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Effect of physical constraints on the AGC dynamic behaviour in an interconnected power system

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Abstract: This paper aims to demonstrate the effect of re-heat and non-reheat turbines and some important physical constraints such as generation rate constraint (GRC), time delay and speed governor dead band on the dynamic behaviour of automatic generation control (AGC) in an interconnected power system. The mentioned constraints imposed to power system by governor-turbine, thermodynamic process, and communication channels. Simple structure beside acceptable response of the conventional integral controller makes it attractive for power system AGC issue. Optimum integral gains are computed by genetic algorithm (GA) technique for an interconnected three control areas with non-reheat/reheat generating units to achieve an optimal performance. Simulation results reveal that the scope of optimum solutions was limited by considering physical constraints in addition to the increasing of settling time and over/under-shoots.

Keywords: genetic algorithm; GA; physical constraint; integral controller; automatic generation control; AGC; interconnected power system; reheat turbines; non-reheat turbines.

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1 Introduction

A large-scale power system consists of number of subsystems interconnected together, and power is exchanging between subsystems over tie-lines. Maintaining important power system criteria such as frequency, voltage profile and power flow configuration at the nominal values guarantees reliable interconnected operation of a power system (Nanda et al., 2009). However, power systems continuously experience changes in the operating conditions due to variations in load/generation and a wide range of disturbances, and hence, frequency and power flow configuration deviate from the nominal values (Golpîra and Bevrani, 2010).

Frequency changes in a power system, as a direct result of the imbalance between the load demand plus associated system losses and the generation from generating units cause undesirable effects (Daneshfar and Bevrani, 2010; Bevrani et al., 2009). Therefore, frequency control strategies employ to maintain system frequency at the scheduled value by keeping balance between the electrical load and the power supplied by the connected generators (Bevrani and Hiyama, 2009).

Frequency control is one of the important power system controller which implements in three different levels. Primary frequency control performs by the speed governors of the generating units. In the presence of primary control, a variation in system frequency greater than the dead band of speed governor causes a change in generation of the generating units (Egido et al., 2004). Secondary frequency control, usually known as automatic generation control (AGC), employs to restore area frequency to its nominal value (Bevrani, 2009). Tertiary frequency control refers to economic dispatch and tries to drive a system as economically as possible (Egido et al., 2009). Due to the increased exchange of power through tie-lines between interconnected subsystems, the AGC becomes one of the important power system control problems for which there have been considerable research works.

Summation of tie-line power deviation (ΔP_{tie}) and weighted frequency deviation ($\beta\Delta f$) from nominal values defines as area control error (ACE) signal which is in turn utilised in AGC systems. AGC systems usually employ a simple integral controller in each area to drive the ACE signal to zero (Bevrani, 2009; Jaleeli et al., 1992). The main issue towards the use of integral controller is how to optimise the controller gain (Matuki et al., 2008; Sato, 2009). Several approaches for finding optimum parameters of secondary frequency control loop are introduced by Nanda et al. (2009), Sheikh et al. (2008), Yang et al. (2005), Chien and Cheng (2007), and Tyagi and Srivastava (2006). Time consumption methods, e.g., trial and error for tuning of integral controller cause to the interest on the meta-heuristic methods such as GA (Sinha et al., 2008).

Most published research works on the AGC studies consider the simplified models for interconnected power system. However, dynamics of power system and sequentially AGC response are highly influenced by the physical constraints. The main physical constraints are (Bevrani, 2009):

1 generation rate constraint (GRC)

2 speed governor dead band

3 time delay.

For a realistic study, these constraints should be included in the dynamic frequency response model.

1.1 GRC

Due to the thermodynamical and mechanical constraints, output of steam turbine can be changed only at a limit rate refers to GRC. Neglecting the delays caused by the crossover elements in a thermal unit in AGC studies give rise to an ideal situation that frequency and tie-line power to be returned to their scheduled value within one second, that is impossible (Bevrani, 2009).

1.2 Speed governor dead band

By changing the input signal, the speed governor may not immediately react until the input reaches a specified value. This limitation called speed governor dead band. All governors have a dead band in response, which is important for power system frequency control in the presence of disturbances (Bevrani, 2009).

1.3 Time delay

Due to the expanding of physical setups and complexity of power systems, the communication delays become a significant challenge in the AGC studies. Most published research works on the AGC design have neglected problems associated with the communication network. However, this is not a valid assumption in the new environment with an open communication infrastructure to support the ancillary services (Bevrani, 2009).

