HYBRID SOFT COMPUTING CONTROL STRATEGIES FOR IMPROVING THE ENERGY CAPTURE OF A WIND FARM

by

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In this paper, a fuzzy controller is proposed for wind turbine control. A model is analyzed and combined with a stochastic wind model for simulation purposes. Based on the model, a fuzzy control of wind turbine is developed. Wind turbine control loop provides the reference inputs for the electric generator control loop in order to make the system run with maximum power. Since the wind speed involved in the aerodynamic equations is a stochastic variable, whose effective value cannot be measured directly, a wind speed estimator is also proposed.

Key words: *computational intelligence, fuzzy control, wind turbine, wind data estimation*

Introduction

The need for energy constantly rises, and even the wealthier countries encounter problems with energy production and consumption. All these facts point to the necessity of transition to the sustainable development, especially to the usage of renewable energy sources. Wind energy is the fastest growing power generating technology in the world due to its availability, purity, large potentials, and environment friendly operation. The present constraints are mostly of financial nature. For the purpose of wind power estimation, the wind atlas method is developed, which has become easy to use with the fast development of computers. The position of a wind turbine is in strong correlation with energy production.

The control design for wind power systems represents an interesting yet challenging research topic. In contrast to conventional power generation, where input energy can be scheduled and regulated, wind energy is not a controllable resource, due to its interchangeable and stochastic nature. Automatic control represents one of the most important factors responsible for the efficiency and reliability of wind power generating systems.

Many researches in relevant fields considering wind turbines have been published in recent years. One area currently under investigation is variable-speed wind turbines. Even if they are less implemented and more complicated to be controlled, variable speed wind turbines (VSWT) show many advantages compared to fixed speed wind turbines [1-3]. Typically, variable-speed turbines use aerodynamic controls in combination with power electronics to regulate torque, rotor speed, and power [1, 4]. The primary advantages claimed for variable-

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speed turbines are increased energy capture and reduced drive train loads. Secondary benefits are acoustic signature and power quality.

Idan *et al.* [5] realized a variable speed wind turbine using robust control. Song *et al.* [6, 7] developed a variable pitch control and variable speed wind turbine using nonlinear and adaptive control, and investigated a memory-based method for variable speed control of wind turbines. The main idea behind this method is to use certain gathered information, such as past and recent rotor speed, as well as previous control experience, to generate a new control action. Boukhezar *et al.* [4-9] suggested nonlinear control of variable speed wind turbines for power optimization, analyzed nonlinear control without wind speed measurement, and compared linear and nonlinear wind turbine control. Camblong *et al.* [10] developed a robust digital control of a wind turbine for a rated-speed and variable-power operation regime.

Some of the papers published during the past few years suggest the implementation of soft computing and artificial intelligence methodologies, such as fuzzy logic control, for high level supervisory control of variable speed wind turbine [11, 12], in order to extract maximum power. In paper [13] a real coded genetic algorithm was used for variable transmission wind turbine PID controller tuning.

Considering high complexity and stochastic nature of dynamics of the variable speed wind turbine, soft computing methods are a logical solution for control problems. In this paper, a fuzzy controller is proposed for wind turbine control. Two mass models proposed in literature [1, 4] are analyzed and then combined with a stochastic wind model for simulation purposes. Based on the model, a fuzzy control of wind turbine is developed. The wind turbine control loop provides the reference inputs for the electric generator control loop. The main idea is to try to get the system to work as efficiently as possible. In order to make the system run with maximum power, the optimal rotation speed of the turbine must be achieved at any time, thus making it, basically, a tracking problem of a nonlinear stochastic system.

Since the wind speed involved in the aerodynamic equations is a stochastic variable, whose effective value cannot be directly measured, a wind speed estimator based on the sequential Monte Carlo technique is developed in this paper, similar to the estimation model presented by Pang *et al.* [14] and Boukhezar *et al.* [8].

Wind data

Within the atmospheric boundary layer (ABL), the wind speed varies with height. Earth surface, being uneven as it is, combined by extremely various vegetation and urban areas, causes the friction forces that slow down the wind speed in the lower layers of the atmosphere. Further from the surface, these effects diminish and disappear in the transition from ABL to the free tropospheric layer, in which there are no changes of wind speed with height. The roughness effects in the ABL can be described in many ways. Usually, a Prandtl logarithmic equation is used:

$$\frac{V_m(z)}{V_m(z_{\text{ref}})} = \frac{\ln z - \ln z_0}{\ln z_{\text{ref}} - \ln z_0} \tag{1}$$

or, for fast assesment, in the following form:

$$\frac{V_m(z)}{V_m(z_{\text{ref}})} = \left(\frac{z}{z_{\text{ref}}}\right)^{\alpha} \tag{2}$$

where z represents the height above the ground, z_{ref} is the reference height (usually 10 m, as the height of the cup anemometers that are usually installed in meteorological stations), z_0 is the roughness height, and α is the terrain roughness coefficient (tab. 1).

