Entropy **2014**, *16*, 3136-3148; doi:10.3390/e16063136

OPEN ACCESS

entropy

ISSN 1099-4300

www.mdpi.com/journal/entropy

Article

Minimum Entropy-Based Cascade Control for Governing Hydroelectric Turbines

Mifeng Ren [1,2], Di Wu [2], Jianhua Zhang [1,*] and Man Jiang [2]

[1] State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China; E-Mail: renmifeng@126.com

[2] School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, China; E-Mails: dxwhfzy@163.com (D.W.); jiangman410@126.com (M.J.)

* Author to whom correspondence should be addressed; E-Mail: zjhncepu@163.com; Tel.: +86-10-6177-2106.

Received: 21 January 2014; in revised form: 21 May 2014 / Accepted: 27 May 2014 / Published: 5 June 2014

Abstract: In this paper, an improved cascade control strategy is presented for hydroturbine speed governors. Different from traditional proportional-integral-derivative (PID) control and model predictive control (MPC) strategies, the performance index of the outer controller is constructed by integrating the entropy and mean value of the tracking error with the constraints on control energy. The inner controller is implemented by a proportional controller. Compared with the conventional PID-P and MPC-P cascade control methods, the proposed cascade control strategy can effectively decrease fluctuations of hydro-turbine speed under non-Gaussian disturbance conditions in practical hydropower plants. Simulation results show the advantages of the proposed cascade control method.

Keywords: minimum entropy; cascade control; hydroelectric turbines; non-Gaussian disturbances

---

1. Introduction

With the high rate of growth of electricity consumption, hydropower plants have been playing a significant role in peak load and frequency regulation of the electric system. Control of hydroturbine speed is economically essential in terms of guaranteeing stability and improving efficiency. Nevertheless, it is challenging because of the complex speed adjusting process characterized by

nonlinearity, uncertainty and various disturbances. The principal control target of hydroturbine speed governors, when various disturbances are imposed and/or the set point changes, is to keep the rotor speed within a proper range by tuning the influent flow of the penstock so that the mechanical transmission torque and the generator torque can arrive at a new balance.

Researchers have made a lot of efforts to develop some advanced control strategies for controlling hydroturbine speed governors. In order to be closer to the actual conditions, more and more studies have focused on nonlinear systems [1]. In the general framework of hydraulic servo systems, Bonchis *et al.* [2] introduced a variable structure methodology into the position control under friction nonlinearity conditions. Sanathanan [3,4] proposed the condensability during water hammer situations by using a frequency domain method to determine the optimum proportional-integral-derivative (PID) gains. Lansberry and Wozniak *et al.* [5] proposed that genetic algorithms can be a means of finding the optimal solution over a parameter space in a hydroturbine speed governing system. This method combined a conventional PID controller with an adaptive control strategy to tune parameters online. Zhong [6] introduced an adaptive inverse control method into hydroturbine speed governing systems with nonlinear, time-variable and non-minimum phase characteristics. This control strategy is based on the function approximation of the wavelet analysis and the self-learning capability of neural network. Considering the disturbance and non-elastic water hammer, Lu *et al.* [7–9] used a linear optimal approach to obtain a new control method which can be implemented easily. Watanabe [10] continued Lu's work by considering the nonlinearity of the state variables. Liu and Cheng *et al.* [11] introduced a new fuzzy control strategy into hydroturbine governing systems. The nonlinear analytical rules were combined with a fuzzy controller to tune fuzzy rules online.

The above advanced strategies have shown their potential use in controller design for hydroturbine speed governing systems. However, when random disturbances are considered, these methods will not achieve ideal control performance. Actually, in the hydroturbine speed governing process, disturbances can cause fluctuations of rotor speed besides variations of load [12,13]. Heng [12] researched μ robust performance of a hydroturbine speed governing system and proposed the optimization of μ synthesis robust PI controllers by selecting the appropriate uncertainty weighting function and the performance weighting function. Assuming water, turbine, load power, speed and load angle disturbances to be zero mean, statistically independent and stationary white driving noise sources with finite variance, [13] proposed a robust single-input multi-output (SIMO) design approach for the governor speed control of a nonlinear hydroturbine model. In this context, disturbances coming from carriers' position and inlet water flow are considered and a cascade control structure is used to control hydroturbine speed. It can reject carriers' position disturbances arising in the inner loop and improve the speed and accuracy of system response with parameter variations in the inner loop. Nevertheless, the inlet water flow disturbance is not included in the inner loop and it is usually non-Gaussian, which makes the speed control problem especially difficult to solve.

Fortunately, stochastic distribution control theory has been established to deal with the stochastic systems with non-Gaussian noises [14–20]. These results can be mainly divided into two categories: (1) probability density function (PDF) shape control and (2) minimum tracking error entropy control. In [19], based on the generalized minimum entropy criterion, a novel run-to-run control methodology for semiconductor processes with uncertain metrology delay was developed from both analytical and numerical viewpoints. Considering the control input constraints, [20] proposed a constrained minimum

entropy control algorithm analytically by using the penalty method. However, this constrained stochastic control method was not applied to any real industrial process. Following the presented stochastic distribution control methods presented in [19,20], the outer controller in hydroturbine speed cascade control systems is designed in the stochastic distribution control framework using an improved minimum entropy criterion, moreover, further stability analysis is performed in this paper. Simulation results show that the proposed minimum entropy based cascade control strategy can effectively reduce the influence of the non-Gaussian disturbances on the hydroturbine speed.

