VARIABLE SPEED WIND GENERATOR AERO TURBINE
OPTIMAL FUZZY CONTROL

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1. Introduction

Interest in renewable energy sources has been increasing all over the world since the awareness of the limited supply of fossil fuels and their harmful impact on the environment raised. Many countries have been planning to meet 10% of their electricity demand from wind energy until 2020.

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. It is one of the most important factors responsible for the efficiency and reliability of wind power conversion systems.

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 show many advantages compared to fixed speed wind turbines [1,2,3]. Typically, variable-speed turbines use aerodynamic controls in combination with power electronics to regulate torque, rotor speed and power. 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.

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 behaviour, the flexibility of the drive-train shaft and the turbulent nature of the wind.

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 [4,5] is analysed and then combined with stochastic wind model for simulation purposes. Based on the model, a fuzzy control of aero turbine is developed. Aero turbine control loop provides the reference inputs for the electric generator control loop. 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.

2. Variable speed wind turbine model

A two-mass model is commonly used in the literature [4,5] to describe the variable speed 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.

![Wind turbine two-mass dynamic model](image_url)

The aerodynamic power captured by the rotor is:

\[ P_a = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v^3 \]  \hspace{1cm} (1)

where \( C_p(\lambda, \beta) \) is power coefficient, \( v \) is wind speed, \( \rho \) 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 $\beta$ and the tip speed ratio $\lambda$. Tip speed ratio $\lambda$ is defined as:

$$\lambda = \frac{\omega R}{v},$$

where $\omega$ is a rotor speed.

The $C_p$ (Figure 2) has a unique maximum value which is given by a pitch angle, in this case 5° and an optimal tip speed ratio.

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

The aerodynamic torque is:

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

where:

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

is a torque coefficient.

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

$$J_r \dot{\omega}_r = T_a - T_h - B_e \omega_r,$$

where the low-speed shaft torque $T_h$ acts as a braking torque on the rotor:

$$T_h = K_{\theta} (\theta - \theta_0) + B_{\theta} (\omega_r - \omega_n),$$

where:

$B_e$ is rotor external damping,
$K_{\theta}$ and $B_{\theta}$ are low speed shaft stiffness and low speed shaft damping,
$\omega_n$ is low speed shaft speed,
$\theta$ and $\theta_0$ 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:

$$J_g \dot{\omega}_g = I_{em} - B_g \omega_g - T_{em},$$

where $B_g$ presents a generator external damping, $\omega_g$ is a generator speed and $T_{em}$ is high speed shaft torque.

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

$$n_g = \frac{T_r}{T_h} = \frac{\omega_g}{\omega_r},$$

and $T_h$ 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:

$$\begin{bmatrix}
\dot{\omega}_r \\
\dot{\omega}_g \\
\dot{T}_h
\end{bmatrix} =
\begin{bmatrix}
A_{3x3} & B_{3x2} & T_{a} \\
0 & 0 & T_{em}
\end{bmatrix}
\begin{bmatrix}
\omega_r \\
\omega_g \\
T_h
\end{bmatrix}$$

where matrix elements are:

$$a_{11} = -\frac{B_e}{J_r}, \quad a_{12} = 0, \quad a_{13} = -\frac{1}{J_r}, \quad a_{21} = 0,$$

$$a_{22} = \frac{B_e}{J_g}, \quad a_{23} = \frac{1}{n_g J_g},$$

$$a_{31} = \frac{K_{\theta} - B_e B_r}{J_r}, \quad a_{32} = \frac{1}{n_g} \left( \frac{B_e B_r - K_{\theta}}{J_g} \right),$$

$$a_{33} = B_{\theta}, \quad b_{11} = \frac{1}{J_r},$$

$$b_{12} = 0, \quad b_{21} = 0, \quad b_{22} = -\frac{1}{J_g}, \quad b_{31} = \frac{B_e}{J_r},$$

$$b_{32} = \frac{B_{\theta}}{n_g J_g}.$$
control. 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,

$$C_p(\lambda_{opt}, \beta_{opt}) = C_{p_{opt}},$$  \hspace{1cm} (10)

where:

$$\lambda_{opt} = \frac{\omega_r R}{v}.$$ \hspace{1cm} (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 $\lambda$ at its optimal value, so the rotor speed $\omega_r$ must be adjusted to track the optimal rotation speed:

$$\omega_r = \frac{\lambda_{opt} v}{R}.$$ \hspace{1cm} (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.

Takagi Sugeno fuzzy controller is applied as a control algorithm for the variable speed aero turbine. The main 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 [6,7,8]. One of the inputs of the controller is rotor speed error $e$, that represents the difference between the measured rotor speed $\omega_r$ and optimal rotor speed $\omega_{r_{opt}}$, and the other input is wind speed $v$. Controller output is electromagnetic torque $T_{em}$, that is result of intelligent interpolation of fuzzy rules outputs.

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. Optimal tuning of the fuzzy controller parameters is done by expert knowledge and genetic algorithm.

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, where average wind speed was 6 [m/s], that lasted 600 seconds, optimal rotor speed was calculated, and compared with simulated response of fuzzy controlled system (Fig. 3).

Figure 4 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. Whole simulation is done assuming that the inner control loop can completely fulfils the supervisory demands for electromagnetic torque without any delay, and this approximation is good enough for the supervisory control verification.

5. Conclusion

In this paper fuzzy control of variable speed wind turbine is proposed in order to extract maximum wind power and achieve maximum energy efficiency. The wind turbine system is a complex multivariable and nonlinear stochastic system which involves some disturbances and has autologous indeterminancy. This system requires outside the box thinking when it comes to control algorithm design, and soft computing techniques
are preferable solution. 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.

Implemented system has satisfactory dynamic and static performances, and simulation system developed in this paper is appropriate for high level control system performance testing and verification. The main advantages of 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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7. References