Table 1. Typical values for z_0 and α

Terain type	z_0	α
Sand	0.2-0.3	0.10
Low grass	1-10	0.13
High grass, bushes	40-100	0.19
Orchards, forests	1000-2000	0.32

As the characteristics of the terrain orography can drastically alter the wind, many possible locations were tested [15,16]. The software used for simulations of wind energy potentials were WAsP (Wind Atlas Analysis and Application Program) [17] and WindSim (part of PHOENICS simulation code) [18]. All sites were tested using the same 2 MW turbine with 138 m in hub height and 82 m in rotor diameter. The wind farm locations are shown in fig. 1 and the summarized data are given in tab. 2.

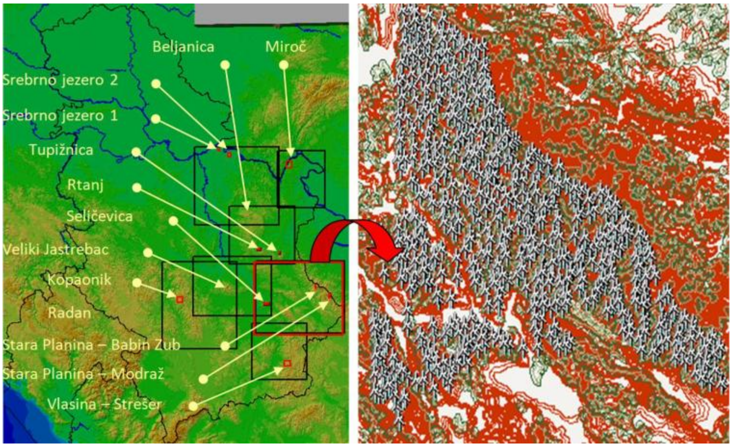

Figure 1. Tested models and Stara Planina farm

Table 2. Summarized results for all wind farms

Location	AEP [GWh]	Turbine No.	Acc. data [%]	Capacity f. [%]
Beljanica	33.527126	16	84.57	11.96
Kopaonik	10.061947	12	83.08	4.79
Miroc	49.568523	18	57.45	15.72
Selicevica	9.5554292	3	58.85	18.18
Srebrno Jezero 1	15.522138	5	80.28	17.72
Srebrno Jezero 2	21.923542	7	80.28	8.00
Stara Planina – Babin Zub	101.51674	15	72.99	38.63
Stara Planina – Modraz	79.800528	12	72.99	37.96
Radan	20.634183	10	59.59	11.78
Rtanj	51.2247	10	84.57	29.24
Tupiznica	25.116965	6	84.57	23.89
Vlasina – Streser	135.28362	25	65.27	30.89
Veliki Jastrebac	348.50418	98	40.90	20.30
Vrska Cuka	41.183638	10	84.57	23.51
Stara Planina – total	5165.0290	682	72.99	40.06

One can notice that the best results were obtained for Stara Planina (Balkan Mountains). All other data will be presented for this wind farm with 682 turbines. The wind data used for this simulation were obtained from the central meteorological station Dimitrovgrad, which is located in the foot of the mountain. The observed wind data are shown in fig. 2.

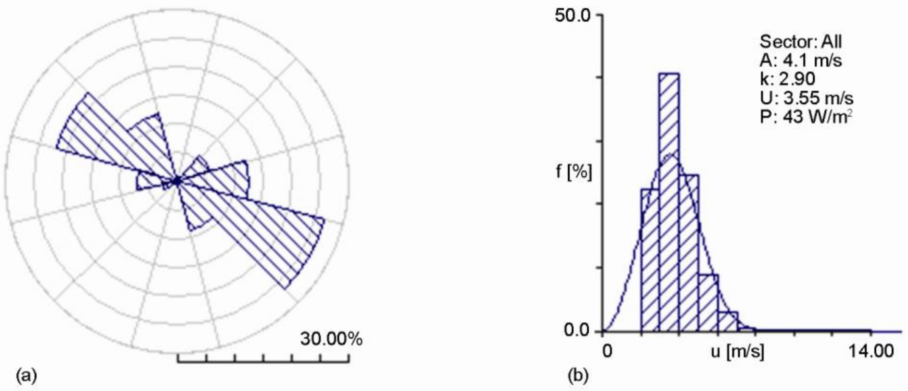

Figure 2. Wind rose (a) and Weibull histogram (b) for the data from the meteorological station Dimitrovgrad

Measurements of wind speed at the turbine site were not available for the case study presented in this paper. The nearest meteorological station was Dimitrovgrad, for which wind speed data were available online [19]. The annual diagram of hourly measured wind speeds in Dimitrovgrad and the estimated wind speed for the discussed location is shown in fig. 3.

