Journal of Applied Sciences

ISSN 1812-5654

science alert

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Journal of Applied Sciences 13 (10): 1684-1690, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.1684.1690
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Convex Polyhedron LPV Controller Design for Variable Speed and Variable Pitch Wind Turbine

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Abstract: According to the dynamic stability of power train, the paper puts forward a new gain scheduling LPV robust H_8 controller design method based on the state space feedback into the field satisfying dynamic response. Taken use of LPV convex decomposition method, transformed wind turbine into convex polyhedron LPV model, designed the global power controller and extended it to the whole running range of wind turbine by using LMI method to design feedback gain which can meet H_8 performance and state space feedback K for each vertex of convex polyhedron. Synthesize each designed feedback controller to get convex polyhedron LPV controller. The simulation is carried on a 1.0MW wind turbine model, given the control result at running point ρ (2.093, 0, 10) and ρ (2.093, 0.314, 20) when the wind speed is 10m/s and 20m/s. The result of simulation validates that the controller has a good control performance.

Key words: LPV (linear parameter varying), convex decomposition, LMI (linear matrix inequalities)

INTRODUCTION

Gain scheduling control is an engineering design method that is widely applied to nonlinear time-varying systems. Recently, with the development of robust control, gain scheduling control has a further study (Apkarian *et al*., 1995; Apkarian and Gahinet, 1995). Especially, gain scheduling control based on LPV method has been applied to actual engineering design (Kajiwara *et al*., 1999). The theory is to get a global controller by designing local controllers with interpolation method. The essential characteristic is to design nonlinear time-varying system controller by using linear controller design method. Dynamic characteristic of wind turbine is a nonlinear system. Main parameters of wind speed, pitch angle and tip speed ratio are nonlinear and time-varying. By model linearization we can get LPV model with these parameters. For MW (megawatt) grade drive system of variable speed and variable pitch wind turbine, the paper puts forward a new method to design gain scheduling robust H_8 controller through combining gain scheduling theory and H_8 control theory and taking use of LPV synthesis method (Wu, 2001). The method ascertains range of variation for selected parameters firstly. Then by using LPV convex decomposition technique, wind turbine model is transformed to convex polyhedron LPV model design separately feedback gain to meet H8 performance and state space and synthesize each designed vertex feedback gain to get convex polyhedron LPV controller.

The aim is to design a controller with disturbance attenuation, robust stabilization and closed-loop response satisfying certain requirements. It can be solved through H_8 synthesis technology and state space feedback. With the application of LMI method, the problem of H_8 control and state space feedback can be described as convex optimization problem including LMIs restriction (Franklin *et al*., 2009). Therefore, by solving a set of LMIs, it can get a multivariable aims controller which meets H_8 performance and has good dynamic characteristics.

LPV CONVEX DECOMPOSITION CONTROLLER DESIGN

Using convex decomposition, the form of matrix convex can be changed to convex hull with same finite dimension matrix N_i:

$$\mathrm{Co}\{N_i, i=1,\ldots k\} := \left\{\sum_{i=1}^{k} a_i N_i \middle| a_i \geq 0, \sum_{i=1}^{k} a_i = 1\right\} \qquad (1)$$

Suppose LPV system can meet the following conditions:

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- The state matrixes of LPV system:

$$A(\rho(t)), B(\rho(t)), C(\rho(t)), D(\rho(t))$$

are radically function of time-varying parameter ρ (t).
- Time varying parameter ρ (t) of LPV system is varying in the polyhedron field Θ whose vertexes are $\rho_1, \rho_2, ..., \rho_k$

