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Magnetic gear generator for wind energy

***Abstract**. For high power generation of future offshore wind turbine application, size and cost were the big challenge . To overcome these problems, this paper presents a new topology approach for wind power generation without mechanical gear. Using magnetic gear coupled mechanically and magnetically with permanent magnet synchronous generator, even under low wind conditions often found inland, and without mechanical gear, the high speed can be reached with this topology. Computer simulation results are given to verify the validity of the proposed machine.*

***Streszczenie.** Generatory używane w morskich turbinach powinny być tanie i niezbyt duże. W artykule zaproponowano nową konstrukcję takiego generatora bez mechanicznej przekładni. Wykorzystano sprzężenie magnetyczne i uzyskano generator pracujący sprawnie nawet przy słabych wiatrach. (**Generator z przekładnią magnetyczną do elektrowni wiatrowych**)*

Keywords: Magnetic gear, permanent magnet synchronous generator, vector control, wind turbine.
Słowa kluczowe: elektrownia wiatrowa, turbina, generator, przekładnia.

Introduction

Due to the high wind speed and more space in the deeper sea, offshore wind energy has become significantly more attractive. Within the last year, the installation of offshore wind turbine have reached 7 MW, in the near future would reach 20 MW. In the other hand, this scaling up is full of serious challenges to introduce novel concepts in the blade design, nacelle weight reduction, new control strategies, huge support structures and the maintenance cost of offshore wind turbine, is very expensive and impossible to do under some weather conditions [1]. Moreover, the big mechanical gearbox, the lubrication system lead to less working space and make it complicated to service the components and the gearbox is usually the most problematic part of a turbine [2].

To reduce the cost and the weight of the nacelle, mechanical gearbox is replaced by magnetic gear generator, which is magnetic gear that employs rare-earth magnets, coupled with conventional permanent magnet synchronous generator [3]. That means reaching high-speed without usual mechanical gearbox, as well allow more space in nacelle to work safely and generate electricity even under low wind conditions often found inland.

Magnetic gears offer several advantages, such as lubricant-free operation, reduced maintenance costs, quiet operation between the input and output shafts, physical isolation between input and output shafts, and inherent overload protection [4]. The topology and a high performance of magnetic has been presented in [3], simulation and experimental studies have shown, that this gear has a transmitted torque density capability comparable with three-stage helical gearboxes, viz. 50-150 KNm/m^3 [4]. Several magnetic gear topology with combined structure have been simulated and constructed [5, 6, 7, 8], which has shown that the magnetic gear has a better efficiency than mechanical gear. It is concluded that may help to initiate a shift from mechanical gears to magnetic gears.

This paper illustrates a different approach to generate electricity, using a proposed magnetic gear generator to a variable speed wind turbine. A description of the system will be presented and it will be described how to collect maximum power to be injected to the grid. Simulation results will be presented and show the performance of the 2MW magnetic gear generator in the wind system.

Principle of operation

The topology of the proposed coupling magnetic gear and permanent magnet synchronous generator is illustrated in Fig. 1. Two permanent magnetic rotors and between the two rotors there are a ferromagnetic pole-pieces rotor, one of the two permanent magnet rotors held stationary. The numbers n_l = 166, p_s = 168 and p_h = 5, present the pole-pieces low-speed ferromagnetic rotor (input rotor), pole-pairs stationary permanent magnet, and pole-poles high-speed permanent magnetic rotor (output rotor) respectively.