2. Description of Plant Model

A hydroturbine is a rotary engine that takes energy from moving water. Flowing water is directed onto the blades of a turbine runner, creating a force on the blades. Since the runner is spinning, the force acts through a distance (force acting through a distance is the definition of work). In this way, energy is transferred from the water flow to the turbine. In the energy conversion process, the inlet total head of turbine, fluctuates of flow and water hammer effect would affect the stability of the control system.

The transfer function between the inlet total head $H_t(s)$ and water flow $V(s)$ can be expressed as [21]:

$$\frac{H_t(s)}{V(s)} = -\Omega_p - 0.5Z_p \tanh(T_e s) \tag{1}$$

where Ω_p and Z_p are the friction factor and surge impedance. T_e is the wave travel time. The hyperbolic function in Equation (1) can be described as [21]:

$$\tanh(sT_e) = \frac{sT_e \prod_{n=1}^{\infty} [1 + (\frac{sT_e}{n\pi})^2]}{\prod_{n=1}^{\infty} \{1 + [\frac{2sT_e}{(2n-1)\pi}]^2\}} \tag{2}$$

The turbine model can be obtained by considering the effects of water hammer, head loss caused by friction and inelastic penstock [21]:

$$G_1(s) = \frac{P_m(s)}{g(s)} = \frac{1 - \Omega_p - Z_p \tanh(sT_e)}{1 + 0.5\Omega_p + 0.5Z_p \tanh(sT_e)} \tag{3}$$

where $P_m(s)$ and $g(s)$ are the mechanical power and gate opening, respectively. Ω_p and Z_p are the friction factor of the penstock and the normalized hydraulic surge impedance respectively.

The synchronous generator model can be expressed by [21]:

$$G_1'(s) = \frac{y(s)}{P_m(s)} = \frac{1}{Hs + D} \tag{4}$$

where $y(s)$ is the speed of the generator; $H \in [4,13.2]$ is the inertia; $D \in [0,1]$ is the generator damping.

The servo motor model is described by [21]:

$$G_2(s) = \frac{g(s)}{u(s)} = \frac{1}{(T_p s + 1)(T_s s + 1)} \tag{5}$$

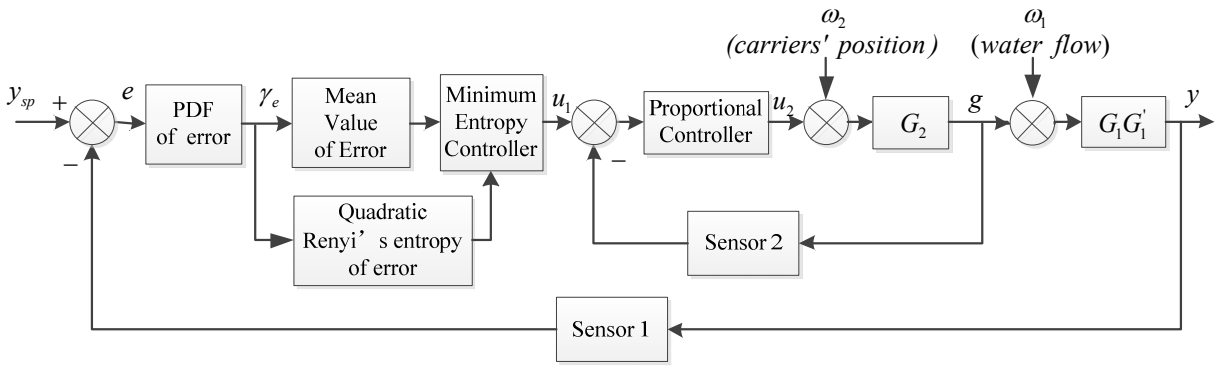
where $u(s)$ is the output signal of the controller, $T_p \in [0.005, 0.02]$ and $T_s \in [0.2, 0.5]$ are the pilot and gate servo motor time constants, respectively.

Carriers' position and inlet water flow disturbances involved in hydroelectric turbines should be paid high attention, since they can cause fluctuations of rotor speed besides variations of load. These disturbances are usually non-Gaussian, which makes the hydroelectric turbine model be a linear, non-Gaussian stochastic dynamic system. Denoting the target hydro-turbine speed as y_{sp}, then the tracking error e can be obtained by subtracting the output speed y from y_{sp}, $e = y_{sp} - y$, which is also a non-Gaussian stochastic process.

3. Minimum Entropy Based Cascade Controller

Figure 1 illustrates the general scheme of the proposed minimum entropy based cascade control for the hydroturbine speed governor. G_1 and $G_1^{'}$ are the transfer functions of the hydroturbine and synchronous generator, respectively. G_2 is the transfer function of the penstock hydraulic servo. ω_1 stands for the inlet water flow disturbance in the outer loop. ω_2 represents the carriers' position disturbance in the inner loop. To achieve the main task proposed in Section 2, the outer controller is designed based on the minimum entropy; while the inner controller is a traditional proportional controller, which roughly regulates the inlet water flow. u_1 and u_2 are outputs of the outer controller and inner controller, respectively.

