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Load frequency control of a realistic power system with multi-source power generation

K.P. Singh Parmar [a,*], S. Majhi [b], D.P. Kothari [c,1]

[a] CAMPS, National Power Training Institute, Faridabad, Haryana 121 003, India
[b] Indian Institute of Technology, Guwahati, India
[c] RAISONI Group of Institutions, Nagpur, India

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ABSTRACT

In this paper, load frequency control (LFC) of a realistic power system with multi-source power generation is presented. The single area power system includes dynamics of thermal with reheat turbine, hydro and gas power plants. Appropriate generation rate constraints (GRCs) are considered for the thermal and hydro plants. In practice, access to all the state variables of a system is not possible and also their measurement is costly and difficult. Usually only a reduced number of state variables or linear combinations thereof, are available. To resolve this difficulty, optimal output feedback controller which uses only the output state variables is proposed. The performances of the proposed controller are compared with the full state feedback controller. The action of this proposed controller provides satisfactory balance between frequency overshoot and transient oscillations with zero steady state error in the multi-source power system environment. The effect of regulation parameter (R) on the frequency deviation response is examined. The sensitivity analysis reveals that the proposed controller is quite robust and optimum controller gains once set for nominal condition need not to be changed for ±25% variations in the system parameters and operating load condition from their nominal values. To show the effectiveness of the proposed controller on the actual power system, the LFC of hydro power plants operational in KHOZESTAN (a province in southwest of Iran) has also been presented.

1. Introduction

Automatic Generation Control (AGC) is an important function in modern Energy Management Systems (EMSs). The successful operation of interconnected power system requires the matching of total generation with total load demand and associated system losses. As the demand deviates from its nominal value with an unpredictable small amount, the operating point of power system changes, and hence, system may experience deviations in nominal system frequency and scheduled power exchanges [1–5]. The main tasks of automatic generation control are to hold system frequency at or very close to a specified nominal value and to maintain the correct value of interchange power between control areas [6].

A literature survey shows that the systems considered for AGC were of single area thermal or hydro and/or two area thermal–thermal or hydro-thermal [4–12]. Moreover, the thermal systems considered generally non-reheat type turbines and therefore, relatively lesser attention has been devoted to the AGC of thermal system with reheat type turbines [4,5,7,13]. Keeping in view the present power scenario, combination of multi-source generators in a control area with their corresponding participation factors is more realistic for the study of LFC. The control area may have the combination of thermal, hydro, gas, nuclear, renewable energy sources, etc. [14].

Most recently many researchers [15–18] have studied the LFC problem of hydro, thermal systems using PID controller, fuzzy controller, decentralized controller and optimal MISO PID controller based on different algorithms and optimization techniques. Alireza et al. [18] studied the LFC of the hydro power system (operational in Iran) using optimal MISO PID controller. Decentralized load frequency controller is presented for the LFC of an interconnected thermal power system [16] which uses large number of states for the controller feedback. Challa et al. [19] has presented the analysis and design of controller for two area hydro-thermal-gas AGC system. They have shown that for LFC study, optimal PI state feedback controller is more robust and performs better than conventional genetic algorithm based PI controller. However, this optimal PI state feedback controller uses all the states for feedback purpose which is practically difficult and results in the increased complexity and cost of the controller. All these controllers discussed have their own advantages and disadvantages.

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* Corresponding author.
E-mail address: kpsingh_jss@rediffmail.com (K.P.S. Parmar).
[1] Formerly with IIT, Delhi, India

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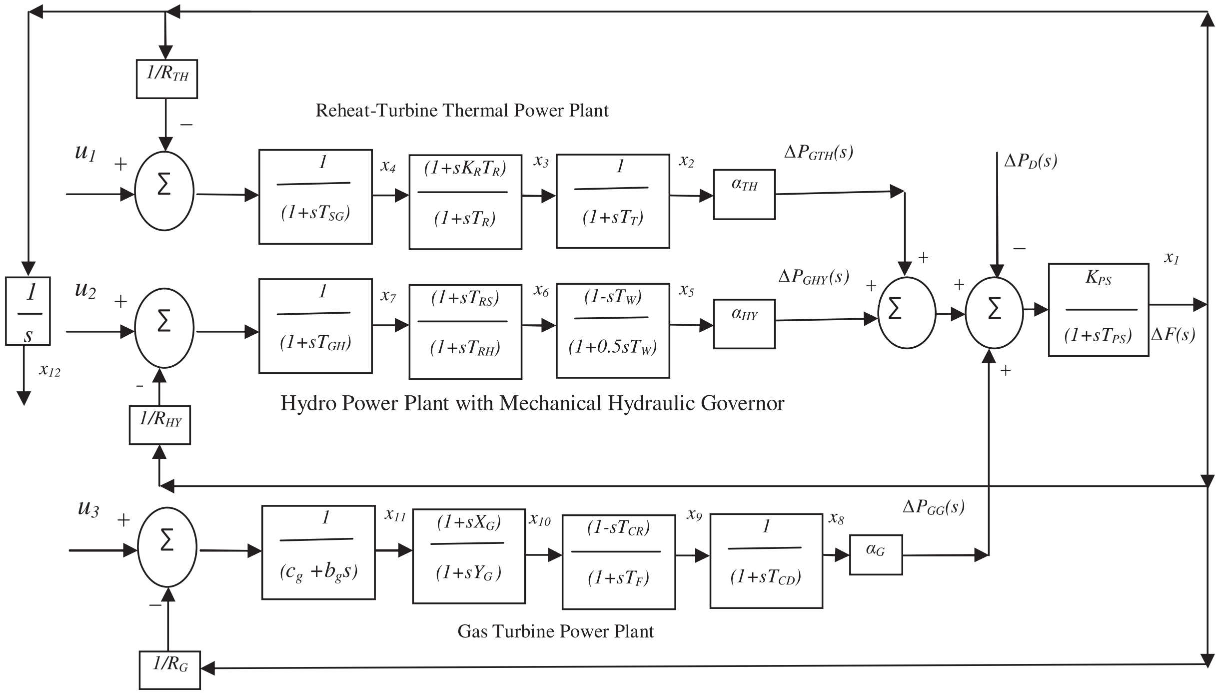


