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HYBRID FUZZY CONTROL STRATEGIES FOR VARIABLE SPEED WIND TURBINES

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Abstract. *Control of variable speed wind turbine system is very complicated because of the stochastic nature of the wind and the complexity of power electronics. In classical control, the controller design needs accurate mathematical model, but this kind of model of the wind turbine system is very difficult to get because of the nonlinear characteristics, stochasticity, disturbances and uncertainties. Two mass-model of the variable speed wind turbine is analyzed, improved and then combined with stochastic wind model for simulation purposes. In order to simplify the design and implementation of controller and to avoid development of more sophisticated mathematical model, fuzzy control system is proposed. In this paper only the case of subcritical wind speed was analyzed and fuzzy controller was applied for supervisory aeroturbine control. Since it is not possible to measure wind speed directly, particle filter is used for estimation of the wind speed used in control loop.*

Key words: *fuzzy control, wind turbine, wind speed estimation, Monte Carlo simulation, particle filter*

1. INTRODUCTION

Because of the limited supply of fossil fuels and their harmful impact on the environment (such as air pollution, acid rain and the greenhouse effect), interest in renewable energy sources has been increasing all over the world. In this context, many countries have been planning to meet 10% of their electricity demand from wind energy until 2020. In terms of electricity production, wind energy is the most promising renewable energy source among others such as solar, geothermal, and biogas [1].

The progress of wind power around the world in recent years has exceeded all the expectations, with Europe leading the global market. The wind turbine capacity installed in Europe increased during the last years at an average annual growth rate superior to 30%.

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Control design for wind power generation systems represents an interesting yet challenging research topic because 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 conversion systems.

Some researches in relevant fields of wind turbines have been published in recent years. The constant speed wind turbine, which was designed with a fixed pitch angle of blades and stall control, was researched in 1980's [2]. Jones and Smith [3] analyzed how to maintain the electric power output of the variable speed wind turbine. Freeman and Balas [4] made the system identification of the dynamic models of wind turbine experimentally.

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 [5,6,7,8]. Typically, variable-speed turbines use aerodynamic controls in combination with power electronics to regulate torque, rotor speed and power [6]. The primary advantages claimed for variable-speed turbines are increased energy capture and reduced drive train loads. Secondary benefits are acoustic signature and power quality.

Idan and Lior [9] realized the variable speed wind turbine using robust control. Song et al. [10] developed the variable pitch control and variable speed wind turbine by the nonlinear and adaptive control. Boukhezar and Siguerdidjane [11] discussed the nonlinear control of variable speed wind turbines without wind speed measurement. Camblong et al. [12] developed a robust digital control of a wind turbine for a rated-speed and variable-power operation regime. The memory-based method for variable speed control of wind turbines was investigated by Song [13]. 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 new control action.

Many of the wind turbines control systems are based on linear models. This is because of several reasons. On the one hand, there are generally simple analytical solutions to many control problems (LQR, pole-placement, Kalman-filtering). On the other hand, it is easier to implement such controllers in practical applications and until now, the major part of implemented wind turbine controllers are based on linearized models. Linear controllers based on the two-mass wind turbine model were proposed in [6,15,16]

The performance of the linear controllers is limited by the highly nonlinear characteristics of the wind turbine. Nonlinear controllers take into consideration the nonlinear nature of the wind turbine behavior, the flexibility of the drive-train shaft and the turbulent nature of the wind. Nonlinear controllers with wind speed estimators have been proposed using a one-mass model [8] and the two-mass model [16].

Some of the papers published during past few years are suggesting implementation of soft computing and artificial intelligence methodologies like fuzzy logic control for high level supervisory control of variable speed wind turbine [17,18,19], or fuzzy pitch angle controller [20] in order to maximize power extraction, or neural network control [1] as pitch angle control supervisor for wind speed higher than nominal. In paper [21] real coded genetic algorithm was used for variable transmission wind turbine PID controller tuning.

