Application of a robust fuzzy control method on wind power systems

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Abstract: - The objective of this study is the extraction maximum wind power (MPPT) by robust controller for nonlinear systems with parametric uncertainties. The Takagi–Sugeno fuzzy model is adopted for fuzzy modeling of the nonlinear system. Sufficient conditions are formulated in the format of linear matrix inequalities. The proposed controller design methodology is finally demonstrated through the model of wind energy systems with a Squirrel-cage induction generator (SCIG) to illustrate the effectiveness of the proposed method. The proposed algorithm maximizes the produced power and maintain a stable system during the parameter uncertainties.

Keywords: SCIG, MPPT, Wind turbine, fuzzy controller, parameters uncertainties.

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1. Introduction

Robust control is the control of unknown plants with unknown dynamics subject to unknown disturbances [1]. From this statement, it is clear that one of the key issues of robust control systems is uncertainty and how the control system deals with it.

To solve the problem of fuzzy control nonlinear system with uncertain parameters and subject to a disturbance of the wind, a robust controller for all non-linear systems. The nonlinear system is modeled by a fuzzy model TS (Takagi-Sugeno) fuzzy and uncertainty of model form a model close to the real system [2].

In this paper a robust controller design is presented, which covers the entire nominal operating Trajectory and takes into account requirements that are met in today's operation of wind turbines. Parameter uncertainties are accounted for in the design, and robustness provides guaranteed stability and performance against these variations [3]. The proposed robust controller design makes it possible to control the wind turbine along the entire nominal operating trajectory using fewer controllers than ordinary robust design methods, while maintaining the required performance [3].

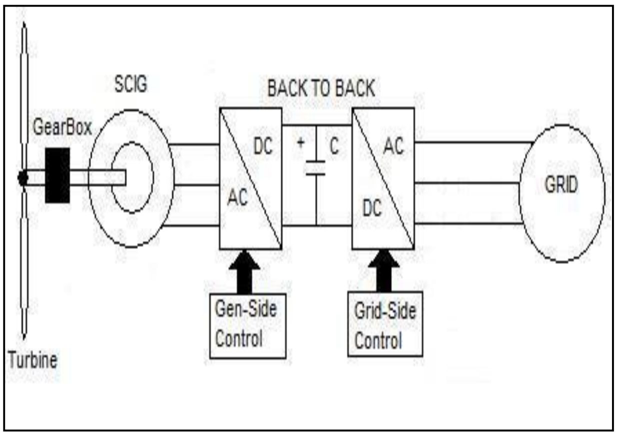

Figure 1. General structure [4].

2. Modeling of the System

Electrical generators are systems whose power regime is generally controlled by means of power electronics converters. From this viewpoint, irrespective of their particular topologies, controlled electrical generators are systems whose inputs are stator and rotor voltages, having as state variables the stator and rotor currents or fluxes. This system is controlled by the fuzzy controller to optimize the maximum power available at the wind turbine blades. The figure 1 shows the overall system studied [4] [5].

2.1 Takagi-sugeno Model with Uncertain Parameters

The fuzzy TS model represents a nonlinear system multi-variable and uncertain as the following equations [6] [7]:

Plant rule i : IF $q_1(t)$ is N_{1i} AND……..AND $q_k(t)$ is N_{ki}
Then $\dot{x}(t) = (A_i + \Delta A_i)\, x(t) + (B_i + \Delta B_i)\, u(t)$
$y(t) = C_i\, x(t) + W d(t) \quad i = 1,2\ldots\ldots p \qquad (1)$
With :
N_{ki} : fuzzy set, $x(t) \in k^{nx1}$: state vector,
$u(t) \in k^{mx1}$: input controller,
$A_i \in k^{nxn}$ and $B_i \in k^{nxm}$: are matrix systems and input matrix,
$\Delta A_i \in k^{nxn}$ and $\Delta B_i \in k^{nxm}$: are non time-varying matrices with appropriate dimensions, which represent parametric uncertainties in the plant model,
$C_i \in k^{gxn}$: output matrix,

p : Number of fuzzy rules TS model, $d(t)$: is assumed known noise matrix.

