Hybrid evolutionary algorithm based fuzzy logic controller for automatic generation control of power systems with governor dead band non-linearity

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Abstract: A new intelligent Automatic Generation Control (AGC) scheme based on Evolutionary Algorithms (EAs) and Fuzzy Logic concept is developed for a multi-area power system. EAs i.e. Genetic Algorithm–Simulated Annealing (GA–SA) are used to optimize the gains of Fuzzy Logic Algorithm (FLA)-based AGC regulators for interconnected power systems. The multi-area power system model has three different types of plants i.e. reheat, non-reheat and hydro, and are interconnected via Extra High Voltage Alternate Current transmission links. The dynamic model of the system is developed considering one of the most important Governor Dead Band (GDB) non-linearity. The designed AGC regulators are implemented in the wake of 1% load perturbation in one of the control areas and the dynamic response plots are obtained for various system states. The investigations carried out in the study reveal that the system dynamic performance with hybrid GA–SA-tuned Fuzzy technique (GASATF)-based AGC controller is appreciably superior as compared to that of integral and FLA-based AGC controllers. It is also observed that the incorporation of governor dead band non-linearity improves the dynamic performance of the AGC controller.
of GDB non-linearity in the system dynamic model has resulted in degraded system dynamic performance.

**Subjects:** Computer & Software Engineering; Electrical & Electronic Engineering; Power Engineering

**Keywords:** automatic generation control; governor dead band; non-linearity; fuzzy logic algorithm; evolutionary algorithms

1. Introduction

The growth of large interconnected power system is to minimize the occurrence of the black outs and providing an increasing power interchange among distinct system under the huge interconnected electric networks. The power system operators enhance load-interchange-generation balance between control areas, and adjust the system frequency as close as possible nominal values. Automatic Generation Control (AGC) is necessary to keep the system frequency and the inter-area tie-line power as close as predefined nominal values. A reliable and committed power utility should cope with load variations and disturbance effectively. It should give permissible high quality of power while controlling frequency within acceptable limits. The problem of AGC has been extensively analysed during the last few decades. Elgerd and Fosha in 1970 were the first to propose the design of optimal AGC regulators using modern control theory for interconnected power systems (Elgerd & Fosha, 1970). The proposed scheme provided better control performance for a wide range of operating conditions than the performance of conventionally designed control schemes. Since the classical gain scheduling methods may be unsuitable in some operating conditions due to the complexity of the power systems such as non-linear load characteristics and variable operating points, the modern approaches were preferred for use. Following the work of Elgerd and Fosha, many AGC schemes based on modern control theory have been suggested in literature (Ibraheem & Kothari, 2005; Shayeghi, Shayanfar, & Jalili, 2009; Singh & Ibraheem, 2013). They were followed by AGC schemes based on intelligent control concepts after a very long time.