Considering high complexity and stochasticity of the variable speed wind turbine dynamics, soft computing methods are logical solution for control problems. In this paper fuzzy controller is proposed for aero turbine control. Two mass model proposed in literature [6,16] is analyzed and then combined with stochastic wind model for simulation purposes. Based on the model, a fuzzy control of aeroturbine is developed. Aero turbine control loop provides the reference inputs for the electric generator control loop. Main idea is to try to make system work as efficiently as it can. In order to make system run with maximum power, optimal rotation speed of the turbine must be achieved at any time, so it is basically tracking problem of nonlinear stochastic system.

Because the wind speed involved in the aerodynamic equations is a stochastic variable, whose effective value that cannot be directly measured, a wind speed estimator based on sequential Monte Carlo technique on is developed in this paper. Rather than considering the wind speed as a linear filtered non-correlated white noise, the effective wind speed is estimated using the wind turbine itself as a measurement device.

2. Variable Speed Wind Turbine Modeling

It is now commonly accepted that variable speed wind turbines can produce up to 20% more power than fixed speed wind turbines [10]. Another advantage to variable speed wind turbines lies is in their torque-absorbing ability which increases the operational life of the mechanical components. These advantages are currently accomplished by allowing the generator and rotor to rotate at varying speeds as the wind speed changes. The disadvantage to this approach is that the variable electricity produced must be rectified and inverted before being added to the grid.

A two-mass model is commonly used in the literature [6,15,16] to describe the wind turbine dynamics. Its scheme is illustrated in Fig. 1. The use of a two-mass model for controller synthesis is motivated by the fact that the control laws derived from this model are more general and can be applied for wind turbines of different sizes. Particularly, these controllers are more adapted for high-flexibility wind turbines that cannot be properly modeled with a one mass model. It is also shown that the two-mass model can report flexible modes in the drive train model that cannot be highlighted with the one mass model [16].

The aerodynamic power captured by the rotor is:

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

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

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

$$\lambda = \frac{\omega_t R}{v}, \tag{2}$$

where ω_t is a rotor speed.

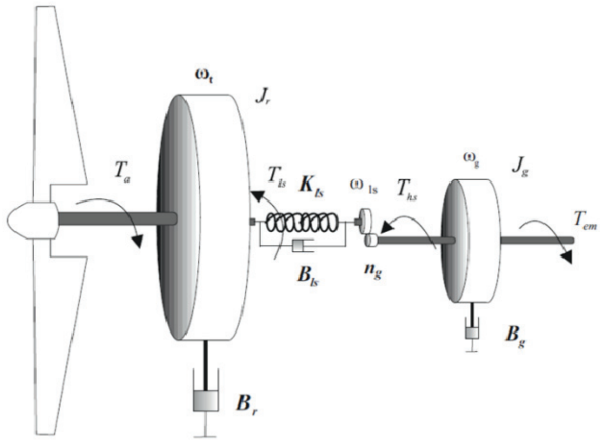

Fig. 1. Wind turbine two-mass dynamic model

The C_p (Figure 2) has a unique maximum value which is given by a pitch angle, in this case 5^o and an optimal tip speed ratio. For the horizontal-axis wind turbine used for simulation purposes the maximum value of C_p is 0.59 and the optimal tip speed ratio is 5.5.

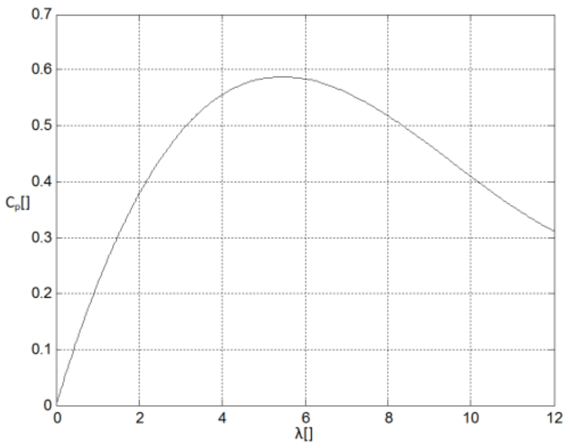

Fig. 2. $C_p(\lambda)$ surface for horizontal-axis wind turbine

The aerodynamic torque is:

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

where:

$$C_q(\lambda,\beta) = \frac{C_p(\lambda,\beta)}{\lambda} \tag{4}$$

is a torque coefficient.

