# 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 as an effective solution for variable-speed constant-frequency operation of wind turbine applications. The E-CVT system consists of two rotors and two stators with no gearbox nor brushes. The structure and operation principle are introduced and the performance is analyzed with time-stepping finite element method (TS-FEM). A global optimal design method based on genetic algorithm (GA) and finite element method (FEM) is proposed to optimize the parameters of the system to realize maximum power density.**

***Index Terms*—E-CVT, electric machine, finite element method, genetic algorithm, parameter optimization, wind power.**

## I. Introduction

WIND POWER is one of the fastest growing renewable energy resources in the world in recent years [1-2]. It is an enormous potential energy source with relatively little environmental impact. To harvest wind energy, researches into electric generator is one of the key focus areas. Many types of machines have been used in wind power systems. Two kinds of machines are most commonly used. One is doubly-fed induction generators (DFIG) with gearbox and the other one is direct-drive permanent magnet synchronous motors (PMSM). With the advent of magnetic materials, PMSM is a potential option in many applications because of its high torque density and high efficiency. However direct-drive PMSM generator usually suffers from bulkiness and heavy weight due to the low turbine speeds. DFIG could realize variable-speed constant-frequency and low speed operation [3]. It improves the energy conversion efficiency and is very suitable for grid-connected direct-drive wind power systems. But its torque density is much lower than those of PMSM systems. The usage of slip rings, brushes, gearbox also decreases the reliability of the DFIG system.

In this paper, a novel brushless electric continuous variable transmission (E-CVT) system which can realize variable-speed constant-frequency operation in wind power generation system is proposed and optimized. With magnetic field modulation and coupling, the novel machine integrates the merits of both PMSM and DFIG. The gearless and brushless E-CVT system could realize variable-speed constant-frequency direct-drive with high torque density. The system is novel and consists of two rotors and two stators. There are two sets of windings housed in the outer and inner stators. One of the rotors is connected with turbine blades to capture the wind power and the other rotor acts as a common rotor to be controlled by the outer stator windings to help producing electricity with constant frequency in the inner stator windings. The innovative wind power generator system has two-fold merits: it has high reliability without those maintenance problems due to gearboxes, slip ring assembly and brushes which are inevitable in conventional doubly-fed generators. The proposed design requires a low-power, and hence inexpensive, frequency converter when compared to that required by conventional direct-drive wind energy system.

Genetic algorithm (GA) is a simulated evolutionary optimization method. It imitates natural selection and genetic evolution [4]. With three operation factors, namely reproduction, crossover and mutation, GA resembles the natural selection process of nature. Reproduction ensures only the fittest individual will survive. Crossover and mutation expand the searching scope. A global optimal design method based on GA and finite element method (FEM) is proposed to optimize the parameters for achieving maximum power density. The principle of this novel machine is explained in this paper and the structure is optimized. Both steady and dynamic performances of the machine are analyzed.

## II. Operation Principle

### *A. Mechanical Structure*

Fig. 1 shows the proposed structure as well as the PMs and modulation steels which are alternatively arranged on the rotors. One piece of PM and one modulation steel segment 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 3-phase concentrated windings are housed on the two stators. The inner winding has 4 pole pairs housed in 9 slots and the outer winding has 21 pole pairs in 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 pairs of PMs and fed with a converter. The inner winding and two rotors can be regarded as a flux modulated PM generator. The inner rotor rotates with the blades. Therefore its speed is variable according to the wind speed. The speed of the outer rotor, which is controlled by the outer windings, will follow the variable speed of the inner rotor. The inner winding is connected directly to the power grid. When an appropriate control strategy is applied, the frequency of the inner winding can be kept constant with suitable speed control of the inner rotor.