In Chown and Hartman (1998), a Fuzzy Logic Controller (FLC) as a part of the AGC system in Eskom’s National Control Centre based on Area Control Error (ACE) as control signal for the plant is described. Moreover, Yousef proposed an adaptive fuzzy logic load frequency control of multi-area power system in Yousef (2015), Yousef et al. (2014). Anand and Jeyakumar (2009) incorporated the system with governor dead band, generation rate constraint and boiler dynamics non-linearities in the system models. Fuzzy Logic Algorithm (FLA) has been employed to design FLC for the system to overcome the drawback of conventional Proportional–Integral Controller. It has circumvented the controller gain problem to some extent but did not give more accurate (Albertos & Sala, 1998) and precise optimal gains for FLC in the AGC due to need of the exact system operating conditions. Therefore, Evolutionary Algorithms (EAs) are introduced to fight with the controller optimum gain problem (Boroujeni, 2012; Devi & Avtar, 2014; Ghoshal, 2004; Yousef, AL-Kharusi, & Mohammed, 2014; Pratyusha & Sekhar, 2014; Saini & Jain, 2014; Singhal & Bano, 2015). Authors discussed classical controller gains tuning through Non-Dominated Shorting Genetic Algorithm-II (NSGA-II) technique for AGC of an interconnected system. Integral Time multiply Absolute Error, minimum damping ratio of dominant eigenvalues and settling times in frequency and tie-line power deviations considered as multiple objectives and NSGA-II is employed to generate Pareto optimal set. Further, a fuzzy-based membership value assignment method was employed to choose the best compromise solution obtained from Pareto solution set. This method was also investigated with non-linear power system model (Yegireddi & Panda, 2013). EAs were found capable to give global optimum gains for FLCs to handling sensitive controlling issue of AGC. FLCs are characterized by a set of parameters, which are optimized using EAs i.e. GA, SA to improve their performance (Boroujeni, 2012; Ghoshal, 2004; Saini & Jain, 2014). EAs were efficiently applied to AGC of power systems and have shown its ameliorated performance without systematic and precise data of the power system model.
In this article, the design of optimal AGC scheme for a three-area interconnected power system is investigated with three diverse controller's i.e. classical integral control, FLA and GASA-tuned FLC controllers. Moreover, a hybrid GASATF technique constitutes GA and SA approach to determine output fitness function from the fuzzy Mamdani algorithm. This is used as the input for GA–SA technique to design the optimal gains for AGC scheme. The designed AGC scheme yielded ameliorated system dynamic performance under various operating conditions of a three-area interconnected hydro-thermal power systems with and without considering Governor Dead Band (GDB). In this article, studies have been carried out by considering 0.01 p.u.MW perturbation in one of the power system areas. The simulation study carried out using MATLAB/SIMULINK toolbox 2014a version platform. The investigations include the non-linear effect of GDB. Power systems dynamic performance has been studied by investigating the response plots of the disturbed areas (∆F₁, ∆F₂, ∆F₃, ∆P₈₁₂, ∆P₈₂₃ and ∆P₈₃₁). Also the investigations of response plots obtained for ∆X₉₁, ∆F₃, ∆P₈₃₁, ACE₃ and U₃ with inclusion of GDBs. The system nominal system parameters are presented in Appendix A.

2. Power system model for investigation

It is a three-area interconnected power system consisting of power plants with reheat, non-reheat thermal and hydro turbines, and is interconnected via EHV AC tie-line. The single-line diagram of the multi-area interconnected power system model is presented by Figure 1. The optimal AGC controllers are designed considering (i) linear model of the system and (ii) non-linear model of the system with GDBs. The transfer function model of both the models with and without GDB non-linearity is shown in Figure 2. This model exhibits linear and non-linear both characteristics of the power system behaviour.

3. Effect of governor dead band non-linearity

Most of the real-time AGC of power systems include non-linearity in itself through several ways. The sort of non-linearity may be materialistic affect, Generation Rate Constraints (GRCs), GDB and load, etc. The real-time simulation cannot be realized without incorporation of non-linearity and the demo of real-time AGC model may also be incomplete without non-linearity. Therefore, one of the most prominent non-linearity in the form of GDB is considered in the proposed power systems model. Movement of thermal or hydro GDB can not be permitted without specified tolerable limits for flow of steam/water.

The GDB effect indeed can be significant in AGC studies. In the model, a GDB impression is supplemented to all control areas to simulate non-linearity (Gozde & Taplamacioglu, 2011; Yegireddi & Panda, 2013). Explaining function method is utilized to exhibit the GDB in the control areas. The GDB non-linearity moves to create a continuous sinusoidal oscillation of natural time schedule near to T₀ = 2 s. GDB linearization is done by the method using means of deviation and rate of deviation in the movement. With these considerations, GDB is taken into account by adding limiters to the turbine input valve. In this work, the backlash of approximately 0.5% is selected. The GDB transfer function in the power systems model is presented as:

![Figure 1. Block diagram of multi-area interconnected power system with AC link.](image-url)
4. Hybrid EA-based fuzzy logic controller structure

Basically, ACE is the measure of short-term error between generation and electric consumer demand. Power system performance is termed as good if a control area closely matches generation with load demand. AGC of the power systems means minimizing the ACE to zero. Hence, the systems frequency and tie-line power flows are maintained at their scheduled values (Elgerd & Fosha, 1970), respectively:

\[ \text{ACE}_i = \sum_i (B_i \Delta F_i + \Delta P_{\text{tie}i}) \]  

where \( i = 1, 2, 3 \).