The output system defuzzification (1) is as followings :

$$\dot{x}(t) = \sum_{i=1}^{p} \mu_i (q(t))[(A_i + \Delta A_i)x(t) + (B_i + \Delta B_i)u(t)]$$
$$y(t) = \sum_{i=1}^{p} \mu_i (q(t))[C_i x(t) + \mathrm{W}d(t)] \qquad (2)$$

with :

$$\Delta A= \sum_{i=1}^{p} \mu_i (q(t))\, \Delta A_i =$$
$$\Delta B= \sum_{i=1}^{p} \mu_i(q(t))\, \Delta B_i =$$

ΔA and ΔB are uncertain parameters, Ai and Bi are nominal parameters the input matrix.

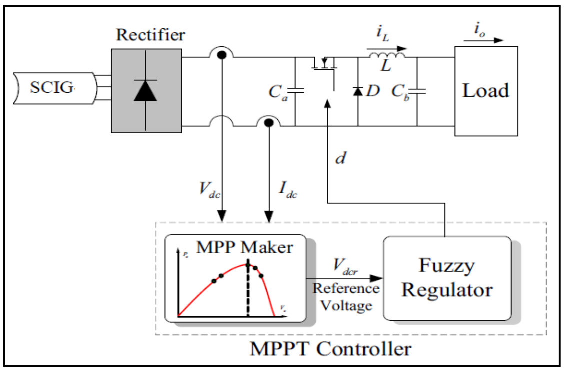

Figure 2. Fuzzy control system [7].

Fuzzy uncertainty regenerator is a fuzzy TS model to regenerate the uncertainties of parameters using fuzzy rules. It is introduced so that the analysis can be performed and the fuzziness planner can be derived. The outputs of the fuzzy regenerator uncertainty are given by [8]:

$$\Delta A= \sum_{l=1}^{n} h_l (\Delta A, \Delta B)\, \Delta A$$
$$\Delta B= \sum_{l=1}^{n} h_l (\Delta A, \Delta B)\, \Delta B$$
$$\sum_{l=1}^{n} h_l (\Delta A, \Delta B) = 1,\ h_l (\Delta A, \Delta B) \in [0,1]\ \forall\ l$$

From the equations (2) and (6) we obtain:

$$\dot{x}(t) = \sum_{i=1}^{p}\sum_{l=1}^{n} \mu_i h_l[(A_i + \Delta A)x(t) + (B_i + \Delta B)u(t)]$$
$$y(t) = \sum_{i=1}^{p} \mu_i\, [Ci\, x(t) + \mathrm{W}d(t)] \qquad (3)$$

We assume that the model of equation (3) fuzzy system is observable:

Observer rule i :IF $q_1(t)$ is N_{1i} AND...AND $q_k(t)$ is N_{ki}
Then $x(t) = A_i x(t) = B_i\, u(t) = K_i\, (y(t) – y(t))$

$y(t) = C_i\, x(t) \qquad i = 1,2.....q$

The observer states are governed by :

$$\dot{x}_s(t) = \sum_{i=1}^{p} \mu_i\, [A_i\, x_s(t) + B_i\, u(t) + K_i\, (y(t) - y_s(t))]$$
$$y_s(t) = \sum_{i=1}^{p} \mu_i\, C_i\, x_s(t) \qquad (4)$$

With :

$x_s(t)$: State vector estimated by the fuzzy observer.
$y_s(t)$: Output fuzzy observer.
K_i : Fuzzy observer gain.

