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Automatic Generation Controller Design in Deregulated and Networked Environment Using Predictive Control Strategy

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Abstract: In this paper, Generalized Predictive Control (GPC) algorithm is applied to design automatic generation control (AGC) systems in deregulated and networked environment. The proposed AGC approach can be used to deal with the effects caused by power market and communication networks. Finally, the developed scheme is implemented in a two-area AGC system, and the simulation results show the effectiveness of the proposed scheme.

1. INTRODUCTION

Traditional automatic generation control (AGC) systems are facing new challenges in deregulated and networked environment. The traditional AGC systems have to be reformulated due to the effects caused by the open market for price based operation and the communication network.

AGC systems after deregulation have been investigated based on optimization or robust control theory. The concept of DISCO participation matrix (DPM) and area participation factor (APF) were introduced to simulate bilateral contract, moreover, trajectory sensitivities were used to obtain optimal parameters of AGC systems using gradient Newton algorithm (Donde et al. , 2001). The genetic algorithm was used to optimize integral gains and bias factors (Demiroren et al., 2006). AGC of a hydro-thermal system with generation rate constraint (GRC) after deregulation is investigated. In particular, the sensitivity of the optimal controller gains to DPM and APF was given in Paridal and Nandal (2005). Robust control algorithms, such as μ -synthesis, H_∞ and mixed H_2/H_∞, were utilized in AGC in a restructured systems (Bevrani 2003; Feliachi 1997, Bevrani 2004). Multi-stage fuzzy PID controller was designed for AGC systems (Shayeghi , 2006).

Recently, modelling and synthesis of conventional AGC systems in communication networked environment also have been published in (Nobile 2000; He 2005; Bevrani 2005). Communication networks inevitably introduced time delays to AGC systems. There are two time delays induced by two main communication links, which includes the delay between RTU and the control centre, and the delay between the control centre to the individual units. In Nobile (2000), the effect of signal delay uncertainties in open communication networks on LFC was investigated by constant, random and exponential delays, respectively. It was also pointed out that the induced delays might cause deterioration of the AGC system performance. Considering the delay between the power plant automation system and the governor in He (2005), a robust H_∞ controller was designed for conventional AGC systems and solved by linear matrix inequalities. In Bevrani (2005), a PI-based LFC with two kinds of communication delays was designed via a mixed H_2/H_∞ control techniques and an iterative LMI algorithm.

At present, little research has been carried out on designing controller for AGC systems in deregulated and networked environment. In Bhowmik et al. (2004), the effect of signal delays on load following is summarized, communication models for third parity LFC was investigated by queuing theory. In Yu and Tomsovic (2004) , the induced time delays in deregulated and networked AGC systems were simplified. Assumed that the control centre waits to receive the tele-metered signals from remote terminal unit (RTU), and it was further assumed that individual units may communicate directly bypassing the control center in case of bilateral contracts, therefore, two delays were aggregated into a single delay from control centre. The robust controller of AGC systems with one communication single delay was presented based on LMI.

Robust control algorithm can guarantee the stability of AGC systems in deregulated and networked environment as long as time delays are bounded. However, how to compensate for the time delay and data dropout has not been considered, moreover, it simply treat networked AGC system as a system with time delays, which ignore some features, e.g., random delay and data transmission in packet. As such, following the approaches presented in (Tang 2006; Liu 2005), predictive control algorithm is applied to design controller for AGC systems in deregulated and networked environment in order to compensate time delay and take advantage of some features caused by communication transmission. In fact, predictive control strategy has been utilized in conventional LFC in (Rerkpreedapong 2003; Atic 2003), because it can deal with the generating rate constraint and incorporate economic objectives as a part of control requirements.

The main objective of this work is to investigate predictive control algorithm for AGC systems in deregulated and networked environment. The rest of this paper is organized as follows. Section 2 designs the predictive controller for networked AGC systems after deregulation. Section 3 shows the application of the proposed controller, and Section 4 concludes this paper.

2. DESIGN OF CONTROLLER

Take a two-area AGC system in deregulated and networked environment as an example, whose block diagram is shown as Fig. 1.

