Paper

Sliding Mode Control of Windmill Power Systems via $H^\infty$ Design

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A method of variable structure control (VSC) using the frequency criteria of $H^\infty$ control theory for sliding surface design is proposed in windmill power systems. Using quasi-linearization transform technique to the windmill power systems, we develop a type of equation which is suitable for $H^\infty$ control full information problem. By solving the Riccati equations arising in $H^\infty$ control a stable sliding surface is decided. Then we design the control law which consists of a linear control law and a nonlinear control law to drive the state variable into the sliding surface and thereafter maintain within this subspace. The capability of the proposed controller to damp out the oscillations of the power and angular velocity, and the robustness with respect to the system parameter variations and model errors are evaluated in the simulation study.

Keywords: $H^\infty$ control, sliding mode control, windmill power systems.

1. Introduction

In recent years there has been a growing interest in wind energy power systems due to the environmental problem and the economic benefits of fuel savings. Such systems are usually connected to the existing power grid for "fuel displacement" purposes as well as for earning some "capacity credit". The generation of electric power by windmill generators depend on the wind power source which changes with time and position, it is, therefore, necessary to have a proper control strategy to maintain a rated value of the wind power generation and the angular velocity although the wind speed changes (1) (2) (3).

Variable structure control (VSC) is a well-known solution to the problem of uncertain systems since it is invariant 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.

In this paper, a method for sliding surface design of VSC using the frequency criteria of $H^\infty$ control theory is presented in windmill power systems. Since the windmill power system is a time varying nonlinear system with the wind speed, usually we can not obtain the exact models of the windmill power systems so that sliding mode control can be applied to it with uncertainties. Here by using quasi-linearization transform technique to the windmill power system, we develop a type of equation which is suitable for $H^\infty$ control full information problem. In the design of sliding mode control, the stability of the sliding surface and the reachability to it should be certified. By solving the Riccati equations arising in $H^\infty$ control full information problem, a stable sliding surface is decided. Then we design the control law which consists of a linear control law and a nonlinear control law to drive the state variable into the sliding surface and thereafter maintain within this subspace. The new design method is proposed to satisfy the requirements of fast response and vibration suppression with strong robustness.

The paper is organized as follows: Section 2.1 presents the basic concept of windmill power system, in which the pitch angle versus wind speed, the voltage equations of the induction generators and the dynamic equations of the windmill power system are introduced. Section 2.2 describes state equations of the windmill power systems. Section 3 develops a practical control design methodology for the windmill power system, in which section 3.1 formulates the problem for the windmill power system; the design of the sliding surface and an assessment of its properties are presented in section 3.2; section 3.3 defines the associated nonlinear control structure. Section 4 considers the simulation of the proposed nonlinear strategy to the design of the windmill power system.

2. Windmill power system

The conceptual figure of a windmill power system is illustrated in Fig.1.

Fig. 1. Windmill power system.

The windmill generator which consists of the propeller
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windmill, the gear-box, and the control equipment for the pitch angle of the blade, is connected to infinity bus through the transformer and the power-transmission line.

2.1 Model of the 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 $\omega$). 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 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, so that, the following dynamics equations of the windmill power system are obtained:

\[ \begin{align*}
    v_{sd} &= \left( \bar{R}_s + \bar{R}_s \frac{d}{dt} \right) i_{sd} + M \frac{d}{dt} i_{rd} - \omega_0 L_s i_{sq} - \omega_0 M i_{rq}, \\
    v_{sq} &= \left( \bar{R}_s + \bar{L}_s \frac{d}{dt} \right) i_{sq} + M \frac{d}{dt} i_{dq} + \omega_0 L_s i_{sd} + \omega_0 M i_{qr}, \\
    0 &= M \frac{d}{dt} i_{sd} - \omega_0 M i_{sq} + \left( R_r + L_r \frac{d}{dt} \right) i_{rd} - \omega_0 L_r i_{rq}, \\
    0 &= \omega_0 M i_{sd} + M \frac{d}{dt} i_{sq} + \omega_0 L_r i_{rd} + \left( R_r + L_r \frac{d}{dt} \right) i_{rq}, \\
    J \frac{d\omega}{dt} &= T_w + T, \\
    \frac{d}{dt} + C_\beta \bar{\beta} = C_\beta \bar{u},
\end{align*} \]

where \( \bar{R}_s \) and \( \bar{L}_s \) are d-q axis voltages; \( i_{sd} \) and \( i_{sq} \) are d-q axis currents of the stator; \( i_{rd} \) and \( i_{rq} \) are those of the rotor; \( u \) is the control input; \( L_s, L_r, M \) are the stator, rotor and mutual inductances; \( R_s, R_r \) are the stator and rotor resistances respectively. The other parameters in the above equations are defined in the appendix 1.