Fig. 1. Block diagram of the single area power system comprising reheat-thermal, hydro and gas generating units.

In this paper, a single area system comprising hydro, thermal with reheat turbine and gas units [14,19] as shown in Fig. 1 is presented for designing controller for the system with corresponding nomenclature given in Appendix A. The linearized models of governors, reheat turbines, Hydro turbines, Gas turbines are used for simulation and LFC study of the power system [5–7,20–23].The effect of generation rate constraints of Hydro and Thermal units on area frequency deviation response is also presented in this paper [1,7]. Using the modern optimal control theory, control engineers can handle a large multivariate control problem with ease. Application of the optimal control theory to power system has shown that an optimal load frequency controller can improve the dynamic stability of a power system [1,13,24]. In this paper, the dynamical response of the LFC problem is improved with a practical point of view. Practically, access to all of the state variables of a system is limited and measurement of all of them is not feasible and also costly. An output feedback controller design is presented in this paper to overcome this problem [1,13,24]. Literature survey shows that most of the researchers applied optimal control theory on non-reheat thermal-thermal power systems only [1,4,8–11,13]. To the best of authors' knowledge, no work has been reported in the literature of AGC for design of the optimal output feedback controller for such a realistic single area power system having generation from a combination of Hydro, thermal and gas units. In view of the above, the following are the main objectives of the present work.

i. To consider a practical combination of generating units in present power scenario for AGC study, i.e. Thermal reheat type, hydro and gas in a single area power system.
ii. To propose optimal output feedback controller for AGC of the proposed realistic power system.
iii. To optimize the optimal output feedback controller gain and full state feedback controller gain and hence study the dynamic performance for the proposed power system.
iv. To compare the dynamic performance of optimal output feedback controller with full state feedback controller for AGC of the proposed power system.
v. To simulate the proposed power system with and without GRC and hence to examine the effect of GRC on the system response.
vi. To examine the effect of speed regulation parameter (R) on the dynamic response of the system and hence selection of best value of R for the proposed power system.
vii. To carry out the sensitivity analysis for ±25% variation in system parameters and operating load condition
viii. To study the LFC system of the hydro power plants operational in KHOZESTAN, Iran using proposed controller.

2. Controller design

In modern control theory approach, inputs u_1, u_2, and u_3 are generated by a linear combination of all the system states (full state feedback approach) or a linear combination of states to be controlled/measurable states (output feedback approach) [1,13,24,25]. The generalized linear model of the power system may be described in state space form as [1,24]

$$\dot{x} = Ax + Bu \tag{1}$$

with the initial condition $x(0) = x_0$ and

$$y = Cx \tag{2}$$

where x is a state vector of the dimension $n \times 1$, n is no. of state variables, u is a control vector of the dimension $m \times 1$, m is no. of control variables, y is a output vector of the dimension $p \times 1$, p is no. of output variables, and A, B and C are constant matrices with dimensions of $n \times n$, $n \times m$ and $p \times n$, respectively. The performance of the system is specified in terms of a performance index or cost function (J),

$$J = \frac{1}{2}\int_0^{\infty} (x^T Q x + u^T R u)dt \tag{3}$$

which is minimized for obtaining parameters of an optimal controller. In the Eq. (3), Q is $n \times n$, symmetric positive semi-definite state cost weighting matrix and R is $m \times m$, symmetric positive semi-definite control cost weighting matrix.

