Choice of Pole-Slot Number Combination for PM Generator Direct-Driven by Wind Turbine

Yue Zhang, and Fengxiang Wang

***Abstract*--The permanent magnet (PM) generator direct-driven by wind turbine has the advantages of high efficiency, simple structure and reliable operation, and the features of low speed, multi-pole and large size. How to utilize sufficiently the structural dimension, improve the performance and reduce the cost of the machine by proper choice of the pole number and stator slot number is an important problem to be solved for the design of a direct-driven PM wind generator. In this paper, the performances of a 1.5MW direct-driven PM wind generator for different pole-slot number combinations with the same machine size are studied based on the circuit-field coupled finite element analysis. The comparative study shows that the choice of pole number and slot number has significant effect on the performance and the better performance can be obtained by proper choice of the pole-slot number combination.**

***Index Terms*-- direct-driven permanent magnet wind generator, circuit-field coupled finite element analysis, cogging torque, combination of pole number with slot number**

I. INTRODUCTION

WIND energy, as a clear and reproducible energy source, has been more and more concerned, especially in the application area of wind power generation. A large wind turbine has large size and low rotating speed. In order to reduce the size of generator, the wind power generation system normally uses gearbox to increase speed of wind turbine. However, the multi-stage mechanical transmission of the gearbox not only increases noise and power loss but also needs maintenance which will reduce the reliability of the wind power system [1-3]. Gearless and brushless are the development directions of the wind power generation technology.

The permanent magnet (PM) generator direct-driven by wind turbine has the advantages of high efficiency, simple structure and reliable operation, and the features of low speed, multi-pole and large size. How to utilize sufficiently the structural dimension, improve the performance and reduce the cost of the machine by proper choice of the pole number and stator slot number is an important problem to be solved for the design of a direct-driven PM wind generator [4-6]. In this paper, the performances of a 1.5MW direct-driven PM wind generator for different pole-slot number combinations with the same machine size are studied based on the circuit-field coupled finite element analysis.

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II. DESIGN FEATURE OF DIRECT-DRIVEN PM WIND GENERATOR

The schematic diagram of a direct-driven wind power generation system using PM generator is as shown in Fig. 1. The wind turbine with variable pitch drives directly the rotor of PM generator without using the speedup gearbox. Because the amplitude and frequency of the output voltage of the PM generator vary with the machine speed, the output power with variable frequency and variable voltage should be converted into constant frequency and constant voltage power through the AC/DC/ AC converter.

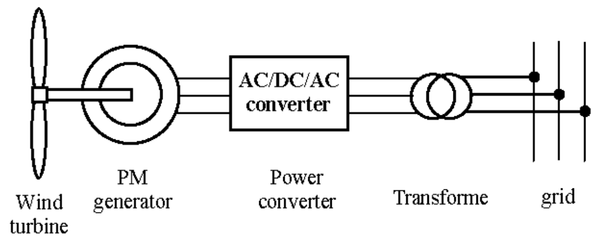


Fig. 1. Schematic diagram of PM generator Direct-driven by wind turbine.

The rotating speed of wind turbine is very low for large wind power generation systems due to the large diameter of the wind turbine. For example, the rated speed is only about 18-20 rpm for a direct-driven wind generator with rated power of 1.5MW. The generator has large size due to low speed. In order to inctrease the induced voltage in the stator windings, the generator has large diameter. The outer diameter of the stator for a 1.5 MW direct-driven wind generator may exceed 4m. The frequency of output voltage of the generator is proportinal to the product of pole pair and rotor speed. It seems that the choice of pole number can be flexible since the variable speed constant frequency control is realized by the AC/DC/AC power converter not by the generator. However, the voltage frequency of generator can not be too low. In order to get the reasonable frequency, a large numer of poles will be needed for the low speed direct-driven wind generator. The numbers of pole and stator slot have imortant effect on the electromagnetic properties of the direct-driven wind PM generator, especially on the cogging torque, which is one of the key techniques for the PM generator design.

III. Effect of Pole-Slot Number Combination on Positioning Torque at No Load

The positioning torque is a pulsating torque which is produced by the action of permanent magnets of the rotor on the teeth and slots of the stator, and dependent upon the rotor position related to the stator. The large positioning torque will make the wind generator difficult to start at no load. Therefore, it is desirable to make the positioning torque as small as possible in order to increase the utilization of wind energy.

