Application of GA optimization for automatic generation control design in an interconnected power system

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\begin{abstract}
This paper addresses a realistic model for automatic generation control (AGC) design in an interconnected power system. The proposed scheme considers generation rate constraint (GRC), dead band, and time delay imposed to the power system by governor-turbine, filters, thermodynamic process, and communication channels. Simplicity of structure and acceptable response of the well-known integral controller make it attractive for the power system AGC design problem. The Genetic algorithm (GA) is used to compute the decentralized control parameters to achieve an optimum operating point. A 3-control area power system is considered as a test system, and the closed-loop performance is examined in the presence of various constraints scenario. It is shown that neglecting above physical constraints simultaneously or in part, leads to impractical and invalid results and may affect the system security, reliability and integrity. Taking into account the advantages of GA besides considering a more complete dynamic model provides a flexible and more realistic AGC system in comparison of existing conventional schemes.
\end{abstract}

1. Introduction

Efficiency of an interconnected power system depends on the existing balance between total generation and total load demand plus associated system losses. Frequency changes are recognized as a direct result of the imbalance between the electrical load and the power supplied by the connected generators [1]. Time variant inherent of power system and disturbances due to the load or generation losses cause changes in operating point of power system. Sequentially, the deviations of frequency and scheduled power exchange between control areas from their nominal values cause undesirable effects [2].

Automatic generation control (AGC) is known as an ancillary service in power system. The AGC employs in power systems to change unit generation by changing the operating point so that equilibrium between demand and generation regains. The AGC system consists of secondary frequency control [3]. Small frequency deviations (greater than the speed governor dead band) can be attenuated by the governor natural autonomous response, called primary frequency control. Transients of primary control are in the time scale of seconds. The secondary frequency control can be used to restore area frequency to its nominal value [4,5]. AGC system plays an important role in power system by maintain-

\bibliography{sample}

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systems. However, easy realization and simplicity of integral controller make it more favorable to achieve zero ACE signal. In most cases, a simplified approach of controlled system adopted by neglecting important physical constraints, simultaneously or in a part. Although considering all dynamics in frequency control synthesis and analysis may be difficult and not useful, it should be noted that to get an accurate perception of the AGC subject it is necessary to consider the important inherent requirement and the basic constraints imposed by the physical system dynamics, and model them for the sake of performance evaluation [4]. The physical constraints which imposed to power system affect dynamics of system and AGC response by increasing overshoot and settling time and hence degrade the performance of the designed controller [4]. Physical constraints are imposed by governor-turbine, filters, communication channels, crossover elements in a thermal unit and behavior of the penstocks in a hydraulic installation. The important constraints affect the power system dynamics are generation rate constraint (GRC), time delay, and governor dead band [4].

An important physical constraint is the rate of power generation due to the limitation of thermal and mechanical movements. The AGC studies that do not take into account the delays caused by the crossover elements in a thermal unit in addition to the sampling interval of the data acquisition system, results in an ideal situation that the frequency and tie-line power to be returned to their scheduled value within 1 s [4]. Thus, in power systems provided by steam plants, power generation can change only at a specified maximum rate. Most of the reheat units have quite low GRC around 3% per minute [9].

By changing the input signal, the speed governor may not immediately react until the input reaches a specified value [4]. This limitation called speed governor dead band. In other word, in the presence of speed governor dead band an increase/decrease in speed (frequency) as dictated by the combined system inertia can occur before the position of the valve changes [10]. The joint American institute of electrical engineers–American society of mechanical engineers (AIEE–ASME) standards for steam and hydraulic turbines define dead band as “the total magnitude of a sustained speed change within which there is no resulting measurable change in the position of the governor controlled valves (or gates)” [10]. Dead band is expressed in percent of rated speed. The standards limit dead band widths to 0.06% (0.036 Hz) [11]. Dead band is caused by mechanical friction and backlash and by valves overlap in hydraulic relays [12,13]. Finally in the practical AGC, rapid responses and varying components of frequency are almost unobservable due to various filters involved in the AGC process [4]. Any signal processing and data gathering introduces a time delay as well, that should be properly considered in the AGC analysis/synthesis which is completely neglected in the recent published research works. On the other hand, owing to the restructuring, expanding of physical setups, functionality and complexity of power systems in a new environment, communication delays become a significant challenge in the AGC synthesis/analysis. Problems associated with the communication network are neglected in most published research works. Although, under the traditional dedicated communication links, this was a valid assumption, however, the use of an open communication infrastructure to support the ancillary services in deregulated environments raises concerns about problems that may arise in the communication system [4].

