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Variable Structure Control Design of Windmill Power Systems

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ABSTRACT

The method of Variable Structure Control (VSC) design of windmill power systems is proposed. In the design of sliding mode control, we use Riccati equations arising in linear H^∞ control to decide a stable sliding surface. Then the reachability to the sliding surface is realized by designing a nonlinear controller for the windmill power system. The capability of the proposed controller to damp out the oscillations of power and the robustness with respect to the system parameter variations and model errors are evaluated in the simulation study.

1. INTRODUCTION

The generation of electric power by wind turbine generators depend on the prime power source which changes with time and position, it is, therefore, necessary to have a proper control strategy to maintain a rated value of wind power generation though wind speed changes[1]. VSC is a well-known solution to the problem of the deterministic control of uncertain systems since it is invariable to a class of parameter variations. The characterizing feature of VSC is sliding motion, which occurs when the system state repeatedly crosses certain subspaces, or sliding surface in the state space. A VSC controller comprises nonlinear and linear parts and is used for the windmill power system control. In this paper, H^∞ optimization theory is used as a tool for designing sliding surface of VSC. However, as the windmill power systems are nonlinear systems, the linear control theory can not be applied without some modifications. For this purpose, in this paper the controller design procedures are divided into two steps. In the first step the total windmill power system is quasi-linearized on the basis of the physical consideration of it's properties; in the second step, sliding-mode control is applied via H^∞ design.

2. WINDMILL POWER SYSTEM

In windmill power systems, the voltage equations of an induction generator are expressed in state variables which are transformed from three-phase to a rotating (d-q) axes frame with synchronous speed; The hydraulic system which adjusts the pitch angle of the blade is modeled by a strictly proper stable first order system. Because the step-up transformer (480[v]/6.6[kv]) is used between the windmill power system and the power-transmission line, the voltage and impedance in the side of infinity bus is calculated to the side of the generator system, that is, calculated to the value dependent on 480[v] voltage series, so that, the following dynamics equations of the windmill power system are obtained:

$$
\begin{aligned}
v_{sd} &= \left(\widetilde{R}_s + \widetilde{L}_s\frac{d}{dt}\right) i_{sd} + M\frac{di_{rd}}{dt} - \omega_0\widetilde{L}_s i_{sq} - \omega_0 M i_{rq},\\
v_{sq} &= \left(\widetilde{R}_s + \widetilde{L}_s\frac{d}{dt}\right) i_{sq} + M\frac{di_{rq}}{dt} + \omega_0\widetilde{L}_s i_{sd} + \omega_0 M i_{rd},\\
0 &= M\frac{di_{sd}}{dt} - s\omega_0 M i_{sq} + \left(R_r + L_r\frac{d}{dt}\right) i_{rd} - s\omega_0 L_r i_{rq},\\
0 &= s\omega_0 M i_{sd} + M\frac{di_{sq}}{dt} + s\omega_0 L_r i_{rd} + \left(R_r + L_r\frac{d}{dt}\right) i_{rq},\\
J\frac{d\Omega}{dt} &= T_w + T,\\
\frac{d\beta}{dt} &+ C_\beta\beta = C_\beta u,
\end{aligned}
\tag{1}
$$

in which,

$$
\begin{aligned}
\widetilde{R}_s &= R_s + R_c, \quad \omega = GP\Omega = (1-s)\omega_0,\\
\widetilde{L}_s &= L_s + L_c, \quad T = \frac{3}{2}MPG(i_{sq}i_{rd} - i_{sd}i_{rq}),\\
\lambda &= \frac{R\Omega}{V_w(t)}, \quad P_e = \omega T,\\
K_t &= \frac{\rho\pi R^3}{2}, \quad T_\omega = C_t K_t V_w^2(t),\\
C_t &= (-C_1\beta - C_2)\lambda + (-C_3\beta + C_4),
\end{aligned}
$$

where v_{sd} and v_{sq} are d-q axis voltages; i_{sd} and i_{sq} are d-q axis currents of the stater; i_{rd} and i_{rq} are those of rotor; u is the control input; L_s, L_r and M are stater, rotor and mutual inductances; R_s and R_r are the stater and rotor resistances respectively.