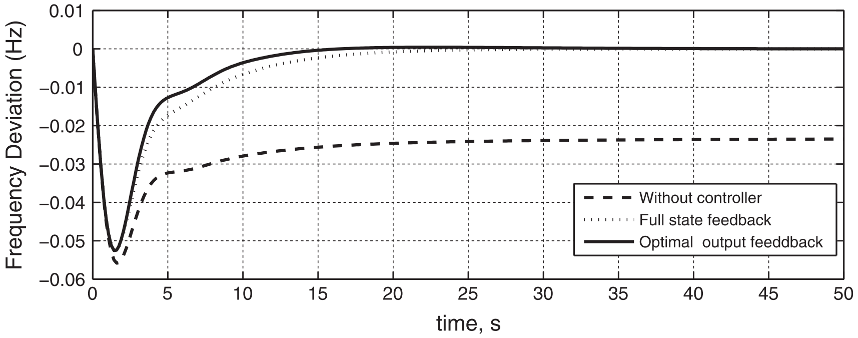


Fig. 2. Frequency deviation response to 1% step load perturbation in the area.

The elements of matrices Q and R are chosen as per the designer's choice. For the dynamic correction of the area control error (ACE), the following design criteria are considered for the present LFC problem [1,13,25]:

1. Excursions of ACEs about their steady values are minimized. The steady values of ACEs are of course zero.
2. Excursions of $\int ACEdt$ about the steady values are minimized. The steady values of $\int ACEdt$ are of course constants.
3. Excursions of control vector about their steady values are minimized. The steady value of the control vector is of course a constant.

The optimal controller law for full state feedback can be defined by [1]

$$u = -\overline{K}x \tag{4}$$

The constant gain matrix $\overline{K}$ of the dimension $m \times n$, is obtained from the solution of the matrix Riccati equation

$$A^TP_1 + P_1A - P_1BR^{-1}B^TP_1 + Q = 0 \tag{5}$$

$$\overline{K} = R^{-1}B^TP_1 \tag{6}$$

For stability, all the eigenvalues of the matrix $(A - B\overline{K})$ should have negative real parts. From Eq. (4), we get the optimal control signal of our choice.

Practically, it is very difficult and often expensive to measure and to have readily available information about all the states in most of the large power systems. Usually reduced number of state variables or a linear combination thereof is available.

Let the output feedback control law be defined as

$$u = -Ky \tag{7}$$

where K is an output feedback gain matrix of dimension $(m \times p)$. In the optimal control scheme the control inputs are generated by means of feedbacks from all the output states with feedback constants to be determined in accordance with optimality criterion. Using Eqs. (7) and (2), the linear model given by Eq. (1) can be arranged as

$$\dot{x} = (A - BKC)x = A_Cx \tag{8}$$

The performance index can be expressed as

$$J = \frac{1}{2}\int_0^\infty (x^T(Q + C^TK^TRKC)x)dt \tag{9}$$

The control problem is now to design the gain matrix K so that J is minimized subject to the dynamical constraint

$$\dot{x} = (A - BKC)x \tag{10}$$

This dynamical optimization problem may be converted into an equivalent static one that is easier to solve. After applying the suitable optimization techniques, we obtain the following optimal gain design equations [24]:

$$0 = A_c^TP + PA_c + C^TK^TRKC + Q \tag{11}$$

$$0 = A_cS + SA_c^T + X \tag{12}$$

$$K = R^{-1}B^TPSC^T(CSC^T)^{-1} \tag{13}$$

where $A_c = A - BKC$ and $X = E\{x(0)x^T(0)\}$.

If initial states are assumed to be uniformly distributed on the unit sphere, then $X = I$, where X is $n \times n$, symmetric matrix and I is an identity matrix. In many applications $x(0)$ may not be known, this dependence is typical of output feedback design. It is usual to sidestep this problem by minimizing not the Performance Index [24] but its expected value $(E\{J\})$,

$$E\{J\} = \frac{1}{2}E\{x^T(0)Px(0)\} = \frac{1}{2}tr(PX) \tag{14}$$

The optimal cost can be given by

$$J_0 = \frac{1}{2}tr(PX) \tag{15}$$

The Eqs. (11) and (12) are Lyapunov equations and the Eq. (13) is an equation for the gain K. To obtain the output feedback gain K minimizing the J_0, these three coupled equations may be solved simultaneously by some iterative technique [24].

3. Realistic power system

The Power system proposed for study is a realistic system comprising Reheat thermal, hydro and gas generating units. The linearized models of governors, reheat-turbines, Hydro turbines, Gas turbines are taken to study the power system as shown in Fig. 1 [6,7,20–23,25–27]. The typical system parameters reported in literature are taken as given in Appendix B [7,19–23,28,29]. The system has $n = 12$ state variables where $x_1 = \Delta f$ and $x_{12} = \int ACEdt = \int \Delta fdt$. The optimum gains of full state feedback controller and optimal output feedback controller have been obtained by running the MATLAB codes generated on the basis of methods described in the controller design section. The computer simulations are carried out with the optimum controller gains. MATLAB control system toolbox [30] has been used to simulate the power system and to obtain dynamic responses of Δf, ΔP_{GTH}, ΔP_{GHY} and ΔP_{GG} for 1% step load perturbation in the area at 1750 MW load. System matrices A, B and C for the Power system under study are as described below:

$$B^T = \begin{bmatrix} 0 & 0 & \frac{K_R}{T_{SG}} & \frac{1}{T_{SG}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{2T_{RS}}{T_{RH}T_{GH}} & \frac{T_{RS}}{T_{RH}T_{GH}} & \frac{1}{T_{GH}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{X_GT_{CR}}{T_FY_G \cdot b_g} & \frac{X_G}{Y_G \cdot b_g} & \frac{1}{b_g} & 0 \end{bmatrix}$$

$$A = \begin{bmatrix} -\frac{1}{T_{PS}} & \frac{K_{PS}\cdot\alpha_{TH}}{T_{PS}} & 0 & 0 & \frac{K_{PS}\cdot\alpha_{HY}}{T_{PS}} & 0 & 0 & \frac{K_{PS}\cdot\alpha_{G}}{T_{PS}} & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_T} & \frac{1}{T_T} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{K_R}{T_{SG}R_{TH}} & 0 & -\frac{1}{T_R} & \frac{1}{T_R}-\frac{K_R}{T_{SG}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{T_{SG}R_{TH}} & 0 & 0 & -\frac{1}{T_{SG}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{2T_{RS}}{T_{RH}T_{GH}R_{HY}} & 0 & 0 & 0 & -\frac{2}{T_W} & \frac{2}{T_W}+\frac{2}{T_{RH}} & \frac{2T_{RS}}{T_{RH}T_{GH}}-\frac{2}{T_{RH}} & 0 & 0 & 0 & 0 & 0 \\ -\frac{T_{RS}}{T_{RH}T_{GH}R_{HY}} & 0 & 0 & 0 & 0 & -\frac{1}{T_{RH}} & \frac{1}{T_{RH}}-\frac{T_{RS}}{T_{RH}T_{GH}} & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{T_{GH}R_{HY}} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{GH}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{CD}} & \frac{1}{T_{CD}} & 0 & 0 & 0 \\ \frac{T_{CR}X_G}{T_F R_G Y_G\cdot b_g} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_F} & \frac{1}{T_F}+\frac{T_{CR}}{T_F Y_G} & \frac{T_{CR}X_G\cdot c_g}{T_F Y_G\cdot b_g}-\frac{T_{CR}}{T_F Y_G} & 0 \\ -\frac{X_G}{R_G Y_G\cdot b_g} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{Y_G} & \frac{1}{Y_G}-\frac{X_G\cdot c_g}{Y_G\cdot b_g} & 0 \\ -\frac{1}{R_G\cdot b_g} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{c_g}{b_g} & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

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

4. Simulation results and analysis

The optimum values of controller gains for full state feedback and optimal output feedback are obtained by minimizing the performance indices. Dynamic responses of the system are obtained for 1% step load perturbation in the area through computer simulation. The frequency deviation responses are depicted in Fig. 2. It has been observed that the output feedback controller gives better frequency deviation response having relatively smaller peak overshoot and lesser settling time with zero steady state error as compared to the full state feedback controller. The output power deviation responses of thermal, hydro and gas units to 1% load perturbation are shown in Figs. 3–5, respectively.

4.1. Generation rate constraint

In most of the research papers, the effect of restriction on the rate of change of power generation is not considered [8,9,13,25]. In power systems having steam plants and hydro plants, power generation can change only at a specified maximum rate [1,27]. Most of the reheat units have a generation rate around 3%/min. Some have a GRC between 5% and 10%/min. If these constraints are not considered, system is likely to chase large momentary disturbances [1]. For testing further the effectiveness of the proposed controller, the GRC for thermal and hydro units is taken into account in the computer simulation model. GRC for hydro unit: for raise 270%/min (0.045 pu/s) and for lower 360%/min (0.06 pu/s) is considered and GRC for reheat turbine thermal unit: for raise and lower 10%/min (0.0017 pu/s) is considered for study.

The proposed power system is simulated with and without the above GRC limits in thermal and hydro power generating units. The effect of GRC on the frequency deviation response of the area obtained with optimal output controller and full state feedback controller at nominal load is shown in Figs. 6 and 7 respectively. It has been observed that GRC results in larger peek overshoot and longer settling time for both the controllers with controller gains optimized for linear system. However in this particular case, dynamic response of the system with GRC satisfies LFC problem requirement. It has been observed if we consider GRC lower than 10 percent/minute for reheat thermal unit, the dynamic performance of the system deteriorates. Therefore GRC must be incorporated for realistic study of the system.

