

Design and Optimization of Electric Continuous Variable Transmission System for Wind Power Generation

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A novel brushless electric continuous variable transmission (E-CVT) system is presented and optimized. The proposed system offers an alternative solution for a variable-speed constant-frequency operation of the wind turbine application. The key is to eliminate the gearbox and brushes in the machine and this E-CVT system comprises of two rotors and two stators within one machine. This design inherits and integrates the merits of the direct-drive permanent magnet generator and the doubly fed induction generator with the additional benefit of the improved torque density and the need for a low-cost partial-scale converter. The structure, operation principle, and performance are analyzed. Genetic algorithm is employed to optimize the parameters for maximizing its power density. Time-stepping finite-element method is used to analyze the dynamic performance of the proposed system.

Index Terms—Electric continuous variable transmission (E-CVT), genetic algorithm (GA), parameter optimize, wind power.

I. INTRODUCTION

WIND POWER is one of the fastest growing renewable energy resources in the world in the recent 20 years [1], [2]. It is an enormous potential energy source with relatively little environmental impact. As the heart of the system, the electric generator is one of the key components. Many types of machines have been investigated in these wind power harvesting systems. Two kinds of machines are most commonly used, they are, namely, the doubly fed machine and the direct-drive synchronous machine. Doubly fed induction generator (DFIG) is usually incorporated with a gear box and can realize variable-speed constant-frequency operation [3]. This is a huge merit for grid-connect wind power systems. But DFIG needs additional slip rings and brush assembly. Compared with DFIG, the brushless doubly fed reluctance generators (BDFRGs) have higher reliability without brush or slip systems. However, a high-ratio gearbox system is essential for DFIG and BDFRG to match the low speeds of the turbines. Alternatively, one can use direct-drive synchronous generator (DRSM) in wind power applications. Compared with DFIG, the DRSM system requires no gearbox and, hence, has lesser maintenance problems. However, a four-quadrant full-rated converter is necessary to realize a variable-speed constant-frequency operation for the grid connection.

Electric-continuously variable transmission (E-CVT) is commonly used in hybrid electric vehicle. Employing a planetary stage gear, the internal combustion engines can operate at its optimal speed range regardless of the speed variations of the vehicle [4]–[6]. The goal of the E-CVT is to match the internal combustion engine optimal operation point to the vehicle operating condition. This is quite similar to the variable-speed constant-frequency operation of the wind power generator systems. The E-CVT system can also be used to match the optimal operating point of the synchronous generators to the speeds of the turbines. Nevertheless, the existence of the complex planetary stage gearbox brings some additional

shortcomings, such as low reliability, low efficiency, and high maintenance cost. A dual mechanical port machine for wind power is proposed in [7]. The planetary stage gear is replaced by a dual-rotor machine. However, the slip and brushes are inevitable due to the windings in the rotor.

In recent years, magnetic gear (MG) is investigated extensively [8]–[10]. By employing the magnetic field modulation effect, the MGs can replace the mechanical counterparts with many advantages, such as low noise and reduced vibration and high reliability. Based on the MG, the flux-modulated machines are studied in [11]–[15]. In the flux-modulated machines, the magnetic field derived from the permanent magnet (PM) rotor is modulated by the steels and coupled with the rotor. The magnetic field modulation effect provides an alternative method in the design of a dual mechanical port machine, which can realize the variable-speed constant-frequency operation without the gearbox and brushes.

In this paper, a novel dual-rotor contra rotating PM synchronous machine (DCR-PMSM), which can realize a variable-speed constant-frequency operation in wind power generation system, is proposed and optimized. This novel system consists of two rotors and two stators. There are two sets of windings housed in the outer and inner stator. The inner rotor is connected with turbine blades to capture the wind power and the outer rotor acts as a common rotor for the outer windings and the inner windings. The outer rotor can be controlled by the outer windings aiming to produce electricity with constant frequency in the inner windings. The innovative wind power generator system has twofold merits: it has high reliability without those maintenance problems due to gearboxes, slip ring assembly, and brushes, which are inevitable in the conventional doubly fed generators and dual-rotor machines. In addition, the proposed design requires a low-power, and hence inexpensive, frequency converter when compared with that required by the conventional direct-drive wind energy system. Principle of this novel machine is illustrated in this paper and its performance is analyzed. Besides introducing the working principle and analysis of the proposed structure, a finite-element method (FEM) and genetic algorithm (GA) coupled algorithm is proposed to optimize the system design. The objective is to guarantee the required output power and maximizes the torque density of machine.

