Analysis of a direct-drive permanent magnet synchronous generator with novel toroidal winding

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Abstract
Direct-drive permanent magnet synchronous generators (DDPMSGs) are gaining more and more attention in the field of wind power because of the advantages of simple structure, high efficiency and high reliability. However, due to the extremely low rotational speed, large volume and heavy weight of DDPMSGs, it poses serious challenges for transportation and installation, which limits its application. Therefore, a DDPMSG with novel toroidal windings (NTW) is proposed to improve power density in this paper. Unlike regular windings, each coil of the NTWs is wound onto the stator yoke in the same direction. The special configuration enables the generator to have higher winding coefficient, so that the DDPMSG with NTWs (NTW-DDPMSG) can achieve higher power density than traditional fractional slot concentrated windings (FCW). The proposed topology and operating principles are described in detail. To verify the merits of the proposed NTW-DDPMSG, the electromagnetic parameters of two external rotor surface-mounted DDPMSGs equipped with NTW and FCW respectively are designed. The characteristics of air-gap magnetic field, no-load electromotive force, output power, loss and efficiency are analysed on the conditions of different loads and speeds. Comparison results show that the proposed NTW-DDPMSG has higher power density than FCW-DDPMSG.

1 | INTRODUCTION

Nowadays, direct-drive permanent magnet synchronous generators (DDPMSGs) are gaining more and more attention in the field of wind power, owing to the merits of simple structure, high efficiency and high reliability [1–3]. However, low-speed generators directly coupled to wind turbines have sufficiently high number of poles on the rotor, which causes problems of large volume and heavy weight. These problems pose serious challenges for transportation and installation, which limits its application [4–6]. Therefore, increasing power density to reduce volume is a key research direction for DDPMSGs.

Generally, the high power density DDPMSGs studied by the majority of scholars can be divided into radial-flux PMSGs, axial-flux PMSGs and transverse-flux PMSGs, based on the direction of flux penetration. The axial-flux PMSG is suitable for low-speed, direct-drive wind energy conversion systems because of their compactness and high power density [7–9]. However, it has the disadvantages of axial magnetic pull force, complicated processing technology and high manufacturing cost. The transverse-flux PMSG is also a promising candidate to get high power density at low speed [10, 11], but its weaknesses, such as complex structure, large magnetic leakage and low power factor, limit its application. Therefore, radial-flux generator is currently the most widely used wind generator type because of the advantages of simple structure and mature manufacturing technology [12]. There are many ways to increase the power density, such as multi-stator multi-rotor structure, adopting hybrid excitation, optimisation design and suitable winding configuration. In [13, 14], a dual-stator PMSG is proposed to reduce the volume and increase the torque density. But the support structure of the generator is complicated by the use of multi-stator or multi-rotor. A hybrid-excited permanent magnet generator is proposed in [15], which adopts two sets of permanent magnets (PMs) and a set of field windings. But the efficiency of the hybrid excited generator is reduced and the amount of PM is increased. In addition, many researchers focus on optimisation design of machines to improve power

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density. In [16, 17], the motor performance was improved by optimising the motor topology. A permanent magnet synchronous motor with V-shaped PMs is proposed in [18] for high power density. Furthermore, the winding configuration has a great influence on the power density of the generator. The performances of DDPMSG with different windings are studied in [19]. Fractional-slot concentrated windings (FCW) has the merits of high power density, high efficiency, short end turns and high slot fill factor [20, 21], which is often used in DDPMSGs.

In [22, 23], a DDPMSG with toroidal windings is proposed and compared with DDPMSG with FCW over a wide power range. But at the small and micropower levels, the performance of the DDPMSG with toroidal winding is not good compared with DDPMSG with FCW.

In this paper, a DDPMSG with novel toroidal winding (NTW-DDPMSG) is proposed to further improve the power...
FIGURE 5 Vector diagram of induced electromotive force (EMF) of simplified 4-pole 6-slot generators (a) novel toroidal windings-direct drive permanent magnet synchronous generators (NTW-DDPMSG) and (b) fractional-slot concentrated windings-permanent magnet synchronous generators (FCW-PMSG) (120° is electrical angle)