The input to ACE, \( U_i \), is rate of change for integral control action. It can be defined as:

\[ U_i = -K_i (\text{ACE}_i) \frac{dt}{dt} \]  

The ACE, is tuned in using of Integral Square Error (ISE) criterion which has the form of:

\[ G(s) = \frac{0.8 - \frac{0.2s}{1 + sT_g}}{1 + sT_g} \]  

\[ \text{ACE}_i = \frac{1}{s} \int \Delta F_i dt + \frac{1}{sT_g} \int \Delta P_{\text{tie}i} dt \]  

\[ G(s) = \frac{0.8 - \frac{0.2s}{1 + sT_g}}{1 + sT_g} \]  

Figure 2. MATLAB/Simulink model of multi-area interconnected power systems with/without GDB with optimal GASA tuned FLCs.
For the present investigation; this error is considered as ACE, and evaluating ISE as a fitness function as:

\[
ISE = \int_0^{\infty} e^2(t) \, dt
\]  

Over the last few decades, FLCs have been developed for analysis and control of several types of systems (Anand & Jeyakumar, 2009; Chown & Hartman, 1998; Yousef, 2015; Yousef et al., 2014). But FLCs have not been exploited to its full capability to counter the problems associated with the systems having non-linear characteristics. It has been demonstrated that its performance is far from being stringent and time optimal (Albertos & Sala, 1998). Subsequently, this problem has been successfully solved using EAs for AGC problem of power systems (Yegireddi & Panda, 2013). Therefore, researchers have proposed the combination of FLA and EAs to design the controllers exploiting the salient features of both the algorithms. The hybrid structure of these techniques exhibited their adaptable qualities in non-linear systems.

FLC consists of FLA approach with integral control action in the closed loop control system. The FLC has input signal, namely ACE, of the systems, and then its output signal \( U_i \) is the input signal for GASATF. FLC feedback gains \( K_i \) are optimized with the help of EAs i.e. combination of GA and SA technique. Finally, the output signal from the GASATF called the new \( U_i \) is used in the AGC of power systems.

These optimal gains are globally optimal for the system to be controlled. These global optimal gains give exact value of the fitness function for developing AGC scheme. These global optimal gains can also handle the AGC problem when system is operating with nominal system parameters. The gain scheduling of the power systems is a very important and effective process of its controlling (Saini & Jain, 2014). In view of this, ultimately GASATF tuned FLC is proposed in the present article. This scheme is shown in Figure 3. The presented GASA strategy enables to evaluate global optimal value of fuzzified \( K_i \) followed by the modification of fuzzified fitness function of the FLC.

The GASATF heuristic incorporates SA in the selection process of Evolutionary Programming (Boroujeni, 2012). The solution string comprises all feedback gains and is encoded as a string of real numbers. The population structure of GASATF is shown in Figure 4. The GASATF heuristic employs blend crossover and a mutation operator suitable for real number representation to provide it a better search capability. The main objective was to minimize the ACE, augmented with penalty terms corresponding to transient response specifications in the system frequency and tie-line power flows. These two disturbances yield the error for the AGC systems. The heuristic is quite general and various aspects like non-linear, discontinuous functions and constraints are easily incorporated as per requirement. The fuzzy fitness function is taken as the summation of the absolute values of the three:

\[
\text{Fitness function (ISE)} = \int_0^{\infty} ACE_i^2 \, dt
\]
at every discrete time instant in the simulation. An optional penalty term is added to take care of the transient response specifications.

The FLA has been investigated with seven triangular membership functions of the FLC. FLC has seven rules for the control of ACE. This controller has a Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB) functions. Mamdani fuzzy rule list is shown in Table 1. In the FLCs, there is an input and output selected in the fuzzy Mamdani inference system which is described in Figure 5. The input and output membership functions of FLA for ACE in both test cases are shown in Figures 6 and 7. A triangular membership function shapes of the derivative error and gains according to integral controller are chosen to be

| Table 1. Mamdani-based fuzzy rule | Mamdani-based Rules for FLCs |
|-----------------------------------|-----------------------------|
| Rule 1                           | If(ACE, is NB) then (U, is PB) |
| Rule 2                           | If(ACE, is NM) then (U, is PM) |
| Rule 3                           | If(ACE, is NS) then (U, is PS) |
| Rule 4                           | If(ACE, is Z) then (U, is Z) |
| Rule 5                           | If(ACE, is PS) then (U, is NS) |
| Rule 6                           | If(ACE, is PM) then (U, is NM) |
| Rule 7                           | If(ACE, is PB) then (U, is NB) |
identical for the FLC. However, its horizontal axis limits are taken at different values for evaluating the controller output. The characteristics of the FLC present a conditional relationship between $ACE_i$ and $U_i$ as shown in Figures 8 and 9.