Manuscript received July 5, 2015; revised August 26, 2015; accepted October 1, 2015. Date of publication October 7, 2015; date of current version February 17, 2016. Corresponding author: S. Niu (e-mail: shuangxia.niu@polyu.edu.hk).

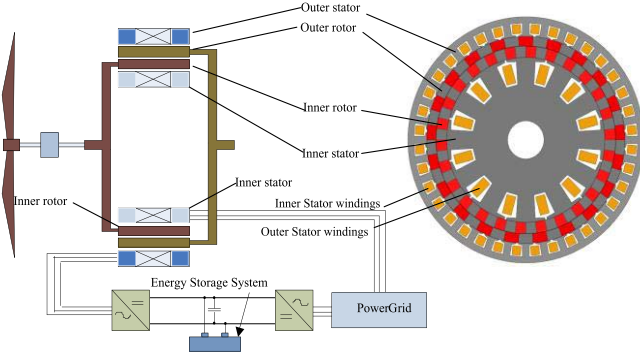


Fig. 1. Structure of the proposed DCR-PMSM system.

II. OPERATION PRINCIPLE

A. Mechanical Structure

Fig. 1 shows an example of the proposed structure which incorporates two stators and two rotors within one machine. PMs and modulation steels are alternatively arranged on the rotors. One piece of PM and modulation steel constitute one pole pair. This model has 26 pole pairs on the inner rotor and 21 pole pairs on the outer rotor. Two sets of three-phase concentrated windings are housed in the two stators. The inner winding has 4 pole pairs with 9 slots and an outer winding has 21 pole pairs with 36 slots.

The novel machine can be divided into two parts. The outer stator and outer rotor consist of a synchronous machine with 21 pole-pair of PMs and is fed by a converter. The inner rotor rotates with the blades. Therefore its speed changes according to the wind speeds. The inner winding and two rotors can be regarded as a flux modulation generator. The inner winding is connected directly to the power grid. The speed of the outer rotor is controlled by the outer windings and follows the variable speed of the inner rotor. When appropriate control strategy is applied, the frequency of the inner winding can be kept constant with controllable inner rotor speed.

B. Mathematic Model

The inspiration of proposed machine arises from the magnetic field modulation principle which is usually used in the MGs. The mathematic model of the MGs is presented in [6]. Because of the modulation function of the modulation steels, the radial component of the flux density distribution derived from the PM is expressed as

$$\begin{aligned}
 B_{\theta}(r, \theta) &= \lambda_0 \sum_{m=1,3,5} b_{\theta m}(r) \cos(mp(\theta - \Omega_r t) + mp\theta_0) \\
 &+ \frac{1}{2} \sum_{m=1,3,5,\dots} \sum_{j=1,3,5,\dots} \lambda_j(r) b_{\theta m}(r) \\
 &\times \cos\left((mp + jn_s)\left(\theta - \frac{mp\Omega_r + jn_s\Omega_s}{mp + jn_s}t\right) + mp\theta_0\right) \\
 &+ \frac{1}{2} \sum_{m=1,3,5,\dots} \sum_{j=1,3,5,\dots} \lambda_j(r) b_{\theta m}(r) \\
 &\times \cos\left((mp + jn_s)\left(\theta - \frac{mp\Omega_r + jn_s\Omega_s}{mp + jn_s}t\right) + mp\theta_0\right) \quad (1)
 \end{aligned}$$

where p is the number of pole pairs of the PM; n_s is the number of modulation steels; Ω_r and Ω_s are the rotational velocities of the PM rotor and the steel pieces, respectively;

