RESEARCH ARTICLE

Generation-based automatic generation control with multisources power system using bacterial foraging algorithm

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Abstract

This article presents an application of bacterial foraging algorithm (BFA) for design and implementation of generation-based PID structured automatic generation control (AGC) in a 2-area multisources power system with hydro, thermal, and gas power plants incorporated in each area. Most of AGC studies carried out so far have considered the initial system loading to be equal to 50% of the area generation capacity. But, AGC controller parameters are uncertain due to stochastic nature of power demand of the end users. Hence, in this article, the design of AGC controller is proposed on the basis of generation schedule by incorporating changes in power system gain constant, power system time constant, frequency bias constant, and so on. The dynamic responses of power system with BFA tuned AGC controller are compared with the genetic algorithm tuned AGC controller. The parameters of the controllers are evaluated by using these techniques and investigations are carried out to find the best performance of the system. Therefore, it is desirable to find the parameters of the generation-based controller depending upon the contribution of its constituent hydro, thermal, and gas energy sources in the total power generation.

KEYWORDS
automatic generation control, multisources power system, generation-based controller, bacterial foraging algorithm

1 | INTRODUCTION

The operating frequency is very important performance indicator for stability and security considerations in the power system. The frequency of the system should lie within a very small and acceptable interval around its nominal value during nominal operation of the power system. Automatic generation control (AGC) controllers are usually implemented to regulate system frequency based on the control center action to achieve real power balance between generation and load. In this way, AGC is a most essential application of control system engineering in power system.

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The main objectives of AGC in power system are: (i) matching of area generation to the area load including scheduled tie-line interchange and (ii) to control the system frequency of the interconnecting control areas. The first objective of the AGC is achieved by means of a secondary control action usually with the implementation of tie-line bias concept. A small deviation in the system load originates proportional variation in the nominal system frequency. The area control error (ACE) in corresponding control center gives approximate information about load deviation and supervises the AGC controller to adjust the input valves of corresponding power units to minimize ACE.

To accomplish the above objectives of AGC, many studies have been conducted to demonstrate the performance of AGC controller. An application of optimal control theory to design state feedback AGC controller along with its performance analysis was first time performed by Elgerd and Fosha for an interconnected 2-area thermal-thermal power system. After that AGC was the subject of research and wide range of publications with state-of-the-art of literature review has been appeared in many References 3, 4. Most widely used controller in the power system is the conventional PI structured controller among different types of AGC controllers. The state vector feedback AGC controller design by using optimal control theory to attain better system performance was carried out in References 2–9. Besides the state feedback controllers, output feedback, decentralized controllers were reported out in References 10–14, suboptimal control (in case measurement from all the states are not available) were also reported in References 15, 16, which are more practical types of AGC controllers.

Many advanced forms of AGC schemes have been witnessed by using intelligent concepts, such as neural networks, fuzzy logic, particle swarm optimization, genetic algorithm (GA), gravitational search algorithm, BAT algorithms, Jaya algorithm, whale algorithm, fruit fly algorithm, and so on, which are very effective and efficient in AGC controller design rather than using conventional AGC design techniques. Recently, few works have addressed some deficiencies in GA performance due to premature convergence of this algorithm, which downgrades its search capability.

A more powerful evolutionary computational algorithm based on behavior of Escherichia coli (E. coli) bacteria, which are present in human intestines called bacterial foraging algorithm (BFA) is available and it has been applied to obtain the design of AGC controllers in References 44–48. This technique is able to remove the downgrade effect of premature convergence in other algorithms like GA and other intelligent algorithms. Therefore, in this work, BFA technique is proposed for designing of generation-based AGC controller in 2-area multisources power system model under consideration.