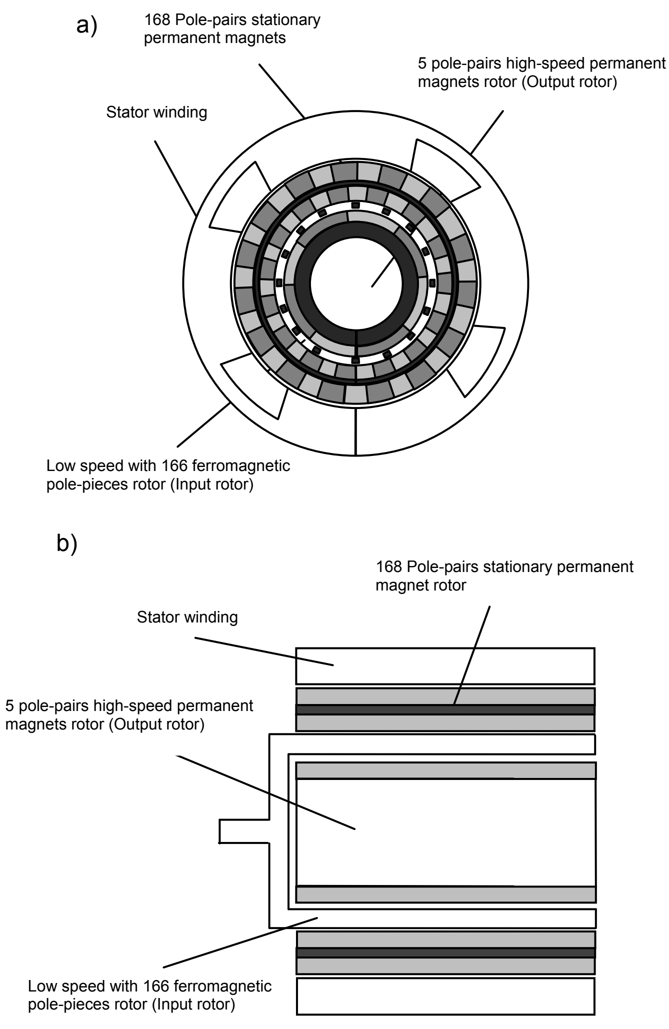


Fig. 1. Magnetic gear generator.
(a) Radial cross section. (b) Axial cross section.

A wind turbine extracts kinetic energy from the swept area of the blades, the mechanical energy is transferred to the shaft of the input rotor, which is transmitted magnetically from the input rotor to the output rotor. The permanent magnet of the output rotor interacts with the stator windings to produce electromagnetic torque. Thus, the power captured by the wind turbine is transmitted to the grid by the stator winding.

The magnetic gear ratio of proposed machine is:

(1) $$G_r = \frac{n_l}{p_h} = 33.2$$

The speed which needs to be applied to the output rotor is independent of the torques of the rotors, and is a function of the applied input speed and gear ratio.

The equation relating the motions of the magnetic gear is given by [3]:

(2) $$p_h \omega_h = n_l \omega_l$$

Where ω_h, and ω_l are the speed of the output and input rotors respectively.

The torque is transmitted magnetically from the input rotor T_l to the output rotor T_h according to the equation [9]:

(3) $$T_h = -\frac{1}{G_r} T_l$$

The torque which needs to be applied to the output rotor is independent of the speeds of the rotors, and is a function of the applied input torque and gear ratio.

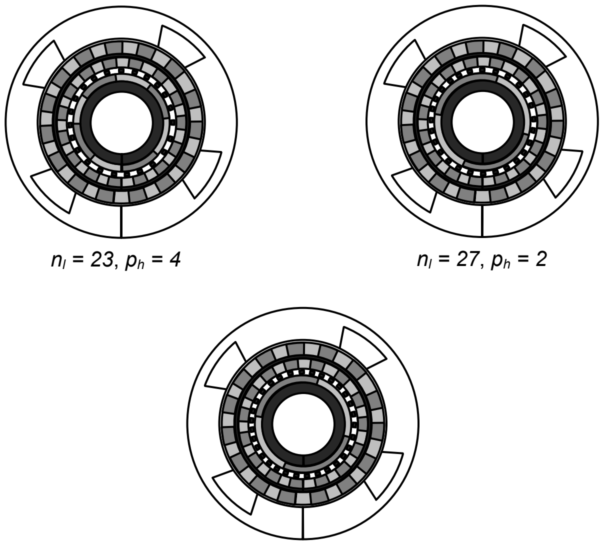


Fig. 2. Schematics of magnetic gears.