In the dynamic equations (1), the deflections of the currents, the angular velocity and the pitch angle from their nominal values are considered to be new state variables. We have the following state equations of the windmill power system:

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{A}\boldsymbol{x} + \widetilde{\omega}\boldsymbol{A}_2(\boldsymbol{x} + \boldsymbol{i}^*), \tag{2}$$

$$\frac{d\widetilde{\omega}}{dt} = g_1(\widetilde{\omega}, t)\widetilde{\beta} + g_2(\boldsymbol{x}, \widetilde{\omega}, t), \tag{3}$$

$$\frac{d\widetilde{\beta}}{dt} = -C_\beta\widetilde{\beta} + C_\beta\widetilde{u}, \tag{4}$$

where

$$\boldsymbol{x} = [x_1, x_2, x_3, x_4]^T, \qquad \boldsymbol{i}^* = [i_{sd}^*, i_{sq}^*, i_{rd}^*, i_{rq}^*]^T,$$

$$A = A_1 + \widetilde{\omega}^* A_2,$$

$$g_1(\widetilde{\omega}, t) = \widetilde{C}_1(t)\widetilde{w} + \widetilde{C}_1(t)\omega^* + \widetilde{C}_3(t),$$

$$g_2(\boldsymbol{x}, \widetilde{\omega}, t) = \boldsymbol{A}_3\boldsymbol{x} + \left\{\widetilde{C}_1(t)\beta^* + \widetilde{C}_2(t)\right\}\widetilde{\omega} + \widetilde{M}(x_2x_3 - x_1x_4),$$

$$A_1 = \frac{1}{\Delta}\begin{bmatrix} -\widetilde{R}_sL_r & \Delta\omega_0 & R_rM & 0 \\ -\Delta\omega_0 & -\widetilde{R}_sL_r & 0 & R_rM \\ \widetilde{R}_sM & 0 & -R_r\widetilde{L}_s & \Delta\omega_0 \\ 0 & \widetilde{R}_sM & -\Delta\omega_0 & -R_r\widetilde{L}_s \end{bmatrix},$$

$$A_2 = \frac{1}{\Delta}\begin{bmatrix} 0 & M^2 & 0 & L_rM \\ -M^2 & 0 & -L_rM & 0 \\ 0 & -\widetilde{L}_sM & 0 & -\widetilde{L}_sL_r \\ \widetilde{L}_sM & 0 & \widetilde{L}_sL_r & 0 \end{bmatrix},$$

$$A_3 = \widetilde{M}\begin{bmatrix} -i^*_{rq} & i^*_{rd} & i^*_{sq} & -i^*_{sd} \end{bmatrix}, \Delta = \widetilde{L}_sL_r - M^2,$$

In the above equations, x_1, x_2, x_3, x_4 are the deflections of the stater currents and the rotor currents of the (d-q) axes from their nominal values $i^*_{sd}, i^*_{sq}, i^*_{rd}, i^*_{rq}$; $\widetilde{\omega}$ is the deflection of the electrical angular velocity of the rotor from its nominal values $\omega^* = (1 - s_0)\omega_0$; $\widetilde{\beta}$ and $\widetilde{u}$ are deflections from their nominal values β^* and u^*. The rated slip ratio is expressed by s_0. It is assumed that $\Delta \neq 0$, which is always satisfied in practical generator systems.

3. SLIDING-MODE CONTROLLER DESIGN

Since the windmill power system is a time varying nonlinear system, we use quasi-linearization transform technique to the windmill power system, and by this transform we develop a type of equation which is suitable for H^∞ control full information problem[3].

3.1 Quasi-linearization

Equations (2), (3),(4) represents the windmill power systems which have strong nonlinearity with the time varying coefficients $\widetilde{C}_1(t), \widetilde{C}_2(t)$ and $\widetilde{C}_3(t)$ depending on wind speed $V_w(t)$. Here we develop the quasi-linearization state equations from (2), (3),(4).

Equations (2), (3),(4) are rewritten as follows:

$$\frac{dx_g}{dt} = A_gx_g + B_gg_1(\widetilde{\omega}, t)\widetilde{\beta} + \xi, \quad (5)$$

$$\frac{d\widetilde{\beta}}{dt} = -C_\beta\widetilde{\beta} + C_\beta\widetilde{u}, \quad (6)$$

where

$$x_g = \begin{bmatrix} x \\ \widetilde{\omega} \end{bmatrix}, \quad A_g = \begin{bmatrix} A & A_2i^* \\ A_3 & 0 \end{bmatrix},$$

$$B_g = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T,$$

$$\xi = \begin{bmatrix} \widetilde{\omega}A_2x \\ (\widetilde{C}_1(t)\beta^* + \widetilde{C}_2(t))\widetilde{\omega} + \widetilde{M}(x_2x_3 - x_1x_4) \end{bmatrix}.$$