TABLE 1 Key specifications and dimensions of the two PMSGs

| Items (Units)          | NTW-DDPMSG | FCW-DDPMSG |
|-----------------------|------------|------------|
| Rated speed (rpm)     | 375        | 375        |
| Number of phases      | 3          | 3          |
| Number of PM poles    | 16         | 16         |
| Number of stator slots| 24         | 24         |
| Slot per pole per phase (SPP) | 0.5   | 0.5        |
| PM thickness (mm)     | 3          | 3          |
| Pole arc coefficient  | 0.75       | 0.75       |
| Rotor outer diameter (mm) | 216    | 216        |
| Rotor inner diameter (mm) | 176    | 176        |
| Stator outer diameter (mm) | 168    | 168        |
| Stator inner diameter (mm) | 100    | 100        |
| Air-gap length (mm)   | 1          | 1          |
| Axial length (mm)     | 68         | 68         |
| PM type               | N38SH      | N38SH      |
| Steel                 | DR510      | DR510      |
| Number of conductors per phase | 880   | 880        |
| Armature resistance per phase (Ω) | 7.4   | 3.7        |

FIGURE 6 Magnetic field of novel toroidal windings-direct drive permanent magnet synchronous generators (NTW-DDPMSG) and fractional-slot concentrated windings-direct drive permanent magnet synchronous generators (FCW-DDPMSG) at no-load operation

density. The proposed generator adopts the outer rotor and mounted PM for the advantages of long air gap, easy layout of PM and simple structure. This paper is organised as follows. In Section 2, the topology structure and operating principle of the proposed NTW-DDPMSG are described in detail. Then, the electromagnetic parameters of NTW-DDPMSG and DDPMSG with FCW (FCW-DDPMSG) are designed with some criteria in Section 3, such as the same structural size and effective volume. In Section 4, the electromagnetic performance of the two generators is analysed and compared, including air-gap magnetic density, output voltage and efficiency at different speed and load. Finally, Section 5 summarises this paper briefly.

2 | TOPOLOGY AND OPERATING PRINCIPLE OF NTW-PMSG

2.1 | Structure topology

The configuration of the proposed NTW-DDPMSG is shown in Figure 1, which adopts the outer rotor and surface-mounted PM. The outer side of the stator core is slotted to have a smaller air gap than slot-less structure, and the stator employs the NTWs. The key of NTWs is that each coil is wound onto the stator yoke in the same direction [24].

A simplified schematic view of a three-phase, two-pole machine with two coils per phase is shown in Figure 2, where the stator slot is omitted. The ingoing ends of all the coils are Y-connected as shown in Figure 2b. It can be found that the directions of all the coils are the same.

Figure 3 shows the topology of the two 24-slots 16-poles PMSGs with NTWs and FCWs. The \( q \) of the two generators is equal to 0.5. The dot and cross indicate the reference directions of the coils. It can be found that the NTWs’ slot conductors facing the PMs have the same direction, which is very different from the traditional windings.

2.2 | Operating principle

As the rotor rotates, the flux linkages of the armature winding change with time. In Figure 4, the no-load induced electromotive force (EMF) of the NTW-PMSG is analysed in detail, for example \( q = 1 \). The effective value of induced EMF of one conductor in the A-phase stator is:

\[
E_{A1} = \sqrt{2NB\tau f} \tag{1}
\]

where \( B \) is the fundamental amplitude of the air-gap magnetic flux density (T), \( N \) is number of turns, \( \tau \) is the polar pitch (m), \( f \) is the effective axial length of the stator (m) and \( f \) is the frequency (Hz).

A-phase induction EMF \( E_A \) is:

\[
E_A = \sqrt{2k_q pNB\tau f} \tag{2}
\]

\[
k_q = \sin \left( q\alpha \right) / \sin \frac{\alpha}{2} \tag{3}
\]
where \( q \) is the number of slots per pole per phase, \( p \) is the number of pole pairs, \( \alpha \) is the electrical angle between adjacent slots and \( k_q \) is the winding coefficient.

Figure 4 shows the vector diagram of induced EMF of simplified 4-pole 6-slot NTW-DDPMSG and FCW-DDPMSG. According to the vector diagram in Figure 5, the winding coefficients of NTW-DDPMSG and FCW-DDPMSG can be calculated as 1 and 0.866, respectively. Therefore, no-load induced EMF of NTW-DDPMSG is 15.47% higher than that of FCW-DDPMSG, when the other structural parameters of the generators are the same.

3 | GENERATOR DESIGN

To verify the performance of NTW-DDPMSG, two 24-slot 16-pole generators with NTWs and FCWs respectively are designed. The design needs to meet the following criteria to ensure fair comparisons:

1. NTW-DDPMSG and FCW-DDPMSG have the same effective axial length, outer diameter of the rotor, inner diameter of the stator and air-gap length. Therefore, the effective volume of the two generators are the same.
2. The amounts of PMs of the two generators are the same.
3. The number of conductors in one slot of the two generators is the same.
4. The two generators have the same rated speed.

Based on the above criteria, the FEA models of NTW-DDPMSG and FCW-DDPMSG have been built, and their key specifications and dimensions are shown in Table 1.