Figure 1. Minimum entropy based hydro-turbine speed cascade control systems.



The main purpose of this paper is to design the outer controller such that the tracking error is minimized both in magnitude and randomness, which means that the PDF of tracking error should be made as sharp and narrow as possible near zero. Since the tracking error e is a non-Gaussian random variable and its PDF may be asymmetric and multimodal, mean and variance cannot characterize the shape of the tracking error PDF. In that case, a more general measure of uncertainty, named Renyi's entropy, is used in this paper. It is known that small entropy corresponding to a narrow and sharp PDF. Furthermore, the mean value of the tracking error and the control energy also should be minimized simultaneously when designing the controller. In order to simplify the controller design problem, the discrete form of the hydroelectric turbine model is considered. Therefore, the following improved minimum entropy criterion at sample time k is formulated as:

$$J = R_1 H_2(e_k) + R_2 \left| E\left(e_k\right) \right| + \frac{1}{2} R_3 u_{1k}^2 \tag{6}$$

where $H_2\left(e_k\right)$ and $E\left(e_k\right)$ are the quadratic Renyi's entropy and mean value of tracking error, respectively; u_{1k} is the control input to be designed. Then, the outer controller can be obtained by minimizing the performance index (6).

3.1. Estimation of the Performance Index

In the improved minimum entropy criterion (6), $H_2(e_k)$ and $E(e_k)$ are defined as:

$$H_2(e_k) = -\log \int_a^b \gamma_{e_k}^2(x)dx = -\log V(e_k) \tag{7}$$

where $V(e_k) = \int_a^b \gamma_{e_k}^2(x)dx$ is called the information potential [22], which increases as the entropy decreases; and:

$$E(e_k) = \int_a^b x\gamma_{e_k}(x)dx \tag{8}$$

where $[a,b]$ and γ_e are the domain of definition and PDF of the tracking error, respectively.

It can be observed from Equations (7) and (8) that the PDF of tracking error should be estimated in order to calculate the criterion (6). As a nonparametric method, the histogram-based estimation approach [23] is used for the PDF estimation in this paper. Suppose the i.i.d. samples $\left\{e_k^{(1)}, e_k^{(2)}, \cdots, e_k^{(N)}\right\}$ take values in $[a,b]$. Equally partition $[a,b]$ into M intervals, the section points are $a = t_0 < t_1 < \cdots < t_M = b$, and the width of each interval is $\Delta = t_{i+1} - t_i = \frac{b-a}{M}$, $i = 0,1,2,\cdots,M-1$. Then the standard histogram PDF estimator with respect to Δ is given by:

$$\hat{\gamma}_{e_k} = \mu\left(\left[t_i, t_{i+1}\right]\right)/\Delta, \quad if\ e_k \in \left[t_i, t_{i+1}\right] \tag{9}$$

where $\mu\left(\left[t_i, t_{i+1}\right]\right)$ is the standard empirical measure of $\left[t_i, t_{i+1}\right]$, *i.e.*,

$$\mu\left(\left[t_i, t_{i+1}\right]\right) = \frac{1}{N}\sum_{j=1}^{N} \mathrm{I}\left(e_k^{(j)} \in \left[t_i, t_{i+1}\right]\right) \tag{10}$$

where $\mathrm{I}(\cdot)$ is the indicator function.

Substituting the histogram PDF Equation (9) into Equation (7), the nonparametric estimator for Renyi's entropy can be obtained:

$$H_2(e_k) = -\log\left(\frac{\mu^2\left(\left[t_i, t_{i+1}\right]\right)}{\Delta^2} \cdot \left(b-a\right)\right), \quad if\ e_k \in \left[t_i, t_{i+1}\right] \tag{11}$$

The mean value of tracking error e_k can be calculated by:

$$E(e_k) = \frac{1}{L}\sum_{j=1}^{L} e_k^{(j)} \tag{12}$$

Therefore, the criterion (6) can then be obtained using Equations (11) and (12).

3.2. Optimal Controller Design

The design object of the minimum entropy controller is to make the performance index J minimum, *i.e.*, $u_{1k}^{*} = \arg\min_{u_{1k}} J$. In this paper, the following incremental control law is used:

$$u_{1k} = u_{1,k-1} + \Delta u_{1k} \tag{13}$$

Denote $S_k = R_1 H_2(e_k) + R_2 \left| E(e_k) \right|$, the Taylor expansion of S_k is:

$$S_k \approx \overline{S_0} + \overline{S_1}\Delta u_{1k} + \frac{1}{2}\overline{S_2}(\Delta u_{1k})^2 \tag{14}$$

where $\overline{S_0} = S_k\big|_{u_{1k}=u_{1,k-1}}$, $\overline{S_1} = \left.\frac{\partial S_k}{\partial u_{1k}}\right|_{u_{1k}=u_{1,k-1}}$, $\overline{S_2} = \left.\frac{\partial^2 S_k}{\partial u_{1k}^2}\right|_{u_{1k}=u_{1,k-1}}$.