2.2 State equations of the windmill power system

In the dynamic equations (1), the deviations 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:

\[ \begin{align*}
    \frac{dx}{dt} &= A x + \omega A_2 (x + t^*), \\
    \frac{d\omega}{dt} &= g_1 (\bar{\omega}, t) \bar{\beta} + g_2 (x, \bar{\omega}, t), \\
    \frac{d\bar{\beta}}{dt} &= -C_\beta \bar{\beta} + C_\beta \bar{u},
\end{align*} \]

where

\[ x = [x_1, x_2, x_3, x_4]^T, \quad t^* = [t^*_{sd}, t^*_{sq}, t^*_{rd}, t^*_{rq}]^T, \]

\[ A = A_1 + \bar{\omega} A_2, \]

\[ g_1(\bar{\omega}, t) = \bar{C}_1(\bar{\omega}, t) \bar{\omega} + \bar{C}_1(t) \omega^* + \bar{C}_3(t), \]

\[ g_2(x, \bar{\omega}, t) = A_3 x + \left( \bar{C}_1(t) \bar{\beta} + \bar{C}_3(t) \right) \bar{\omega} + \bar{M} (x_2 x_3 - x_1 x_4), \]

\[ A_1 = \frac{1}{\Delta} \begin{bmatrix}
    -\bar{R}_s L_r & \Delta\omega_0 & \bar{R}_r M & 0 \\
    -\Delta\omega_0 & -\bar{R}_s L_r & 0 & \bar{R}_r M \\
    \bar{R}_r M & 0 & -\bar{R}_s L_s & \Delta\omega_0 \\
    0 & \bar{R}_r M & -\Delta\omega_0 & -\bar{R}_s L_s
\end{bmatrix}, \]

\[ A_2 = \frac{1}{\Delta} \begin{bmatrix}
    0 & M^2 & \bar{L}_s M & 0 \\
    -M^2 & 0 & -\bar{L}_s M & \bar{L}_r M \\
    0 & -\bar{L}_s M & 0 & -\bar{L}_r M \\
    \bar{L}_s M & 0 & \bar{L}_s M & \bar{L}_r M
\end{bmatrix}, \]

\[ A_3 = \bar{M} \begin{bmatrix}
    -i_{sq}^* & i_{rd}^* & i_{rq}^* & -i_{sd}^*
\end{bmatrix}, \]

\[ \Delta = \bar{L}_s L_r - M^2, \]

\[ \bar{C}_1(t) = -\frac{C_1 R K_i V_u(t)}{J}, \quad \bar{C}_2(t) = -\frac{C_2 R K_i V_u(t)}{J}, \]

\[ \bar{C}_3(t) = -\frac{C_3 P G K_i V_s^2(t)}{J}, \quad \bar{M} = 3 M P^2 G^2 \]

In the above equations, \( x_1, x_2, x_3, x_4 \) are the deviations of the stator currents and the rotor currents of the (d-q) axes from their nominal values \( i_{sd}^*, i_{sq}^*, i_{rd}^*, i_{rq}^* \); \( \bar{\omega} \) is the deviation of the electric angular velocity of the rotor from its nominal values \( \omega^* = (1 - s_0) \omega_0 \); \( \bar{\beta} \) and \( \bar{u} \) are deviations from their nominal values \( \beta^* \) and \( u^* \). The rated slip 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 of the windmill power system

Since the windmill power system is a time varying nonlinear system, the linear control theory can not be applied without some modifications. Here we use quasi-linearization transform to the windmill power system. By this transform we develop a type of equation
which is suitable for $H^\infty$ control full information problem \cite{7}. In the design of sliding mode surface, the stability of the sliding surface and the reachability to it should be certified \cite{9}. Here we use Riccati equations arising in linear $H^\infty$ control to decide a stable sliding surface for the quasi-linearized windmill power system with disturbance \cite{9} \cite{10}. Then we design the control law which consists of a linear control law and a nonlinear control law to drive the state variable into the sliding surface and thereafter maintain within this subspace. For this purpose, a quasi-linearization of the windmill power system is performed in the first step of the controller design procedure, and then the sliding mode control via $H^\infty$ theory is applied.