That is:

$$\rho\ (t) \in \Theta: = \text{Co}\ \{\rho_1, \rho_2, ..., \rho_5\}$$

So the state matrixes of LPV system:

$$A(\rho(t)), B(\rho(t)), C(\rho(t)), D(\rho(t))$$

are varying in the matrix convex whose vertexes radial functions are of $\rho_1, \rho_2, ..., \rho_k$:

$$\begin{bmatrix} A(\rho(t)) & B(\rho(t)) \\ C(\rho(t)) & D(\rho(t)) \end{bmatrix} \in \text{Co}\begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} := \text{Co}\begin{bmatrix} A(\rho_i) & B(\rho_i) \\ C(\rho_i) & D(\rho_i) \end{bmatrix}, i = 1, \cdots, k$$

Suppose wind turbine is a LPV convex:

$$\begin{aligned} \dot{x} &= A(\rho(t))x + B(\rho(t))u \\ u &= C(\rho(t))x + D(\rho(t))u \end{aligned} \tag{2}$$

Where:

$$\begin{bmatrix} A(\rho(t)) & B(\rho(t)) \\ C(\rho(t)) & D(\rho(t)) \end{bmatrix} \in P := \text{Co}\left\{\begin{bmatrix} A(\rho_i) & B(\rho_i) \\ C(\rho_i) & D(\rho_i) \end{bmatrix}, i = 1, \cdots, k\right\}$$

It can be proved any vertex ρ_i meets (Bianchi *et al*., 2006):

$$\begin{aligned} \dot{x} &= A(\rho_i(t))x + B(\rho_i(t))u \\ u &= C(\rho_i(t))x + D(\rho_i(t))u \end{aligned} \tag{3}$$

Find a state feedback gain K_i which can make the system stable and controller:

$$\Omega_i = \begin{bmatrix} A_{kl} & B_{kl} \\ C_{kl} & D_{kl} \end{bmatrix}$$

can be solved by LMI or linear algebra operation:

$$\Omega(\rho(t)) = \sum_{i=1}^{k} a_i\, \Omega_i = \sum_{i=1}^{k} a_i \begin{bmatrix} A_{kl} & B_{kl} \\ C_{kl} & D_{kl} \end{bmatrix}$$

VARIABLE SPEED CONSTANT FREQUENCY WIND TURBINE with LPV

According to third order model of power train (Dengying and Zhoujie, 2008):

$$\begin{bmatrix} \dot{\theta}_s \\ \dot{\omega}_r \\ \dot{\omega}_g \end{bmatrix} = \begin{bmatrix} 0 & 1 & -1 \\ -\frac{K_s}{J_r} & -\frac{B_s}{J_r} & \frac{B_s}{J_r} \\ \frac{K_s}{J_g} & \frac{B_s}{J_g} & -\frac{B_s}{J_g} \end{bmatrix} \cdot \begin{bmatrix} \theta_s \\ \omega_r \\ \omega_g \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{T_r}{J_r} & 0 \\ 0 & -\frac{T_g}{J_g} \end{bmatrix} \tag{4}$$

where, ω_r is rotor speed, ω_g generator speed, J_r rotational inertia of rotor, J_g rotational inertia of generator, K_s stiffness of drive train, B_s damp of drive train, C_Q torque coefficient

Tr is aerodynamic torque and it can be described as:

$$T_r = \frac{1}{2}\rho\pi R^3\, C_Q\, (\lambda, \beta) v^2 \tag{5}$$

Generator torque can be described as:

$$T_g = B_g\, (\omega_g\text{-}\omega_z) \tag{6}$$

In its linear field: Tr is a nonlinear function of wind speed, rotor speed and pitch angle. It can be linearization at manipulated point:

$$\hat{T}_r = -B_r(\bar{\omega}, \bar{\beta}, \bar{v}) \cdot \hat{\omega}_r + k_{r,v}(\bar{\omega}, \bar{\beta}, \bar{v}) \cdot \hat{v} + k_{r,\beta}(\bar{\omega}, \bar{\beta}, \bar{v}) \cdot \hat{\beta} \tag{7}$$