The rotor-side inertia J_r dynamics are given by the first order differential equation:

$$J_r \dot{\omega}_t = T_a - T_{ls} - B_r \omega_t \,, \tag{5}$$

where the low-speed shaft torque T_{ls} acts as a braking torque on the rotor:

$$T_{ls} = K_{ls}(\theta_t - \theta_{ls}) + B_{ls}(\omega_t - \omega_{ls}) \,, \tag{6}$$

B_r is rotor external damping, K_{ls} and B_{ls} are low speed shaft stiffness and low speed shaft damping, $\omega_{ls}$is low speed shaft speed, θ_t, θ_{ls} and θ_g are rotor side angular deviation, gearbox side angular deviation and generator side angular deviation.

The generator inertia J_g is driven by the high-speed shaft torque and braked by the electromagnetic torque T_{em} and generator damping:

$$J_g \dot{\omega}_g = T_{hs} - B_g \omega_g - T_{em} \,, \tag{7}$$

where B_g presents a generator external damping, ω_g is a generator speed and T_{hs} is high speed shaft torque.

If an ideal gearbox with a ratio n_g is assumed, where:

$$n_g = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_{ls}} = \frac{\theta_g}{\theta_{ls}} \,, \tag{8}$$

and T_{ls} is calculated as a time derivative from (6) and then incorporated in (7) and (8), the whole dynamic system can be presented in state space as:

$$\begin{bmatrix} \dot{\omega}_t \\ \dot{\omega}_g \\ \dot{T}_{ls} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} \omega_t \\ \omega_g \\ T_{ls} \end{bmatrix} + \begin{bmatrix} b_{11} \\ a_{21} \\ a_{31} \end{bmatrix} T_a + \begin{bmatrix} b_{12} \\ a_{22} \\ a_{32} \end{bmatrix} T_{em} \,, \tag{9}$$

where:

$$a_{11} = -\frac{B_r}{J_r}, a_{12} = 0,\ a_{13} = -\frac{1}{J_r}, a_{21} = 0,\ a_{22} = -\frac{B_g}{J_g},\ a_{23} = \frac{1}{n_g J_g},$$

$$a_{31} = \left(K_{ls} - \frac{B_{ls} B_r}{J_r} \right), a_{32} = \frac{1}{n_g} \left(\frac{B_{ls} B_r}{J_g} - K_{ls} \right),\ a_{33} = B_{ls} \frac{1}{n_g} \left(\frac{J_r + n_g{}^2 J_g}{n_g{}^2 J_g J_r} \right)_{ls} \text{ and}$$

$$b_{11} = \frac{1}{J_r},\ b_{12} = 0,\ b_{21} = 0,\ b_{22} = -\frac{1}{J_g},\ b_{31} = \frac{B_{ls}}{J_r},\ b_{32} = \frac{B_{ls}}{n_g J_g}.$$

This part of dynamic system is linear and further improvement can be done by introducing some nonlinearities that occur in order to achieve better agreement between experimental and simulation results.

3. Wind Power Turbine Control Strategies

3.1. Control objectives

Since the wind turbine electric system time responses are much faster than responses of mechanical parts of the wind turbine, it is possible to develop a control structure around two control loops, the lower control level loop that controls the electric generator via the power converters and the higher level control loop that controls the aero turbine by providing the reference inputs of the lower level control loop.

Many papers analyze, develop and discuss the electrical part control without considering the aero turbine control, and therefore assumption can be made that the internal, electrical loop is well controlled. This paper focuses on the higher level wind turbine control – the aero turbine control.