The effect of pole number and slot number on the positioning torque was investigated for a 3-phase 1.5MW direct-driven wind PM generator. Table I shows the positioning torque for different combinations of pole number and stator slot number under the same machine size and operation conditions. It can be seen that the difference of positioning torque for different pole-slot number combinations is quite large. For instance, the positioning torque for the combination of 120-pole and 432-slot is about 330 times of that for the 120-pole and 378-slot combination. The feature of the pole-slot number combination can be depicted by the slot number per pole and per phase as follows

$$q = \frac{Z}{2pm} = b\frac{c}{d} \tag{1}$$

where Z, $2p$ and m are the numbers of stator slot, pole and phase respectively, d is the denominator of q. The values of d for different pole-slot number combinations are also given in the Table I.

TABLE I
POSITIONING TORQUE FOR DIFFERENT POLE-SLOT NUMBER COMBINATIONS

Number of poles	Number of slots	d in (1)	Positioning torque (Nm)
120	378	20	8
120	396	10	80
120	432	5	2647
144	378	8	38
144	396	4	9825
156	378	26	30
156	396	13	31
156	432	13	26
156	450	26	25

Fig. 2 shows the effect of the denominator d of the slot number per pole and per phase q on the positioning torque at no load. From the comparison of d for different pole-slot combinations it can be observed that the positioning torque decreases along with the increment of d. The difference of positioning torques for different pole-slot number combinations can be more than thousands times. Therefore, the choice of pole and slot numbers should be careful for the design of direct-driven wind PM generator.

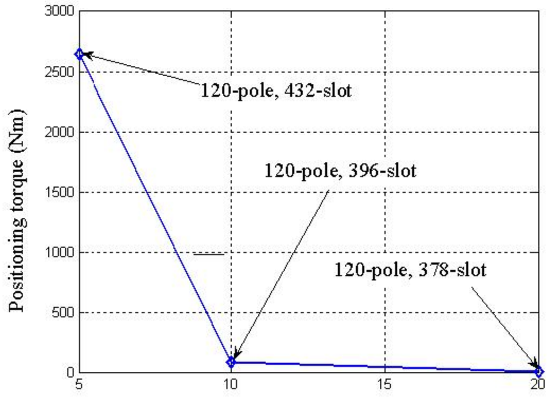


Fig. 2. Relationship between positioning torque and d for same pole number and different slot numbers.

IV. Effect of Pole-Slot Number Combinations on Load Performances

The electromagnetic torque, output power, losses and efficiency under rated speed for different pole-slot number combinations have been comparatively studied by the dynamic finite element analysis based on the coupled circuit-field model for the same machine size and operation condition.

Fig. 3 shows the effect of the denominator d of the slot number per pole and per phase q on the electromagnetic torque at full load. From the comparison of Fig. 2 with Fig. 3 it can be seen that the effect of pole-slot number combinations on the cogging torque at load condition is not as large as that on the positioning torque at no load.

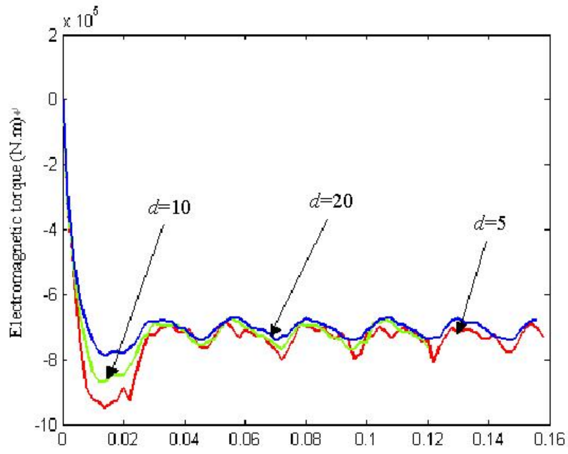


Fig. 3. Relationship between electromagnetic torque and d at full load.

Fig. 4 and Fig. 5 show respectively the effect of the pole-slot number combinations on the output power of the PM generator for the same pole number with different slot numbers, and for the same slot number with different pole numbers at full load. It can be observed from Fig. 4 and Fig. 5 that the average and fluctuate of the output power increase along with the decrement of the pole number for the same slot number. The average and fluctuate of the output power increase also along with the increment of the slot number for the same pole number.

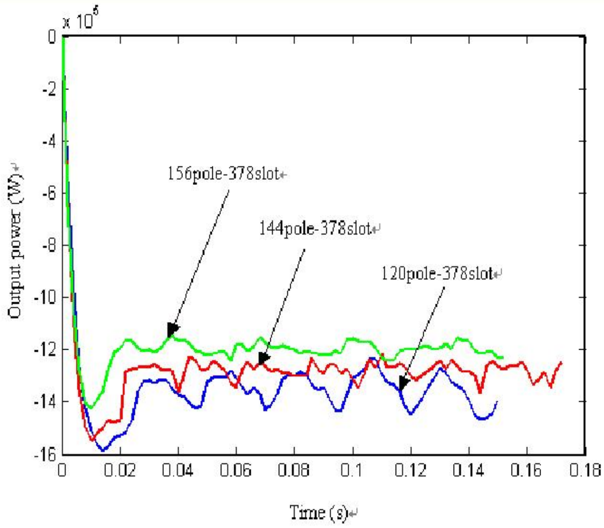


Fig. 4. Effect of pole numbers on output power for same slot number at full load.

