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Sensorless estimation of wind speed by adaptive neuro-fuzzy methodology

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ABSTRACT

The wind speed has a huge impact on the wind turbine output energy and safety. Because of this, many control algorithms use a measure of the wind speed to increase performance. Unfortunately, no precise measurement of the effective wind speed is online available from direct measurements, which means that it must be estimated in order to make such control methods applicable in practice. In this paper, a novel algorithm for wind speed estimation in wind-power generation systems is proposed, which is based on adaptive neuro-fuzzy inference system (ANFIS). The inputs of the ANFIS wind speed estimator are chosen as the wind turbine power coefficient, rotational speed and blade pitch angle. During the off-line training, a specified model, which relates the inputs to the output, is obtained. Then, the wind speed is determined online from the instantaneous inputs. Neural network in ANFIS adjusts parameters of membership function in the fuzzy logic of the fuzzy inference system (FIS). This intelligent estimator is implemented using Matlab/Simulink and the performances are investigated. The simulation results presented in this paper show the effectiveness of the developed method.

Introduction

Due to the environmental problem and lack of power, wind power, as a renewable energy, has received much concern and noticeable attention all over the world. The use of wind energy has developed greatly throughout the world in hopes of achieving the ideal of a future with environmentally familiar electrical generation [1]. However, wind is considered to be one of the weather variables that are more problematic to estimate [2,3]. Wind speed estimation is very important in power systems due to the fact that insight of wind speed is needed for estimation the energy output of a wind speed energy conversion system [4,5].

In all types of wind power conversion system, variable speed power generation system [6] is more remarkable than others because of its high power extraction ability and high power quality [7,8]. In the performing wind speed range, in order to achieve the maximum power of wind turbine, the turbine shaft rotational speed should be adapted optimally with respect to the variable wind speed [9]. Such turbine rotor speed control should base on the real-time information of wind speed [10,11]. Normally, wind speed anemometers are dedicated for the wind speed estimation. However, high cost of precise anemometer restraints the major use of this apparatus. For example, the surrounded installed anemometers cannot provide decent and precise wind speed information for every wind turbine in wind farms [12]. The anemometer mounted on the top of nacelle may be a origin of inaccurate measurement of the wind speed [13]. In wind farms, several anemometers are often placed at some positions to measure the average wind speed [14]. The use of anemometers boosts a problem of adjustment and measurement accuracy, as well as increasing the initial cost of the wind generation systems [15]. For these reasons, it is desirable to replace the mechanical anemometers by the digital wind-speed estimator based on the turbine attribute [16,17]. Recently, the wind-speed estimation methods have been reported in the literature [18–22].

Paper [23] presented a performance analysis of short-term wind speed prediction techniques based on soft computing models formulated on a backpropagation neural network (BPNN), a radial basis function neural network (RBFNN), and an adaptive

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neuro-fuzzy inference system (ANFIS). The test results obtained for 1-h-ahead and 3-h-ahead forecasts confirm that the proposed wind speed forecasting algorithm based on ANFIS was capable of transforming the historical numerical weather data into wind speed predictions with higher accuracy. Wind speed forecasting is important for the security of wind power integration. Based on the theories of wavelet, wavelet packet, time series analysis and artificial neural networks, three hybrid models were proposed in Ref. [24] to predict the wind speed. The presented models are compared with some other classical wind speed forecasting methods including neuro-fuzzy, ANFIS, wavelet packet-RBF (radial basis function) and PM (Persistent Model). The results of three experimental cases shown that the proposed three hybrid models have satisfactory performance in the wind speed predictions. There are always some missing and invalid data in wind measurement, which poses the main challenges for wind energy resources assessment. An ANFIS model was proposed in Ref. [25], in which fuzzy inference algorithm were used to interpolate the missing and invalid wind data. The paper [26] demonstrated the viability of ANFIS method for the estimation of wind speed at a higher heights based on wind speed knowledge at lower heights. The close agreement between estimated and measured wind speed at 40 m indicated the viability of the proposed method.