2.2 Scig Modeling

Squirrel-cage induction generator model is given by the following matrix system [9] [10]:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + P.L_s & -L_s.\omega_s & P.M & -\omega_r.M \\ \omega_s.L_s & R_s + P.L_s & \omega_s.M & P.M \\ P.M & -\omega_r.M & R_r + P.L_r & \omega_r.L_r \\ M.L_R & P.M & \omega_r.L_r & R_r + P.L_r \end{bmatrix} . \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix} \qquad (5)$$

Where V_{ds}, V_{qs}, I_{ds}, I_{qs}, I_{dr}, I_{qr}, R_s,R_r L_s, L_r are the voltages and currents in direct and quadrature inductances and resistances cyclic stator and rotor respectively . The hypothesis proposed for high power machines used for wind generation is that the stator flux is constant and the resistance Rs is negligible. However, aerodynamic torque expressions are given by:

$$T_r = K_{opt}\Omega_r^2$$
$$Were\ \ K_{opt} = 0.5\rho\pi R^5 C_{p\max} / \lambda_{opt}^2 \qquad (5)$$

obtained by integrating the following differential equations:

$$\begin{bmatrix} \dfrac{di_{Sd}}{dt} = \dfrac{V_{Sd}}{L_S} - \dfrac{R_S}{L_S}.i_{Sd} - \dfrac{L_m}{L_S}.\dfrac{di_{Rd}}{dt} + \omega_S.(i_{Sq} + \dfrac{L_m}{L_S}.i_{Rq} \\ \dfrac{di_{Sq}}{dt} = \dfrac{V_{Sq}}{L_S} - \dfrac{R_S}{L_S}.i_{Sq} - \dfrac{L_m}{L_S}.\dfrac{di_{Rq}}{dt} + \omega_S.(i_{Sd} + \dfrac{L_m}{L_S}.i_{Rd} \\ \dfrac{di_{Rd}}{dt} = -\dfrac{R_R}{L_R}.i_{Rd} - \dfrac{L_m}{L_R}.\dfrac{di_{Sd}}{dt} + (\omega_S - \omega).(i_{Rq} + \dfrac{L_m}{L_R}.i_{Sq} \\ \dfrac{di_{Rq}}{dt} = -\dfrac{R_R}{L_R}.i_{Rq} - \dfrac{L_m}{L_R}.\dfrac{di_{Sq}}{dt} + (\omega_S - \omega).(i_{Rd} + \dfrac{L_m}{L_R}.i_{Sd} \end{bmatrix} \qquad (6)$$

for the state and input vector respectively, the SCIG state model can be presented as a eight-order model [11]:

$$\dot{x}(t) = A(x)\, x(t) + B\, u(t),$$
$$y(t) = C(x)\, x(t)$$

where $\sigma = 1 - \dfrac{L_m^2}{L_S L_R}$

By adopting the notation we get :

$$x(t) = \left[i_{sd}(t)\ i_{sq}(t)\ i_{rd}(t)\ i_{rq}(t)\ \Omega_r(t)\ \Omega_g(t)\ T_h(t)\ T_g(t)\right]^T$$
$$= \left[x_1(t)\ x_2(t)\ x_3(t)\ x_4(t)\ x_5(t)\ x_6(t)\ x_7(t)\ x_8(t)\right]^T$$

$$A(x)=.\begin{bmatrix} -\frac{R_S}{\sigma L_S} & \omega_S+\frac{(1-\sigma)n_p\,\Omega_g(t)}{\sigma} & \frac{L_mR_R}{\sigma L_SL_R} & \frac{L_mn_p\Omega_g(t)}{\sigma L_S} & 0 & 0 & 0 & 0 \\ -\frac{R_S}{\sigma L_S} & -\left(\omega_S+\frac{(1-\sigma)n_p\,\Omega_g(t)}{\sigma}\right) & \frac{L_mR_R}{\sigma L_SL_R} & -\frac{L_mn_p\Omega_g(t)}{\sigma L_S} & 0 & 0 & 0 & 0 \\ \frac{R_SL_m}{\sigma L_rL_S} & -\frac{L_mn_p\Omega_g(t)}{\sigma L_r} & -\frac{R_r}{\sigma L_r} & \omega_S-\frac{n_p\,\Omega_g(t)}{\sigma} & 0 & 0 & 0 & 0 \\ \frac{R_SL_m}{\sigma L_rL_S} & \frac{L_mn_p\Omega_g(t)}{\sigma L_r} & -\frac{R_r}{\sigma L_r} & -\omega_S+\frac{n_p\,\Omega_g(t)}{\sigma} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \left(\frac{D_r}{J_r}+\frac{K_{opt}}{J_R}\Omega_R(t)\right) & 0 & -\frac{n_b}{J_g} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{D_g}{J_g} & \frac{1}{j_g} & -\frac{1}{j_g} \\ 0 & 0 & 0 & 0 & \frac{J_rK_{ls}-D_rD_{ls}+D_{ls}K_{opt}\Omega_r(t)}{n_bJ_r} & \frac{D_gD_{ls}-J_gK_{ls}}{n_b^2J_g} & -D_{ls}(\frac{1}{J_r}+\frac{1}{n_b^2J_g}) & \frac{D_{ls}}{n_b^2J_g} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{\tau_g} \end{bmatrix}$$