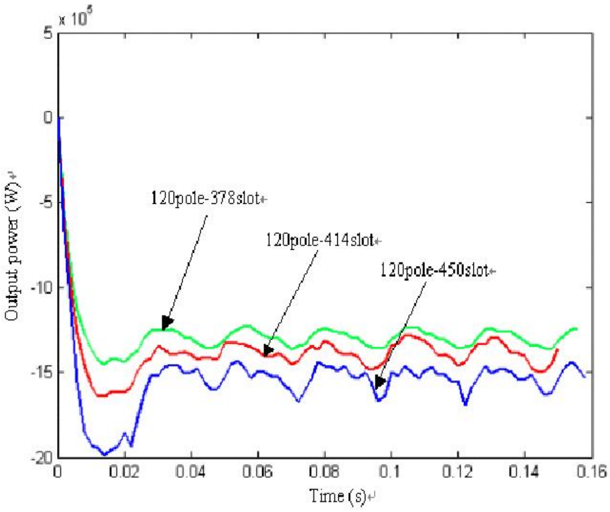
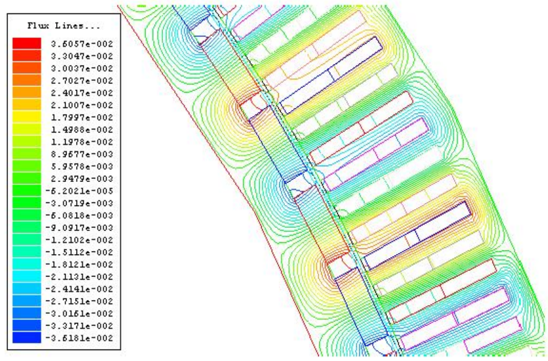


Fig. 5. Effect of slot numbers on output power for the same pole number at full load.

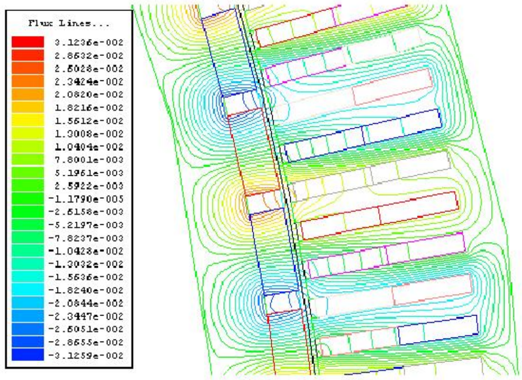
Fig. 6 shows the magnetic field distributions of the PM generator at load condition for three different pole-slot number combinations: 120-pole and 378-slot, 144-pole and 378-slot, 156-pole and 378-slot. From the comparison it can be seen that for the same slot number, when the pole number increases, the stator teeth per pole decreases and the demagnetization effect of the stator winding current on the magnetic field produced by the PM increases which will reduce the output voltage of the generator. That is the reason why the output power decreases along with the increment of the pole number for the same slot number.

V. Effect of Pole-Arc Coefficient on Performances

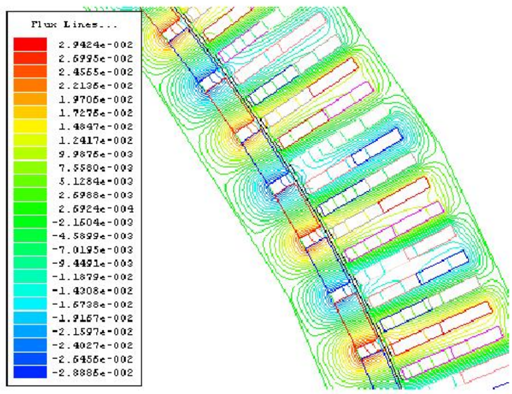
Besides the pole-slot number combination, the pole-arc coefficient which is defined as the ratio of the width of the



a) 120-pole and 378-slot



c) 144-pole and 378-slot



b) 156-pole and 378-slot

Fig. 6. Magnetic flux line distributions for the same slot number and different pole numbers.

permanent magnet to the pole pitch affects the performances of the PM generator.

Fig. 7 shows the effects of pole-arc coefficient on the cogging torque for 120-pole and 378-slot. It can be seen that the cogging torque has the minimum value when the pole-arc coefficient is around 0.45. When the pole-arc coefficient is above 0.5, the cogging torque will increase along with the increment of the pole-arc coefficient. It is apparent that the pole-arc coefficient cannot be chosen less than 0.5 which is too small and not beneficial to the output power.