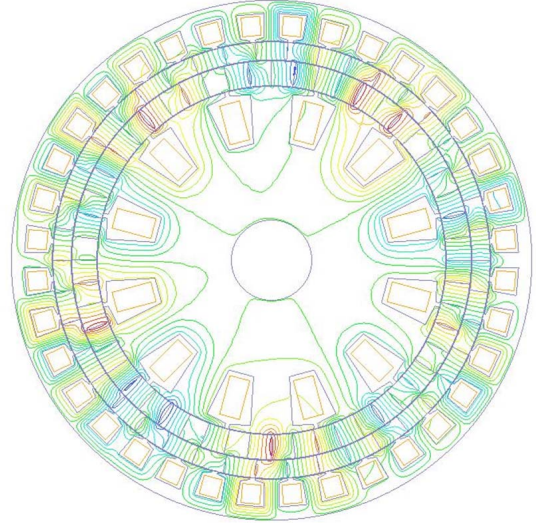


Fig. 2. Flux lines distribution of the proposed machine with full-load.

and m and k represent the orders of the space harmonic. The number of pole pairs of the space harmonic is given by

$$p_{m,k} = |mp + kn_s|. \quad (2)$$

Harmonic rotational velocity relationship is

$$\Omega_{m,k} = \frac{mp}{mp + kn_s} \Omega_r + \frac{kn_s}{mp + kn_s} \Omega_s \quad (3)$$

where $\Omega_{m,k}$ is the mechanical rotational velocity of the space harmonics. Generally the highest space harmonic with $m = 1$ and $k = -1$ is employed. The number of pole pairs of the inner winding is regarded as the fundamental pole pairs. Therefore, there are two sets of modulation combinations in the machine at the same time. The inner rotor ferromagnetic steels and outer rotor PM consist of one set. The other set is the outer rotor steels and the inner rotor PM. For both combinations, the winding frequency and rotor speed relationship could be written as

$$f_1 = \frac{n_1 \Omega_1 - n_2 \Omega_2}{60} \quad (4)$$

where n_1 and n_2 are the number of pole pairs of the outer rotor and inner rotor respectively. Ω_1 and Ω_2 are the rotational velocities of the inner rotor and the outer pieces, respectively. The outer rotor and the outer windings form a normal PM synchronous machine, the speed of the outer rotor is decided by the frequency of outer winding

$$\Omega_2 = 60 \times f_2. \quad (5)$$

When the speed of the inner rotor varies with the wind velocity, the converter adjusts the frequency of the outer winding to change the speed of outer rotor correspondingly. The frequency of the inner winding can be kept constant while the speeds of both rotors vary synchronously as shown in (4). Therefore, the outer rotor speed is controlled by the converter through the outer winding, and the inner winding frequency can be kept constant when the inner rotor speed changes with the wind speed.

TABLE I
BASIC PARAMETERS OF THE PROTOTYPE FOR THE
PROPOSED POWER GENERATION SYSTEM

Symbol	Quantity	Value
l_s	Stack length	200mm
D_{s1}	Diameter of Outer Stator	356mm
D_{s2}	Diameter of inner Stator	238mm
h_1	Thickness of outer rotor PM	13.4mm
h_2	Thickness of inner rotor PM	16.6mm
$g1$	Inner air-gap	0.5mm
$g2$	Outer air-gap	0.5mm
p_1	Inner stator winding pole-pairs	5
p_2	Outer stator winding pole-pairs	21
N_1	Inner rotor PM pole-pairs	26
N_2	Outer rotor PM pole-pairs	21

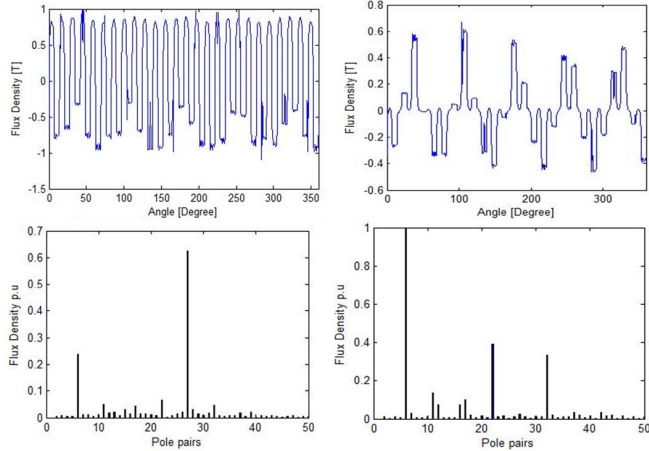


Fig. 3. Flux density in the inner air gap. (a) Due to outer rotor PMs (top) and its space harmonic spectra (bottom). (b) Due to inner rotor PMs and its space harmonic spectra.