Torque production and torque transmission are coupled. Thus, the equations which govern the rotors motion are given by [9]:

(4) $$J_l \frac{d^2 \theta_l}{dt^2} = T_l - T_{max} \sin\left(n_p \theta_p - p_h \theta_h\right)$$

(5) $$J_h \frac{d^2 \theta_h}{dt^2} = T_h - T_{max} \frac{p_h}{n_l} \sin\left(p_h \theta_h - n_l \theta_l\right)$$

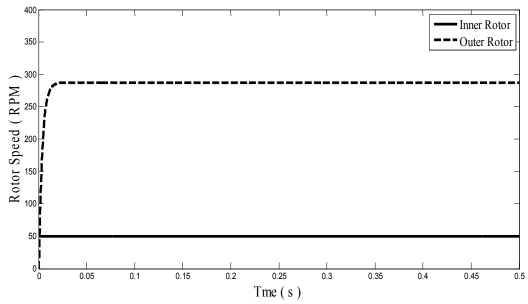
(6) $$T_h = \frac{3}{2} p_h \left(\varphi_{sd} i_{sq} - \varphi_{sq} i_{sd}\right)$$

where θ_h and θ_l are the angular position of the output rotor and the input rotor respectively, φ is flux linkage, i is the current, s indicate the stator winding, T_l is the wind turbine torque, T_h is the electromagnetic torque which results from the interaction between the permanent magnets on output rotor and the stator winding, T_{max} is the maximum torque which can be produced by the magnetic gear and J_h and J_l are the inertias of the output rotor and the input rotor respectively.

Fig. 2 illustrates representation of three magnetic gears, having gear ratios of 5.75, 13.5 and 15.5, which have been selected.

For standard step response tests, the representations relating the mentions of the inner rotor and the outer rotor of previous gears ratios are given by Fig. 3.

a)



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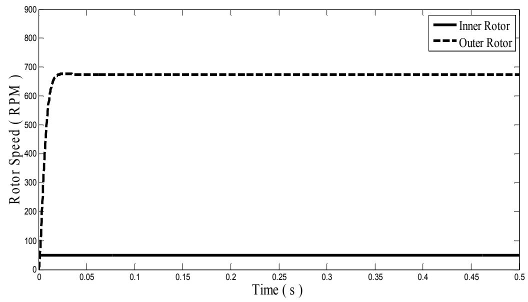

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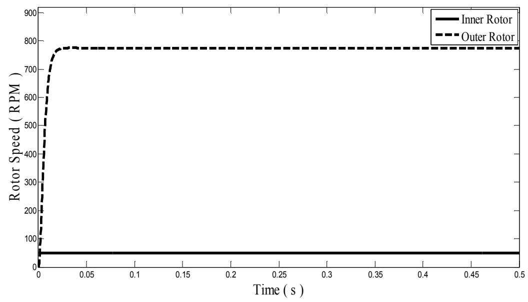

Fig. 3. Standard step response of magnetic gear.
(a) For 5.75 gear ratio. (b) For 13.5 gear ration. (c) For 15.5 gear ratio.

For a given input speed, which is governed by the turbine speed Fig. 3, it can clearly seen that the output rotor speed is a function of the applied input speed and the gear ratio of the magnetic gear, $\omega_h = G_r\, \omega_l$. It can be seen that the choice of the combination of the number of pole-pairs n_l et p_h has a significant influence the maximum speed and torque transmission capability. Using magnetic gear with wind power system, even under low wind conditions often found inland, and without mechanical gear, the high speed can be reached with this topology**.**

Control strategy

Fig. 4 shows the proposed control topology of wind power generation system, which used a magnetic gear generator connected to the grid through a back-to-back converter [10]. A wind turbine extracts kinetic energy from the swept area of the blades, the power transferred to the wind turbine rotor [11] is:

(7) $$P_t = \frac{1}{2} C_p(\beta,\alpha)\rho A V^3$$

Where P_t is wind turbine power, C_p the power coefficient, ρ the air density, A the swept area of rotor, V the wind speed, β the blade pitch angle and α the angle of attack.
The tip speed ratio is defined as the ratio between the blade tip speed and the wind speed V [11, 12]:

(8) $$\lambda = \omega \cdot \frac{R}{V}$$

where ω is the turbine rotor speed and R the radius of the wind turbine blade.

