FUZZY ROBUST CONTROL OF DOUBLE FED INDUCTION GENERATOR WITH PARAMETER UNCERTAINTIES

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Key words: Wind turbine, Double fed induction generator (DFIG), Takagi Sugeno (TS) fuzzy controller, Parameters uncertainties.

The objective of this study is to simulate the nonlinear system by using the robust fuzzy controller. This method constitutes a robust tool enough to stabilize a nonlinear system with parametric uncertainties and the wind disturbance. The considered systems are Takagi-Sugeno type characterized by a nonlinear representation. This algorithm uses the local models of the system, obtained around operating points established by human expertise in the form of rules IF-THEN type. It is developed as shown by the model relative to the wind energy systems having a double-fed induction generator (DFIG) which is considered to illustrate the effectiveness of the proposed method. Hence, the proposed algorithm maximizes power output and ensures the stability of the system in term of the parameter uncertainties and to show its performances, results obtained by retained algorithm are compared to those obtained by the proportional integral (PI) controller algorithm.

1. INTRODUCTION

One of the most fundamental problems of the theory of control systems is the analysis of robust stability and synthesis of uncertain systems. Recently [1, 2], the issue of stability of nonlinear systems begin to accrue interest for the researchers, because it can provide an effective solution for controlling complex processes, uncertain and unclear [3]. The robust stability is another important requirement to be considered in the control study of uncertain and nonlinear systems [4]. To solve the fuzzy control nonlinear system problem by considering the uncertain parameters and subject to a disturbance of the wind, a robust controller for all non-linear systems [5] is used. The nonlinear system is modeled by a fuzzy model Takagi-Sugeno (TS) fuzzy and uncertainty of model form a model close to the real system [6, 7].

In this paper a robust controller design is presented, which covers the entire nominal operating trajectory. It takes into account requirements that are met in today's operation of wind turbines. Parameter uncertainties are also accounted in the design, and robustness provides guaranteed stability and performance against these variations [8, 9]. The proposed robust controller design makes it possible to control the wind turbine along the entire nominal operating trajectory using fewer controllers than those considered in the ordinary robust design methods, while maintaining the required performance [10, 11].

2. SYSTEM MODELING

The global model of the wind turbine system, based on the double-fed asynchronous generator to supply power to the grid is made up of the wind turbine and the double-fed asynchronous generator coupled to the cascaded converter (rectifier-inverter). This system is controlled by the fuzzy controller to optimize the maximum power available at the wind turbine blades. Figure 1 shows the overall system studied [11, 12].

![Fig. 1 – General structure [11].](image)

2.1. TAKAGI-SUGENO MODEL WITH UNCERTAIN PARAMETERS

The fuzzy TS model (Fig. 2) presents a nonlinear system multi-variable and uncertain as the following equations [13–16]:

Plant rule $i$:

IF $q_i(t)$ is $N_{ki}$ AND ……..AND $q_{ki}(t)$ is $N_{ki}$

Then

$$\begin{align*}
\dot{x}(t) &= (A_i + \Delta A_i)x(t) + (B_i + \Delta B_i)u(t) \\
y(t) &= C_i x(t) + Wd(t) \quad i = 1, 2, ..., p
\end{align*}$$

with: $N_{ki}$ – fuzzy set, $x(t) \in k^{n \times 1}$ – state vector, $u(t) \in k^{m \times 1}$ – input controller, $A_i \in k^{n \times n}$ and $B_i \in k^{n \times m}$ – matrix systems and input matrix, $\Delta A_i \in k^{n \times n}$ and $\Delta B_i \in k^{n \times m}$ – non time-varying matrices with appropriate dimensions, which represent parametric uncertainties in the plant model, $C_i \in k^{p \times n}$ – output matrix, $p$ – number of fuzzy rules TS model, $d(t)$: assumed known noise matrix.

The output system defuzzification (1) takes the form in following:
\[
\dot{x}(t) = \sum_{i=1}^{p} \mu_i q(t)[(A_i + \Delta A_i)x(t) + (B_i + \Delta B_i)u(t)] \\
y(t) = \sum_{i=1}^{p} \mu_i q(t)[C_i x(t) + Wd(t)] 
\]

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

\(\Delta A\) and \(\Delta B\) are uncertain parameters, \(A_i\) and \(B_i\) are nominal parameters of the input matrix.