Where:

$$B_r(\bar{\omega}, \bar{ß}, \bar{v}) = -\left.\frac{\partial T_r}{\partial \omega_r}\right|_{(\bar{\Omega}, \bar{ß}, \bar{v})} = -\frac{T_r(\bar{\omega}, \bar{ß}, \bar{v})}{\bar{\omega}} \left.\frac{\partial C_Q / \partial ?}{C_Q / ?}\right|_{(\bar{?}, \bar{v}, \bar{ß})}$$

$$k_{r,V}(\bar{\omega}, \bar{ß}, \bar{v}) = -\left.\frac{\partial T_r}{\partial v}\right|_{(\bar{\omega}, \bar{ß}, \bar{v})} = \frac{T_r(\bar{\omega}, \bar{ß}, \bar{v})}{\bar{v}} \left(2 - \left.\frac{\partial C_Q / \partial ?}{C_Q / ?}\right|_{(\bar{?}, \bar{v}, \bar{ß})}\right)$$

$$k_{r,\beta}(\bar{\omega}, \bar{ß}, \bar{v}) = \left.\frac{\partial T_r}{\partial ß}\right|_{(\bar{\omega}, \bar{ß}, \bar{v})} = \frac{T_r(\bar{\omega}, \bar{ß}, \bar{v})}{\bar{ß}} \left.\frac{\partial C_Q / \partial ß}{C_Q / ß}\right|_{(\bar{?}, \bar{v}, \bar{ß})}$$

In pitch control, equation of motion of pitch angle can be described as:

$$\dot{\beta} = -\frac{1}{\tau}\beta + \frac{1}{\tau}\beta_d \tag{8}$$

In its linear manipulated field.

So LPV varying parameter model can be expressed:

$$G: \begin{cases} \dot{x} = A(\rho)x + B_v(\rho)\hat{V} + B(\rho)u, \\ \hat{T}_s = C_t x, \\ y = Cx + Du, \end{cases} \tag{9}$$

Where:

$$x = \begin{bmatrix} \hat{\theta}_s & \hat{\omega}_r & \hat{\omega}_g & \hat{\beta} \end{bmatrix}$$

$$u = \begin{bmatrix} \hat{\beta}_d & \hat{\omega}_z \end{bmatrix}$$

$$y = \begin{bmatrix} \hat{\omega}_g & \hat{T}_g \end{bmatrix}$$

LPV model matrix is:

$$A(\rho) = \begin{bmatrix} 0 & 1 & -1 & 0 \\ -\frac{K_s}{J_r} & -\frac{B_r(\rho)+B_s}{J_r} & \frac{B_s}{J_r} & \frac{k_{r,\beta}(\rho)}{J_r} \\ \frac{K_s}{J_g} & \frac{B_s}{J_g} & -\frac{B_s+B_g}{J_g} & 0 \\ 0 & 0 & 0 & -\frac{1}{\tau} \end{bmatrix}$$

$$B_v(\rho) = \begin{bmatrix} 0 & \frac{k_{r,V}(\rho)}{J_r} & 0 & 0 \end{bmatrix}^T$$

$$B(\rho) = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{\tau} \\ 0 & 0 & \frac{B_g}{J_g} & 0 \end{bmatrix}^T$$

$$C_t = [K_s \quad B_s\text{-}B_s \quad 0]$$

$$C = [0 \quad 0 \quad 1 \quad 0],\ D = 0$$

Where:

$$\rho = \begin{bmatrix} \bar{v} & \bar{\varpi} & \bar{\beta} \end{bmatrix}^T$$

If the convex i is be constituted by manipulated point $\rho_i(\bar{\varpi}_i, \bar{\beta}_i, \bar{v}_i)$ of n Bin intervals of static power curve, I different linear matrices can be got which are expressed as Eq. 4 and a designed state feedback gain K_i can also be met:

$$\Omega_i = \begin{bmatrix} A_{kl} & B_{kl} \\ C_{kl} & D_{kl} \end{bmatrix}$$

For any fixed-parameter ρ, LPV model will generate a LTI (linear time invariant). LTI can be described by local characteristic around equilibrium point of nonlinear dynamical system.