It should be noted that to get an accurate perception of the AGC subject, it is necessary to consider the basic physical constraints (Bevrani, 2009). However, in the previous studies speed governor dead band, GRC, and delays associated with communication channels are often neglected. Yang et al. (2005) modelled a system with non-commensurate communication delays. The model for interconnected power system which consider GRC is used by Nanda et al. (1983, 2009), Kothari et al. (1981) and Hari et al. (1991). Sheikh et al. (2008) and Mohamed et al. (2011) improved the previous studies by considering GRC and speed governor dead band, simultaneously. However, it seems that considering the neglected physical constraints in these researches could affect system's dynamics.

This paper aims to demonstrate the effects of physical constraints on the performance of AGC system in an interconnected power system. Similar to real AGC systems, integral controller is used to optimise the system performance. Optimum integral gains are calculated by genetic algorithm (GA) technique to achieve a desirable performance.

The rest of this paper is organised as follows. In Section 2, the test case is introduced. Section 3 discusses the GA. In Section 4, simulation results are explained in detail; and finally, Section 5 concludes the paper.

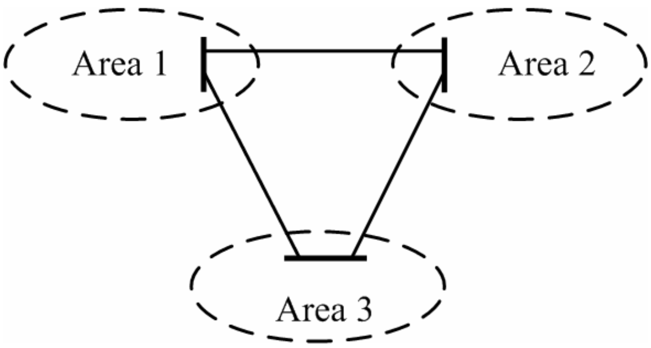
2 Test case

The GA is applied to the three-control area power system with equal loads, supplied by non-reheat/single-reheat turbine in each area. The physical constraints are assumed as shown in Table 1.

Table 1 Physical constraints

GRC	*Time delay*	*Dead-band*
3% [p.u.MW/min]	5 [sec]	0.036 [Hz]

Figure 1 Three-control area power system



The nominal parameters of the system are taken from (Bevrani, 2009) and represented in Appendix. The schematically model of the three-control area power system is shown in Figure 1. The proposed model for area *i* is depicted in Figure 2.

3 Genetic algorithm

GA is a direct random search technique which guarantees survival of the fittest by extending the search space to a multidimensional one. GA operators act on the initial and re-generated populations to converge at the fittest (Ghoshal and Goswami, 2003). There are three genetic operators to use in the process of finding the optimum solution (Huddar and Kulkarni, 2008):

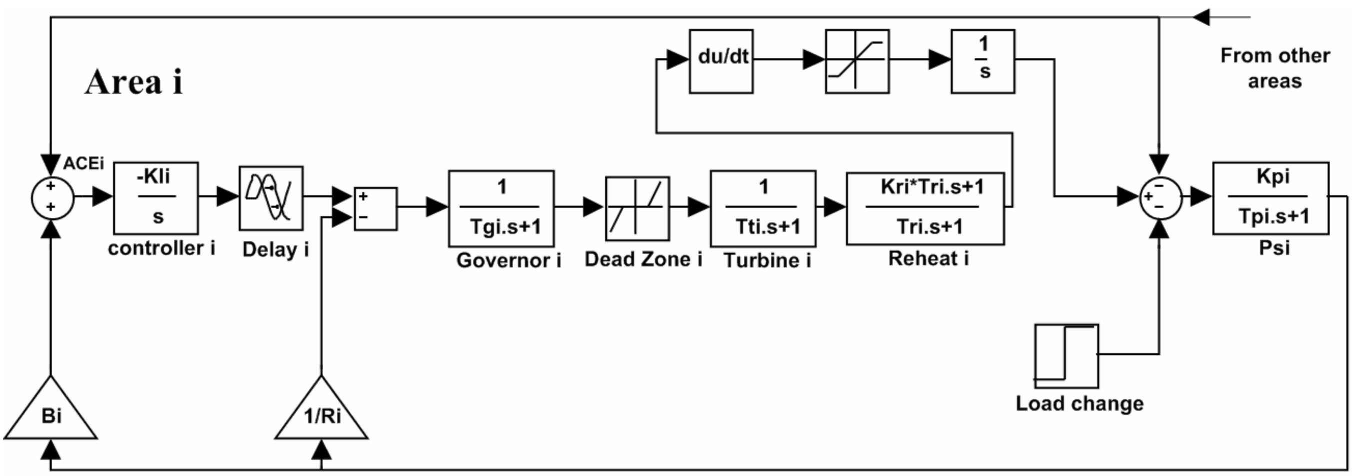
1 Selection: selects the fittest individuals in the current population to be used in the next generation.