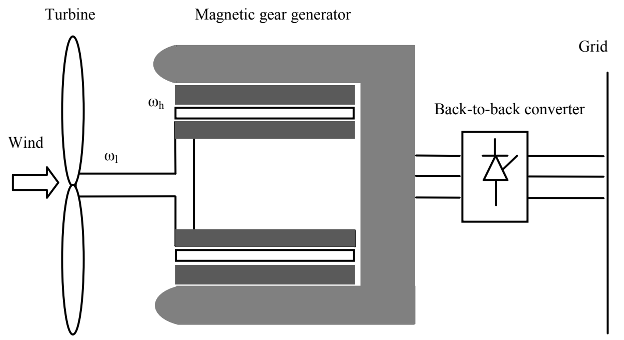

Fig. 4. Magnetic gear generation topology.

The magnetic gear generator side converter is controlled the output rotor to the reference speed or using maximum power tracking algorithm to extract maximum power from wind turbine [13, 14, 15, 16]. In this paper, the proposed converter is controlled the outer rotor to the rated reference speed.

The grid side inverter controls the active and reactive power flowing between the inverter and the grid [17].

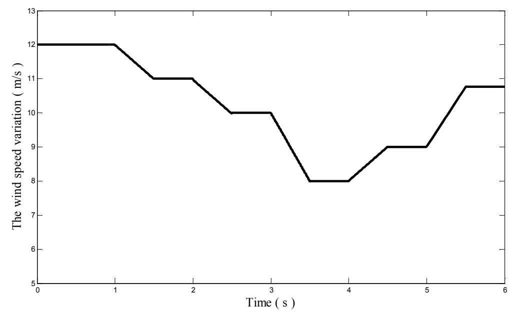

Fig. 5. The wind speed variation.

Simulation results

The simulation was presented to evaluate the high performance of 2 MW magnetic gear generator. The dynamic simulation is performed with variable wind speed. Table 1 shows the parameters of the magnetic gear generator.

Table 1. Parameters of magnetic gear generator.

Magnetic gear generator	values
Rated Power	2 MW
Rated Voltage	900 V
Stator Phase Resistance	0.001Ω
Inductance L_d	0.00007 H
Inductance L_q	0.00007 H
Number Of Pole-Pairs Inner-Rotors	166
Number Of Pole-Pairs Outer-Rotors	5

To show the impact of the variable wind speed against the proposed magnetic gear generator, the wind speed variation is chosen Fig. 5.

The simulation results of the torque on the outer rotor and of the inner rotor are depicted in Fig. 6. The gear ratio can be verified between any of the rotors using these wavelength torque curves. We can see that, the electromagnetic torque which needs to be applied is independent of the speed of the rotors, and is a function of the applied input rotor torque and the gear ratio.

a)

b)

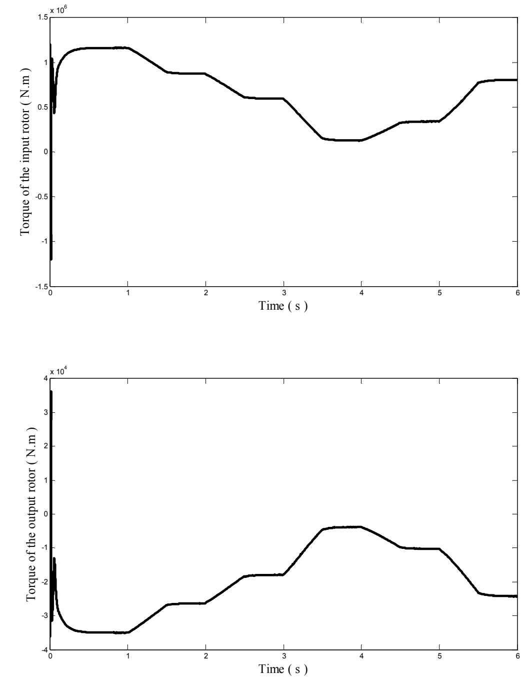

Fig. 6. Torque of the magnetic gear generator.
(a) Torque of input rotor. (b) Torque of output rotor.