In this paper, a novel algorithm for wind speed estimation in wind power generation systems is proposed, which is based on the adaptive neuro-fuzzy inference system (ANFIS). ANFIS [27], as a hybrid intelligent system that reinforces the ability to automatically learn and adapt, was used by researchers for modeling [28–31], predictions [32–34] and control [35–39] 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 [40–47]. The inputs of the ANFIS wind-speed estimator are chosen as the wind turbine power coefficient, rotational speed and blade pitch angle. During the offline training, a stated model, which relates the inputs to the output, is obtained. Then, the wind speed is determined online from the instantaneous inputs. The experimental results have verified the validity of the proposed estimation algorithm.

Materials and methods

Wind energy conversion system

The primary components of a typical wind energy conversion system are wind turbine, a generator, interconnection devices 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 contains 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 as expressed as:

$$P_w = \frac{1}{2}\rho A v^3$$

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 portion of the power available from the wind. The ratio of captured power to available power is referred to as the power coefficient

$$C_p(\beta,\ V_e,\ \Omega_r,\ R)$$

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 [48] as:

$$C_p(\beta,\ V_e,\ \Omega_r,\ R) = 0.5176\left(\frac{116}{\frac{1}{\frac{R\Omega_r}{V_e}-0.08\beta}-\frac{0.035}{\beta^3+1}} - 0.4\beta - 5\right)e^{\frac{-21}{\frac{1}{\frac{R\Omega_r}{V_e}-0.08\beta}-\frac{0.035}{\beta^3+1}}} + 0.0068\frac{R\Omega_r}{V_e} \tag{1}$$

In this article the main aim is to express wind speed V_e in relation to the three wind turbine parameters: blade pitch angle β, rotor speed Ω_r and power coefficient C_p for rotor radius $R = 75$ m:

$$V_e(C_p,\ \beta,\ \Omega_r) \tag{2}$$

For this purpose, adaptive neuro-fuzzy inference system (ANFIS) is used. Afterwards according to the three wind turbine parameters the ANFIS should estimate wind speed.

Input parameters

As a data-driven model, the ability of the ANFIS to make reasonable estimations is mostly dependent on input parameter selection. Adequate consideration of the factors controlling the system studied is therefore crucial to developing a reliable network. According to the experiments [49], the inputs parameters (rotor speed, blade pitch angle and power coefficient) are collected in wind turbine and defined as input for the learning technique. The data are collected by National Instruments DAQ card. For the experiments, 70% of the data was used to train samples and the subsequent 30% served to test samples. A summary of the statistical properties of the wind turbine database is provided in Table 1.

Sensorless ANFIS estimator of wind speed

An estimator is a device which estimated each and every operation in a decision-making system. It may be a hardware-based estimator or a software-based estimator or a combination of both. In this section, the development of the estimator strategy for estimation of the wind speed is presented using the concepts of ANFIS scheme. The fuzzy logic provides an algorithm, which converts the linguistic estimation, based on expert knowledge, into an automatic estimation strategy. Linguistic variables, defined as variables whose values are sentences in a natural language (such as large or small), may be represented by the fuzzy sets. A fuzzy set is an extension of a 'crisp' set where an element can only belong to a set (full membership) or not belong at all (no membership). Fuzzy sets allow partial membership, which means that an element may partially belong to more than one set. Therefore, the fuzzy logic algorithm is much closer in spirit to human thinking than traditional logical systems. The main problem with the fuzzy logic generation is related to the choice of the regulator parameters. For this reason, we apply the ANFIS methodology to adapt the parameters of the fuzzy logic according to real data about the problem.

Table 1
Statistical properties of wind turbine database.

Input parameters	Average value $\bar{x}$	Maximum value (x_{max})	Minimum value (x_{min})
Wind turbine			
Rotor speed (rpm)	7.988345	13.3733	1.03275
Blade pitch angle (deg)	20.57143	45	0
Power coefficient (Cp)	0.206539	0.480012	0.069299