Input parameters of wind turbine: wind speed $v_{min} \le v \le v_{min}$, pitch angle $\beta_{min} \le \beta \le \beta_{min}$, rotation speed of the rotor $\omega_{min} \le \omega \le \omega_{min}$, so different LPV controllers for different working regions. From low to high wind speed through rated wind speed, there is always a corresponding scheduling parameter ρ for each region. For each of manipulated point $\rho_1 \ldots \rho_{j-1}, \rho_{j+1}, \ldots \rho_n$ a point composes a dimension convex and a LPV $\in \Theta(\hat{\Omega}, \hat{\beta}, \hat{V})$ state space model. By convex decomposition technique, power system LPV can be expressed as n vertexes of n faces convex:

$$\dot{x} = \left[\sum_{i=1}^{n} a_i A(\rho_i)\right] x + \left[\sum_{i=1}^{n} b_i B(\rho_i)\right] u \tag{10}$$

Where:

$$\rho_1(\theta) = \frac{(\hat{\omega} - \bar{\varpi}_{min})(\hat{v} - \bar{v}_{min})(\hat{\beta} - \bar{\beta}_{min})}{(\bar{\varpi}_{max} - \bar{\varpi}_{min})(\bar{v}_{max} - \bar{v}_{min})(\bar{\beta}_{max} - \bar{\beta}_{min})}$$

$$\rho_i(\theta) = \frac{(\bar{\beta}_i - \hat{\beta})(\bar{v}_i - \hat{v})(\bar{\varpi}_i - \hat{\omega})}{(\bar{\varpi}_{max} - \bar{\varpi}_{min})(\bar{v}_{max} - \bar{v}_{min})(\bar{\beta}_{max} - \bar{\beta}_{min})}$$

$$\rho_n(\theta) = \frac{(\bar{\beta}_{max} - \hat{\beta})(\bar{v}_{max} - \hat{v})(\bar{\varpi}_{max} - \hat{\omega})}{(\bar{\varpi}_{max} - \bar{\varpi}_{min})(\bar{v}_{max} - \bar{v}_{min})(\bar{\beta}_{max} - \bar{\beta}_{min})}$$

For convex polyhedron LPV model 3, state feedback gain $K_1, K_2, \ldots, K_i, \ldots, K_n$ is designed separately to meet vertexes $\rho_1, \ldots, \rho_{i-1}, \rho_{i+1}, \ldots, \rho_n$. Similar to LPV convex decomposition, with vertex feedback gain $K_1 \ldots K_n$ as n vertexes of convex polyhedron LPV controller, at any position θ in convex polyhedron, synthesize to get convex polyhedron LPV controller through designing feedback controller for each vertex (Burzelius, 2002). Below is Fig. 1.

It can be expressed as:

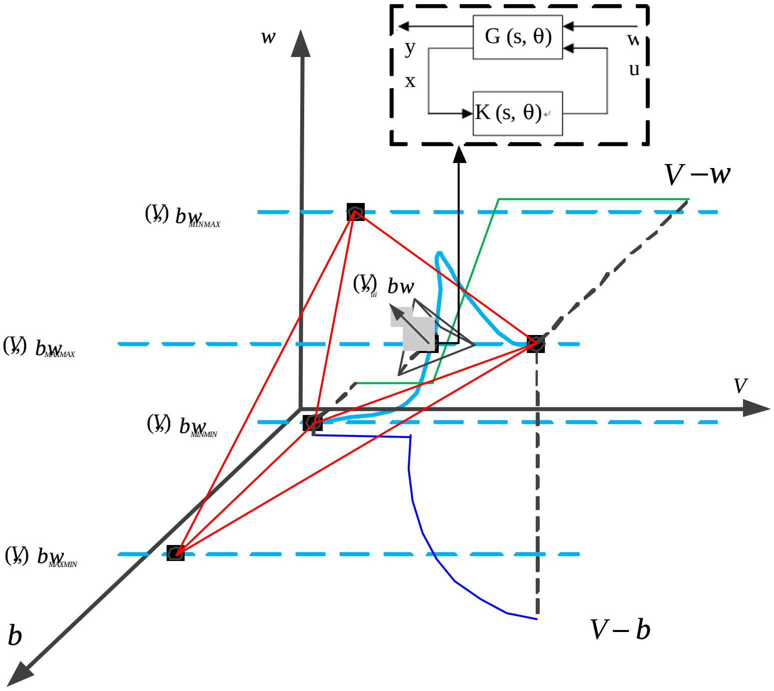

Fig. 1: Convex polyhedron LPV control system

$$K = \rho_1(\theta)K_1 + \rho_2(\theta)K_2 + ... + \rho_i(\theta)K_i + ... + \rho_n(\theta)K_n \quad (11)$$

At each vertex, design satisfying controller using LMI method (Dengying and Zhoujie, 2008). If LMI is available, there will be a group of parameters(R, S) and will get a full feedback controller according to this (R, S) by following steps:

Step 1: Using the singular values calculated, respectively the solution of matrix MN^T = I-RS, the solution is meet to matrix (RS+I) of full rank

Step 2: Solve the linear Eq. 10 to get controller parameters A_c, B_c, C_c, D_c

Step 3: Command $K(s) = D_c + C_c(sI - A_c)^{-1} B_c$, so $K(s)$ is an n-order controller which makes $\|T_{wz}\|_\infty \leq \gamma$ and closed-loop pole in D

After getting required feedback gain for each vertex by theorem, any feedback gain K can be got at any θ through convex LPV controller.

SIMULATION RESEARCH

Take a 1MW wind turbine as example, the linearized model is obtained by GH-Bladed.

Main input parameters are shown as below:

Power-train stiffness and damping:

$$K_s = 1.566 \times 10^6,\ B_s = 1421.1$$

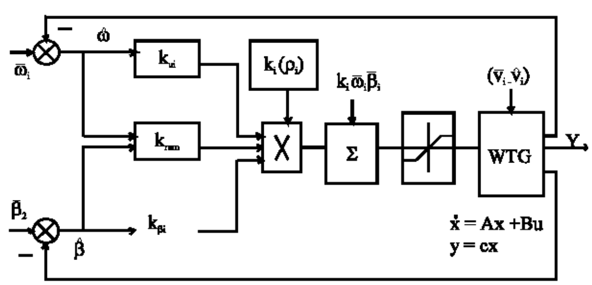

Fig. 2: Principle of variable-gain control

Generator stiffness and damping:

$$K_g = K^*1.5 = 13109.89$$

$$B_g = 415.9935$$

Generator and aerodynamic moment of inertia:

$$J_g = 4.95\ \text{KGM}^2,\ J_r = 830000\ \text{KGM}^2$$

The air density is 1.225 kg m^{-3}, blade radius is 30.3m, rated wind speed v_0 = 11.5 m sec^{-1}, rated rotor speed n = 1800 r min^{-1}.

The actual domination principle of system is shown as Fig. 2.

The followings are simulations for drive system in low and high wind speed field separately, 10 m sec^{-1} wind