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, as it was already shown (Fig. 2).

$$C_p(\lambda_{opt},\beta_{opt}) = C_{p_{opt}}\,, \tag{10}$$

where:

$$\lambda_{opt} = \frac{\omega_{t_{opt}} R}{v}\,. \tag{11}$$

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

$$\omega_{t_{opt}} = \frac{\lambda_{opt}}{R} v\,. \tag{12}$$

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

In this paper only the cases where wind speed is below critical was analyzed. The average wind speed analyzed was around 6 [m/s] and for the simulation purposes Monte Carlo simulation of this stochastic process was done for 10 minutes, as shown in figure 3.

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

The wind speed cannot be directly measured and often wind turbine itself is used as a measuring device. If that is the case, an estimator must be used to predict wind speed based on system states, mainly rotor speed and aerodynamic torque. Some researchers [16] are using aerodynamic torque predicted by Kalman filter for further wind speed estimation.

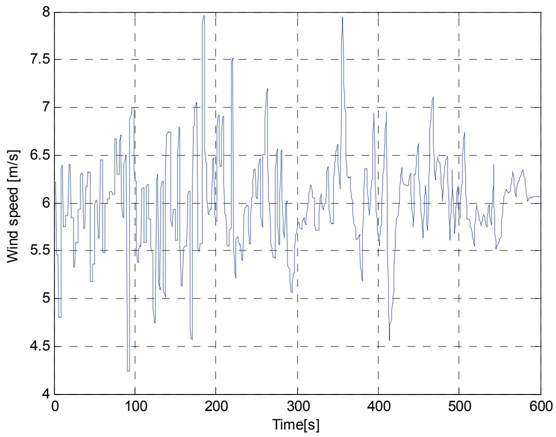

Fig. 3. Wind speed v

Takagi Sugeno fuzzy controller is combined with particle wind speed estimator and applied as a hybrid fuzzy control algorithm for the variable speed aero turbine, as shown in Fig. 4.

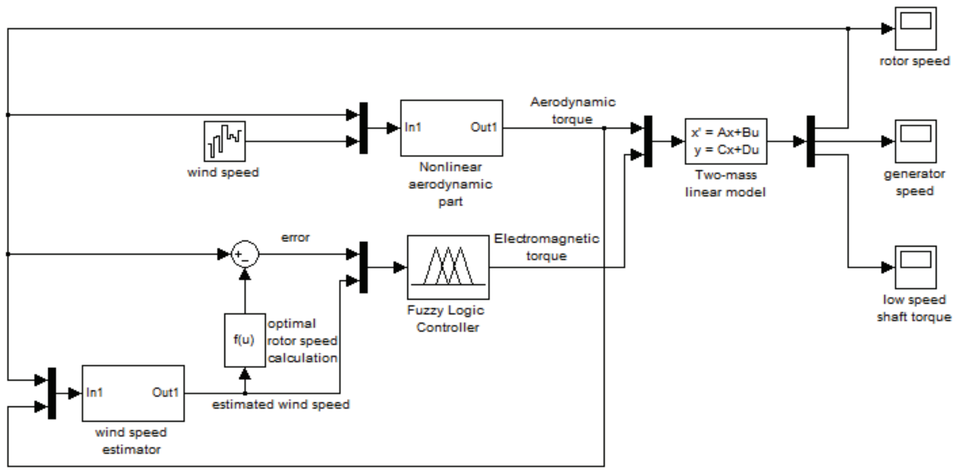

Fig. 4. Hybrid fuzzy control scheme of the aero turbine

3.2. Aero turbine fuzzy control

Rule based fuzzy logic controllers are useful when the system dynamics are not well known or when they contain significant nonlinearities, such as the un-stationary 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 needs to be neither accurately described nor linear [17,18,19]. 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 output signal, known as defuzzification.