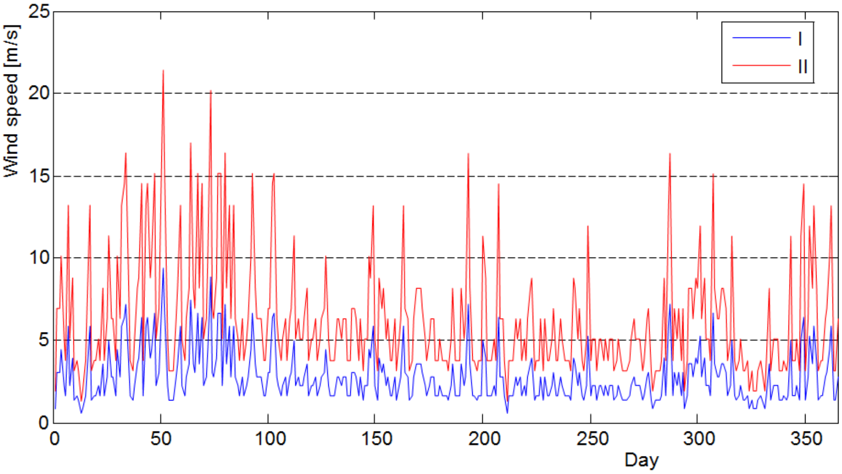

Figure 3. Annual wind data for: (I) Meteorological station Dimitrovgrad, and (II) wind farm location (estimated)

The wind speed was measured 10 m above the ground. Having in mind the wind speed, the wind turbine hub height of 138 m, terrain configuration, and the fact that the suggested location of the wind farm was about 600 m above the meteorological station, the approximate wind speed for the discussed location was calculated based on the previously explained methodology.

Wind power turbine control strategies

Control objectives

It is well known that the wind turbine electric system time responses are much faster than the responses of mechanical parts of the wind turbine. Considering this fact, it is possible to develop a control structure around two control loops, the lower-level control loop that controls the electric generator via the power converters, and the higher-level control loop that controls the wind turbine by providing the reference inputs of the lower level control loop [20].

Many papers have analyzed, developed, and discussed the electrical part control without considering the wind turbine control, therefore, it is possible to assume that the internal, electrical loop is well controlled. This paper focuses on the higher-level wind turbine control – the wind turbine control.

The aerodynamic power captured by the rotor [10] is:

$$P_a = \frac{1}{2}\rho\pi R^2 C_p(\lambda, \beta) v^3 \tag{3}$$

where $C_p(\lambda, \beta)$ is the power coefficient, v – the wind speed, ρ – the air density, R – the rotor radius, and P_a – the aerodynamic power.

The power coefficient C_p is the ratio between the available wind power and the captured wind power, the variable that depends on the blade pitch angle β and the tip speed ratio λ. Tip speed ratio λ is defined as:

$$\lambda = \frac{\omega_t R}{v} \tag{4}$$

where ω_t is the rotor speed.

There are two operating areas of a variable speed wind turbine, below and above the rated wind speed. Below the nominal power, the main control objectives are to maximize wind power capture and to reduce the loads submitted by the drive train shaft. The power coefficient curve $C_p(\lambda, \beta)$ has a unique maximum that corresponds to an optimal wind energy capture:

$$C_p(\lambda_{\text{opt}}, \beta_{\text{opt}}) = C_{p\text{opt}} \tag{5}$$

where

$$\lambda_{\text{opt}} = \frac{\omega_{t\text{opt}} R}{v} \tag{6}$$

In order to maximize wind power extraction, for the system that operates below nominal power, therefore, having the constant blade pitch angle, the goal is to maintain λ at its optimal value, thus the rotor speed ω_t must be adjusted to track the optimal rotation speed:

$$\omega_{t\text{opt}} = \frac{\lambda_{\text{opt}}}{R} v \tag{7}$$

With a variable speed wind turbine, optimal energy is achieved by keeping the tip-speed ratio at its optimal value $\lambda_{\text{opt}} = 5.5$. The turbine must then track the variations of the wind speed, which demands large variations of torque and speed.