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 [17] as in the following equations:
\[
\Delta A = \sum_{i=1}^{n} h_i (\Delta A, \Delta B) \Delta A_i, \Delta B = \sum_{i=1}^{n} h_i (\Delta A, \Delta B) \Delta B_i,
\]
where \(n = 2^b\) is the number of fuzzy rules; \(b\) is the number of uncertain elements in \(\Delta A\) and \(\Delta B\); \(l = 1,2,\ldots,n\).

From the equations (1) and (2) we obtain:
\[
\dot{x}(t) = \sum_{i=1}^{n} \sum_{j=1}^{l} \mu_i h_j [(A_i + \Delta A_i)x(t) + (B_i + \Delta B_i)u(t)] \\
y(t) = \sum_{i=1}^{n} \mu_i [C_i x(t) + Wd(t)].
\]

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

Observer rule \(i\):

IF \(q_j(t)\) is \(N_j_i\) AND...AND \(q_i(t)\) is \(N_k_i\).

Then
\[
\dot{x}_i(t) = A_i x(t) + B_i u(t) + K_i (y(t) - y_s(t)) \\
y_s(t) = C_i x(t) \\
i = 1,2,\ldots,q.
\]

The observer states are governed by:
\[
\dot{x}_i(t) = \sum_{i=1}^{p} \mu_i [A_i x(t) + B_i u(t) + K_i (y(t) - y_s(t))] \\
y_s(t) = \sum_{i=1}^{p} \mu_i C_i x(t)
\]
with: \(x_i(t)\) – state vector estimated by the fuzzy observer, \(y_s(t)\) – output fuzzy observer, \(K_i\) – fuzzy observer gain.

**2.2. DFIG MODELING**

Double-fed asynchronous generators model is given by the following matrix system [18, 19]:
\[
\begin{bmatrix}
\begin{array}{c}
V_{sd} \\
V_{sq} \\
V_{dr} \\
V_{qr}
\end{array}
\end{bmatrix}
= 
\begin{bmatrix}
R_s + PL_s & -L_s & \omega_s & PM & -\omega_M \\
\omega_s L_s & R_s + PL_s & \omega_M & PM \\
PM & -\omega_M & R_s + PL_r & \omega_L_r \\
ML_r & PM & \omega_L_r & R_s + PL_r
\end{bmatrix}
\begin{bmatrix}
I_{sd} \\
I_{sq} \\
I_{dr} \\
I_{qr}
\end{bmatrix}
\]

where \(V_{sd}, V_{sq}, V_{dr}, V_{qr}, I_{sd}, I_{sq}, I_{dr}, I_{qr}, R_s, R_r, L_s, L_r\) are the voltages and currents in direct and quadrature inductances and resistances cyclic stator and rotor respectively. The assumptions proposed for high power machines used for wind generation corresponds to that in where it is considered the stator flux is constant and the resistance \(R_s\) is negligible. However, aerodynamic torque expressions are given by:
\[
T_e = K_{opt} \Omega^2_r,
\]
where
\[
K_{opt} = 0.5 \rho \pi \lambda^2 / \chi_{opt}.
\]

obtained by integrating the following differential equations [20, 21]:
\[
\begin{align*}
\frac{d}{dr} \left[ \frac{V_{sd}}{L_s} \right] &= \frac{R_s}{L_s} I_{sd} - \frac{L_m}{L_s} I_{dq} + \omega_s (i_{dq}^m + I_{sd} - I_{dq}) \\
\frac{d}{dr} \left[ \frac{V_{sq}}{L_s} \right] &= \frac{R_s}{L_s} I_{sq} - \frac{L_m}{L_s} I_{ds} + \omega_s (i_{ds} + I_{sq} - I_{ds}) \\
\frac{d}{dr} \left[ \frac{V_{dr}}{L_r} \right] &= \frac{R_r}{L_r} I_{dr} - \frac{L_m}{L_r} I_{dq} + (\omega_s - \omega) (i_{dq}^m + L_{m} - I_{dq}) \\
\frac{d}{dr} \left[ \frac{V_{qr}}{L_r} \right] &= \frac{R_r}{L_r} I_{qr} - \frac{L_m}{L_r} I_{ds} + (\omega_s - \omega) (i_{ds} + L_{m} - I_{ds})
\end{align*}
\]