III. MACHINE PERFORMANCE ANALYSIS

The magnetic field distribution of the proposed machine is shown in Fig. 2. The 5 pole-pair magnetic field derived from the field modulation is obviously present in the inner stator yoke. Table I shows the prototype design data of the proposed system.

To verify the mathematic model of the novel machine, a 3-D model is analyzed using time-stepping FEM. The flux density distribution in the outer air gap coupled with the inner winding is the foundation of a mathematic model. Therefore, the radial flux densities due to both PMs of the two rotors are analyzed separately. Fig. 3(a) shows the flux density due to the outer PM excitation and its space harmonic spectra. Fig. 3(b) shows the flux density due to the inner PM excitation and its space harmonic spectra. The space harmonic spectra indicate that the space harmonics are amplified by the modulation steels as discussed in Section II, and the space harmonic with $m = 1$ and $n = -1$ is obviously higher than the others.

Fig. 4 shows the potential of the machine's variable-speed constant-frequency operation when the inner rotor speed changes from 50.77 to 75 r/min due to variations of the wind velocity at 73 ms, as shown in Fig. 4(b). It can be seen that the outer rotor speed is controlled by the outer windings and changes from -80 to -50 r/min following the inner rotor at the same time, as shown in Fig. 4(c). Therefore, the frequency

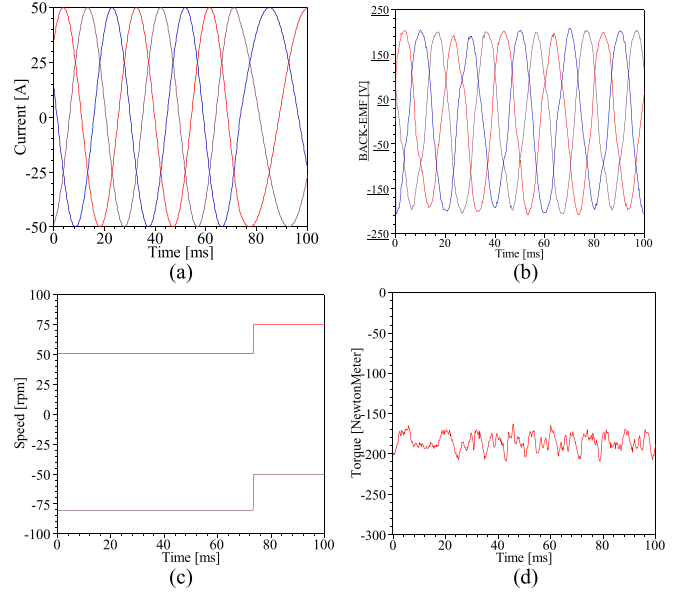


Fig. 4. FEM analysis result. (a) Back EMF of outer windings. (b) Back EMF of inner windings. (c) Speed of inner and outer rotor. (d) Steady torque of the inner rotor.

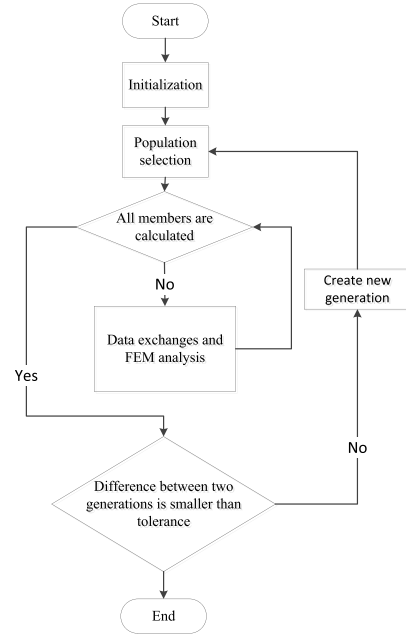


Fig. 5. Flowchart of the coupled FEM and GA optimization.

of outer windings is changed from 28 to 17.5 Hz accordingly as shown in Fig. 4(a). As a result, the frequency of the inner winding no-load electromotive force (EMF) is kept as 50 Hz during the speed variations of both rotors. It is obvious that the inner rotor speed variation has no effect on torque and winding frequency with proper control strategy. As the result shows, the proposed machine can realize a variable-speed constant-frequency operation for wind power generation.