To perform quasi-linearization, by defining $\widetilde{\beta}_g$ as $\widetilde{\beta}_g = g_1(\widetilde{\omega}, t)\widetilde{\beta}$ we get the following equation:

$$\frac{d\widetilde{\beta}_g}{dt} = \frac{dg_1(\widetilde{\omega}, t)}{dt}\widetilde{\beta} - C_\beta\widetilde{\beta}_g + g_1(\widetilde{\omega}, t)C_\beta\widetilde{u}. \quad (7)$$

Then we define

$$\widetilde{u} = \frac{1}{g_1(\widetilde{\omega}, t)C_\beta} \times \left[-\frac{dg_1(\widetilde{\omega}, t)}{dt}\widetilde{\beta} + \widetilde{u}_g\right], \quad (8)$$

where $\widetilde{u}_g$ is the control force which controls $\widetilde{\beta}_g$ with the varying of wind speed. We assume that $g_1(\widetilde{\omega}, t) \neq 0$ and $dg_1(\widetilde{\omega}, t)/dt$ is bounded.

By putting (8) into (7), equations (5) and (7) are rewritten as

$$\frac{d}{dt}\begin{bmatrix} x_g \\ \widetilde{\beta}_g \end{bmatrix} = \begin{bmatrix} A_g & B_g \\ 0 & -C_\beta \end{bmatrix}\begin{bmatrix} x_g \\ \widetilde{\beta}_g \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix}\widetilde{u}_g + \begin{bmatrix} \xi \\ 0 \end{bmatrix}. \quad (9)$$

3.2 Sliding mode surface design via H^∞ theory

Here we use H^∞ approach to obtain a sliding mode surface[2]. The basic idea consists in designing a H^∞ sub-optimal controller and then modifying it byx defining a subset of the state space, called sliding surface. In particular, the conventional stability conditions of sliding surface are replaced by some new conditions that describe structural properties of the windmill power system.

A switching surface is defined as

$$\sigma = Fx_g + \widetilde{\beta}_g, \quad (10)$$

Design of the sliding surface σ=0 can be regarded as a linear state feedback control design for the upper equation of (9) in which $\widetilde{\beta}_g$ is considered to be the input of this subsystem. The state feedback controller $\widetilde{\beta}_g = -Fx_g$ for this subsystem gives the sliding surface of the total system, namely $\sigma = \widetilde{\beta}_g + Fx_g$=0

Considering the upper subsystem of (9), the cost function for LQ design contains both the state vector and control input cost terms. We define the output z that contains the weighted state variable $Q^{\frac{1}{2}}x_g$ and the weighted control input $\sqrt{r}\widetilde{\beta}_g$, that is ,

$$z = \begin{bmatrix} Q^{\frac{1}{2}}x_g \\ \sqrt{r}\widetilde{\beta}_g \end{bmatrix}, \quad (11)$$

in which Q =diag $\begin{bmatrix} q_1 & q_2 & q_3 & q_4 & q_5 \end{bmatrix} \geq 0$ and $r > 0$.

The following assumptions are made in the implementation of the H^∞ algorithm and must be satisfied: (i) $\begin{bmatrix} A_g & B_g \end{bmatrix}$ is stable; (ii) $\begin{bmatrix} A_g & Q^{\frac{1}{2}} \end{bmatrix}$ is observable. In this subsystem, we define the state feedback control based on Riccati equation. It gives

$$\widetilde{\beta}_g = -Fx_g = -\frac{1}{r}B_g^TPx_g. \quad (12)$$

By putting (12) into (11), we have

$$z = \begin{bmatrix} Q^{\frac{1}{2}} \\ -\frac{1}{\sqrt{r}} B_g^T P \end{bmatrix} x_g. \tag{13}$$

Here, constant α_∞ is defined as

$$\begin{aligned} \alpha_\infty &= \inf_\omega \sup_\xi \left[\frac{\|z\|^2}{\|\xi\|^2} \right] \\ &= \inf_\omega \sup_\xi \left[\frac{| x_g^T Q x_g + \widetilde{\beta}_g^T r \widetilde{\beta}_g |}{\|\xi\|^2} \right], \end{aligned} \tag{14}$$

in which, α_∞ represents the magnitude of influence which affect the system by the maximum disturbance under the minimum control. Therefore, H^∞ norm of the close-loop transfer function $T(s)$ from the disturbance ξ to the output z determines the control $\widetilde{\beta}_g$ under which the next bound condition is satisfied:

$$\alpha_\infty \le \|T(s)\|_\infty \le \alpha \tag{15}$$

The state feedback controller which satisfies the condition of (15) is given by the solution of the next Ricatti equation[3][4].

$$A_g^T P + P A_g + Q - \frac{1}{r} P B_g B_g^T P + \frac{1}{\alpha^2} P P = 0. \tag{16}$$