4.2. Governor speed regulation parameter (R)

Fig. 8 shows the frequency deviation response to 1% load perturbation in the area at nominal load with R varying from 1% to

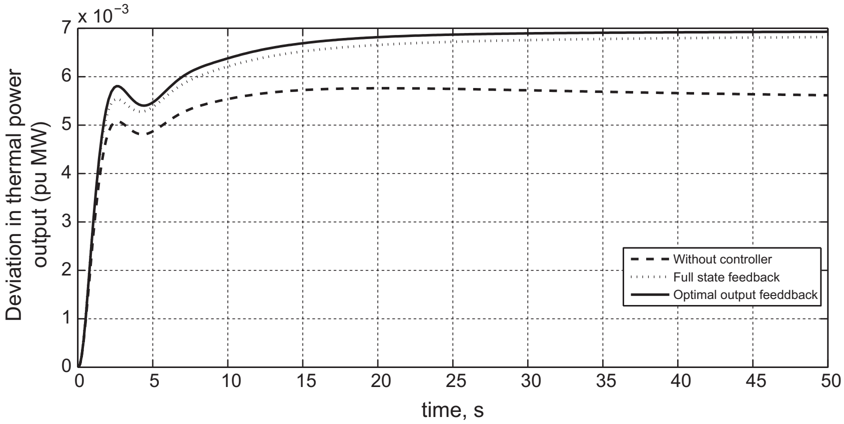


Fig. 3. Thermal unit power output deviation response to 1% step load perturbation in the area.

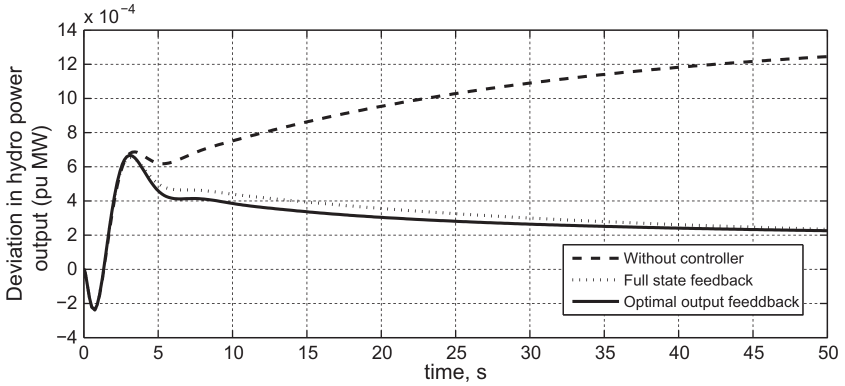


Fig. 4. Hydro unit power output deviation response to 1% step load perturbation in the area.

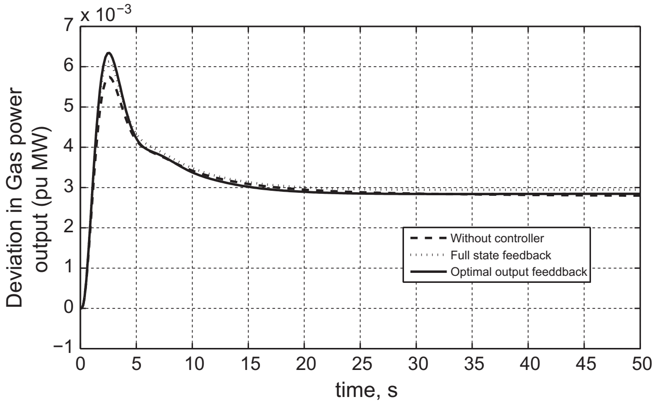


Fig. 5. Gas unit power output deviation response to 1% step load perturbation in the area.

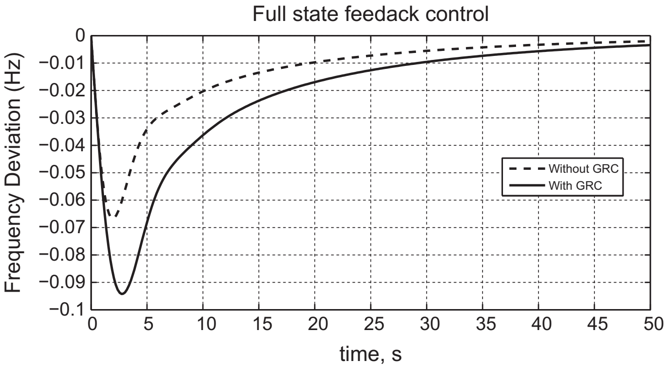


Fig. 7. Frequency deviation response to 1% step load perturbation in the area considering GRC (full state feedback controller).

8%. It has been observed that for higher values of *R*, i.e. 6% and 8%, the peak overshoot and settling time increases; if we further increase the value of *R*, the system gives larger frequency deviation oscillations and tends towards instability. The system frequency deviation oscillations are minimum at 4% value of *R*. For lower values of *R*, i.e. 1% and 2% the system becomes more oscillatory. Findings reveal that there is no need of going for the lower values and the higher values of *R*, since medium value of *R* (3–4%) with corresponding optimum controller gains can be preferred to provide better dynamic response of AGC for the proposed system.