According to Equations (13) and (14), the performance index (6) can be rewritten as:

$$\begin{aligned} J &= \overline{S_0} + \overline{S_1}\Delta u_{1k} + \frac{1}{2}\overline{S_2}\Delta u_{1k}^2 + \frac{1}{2}R_3 u_{1k}^2 \\ &= (\overline{S_0} + \frac{1}{2}R_3 u_{1,k-1}^2)u_{1,k-1}^2 + (\overline{S_1} + R_3 u_{1,k-1})\Delta u_{1k} + \frac{1}{2}(\overline{S_2} + R_3)\Delta u_{1k}^2 \end{aligned} \tag{15}$$

The optimal control input u_{1k} can be obtained by solving:

$$\frac{\partial J}{\partial \Delta u_{1k}} = 0 \tag{16}$$

Then, the recursive sub-optimal control law can be obtained as follows:

$$u_{1k} = u_{1,k-1} - \frac{\overline{S}_1 + R_3 u_{1,k-1}}{\overline{S}_2 + R_3} \tag{17}$$

satisfying $\overline{S}_2 + R_3 > 0$.

Remark 1. The above proposed control law is a type of "greedy" control law, which is easy to implement. In the next section, an improved optimal control law will be proposed to guarantee the closed-loop stability of the hydroturbine speed control system.

3.3. Stabilization Controller Design

In order to analyze the stability of the proposed system, the model of the equivalent plant in outer loop should be formulated first.

Denote the transfer functions of inner proportional controller and sensor 2 in Figure 1 as $G_{c_2}(s) = K_{c_2}$ and $G_{s_2}(s) = K_{s_2}$, respectively. Then, the closed-loop transfer function of the inner loop can be expressed as:

$$G_{inner}(s) = \frac{G_{c_2} G_2(s)}{1 + G_{c_2} G_2(s) G_{s_2}} = \frac{K_{c_2} G_2(s)}{1 + K_{c_2} G_2(s) K_{s_2}} \tag{18}$$

Since the tuned value of K_{c_2} is usually very big, $G_{c_2}G_2(s)G_{s_2} \gg 1$. Therefore, Equation (18) can be rewritten as:

$$G_{inner}(s) \approx \frac{K_{c_2}G_2(s)}{K_{c_2}G_2(s)K_{s_2}} = \frac{1}{K_{s_2}} \tag{19}$$

Therefore, the transfer function of the equivalent plant in outer loop can be formulated by:

$$G_{outer}(s) = G_{inner}(s)G_1(s)G_1^{'}(s)G_{s_1}(s) = \frac{K_{s_1}}{K_{s_2}}G_1(s)G_1^{'}(s) \tag{20}$$

where $G_{s_1}(s) = K_{s_1}$ is the transfer function of sensor 1 in outer loop.

Since cascade control can reject disturbances introduced in the inner loop, ω_2 in Figure 1 is omitted for simplicity when analyzing the stability of the outer close-loop system. Discretize Equation (20) and consider the non-Gaussian disturbance ω_1 entered in outer loop, the equivalent plant in the hydro-turbine speed control system can be modeled by a general ARMAX model as follows:

$$y_k = \sum_{i=1}^{n} a_i y_{k-i} + \sum_{j=0}^{m} b_j u_{1,k-j} + \omega_{1k} \tag{21}$$

a_i $(i = 1,\cdots,n)$, b_j $(j = 0,\cdots,m)$ and $n, m \in \mathbb{Z}$ can be determined from Equation (20) and the calculation processes are omitted here for simplicity.

In order to analyze the closed-loop stability of the hydro-turbine speed control system, the increment form of Equation (21) is formulated as:

$$\Delta y_k = \sum_{i=1}^{n} a_i \Delta y_{k-i} + \sum_{j=0}^{m} b_j \Delta u_{1,k-j} + \Delta\omega_{1k} \tag{22}$$

where $\Delta y_k = y_k - y_{k-1}$, $\Delta u_{1k} = u_{1k} - u_{1,k-1}$ and $\Delta\omega_k = \omega_k - \omega_{k-1}$.

Motivated by the analytical method in [24], different from Equation (14), the following approximation for both Δu_{1k} and Δy_k is presented as:

$$S_k \approx S_{00} + S_{10}\Delta u_{1k} + S_{02}\Delta y_k + S_{12}\Delta u_{1k}\Delta y_k + \frac{1}{2}S_{11}\left(\Delta u_{1k}\right)^2 + \frac{1}{2}S_{22}\left(\Delta y_k\right)^2 \tag{23}$$

where $S_{00} = S_k\big|_{k-1}$, $S_{10} = \left.\frac{\partial S_k}{\partial u_{1k}}\right|_{k-1}$, $S_{02} = \left.\frac{\partial S_k}{\partial y_k}\right|_{k-1}$, $S_{12} = \left.\frac{\partial^2 S_k}{\partial u_{1k}\partial y_k}\right|_{k-1}$, $S_{11} = \left.\frac{\partial^2 S_k}{\partial u_{1k}\partial u_{1k}}\right|_{k-1}$ and $S_{22} = \left.\frac{\partial^2 S_k}{\partial y_k\partial y_k}\right|_{k-1}$.