In the previous studies, governor dead band, practical limits on the increment rate of turbine output (GRC), and delays associated with signal processing and communication channels are often neglected. Bacterial foraging (BF) is applied to the integral controller gains, speed governor regulation and frequency bias parameters in an interconnected power system with GRC to improve the AGC performance in Ref. [6]. The models for interconnected power system which simultaneously consider the GRC and speed governor dead band are proposed in [8,14,15]. Ref. [8] is focused on the effect of non-linearities, AC–DC tie-lines and Superconducting Magnetic Energy Storage (SMES) on the dynamic behavior of two area interconnected power system. A fuzzy gain scheduled supplementary control scheme with SMES applied to the AGC system in an interconnected power system is presented in [14]. A model predictive control (MPC) is applied to an interconnected power system with GRC and speed governor dead band in [15] to improve the performance of the closed-loop system. In these researches, the dynamics associated with time delay are neglected. In the control systems, it is well-known that time delays can degrade a system’s performance and even cause system instability [4]. In order to satisfy the desired performance for a multi-area power system, the design of a controller should take into account these delays. Recently, several papers have been published to address AGC modeling/synthesis in the presence of communication delays [16–21]. East China power system with non-commensurate communication delays is modeled in Ref. [16]. Network delay models and communication network requirement for a third party AGC service are introduced in Ref. [17]. A compensation method for communication time delay in the AGC systems is addressed in Ref. [18]. Linear matrix inequalities (LMI) based control approach is proposed for an AGC system with communication delays in Ref. [19]. Static output feedback (SOF) is employed in [20,21] to design a robust decentralized controller for AGC system with communication delays. The proposed control method by Bevrani and Hiyama [21] gives a suboptimal solution using a developed iterative linear matrix inequalities algorithm via the mixed H2/H∞ control technique. These researches do not take into account the GRC and speed governor

### Nomenclature

- **i**: subscript referred to area *i*
- **Hi**: inertia constant of area *i* (s)
- **ΔP_Di**: incremental load change in area (p.u.)
- **Δf**: incremental change in frequency of area *i* (Hz)
- **ΔP_f,i**: incremental change in tie power of tie *i* (p.u.)
- **ΔP_T,i**: rated power of area *i* (MW)
- **T_Di**: steam governor time constant of area *i* (s)
- **K_g**: gain of integral controller in area *i*
- **R_c**: governor speed regulation parameter of area *i* (Hz/ p.u. MW)
- **β_i**: Δf + 1/R_c (i.e., frequency response characteristics of area *i*)
- **f**: nominal system frequency (Hz)
- **T_m**: 2Hi/D_i (s)
- **K_p**: 1/D_i (Hz/p.u.)
- **K_I**: gain of integral controller in area *i*
- **K_e**: optimal solution using a developed iterative linear matrix inequality
- **K**: LPF low pass filter
- **T**: simulation time (s)
- **ACE**: area control error

### Mathematical Formulation

- **P_Di**: incremental change in tie power of tie *i* (p.u.)
- **P_T,i**: rated power of area *i* (MW)
- **T_Di**: steam governor time constant of area *i* (s)
- **Bi**: frequency bias of area *i*
dead band. In the presence of GRC and speed governor dead band, the system becomes highly non-linear (even for small load perturbation) and hence in a real power system, the performance of the designed controller is significantly degraded. In addition to the neglecting of GRC and speed governor dead band, these researches consider only time delay associated with communication channels. Considering delays caused by filtering and data gathering give rise to increasing of the introduced time delay in system. It is shown that the frequency control performance declines when the time delay increases [4]. Moreover, in real power system, to remove the fast changes and probable added noises, system frequency gradient and ACE signals must be filtered before being used, which is completely missed in the recent literatures.

In general, all of the recent models used for the AGC analysis/synthesis neglect some of the important physical constraints and related dynamics while dynamics associated with signal processing and filtering is completely missed. A more realistic model with substantial modification in comparison with models introduced in recent published literatures is addressed in this paper. The model considers GRC, Speed governor dead band, filters and time delay associated with both communication channels and signal processing simultaneously. Considering important physical constraints in the proposed scheme provides a more accurate model for digital simulations and makes it appropriate for a wide range of interconnected system studies. Similar to the real AGC systems, an integral controller is used to optimize the system performance. To achieve an optimum operating point, the GA is implemented to calculate the controller gains.

The rest of this paper is organized as follows. Section 2 discusses the GA and application of GA in AGC studies. In Section 3, the proposed model is introduced. In Section 4, simulation details and simulation results are explained, and finally Section 5 concludes the paper.