3.1 Quasi-linearization

Equations (2), (3), (4) represents the windmill power systems which have strong nonlinearity with the time varying parameters $C_1(t)$, $C_2(t)$ and $C_3(t)$ 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:

\[
\frac{dx_g}{dt} = A_g x_g + B_g g_1(\bar{w}(t),t)\bar{\beta} + \xi, \quad \cdots (5)
\]

\[
\frac{d\bar{\beta}}{dt} = -C_\beta \bar{\beta} + C_\beta \bar{u}, \quad \cdots (6)
\]

where

\[
x_g = \begin{bmatrix} x \\ \bar{w} \end{bmatrix}, \quad A_g = \begin{bmatrix} A & A_3 \xi^* \\ A_3 & 0 \end{bmatrix},
\]

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

\[
\xi = \begin{bmatrix} \bar{w}A_2 x \\ (C_1(t)\beta^* + C_2(t)\bar{\beta} + \tilde{M}(x_2 x_3 - x_1 x_4) \end{bmatrix}.
\]

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

\[
\frac{d\bar{\beta}_g}{dt} = \frac{dg_1(\bar{w}(t),t)}{dt} \bar{\beta} - C_\beta \bar{\beta}_g + g_1(\bar{w}(t),t)C_\beta \bar{u}, \cdots (7)
\]

Then we define

\[
\bar{u} = \frac{1}{g_1(\bar{w}(t),t)C_\beta} \times \left[ \frac{dg_1(\bar{w}(t),t)}{dt} \bar{\beta} + \bar{u}_g \right], \cdots (8)
\]

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

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

\[
\frac{d}{dt} \begin{bmatrix} x_g \\ \bar{\beta}_g \end{bmatrix} = \begin{bmatrix} A_g & B_g \\ 0 & -C_\beta \end{bmatrix} \begin{bmatrix} x_g \\ \bar{\beta}_g \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \bar{u}_g + \begin{bmatrix} \xi \\ 0 \end{bmatrix} \quad \cdots (9)
\]

3.2 Sliding mode surface design via $H^\infty$ theory

Here we use $H^\infty$ approach to obtain a sliding mode surface \cite{8} \cite{11}. The basic idea consists in designing a $H^\infty$ controller and then modifying it by defining a subset of the state space, called sliding surface. Particularly, 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

\[
\sigma = F x_g + \bar{\beta}_g, \quad \cdots (10)
\]

\[
F = \begin{bmatrix} f_1 & f_2 & f_3 & f_4 & f_5 \end{bmatrix}. \]

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

Considering the upper subsystem of (9), the cost function for LQ design contains both the state vector and control input cost terms \cite{8} \cite{9} \cite{10}. We define the output $z$ that contains the weighted state variable $Q^{\frac{1}{2}} x_g$ and the weighted control input input $\sqrt{r} \bar{\beta}_g$, that is,

\[
z = \begin{bmatrix} Q^{\frac{1}{2}} x_g \\ \sqrt{r} \bar{\beta}_g \end{bmatrix}, \quad \cdots (11)
\]

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

The following assumptions are made in the implementation of the $H^\infty$ algorithm and must be satisfied:

\begin{align}
(1) \quad & \begin{bmatrix} A_g & B_g \end{bmatrix} \text{ is stable} ; \\
(2) \quad & \begin{bmatrix} A_g & Q^{\frac{1}{2}} \end{bmatrix} \text{ is observable}.
\end{align}

In this subsystem, we define the state feedback control based on Riccati equation. It gives

\[
\bar{\beta}_g = -Fx_g = -\frac{1}{r} B_g^T P x_g, \quad \cdots (12)
\]

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

\[
z = H x_g, \quad \cdots (13)
\]

in which,

\[
H = \begin{bmatrix} \frac{Q^{\frac{1}{2}}}{\sqrt{r}} B_g^T P \end{bmatrix}. \quad \cdots (14)
\]

Here, we define constant $\alpha_\infty$ as

\[
\alpha_\infty = \inf_{\omega} \sup_{\xi} \frac{\|x\|^2}{\|\xi\|^2} \quad \cdots (15)
\]

in which, $\alpha_\infty$ represents the magnitude of influence which affect the system by the maximum disturbance.
under the minimum control in the whole frequency domain. \( H^\infty \) norm of the close-loop transfer function \( T(s) \) from the disturbance \( \xi \) to the output \( z \) determines the control \( \beta_g \) under which the next bound condition is satisfied.