In this graph, $x$-level shows the controller’s input and $y$-level presents output of the FLC. Rule base are defined in the scaling range of $[-1, 1]$ without GDB, and $[-1.3, 1.3]$ with GDB of the power system.

Initially, population size is 100 and number of parents are 10. Subsequently, Boltzmann initial probability factor is 0.99 and final is 0.0001. Approximate parameters are utilized as initial cost (1,000,000), total iterations (120), crossover rate (0.6), probability: exp(generation/maximum generation) and mutation probability rate (0.002).
4.1. Pseudo code
The proposed technique can be understood from the following pseudo code which is given below in the steps of implementation;

Step 1: Create random population.

Step 2: In the beginning, assume the current temperature \(T\), initial temperature \(T_1\) and final temperature \(T_{MAX}\), parent strings \(N\), children strings \(M\) as per FLC structure with scaling factor limits (fitness function limits) (Singh & Das, 2008).

Step 3: For each and every parent number is defined by \(i\). Then, create \(m(i)\) children using crossover process.

Step 4: Modify the mutation operator with the probability margin \(P_m\).

Step 5: Obtain the best child for every parent (initial competition level in that process).

Step 6: Select the best child as a parent for the future generation.

For every family, accept the best child as the parent for future generation if objective quantity of the best child \(Y_1\) is less than objective quantity of its parent \(Y_2\) that is equal to \(Y_1 < Y_2\) or \(\exp(Y_2 - Y_1) \geq \rho\) (a random number uniformly divided between 0 and 1).

Step 7: Reschedule steps 8–11 for every family.

Step 8: Counting initiate from zero \(\text{count} = 0\).

Step 9: Reschedule step 10 for every child; go to step 11.

Step 10: Increase every count by 1, If \(Y_1 < Y_2\) or \(\exp(Y_{LOWEST} - Y_1) \geq \rho\) in which \(T_c\) is the current temperature at that time and \(Y_{LOWEST}\) is the lowest objective quantity ever got in the calculations.

Step 11: Acceptance number of the family is equal to \(\text{count} (A)\).

Step 12: Add up the acceptance numbers of all the families \(S\).

Step 13: For every family \(i\), evaluate the number of children to be generated in the next generation as per the following formula: \(m(i) = \exp(\text{count}(i) \times A)\); in which total number of children generated by all the families \(TC\).

Step 14: Decrease the temperature after the each iteration.

Step 15: Repeat the steps number 3–14 until a defined number of iterations have been achieved or desired result has been completed.

| Table 2. New generation (best population) |
|--------------------------|
| **Best population**      |
| GASATF (without GDB)     | [1.2934  −0.2751  0.7940 0.5839 0.1796 0.5284  
|                          | −0.0002 0.9710 0.1931 1.3231 0.6587 0.6180 0.8957] |
| GASATF (with GDB)        | [1.4658 0.2928  −1.4513  −6.1149 0.6008  −0.1285 0.474  
|                          | 3 0.0085 0.1239 0.0053 1.1172 0.1076 0.0378 0.3649] |
The GASATF presented for straightforward calculation of the fuzzy fitness function. After the fuzzy fitness function tuning, GASATF technique creates global optimal feedback gains for the AGC. For adopting the best generation the criteria is created by optimal GASATF approach which is reported in Table 2.