For the state and input vector respectively, the DFIG state model can be presented as an eight-order model [22]:
\[
\begin{bmatrix}
\dot{x}(t) = A(x)x(t) + Bu(t) \\
y(t) = \sigma(x)x(t)
\end{bmatrix}
\]

where \(\sigma = 1 - \frac{L_s^2}{L_s L_r}\).
Fuzzy robust control of double fed induction generator

By adopting the notation we get:

\[
x(t) = \begin{bmatrix} i_{sd}(t) & i_{sq}(t) & i_{rd}(t) & i_{rq}(t) & \Omega_x(t) & \Omega_y(t) & T_x(t) & T_y(t) \end{bmatrix}^T
\]

\[
x(t) = \begin{bmatrix} x_1(t) & x_2(t) & x_3(t) & x_4(t) & x_5(t) & x_6(t) & x_7(t) & x_8(t) \end{bmatrix}^T
\]

(10)

The electromagnetic torque expressions are given by:

\[
\Gamma = \frac{3}{2} p L_m (i_{sq} i_{rd} - i_{rq} i_{sd})
\]

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

One can note that matrix \( A \) depends on the rotational speed, \( \Omega \), which is an interaction variable. The output variable is the electromagnetic torque, given by equation (15). The torque characteristic of the induction machine is represented in Fig. 3 [23, 24].

\[\text{Fig. 3 – Mechanical characteristic of the DFIG [24].}\]

3. RESULTS AND DISCUSSION

Figure 4 shows the wind profile applied to the wind turbine, and Fig. 5 shows the rotation speed profile. 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. The parametric uncertainties $L_r$, $R_s$, and $R_r$ are considered within 40% of their nominal values.

Figure 7 shows the power coefficient, proving the effectiveness of the proposed algorithm. The simulation results demonstrate the effectiveness of the proposed control approach. The proposed control scheme can ensure the stability of the closed-loop system and ensure also the convergence of the output tracking error.

Fig. 4 – Wind speed profile.

Fig. 5 – Rotation speed profile.

Figures 6 and 7 show the power and power coefficient, it is clear that the $C_{p_{max}} \approx 0.48$.

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.

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. Thus, the obtained results shown that the developed controller leads stabilizing the output energy from the wind system.

APPENDIX

DFIG parameters are:

- $P_n = 1.5$ MW, $p = 3$ and frequency = 50 Hz,
- $R_s = 0.012 \ \Omega$, $R_r = 0.021 \Omega$, $M = 0.0135$ H,
- $L_s = 0.0137$ H, $L_r = 0.0136$ H, $V = 690$ V.

Wind turbine parameters are:

- Number of blade = 3
- Blade diameter: $R = 70.5$ mm
- Gearbox ration: $n_b = 75$.
- Inertia of the turbine: $J = 0.042$ kg.m$^2$.
- Viscosity: $f = 0.017$ m·s$^{-1}$.

NOMENCLATURE

- $J_r$, $J_g$ – Moments of inertia, rotor and generator
- $T_p$, $T_{gref}$ – Generator torque and required generator torque
- $\rho$ – Air density [kg/m$^3$]
- $R$ – Turbine radius [m]
- $\lambda$ – Tip speed ratio
- $C_p$ – Power coefficient
- $\omega_s$ – Stator angular frequencies
- $\Omega_g$ – Mechanical generator speed
- $\Omega_r$ – Turbine rotational speed
- $n_p$ – Number of pole pairs
- $i_{sd}$, $i_{rd}$ – Stator and rotor currents in axis d
- $V_{sd}$, $V_{rd}$ – Stator and rotor voltage in axis d
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