\[
\alpha_\infty \leq \| T(s) \|_\infty \leq \alpha. \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (16)
\]

The state feedback controller which satisfies the condition of (16) is given by the solution of the next Ricatti equation \((17)\).

\[
A_g^T P + PA_g + Q - \frac{1}{\alpha} PB_g B_g^T P + \frac{1}{\alpha^2} PP = 0, \quad (17)
\]

in which, \( \alpha \) is the level achieved along with optional additional outputs of Riccati solutions in \( H^\infty \) control algorithms. As the influence of disturbance is not considered in the conventional optimum regulator, it is the case of \( \alpha \to \infty \); When the influence of disturbance is considered in \( H^\infty \) control, it is the case of \( \alpha \to \alpha_\infty \). This shows the purpose of minimizing the \( H^\infty \) norm of the transfer function. Moreover, by minimizing the \( H^\infty \) norm of the transfer function \( T(s) \), the closed-loop is internally stable\((7)\).

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 \( \bar{u}_g \) which will drive the state variable into the sliding surface \( \sigma \) 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 \( \bar{u}_g \). The state is constrained in the vicinity of \( \sigma = 0 \) by the control law\((8)\).

\[
\bar{u}_g = \left[ \begin{array}{c} \Omega F - FA_g \cr C_{g} \Omega \cr -FB_g \end{array} \right] \left[ \begin{array}{c} x_g \cr \bar{\beta}_g \end{array} \right] \quad - \frac{P_1 \begin{bmatrix} F & 1 \end{bmatrix} \left[ \begin{array}{c} x_g \cr \bar{\beta}_g \end{array} \right]}{\| P_1 \begin{bmatrix} F & 1 \end{bmatrix} \left[ \begin{array}{c} x_g \cr \bar{\beta}_g \end{array} \right] \| + \delta}, \quad \cdots \cdots (18)
\]

where \( P_1 \) is a positive definite solution of Lyapunov equation

\[
P_1 \Omega^* + \Omega^* P_1 = -1
\]

in which \( \Omega^* < 0 \) is a design parameter which contribute to the rate of decay of the range space states into the neighborhood of \( \sigma \). Discontinuous control produces chatter motion in the neighborhood of the sliding surface. \( \delta \) is used to "smooth" the control function\((8)\).

Putting (18) into (8), we get the controller for the windmill power system

\[
\bar{u} = -\frac{1}{g_1(\omega, t)C_{g}} \left\{ \begin{array}{c} \frac{dg_1(\omega, t)}{dt} \bar{\beta}_g - \left[ \begin{array}{c} \Omega F - FA_g \cr C_{g} \Omega \cr -FB_g \end{array} \right] \left[ \begin{array}{c} x_g \cr \bar{\beta}_g \end{array} \right] \right\} \quad + \frac{P_1 \begin{bmatrix} F & 1 \end{bmatrix} \left[ \begin{array}{c} x_g \cr \bar{\beta}_g \end{array} \right]}{\| P_1 \begin{bmatrix} F & 1 \end{bmatrix} \left[ \begin{array}{c} x_g \cr \bar{\beta}_g \end{array} \right] \| + \delta}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (19)
\]

4. Simulation results

In order to verify the effectiveness of the proposed controller which regulates the pitch angle to keep the rated values of the electric angular velocity and the windmill power generation in the range of high wind speed, a simulation was carried out.

4.1 Simulation conditions of windmill power system The validity of the scheme is tested by the windmill induction generator system which is connected to infinity bus as shown in Fig.1.

The basic control movements of the pitch angle of blade in the windmill induction generator system are determined by dividing the speed of wind \( V_w(t) \) into the following four ranges:

(i) less than the cut-in speed, \( V_w(t) < 5.5 \) [m/sec];
(ii) from the cut-in speed to the rated wind speed, \( 5.5 \) [m/sec] \( \leq V_w(t) \leq 12.4 \) [m/sec];
(iii) from the rated wind speed to the cut-out speed, \( 12.4 \) [m/sec] \( \leq V_w(t) \leq 24 \) [m/sec];
(iv) more than the cut-out speed, \( 24 \) [m/sec] \( \leq V_w(t) \).

The relation between the pitch angle \( \beta \) and the generator power \( P_g \) of windmill versus wind speed is shown in Fig.2.