Since the nonlinearity of the process depends significantly on the wind speed, it seems that the wind speed is vital to the behavior of the system.

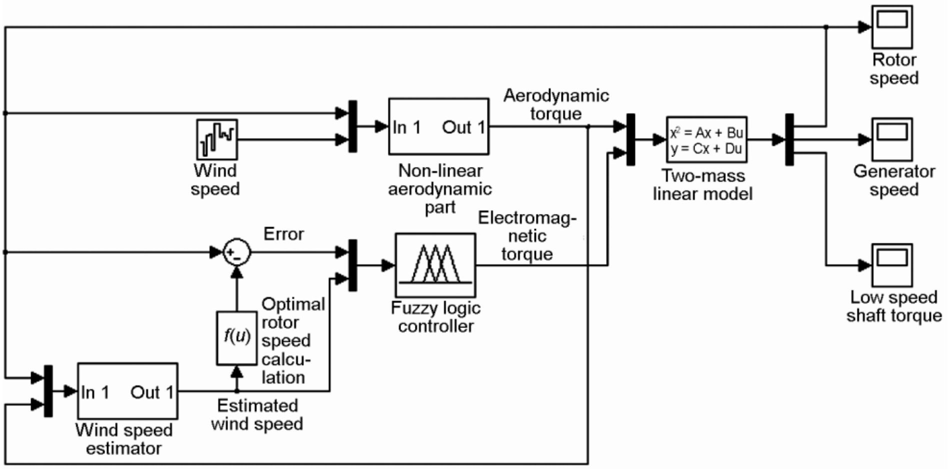

Figure 4. Hybrid fuzzy control scheme of the aero turbine

Takagi Sugeno fuzzy controller is tuned and combined with a wind speed estimator and applied as a hybrid fuzzy control algorithm for the variable speed aero turbine [3], fig. 4.

Wind turbine fuzzy control

Rule based fuzzy logic controllers are useful when the system dynamics is not well known or when there are significant nonlinearities, such as the unsteady wind that contains large turbulence. Fuzzy logic controllers apply reasoning, similar to how human beings make decisions, and thus the controller rules contain expert knowledge of the system. The big advantages of fuzzy logic control when applied to a wind turbine are that the turbine system neither needs to be accurately described nor does it need to be linear [3]. The design process for a fuzzy logic controller consists of determining the inputs, setting up the rules, and designing a method to convert the fuzzy result of the rules into an output signal, known as defuzzification.

Since one of the inputs of the controller is the rotor speed error e, which represents the difference between the measured rotor speed ω_t and the optimal rotor speed ω_{topt}, and the other input is the wind speed v, and the controller output is the electromagnetic torque T_{em}, the generalized fuzzy rule is:

$$R_{ij}\text{: If } e \text{ is } e_i \text{ and } v \text{ is } v_j \text{ then } T_{em} \text{ is } T_{ij}$$

The main idea of a fuzzy logic controller implemented in a control loop is to ensure maximum energy efficiency by maximizing the captured wind power. In order to achieve that, tracking control of optimal rotor speed must be ensured. Tuning of the parameters for the generator torque T_{ij} is done by expert knowledge and after optimization [3].

Simulation results

In order to verify the control principle given in this paper, a detailed simulation model of the control system was developed. For the Monte Carlo simulation of the wind speed that lasted 10 minutes, the optimal rotor speed was calculated and compared with a simulated response of a fuzzy controlled system (fig. 5). The reference for the fuzzy control system was given by the estimated wind speed. Having this in mind, the response was more than satisfactory.