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

R_1: If e is *negative* and v is *low* then T_{em} is *low*;
R_2: If e is *negative* and v is *average* then T_{em} is *low*;
R_3: If e is *negative* and v is *high* then T_{em} is *average*;
R_4: If e is *zero* and v is *low* then T_{em} is *low*;
R_5: If e is *zero* and v is *average* then T_{em} is *average*;
R_6: If e is *zero* and v is *high* then T_{em} is *high*;
R_7: If e is *positive* and v is *low* then T_{em} is *average*;
R_8: If e is *positive* and v is *average* then T_{em} is *high*;
R_9: If e is *positive* and v is *high* then T_{em} is *high*.

The membership functions for both inputs are the same and shown in Fig. 5.

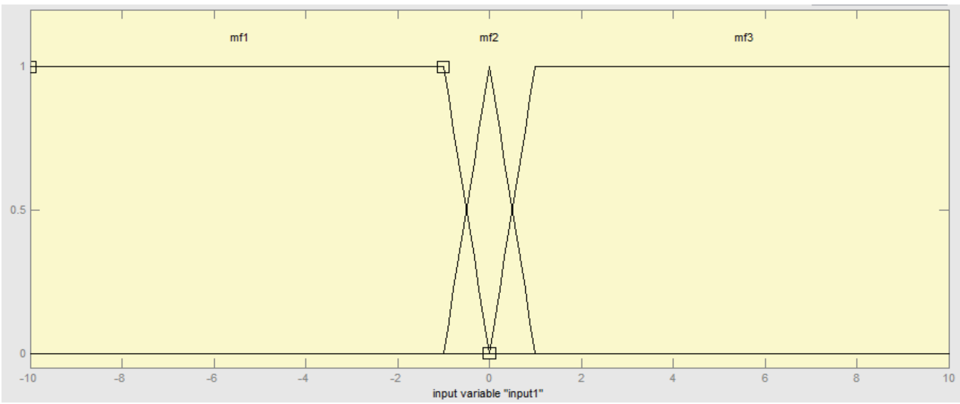

Fig. 5. Fuzzy controller input variables membership functions

The main idea of fuzzy logic controller implemented in control loop is to ensure maximum energy efficiency by maximizing captured wind power. In order to achieve that, tracking control of optimal rotor speed must be ensured. Tuning of the parameters for the *low*, *average* and *high* generator torque T_{em} is done by expert knowledge and after many simulation trials.

3.3. Wind speed estimator

Since it is not possible directly to measure wind speed, in order to determine optimal rotor speed and consequently optimal control action, the estimated wind speed must be used. The estimation of v is done by sequential Monte Carlo estimator from aerodynamic torque T_a and measured rotor speed ω_t.

Monte Carlo simulation is used for simulation of real-life processes and phenomena. The algorithms just follow the corresponding physical, chemical or biological processes under consideration. In such simulations Monte Carlo is used as a tool for choosing one of many different possible outcomes of a particular process. Monte Carlo simulation could be considered as a method for solving probabilistic problems using some kind of simulations of random variables or random fields.

The most popular methods for dynamic state estimation belong to the family of recursive Bayesian estimators, which include Kalman filters and sequential Monte Carlo estimators, also known as particle filters. Particle filters are practical implementations of recursive Bayesian estimators using Monte Carlo simulations [22]. Since their introduction in 1993, particle filters have become a very popular class of numerical methods for the solution of optimal estimation problems in non-linear non-Gaussian scenarios. In comparison with standard approximation methods, such as the popular Extended Kalman Filter, the principal advantage of particle methods is that they do not rely on any local linearization technique or any crude functional approximation [23].