3.3 Sliding mode controller design

Once the sliding surface have been selected, attention must be turned to solve the reachability problem. This involves the selection of a state feedback control function u_g which will drive the state variable into the sliding surface σ and thereafter maintains within this subspace. Here variable structure control law consists of two additive parts: a linear control law, and a nonlinear part which are added to form $\widetilde{u}_g$. The state is constrained in the vicinity of $\sigma = 0$ by the control law[2]

$$\begin{aligned} \widetilde{u}_g &= \begin{bmatrix} \Omega^* F - F A_g & C_\beta \Omega^* - F B_g \end{bmatrix} \begin{bmatrix} x_g & \widetilde{\beta}_g \end{bmatrix}^T \\ &- \mu \frac{P_1 \begin{bmatrix} F & 1 \end{bmatrix} \begin{bmatrix} x_g & \widetilde{\beta}_g \end{bmatrix}^T}{\|P_1 \begin{bmatrix} F & 1 \end{bmatrix} \begin{bmatrix} x_g & \widetilde{\beta}_g \end{bmatrix}^T \| + \delta}, \end{aligned} \tag{17}$$

where P_1 is a positive definite solution of Lyapunov equation

$$P_1 \Omega^* + \Omega^{*T} P_1 = -I$$

in which $\Omega^* < 0$ is a design parameter which contribute to the rate of decay of the range space states into the neighborhood of σ. Discontinuous control produces chatter motion in the neighborhood of the sliding surface. δ is used to "smooth" the control function[2]. Putting (17) into (8), we get the controller for the windmill power system

$$\begin{aligned} \widetilde{u} = \frac{-1}{g_1(\widetilde{\omega}, t) C_\beta} \times \Bigg\{ & \frac{d g_1(\widetilde{\omega}, t)}{dt} \widetilde{\beta} \\ & + \begin{bmatrix} \Omega^* F - F A_g & C_\beta \Omega^* - F B_g \end{bmatrix} \begin{bmatrix} x_g & \widetilde{\beta}_g \end{bmatrix}^T \\ & + \mu \frac{P_1 \begin{bmatrix} F & 1 \end{bmatrix} \begin{bmatrix} x_g & \widetilde{\beta}_g \end{bmatrix}^T}{\|P_1 \begin{bmatrix} F & 1 \end{bmatrix} \begin{bmatrix} x_g & \widetilde{\beta}_g \end{bmatrix}^T \| + \delta} \Bigg\}. \end{aligned} \tag{18}$$

4. SIMULATION RESULTS

The validity of the scheme is tested by the windmill induction generator system which consists of one generator-infinity bus system. The system coefficients and rated values of the windmill induction generator system are shown in table 1.

(i) propeller windmill
$J = 2.56 \times 10^5$[kg.m^2],R=14[m], G=42 ,
$\rho = 1.225$[kg/m^3], $C_1 = 1.3668 \times 10^{-4}$,
$C_2 = 2.02 \times 10^{-6}, C_3 = 4.09 \times 10^{-4}$,
$C_4 = 7.954 \times 10^{-2}$.
(ii) induction generator
$R_s = 0.006[\Omega]$, $R_r = 0.0042[\Omega]$, $L_s = 5.67$[mH],
$L_r = 5.70$[mH],$M = 5.51$[mH],$s = -0.0049$.
(iii) hydraulic system
$C_\beta = 6.5$[1/sec].
(iv) electrical power system
$R_c = 0.02[\Omega]$, $L_c = 0.078$[mH].

Table 1. System constants and rated values

The test wind pattern was made from the actual wind speed data measured at Miyako Island, Okinawa, Japan on December in 1994 shown in Figure 1. The proposed controller is evaluated by the deflection of angular velocity $\widetilde{\omega}$ of generator, the wind power generation P_e, the pitch angle of blade β and the control u.

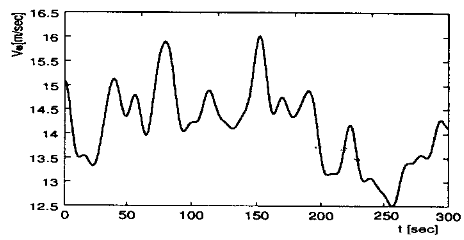

Figure 1. The actual wind speed.

4.1 System responses with normal parameters

Figure 2 shows the deflection of angular velocity $\widetilde{\omega}$ of generator,the wind power generation, the pitch angle of blade β and the control u with the normal parameter condition. It is observed that, with the variation of the input wind speed, the blade pitch control mechanism brings the change of the pitch angle so as to stabilize the angular velocity and the wind power generation. It shows that the angular velocity and the wind power generation are restrained sufficiently and that they converge into the rated values quickly by using the proposed controller.