5. Results and discussion

The power system model under investigation is simulated on MATLAB/SIMULINK platform to carry out investigations with GASA-tuned FLC for the AGC scheme. The dynamic responses of power system models are obtained using GASATF-based AGC schemes by creating 1% load perturbation in area-3. The optimal feedback gains for all investigated controllers are presented in Table 3. In Table 4, frequency dynamic of area-3 is exhibited by numerical analysis. These dynamic responses are plotted in Figures 10–15. The proposed controller resulted in the response plots with less settling time, minimum peak overshoot and undershoot as compared to those obtained with IC and FLC-based AGC schemes. Further, the investigation of these dynamic responses reveals that the dynamic performance with GASATF controller is better than that obtained other compared controllers. However, an appreciable improvement in the dynamic performance of power system is visible while using proposed controller rather than using IC and FLC.

The dynamic performance of proposed AGC controller is also obtained by considering effect of GDB non-linearity. The plot of Figure 16 presents the effect of the GDB on dynamic response of speed governor systems. Dynamic response of the governor valve reveals that opening of valve is faster in non-reheat turbine as compared the reheat and hydro turbines. Figure 16 shows that governor valve movement in hydro turbine is slow. The dynamic responses of speed governor of non-reheat thermal turbine are found to be more oscillatory than speed governor of other turbines. The speed governor responses are found to be uniform and proportional to the area inertia, the control output \( U_3 \) remains unchanged from its value just following the disturbance until AGC scheme becomes effective after 1–4 s. The investigation of the dynamic response of Figures 17–20 reveals that the dynamic responses are more oscillatory due to presence of GDB. The realistic behaviour of GDB is shown by these dynamic responses which are taken different scenarios.

Further inspection of these system responses reveals that AGC controllers based on integral control action offer a very sluggish response trends associated with large number of oscillatory modes, large settling time and a considerable amount of steady state error. Whereas, the dynamic response

| Controllers | \( K_I \) | \( B_1 \) | \( B_2 \) | \( B_3 \) |
|-------------|--------|--------|--------|--------|
| IC          | 0.341  | 0.425  | 0.425  | 0.425  |
|             | 0.132  |        |        |        |
|             | 0.129  |        |        |        |
| FLC         | 0.299  | 0.115  | 0.115  | 0.115  |
|             | 0.275  |        |        |        |
|             | 0.264  |        |        |        |
| GASATF      | 0.349  | 0.287  | 0.287  | 0.287  |
|             | 0.358  |        |        |        |
|             | 0.357  |        |        |        |

| Controllers | Peak overshoot (\( \Delta F_3 \)), p.u. | Peak undershoot (\( \Delta F_3 \)), p.u. | Settling time (\( \Delta F_3 \)), s |
|-------------|----------------------------------------|----------------------------------------|----------------------------------|
| IC          | 0.0554                                 | −0.1113                                | More than 12                     |
| FLC         | 0.1431                                 | −0.1328                                | 4.46                             |
| GASATF      | 0.0103                                 | −0.1015                                | 1.56                             |
Figure 10. Dynamic response of $\Delta F_1$ for power system model.

![Graph of $\Delta F_1$ for power system model.]

Figure 11. Dynamic response of $\Delta F_2$ for power system model.

![Graph of $\Delta F_2$ for power system model.]

Figure 12. Dynamic response of $\Delta F_3$ for power system model.

![Graph of $\Delta F_3$ for power system model.]
Figure 13. Dynamic response of $\Delta P_{tie12}$ for power system model.

Figure 14. Dynamic response of $\Delta P_{tie23}$ for power system model.

Figure 15. Dynamic response of $\Delta P_{tie31}$ for power system model.
Figure 16. Dynamic response of $\Delta X_g$ with GDBs.

Figure 17. Dynamic response of $\Delta F_3$ with and without GDBs.

Figure 18. Dynamic response of $\Delta P_{tie31}$ with and without GDBs.
Figure 19. Dynamic response of $ACE_3$ with and without GDBs.

Figure 20. Dynamic response of $U_3$ with and without GDBs.

achieved with AGC controller based on GASATF control action settles quickly as compared to that obtained with other controllers. The responses are not only settling quickly but also the settling trend is very smooth, and associated with a few number of oscillatory modes.

6. Conclusion
In a nutshell, the present work includes a new method for calculating optimal feedback gains of AGC controller is presented using hybrid GASA-tuned fuzzy logic design technique. From the exhibited results, the dynamic performance of proposed hybrid AGC controller is found to be superior over classical and fuzzy AGC controllers. It is also observed that the GDB non-linearity produced oscillation in dynamic responses of power systems model under investigation until AGC become effective after 1–4 s. The GASATF controller gives ameliorated performance in the multi-area interconnected power systems including different sort of turbines.