In the Bayesian approach to dynamic state estimation, one attempts to construct the posterior probability density function of the state based on all available information, including the set of received measurements. Since this density function embodies all available statistical information, it may be said to be the complete solution to the estimation problem [23,24]. In principle, an optimal (with respect to any criterion) estimate of the state may be obtained from the density function. A measure of the accuracy of the estimate may also be obtained. For many problems, an estimate is required every time that a measurement is received. In this case, a recursive filter is a convenient solution. A recursive filtering approach means that received data can be processed sequentially rather than as a batch so that it is neither necessary to store the complete data set nor to reprocess existing data if a new measurement becomes available. Essentially such a filter consists of two stages: prediction and update. The prediction stage uses the system model to predict the state density function forward from one measurement time to the next. Since the state is usually subject to unknown disturbances (modeled as random noise), prediction generally translates, deforms, and spreads the state density function. The update operation uses the latest measurement to modify the prediction density function. This is achieved using Bayes theorem, which is the mechanism for updating knowledge about the target state in the light of extra information from new data [24].

4. Simulation Results

In order to verify control principle given in this paper, detailed simulation model of the control system has been developed. For the Monte Carlo simulation of the wind speed that lasted 10 minutes, optimal rotor speed was calculated, and compared with simulated response of fuzzy controlled system (Fig. 6). Reference for the fuzzy control system is given by the estimated wind speed, so having this in mind the response is more than satisfactory.

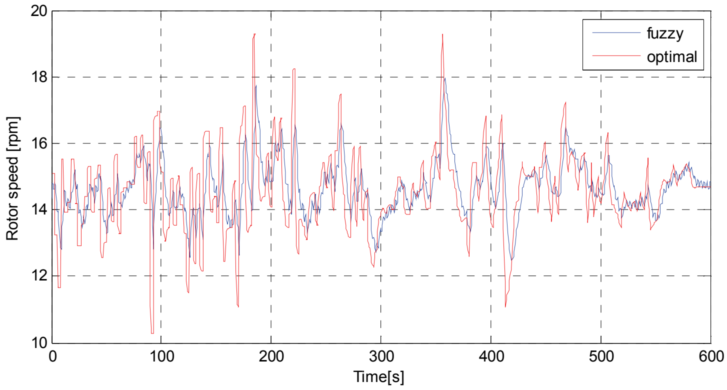

Fig. 6. Rotor speed ω_t

The fuzzy controller output, generator torque T_{em}, is shown in figure 7. The whole simulation is done assuming that the inner control loop can completely fulfill the supervisory demands for electromagnetic torque without any delay, and this approximation is good enough for the supervisory control verification; however, the simulation results cannot be compared to experimental results unless the power electronic control loop is developed for the simulation purposes.

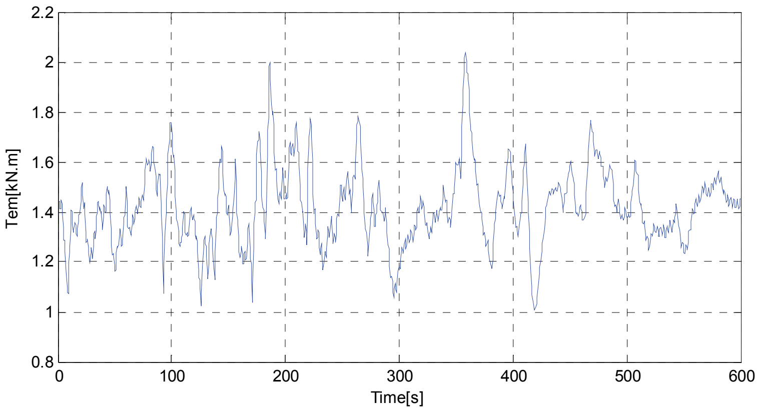

Fig. 7. Electromagnetic torque T_a as an fuzzy controller output

Figure 8 represents the comparison between maximal (optimal) aerodynamic power and the aerodynamic power extracted by the system with fuzzy outer loop control and wind speed estimator.