Using the condition (16), we have:

$$\Delta u_{1k} = -\frac{S_{10} + S_{12}\Delta y_k + R_3 u_{1,k-1}}{S_{11} + R_3} \tag{24}$$

Substituting Equation (24) into Equation (22), we have:

$$\begin{aligned}\Delta y_k &= \sum_{i=1}^{n} a_i \Delta y_{k-i} + \sum_{j=1}^{m} b_j \Delta u_{1,k-j} - b_0 \frac{S_{10} + S_{12}\Delta y_k + R_3 u_{1,k-1}}{S_{11} + R_3} + \Delta\omega_{1k} \\ &= \sum_{i=1}^{n} a_i \Delta y_{k-i} - \frac{b_0 \Delta y_k}{S_{11} + R_3} + \left(\sum_{j=1}^{m} b_j \Delta u_{1,k-j} - \frac{b_0 S_{10} + b_0 R_3 u_{1,k-1}}{S_{11} + R_3} + \Delta\omega_{1k} \right)\end{aligned} \tag{25}$$

Denote $\xi_k = \dfrac{S_{11} + R_3}{S_{11} + R_3 + b_0}\left(\sum_{j=1}^{m} b_j \Delta u_{1,k-j} - \dfrac{b_0 S_{10} + b_0 R_3 u_{1,k-1}}{S_{11} + R_3} + \Delta\omega_{1k} \right)$, $Y(k) = [\Delta y_{k-n}\ \Delta y_{k-n+1} \cdots \Delta y_{k-1}]$, the following state-space representation of Δy_k can then be formulated as:

$$\begin{aligned} Y(k+1) &= \begin{bmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ \alpha_n(k) & \alpha_{n-1}(k) & \cdots & \alpha_1(k) \end{bmatrix} Y(k) + \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \xi_k \\ &= A(k) Y_k + b\xi_k \end{aligned} \tag{26}$$

where $\alpha_i(k) = \dfrac{S_{11} + R_3}{S_{11} + R_3 + b_0} a_i \quad (i = 1, 2, \cdots, n)$.

Finally, the stability condition of the outer closed-loop system is:

$$\left\| A(k) \right\| < 1 \tag{27}$$

4. Simulation Results

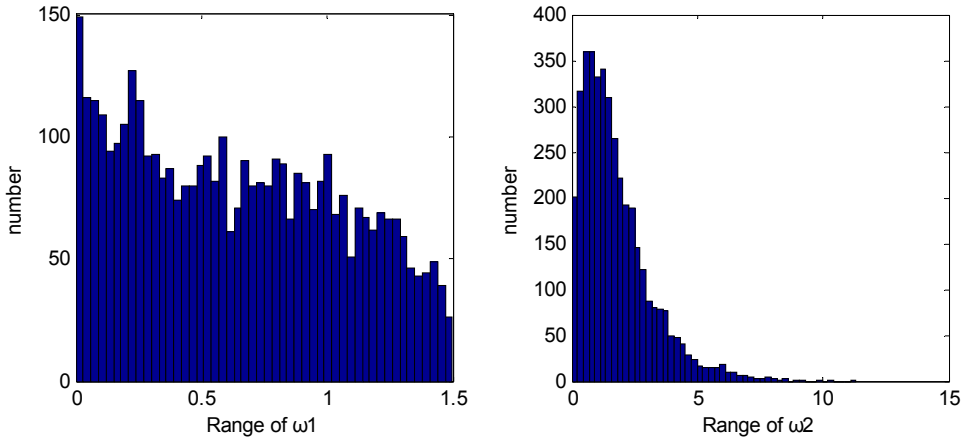
The proposed cascade control method is applied to regulate the hydroturbine rotation speed. In this simulation, the transfer functions of the penstock hydraulic servo system, hydroturbine with elastic water hammer effect and synchronous generator are chosen as, $G_2(s) = \dfrac{1}{(0.01s+1)(0.25s+1)}$ $G_1(s) = \dfrac{-0.0486s^3 + 0.0648s^2 - 0.3s + 1}{0.0243s^3 + 0.0648s^2 + 1.5s + 1}$, and $G_1'(s) = \dfrac{2}{13.5s+1}$, respectively [25]. $K_{s_2} = 98$.

The outer controller is the given optimization controller using minimum entropy criterion and the inner controller is a conventional proportional controller $G_{c_2}(s) = 0.3$. The process is also subjected to non-Gaussian carriers' position disturbance ω_1 and inlet water flow disturbance ω_2, whose distributions are approximated by β-distribution and γ-distribution shown in Figure 2. The sampling period is $T = 1s$, weights in the performance index (5) are set to $R_1 = 6.3$, $R_2 = 3.8$ and $R_3 = 0.0001$. In the histogram-based PDF estimation process, the sample and partition numbers are N = 2500 and M = 50, respectively. Some comparative results with a conventional PID controller and a model predictive controller (MPC) [26] for the outer controller are given to illustrate the superiority of the proposed stochastic distribution control (SDC) method. The transfer function of the PID controller is chosen as $G_{PID}(s) = 1 + \dfrac{1}{0.5s} + 0.5s$. The prediction horizon and control horizon in the MPC algorithm are set to be $N = 280$ and $M = 2$, respectively.