2 Cross-over: combines the pairs of chromosomes promoted by the selection operator to generate the new individuals.

3 Mutation: changes the single bit in the individuals based on some probabilistic rules.

Ability of GA to exploit historical information structures, in an attempt to increase performance of future solutions, makes the GA attractive for engineering and optimisation problems (Ghoshal, 2004). Figure 3 shows a flow chart representation of GA. For any generation, a fitness value assigns to each decoded candidate solution. The fitter solutions will only survive for the next generation and the demerit individuals will die. This process continues until the optimum values will be obtained (Ghoshal, 2004). Many investigations in the area of heuristic methods, especially GA application in the AGC studies have been reported in the past (Ghoshal, 2004; Nidul et al., 2008; Bhat et al., 2010).

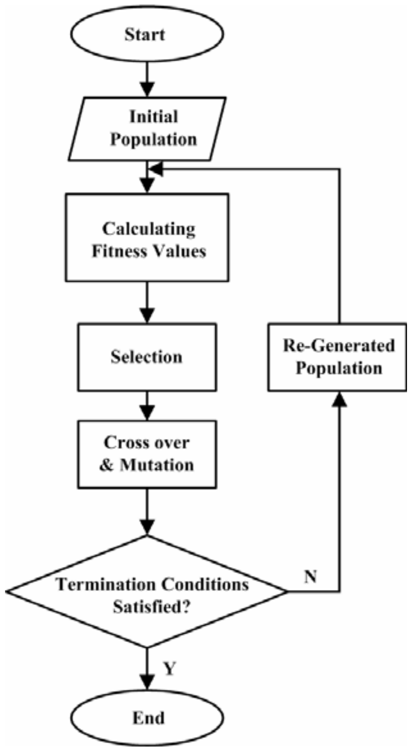
Figure 2 Proposed model for area *i*



In this paper, the initial population consists of 100 chromosomes; each one contains 48 binary bits (16 bits for each controller gain). The crossover and mutation probability are considered as 0.8 and 0.2, respectively. The cost function is considered as follows:

$$J = \int_0^T \left(ACE_i\right)^2 \tag{1}$$

Figure 3 GA flow chart



4 Simulation results and discussion

To investigate the importance of considering physical constraints/turbine type on the dynamic behaviour of system, three simulation scenarios are performed (Table 2). These scenarios are:

1 A: Non-reheat system without any constraint is considered.

2 B: Reheat system with speed governor dead band and GRC is considered.

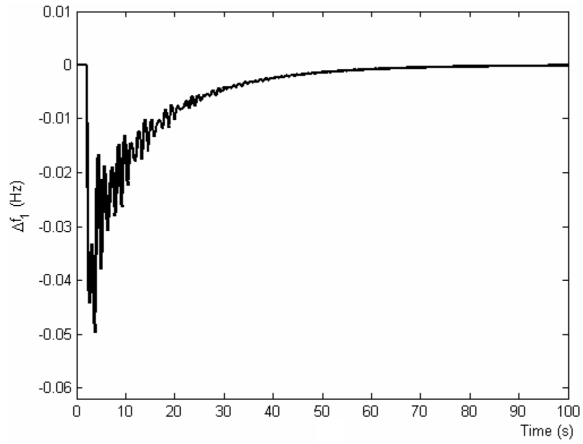
3 C: Time delay is added to the scenario B.

Table 2 Optimum value of integral gains

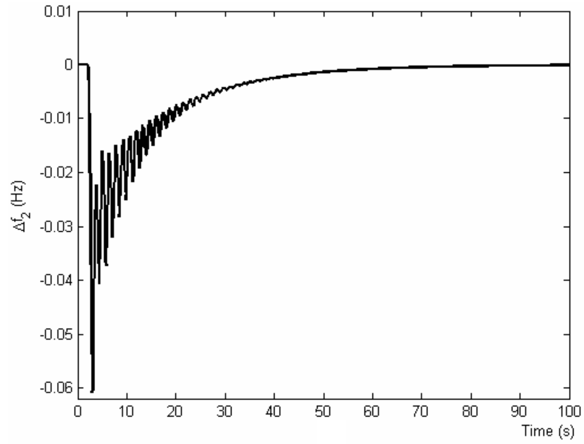
Gain	*Scenario A*	*Scenario B*	*Scenario C*
KI_1	0.1290	0.3451	0.1232
KI_2	0.2649	0.4614	0.0147
KI_3	0.0626	0.4409	0.0538

Dynamic response for each scenario is obtained considering 0.02 p.u. step load perturbation (SLP) in areas 1 and 3.