In References 22, 44–46, the gains of AGC controller have been optimized using BFA optimization technique in power system for constant loading conditions. In addition, the gains of PI structured AGC controller for 30% and 70% loading in an interconnected 3-area power system have been optimized in Reference 44. However, the gains of PID structured AGC regulators have been optimized by applying BFA techniques to demonstrate the effect of types of generation participating in an AGC scheme in Reference 48. These studies so far have not considered the scheduling effect due to different loading conditions and also type of generation allocated among the generations by economic dispatch centre (EDC) for balancing the scheduled load.

In the majority of research works, AGC study is carried out by considering single energy source based power plants in each corresponding control areas. Instead of having single source of power generation in a control area a more practical type of control area structure with multisources of power generation have been taken into consideration in References 5–7, 30–33, 35, 39–42, 48.

Almost all the AGC studies have been identified so far by considering initial system loading is equal to initial power generation at the value of 50% of the area generation capacity by assuming decoupling between AGC and EDC on time scale. But the parameters of power system are uncertain due to stochastic nature of power demand of the end users. However, structural changes have been witnessed in power system for incorporating variations of types of generation, amount of generation, and scheduled load demand. Due to these structural changes, power system gain constant, power system time constant, frequency bias constant are also needed to be redesigned for different loading conditions.

The power system structural changes due to variations of types of generation, MW of generation and scheduled load demand, however, were not incorporated in References 1–40, 44–48. Therefore, this article presents a novel AGC study of design and performance investigation of generation-based PID structured AGC controller in 2-area multisources power system with power generation of using hydro, thermal, and gas based energy sources. The gains of generation-based proposed controller are tuned using BFA optimization technique and results are compared with GA tuned AGC regulator. Moreover, system dynamic performances with generation-based controller are also investigated for disturbance of 1% increase in step load in the respective control areas.
2 | TRANSFER FUNCTION MODEL OF POWER SYSTEM UNDER EXAMINATION

A generalized model of 2-area power system under examination with multisources of generation connected by AC tie-line is shown in Figure 1. Each control area consists of hydro, thermal, and gas power plants. The power system control areas are interconnected via AC tie-line. The subscripts “i” and “j” refer to area 1 and 2, respectively.

The load frequency damping characteristic \( D_i \), power system gains constant \( K_{PSi} \), power system time constant \( T_{PSi} \), and area frequency response characteristic \( \beta_i \) also taken as frequency bias constant for ith area connected to jth control area can be given by Reference 2.

\[
D_i = \frac{\partial P_L}{\partial F_i} \frac{1}{P_{ri}}, \tag{1}
\]

\[
K_{PSi} = \frac{1}{D_i}, \tag{2}
\]

\[
T_{PSi} = \frac{2H_i}{F_iD_i}, \tag{3}
\]

\[
\beta_i = D_i + \frac{1}{R_i}, \tag{4}
\]

where; \( P_L \) is operating load, \( P_r \) is power rating of a control area, and \( F \) is the nominal frequency of the power system.\(^2\) The above parameters of the power system depend upon distribution of generation from EDC in the context of \( P_L \). However, the values of these parameters are not affected by small load perturbations under the scope of AGC. The transfer function model of power system under investigation is shown in Figure 2 with the help of Reference 48.

Mathematically, the share of contribution of hydro, thermal, and gas power plants in areas-1 and 2 are given by;

\[
K_{t1} + K_{h1} + K_{g1} = 1, \tag{5}
\]

\[
K_{t2} + K_{h2} + K_{g2} = 1. \tag{6}
\]

For small step load perturbation \( \Delta P_{di} \) in the ith control area; the deviation in power generation \( \Delta P_{Gi} \) and \( \Delta P_{Gj} \) are given by;

\[
\Delta P_{Gi} = \Delta P_i + \Delta P_{tie_{ij}} + \Delta P_{di}, \tag{7}
\]

\[
\Delta P_{Gj} = \Delta P_j + \alpha_{ij} \Delta P_{tie_{ij}}, \tag{8}
\]