$$B=.\begin{bmatrix} -\frac{1}{\sigma L_s} & 0 & \frac{L_m}{\sigma L_sL_r} & 0 & 0 \\ 0 & -\frac{1}{\sigma L_s} & 0 & \frac{L_m}{\sigma L_sL_r} & 0 \\ \frac{L_m}{\sigma L_sL_r} & 0 & -\frac{1}{\sigma L_s} & 0 & 0 \\ 0 & \frac{L_m}{\sigma L_sL_r} & 0 & -\frac{1}{\sigma L_s} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\tau_g} \end{bmatrix}$$

$$C(x)=.\begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -\frac{L_mV_s}{L_s} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{V_s^2}{i_{rd}\omega_sL_s} & -\frac{L_mV_s}{L_s} & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$y(t)=.\begin{bmatrix} \Omega_r(t) \\ \Omega_g(t) \\ P_s(t) \\ Q_s(t) \end{bmatrix}=\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}$$

$$u(t)=.\begin{vmatrix} u_{sd}(t) \\ u_{sq}(t) \\ T_{g.ref}(t) \end{vmatrix}=\begin{bmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \end{bmatrix}$$

The electromagnetic torque expressions are given by:

$$\Gamma_G=\frac{3}{2}pL_m(i_{sq}i_{rd}-i_{rq}i_{sd}) \qquad (7)$$

With p being the pole pairs number, L_m the stator-rotor mutual inductance, i_{sd}, i_{sq}, i_{rd} and i_{rq} are the stator, respectively rotor current (d,q) components.

3. Results and Discussion

The figure 3 shows the wind profile applied to the wind turbine. Simulations were performed in MATLAB using the non linear model. the proposed controller is tested for a random variation of wind speed. the control objective of this section is to design a robust fuzzy control law for the system 1. The parametric uncertainties L_r, R_s and R_r are considered within 40 percent of their nominal values.

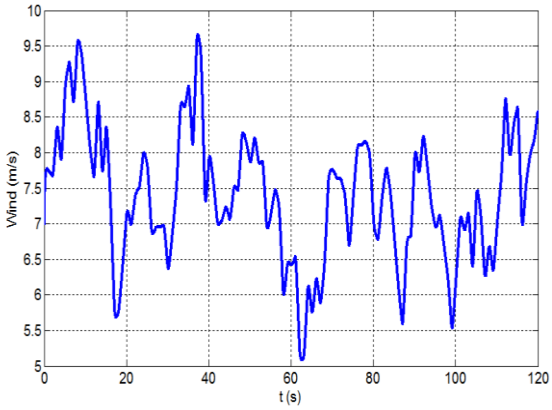

Figure 3. Wind speed profile.

Figure 4 and figure 5 show the rotational speed and power profile of the wind turbine. From the simulation results using the proposed control scheme, we can observe that the outputs of the system are bounded and good tracking performance can be obtained through the uncertain nonlinearities of the system.

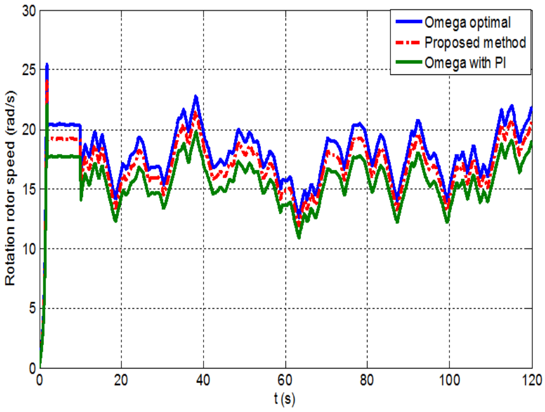

Figure 4. Rotation speed profile (with three cases).