5. Sensitivity analysis

Lesser attention has been paid to this aspect of AGC problem. Investigations carried out to study the effect of variation in the system parameters and operating conditions on the optimum controller gain settings and the system dynamic performances. The system parameters and operating load condition are varied by ±25% from their nominal values, taking one at a time. Table 1 gives the optimum controller gain settings for varied system parameters and operating load condition using optimal output feedback controller. Investigations reveal that the dynamic responses hardly change when system parameters and operating load condition

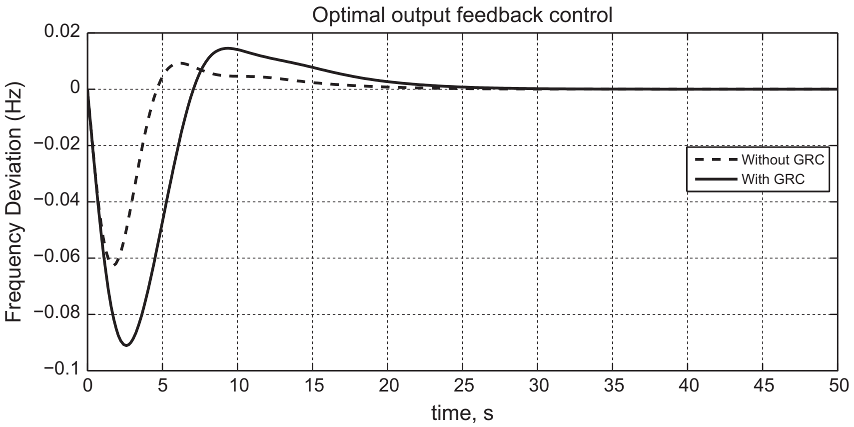


Fig. 6. Frequency deviation response to 1% step load perturbation in the area considering GRC (optimal output feedback controller).

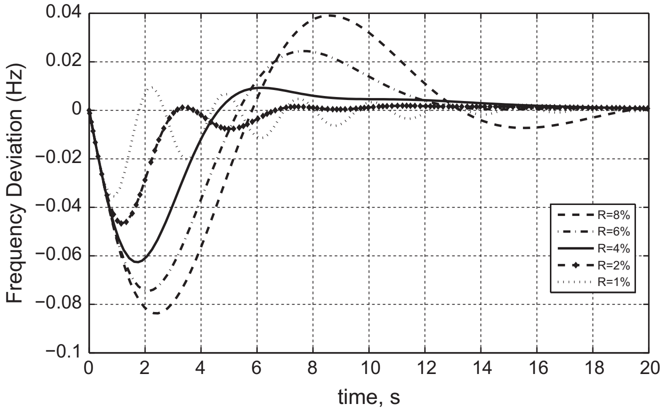


Fig. 8. Frequency deviation response to 1% step load perturbation in the area with varying *R* from 1% to 8%.

are changed by ±25% from their nominal values with their corresponding optimum controller gains. As an example frequency deviation responses for varied load condition and Speed governor time constant (T_{SG}) are shown in Figs. 9 and 10, respectively. It is evident that there is negligible effect of the variation of Speed governor time constant and operating load condition on the frequency deviation responses obtained at nominal values.

6. LFC of hydro power plants, KHOZESTAN, Iran

To ensure the good performance of the proposed optimal output feedback method on an actual power system, hydro power plants operational in KHOZESTAN (a province in southwest of Iran) [18] are taken as an additional case study in this section. Dez output power is 520 MW whereas Karoon3 output power is 1000 MW operational and 2000 MW nominal. The control area is linked to other control areas of an interconnected power system. The control area includes Karoon3 and Dez hydro power plants where variation of area load and interaction of other control areas are considered as two disturbances in control area.

Most recently (2012), Alireza et al. [18] studied the LFC of this operational plant using a robust optimal MISO PID controller where the tuning of PID controller is stated as an optimization problem in which a combination of quadratic index and maximal complex/real ratio of the closed loop poles is minimized subject to some constraints on characteristic matrix Eigenvalues.

For analysis, their system dynamics, system parameter values, load disturbance conditions and assumptions are considered here. For clarity, nomenclature of system parameters in this discussion are kept same as in [18]. Block diagram of a control area including two hydro power plants [18] is referred for formulating the state equations. Refering Eqs. (1) and (2), in this case study $n = 7$, $m = 1$, and $p = 3$, where the state vector is $x = [\Delta f \Delta P_{tie} \Delta P_{tK} \Delta P_{tD} \Delta P_{gK} \Delta P_{gD} \int ACE]^T$ and the output state vector is $y = [\Delta f \Delta P_{tie} \int ACE]^T$.

Table 1
Sensitivity analysis.