For the direct-drive grid connection system, the proposed DCR-PMSM can realize the contra rotation operation, which means the rotation directions of the two rotors are opposite. The contra rotating structure improves the winding power utilization dramatically. Since the inner power windings are directly connected to the grid, only a small ac/ac converter

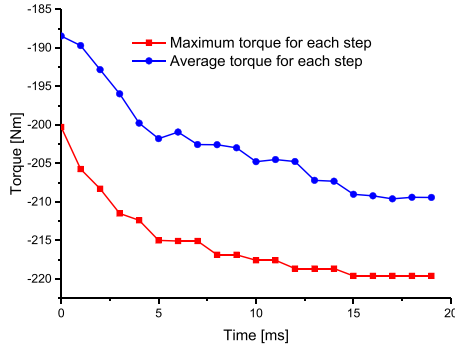


Fig. 6. Maximum and average torque for each steps of GA optimization.

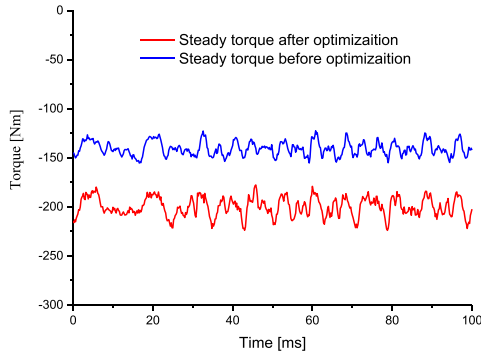


Fig. 7. Optimization result of the steady torque.

is needed for the outer control windings, which makes the system highly efficient and inexpensive.

IV. PARAMETER OPTIMIZATION

It is important for the winding power generation system to reduce the system cost and space occupation. Therefore, it is essential to optimize the torque density of the proposed system. Because of the complexity of the magnetic field harmonic distribution, it is difficult to optimize the E-CVT system by the traditional analytical method. GA is a better optimization option. GA can find the optimal solution by imitating the natural selection. With the three operation factors, which are, namely, reproduction, crossover, and mutation, the GA resembles the natural selection [16]. Reproduction makes the fittest individual survive. Crossover and mutation expand the searching scope. As shown in Fig. 5, the combination optimization with the FEM and GA is employed to optimize the rotor parameters of the E-CVT system. The combination of the FEM and GA method dramatically cutoff the time consumption for the design and optimization of the prototype. To realize the combination analysis, a program to realize the data communication between the FEM analysis and GA optimization is developed. Maximum torque density is pursued as the goal function through three parameters: 1) inner rotor PM angle; 2) outer rotor PM angle; and 3) the ratio of the inner rotor and outer rotor thickness.

Fig. 6 shows the evolutionary process of the GA. The torque value rises rapidly from the previous steps and reaches the steady state after 15 steps.

Optimization result is shown in Fig. 7. The red line and blue line are the torque curves with and without optimization, respectively. The average value of the goal function is increased from 150 to 209 Nm.

V. CONCLUSION

In this paper, an E-CVT system is proposed. It is an alternative solution for the variable-speed constant-frequency operation for wind turbine application. The novel system can realize a dual-rotor contra rotating operation of direct-drive for grid connection wind power generation system. The contra rotating structure improves the winding power utilization for the whole generation system. By employing the magnetic field modulation effect, the planetary stage gear is eliminated. Therefore, the reliability of the system is dramatically improved and the maintenance cost is reduced. GA is employed to optimize the rotor parameters for the maximization of torque density.

ACKNOWLEDGMENT

This work was supported by the Research Grants through the Research Grants Council, Hong Kong, under Project PolyU 5388/13E and Project PolyU 152130/14E.

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