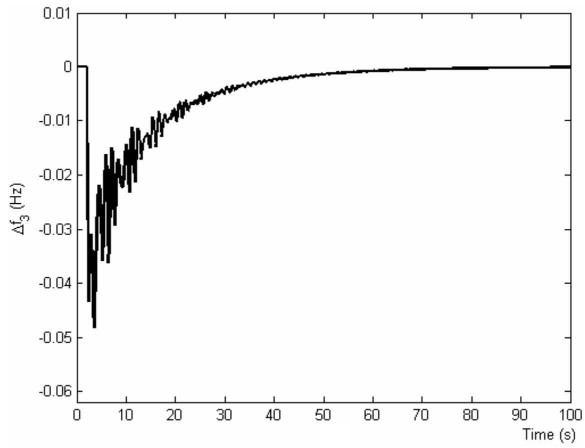
Figure 4 Frequency responses for scenario A, (a) area 1 (b) area 2 (c) area 3



(a)



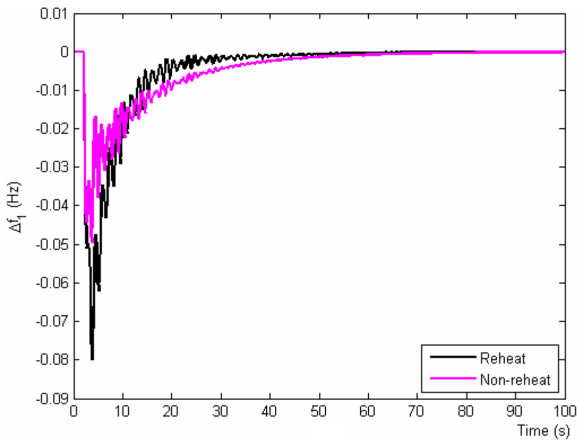
(b)



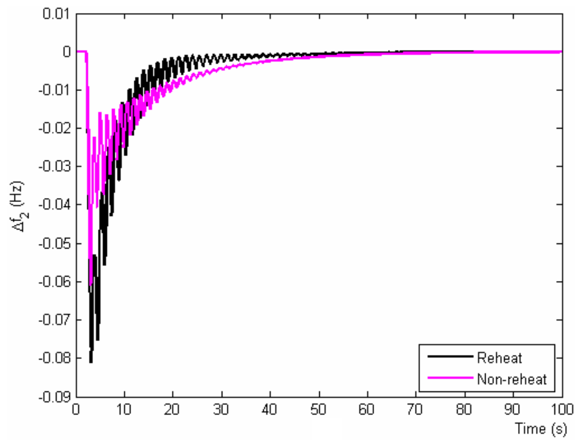
(c)

In scenario A, the GA attempts to minimise the cost function while no constraint is considered in the system supplied by non-reheat turbines. The optimum calculated parameters are reported in Table 2 and the frequency responses are shown in Figure 4. The optimum reported parameters are obtained based on minimising over-shoot. At the next step, the optimum calculated parameters for scenario A are applied to the system supplied by reheat turbines and the results are compared in Figure 5. It could be seen that the system supplied by reheat turbines encounter with a greater under-shoot in comparison with system supplied by non-reheat turbines for the same SLP. The effect of reheat turbines on the dynamics of the system becomes more noticeable when the GRC is considered in the system. In this case, the generating units try to reject the disturbance effect rapidly. However, GRC degrades the ability of the generating units due to the greater under-shoot.

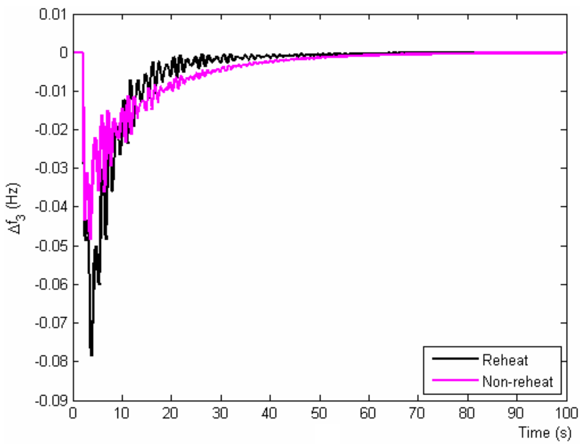
Figure 5 Effect of reheat turbines, (a) area 1 (b) area 2 (c) area 3 (see online version for colours)