Parameter variation	% Change	Optimal output feedback controller gains			Performance index J_0
		K_{11}	K_{21}	K_{31}	
All nominal	0	0.1514	0.0131	0.0708	0.414996
Loading	+25	0.1537	0.0142	0.0719	0.406347
Condition	−25	0.1491	0.0119	0.0696	0.424447
T_{SG}	+25	0.1496	0.0130	0.0708	0.419149
T_{SG}	−25	0.1532	0.0131	0.0708	0.410883
T_{GH}	+25	0.1510	0.0126	0.0706	0.416183
T_{GH}	−25	0.1519	0.0136	0.0711	0.413668
T_R	+25	0.1540	0.0151	0.0758	0.41860
T_R	−25	0.1482	0.0107	0.0643	0.409793
T_T	+25	0.1454	0.0126	0.0706	0.429905
T_T	−25	0.1577	0.0135	0.0709	0.400242
T_{RH}	+25	0.1515	0.0103	0.0713	0.414982
T_{RH}	−25	0.1508	0.0175	0.0698	0.417074
T_W	+25	0.1503	0.0051	0.0698	0.426905
T_W	−25	0.1526	0.0221	0.0718	0.402864
T_{CD}	+25	0.1521	0.0218	0.0694	0.406546
T_{CD}	−25	0.1531	0.0224	0.0743	0.399133

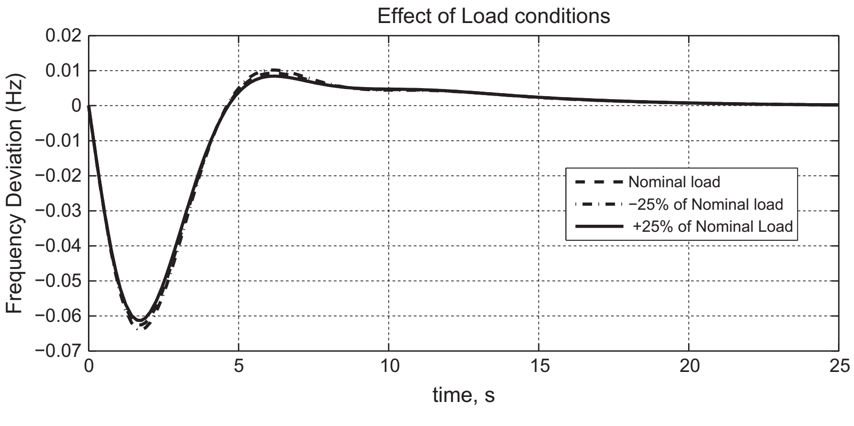


Fig. 9. Frequency deviation response to 1% step load perturbation in the area with varying load conditions.

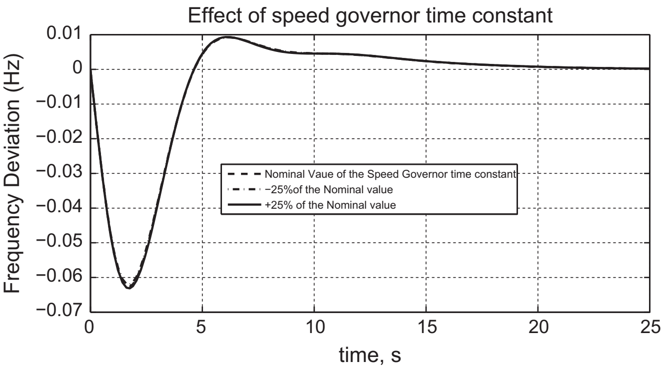
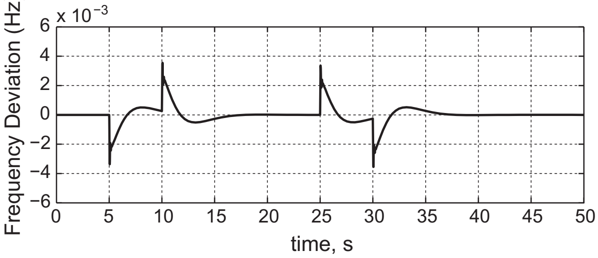
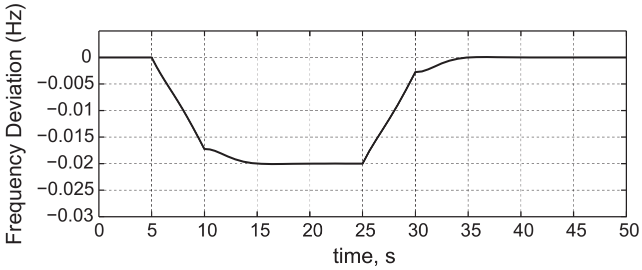


Fig. 10. Frequency deviation response to 1% step load perturbation in the area with varying speed governor time constant.



(a) Frequency deviation response for load disturbance of first situation



(b) Frequency deviation response for load disturbance of second situation

Fig. 11. Frequency deviation responses for the hydro plants (Iran) using optimal output feedback controller for LFC.

System dynamic responses are obtained with optimal output feedback controller gains for two different situations based on the two types of the present disturbances in the system. In the first situation, the effects of load disturbances in the area itself are examined, whereas in the second situation, the effects of disturbances due to neighboring interconnected control areas are examined which affect the area under control.The load disturbance patterns taken in both the situations are illustrated in [18].