The most important feature of the design of optimal AGC controller is that the proposed algorithm considers transient response characteristics as hard constraints which are strictly satisfied in the solutions. This is in contrast to the classical technique-based regulator designs where these constraints are treated as soft constraints. The proposed technique has been tested on a power system model under a disturbance condition and found good enough to give desired results. This proves to be a good alternative for optimal controller design where direct treatment of response specifications is required.
**Nomenclature**

\[ \Delta F_i \]  
incremental change in frequency  
\( (i = 1, 2, 3) \)  
subscript referring to area

\[ \Delta X_{g1}, \Delta X_{g2}, \Delta X_{g3} \]  
incremental change in governor valve position  
\[ K_g \]  
speed governor gain constants

\[ T_{gt1}, T_{gt2} \]  
thermal speed governor time constant (s)  
\[ T_g \]  
governor dead band time constant (s)

\[ K_{r1}, K_{r2} \]  
reheat thermal turbine gain constant  
\[ K_{t1}, K_{t2} \]  
non-reheat thermal turbine gain constant

\[ T_{t1}, T_{t2} \]  
turbine time constants (s)  
\[ K_{t1}, T_{t1} \]  
reheat coefficients and reheat times (s)

\[ T_1 \]  
speed governor time constant of hydro area (s)  
\[ T_{t1}, T_{t3} \]  
time constants associated with hydro governor (s)

\[ T_w \]  
hydro turbine time constant (s)  
\[ K_p \]  
electric system gain constants

\[ T_p \]  
electric system time constants (s)  
\[ B_i \]  
frequency bias constant (p.u.MW/Hz)

\[ R_i \]  
speed regulation parameter (Hz/p.u.MW)

\[ \Delta P_{r1} \]  
change in re heater output  
\[ \Delta P_{d1} \]  
incremental change in load demand (p.u.MW/Hz)

\[ \Delta P_{ci} \text{ or } U_i \]  
variation in controller output  
\[ \Delta P_{gi} \]  
incremental change in power generation (MW)

\[ \Delta P_{tie} \]  
change in AC tie-line power (MW)

\[ T_{ij} \]  
synchronizing coefficient of AC tie-line  
\[ \Delta F_i \]  
incremental change in frequency  
\( (i = 1, 2, 3) \)  
subscript referring to area

\[ \Delta X_{g1}, \Delta X_{g2}, \Delta X_{g3} \]  
incremental change in governor valve position  
\[ K_g \]  
speed governor gain constants

\[ T_{gt1}, T_{gt2} \]  
thermal speed governor time constant (s)
Appendix A

Reheat, non-reheat thermal and hydro plants

\[ f = 50 \text{ Hz}, K_{g1} = K_{g2} = K_{g3} = 1.0, K_{t1} = K_{t2} = 1.0, K_{p1} = K_{p2} = 120, T_{g1} = T_{g2} = 0.08 \text{ s}, T_{r1} = 10 \text{ s}, T_{t1} = T_{t2} = 0.3 \text{ s}, T_{s1} = T_{s2} = 20 \text{ s}, T_{r2} = 0.6 \text{ s}, T_{s2} = 5 \text{ s}, T_{r3} = 32 \text{ s}, T_{w} = 1.0 \text{ s}, K_{p3} = 20, T_{p3} = 3.76 \text{ s}, T_{g1} = T_{g2} = T_{g3} = 0.2 \text{ s}, R_{1} = R_{2} = R_{3} = 2.4 \text{ Hz/p.u.MW}, B_{1} = B_{2} = B_{3} = 0.425 \text{ p.u.MW/Hz}, P_{\text{tie-max}} = 2000 \text{ MW}, 2\pi T_{\gamma} = 0.545 \text{ p.u.MW}, \delta_{i} - \delta_{j} = 30^\circ, \delta_{i} \neq \text{area}(i = 1, 2, 3) \text{ and } (i \neq j), \Delta P_{d_{i}} = 0.01 \text{ p.u.MW}. \]