4 | ELECTROMAGNETIC PERFORMANCE ANALYSIS

According to the generator parameters in Table 1, the finite element models of the two generators are established and analysed. The simulation step size of the finite element simulation is 0.2 ms.

4.1 | No-load characteristics

Figure 6 shows the magnetic flux and magnetic density distribution of NTW-DDPMSG and FCW-DDPMSG in no-load conditions. It can be found that the no-load magnetic fields of the two generators are almost identical. It is because the structures of the rotor and stator core of the two generators are exactly the same. In addition, the maximum magnetic density of the stator teeth is 1.79 T and the maximum air-gap magnetic density is 0.89 T.

Figure 7a shows the air gap magnetic density of NTW-DDPMSG and FCW-DDPMSG in no-load conditions. Due to the same no-load magnetic fields of the two generators, the harmonic decompositions of the two generators are the same as shown in the Figure 7b, and the fundamental amplitudes of the air-gap magnetic flux density for both are 1.02 T.

The no-load back electromotive force (back-EMF) waveforms and corresponding spectra of NTW-DDPMSG and FCW-DDPMSG at a rated speed of 375 r/min are shown in Figure 8. It can be seen that the magnitude of no-load back-EMF of NTW-DDPMSG is higher than that of FCW-DDPMSG. The fundamental amplitudes of the no-load back-EMF of NTW-DDPMSG and FCW-DDPMSG are 191.53 and 165.86 V, respectively. And the fundamental amplitude of NTW-DDPMSG is 15.47% higher than that of FCW-DDPMSG, which is consistent with the previous theoretical analysis. The THD$_{EMF}$ of NTW-DDPMSG and FCW-DDPMSG are 6.12% and 15.59%, respectively. It also can be found that NTW-DDPMSG has larger harmonics than FCW-DDPMSG, especially the 3rd and 9th harmonics. Due to the employing of symmetrical three-phase windings, when connected to an external circuit, the 3rd and 9th harmonics can be eliminated.

4.2 | Load characteristics

Figure 9 shows the magnetic flux and magnetic density distribution of NTW-DDPMSG and FCW-DDPMSG with a resistive load of 35 Ω. It can be found that the maximum magnetic density of the stator teeth of NTW-DDPMSG and FCW-DDPMSG are 1.73 and 1.70 T, respectively.

Figure 10 shows the air gap magnetic density and harmonic decomposition of NTW-DDPMSG and FCW-DDPMSG at a resistive load of 35 Ω. It can be seen that the air-gap magnetic density of NTW-DDPMSG is higher than that of FCW-DDPMSG. The fundamental amplitudes of the air-gap magnetic flux density of NTW-DDPMSG and FCW-DDPMSG are 1.02 T and 0.99 T, respectively. Although the no-load air gap magnetic density of the two generators is exactly the same, the fundamental amplitudes of the load air-gap magnetic flux density of NTW-DDPMSG is 3% higher than that of FCW-DDPMSG.

Figure 11 shows the output voltage waveform and harmonic analysis diagram of the NTW-DDPMSG and FCW-DDPMSG with a resistive load of 35 Ω. It can be found that the output voltage of NTW-DDPMSG is higher than that of FCW-DDPMSG in Figure 11a. It can be seen that the fundamental amplitudes of the output voltage of NTW-DDPMSG and FCW-DDPMSG are 154.7 and 144.2 V, respectively. The output voltage of NTW-DDPMSG is 7.3% higher than that of FCW-DDPMSG. However, the sinusoidal characteristic of the output voltage waveform of both generators are not good. The THD$_{load}$ of NTW-DDPMSG and FCW-DDPMSG are 6.6% and 5.66%, respectively. It can be found that the THD$_{load}$ of NTW-DDPMSG is lower than the THD$_{EMF}$. This is because the 3rd and 9th harmonics of voltage are eliminated. Furthermore, the output power of NTW-DDPMSG and FCW-DDPMSG are 1026 W and 892 W, respectively. Because the effective volume of the two generators is the same, the power density of NTW-DDPMSG is 15.1% higher than that of FCW-DDPMSG.

The loss and efficiency $\eta$ of NTW-DDPMSG and FCW-DDPMSG are calculated and compared while ignoring mechanical and stray losses, as shown in Table 2. It can be found that the copper loss of NTW-DDPMSG is relatively large. This is because in a single-rotor generator, the number of windings of NTW-DDPMSG is twice that of FCW-DDPMSG. This ultimately resulted in the resistance of the NTW-DDPMSG...
armature windings being twice that of FCW-DDPMSG. Furthermore, the efficiency of NTW-DDPMSG is 7.2% lower than that of FCW-DDPMSG.