**Figure 1** Generalized model of 2-area power system with multi-generation sources
Similarly, for small load perturbation ($\Delta P_{dj}$) in the $j$th control area; the deviations in power generation ($\Delta P_{Gj}$ and $\Delta P_{Gi}$) are given by:

\[
\Delta P_{Gj} = \Delta P_i + \alpha_{ij} \Delta \text{Ptie}_{ij} + \Delta P_{dj},
\]

(9)

\[
\Delta P_{Gi} = \Delta P_i + \Delta \text{Ptie}_{ij}.
\]

(10)

The parameters of power system for control areas are identified in Tables 1 to 3 for investigating the effect of distribution of load by EDC between the multisource power plants. To examine the system dynamic performance with implementation of proposed control scheme, different types of power plants-based generation are selected one by one for above scheduled load distribution by EDC for 1% step load perturbation in one of the connected control areas. The types of power plants are selected by EDC for supplying the increased scheduled load of 900 to 1000, 1000 to 1100, and 1100 to 1200 MW as given in Tables 1 to 3 while other generations are kept constant, respectively, with the following case studies.

1. Hydropower plants only as given in Table 1.
2. Thermal power plants only as given in Table 2.
3. Gas power plants only as given in Table 3.

**TABLE 1  Parameters of power system for case study 1**

| Initial loading (MW) | Initial loading in % of $P_{ct}$ | Generation (MW) | Share of power generation | $K_i$ | $K_{hi}$ | $K_{gi}$ | $K_{psi}$ | $T_{psi}$ (seconds) | $\beta_i$ (pu MW/Hz) | Hydro generation in % of $P_{ct}$ |
|----------------------|----------------------------------|-----------------|---------------------------|-------|---------|---------|----------|-----------------|----------------|------------------------|
| 900                  | 45%                              | 300             | 300                       | 300   | 1/3     | 1/3     | 1/3      | 133.33          | 22.22           | 0.4242                 | 15%                    |
| 1000                 | 50%                              | 300             | 400                       | 300   | 3/10    | 2/5     | 3/10     | 120             | 20              | 0.4250                 | 20%                    |
| 1100                 | 55%                              | 300             | 500                       | 300   | 3/11    | 5/11    | 3/11     | 109.09          | 18.18           | 0.4258                 | 25%                    |
| 1200                 | 60%                              | 300             | 600                       | 300   | 1/4     | 1/2     | 1/4      | 100             | 16.67           | 0.4267                 | 30%                    |
TABLE 2 Parameters of power system for case study 2

| Initial loading (MW) | Initial loading in % of $P_{ni}$ | Generation (MW) | Share of power generation | $T_{PSi}$ (seconds) | $\beta_i$ (pu MW/Hz) | Thermal generation in % of $P_{ni}$ |
|----------------------|----------------------------------|-----------------|---------------------------|---------------------|----------------------|-------------------------------------|
| 900                  | 45%                              | 300 300 300     | 1/3 1/3 1/3              | 133.33              | 22.22                | 0.4242 15%                         |
| 1000                 | 50%                              | 400 300 300     | 2/5 3/10 3/10           | 120 20               | 0.4250               | 20%                                 |
| 1100                 | 55%                              | 500 300 300     | 5/11 3/11 3/11          | 109.09 18.18         | 0.4258               | 25%                                 |
| 1200                 | 60%                              | 600 300 300     | 1/2 1/4 1/4             | 100 16.67            | 0.4267               | 30%                                 |

TABLE 3 Parameters of power system for case study 3

| Initial loading (MW) | Initial loading in % of $P_{ni}$ | Generation (MW) | Share of power generation | $T_{PSi}$ (seconds) | $\beta_i$ (pu MW/Hz) | Gas generation in % of $P_{ni}$ |
|----------------------|----------------------------------|-----------------|---------------------------|---------------------|----------------------|--------------------------------|
| 900                  | 45%                              | 300 300 300     | 1/3 1/3 1/3              | 133.33              | 22.22                | 0.4242 15%                         |
| 1000                 | 50%                              | 300 400 400     | 3/10 3/10 2/5           | 120 20               | 0.4250               | 20%                                 |
| 1100                 | 55%                              | 500 300 500     | 3/11 3/11 5/11          | 109.09 18.18         | 0.4258               | 25%                                 |
| 1200                 | 60%                              | 600 300 600     | 1/4 1/4 1/4             | 100 16.67            | 0.4267               | 30%                                 |