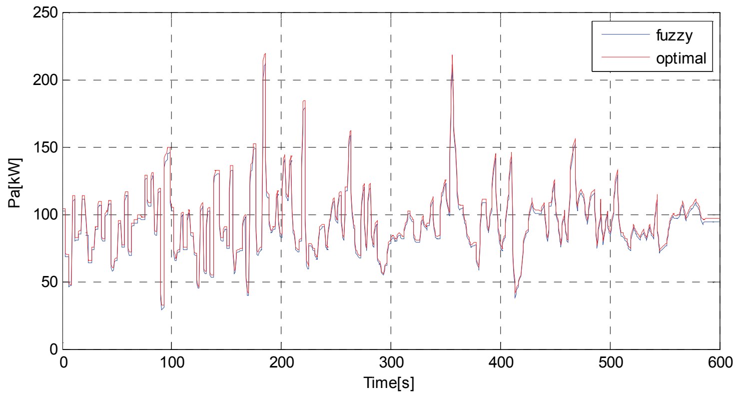

Fig. 8. Simulated aerodynamic power P_a

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

5. Conclusion

The wind turbine system is a complex multivariable and nonlinear stochastic system which involves some disturbances and has autologous indeterminacy. This system requires thinking outside the box when it comes to control algorithm design, and soft computing techniques are then logical solution. In this paper fuzzy control of variable speed wind turbine is proposed in order to extract maximum wind power and achieve maximum energy efficiency. All the techniques whose implementation was proposed were thoroughly described and verified through the simulation. The implemented fuzzy controller is continuously adapting the rotation speed of the rotor speed according to the wind speed in a way that the turbine operates at its optimum level of aerodynamic efficiency. The supervisory fuzzy control loop output is optimal generator torque that low level control loop of power electronic is then tracking.

The possible solution that can be further analyzed is for every fuzzy rule to have $T_{em\,i}$, where i=1, 2,…, 9, as output, and to use some optimization criterion in order to minimize tracking error, for parameter calculation. It is also possible to optimally adjust normalization and denormalization parameters, as well as input and output membership functions shape and parameters [25].

Another important part of the control system, that changes Takagi Sugeno fuzzy control into hybrid fuzzy system is wind speed estimator. Since it is not possible to measure directly current wind speed value, it is necessary to develop some sort of estimation. Wind turbine is often used as a wind speed measuring device, so sequential Monte Carlo estimator was developed and wind turbine states were used as convenient estimator inputs. Further research can include different filter development and performance comparison in order to estimate wind speed most accurately.

Implemented system has satisfactory dynamic and static performances, but simulation system developed in this paper is appropriate just for high level control system performance testing and verification. If the intention is to develop and simulate the whole system, it is necessary to develop a power electronic system and its appropriate control system and only then the comparison between simulation and experimental data has its point.

Finally, 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.

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HIBRIDNE FAZI STRATEGIJE UPRAVLJANJA VETROTURBINAMA PROMENLJIVE BRZINE

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Upravljanje vetro-turbinama promenljive brzine nije jednostavno, kako zbog stohastičke prirode vetra, tako i zbog kompleksnosti energetske elektronike. Kod klasičnog upravljanja projektovanje kontrolera zahteva precizan matematički model do koga je kod vetroturbina jako teško doći zbog nelinearnih karakteristika, stohastičke prirode procesa, smetnji i nepouzdanosti. Model vetroturbine promenljive brzine sa dve mase je analiziran, unapredjen i potom kombinovan sa stohastičkim modelom vetra kako bi se potom mogao koristiti za odgovarajuće simulacije. U cilju pojednostavljenja projektovanja i implementacije kontrolera, kao i izbegavanja razvoja sofisticiranijeg matematičkog modela, predložen je fazi sistem upravljanja. Razmatran je samo slučaj podkritične brzine vetra i fazi kontroler je primenjen za supervizijsko upravljanje aeroturbinom. Pošto brzinu vetra nije moguće direktno meriti, partikl filter je u upravljačkom kolu korišćen za ocenu brzine vetra.

Ključne reči: *fazi upravljanje, vetro turbine, ocena brzine vetra, partikl filter*