2. GA and application in AGC

Time consumption and inaccurate methods such as classical, experience-based and trial and error for tuning of integral controller cause to the interest on the meta-heuristic methods such as GA. The GA becomes a very useful tool for the tuning of control parameters in AGC systems. Genetic algorithm (GA) is a numerical optimization algorithm, capable of being applied to a wide range of optimization problems that guarantees the survival of the fittest [22]. The algorithm begins with a set of initial random population represented in chromosomes; each one consists of some genes (binary bits). These binary bits are suitably decoded to provide proper string for the optimization problem. Genetic operators act on this initial population and regenerate the new populations to converge at the fittest. A function called fitness function is employed to aid regeneration of new population from the older one, i.e. initial population. Fitness function assigns a value to each chromosome (solution candidate) which specifies its fitness. According to the fitness values, the results are sorted and elite strings are employed to generate a new population by the specified operators [23]. The GA employs selection, crossover and mutation operators to converge at the global optimum. Selection procedure is a stage that individual chromosomes are selected from the population for the later recombination/crossover [24]. The fitness values are normalized by dividing each one by the sum of all fitness values named selection probability. The chromosomes with higher selection probability have a higher chance to be selected for later breeding. Crossover combines the pairs of chromosomes promoted by selection operator to generate the new ones. Mutation changes a single bit value in chromosomes randomly. The new population consists of the fitter chromosomes of the old population (parents) and the new ones created by crossover and mutation [25]. The assigned coefficients to the crossover and mutation specify number of the children. The above statements are schematically depicted in Fig. 1.

In this paper, the initial population consists of 100 chromosomes; each one contains 48 binary bits (genes). Fitness proportionate selection method (known as roulette-wheel selection method) is used to select the elite strings for recombination. The crossover and mutation coefficients are considered as 0.8 and 0.2. The objective (cost) function which should be minimized is considered as follows:

\[
J = \int_0^T (ACE)^2 \, dt
\]

where \(T\) is the simulation time, and

\[
ACE_i = \Delta P_{reg} + \beta_i \Delta f_i
\]

\[
\beta_i = \frac{1}{R_i} + D_i
\]

A general description of the applied GA can be stated as:

- **Step 1:** The initial population of 100 random binary string of length 48 is made (each controller gain by 16 genes).
- **Step 2:** The strings are decoded to the real number between [0, 1].
- **Step 3:** Fitness value is calculated for each chromosome.
- **Step 4:** The elite strings (fitter ones) are selected as parents.
- **Step 5:** Some pairs of promoted parents by selection operator are recombined to generate children.
- **Step 6:** Mutation is rarely applied to the children.
- **Step 7:** The new population are regenerated by allowing parents and children together.
- **Step 8:** Return to step 2 and repeat until terminate conditions are satisfied [25].

The GA attempts to conduct the frequency to the nominal value for each area in the independent manner. In other word, the proposed control strategy is decentralized one. In the decentralized control strategies for multi-area AGC systems, each area controller uses only the local states for feedback and thus, the controller structure becomes simpler.

Several investigations have been reported in the past, pertaining to the application of GA in the AGC design. Most of these papers consider a simplified model for interconnected power system without any constraint. Too simplification in frequency response models leads to find a wide range of optimum solutions that may not applicable in practice.

The introduced AGC model in the present paper limits the scope of optimum solutions. The problem of controller parameters tuning to achieve an optimum solution in the presence of various non-linearities and physical constraints can be effectively covered by using the GA approach.

3. Case study

The GA carried out on a three-area power system with equal loads and provided by single reheats turbines and integral controllers. The physical constraints are assumed as shown in Table 1. The nominal parameters of the system are taken from [4], and

<table>
<thead>
<tr>
<th>Table 1 Physical constraints.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRC</td>
</tr>
<tr>
<td>3% p.u. MW/min</td>
</tr>
</tbody>
</table>
represented in Appendix A. The dynamic frequency response model of three-area power system is shown in Fig. 2. For a system with unequal loads, per unit values of parameters for each single area in its related base are considered for the interconnected system. Hence, the quantities $a_{12} = P_1/P_2$, $a_{13} = P_1/P_3$, $a_{23} = P_2/P_3$ are employed to take into account inequality of loads in interconnected system [6]. As previously stated, performance of a designed AGC system depends on how generation units respond to the control signal. A very fast response for the AGC system is neither possible nor desirable. A useful control strategy must be able to maintain sufficient levels of reserved control range and control rate. Thus, in the performed model, a low pass filter is employed to reject the fast control signal variation.