**TABLE 2** Loss and efficiency with rated load (35 Ω)

| Items          | \( P_N \) (W) | \( P_{Cu} \) (W) | \( P_{Fe} \) (W) | \( \eta \) (%) |
|----------------|---------------|-----------------|-----------------|----------------|
| NTW-DDPMSG     | 1026          | 216.9           | 27.8            | 80.74          |
| FCW-DDPMSG     | 892           | 94.3            | 28.0            | 87.94          |

Abbreviations: NTW-DDPMSG, novel toroidal windings-direct drive permanent magnet synchronous generators; FCW-DDPMSG, fractional-slot concentrated windings-direct drive permanent magnet synchronous generators

Figure 12 shows the output power, armature current and efficiency of NTW-DDPMSG and FCW-DDPMSG versus the resistance of load at a constant speed of 375 r/min. Figure 13 shows the output power, armature current and efficiency of NTW-DDPMSG and FCW-DDPMSG versus speed with a resistive load of 35 Ω. It can be found that the power of NTW-DDPMSG is higher than that of FCW-DDPMSG with different loads or at different speeds. But the efficiency of NTW-DDPMSG is lower than that of FCW-DDPMSG due to the armature resistance.

Figure 14 shows the output voltage and current waveforms and harmonic analysis diagrams of the NTW-DDPMSG and
FIGURE 12 Performances of novel toroidal windings-direct drive permanent magnet synchronous generators (NTW-DDPMSG) and fractional-slot concentrated windings-direct drive permanent magnet synchronous generators (FCW-DDPMSG) with different loads: (a) output power, (b) armature current and (c) efficiency.

It can be found that the output voltage and current of NTW-DDPMSG are higher than those of FCW-DDPMSG. It can be seen that the fundamental amplitudes of the output voltage of NTW-DDPMSG and FCW-DDPMSG are 172.8 and 148.8 V, respectively. The output voltage of NTW-DDPMSG is 16.1% higher than that of FCW-DDPMSG. The THD of output voltage of NTW-DDPMSG and FCW-DDPMSG are 6.12% and 6.05%, respectively. The THD of current of NTW-DDPMSG and FCW-DDPMSG are both 0.82%. Furthermore, the output power of NTW-DDPMSG and FCW-DDPMSG are 464 and 337 W, respectively. The power density of NTW-DDPMSG is 34.7% higher than that of FCW-DDPMSG.

The loss and efficiency $\eta$ of NTW-DDPMSG and FCW-DDPMSG with inductive load are calculated and compared while ignoring mechanical and stray losses, as shown in Table 3. It can be found that the efficiency of NTW-DDPMSG is 1.99% lower than that of FCW-DDPMSG. The efficiency of NTW-DDPMSG with inductive load is higher than NTW-DDPMSG with pure resistor.

FCW-DDPMSG with inductive load ($R = 35 \, \Omega$, $L = 0.264 \, H$).

FIGURE 13 Performances of novel toroidal windings-direct drive permanent magnet synchronous generators (NTW-DDPMSG) and fractional-slot concentrated windings-direct drive permanent magnet synchronous generators (FCW-DDPMSG) at different speeds: (a) output power, (b) armature current and (c) efficiency.
5 | CONCLUSION

This paper proposes an NTW-DDPMSG with high power density. The topology of NTW-DDPMSG is introduced, and its operating principle is analysed. NTW-DDPMSG and FCW-DDPMSG are designed under the premise of the same speed, effective volume and total amount of permanent magnet material. The no-load and load characteristics of the proposed NTW-PMSG are analysed and compared with FCW-DDPMSG. The comparison results are concluded as follows:

1. The winding coefficients of NTW-DDPMSG is 15.47% higher than that of FCW-DDPMSG.
2. The no-load EMF of NTW-DDPMSG is 15.47% higher than that of FCW-DDPMSG.
3. The power density of NTW-DDPMSG is 15.1% higher than that of FCW-DDPMSG with resistor load.
4. The power density of NTW-DDPMSG is 34.7% higher than that of FCW-DDPMSG with resistor-inductive load.
5. The efficiency of NTW-DDPMSG is lower than that of FCW-DDPMSG due to the larger armature-winding resistance.

The proposed generator has the advantages of high winding coefficient and power density, but its armature-winding resistance is high, which leads to high copper losses and low efficiency. Therefore, reducing copper loss is a future research.