4.2 Robustness of sliding mode

Figure 3 shows the transient response curves for the windmill power system with 10% changes of the coefficients C_1, C_2, C_3, C_4 of windmill and C_β of hydraulic system. Though the amplitude of both the pitch angle of blade shown in Figure 3 (c) and the control shown

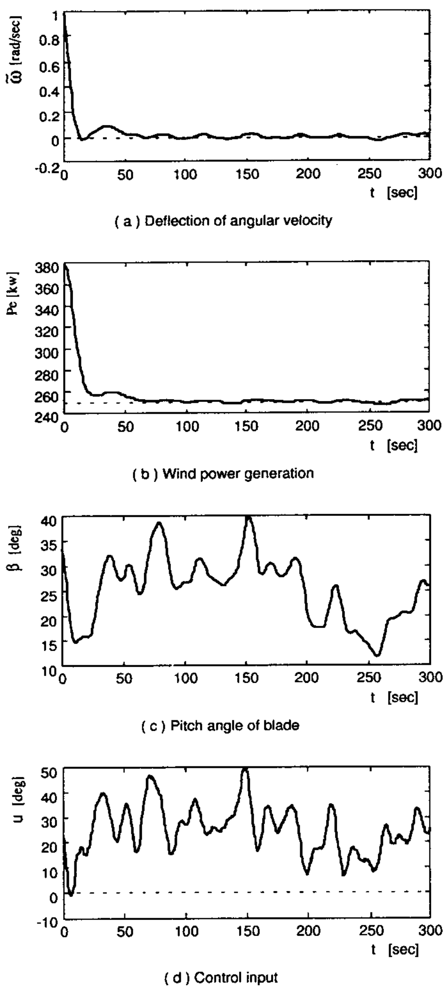

Figure 2. Responses with normal parameters

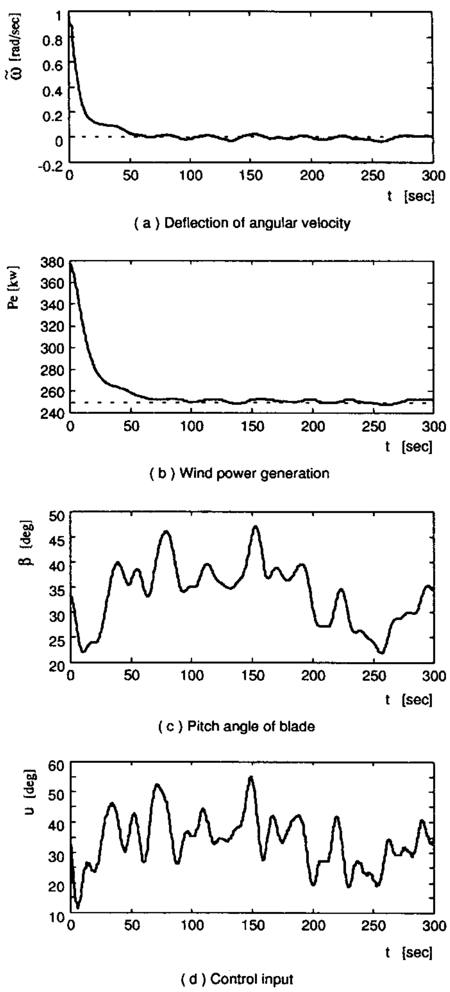

Figure 3. Response with 10% changes of coefficients C_1, C_2, C_3, C_4 and C_β

in Figure 3 (d) have increased, the deflection of angular velocity and the wind power generation can still be restrained sufficiently and converge into the rated values in the same way with that of the normal parameter condition. In this case also, it is observed from the responses that the settling time is some longer than that of the normal parameter condition and performance deteriorates before the state variables fall into the sliding surface.

Comparing the system response with that simulated under the normal conditions, it can be seen that the sliding mode can still provide consistent control performance even the system parameters are changed and it holds almost the same responses with that of normal parameters. It is clear that the proposed controller functions satisfactorily by nullifying the variation of parameters.

5. CONCLUSIONS

In this paper, we present a method of VSC design of the windmill power systems. The scheme consists of two steps: first a sliding surface is designed via H^∞ suboptimal theory and second a sliding mode technique is used to design the controller of the total windmill power system. The capability of the proposed controller to damp out the oscillations of power and the robustness with respect to the system parameter variations and model errors have been evaluated in the simulation study.

6. REFERENCES

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