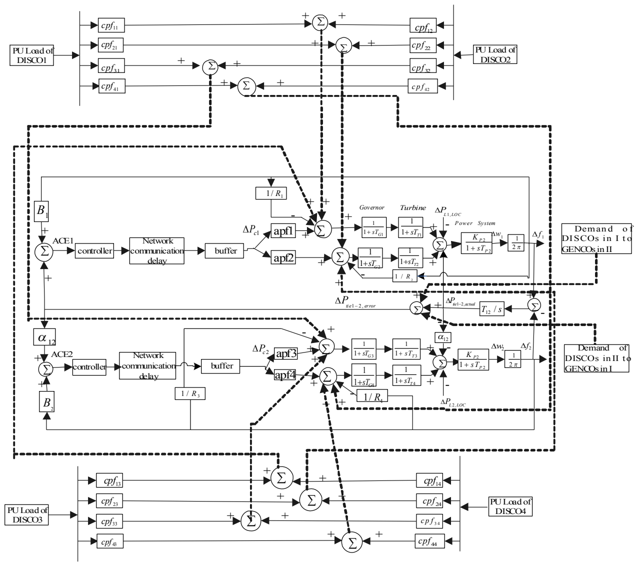


Fig. 1 Two-area AGC system in deregulated and networked environment

In deregulated environment, GENCOs sell power to various DISCOs at competitive prices. A DISCOs may make contracts with any available GENCOs in their own or other areas. Thus, it leads to various combinations of the possible contracted scenarios between DISCOs and GENCOs. The restructured AGC system is modeled based on DISCO participation matrix (DPM) presented in (Donde et al. , 2001), the element of DPM named cpf (contract participation factor) represents the participation of a DISCO in a contract with a GENCO. Likewise, ACE participation factors are employed to the distribution relation between ACE signal and each GENCO.

The time delays induced by communication channels in AGC systems can be classified into forward-link delay and feedback-link delay. The forward-link delay is between the controller and the governor due to transmitting control law to the individual units; the feedback-link delay is between RTU and the control centre due to transmitting tele-metered frequency and power tie-line flow signals. In this work, the feedback-link delay is ignored as shown in Fig. 1. In fact, it is approximately 80-200 milliseconds if the tele-metered signals are transmitted via dedicated channel in Synchronous Digital Hierarchy (SDH) or IP switch mode. Or, the feedback-link and forward-link delays can be regarded as a single delay under some reasonable assumptions (Yu and Tomsovic, 2004).

The following assumptions can reasonably be made when studying networked AGC systems:

A1) The random delay τ induced by network is bounded.

A2) The number of consecutive data dropouts is also bounded.

A3) The data are transmitted through network with a time-stamp so that the delay information can be extracted at the governor node.

A4) The bandwidth of the communication network is not limited.

For a two-area AGC system, it can be modelled as the following state space equations

$$\begin{cases} \dot{X}(t) = A_1 X(t) + B_1 u(t) + B_2 V(t) \\ y(t) = CX(t) \end{cases} \tag{1}$$

where $X = [\Delta w_1\ \Delta w_2\ \Delta P_{tie}\ \Delta P_{T_1}\ \Delta P_{T_2}\ \Delta P_{T_3}\ \Delta P_{T_4}\ \Delta P_{V_1}\ \Delta P_{V_2}\ \Delta P_{V_3}\ \Delta P_{V_4}\ ]^T$ represents the state of the system; $u = [\Delta P_{c1}\ \Delta P_{c2}]^T$ is the manipulated variables or command inputs prior to communication channels. $V = [\Delta P_{L1}\ \Delta P_{L2}\ \Delta P_{L3}\ \Delta P_{L4}]^T$ is the vector of power demands of the DISCOs. A_1, B_1 and B_2 are appropriate dimension matrixes. The parameters of the power system are given in Appendix A.

The above AGC model can be transformed to the following CARIMA model

$$A(z^{-1})y(t) = B(z^{-1})u(t-1) + D(z^{-1})v(t) + \frac{1}{\Delta}C(z^{-1})e(t) \tag{2}$$

where $y(t) \in R^n$, $u(t-1) \in R^m$ are the output and control sequence of AGC system. $v(t) \in R^l$ is a vector of measured disturbance and $e(t)$ is a zero mean white noise, the operator Δ is defined as $\Delta = 1 - z^{-1}$, $A(z^{-1})$ and $C(z^{-1})$ are $n \times n$ monic polynomial matrices , $B(z^{-1})$ is an $n \times m$ polynomial matrix and $D(z^{-1})$ is an $n \times l$ polynomial matrix.