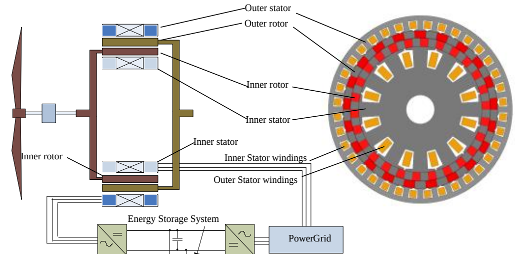


Fig. 1. Structure of proposed E-CVT system

### *B. Mathematic Model*

The design of the proposed machine models on the magnetic field modulation principle commonly exploited in magnetic gears. The magnetic field produced by the PMs or 3-phases winding are modulated by the modulation steels. The rotational velocity relationship of the harmonics are shown below:

$$\Omega_{m,k} = \frac{mp}{mp + kn_s}\Omega_f + \frac{kn_s}{mp + kn_s}\Omega_s \quad (1)$$

where; $\Omega_f$ , $\Omega_s$ and $\Omega_{m,k}$ are the mechanical rotational velocity of the fundamental, modulation steels and space harmonics, respectively. 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, two sets of modulation combinations exist at the same time. The inner rotor ferromagnetic steels and the outer rotor PM belong to one set. The other set is the outer rotor steels and the inner rotor PM. For the first combination set, the winding frequency and rotor speed relationship could be written as:

$$f = \frac{(p - n_s)\Omega_{1,-1}}{60} = \frac{p\Omega_f - n_s\Omega_s}{60} \quad (2)$$

For the second combination set, the relationship is the same as those of the first one. Since the outer rotor speed is controlled by the converter through the outer winding, the inner winding frequency can be kept constant as the inner rotor speed changes with the wind speeds.

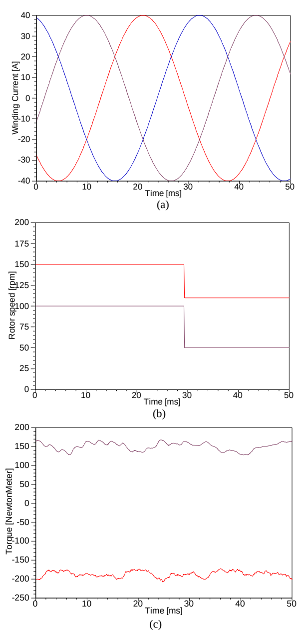


Fig. 2. Performance analysis of E-CVT. (a) Back-emf of inner windings. (b) Inner rotor speed and outer rotor speed. (c) Torque on inner and outer rotors.

## III. FEM ANALYSIS

With TS-FEM, the proposed machine performance is analyzed. As shown in Fig. 2, when the inner rotor speed changes from 150rpm to 109.6rpm at 20ms and the speed of outer rotor is controlled to change accordingly from 100rpm to 50rpm, the inner winding output current frequency is kept constant at 30Hz. It is obvious that with proper control strategy, the inner rotor speed variation has no effect upon the torque and the winding frequency. As the result shows, the proposed machine can realize variable-speed constant-frequency operation for wind power generation.

## IV. PARAMETER OPTIMIZATION

Because of the complexity of the magnetic field harmonic distribution, it is difficult to optimize the E-CVT system by traditional analytical method. GA is a better optimization option. GA can find the optimal solution by imitating the natural selection. The parameters of the E-CVT system is optimized using FEM coupled with GA. Maximum torque density is pursued as the goal function through three parameters: inner rotor PM angle, outer rotor PM angle and the ratio of the inner rotor and outer rotor thickness.

Fig. 4 shows the evolutionary process of the GA. The torque value rises up rapidly at previous generations and reaches steady state after 15 steps.

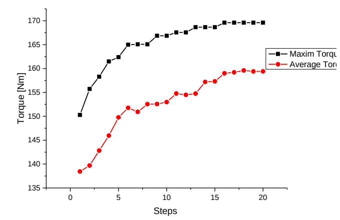


Fig.4. Maxim and average torque for each generation of GA optimization.

Optimization result is shown in Fig. 5. The red line and black line are the torque curve before and after optimization, respectively. The average value of the goal function is increased from 100Nm to 156Nm.

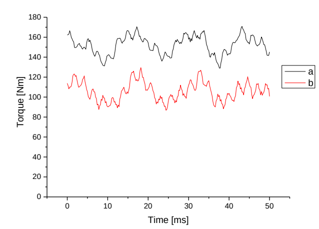


Fig. 5. Optimization result. (a) Transient torque without optimization.
(b) Transient torque with optimization

## V.CONCLUSION

In this paper, an electrical continuous variable transmission (E-CVT) system is proposed. The novel machine has the merits of both PMSM and DFIG. It could realize direct drive with high torque density. Genetic algorithm is employed to optimize the rotor parameters for maximum torque density.

## VI. REFERANCES


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