The hydroturbine rotation speed is governed at a steady state before 500 s, the target rotating speed increases from 500 rpm to 510 rpm at 500 s and lasts forever. The responses of the hydroturbine

rotation speed with three different controllers are shown in Figure 3. It can be seen that all three control strategies can stabilize the hydroturbine rotation speed around the set point with small oscillations. Nevertheless, it is obvious that the fluctuation of hydroturbine rotation speed is the smallest using the proposed controller.

Figure 2. Distributions of disturbances ω_1 and ω_2.



The responses of the outer controllers are shown in Figure 4. It can be seen that the control input of the proposed controller is more stable than the PID controller and MPC controller. Figure 5 shows the variation trend of the performance index which has a jump at 500 s with the change of set point, then decreases rapidly until it stabilizes at a low level with the minimum entropy controller. Figure 6 shows that the information potential of the tracking error increases and the entropy decreases corresponding to the performance index. The 3-D mesh plot of the PDF of tracking error is shown in Figure 7. It can be seen that the shape of the PDF becomes more and more sharp and narrow along with the sampling time. It demonstrates that the proposed control strategy has a good effect in dealing with non-Gaussian disturbances. It also can be verified in Figure 8, where PDFs at some typical instants are given. Therefore, the simulation results are consistent with the theoretical analysis.

Figure 3. Responses of the hydroturbine rotation speed.

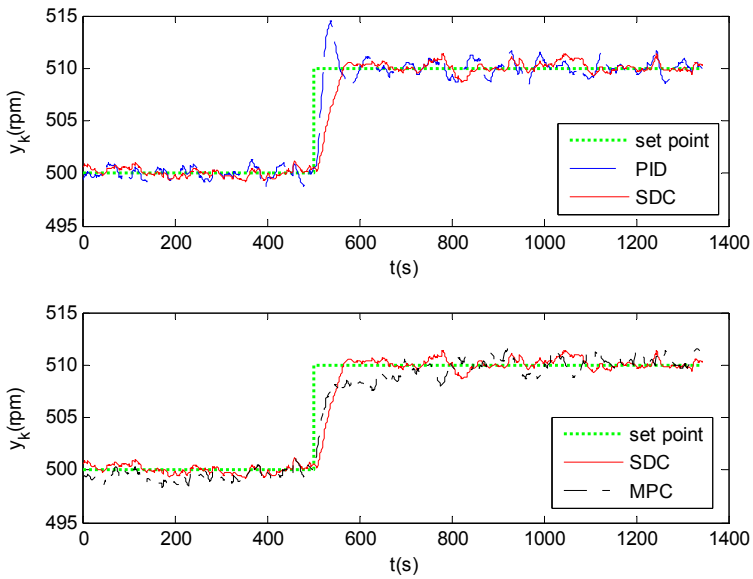


Figure 4. Responses of the outer controller.

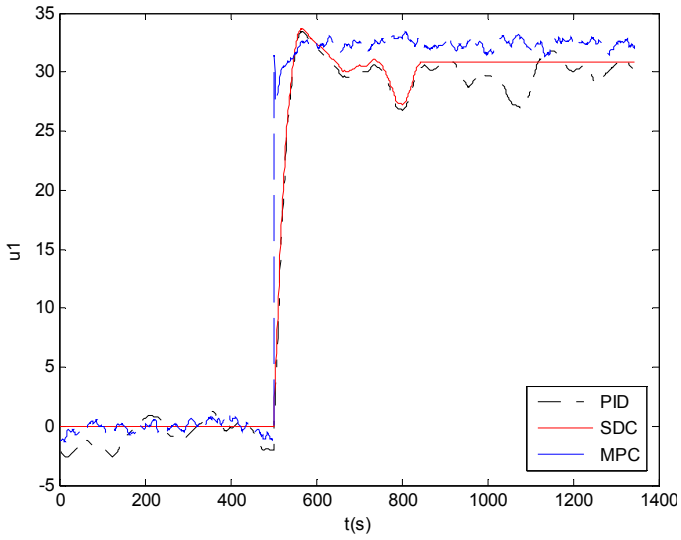


Figure 5. Performance index.

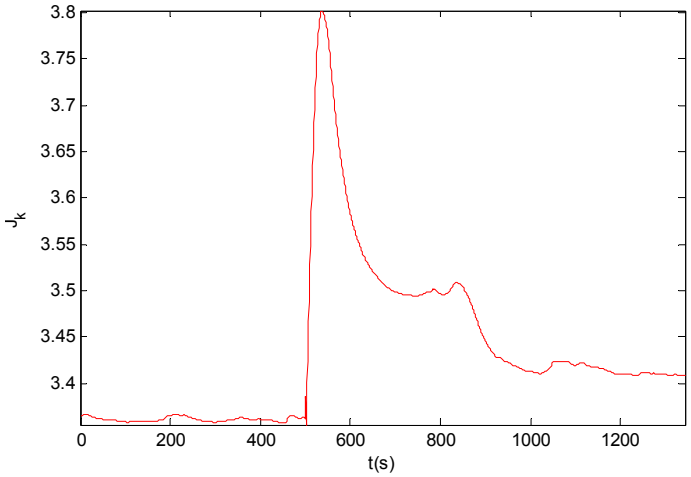


Figure 6. Information potential and entropy of the tracking error.