Fig. 11 shows the frequency deviation responses obtained using proposed controller. As compared, the trajectories of deviation and settling time are more and less same whereas overshoots in frequency deviations observed at each time instant of load changes are improved remarkably and reduction is becoming more than 80%. Further, it is observed from extensive simulation studies that improvement in the responses of tie line power and ACE deviations can be achieved with the help of the proposed controller.

Like MISO PID controller, the proposed controller also guarantees the good performance, such as frequency deviation elimination and disturbance attenuation as well as robustness under area load changes or frequency variation of interconnected areas scenarios. As compared, the overshoots in frequency deviation responses obtained with proposed controller are very less resulting in remarkable improvement in the frequency deviation response which is the most important parameter.

7. Conclusion

In this paper an optimal output feedback controller design method is proposed for the LFC of a realistic power system. The performance of the proposed controller is demonstrated on the multi-source power system and its dynamic responses are compared with full state feedback controller. The effect of GRC on frequency deviation response is discussed. The dynamic performance of the system deteriorates if GRC is not incorporated for realistic study of the system. Frequency deviation response of the area and generator output power deviation response to 1% step load perturbations have been obtained. The output feedback controller gives better frequency deviation response having relatively smaller peak overshoot and lesser settling time with zero steady state error as compared to full state feedback controller response. The effect of varying the regulation parameter has been examined. It is better to prefer the value of R between 3% and 4% with corresponding optimum controller gains to provide better dynamic response of AGC for the proposed system. The sensitivity analysis reveals that ±25% change in system parameters and operating load condition from their nominal values considering their optimum controller gains do not affect the system responses appreciably. Thus the optimum values of controller gains obtained for nominal system parameters and load condition are quite insensitive to wide parameter variation ±25%. The LFC of hydro power plants operational in Iran has also been studied. The proposed controller performs well on this system and improves the frequency deviation responses remarkably. Hence for all practical purposes, the controller is quite robust. Application of optimal output feedback controller is more simple and economic as lesser no. of sensors/information is required and satisfies the LFC problem requirements.

Appendix A. Nomenclature

ACE	area control error
P_{rt}	rated capacity of the area, MW
f	nominal system frequency, Hz
D	system damping of area, pu MW/Hz
T_{SG}	speed governor time constant, s
T_T	steam turbine time constant, s
T_{PS}	power system time constant, s
R_{TH}, R_{HY}, and R_G	governor speed regulation parameters of thermal, hydro and gas generating units, respectively, Hz/pu MW
K_{PS}	power system gain, Hz/pu MW
K_R	steam turbine reheat constant
T_R	steam turbine reheat time constant, s
T_W	nominal starting time of water in penstock, s
T_{RS}	hydro turbine speed governor reset time, s
T_{RH}	hydro turbine speed governor transient droop time constant, s
T_{GH}	hydro turbine speed governor main servo time constant, s
X_G	lead time constant of gas turbine speed governor, s
Y_G	lag time constant of gas turbine speed governor, s
c_g	gas turbine valve positioner
b_g	gas turbine constant of valve positioner, s
T_F	gas turbine fuel time constant, s
T_{CR}	gas turbine combustion reaction time delay, s
T_{CD}	gas turbine compressor discharge volume-time constant, s

α_{TH}, α_{HY} and α_G	participation factors of thermal, hydro and gas generating units, respectively
Δf	incremental change in frequency, Hz
ΔP_D	incremental load change, pu MW
ΔP_{GTH}, ΔP_{GHY} and ΔP_{GG}	incremental change in power outputs of thermal, hydro and gas generating units, respectively, pu MW

Appendix B. System parameters

$P_{rt} = 2000$ MW
$P_L = 1840$ MW (nominal load of the area)
$f = 60$ Hz, $H = 5$ MW − s/MVA
$D = \frac{\partial P_L}{\partial f}\frac{1}{P_{rt}}$ pu MW/Hz
$K_{PS} = \frac{1}{D}$ Hz/pu MW
$T_{PS} = \frac{2 \cdot H}{f \cdot D}$ s
$T_{SG} = 0.08$ s, $T_T = 0.3$ s
$R_{TH} = R_{HY} = R_G = R = 2.4$ Hz/pu MW
$K_R = 0.3$, $T_R = 10$ s, $T_W = 1.0$ s,
$T_{RS} = 5$ s, $T_{RH} = 28.75$ s, $\alpha_{TH} = 0.543478$
$\alpha_{HY} = 0.326084$, $\alpha_G = 0.130438$
$T_{GH} = 0.2$ s, $X_G = 0.6$ s, $Y_G = 1.0$ s
$c_g = 1$, $b_g = 0.05$ s, $T_F = 0.23$ s
$T_{CR} = 0.01$ s, $T_{CD} = 0.2$ s

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