(a)

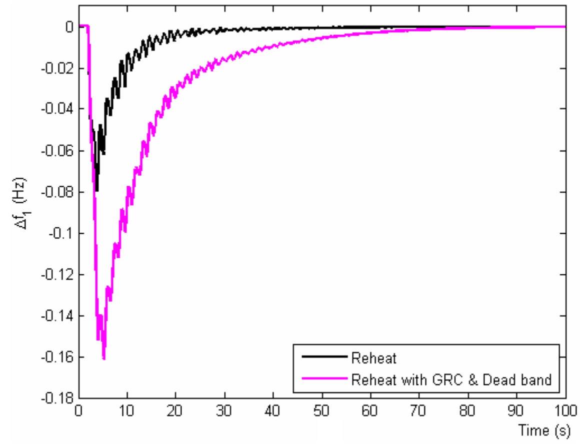


(b)

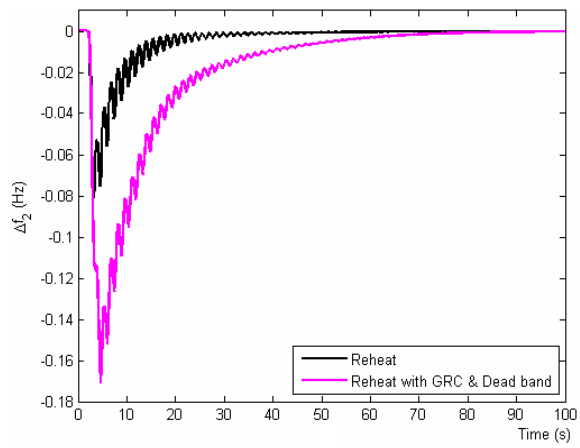


(c)

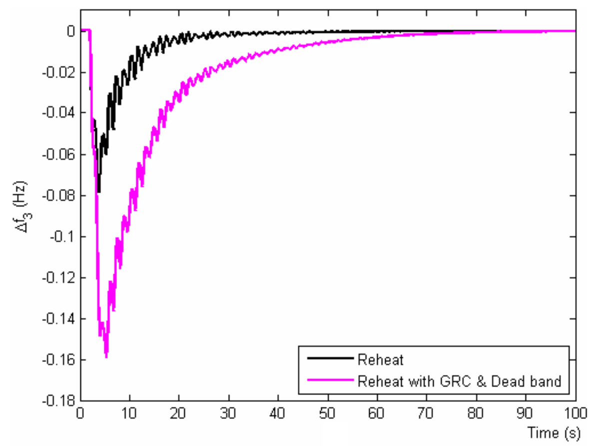
Figure 6 Effect of GRC and speed governor dead band, (a) area 1 (b) area 2 (c) area 3 (see online version for colours)



(a)



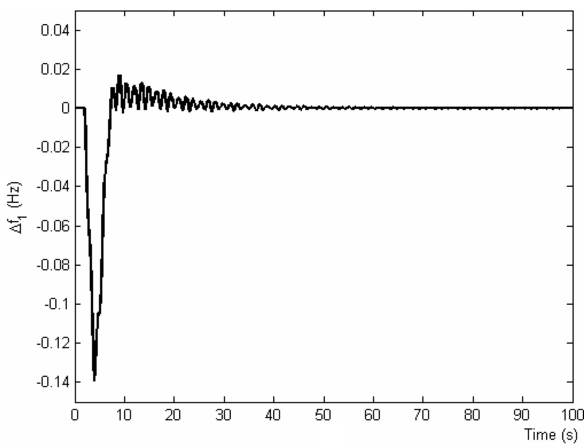
(b)



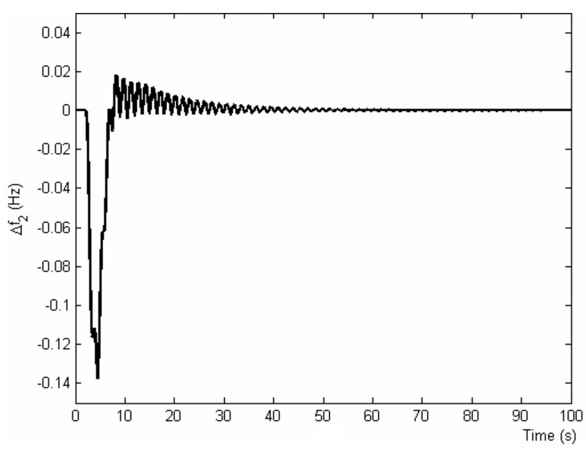
(c)

Effect of the speed governor dead band and GRC on the dynamic behaviour of the system supplied by reheat turbines could be demonstrated by adding them to the scenario A. The optimum reported parameters in Table 2 for scenario A are applied to scenario B and the frequency responses are compared in Figure 6. The GRC and speed governor dead band affect dynamics of the system by increasing under-shoot and settling time. The desired performance of the system characterised by settling time and over/under-shoot could be achieved by retuning of the controller parameters (Table 2). The frequency responses related to the reported parameters in Table 2 are shown in Figure 7.