![Fig. 2. Relation between generated power of windmill and pitch angle versus wind speed.](image)

In case (i) and (iv), the pitch angle \( \beta \) is forced to 90 [deg] and the windmill is stopped by releasing wind energy. In case (ii), in order to make use of wind energy to the most extent, the pitch angle is fixed at 10 [deg] and the windmill induction generator is connected to the power system. As shown in Fig.2, the output of the induction generator is determined depending on wind speed.

When the wind speed is in the range from the rated wind speed to the cut-out speed, in order to keep the rated power output and the rated speed of the induction generator, the pitch angle of the blade is controlled by the hydraulic system and it varies from 10 [deg] to 90 [deg]. In this paper, we design the controller for this case. The pitch angle is controlled by a hydraulic system, it's rate is limited to \( |d\beta/dt| \leq 10 [\deg/sec] \) due to the limited response speed of the hydraulic system.

The system parameters and rated values of the windmill induction generator system, which consists of the
windmill induction generator, the hydraulic system and the electric power system, are shown in Table 1. They are supplied by Mitsubishi Heavy Industries, LTD., Japan.

The simulation is carried out under the system operation conditions described in Table 1. Based on equations (5), (6) and (19), compromising a wide range of operation conditions, the controller design parameters are chosen as: $q_i = 0.024$, $r = 0.8$, $\delta = 0.15$, $\mu = 0.01$, $\Omega^* = -12.45$. The test wind pattern was made from the actual wind speed data measured at Miyako Island, Okinawa, Japan on December in 1994. In the simulation, as shown in Fig. 3, the wind speed changed in the range of $12.5 [m/sec] \leq V_w \leq 16 [m/sec]$.

![Fig. 3. The actual wind speed.](image)

The proposed controller is evaluated by the deviation of angular velocity $\dot{\omega}$ of generator, the windmill power generation $P_e$, the pitch angle of blade $\beta$ and the control $u$.

4.2 System responses with normal parameters

Fig. 4 shows the deviation of angular velocity $\dot{\omega}$ of generator, the windmill power generation, the pitch angle of blade $\beta$ 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 windmill power generation. It shows that the angular velocity and the windmill power generation are restrained sufficiently and that they converge on the rated values quickly by using the proposed controller.

4.3 Robustness of sliding mode

In theory, designing the controller requires an accurate system model. However, in practice, an accurate model of the windmill power system is not available and the mathematical model could not represent the generator and the windmill units precisely. It is required to investigate the robustness of the proposed controller with system parameter variations and model errors.

![Fig. 4. Responses with normal parameters by the proposed method.](image)

Table 1: System parameters and rated values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J$</td>
<td>$2.56 \times 10^3 (kg \cdot m^2)$</td>
</tr>
<tr>
<td>$R_i$</td>
<td>$9.924 (kg \cdot m^3)$</td>
</tr>
<tr>
<td>$G$</td>
<td>$-42$</td>
</tr>
<tr>
<td>$C_s$</td>
<td>$1.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>$C_3$</td>
<td>$1.3668 \times 10^{-4}$</td>
</tr>
<tr>
<td>$C_2$</td>
<td>$2.02 \times 10^{-6}$</td>
</tr>
<tr>
<td>$C_1$</td>
<td>$4.90 \times 10^{-4}$</td>
</tr>
<tr>
<td>$r$</td>
<td>$7.954 \times 10^{-3}$</td>
</tr>
<tr>
<td>$R_w$</td>
<td>$0.0042 (\Omega)$</td>
</tr>
<tr>
<td>$L_w$</td>
<td>$5.67 (mH)$</td>
</tr>
<tr>
<td>$C_0$</td>
<td>$6.51 (\Omega)$</td>
</tr>
<tr>
<td>$V_{in}$</td>
<td>$480 (V)$</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>$480 (V)$</td>
</tr>
<tr>
<td>$V_{bus}$</td>
<td>$6600 (V)$</td>
</tr>
</tbody>
</table>
4.3.1 Change of inertia moment In the next, the same windmill power system but with a 10% increase of inertia moment $J$ is considered for simulation. The transient responses for this case are shown in Fig. 5. In comparison with the normal parameter condition, it is observed from Fig. 5 (c) and (d) that the pitch angle $\beta$ and the control $u$ is almost the same, and from Fig. 5 (a) and (b) although the settling time is a little more, the deviation of angular velocity and the wind power generation converge on the rated values in the same way. In this case, it is also observed from the responses that performance deteriorates before the state variables fall into the sliding surface.