3 | AGC IN THE FORM OF AN OPTIMIZATION PROBLEM

The objective function in the form of cost function is described for designing of intelligent technique-based controller along with required specifications and constraints. The cost function is formulated by using certain system performance index. It is reported that integral squared error (ISE) performance index is a better objective function in AGC studies since this is able to encounter negative and positive both types of errors. Hence, in this work, ISE performance index is used to formulate cost function for converting AGC problem in the form of optimization problem. The expression for the ISE objective function is depicted in (11);

$$J = \int_0^T ACE^2 dt. \quad (11)$$

In the above equations, $T$ is the simulation time and optimization constraints are the upper and lower bounds of the PID controller. Consequently, with the above objective function, the AGC controller design problem in interconnected power system is formulated in the form of the following equation;

Minimize $J$.

Subjected to the constraints:

$$\begin{align*}
K_{pi}^{\text{min}} & \leq K_{pi} \leq K_{pi}^{\text{max}} \\
K_{ii}^{\text{min}} & \leq K_{ii} \leq K_{ii}^{\text{max}} \\
K_{di}^{\text{min}} & \leq K_{di} \leq K_{di}^{\text{max}}
\end{align*} \quad (12)$$

where, $K_{pi}$, $K_{ii}$, and $K_{di}$ are the proportional, integral, and derivative gains of $i$th controller, respectively, with associated control area. The control signal ($\Delta P_{Ci}$) for $i$th control area connected $j$th control area is given as:

$$\Delta P_{Ci} = \left( K_{pi} + \frac{K_{ii}}{s} + sK_{di} \right) ACE_i. \quad (13)$$

where; $ACE_i$ is given by;

$$ACE_i = \beta_i \Delta F_i + \Delta P_{tiei}. \quad (14)$$
GA is most famous and widely used intelligent algorithms for solving complex as well as nonlinear optimization problems such as design of AGC/LFC controller in power system. The application of GA for solving the system problem with highly epistatic objective function have been found of showing premature convergence which in turn reduces its performance and search capability. This deficiency of GA has been removed to a great extent by BFA, which is an evolutionary artificial intelligent optimization technique. This technique was developed by Passino,\textsuperscript{43} which is based on modeling behavior of \textit{E. coli} bacteria. It has been proven to be effective and efficient for solving the system problem with highly epistatic objective function problems. Moreover, BFA optimization algorithm is able to obtain favorable regions because of its unique dispersal and elimination technique when small population of the bacteria is involved.

The above unique features of this algorithm remove the premature convergence deficiency as well as enhance the search capability to solve many complex problems. The other advantages of BFA are:

1. The BFA technique is especially unaffected by the size and presence of nonlinearity in the power system.
2. The BFA technique has converged to the optimal solution of an optimization problem where other analytical methods have not able to converge.
3. BFA also has merits such as very less computational processing burden, global convergence, small computational time requirement, and successfully handle a larger number of objective functions in comparison to the other intelligent algorithms.

Hence, it is highly suitable optimization tool to design an efficient AGC controller for interconnected power system.

In BFA, the foraging activities of \textit{E. coli} bacteria residing in human intestine are mimicked. The control mechanism of \textit{E. coli} bacteria can be subdivided into four segments, namely; (a) Chemotaxis, (b) Swarming, (c) reproduction, and (d) elimination and dispersal. These activities among the bacteria are exercised for searching the total solution space. Therefore, the prospect of evading local minimum and attaining sooner convergence is elevated than GA. The detailed description of BFA artificial intelligent technique is given in References \textsuperscript{24}, \textsuperscript{46–48}. In this research work, the flow chart for tuning of PID structured AGC regulator using BFA optimization technique is shown in Figure 3. This flow chart is used for designing of gains of AGC controller in the following section, which deals with the simulation of results.