$$A(z^{-1}) = I_{n\times n} + A_1 z^{-1} + A_2 z^{-2} + \ldots + A_{na} z^{-n_a}$$
$$B(z^{-1}) = B_0 + B_1 z^{-1} + B_2 z^{-2} + \ldots + B_{nb} z^{-n_b}$$
$$C(z^{-1}) = I_{n\times n} + C_1 z^{-1} + C_2 z^{-2} + \ldots + C_{nc} z^{-n_c}$$
$$D(z^{-1}) = D_0 + D_1 z^{-1} + D_2 z^{-2} + \ldots + D_{nd} z^{-n_d}$$

For simplicity, in the following the C polynomial matrix is chosen to be $I_{n\times n}$. Let us consider the following finite horizon quadratic criterion:

$$J(N, Nu) = \sum_{j=1}^{N} \left\| \hat{y}(t+j\,|\,t) - w(t+j) \right\|_R^2 + \sum_{j=1}^{N_u} \left\| \Delta u(t+j-1) \right\|_Q^2 \tag{3}$$

where $\hat{y}(t+j\,|\,t)$ is an optimal j-step ahead prediction of the system output on data up to time t, N is the prediction horizon and Nu is control horizon, $w(t+j)$ is a future set-point or reference for the output vector. R and Q are positive definite weighting matrices.

Multiplying (2) by $\Delta E_j(z^{-1})z^j$, and employing the following Diophantine equation:

$$I_{n\times n} = E_j(z^{-1})\tilde{A}(z^{-1}) + z^{-j}F_j(z^{-1}) \tag{4}$$

$$E_j(z^{-1})B(z^{-1}) = G_j(z^{-1}) + z^{-j}G_{jp}(z^{-1}) \tag{5}$$

$$E_j(z^{-1})D(z^{-1}) = H_j(z^{-1}) + z^{-j}H_{jp}(z^{-1}) \tag{6}$$

where $j = 1,2,.....N$,

$E_j(z^{-1}) = E_{j,0} + E_{j,1}z^{-1} + ... + E_{j,j-1}z^{-j+1}$

$F_j(z^{-1}) = F_{j,0} + F_{j,1}z^{-1} + ... + F_{j,na}z^{-na}$

$G_j(z^{-1}) = G_0 + G_1z^{-1} + ... + G_{j-1}z^{-j+1}$

$G_{jp}(z^{-1}) = G_0^{jp} + G_1^{jp}z^{-1} + ... + G_{n_b-1}^{jp}z^{-n_b+1}$

$H_j(z^{-1}) = H_0 + H_1z^{-1} + ... + H_jz^{-j+1}$

$H_{jp}(z^{-1}) = H_0^{jp} + H_1^{jp}z^{-1} + ... + H_{n_d}^{jp}z^{-n_d+1}$

we can obtain

$$\hat{y}(t+j\,|\,t) = G_j(z^{-1})\Delta u(t+j-1) + H_j(z^{-1})\Delta v(t+j) + f_j \tag{7}$$

where $f_j = G_{jp}(z^{-1})\Delta u(t-1) + H_{jp}(z^{-1})\Delta v(t) + F_j(z^{-1})y(t)$

The predictions can be expressed in condensed form as:

$$y = Gu + Hv + f \tag{8}$$

where $y = [\hat{y}(t+1\,|\,t)\ ,..., \hat{y}(t+N\,|\,t)\ ]^T$

$u(t\,|\,t) = [\Delta u(t)\ , \Delta u(t+1),..., \Delta u(t+Nu-1)\ ]^T$

$v = [\Delta v(t+1)\ , \Delta v(t+2)..., \Delta v(t+N)]^T$

$f = [f_1\ ,..., f_N]^T$

$$G = \begin{bmatrix} G_0 & 0 & \cdots & 0 \\ G_1 & G_0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ G_{N_u-1} & G_{N_u-2} & \cdots & G_0 \\ G_{N-1} & G_{N-2} & \cdots & G_{N-N_u} \end{bmatrix}_{Nn\times N_u m}$$

$$H = \begin{bmatrix} H_0 & 0 & \cdots & 0 \\ H_1 & H_0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ H_{N_u-1} & H_{N_u-2} & \cdots & H_0 \\ H_{N-1} & H_{N-2} & \cdots & H_{N-N_u} \end{bmatrix}_{Nn\times N_u l}$$