4. Simulation results and evaluation

The GA is applied to the power system case study to obtain the optimum values for integral gains in 3-control area. To investigate the importance of considering the physical constraints, four simulation scenarios are performed (Table 2).

In scenario A, no physical constraint is considered in the implementation of the AGC model. In scenario B, only speed governor dead band is considered, and the GRC and time delay are neglected. In scenario C, the speed governor dead band and time delay are considered while the GRC is neglected. Finally in scenario D, all of three constraints are considered together and the ACE signal is filtered before being used. For each scenario, a 0.02 p.u. step load

Table 2
Optimum values of integral gains.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{I1}$</td>
<td>0.7703</td>
<td>0.5800</td>
<td>0.1332</td>
<td>0.2594</td>
</tr>
<tr>
<td>$K_{I2}$</td>
<td>0.5439</td>
<td>0.1920</td>
<td>0.3395</td>
<td>0.2780</td>
</tr>
<tr>
<td>$K_{I3}$</td>
<td>0.3254</td>
<td>0.1740</td>
<td>0.1711</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

Fig. 1. A general scheme for genetic algorithm.

Fig. 2. Thermal 3-control area power system considering the generation rate constraint, time delay, and speed governor dead band.
perturbation (SLP) is applied to areas 1 and 3 at 2nd second, simultaneously.

In scenario A, the GA attempts to minimize the cost function while no constraint is considered in the model. The optimum calculated parameters are reported in Table 2. As previously stated, a wide range of optimum solutions exists for such simplified model. Therefore, the reported parameters in Table 2 for scenario A are obtained based on minimizing settling time. The frequency response and the net tie-line power change in each area are shown in Fig. 3. It is obvious that the frequency and net power exchanged between control areas deviations are became zero in steady-state. The optimum parameters which obtained for scenario A are applied to the scenario B, and the results are compared in Fig. 4. It could be seen that the speed governor dead band affects dynamics of the power system by increasing the overshoot/undershoot and apparent steady-state speed regulation. The greater frequency excursion from the nominal value (greater overshoot/undershoot) shows more noticeable imbalance between the generation and the load demand plus the losses. Therefore, the generating units must provide higher power with appropriate rate to regain the stable, secure and reliable operating point. Therefore, the effect of speed governor dead band becomes more important when it combines with the GRC, and hence the system frequency cannot regain its nominal value in a specified time (determined by relays setting time) and thus the protective devices and relays react. Therefore, the system falls into the unstable condition.

High level performance of the power system in scenario B can be achieved by retuning of the controller gains. The optimum calculated parameters are reported in Table 2. For these values the frequency response and the net tie-line power exchanged for each area are shown in Fig. 5. It is obvious that the frequency deviations are canceled via the AGC loop in steady-state. By taking into account the speed governor dead band in the process of controller design, the over shoot is eliminated in the frequency response. The optimum parameters (which obtained for scenario B) are used in scenario C, and the results are compared in Fig. 6. It could be seen that the calculated integral gains for scenario B (to achieve the optimum operation point) are not suitable for scenario C. In the presence of time delay, the impact of disturbance is amplified during the 2 s delay in the reaction of controller to the related control signal. Sequentially, settling time noticeably increases and power system encounters with high magnitude oscillation and low damping characteristics. Therefore, the problem which associated with scenario A (reacting of protective device) is exist in this scenario, too. Another important problem is on the mechanical strength of rotor. The high overshoot with great settling time cause the rotor work under torsional torque. Thus, the rotor will be damaged in the short time.

The optimum operating point for scenario C is achieved by retuning of the controller parameters. The results are shown in Table 2. The updated parameters conduct the system in a stable mode with satisfactory settling time and desirable performance. The frequency deviation becomes zero at steady-state as shown in Fig. 7. The updated control parameters for scenario C are applied to the
complete model (scenario D) with three physical constraints, and the related results are shown in Fig. 8. The later parameters could encounter the system with increased oscillation characteristic at steady-state, and hence reliability and security of the system are reduced. The required power to maintain the system in normal condition is prepared by limit rate due to the GRC. Thus this limitation must be considered to avoid instability in the realistic multi-area power systems.

In the presence of all mentioned physical constraints, optimization is done and results are shown in Fig. 9. The effect of the GRC will be more noticeable when the system encounters with greater SLP or increasing in time delay. In this way, the system attempts to provide greater power in a fast time horizon to ensure integrity of the interconnected system, but the GRC limits the response of the generating units by reducing the rate of increasing required power to reject the disturbances. Effect of increasing time delay on the dynamic behavior of the system is shown in Fig. 10. Considering time delay associated with signal processing in addition to the communication channel effects causes increasing of time delay in Fig. 10. It could be seen that increasing of time delay by 4 s (typical time delay associated with signal processing and filtering [4]) conducts the system to unstable condition.