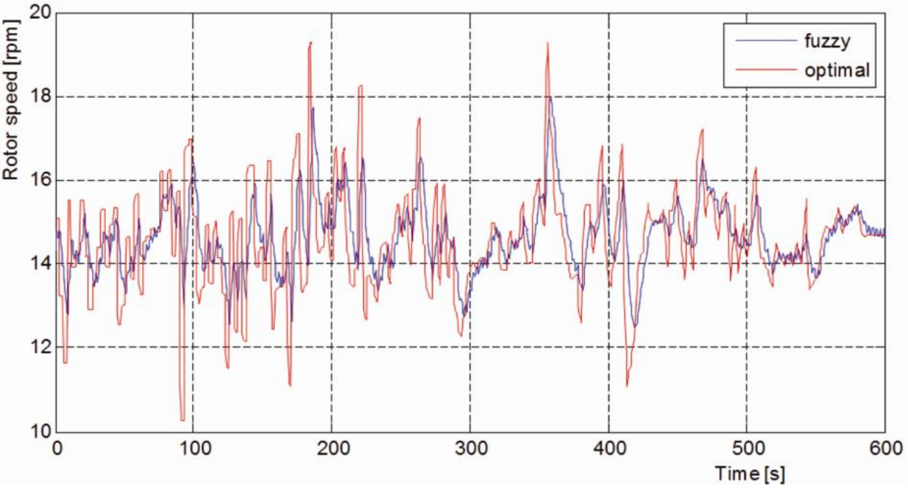

Figure 5. Rotor speed ω_t

It is obvious that the wind turbine with a fuzzy controller used for the high-level control can track the maximum power delivery operating point. Again, the simulation could have achieved more data that were accurate if the power electronic system had been simulated as well, but the simulation data were good enough for the proposed control approach verification.

Energy output estimation for wind turbines of different power ranges has been the subject of a number of papers. Most of these studies have used the wind speed pattern of a region to estimate the wind speed distribution of that region, and then, by knowing the wind turbine specifications, to estimate the energy output of that turbine. Average wind turbine power production per annum is presented in fig. 6.

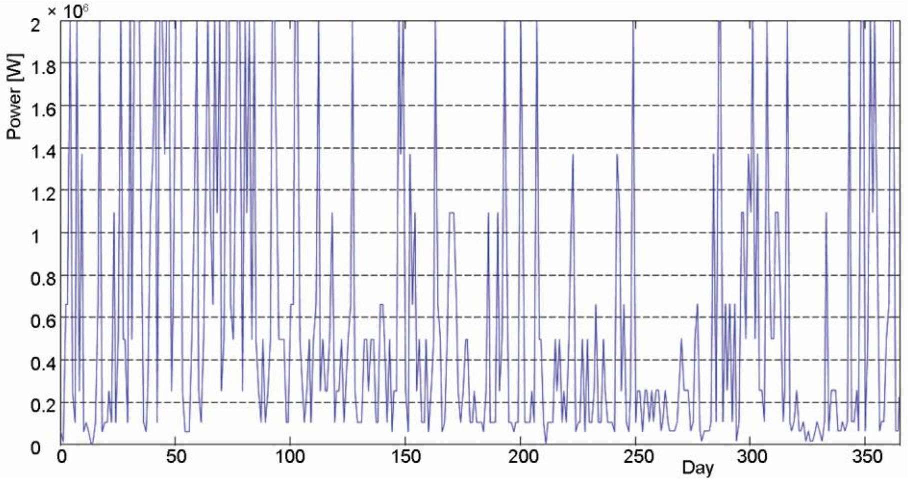

Figure 6. Annual power production for variable speed 2 MW wind turbine

A 2 MW three blade wind turbine with the rotor diameter D = 82 m was used for simulation purposes. Such a turbine could produce up to 8.09 GWh electric energy per annum if the suggested advanced control algorithm is used. A wind farm with 682 wind turbines could produce 5516.02 GWh.

One of the disadvantages of this model is that for any wind turbine a new model should be built, but the model built for an arbitrary wind turbine can be used with other similar ones by means of making some minor changes to the former model. To make these changes, the rated power, the hub height, and the rated wind speed of the former and the latter wind turbine should be known.

Conclusions

In this paper, fuzzy control of a variable speed wind turbine is proposed in order to extract the maximum wind power and achieve maximum energy efficiency. The wind turbine system is a complex multivariable and nonlinear stochastic system. This system involves some disturbances and has autologous indeterminacy. The implemented fuzzy controller makes the turbine operate at its optimum level of aerodynamic efficiency by continuously adapting the rotation speed of the rotor. The supervisory fuzzy control loop output is the optimal generator torque, which is then tracked by the low level control loop of power electronics . For such an optimal behavior, a genetic algorithm was used for parameter tuning.

Another important part of the control system, that changes the Takagi Sugeno fuzzy control into a hybrid fuzzy system, is the wind speed estimator. Since it was not possible to directly measure the current wind speed value, it was necessary to develop some sort of estimation.

The implemented system had satisfactory dynamic and static performances. The main advantages of the suggested hybrid fuzzy control algorithm are relative simplicity, universal control algorithm, fast response, and parameter insensitivity followed by maximum wind power extraction.

Another use of the simulation system developed in this paper is the estimation of average annual energy output of a wind turbine and, therefore, of a whole wind farm.

Finally, using the wind power simulating software, it was estimated that the annual power output would be 5165.029 GWh, while with fuzzy control this output could be enlarged to 5516.02 GWh], which is an improvement of about 6.8%, that makes this methodology highly desirable and applicable.

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