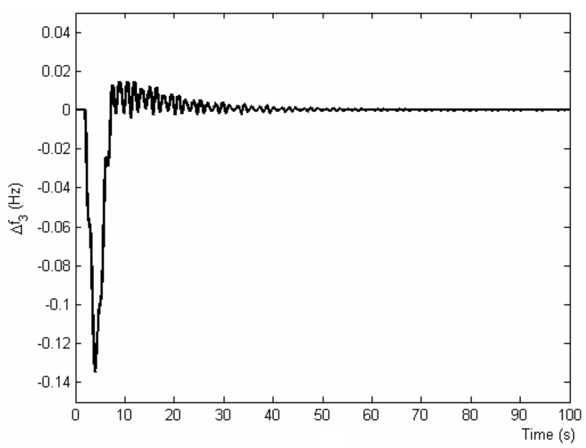
Figure 7 Frequency responses for scenario B, (a) area 1 (b) area 2 (c) area 3



(a)

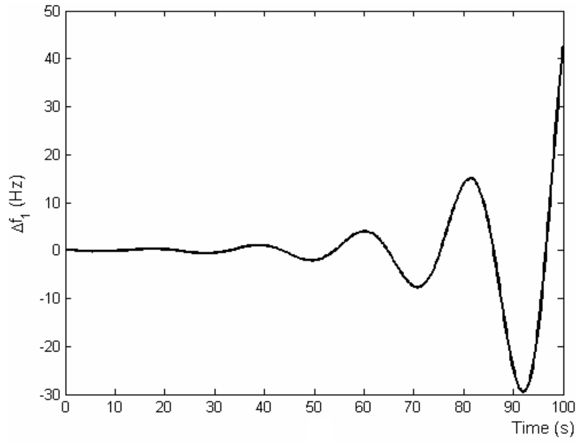


(b)

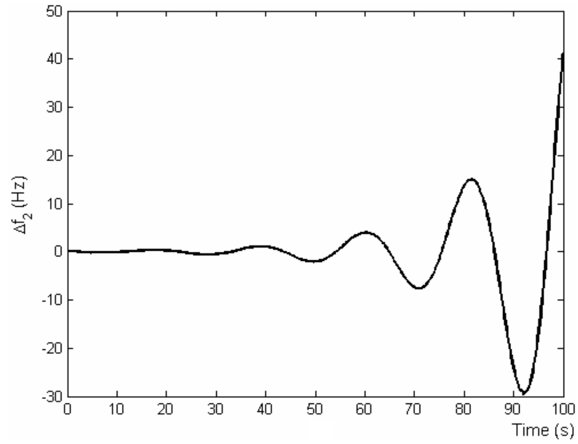


(c)

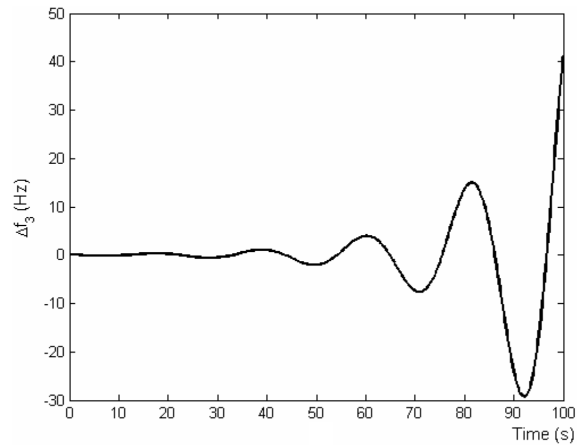
Figure 8 Effect of time delay, (a) area 1 (b) area 2 (c) area 3



(a)