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REFERENCES

1. Tiegna, H., et al.: Overview of high power wind turbine generators. In: International Conference on Renewable Energy Research and Applications (ICRERA 2012), Nagasaki, Japan, 11–14 November 2012
2. Schreiber, A., et al.: Comparative life cycle assessment of electricity generation by different wind turbine types. J. Cleaner Prod. 233, 561–572 (2019)
3. Polinder, H., et al.: Comparison of direct-drive and geared generator concepts for wind turbines. IEEE Trans. Energy Convers. 21(3), 725–733 (2006)
4. Hossain, M.M., Ali, M.H.: Future research directions for the wind turbine generator system. Renewable Sustainable Energy Rev. 49, 481–489 (2015)
5. Semken, R.S., et al.: Direct-drive permanent magnet generators for high-power wind turbines: Benefits and limiting factors. IET Renewable Power Gener. 6(1), 1–8 (2012)
6. Orlòa, S., et al.: Active zone of permanent magnet synchronous machine with a non-overlapping concentrated winding. Latv. J. Phys. Tech. Sci. 55(4), 3–12 (2018)
7. Wu, D.Q., et al.: Axial-flux permanent-magnet synchronous generator with coreless armature and non-integral coil-pole ratio. IET Renewable Power Gener. 13(2), 245–252 (2019)
8. Sabioni, C.L., et al.: Robust design of an axial-flux permanent magnet synchronous generator based on many-objective optimization approach. IEEE Trans. Magn. 54(3), (2018) https://doi.org/10.1109/TMAG.2017.2766229
9. Eldoromi, M.: Improved design of axial flux permanent magnet generator for small-scale wind turbine. Turk. J. Electr. Eng Comput. Sci. 26(6), 3084–3099 (2018)
10. Wan, Z.: Design of a stator permanent magnet transverse flux machine for direct-drive application. Dissertation, (Ph.D. thesis), North Carolina State University (2018)
11. Hasan, I.: Modeling and analysis of high torque density transverse flux machines for direct-drive applications. Dissertation, (Ph.D. thesis), University of Akron (2017)
12. Li, H., Chen, Z.: Overview of different wind generator systems and their comparisons. IET Renewable Power Gener. 2(2), 123–138 (2008)
13. Yousefian, H.A., Kelk, H.M.: A unique optimized double-stator permanent-magnet synchronous generator in high-power wind plants. Energy 143, 973–979 (2018)
14. Gul, W., et al.: Optimal design of a 5mw double-stator single-rotor PMSG for offshore direct drive wind turbines. IEEE Trans. Ind. Appl. 56(1) 216–225 (2019)
15. Wang, Q.S., et al.: Design optimization of a novel scale-down hybrid-excited dual permanent magnet generator for direct-drive wind power application. IEEE Trans. Magn. 54(3), (2018) https://doi.org/10.1109/TMAG.2017.2758021
16. Sun, X., et al.: Analysis and design optimization of a permanent magnet synchronous motor for a campus patrol electric vehicle. IEEE Trans. Veh. Technol. 68(11), 10535–10544 (2019)
17. Sindhya, K., et al.: Design of a permanent magnet synchronous generator using interactive multi-objective optimization. IEEE Trans. Ind. Electron. 64(12), 9776–9783 (2017)
18. Sun, X., et al.: Performance analysis of suspension force and torque in an IBPMSM with V-shaped PMs for flywheel batteries. IEEE Trans. Magn. 54(11), 1–4 (2018) https://doi.org/10.1109/TMAG.2018.2827103
19. Jia, S., et al.: Study of direct-drive permanent-magnet synchronous generators with solid rotor back iron and different windings. IEEE Trans. Ind. Appl. 52(2), 1369–1379 (2016)
20. Tanguyu, J.K.: On modeling and design of fractional-slot concentrated-winding interior permanent magnet machines. Dissertation, (Ph.D. thesis), University of Wisconsin–Madison (2011)
21. El-Refaie, A.M.: Fractional-slot concentrated-windings synchronous permanent magnet machines: Opportunities and challenges. IEEE Trans. Ind. Electron. 57(1), 107–121 (2010)
22. Potgieter, J.H.J., Kamper, M.J.: Double PM-rotor, toothed, toroidal-winding wind generator: A comparison with conventional winding direct-drive PM wind generators over a wide power range. IEEE Trans. Ind. Appl. 52(4), 2881–2891 (2016)
23. Potgieter, J.H.J., Kamper, M.J.: Design optimization of directly grid-connected PM machines for wind energy applications. IEEE Trans. Ind. Appl. 51(4), 2949–2958 (2015)
24. Gao, C.X., et al.: A novel direct-drive permanent magnet synchronous motor with toroidal windings. Energies 12(3), 432 (2019) https://doi.org/10.3390/en12030432

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