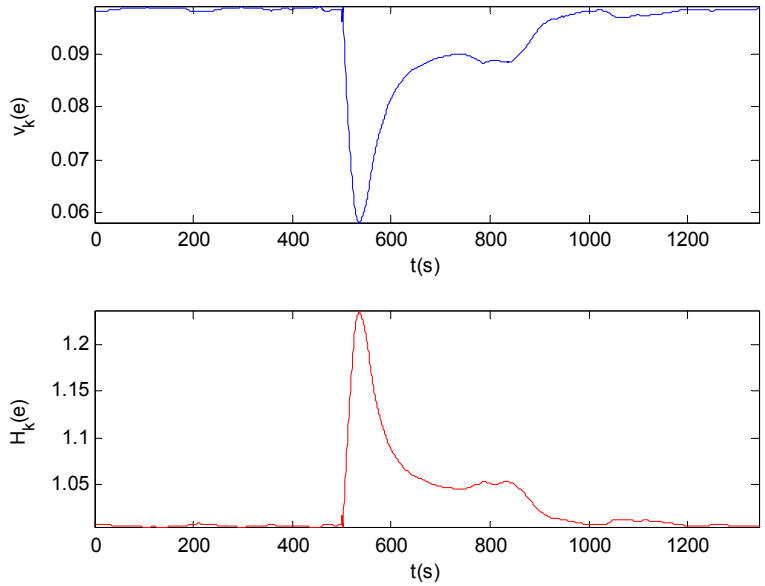


Figure 7. PDF of the tracking error.

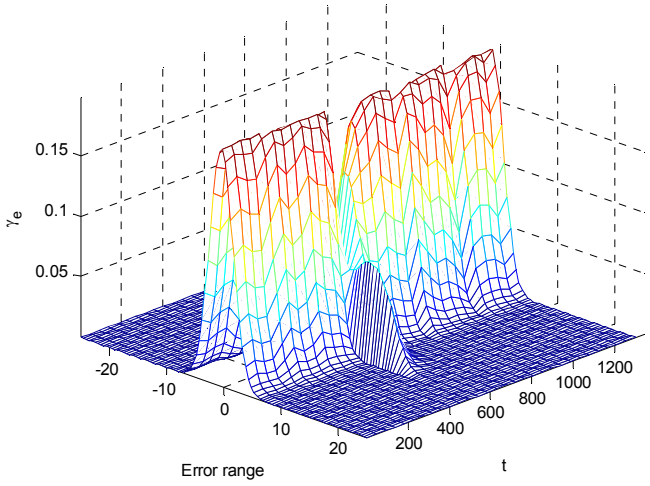
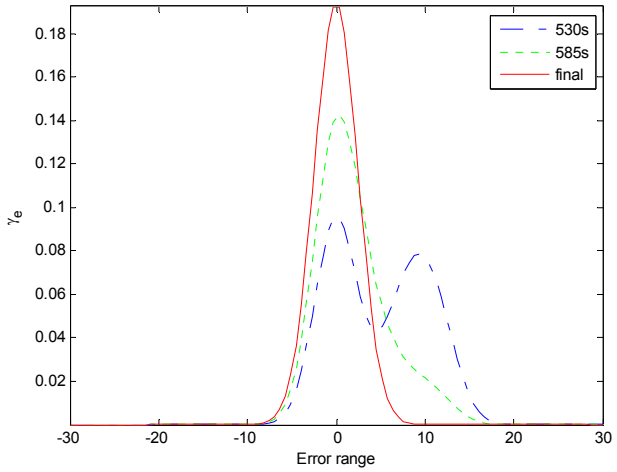


Figure 8. PDFs at typical instants.



5. Conclusions

This paper investigates the minimum entropy-based cascade control problem for hydroturbine speed control systems with non-Gaussian disturbances. The performance index of a closed-loop control system consists of entropy, mean value of tracking error and control energy constraint. In this regard, the task of control is to design the control algorithm so that the established criterion is minimized. The histogram-based estimation approach is adopted to obtain the nonparametric estimation of the tracking error PDF, and then the whole performance index can be obtained. By minimizing the improved minimum entropy criterion, an incremental control law is eventually formulated. Comparative simulation results show that the presented method can achieve better speed control performance in dealing with non-Gaussian disturbances. Future work incorporates considering nonlinearities exist in the hydroturbine speed control systems and doing experiments on a real turbine.

Acknowledgments

This work was supported by National Basic Research Program of China under Grant (973 Program 2011 CB710706) and China National Science Foundation under Grant (60974029). These are gratefully

acknowledged. The authors wish to thank Ting Zhang for relevant simulations. We also wish to thank Guolian Hou and Fang Fang for their constructive suggestions when the paper was revised.