a)

b)

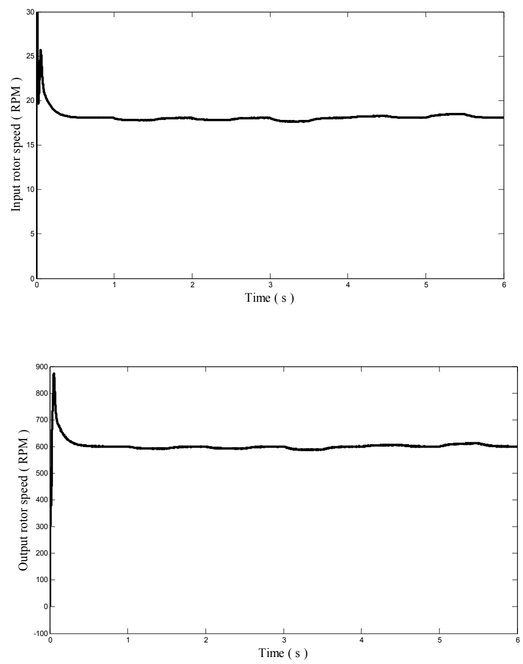

Fig. 7. Rotors speed of the magnetic gear generator
(a) Input rotor. (b) Output rotor.

The magnetic gear side converter is controlled to maintain the output rotor to the rated speed 600 rpm. Fig. 7 shows the output and input rotors variation, it is clear that:

$\omega_h = G_r\ \omega_l$, that mean even under low wind conditions often found inland, and without mechanical gear, the high speed can be reached using magnetic gear generator.

To collect the maximum power produce by the magnetic gear generator, the dc-link voltage is adjusted to a high level than the amplitude of the grid voltage. From Fig. 8, we can see the dc-link voltage is kept constant to the reference value that means, the dc-link controller reacts fast enough to control the voltage.

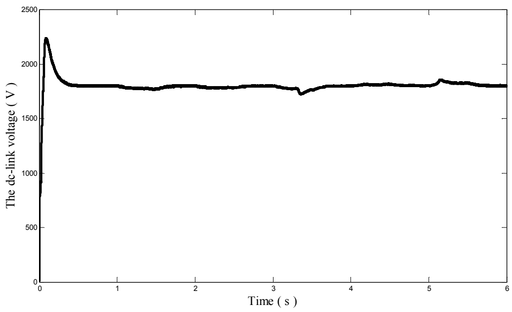

Fig. 8. The dc-link voltage.

Fig. 9 shows the variation of the active power produce by the magnetic gear generator witch transmitted to the grid, the nominal power injected to the grid is about 2 MW.

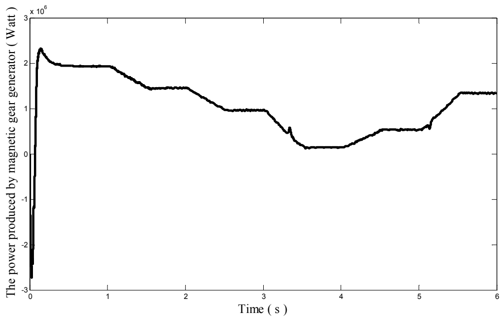

Fig. 9. The power produced by magnetic gear generator.

Conclusion

This paper presents a coupling magnetic gear with permanent magnet synchronous generator for 2 MW wind turbine. We have described the different gear ratio of magnetic gear. We have seen that, with low wind conditions often found inland, we can achieve high speed variation using the proposed magnetic gear generator also, we do not require to the huge mechanical gearbox and the system of lubrication. So, we can overcome the dimension problem of the nacelle, and allow more space to work safely. The dynamic behaviour of the magnetic gear generator with variable speed was explored; the simulation results confirm the benefits of the proposed magnetic gear generator.

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