![Fig. 5. Responses with 10% increase of inertia moment $J$ by the proposed method](image)

![Fig. 6. Response with 10% increases of parameters $C_1, C_2, C_3, C_4$ and $C_5$ by the proposed method](image)
4.3.2 Change of parameters of windmill and hydraulic systems  Fig.6 shows the transient response curves for the windmill power system with 10% increases of the parameters $C_1, C_2, C_3, C_4$ of windmill and $C_p$ of hydraulic system. Though the amplitude of both the pitch angle of blade shown in Fig.6 (c) and the control shown in Fig.6 (d) have increased, the deviation of angular velocity and the windmill power generation can still be restrained sufficiently and converge on 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 parameter. It is clear that the proposed controller functions satisfactorily by nullifying the variation of parameters. As demonstrated above, when the controller is used, though the wind speed which is in the range of high wind speed changes, the deviation of angular speed and the wind power generation of the windmill induction generator are keep in the rated values. The simulation results show that the responses of the windmill power system is effectively obtained by using the proposed controller.

4.3.3 Comparison with backstepping control method (12) In order to further to show the robustness of the proposed controller, we also give the simulation result of the windmill power system by backstepping controller design method. This is a design method for the windmill power system without considering disturbance and model errors. As shown in Fig.7 (a) and (b), the deviation of the angular velocity and the wind power generation converge on the rated values in a good performance with the normal parameters, but, when the parameters are increased with 10% of their normal values, there are bigger vibration than those shown in Fig.5 and Fig.6. This shows the stronger robustness of the controller proposed in the paper. Fig.7 (c) and (d) show the performance of pitch angle of blade and the control input with normal and change parameter conditions of backstepping control method.

5. Conclusions

In this paper, the method of VSC using frequency criteria of $H^\infty$ control theory for sliding surface design in windmill power systems is proposed. Using quasi-linearization transform technique to the windmill power system, a type of equation which is suitable for $H^\infty$ control full information problem is developed. By solving the Riccati equations arising $H^\infty$ control full information problem a stable sliding surface is decided. Then we design the control law which consists of a linear control law and a nonlinear control law to drive the state variable into the sliding surface and thereafter maintain within this subspace. The capability of the proposed controller to damp out the oscillations of the power and the angular velocity, and the robustness with respect to the system parameter variations and model errors have been evaluated in the simulation study. The simulation results show that
(1) the proposed scheme can damp out oscillations of the windmill power system effectively and keep the wind power generation of windmill generator at the rated value under the varying wind speed.

(2) the angular velocity of windmill generator is kept at the rated value though the wind speed changes.

(3) the scheme is not sensitive to system parameter variations and model errors.

(Manuscript received December 6, 1999, revised March 23, 2000)

References


Appendix

List of symbols:

\( R_s \): stator resistance [Ω].

\( R_r \): rotor resistance [Ω].

\( L_s \): stator inductance [H].

\( L_r \): rotor inductance [H].

\( M \): mutual inductance between stator and rotor [H].

\( R_c \): system line resistance which is calculated to the side of generator.

\( L_{sc} \): system line inductance which is calculated to the side of generator.

\( \omega \): electric angular velocity [rad/sec].

\( \omega_p \): synchronous angular velocity [rad/sec].

\( \Omega \): mechanical angular velocity [rad/sec].

\( s \): slip of angular velocity.

\( J \): inertia moment of windmill [kg·m²].

\( T_w \): torque of windmill [N·m].

\( T \): load torque of induction motor [N·m].

\( P_e \): output of induction generator [w].

\( P \): pole pairs of induction generator.

\( G \): gear ratio of gearbox.

\( \beta \): pitch angle of blade of windmill [deg].

\( C_{1}, C_{2}, C_{3}, C_{4} \): constants of windmill.

\( \lambda \): angular speed rate of windmill.

\( \rho \): density of air.

\( R \): radius of windmill [m].

\( u \): control input.

\( V_{cu} (t) \): speed of wind [m/sec].

\( V_{sd}, V_{sq} \): d axis and q axis voltages of generator which is calculated from the infinity bus [V].

\( V_{bus} \): voltage in the side of infinity bus [V].

\( isd, isq \): d axis and q axis currents of stator [A].

\( id, iq \): d axis and q axis currents of rotor [A].

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