Fig. 8 shows the effect of pole-arc coefficient on the output power for the 120-pole and 378-slot PM generator. It can be seen that the output power of the generator will increase along with the increment of the pole-arc coefficient for a fixed pole-slot number combination because the larger width of magnet will provide more magnetic flux.

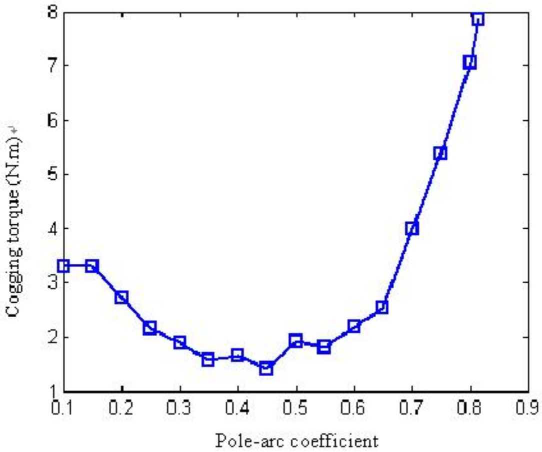


Fig. 7. Relationship between cogging torque and pole-arc coefficient.

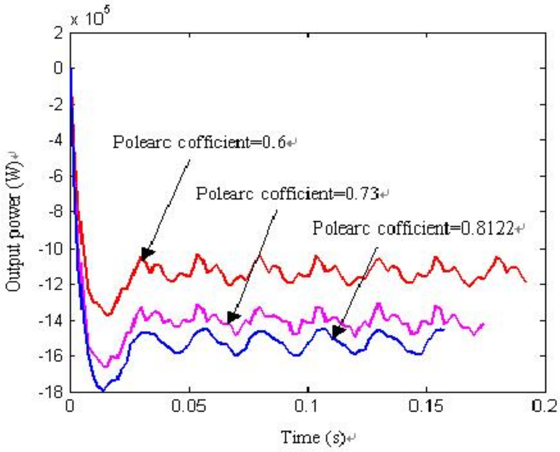


Fig. 8. Effect of pole-arc coefficient on output power for 120-pole and 378-slot PM generator.

Combing the effects of pole-arc coefficient on the cogging torque and output power as shown in Fig.7 and Fig. 8, the larger pole-arc coefficient is preferable which can provide more output power. Because the cogging torque for the pole-slot number combination of 120-pole and 378-slot is so small within the whole variation range of pole-arc coefficient, the effect of the pole-arc coefficient on the cogging torque can be negligible. For the 120-pole and 378-slot PM generator, the pole-arc coefficient of 0.8 is a better choice.

VI. Conclusions

Based on comparative study on different pole-slot number combinations and pole-arc coefficients for the 1.5MW direct-driven PM wind generator, the following conclusions can be deduced:

1) The pole-slot number combination has significant effect on the positioning torque at no load. Choosing the fractional slot number per pole and per phase is an effective approach to reduce the positioning torque. The positioning torque reduces along with the increment of denominator of the fractional slot number per pole and per phase. However, the effect of pole-slot number combinations on the cogging torque at load condition is not as large as that at no load.
2) The average and fluctuate of the output power increase along with the decrement of the pole number for the same slot number. The average and fluctuate of the output power increase also along with the increment of the slot number for the same pole number.
3) The output power and cogging torque increase along with the increment of the pole-arc coefficient for a fixed pole-slot number combination.

VII. References

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VIII. Biographies

Yue Zhang was born in Liaoning Province, China in 1965, received the B.S. degree from Benxi University, Benxi, China in 1987, and the M.S. degree from Northeast University, Shenyang, China in 1992 respectively. He is an associate professor of Liaoning Institute of Science and Technology, Benxi, China. He is currently working towards the PhD degree in the School of Electrical Engineering, Shenyang University of Technology, Shenyang, China. His interests include doubly-fed brushless machine and wind power generation system.

Fengxiang Wang was born in Shandong Province, China in 1938, received the B.S. and M.S. degrees in electrical engineering from Tsinghua University, Beijing, China, in 1962 and 1966 respectively. Since 1966, he has been working at the Shenyang University of Technology, Shenyang, China, where he is currently a Professor. From 1981 to 1983, he was a Visiting Scholar at the University of Wisconsin-Madison, Madison, USA. From 1992 to 1993, he was a Senior Visiting Scholar at the University of Toronto, Toronto, Canada. As a Visiting Professor from 1996 to 1997, he worked in the Department of Electrical Engineering at the Ohio-State University, Columbus, USA. His main research interests encompass the electrical machines, drives and power conversion systems.