![BFA flow chart for tuning of PID structured AGC controller](image)
5 | SIMULATION RESULTS

Simulation studies are carried out by using the power system data and PID controller parameters as given in Appendix A and B for the system shown in Figure 2. The generation-dependent parameters are shown in Tables 1 to 3.

The optimal parameters of PID structure based AGC controller are evaluated by using GA and BFA technique for 1200 MW load of case study 2 and these values are given in Table 4. The dynamic performances of the power system with above designed AGC controller for a disturbance of 1% step load increase in area-1 are shown in Figure 4. The optimal gains of PID structured AGC controllers are obtained with BFA technique for disturbance of 1% step load increase in area-1 and area-2 and these design values are given in Tables 5 and 6, respectively.

The dynamic responses of power system with BFA tuned generation-based AGC controllers for disturbance of 1% step increase in load in control area-1 are shown in Figures 5 to 7 for various case studies under consideration.

6 | DISCUSSION OF RESULTS

The dynamic performances of the system for optimum values of AGC controller using BFA technique and GA technique have been compared in Figure 4. It has been observed that the transient performance of power system under similar operating conditions with optimum tuning by BFA technique is better than optimum tuned by GA technique. Therefore, BFA technique is used to design AGC controllers for various case studies as identified in Tables 1 to 3. The investigation of results shown in Tables 5 and 6, it has been revealed that the gains of BFA tuned PID structured AGC controller depends on scheduled load as well as type of generation selected by EDC. This infers that optimal gains of AGC controllers are sensitive to the scheduled load distributed by EDC among various sources of power generation under consideration.

The dynamic responses of $\Delta F_1$, $\Delta F_2$, $\Delta P_{tie12}$, $\Delta P_{G1}$, and $\Delta P_{G2}$ for case study 1 to 3 with generation-based BFA tuned AGC regulators have been shown in Figures 5 to 7 for disturbance of 1% step increase in load, respectively. The examination of these graphs concludes that the generation-based BFA tuned AGC regulators are capable to meet AGC requirement in an effective manner.

The dynamic responses of the system for case study 1 have been shown in Figure 5 for disturbance of 1% step increase in load in area-1 when scheduled generation is varied from 900 to 1200 MW as per scheduled loadings of 45%, 50%, 55%, and 60% with respect to rated area capacity as identified in Table 1. The schedules of hydro generation are 15%, 20%, 25%, and 30% with respect to rated area capacity to balance the above scheduled loadings. In this case study, increased load is contributed by hydropower plant only by keeping other generation at their previous generation setting. It has been observed that the dynamic performance of the system reduces with increase in contribution of generation from hydropower plant for balancing the scheduled load. However, this reduction in the system performance has been observed due to nonminimum phase characteristics of the hydro turbine.

The dynamic performance of the system improves appreciably, as shown in Figure 6, in terms of gradual reduction in the first peak with subsequent oscillations and settling time of the power system when thermal power plant is selected by EDC to supply additional power required by the increased scheduled load as identified in Table 2 for case study 2. Similar conclusion has been drawn for case study 3 by observing Figure 7, where only gas power plant is used to supply the power for balancing the scheduled load under similar conditions as given in Table 3.