Author Contributions

Jianhua Zhang conceived the project. Mifeng Ren, Di Wu, Jianhua Zhang and Man Jiang searched relevant literatures. Mifeng Ren and Jianhua Zhang carried out the theoretical derivation. Di Wu provided the simulation results. Mifeng Ren, Jianhua Zhang and Di Wu analyzed the simulation results and wrote the paper. Correspondence and requests for materials should be addressed to Jianhua Zhang.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Kishor, N.; Saini, R.P.; Singh, S.P. A review on hydropower plant models and control. *Renew. Sustain. Energy Rev.* **2007**, *11*, 776–796.
2. Bonchis, A.; Corke, P.I.; Rye, D.C.; Ha, Q.P. Variable structure methods in hydraulic servo systems control. *Automatica* **2001**, *37*, 589–595.
3. Sanathanan, C.K. Accurate low order model for hydraulic turbine-penstock. *IEEE Trans. Energy Convers.* **1987**, *2*, 196–200.
4. Sanathanan, C.K. A frequency domain method for tuning hydro governors. *IEEE Trans. Energy Convers.* **1988**, *3*, 14–17.
5. Lansberry, J.E.; Wozniak, L.; Goldberg, D.E. Optimal hydrogenerator governor tuning with a genetic algorithm. *IEEE Trans. Energy Convers.* **1992**, *7*, 623–630.
6. Zhong, L. The application of wavelet neural network in adaptive inverse control of hydro-turbine governing system. In Proceedings of the International Conference on Artificial Intelligence and Computational Intelligence, Shanghai, China, 7–8 November 2009; Volume 2, pp. 163–166.
7. Lu, Q.; Mei, S.; Hu, W.; Song, Y.H.; Goto, M.; Konishi, H. Decentralised nonlinear H_∞ excitation control based on regulation linearisation. *IEE Proc. Gener. Transm. Distrib.* **2000**, *147*, 245–251.
8. Lu, Q. SDM hybrid control approach for nonlinear systems and application to power systems. In Proceedings of the International Conference on Power System Technology, Kunming, China, 13–17 October 2002; Volume 1, pp. 18–23.
9. Lu, Q.; Sun, Y.; Sun, Y.; Wu, F.F.; Ni, Y.; Yokoyama, A.; Goto, M.; Konishid, H. Nonlinear decentralized robust governor control for hydroturbine-generator sets in multi-machine power systems. *Int. J. Electr. Power Energy Syst.* **2004**, *26*, 333–339.
10. Watanabe, T. Robust decentralized turbine-governor control subject to saturation nonlinearity. In Proceedings of the 2002 American Control Conference, Anchorage, AK, USA, 8–10 May 2002; Volume 3, pp. 1948–1953.

11. Liu, S.; Cheng, Y.; Ye, L. Nonlinear analytical rules based fuzzy control for the hydro turbine governing system. In Proceedings of the 2009 Asia-Pacific Power and Energy Engineering Conference, Wuhan, China, 27–31 March 2009; pp. 1–4.
12. Hen, Q.; Lu, Q.; Lu, Y. Robust control of hydro turbine speed governor. In Proceedings of the 10th World Congress on Intelligent Control and Automation, Beijing, China, 6–8 July 2012; pp. 2680–2684.
13. Eker, I. Governors for hydro-turbine speed control in power generation: A SIMO robust design approach. *Energy Convers. Manag.***2004**, *45*, 2207–2221.
14. Wang, H.; Zhang, J.H. Bounded stochastic distributions control for pseudo-ARMAX stochastic systems. *IEEE Trans. Autom. Control* **2001**, *46*, 486–490.
15. Guo, L.; Wang, H. *Stochastic Distribution Control System Design: A Convex Optimization Approach*; Springer: London, UK, 2010.
16. Yue, H.; Wang, H. Minimum entropy control of closed-loop tracking errors for dynamic stochastic systems. *IEEE Trans. Autom. Control* **2003**, *48*, 118–122.
17. Yue, H.; Zhou, J.; Wang, H. Minimum entropy of B-spline PDF systems with mean constraint. *Automatica* **2006**, *42*, 989–994.
18. Wang, H. *Bounded Dynamic Stochastic Systems: Modelling and Control*; Springer: London, UK, 2000.
19. Zhang, J.; Chu, C.C.; Munoz, J.; Chen, J. Minimum entropy based run-to-run control for semiconductor processes with uncertain metrology delay. *J. Process Control* **2009**, *19*, 1688–1697.
20. Zhang, J.; Ren, M.; Tian, Y.; Hou, G.; Fang, F. Constrained stochastic distribution control for nonlinear stochastic systems with non-Gaussian noises, *Int. J. Innov. Comput. Inf. Control* **2013**, *9*, 1759–1767.
21. Eker, I. Governors for hydro-turbine speed control in power generation: A SIMO robust design approach. *Energy Convers. Manag.* **2004**, *45*, 2207–2221.
22. Principe, J.C.; Xu, D.; Fisher, J. Information theoretic learning. *Unsupervised Adapt. Filter.* **2000**, *1*, 265–319.
23. Chen, B.; Zhu, Y.; Hu, J.; Principe, J.C. System identification under information divergence criteria. In *System Parameter Identification: Information Criteria and Algorithms*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2013; pp. 184–185.
24. Guo, L.; Yin, L. Robust PDF control with guaranteed stability for non-linear stochastic systems under modelling errors. *IET Control Theory Appl.* **2009**, *3*, 575–582.
25. Vournas, C.D.; Zaharakis, A. Hydro turbine transfer functions with hydraulic coupling. *IEEE Trans. Energy Convers* **1993**, *8*, 527–532.
26. Rawlings, J.B.; Mayne, D.Q. *Model Predictive Control: Theory and Design*; Nob Hill Publishing: London, UK, 2009.