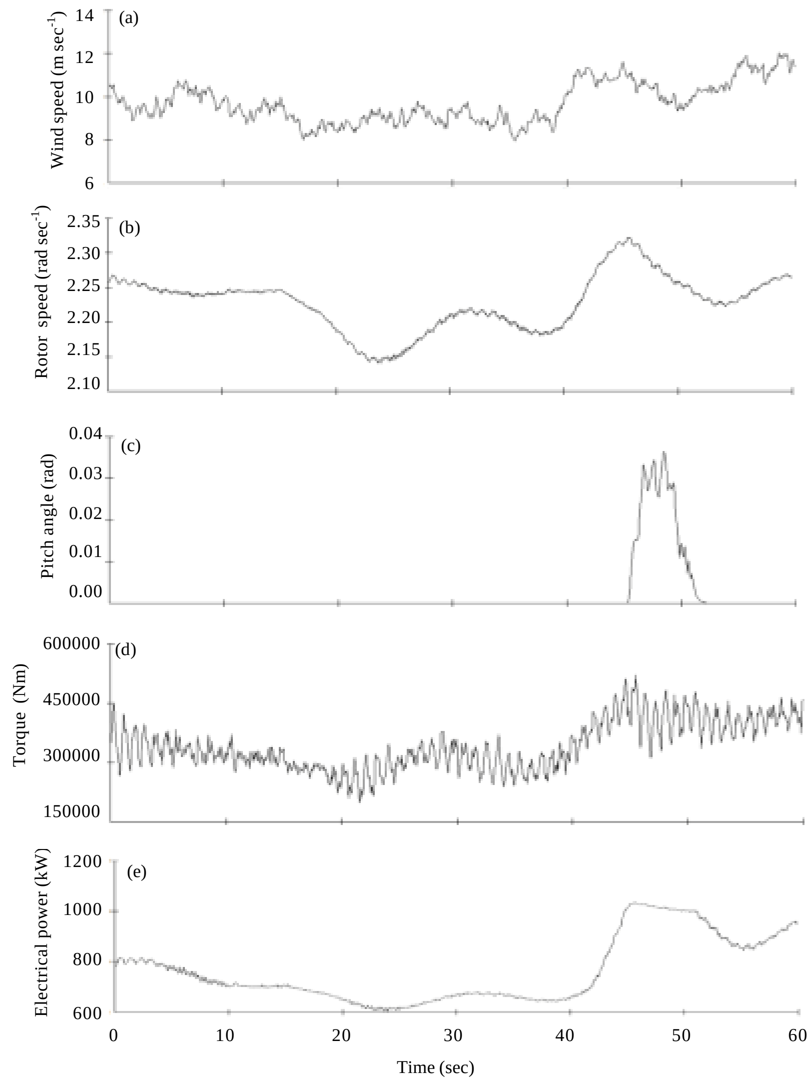

Fig. 3(a-e): Simulation result of 10 m sec^{-1}

speed corresponding vertex ρ_9 (1.884, 0, 10). The simulation results are as shown in Fig. 3.

The Kaimal turbulence is Fig. 3a, rotor speed is Fig. 3b, pitch angle is Fig. 3c, torque curve is Fig. 3d and power curve is Fig. 3e.

When wind speed is changed to 20m/s, the corresponding vertex is changed to ρ_{31} (188.4, 0.058, 20). The following is simulation result, shown in Fig. 4.

The Kaimal turbulence is Fig. 4a, rotor speed is Fig. 4b, pitch angle is Fig. 4c, torque curve is Fig. 4d and power curve is Fig. 4e. From results, in under the action of convex polyhedral LPV controller, output rotor speed, pitch angle, torque and electric power follows changes of input wind speed and has a good tracking performance.

When wind speed is higher, it is between 12-25 m sec^{-1}, the input speed is steady, the changes of rotor speed is small; when wind speed increases, pitch angle and rotor speed have a larger fluctuations, but at the same time the changes of electric power is small.

