltage, the experimental THD value is 2.05% and the finite element analysis is 2.5%. In the error range, the experiment and simulation results are similar, which verifies the correctness of the above theoretical analysis.



(a)



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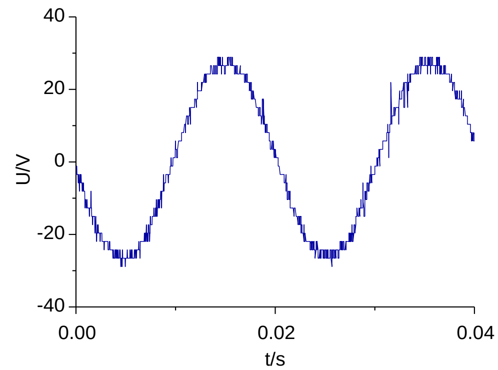

(c)

Fig. 9. Measured output voltage waveform of prototype at different rotational speeds: (a) at 150 rpm speed, (b) at 250 rpm speed, and (c) at 300 rpm speed.

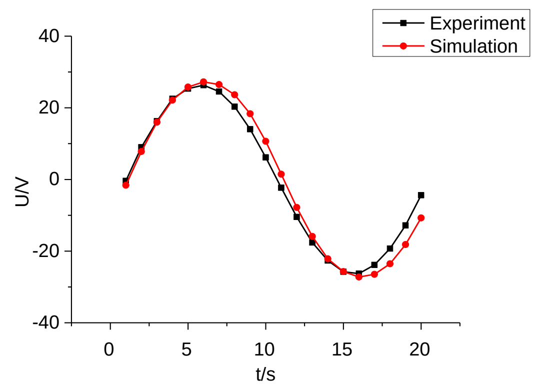

Fig. 10. Comparison of output voltage waveforms.

V. CONCLUSION

This paper divides the structure of TORUS-NN and TORUS-NS into two cases. The efficiency of TORUS-NN structure is only 0.22% higher than that of TORUS-NS structure when the amount of magnet steel is the same, but the efficiency of TORUS-NS structure is 8.5% higher than that of TORUS-NN structure when the amount of magnet steel and winding is the same. Because of the cogging torque, the torque ripple of the TORUS-NN structure is greatly. TORUS-NS structure does not need stator core as magnetic path, which reduces the cost of generators. Comprehensive analysis of TORUS-NS structure as generator structure has great advantages. The prototype data produced are similar to the finite element simulation results, and it is suitable for the generator with vertical axial flux.

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REFERENCES

[1] K.-Y. Shen, "Wind energy resources and wind power generation in China," *Northwest Hydropower*, vol. 29, no. 1, pp. 76-80, 2010.

[2] Y. Huang, T. Zhou, and J. Dong, "An overview on developments and researches of axial flux permanent magnet machines," *Proceedings of the CSEE*, vol. 35, no. 1, pp. 192-204, 2015.

[3] Z. Geng and G. Li, "Overview of axial flux permanent — magnet machine," *Small & Special Electrical Machines*, vol. 43, no. 9, pp. 88-99, 2015.

[4] D. He, "The Design Study for Disk-type Permanent-magnet Synchronous Generator in the Wind Power Generation System," *Changsha: Hunan University*, 2006.

[5] X. Wei, "Research of a Multistage Axial Flux Permanent Magnet Machine," *Wuhan: Huazhong University of Science and Technology*, 2015.

[6] F. G. Cappon, G. De Donato, and F. Caricchi, "Recent advances in axial-flux permanent-magnet machine technology," *IEEE Transactions on Industry Applications*, vol. 48, no. 6, pp. 2190-2203, 2012.

[7] T. J. Woolmer and M. D. McCulloch, "Analysis of the yokeless and segmented armature machine," *International Electric Machines & Drives Conference, IEEE*, Antalya, 2007.

[8] T. Sun, "Research on Small Vertical - Axis Wind Turbine for Distributed Power Generation," *Shijiazhuang: Hebei University of Science and Technology*, 2017.

[9] J. Zhu, D.-D. Song, and Q.-L. Han, "Comparative research on performance of iron and ironless axial flux wind generators," *Journal of Astronautic Metrology and Measurement*, vol. 38, no. 4, pp. 79-85, 2018.

[10] X. Wang and R. Tang, "Optimization of disk coreless permanent magnet synchronous motor based on Halbach—the wedgy airgap motor," *Transactions of China Electrotechnical Society*, vol. 22, no. 3, pp. 2-5, 2007.

[11] H. Li and J. Shen, "FEA-based design and comparative study of axial flux permanent magnet machines with various topologies," *Transactions of China, Electrotechnical Society*, vol. 30, no. 14, pp. 32-40, 2015.

[12] A. Arkadan, T. M. Hijazi, and B. Masri, "Design evaluation of conventional and toothless stator wind power axial-flux PM generator," *IEEE Transactions on Magnetics*, vol. 53, no. 6, pp. 1-4, 2017.

[13] C. Chen and Y. Wang, "Optimal design of axial-flux permanent magnet motors based on the efficiency and temperature rise," *Proceedings of the CSEE*, vol. 36, no. 6, pp. 1686-1692, 2016.

[14] Y. Cao, Y. Huang, L. Jin, and M. Hu, "Design and analysis of a stator coreless axial-flux permanent magnet machine with module poles," *Proceedings of the CSEE*, vol. 34, no. 6, pp. 903-907, 2014.

[15] J.-C. Zhao, "Electromagnetic design and simulation of disc type coreless permanent generator," *Small & Special Electrical Machines*, vol. 45, no. 6, pp. 45-53, 2017.

[16] J. Zhu and S. Li, "Multi-objective optimisation design of air cored axial flux PM generator," *IET Electric Power Applications*, vol. 12, no. 9, pp. 1390-1395, 2018.

[17] E. Aycicek, N. Bekiroglu, and I. Senol, "Rotor configuration for cogging torque minimization of the open-slot structured axial flux permanent magnet synchronous motors," *The Applied Computational Electromagnetics Society*, vol. 30, no. 4, pp. 396-408, 2015.

[18] S. Wu and S. Zuo, "Magnet modification to reduce pulsating torque for axial flux permanent magnet synchronous machines," *The Applied Computational Electromagnetics Society*, vol. 31, no. 3, pp. 294-303, 2016.

[19] B. Xia, "Research on Axial Flux Permanent Magnet Machine for Small-scale Vertical-axis Wind Power Application," *Hangzhou: Zhejiang University*, 2011.

[20] D.-R. Luo and Y.-N. Wang, "Design study of disk-type permanent-magnet synchronous generator," *Journal of Hunan University (Natural Sciences)*, vol. 33, no. 3, pp. 46-49.

Zhu Jun is engaged in the research of new energy wind power generation and sensorless control theory. Currently, the author has presided over more than 10 provincial projects; published more than 40 academic papers, including more than 20 SCI/EI; application for more than 10 patents. The current projects are: key scientific and technological breakthrough projects in Henan Province: the research of low-speed direct-drive magnetic levitation axial flux wind turbine is conducted from September 2017 to September 2019 with its project number

Cao Di is a graduate student, engaged in the design of the magnetic levitation new energy wind generator.