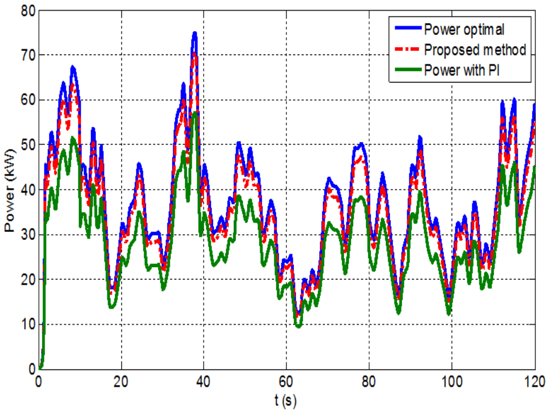

Figure 5. Wind turbine power profile (with three cases).

Figure 6 show the power coefficient, it is clear that the $C_{pmax} \approx 0.48$

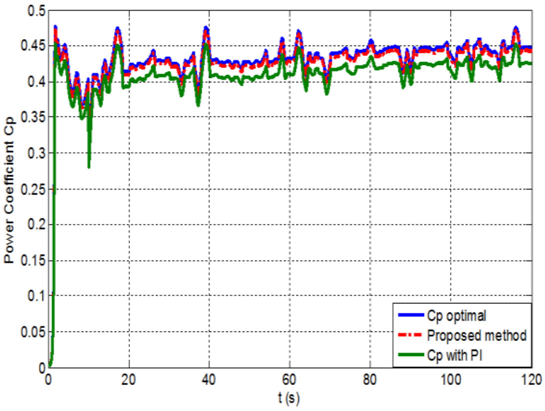

Figure 6. power coefficient profile (with three cases).

In order to obtain maximum output power from a wind turbine generator system, it is necessary to drive the wind turbine at an optimal rotor speed for a particular wind speed, and keep the power coefficient at 0.48. Figure 8 shows the power coefficient; it can be seen that , which proves the effectiveness of the proposed algorithm.

The simulation results demonstrate the effectiveness of the proposed control approach. The proposed control scheme can guarantee the stability of the closed-loop system and the convergence of the output tracking error.

4. Conclusion

The proposed algorithm allows the stabilization of nonlinear system with parametric uncertainties. The designed controller uses fuzzy systems of Takagi-Sugeno models and operates local systems obtained by linearization around a few operating points. The principle of this approach is to design a state feedback control capable of stabilizing the closed loop system. A simulation example is presented to illustrate the proposed approach. The simulation results show that the developed controller stabilizes the wind energy system.

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ANNEX

ω_s, ω_r : Stator and rotor angular frequencies,
Ω_g : Mechanical generator speed,
n_p : Number of pole pairs,
i_{sd}, i_{rd} : Stator and rotor currents in axis d,
i_{sq}, i_{rq} : Stator and rotor currents in axis q,
R_s, R_r : Stator and rotor resistance,
L_s, L_r, L_m : Stator, rotor leakage, and magnetizing inductances,
V_s : Stator voltage magnitude,
τ_g : Time constant of the model,
T_h : High-speed shaft torque,
n_b : Gearbox ratio,
D_r, D_g and D_{ls} : Damping constants for the rotor, generator, and the equivalent low-speed shaft,
K_{ls} : Equivalent torsional stiffness of the low-speed shaft,
J_r, J_g : Moments of inertia of the rotor and generator,
T_g, $T_{g.ref}$: Generator torque and required generator torque.

SCIG parameters are:
P_n = 75 kW, V = 690 V and f =50Hz,
Stator resistance: Rs = 0,039Ω ;
Rotor resistance: Rr = 0,022Ω ;
Stator inductance: Ls = 0,017 H ;
Rotor inductance: Lr = 0,017 H;