The deviations in area generation; $\Delta P_{G1}$ and $\Delta P_{G2}$ have been shown in Figures 5(D)-(E), 6(D)-(E) and 7(D)-(E) for cases 1 to 3, respectively. It has been observed that each area is able to meet the demand change by increasing its own generation with no additional transfer of power on tie-line under steady state condition. The steady state condition has

| Techniques and load | Gains of AGC regulators in area-1 | Gains of AGC regulators in area-2 |
|---------------------|----------------------------------|----------------------------------|
|                     | $K_{P1}$ | $K_{I1}$ | $K_{D1}$ | $K_{P2}$ | $K_{I2}$ | $K_{D2}$ |
| GA 1200 MW          | -4.2993  | -4.6376  | -4.1970  | -0.0260  | -1.0959  | -0.6929  |
| BFA 1200 MW         | -4.6663  | -4.2453  | -4.9213  | -1.7462  | -1.4004  | -0.7187  |

Abbreviations: AGC, automatic generation control; BFA, bacterial foraging algorithm; GA, genetic algorithm.
FIGURE 4  Comparison of dynamic performance of power system model (case study 2 and 1200 MW load) for 1% step load disturbance in area-1; (A) $\Delta F_1$ vs Time, (B) $\Delta F_2$ vs Time, and (C) $\Delta P_{tie_{12}}$ vs Time
TABLE 5 Optimal gains of generation-based AGC controllers for step load disturbance in area-1

| Type of generation (MW) | $K_{P1}$ | $K_{I1}$ | $K_{D1}$ | $K_{P2}$ | $K_{I2}$ | $K_{D2}$ |
|-------------------------|----------|----------|----------|----------|----------|----------|
| Hydro                   |          |          |          |          |          |          |
| 300                     | -4.4922  | -4.8365  | -4.2634  | -2.1628  | -0.3379  | -0.4074  |
| 400                     | -4.6663  | -4.2453  | -4.9213  | -1.7462  | -1.4004  | -0.7187  |
| 500                     | -4.6736  | -4.5662  | -4.0477  | -2.0630  | -0.6026  | -0.5610  |
| 600                     | -4.0830  | -4.6376  | -3.8868  | -1.7749  | -0.0050  | -1.0711  |
| Thermal                 |          |          |          |          |          |          |
| 300                     | -4.4922  | -4.8365  | -4.2634  | -2.1628  | -0.3379  | -0.4074  |
| 400                     | -4.8211  | -4.4932  | -4.2354  | -1.7377  | -0.7877  | -0.6970  |
| 500                     | -4.6782  | -4.1932  | -4.1179  | -1.4418  | -0.7205  | -0.6890  |
| 600                     | -4.6663  | -4.2453  | -4.9213  | -1.7462  | -1.4004  | -0.7187  |
| Gas                     |          |          |          |          |          |          |
| 300                     | -4.4922  | -4.8365  | -4.2634  | -2.1628  | -0.3379  | -0.4074  |
| 400                     | -4.3823  | -4.9496  | -4.2329  | -2.3297  | -0.3446  | -0.6002  |
| 500                     | -4.6882  | -4.8401  | -3.8818  | -1.0489  | -0.3919  | -1.0511  |
| 600                     | -4.6736  | -4.5662  | -4.0477  | -2.0630  | -0.6026  | -0.5610  |

Abbreviations: AGC, automatic generation control.

TABLE 6 Optimal gains of generation-based AGC controllers for step load disturbance in area-2