Equation (3) can be written as follows:

$$J = (Gu + Hv + f - w)^T R(Gu + Hv + f - w) + u^T Qu \tag{9}$$

where $w = [w(t+1), w(t+2)...w(t+N)]^T$

Optimizing J, we have

$$u(t\,|\,t) = (G^T RG + Q)^{-1}G^T R[w - f - Hv] \tag{10}$$

In order to compensate for the network communication time delay, a network delay compensator is used. Since network can transmit a set of data obtained from GPC algorithm at the same time, all control prediction at time t are packed and send to governor through network (Liu et al. 2005). The latest control value chosen from the control prediction sequences then actuates the governor. For example, if the following control prediction sequence are received at governor node:

$$\begin{bmatrix} u(t-d_1\,|\,t-d_1) \\ u(t-d_1+1\,|\,t-d_1) \\ \vdots \\ u(t\,|\,t-d_1) \\ \vdots \\ u(t+N_u-d_1\,|\,t-d_1) \end{bmatrix}, \ldots, \begin{bmatrix} u(t-d_t\,|\,t-d_t) \\ u(t-d_t+1\,|\,t-d_t) \\ \vdots \\ u(t\,|\,t-d_t) \\ \vdots \\ u(t+N_u-d_t\,|\,t-d_t) \end{bmatrix} \tag{11}$$

where the control value $u(t\,|\,t-d_i)$ for $i = 1,2,...,t$, are available to be chosen as the control input at time t, the actuating signal is

$$u(t) = u(t\,|\,t - \min\{d_1, d_2, ..., d_t\})$$

which is the latest predictive control value for time t. d_i is the delay extracted by time-stamp at instant i.

3. SIMULATION OF A NETWORKED AND DEREGULATED AGC SYSTEM

In order to demonstrate the effectiveness of the proposed strategy, some simulations were conducted to a two-area networked AGC system in deregulated environment. Consider a case in Bhowmik et al. (2004), where all the DISCOs contract with the GENCOs for power as per the following DPM, which is chosen on the basis of market economics.

$$DPM = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix}$$

In addition, we assume that the ACE participation factors are $apf_1 = 0.6$, $apf_2 = 1 - apf_1 = 0.4$, $apf_3 = 0.5$ and $apf_4 = 1 - apf_3 = 0.5$ respectively. Also, assume each DISCO in each area demands 0.01 p.u.MW power. For this DPM the schedule generations of the GENCOs and the tie-line flow are

$GENCO_{1(schedule)} = (0.5 + 0.25 + 0 + 0.3) \times 0.01 = 0.0105\,p.u.MW$

$GENCO_{2(schedule)} = (0.2 + 0.25 + 0 + 0) \times 0.01 = 0.0045\,p.u.MW$

$GENCO_{3(schedule)} = (0 + 0.25 + 1 + 0.7) \times 0.01 = 0.0195\,p.u.MW$

$GENCO_{4(schedule)} = (0.3 + 0.25 + 0 + 0) \times 0.01 = 0.0055\,p.u.MW$

$$\Delta P_{tie1-2,scheduled} = 0 \times \Delta P_{L3} + 0.3 \times \Delta P_{L4} - 0.3 \times \Delta P_{L1} - 0.5 \times \Delta P_{L2} = -0.005 \quad p.u.MW$$

In the simulation, the sampling period is T=0.3s, the random delays are imposed between the GPC controller and governor all the time, whose upper bound is 0.9s. Fig.2 shows the random network delay in this simulation. Let the predictive horizon $N = 3$, the control horizon $Nu = 3$, $R = 0.001 \times I_{nN \times nN}$, $Q = 0.25 \times \mathrm{I}_{mM \times mM}$. Each of the DISCOs in the two areas demands 0.01 p.u.MW power at 9s, Figs. 3, 4 and 5 depict the excursions of area frequencies, tie-line power flow and GENCOs outputs respectively.

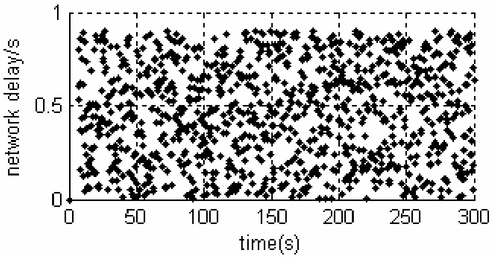
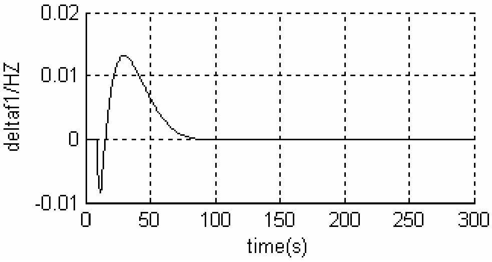
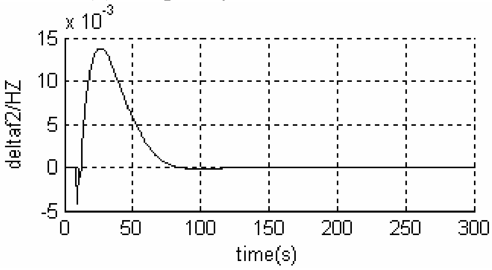