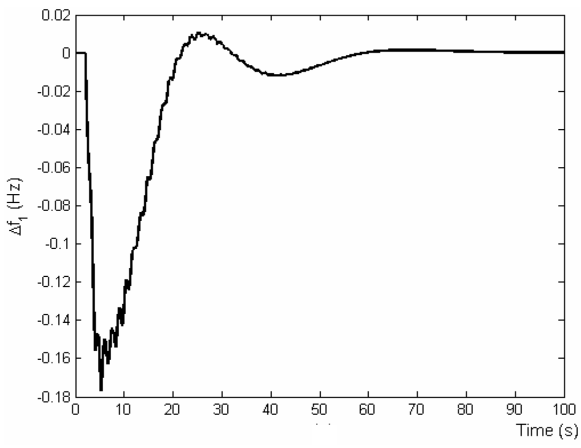
(b)



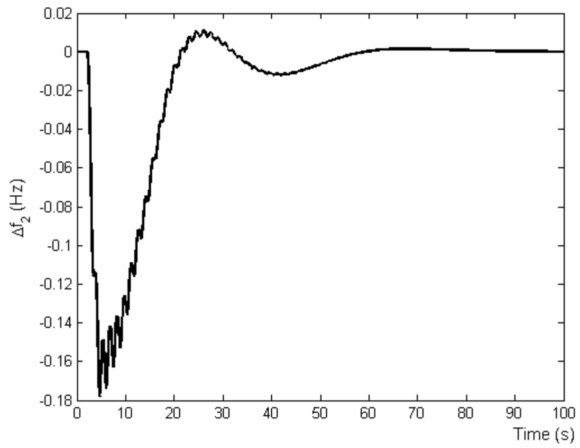
(c)

Scenario C tries to emphasise the effect of delay in communication channels on the dynamic behaviour of the system. For this proposes, time delay caused by communication channels is added to the scenario B and the frequency responses related to the optimum parameters of scenario B are shown in Figure 8. It is obvious that neglecting delays of communication channels could endanger system reliability, security and stability. In the presence of time delay, the impact of disturbance is amplified, and for five seconds delay in the controller response, the AGC system is unable to hold the system frequency. The stable operating point of the system in the presence of time delay could be obtained by retuning of the controller parameters. The optimum parameters are reported in Table 2 and the related frequency responses are shown in Figure 9. It could be seen that the frequency deviations become zero via the AGC loop in steady state.

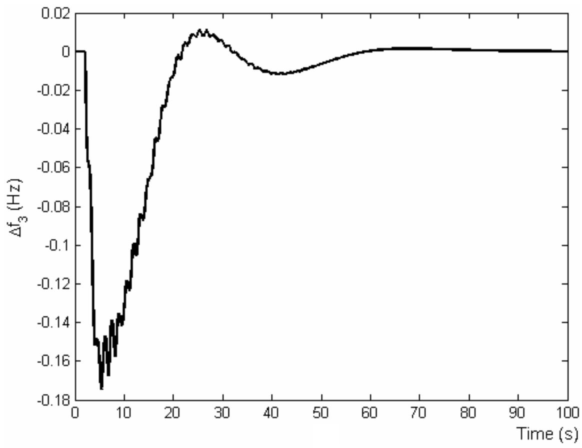
Figure 9 Frequency responses for scenario C, (a) area 1 (b) area 2 (c) area 3



(a)



(b)

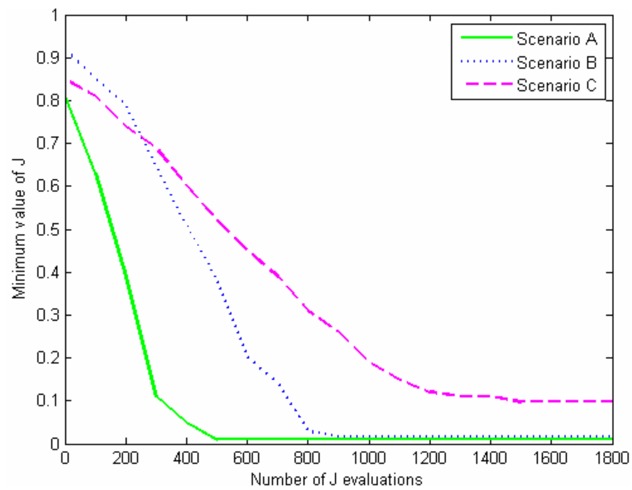


(c)

The convergence characteristics of the GA for the three mentioned scenarios are depicted in Figure 10. In the optimisation problem, calculation of '*J*' (cost function) takes all the computational time and hence, the 'number of J evaluation' could be assumed as the calculating time of integral controllers. From Figure 10, it is clear that the convergence of GA for scenario A is faster than the scenarios B and C. The lower convergence speed of the scenario C in comparison with the scenario B and lower one for the scenario B in comparison with the scenario A reveals that considering more physical constraints in the model increases computational time. Therefore, in addition to the increasing settling time and under/over-shoot, considering physical constraints limit the scope of optimum solutions.

