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Analysis of the maximization of wind turbine energy yield using a continuously variable transmission system

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ABSTRACT

In this paper, an analytic study of the subject of mechanical power transmission in HAWT wind turbine has been carried out. For the most part, the study analyzes the use of continuously variable transmission (CVT) in order to allow the turbine and the electric generator to couple, allowing in turn, an unremitting transmission ratio adjustment. In low-wind sites, the design criteria suggest an oversizing of the wind turbine in order to generate adequate electrical power even at low wind speed. The proposed solution enhances the space of operating points since it allows the electric generator to release the rotational speed from the turbine one (limited due to structural integrity). Employing a CVT transmission, the modulation system of the input power to the turbine starts operating at higher wind speeds when compared to a conventional direct-drive case: this corresponds with the possibility to fully exploit the wind power at a higher speed range, therefore maximizing the wind turbine's energy production. The analysis has showed that, in the case of CVT configuration, the annual energy yield increases of about 50% compared to direct-drive solution.

1. Introduction

Nowadays, most of the global electric energy production comes from non-renewable sources which, emitting high level of pollutants, cause serious global environmental damages. In order to meet the increasing demand for electric energy, in the last few years the research of innovative solutions in the renewable energy field has become strategic.

In particular, there is a widespread interest in wind energy production. The scientific research in the wind turbines field aims at finding innovative solutions which might increase the performance of the turbine components. Many studies involve a variety of aspects such as the aerodynamic of the blades, the control systems, the power transmission, the electrical efficiency of the plants.

Typically, the design goal is to reach the maximum aerodynamic efficiency at a given wind speed. Glauert [1] shows that a constant induction factor leads to maximum efficiency for an ideal rotor. Hoadley et al. [2] extended this theory in order to include the tip correction and the airfoil drag. Many studies have been reported on the optimal site matching of wind turbines [3–6] because the wind power highly depends on the location. Jowder [3] performed site-matching study in Kingdom of Bahrain using the measured wind speed data. Adaramola et al. [4] conducted the assessment of wind power generation along the coast of Ghana. EL-Shimy [5] studied optimal site matching of the wind turbines in the region of the Gulf of Suez. Dong et al. [6] conducted the assessment of wind potential and selected suitable wind turbine in Huitengxile, Inner Mongolia (China). Muljadi et al. [7] postulated a strategy to control rotational speed by specifying the requested generator torque. In Ref. [8], a grid power flux control of a variable speed wind generator which consists in a doubly-fed induction generator is analysed. A nonlinear predictive control approach is developed for a doubly-fed induction generator in Ref. [9]. An unconventional converter is proposed in Ref. [10]. In order to improve the used conversion energy system, the proposed converter has been connected to the rotor of the doubly-fed generator with a fraction equal to 30% of the total power. Yong et al. [11] conducted a study on a double stator induction machine in order to reach the speed, up to twice the nominal value. Taraft et al. [12] proposed a strategy for power optimization of a wind energy conversion system which consists in a double fed induction generator whose stator is connected directly to the grid and its rotor is supplied by matrix converter. Mirghaed et al. [13] optimized a wind turbine design using Cost of Energy (COE) as an objective function and Maki et al. [14] also developed

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the multi-level system design algorithm for wind turbines based on COE. Although the COE considers the initial capital cost as well as the energy production, the net profit is not calculated; thus, it cannot judge the economic feasibility. Regarding the use of CVT system about wind turbine, Rex et al. [15] applied the CVT in order to obtain positive effects in terms of aerodynamic efficiency and fatigue loads. The study shows interesting results which highlight the better performances of a CVT wind turbine in comparison with a traditional equipment. The simulation time employed by the authors is limited to a little more than a minute, in order to drastically reduce the computation time. As a matter of fact, a realistic analysis, due to the model complexity and to the evaluation of all parameters, requires a longer simulation time. Moreover, the authors assert that energy losses due to the CVT have been neglected in the study. Zhao et al. [16] has realized a mathematical model about CVT transmission in wind turbine. Compared with fixed pitch wind power, the relation among wind energy utilization coefficient, power and wind speed are studied. The authors focus their attention on the instantaneous power values employing CVT and direct transmission equipment. Furthermore, the annual energy produced is not reported. In order to maintain the maximal output power of wind turbine, Petković et al. [17] designed an innovative intelligent controller based on the adaptive neuro-fuzzy inference system (ANFIS). In order to improve the wind energy available in an erratic wind speed regime, a wind generator equipped with continuously variable transmission has been proposed. Shamshirband et al. [18] claimed that, in order to optimize the power produced in a wind turbine, the turbine speed should vary according to wind speed. Variable speed operation of wind turbines presents several advantages over constant speed operation. Moreover, authors investigated on the use of a power-split hydrostatic continuously variable transmission in order to maximize the aerodynamic efficiency. The objective of this article is to capture maximum energy from the wind by predicting the optimal values of the wind turbine reaction torque. However, a comparison between direct drive and CVT transmission has not been carried out nor has the annual energy produced been evaluated. Yin et al. [19] proposed a hydro-viscous transmission based on continuously variable speed wind turbine so as to smooth the output power fluctuations in the full-load region. For what concerns energy, results are not shown yet it is possible to think that this strategy, based on energy losses does not allow to fully exploit the wind energy.