5. Discussion

After a load disturbance in a system, ACE signals and control signals deviate from zero. Because of dead band and introduced time delay in the system, attempt to readjusting of generator set point is performed by delay. In this period, the effect of disturbance becomes more noticeable by larger frequency deviation from nominal one. After readjusting of generator set point, the required power to compensate frequency deviations is provided through a specific ramp rate. Simulation results show that simultaneously considering all of important physical constraints in the model is essential to get an accurate scheme of real power system. Results of scenarios A and C show that the obtained parameters by Nanda et al. [6], which only considers the GRC as a physical constraint may not fully suitable for a realistic power system. Neglecting speed governor dead band and time delay decreases efficiency of the controller in rejection of disturbances in an acceptable time. Both of these constraints affect the system in the same way by increasing overshoot and settling time but with different intensity. Therefore, these dynamics must be considered in the design of integral controller to eliminate their detrimental effects. Bevrani and Hiyama [21] emphasizes the effect of time delay caused by communication channels by experimental results. However, scenarios A and D show neglecting inherent constraints of generators (e.g. GRC and speed governor dead band) deteriorates performance of the designed controller seriously. The speed governor dead band and GRC limit the immediate response of the power system to reject disturbances. Moreover, neglecting of time delay caused

![Fig. 5. Frequency and tie-line power responses for scenario B: (a) Area 1, (b) Area 2, and (c) Area 3.](image1)

![Fig. 6. Compare of frequency response for scenarios B and C: (a) Area 1, (b) Area 2, and (c) Area 3.](image2)
by signal processing and filters could endanger security, reliability and stability of power system. The problems which associated with [6] are not solved by [8,14,15], where GRC and speed governor dead band are simultaneously considered. The speed governor dead band in [8,14,15] causes the system encounters with higher magnitude overshoot in comparison with [6].

Fig. 7. Frequency and tie-line power responses for scenario C: (a) Area 1, (b) Area 2, and (c) Area 3.

Fig. 8. Compare of frequency response for scenarios C and D: (a) Area 1, (b) Area 2, and (c) Area 3.

Fig. 9. Frequency and tie-line power responses for scenario D: (a) Area 1, (b) Area 2, and (c) Area 3.
A more complete scheme is performed for AGC systems in the interconnected power systems. The proposed scheme considers three physical constraints including time delay, GRC and speed governor dead band. By considering these constraints the dynamic behavior of realistic interconnected power systems can be represented. These constraints cause system to be severely non-linear and therefore tuning of controller parameters may not so straightforward. The GA is used to calculate the integral controller gain which conduct the system to a normal condition following disturbances.

The GA was applied to a 3-control area power system and was tested for different scenarios. Four scenarios are considered to demonstrate the impact of each constraint on the dynamic behavior of interconnected power system. Firstly, the system without any constraint is optimized and then the model was completed step by step by considering the constraints. Neglecting of each constraint causes to the optimal solution which conducts the realistic interconnected power system to the unstable or unreliable operating point. Time delay and speed governor dead band cause to the greater overshoot/undershoot after a disturbance and become a concern when combined with GRC. In this case, the system could not regain the match between the generation and demand plus losses in the specified time (determined by relay setting) and therefore the system losses its integrity and operate as islands. The results show the crudity of the models introduced in the recent publications which consider only one or rarely two aspects of constraints.

### Appendix A

\[ D_1 = D_3 = 0.015, D_2 = 0.016 \] (p.u./Hz); \[ 2H_1 = 0.1667, 2H_2 = 0.2017, 2H_3 = 0.1247 \] (p.u./s); \[ R_1 = 3, R_2 = 2.73, R_3 = 2.82 \] ([Hz/p.u.]); \[ T_{r1} = 0.08, T_{r2} = 0.06, T_{r3} = 0.07 \] (s); \[ T_{i1} = 0.4, T_{i2} = 0.44, T_{i3} = 0.3 \] (s); \[ \beta_1 = 0.3483, \beta_2 = 0.3827, \beta_3 = 0.3692 \] (p.u./Hz); \[ T_{12} = 0.2, T_{13} = 0.25, T_{23} = 0.12 \] (p.u./Hz); \[ K_r = K_r = K_r = 0.5; T_{r1} = T_{r2} = T_{r3} = 10 \] (s).

### References


![Fig. 10. Effect of increasing time delay: (a) Area 1, (b) Area 2, and (c) Area 3.](image-url)

