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Adaptive neuro-fuzzy maximal power extraction of wind turbine with continuously variable transmission

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ABSTRACT

In recent years the use of renewable energy including wind energy has risen dramatically. Because of the increasing development of wind power production, improvement of the control of wind turbines using classical or intelligent methods is necessary. To optimize the power produced in a wind turbine, the speed of the turbine should vary with the wind speed. Variable-speed operation of wind turbines presents certain advantages over constant-speed operation. In this paper, in order to maintain the maximal output power of wind turbine, a novel intelligent controller based on the adaptive neuro-fuzzy inference system (ANFIS) is designed. To improve the wind energy available in an erratic wind speed regime, a wind generator equipped with continuously variable transmission (CVT) was proposed. In this model the ANFIS regulator adjusts the system speed, i.e. CVT ratio, for operating at the highest efficiency point. The performance of proposed controller is confirmed by simulation results. Some outstanding properties of this new controller are online implementation capability, structural simplicity and its robustness against any changes in wind speed and system parameter variations. Based on the simulation results, the effectiveness of the proposed controllers was verified.

1. Introduction

Renewable energies such as wind and solar energy conversion systems have driven attention during the past decade due to the environmental concerns. Wind is a natural resource that features many advantages since it is clean and considered reliable in some areas.

A wind turbine system is a system that converts the wind turbine's mechanical energy obtained from wind into electrical energy through a generator and can be categorized by the types of generators used, power control methods, constant- or variable-speed operation, and methods of interconnecting with the grid [1]. Variable-speed operation of a wind turbine is generally more advantageous over constant-speed operation since a variable-speed operation is able to track the maximum power of the wind turbine with wind speed changes. Modern high-power wind turbines are equipped with adjustable speed generators [2]. It was shown that the control strategies have a major effect on the wind turbine and whatever the kind of the wind turbine, the control strategy remains a key factor [3–6].

As wind energy becomes more dominant there is growing interest in controlling wind turbines or wind plants in an intelligent manner to minimize the cost of wind energy. This can be done by controlling the turbines to extract more energy from the wind. In the wind energy conversion systems, the control problem consists of delivering the maximum power available from the wind to ensure the system reliability and security in order to deal with the variable nature of the generated energy [7–9]. Wind power conversion depends essentially on the power coefficient, "C_p" of the machine which transforms the efficiency of converting wind power to electrical power. In order to implement maximum wind power extraction, the wind turbine generator must be operated at variable-speed mode. The power coefficient is characterized as a function of both tip speed ratio and the blade pitch angle. The tip speed ratio is the ratio of linear speed at the tip of blades to the speed of the wind. Optimal performance of the wind turbine can be obtained if the transmission ratio could change with the wind speed [10,11]. In this paper a continuously variable transmission (CVT) has been installed between a wind turbine and a generator to make the turbine operate along the maximum efficiency. The aim of the investigation was to change the transmission ratio between the wind turbine and the

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generator at different wind speeds so that the turbine may be kept running at maximum efficiency levels at all wind speeds. It is known about automatic CVT regulation to adjust and stabilize their transmission ratio according to transmitted torques without relying on other regulating or control mechanisms [12,13]. Considering all these, it is interesting to explore the feasibility of installing an automatic CVT in a wind turbine since such a solution may optimize the efficiency of these systems by means of simple technologies.

To improve the control of the wind turbines, fuzzy logic (FL) [14–19] or artificial neural network (ANN) control has attracted much attention in recent years [20–27]. As a non-linear function [28–31], ANNs can be used for identifying the extremely non-linear system parameters with high accuracy. Neural networks can learn from data. However, understanding the knowledge learned by neural networks has been difficult. In contrast, fuzzy rule based models are easy to understand because they use linguistic terms and the structure of IF-THEN rules. Unlike neural networks, however, fuzzy logic by itself cannot learn [32]. Since neural networks can learn, it is natural to merge these two techniques. This merged technique of the learning power of the ANNs with the knowledge representation of FL has created a new hybrid technique, called neuro-fuzzy networks or adaptive neuro-fuzzy inference system (ANFIS) [33]. ANFIS, as a hybrid intelligent system that enhances the ability to automatically learn and adapt, was used by researchers for modeling [34–37], predictions [38–40] and control [41–45] in various engineering systems. The basic idea behind these neuro-adaptive learning techniques is to provide a method for the fuzzy modeling procedure to learn information about data [46–53].

In this paper, the application of ANFIS is proposed to control the CVT ratio to extract the maximal wind energy through the wind turbine. As inputs in the controller, current wind speed and current wind turbine rotor speed are used. The output should be optimal generator speed.