Scenario B demonstrates that considering time delay without GRC and speed governor dead band which introduced by Yang et al. (2005) cannot guarantee the power system reliability. Speed governor dead band and GRC limit the immediate response of the power system to disturbances. Scenario C reveals that the obtained parameters by Nanda et al. (1983, 2009), Kothari et al. (1981) and Hari et al. (1991), which consider only GRC as physical constraint are not optimal for a realistic power system. Also, the results of scenario C show that considering speed governor dead band and GRC without time delay which introduced by Sheikh et al. (2008) and Mohamed et al. (2011) cannot guarantee power system stability.

Figure 10 Convergence characteristics of GA for the three scenarios (see online version for colours)



5 Conclusions

The effect of main physical constraints such as speed governor dead band, time delay and GRC on the dynamic behaviour of a reheat/non-reheat interconnected power system investigated. By considering constraints, the dynamic behaviour of realistic interconnected power system could be represented. Neglecting of each one, for the sake of simplicity, concludes impractical and invalid results and may affect system security and integrity.

The GA was employed to calculate the AGC parameters which conduct the system to a normal condition following disturbances. It was applied to a three-control area power system and was tested for different scenarios. The results reveal that:

- Reheat turbines affect dynamics of power system by increasing the under-shoots and hence, becomes a significant challenge when combines with GRC.
- Neglecting the speed governor dead band and GRC decreases efficiency of the controller in rejection of disturbances. These constraints result in a greater over-shoot and settling time.
- The speed governor dead band and GRC limit the immediate response of the power system to disturbances. The GRC limits the response of generating units to compensate the required power to track disturbances.
- Dynamics of power system are strongly affected by the time delay which caused by communication channels.
- The recent published papers which consider only one or rarely two aspects of physical constraints are not suitable for practical analysis.

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Nomenclature

i	Subscript referred to area i
H_i	Inertia constant of area $i(s)$
D_i	$\Delta P_{Di} / \Delta f_i$ (p.u./Hz)
Δf_i	Incremental change in frequency of area i (Hz)
$\Delta P_{tie,i}$	Incremental change in the power of tie-line i (p.u.)
T_{gi}	Governor time constant of area $i(s)$
K_{ri}	Turbine gain constant of area i
T_{ri}	Turbine reheat time constant of area $i(s)$
T_{ti}	Turbine time constant of area $i(s)$
T_{pi}	$2H_i / fD_i$ (s)
KI_i	Gain of integral controller in area i
R_i	Governor speed regulation parameter of area i (Hz/p.u.MW)
ACE_i	$\Delta P_{tie,i} + \beta_i \Delta f_i$ (Area control error)
β_i	$1 / R_i + D_i$ (Frequency bias of area i)
ΔP_{gi}	Incremental generation change (p.u.)
ΔPD_i	Incremental load change (p.u.)
f	Nominal system frequency (Hz)
K_{pi}	$1 / Di$ (Hz/p.u.)
T	Simulation time
J	Cost function $\left(J = \int_0^T \left(ACE_i \right)^2 \right)$
PS_i	Rotating mass and load i
$\Delta P_{tie\ 1\text{–}2}$	Incremental change in tie-line power of areas 1 and 2 (p.u.)
$\Delta P_{tie\ 1\text{–}3}$	Incremental change in tie-line power of areas 1 and 3 (p.u.)
$\Delta P_{tie\ 2\text{–}3}$	Incremental change in tie-line power of areas 2 and 3 (p.u.)

Appendix

$2H_1 = 0.1667$, $2H_2 = 0.2017$, $2H_3 = 0.1247$ [p.u. s]; $R_1 = 3$, $R_2 = 2.73$, $R_3 = 2.82$ [Hz/p.u.]; $T_{g1} = 0.08$, $T_{g2} = 0.06$, $T_{g3} = 0.07$ [s]; $T_{t1} = 0.4$, $T_{t2} = 0.44$, $T_{t3} = 0.3$ [s]; $\beta_1 = 0.3483$, $\beta_2 = 0.3827$, $\beta_3 = 0.3692$; $T_{12} = 0.20$, $T_{13} = 0.25$, $T_{23} = 0.12$ [p.u./Hz]; $K_{r1} = K_{r2} = K_{r3} = 0.5$; $T_{r1} = T_{r2} = T_{r3} = 10$ [s]; $D_1 = D_3 = 0.015$, $D_2 = 0.016$ [p.u./Hz].