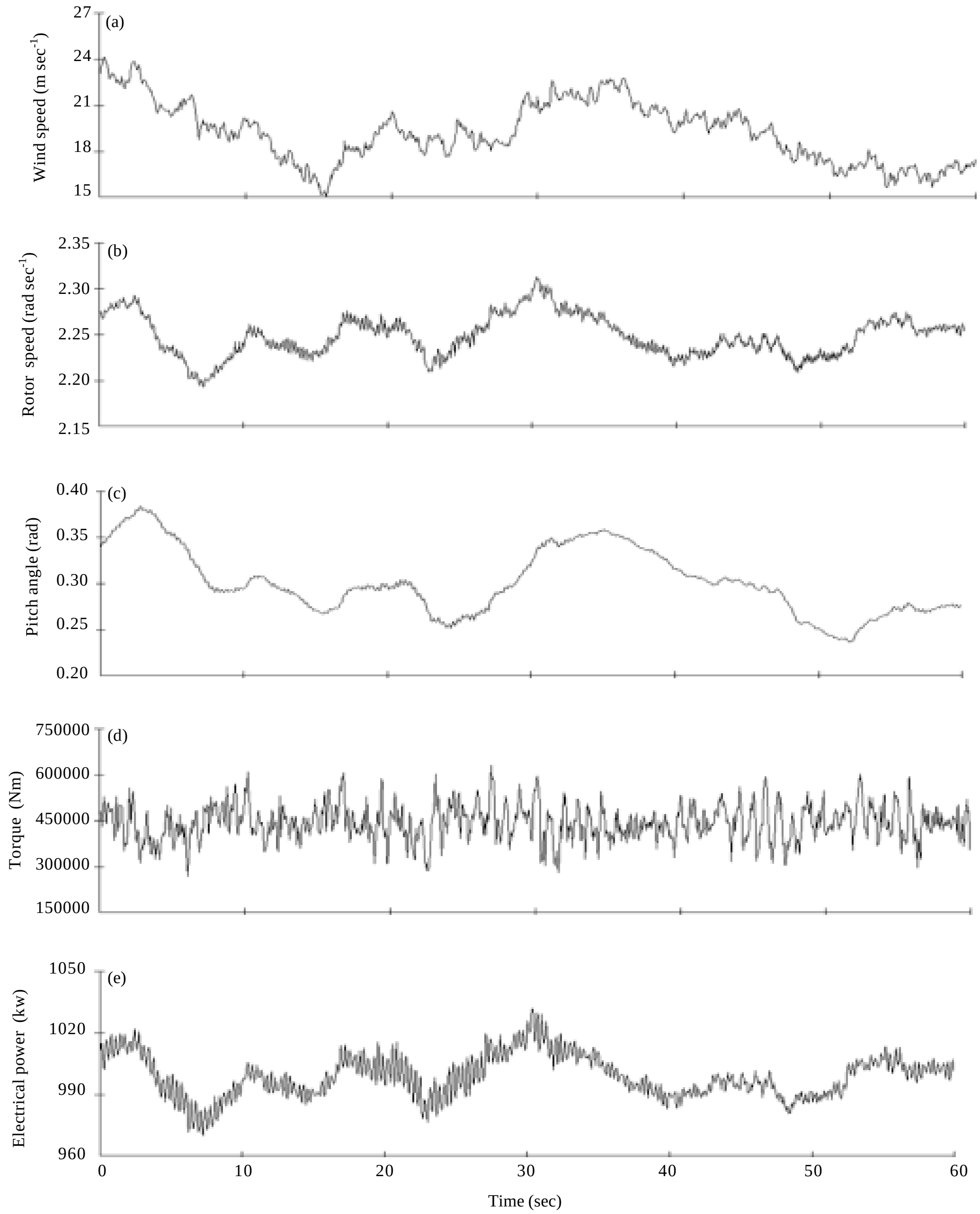

Fig. 4(a-e): Simulation result of 20 m sec^{-1}

CONCLUSION

Combining gain scheduling with H_8 theory and using LPV synthesis technique, the paper puts forward a new convex polyhedron gain scheduling LPV robust H8 controller design method. The method transforms wind turbine model into convex polyhedron LPV model through LPV convex decomposition technique. Design separately feedback gain for each vertex to meet H8 performance and dynamic characteristic and then synthesize every vertex feedback gain to obtain convex polyhedron LPV controller. In the process of designing of vertex controller, LMI method is applied to get optimized solution. Convex polyhedron LPV controller has a small calculation and is easily achieved. The simulation results validate the designed LPV controller has good dynamic response performance.

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