In this paper it has been proposed an innovative solution which involves the use of a CVT system, in order to maximize the energy yield of small wind turbine (equipped with permanent magnet generator). More in details, the study aims at optimizing the matching between turbine and generator in order to take advantage of the wind energy on a wider range of wind speed. Several authors [15–19] studied the application of CVT system on the wind turbine field, focusing on aerodynamic and/or electrical optimization. The aerodynamic optimization provides that the turbine operates at variable speed in order to guarantee an optimum TSR (Tip Speed Ratio). The electrical optimization provides that the electrical generator operates at maximum efficiency speed. In low wind sites, designers tend to choose large diameter rotors which, due to structural reasons, have to operate at a limited rotational speed. As a result, in order to produce the rated power at low wind speeds, a permanent magnet generator must be chosen. Therefore, the dimensioning criteria lead to the choice of an oversized electric generator (this last statement will be clarified in the following sections).

In the case of direct-drive transmission, when the instantaneous wind speed exceeds a wind speed limit, the pitch control mechanism changes the angle of attack of the blades in order to maintain the rotor speed under the allowed value. Therefore, the exceeding power that the generator could provide rotating at higher rotational speeds is not used. The use of CVT system allows to take full advantage of high wind speeds, by operating the electric generator as much as possible at the maximum power. Some authors have analysed the use of CVT system in fixed pitch turbines [16] whereas in this paper, the CVT system does not replace the pitch mechanism but it delays its action. In other words, the pitch mechanism starts to reduce the turbine input power when the wind speed is higher than 40% compared to direct-drive wind turbines. Using a CVT system, the study has showed the possibility to obtain an increment of the annual energy yield of about 50% when compared to direct-drive solution.

2. Direct-drive case

Direct-drive coupling between the turbine and the generator is achieved through the usage of permanent magnet generators. Indeed, the latter are properly designed to operate and produce power even at very low rotational speed. The limit of maximum rotational speed depends on the rotor diameter. In fact, the structural integrity of blades should be safeguarded, maintaining centrifugal forces up to given limits. The wind turbine considered in this paper consists of a rotor and a generator (Specifications shown in Table 1).

In a direct-drive coupling, the rotational speed of the system is limited to 38 rpm. This represents a great restriction of the possibility to improve the employ of the generator since the power it can produce at 38 rpm is about 60 kW (wind speed about 7 m/s): a low value compared to the maximum power of 200 kW. The power curves as a function of the turbine and generator rotational speed under different wind speed conditions are reported in Fig. 1.

The pitch mechanism allows to limit the input power, therefore maintaining a constant power even at higher wind speeds. More in details, the turbine generates a power of 60 kW at 38 rpm when the wind speed is about 7 m/s. When the wind speed exceeds this value, the turbine input power begins to increase and the operating point to move towards higher values of rotational speed. In this case, the pitch mechanism enables the rotation of the blades on their longitudinal axis, therefore it changes the angle of attack of the blades with respect to the wind, limiting the output power and

Table 1
Wind turbine specifications.

Rotor/Blade	
Length:	13.40 m
Root geometry	Circular root (BCD 500)
Rotor Diameter	28 m
Hub diameter	1.10 m
Number of blades	3
Rotation speed	38 rpm
Hub height	32 m
Rated Power	230 kW
No load Power Loss	500 W
Power Train Efficiency	90%
Cut-in wind speed	1 m/s
Cut-out wind speed	25 m/s
Generator	
Type	Permanent magnet
Output voltage	No Load = 400 V ± 5%
	Full Load = 350 V ± 5%
Rated power	200 kW
Max. rotational speed	120 rpm
Overspeed	190 rpm