Fig.2 random network delay



(a) Frequency deviation of area1



(b) Frequency deviation of area2

Fig.3 Frequency deviation

In Fig.3,it can be seen that the frequency deviation in each area approaches zero at 80s around， the maximum value is 0.014. Fig.4 shows the actual tie line power, and it reaches -0.005 p.u.MW, which is the scheduled power on the tie line in the steady state. Fig.5 shows actual generated powers of the GENCOs. The trajectories settle respective desired generations in the steady state. The simulation results show the validity of the proposed method.

4. CONCLUSIONS

This paper has studied the design, simulation and implementation of the networked AGC systems after deregulation. A GPC controller was used to the networked and deregulated AGC systems. All control predictions to governor are transmitted in single package mode. In addition, the data are transmitted with time–stamp, consequently, the time delay and dropouts can be compensated. The simulation results demonstrate effectiveness of the presented approach.

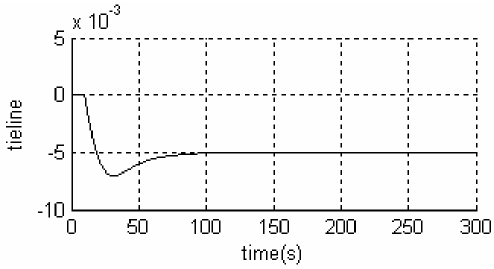
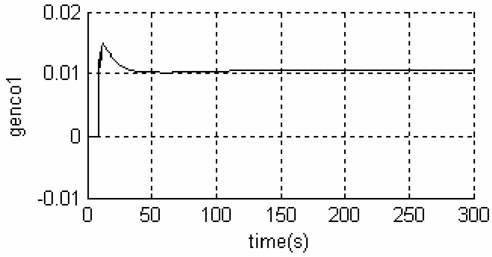
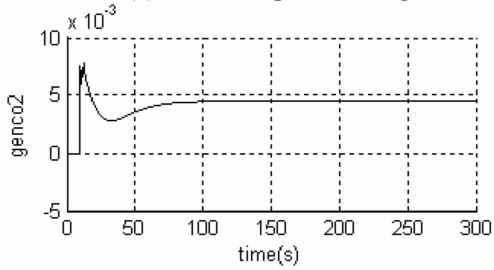


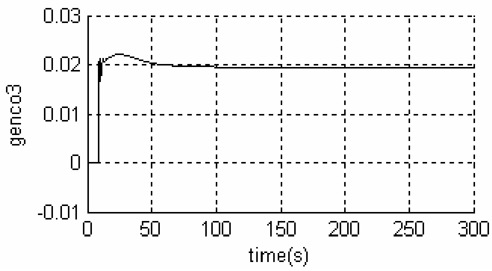
Fig.4 Deviation of tie line power flow



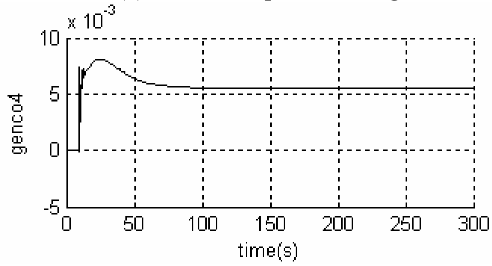
(a) GENCO1 power change



(b) GENCO2 power change



(c) GENCO3 power change



(d) GENCO4 power change

Fig.5 GENCO power change

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Appendix A.

$T_{P1,2} = 20.0\ s$, $K_{P1,2} = 120 Hz / p.u.MW$, $T_{T1,2,3,4} = 0.3\ s$, $T_{G1,2,3,4} = 0.08\ s$, $f = 60 Hz$, $R_{1,2} = 2.4\ Hz / p.u.MW$, $T_{12} = 0.086 p.u.MW / Radian$, $D_{1,2} = 8.33 \times 10^{-3}\ p.u.MW / Hz$.

Acknowledgements

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