2. Wind turbine power extraction and continuously variable transmission

The major components of a typical wind energy conversion system include a wind turbine, a generator, interconnection apparatus, and control system. Therefore, the design of a wind energy conversion system is complex. The most important part of a wind energy conversion system is the wind turbine transforming the wind kinetic energy into mechanical or electric energy. The system basically comprises a blade, a mechanical part and an electric engine coupled to each other. The kinetic energy of wind is the function of wind speed, the specific mass of air, the area of air space where the wind is captured and the height at which the rotor is placed. The power available in a uniform wind field can be expressed as

$$P_{\mathrm{w}} = \frac{1}{2}\rho A v^{3}$$

where P_{w} is the power [W] of the wind with air density ρ [kg/m^3] and wind speed v [m/s] is passing through the swept area A [m^2] of a rotor disk that is perpendicular to the wind flow. The wind turbine can only capture a fraction of the power available from the wind. The ratio of captured power to available power is referred to as the power coefficient

$$C_{\mathrm{p}}(\beta, V_{\mathrm{e}}, \Omega_{\mathrm{r}}, R)$$

which is a function of the collective blade pitch angle β, effective wind speed V_{e}, rotor speed Ω_{r} and rotor radius R. The value of C_{p} can be expressed according to Ref. [54] as:

$$C_{\mathrm{p}}(\beta, V_{\mathrm{e}}, \Omega_{\mathrm{r}}, R) = 0.5176\left(\frac{116}{\dfrac{1}{\frac{R\Omega_{\mathrm{r}}}{V_e} - 0.08\beta} - \dfrac{0.035}{\beta^3+1}} - 0.4\beta - 5\right)e^{\frac{-21}{\frac{1}{\frac{R\Omega_{\mathrm{r}}}{V_{\mathrm{e}}}-0.08\beta}-\frac{0.035}{\beta^3+1}}} + 0.0068\frac{R\Omega_{\mathrm{r}}}{V_{\mathrm{e}}}$$

A characterization of the power coefficient C_{p} for the wind turbine used in this study is optimized to achieve maximum value. The optimization procedures is expressed as

$$\begin{aligned} &\max C_{\mathrm{p}} = C_{\mathrm{p}}(\beta, V_{\mathrm{e}}, \Omega_{\mathrm{r}}, R) \\ &45^{\circ} \geq \beta \geq 0^{\circ} \\ &50\ \mathrm{m/s} \geq V_{\mathrm{e}} \geq 8\ \mathrm{m/s} \\ &30\ \mathrm{rpm} \geq \Omega_{\mathrm{r}} \geq 60\ \mathrm{rpm} \\ &R = 25\ \mathrm{m} \end{aligned} \tag{1}$$

In this paper a new approach to a CVT power transmission system is presented. It is added just before the generator, avoiding the need to change the main gearbox and the aerodynamic tip brake control pipes. Fig. 1 shows a widely used power transmission system of a wind turbine with the proposed CVT system installed. The power flows from the rotor hub through the input shaft to the main gearbox. It is the same unit that is used in a fixed speed wind turbine. This gearbox could consist of a planetary stage and two simple spur gear stages. The disc brake is conventionally installed after the main gearbox. In a fixed speed design the power would flow from the main gearbox directly to the generator. This is the point where the proposed CVT system is installed. It is suggested to use for CVT system two spring-loaded pulleys, one at the driving shaft and one at the driven shaft. With such a simple and inexpensive solution, the CVT was automatically regulated and adjusted its transmission ratio to the torque applied on the driving pulley. A layout of the drive train components of the wind turbine is illustrated in Fig. 2.

The general speed ratio i_{CVT} is given by:

$$i_{\mathrm{CVT}} = \frac{\omega_{\mathrm{A}}}{\omega_{\mathrm{B}}}$$

where ω_{A} is the angular velocity of the power input shaft and is connected to the output shaft of the main gearbox. The ω_{B} is the angular velocity of the output shaft connected to the generator. Finally there is adjustment shaft with angular velocity ω_{C} which is connected to the hydraulic system. Variation of the speed of the adjustment shaft leads to variation of the total transmission ratio of the gearbox. The angular velocities of the three shafts ω_{A}, ω_{B}, ω_{C} fulfill the following relationship:

$$\omega_{\mathrm{C}} = x\cdot\omega_{\mathrm{A}} + y\cdot\omega_{\mathrm{B}}$$

where x and y are constants defined by the numbers of teeth of each gear and the overall gearbox system. In the special case where

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