| Type of generation (MW) | $K_{P1}$ | $K_{I1}$ | $K_{D1}$ | $K_{P2}$ | $K_{I2}$ | $K_{D2}$ |
|-------------------------|----------|----------|----------|----------|----------|----------|
| Hydro                   |          |          |          |          |          |          |
| 300                     | -2.1628  | -0.3379  | -0.4074  | -4.4922  | -4.8365  | -4.2634  |
| 400                     | -1.7462  | -1.4004  | -0.7187  | -4.6663  | -4.2453  | -4.9213  |
| 500                     | -2.0630  | -0.6026  | -0.5610  | -4.6736  | -4.5662  | -4.0477  |
| 600                     | -1.7749  | -0.0050  | -1.0711  | -4.0830  | -4.6376  | -3.8868  |
| Thermal                 |          |          |          |          |          |          |
| 300                     | -2.1628  | -0.3379  | -0.4074  | -4.4922  | -4.8365  | -4.2634  |
| 400                     | -1.7377  | -0.7877  | -0.6970  | -4.8211  | -4.4932  | -4.2354  |
| 500                     | -1.4418  | -0.7205  | -0.6890  | -4.6782  | -4.1932  | -4.1179  |
| 600                     | -1.7462  | -1.4004  | -0.7187  | -4.6663  | -4.2453  | -4.9213  |
| Gas                     |          |          |          |          |          |          |
| 300                     | -2.1628  | -0.3379  | -0.4074  | -4.4922  | -4.8365  | -4.2634  |
| 400                     | -2.3297  | -0.3446  | -0.6002  | -4.3823  | -4.9496  | -4.2329  |
| 500                     | -1.0489  | -0.3919  | -1.0511  | -4.6882  | -4.8401  | -3.8818  |
| 600                     | -2.0630  | -0.6026  | -0.5610  | -4.6736  | -4.5662  | -4.0477  |

Abbreviations: AGC, automatic generation control.

been achieved faster in case of increase in power from thermal plants. In this way, the generation-based AGC controllers are able to meet whole load demand based on the participation factors of hydro, thermal, and gas power plants in 2-area interconnected power system.
**FIGURE 5** Dynamic performance of power system model for variation in hydro generation for 1% step load disturbance in area-1: A, $\Delta F_1$ vs Time, B, $\Delta F_2$ vs Time, C, $\Delta P_{tie12}$ vs Time, D, $\Delta P_{G1}$ vs Time, and E, $\Delta P_{G2}$ vs Time.
FIGURE 5  Continued

FIGURE 6  Dynamic performance of power system model for variation in thermal generation for 1% step load disturbance in area-1; A, $\Delta F_1$ vs Time, B, $\Delta F_2$ vs Time, C, $\Delta P_{tie12}$ vs Time, D, $\Delta P_{G1}$ vs Time, and E, $\Delta P_{G2}$ vs Time
FIGURE 6  Continued
FIGURE 7 Dynamic performance of power system model for variation in gas generation for 1% step load disturbance in area-1: A, $\Delta F_1$ vs Time, B, $\Delta F_2$ vs Time, C, $\Delta P_{tie_{12}}$ vs Time, D, $\Delta P_{G1}$ vs Time, and E $\Delta P_{G2}$ vs Time
7 | CONCLUSIONS

This article presents an application of BFA for optimum designing of generation-based PID structured AGC controller in a 2-area multisources power system having hydro, thermal, and gas power generations in each interconnected control areas with following conclusions:

1. It has been shown that dynamic responses of power system with BFA tuned AGC controller are better than GA tuned controller.
2. The optimal gains of generation-based AGC controllers have been found to be sensitive to the scheduled load distributed by EDC among various sources of power generation.
3. The significant improvement in dynamic performance of power system has been observed in case when thermal or gas power plants contribute more to the scheduled power generation.
4. A degraded system performance has been exhibited in case when hydropower plant is used to contribute more to the scheduled power generation.
5. Further, it may be stated that an increase in thermal or gas generation results in improved dynamic performance of the power system while it degrades when similar variation is accomplished in hydro generation.
6. In general, it can be concluded that BFA tuned generation-based AGC regulators gratify AGC obligations effectively under varied operating conditions.

In addition to above, the design and implementation of generation-based AGC controller in the presence of nonlinearities such as; governor dead band, boiler dynamic, generation rate constraints, and communication delay in the multisources power system model by using recent intelligent techniques would be the future work of this study.
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CONFLICT OF INTEREST

Authors have no conflict of interest relevant to this article.

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REFERENCES

1. Elgerd OI, Fosha CE. Optimum megawatt-frequency control of multi-area electric energy systems. IEEE Trans Power Appar Syst. 1970;PAS-89(4):556-563.
2. Fosha CE, Elgerd OI. The megawatt frequency control problem: a new approach via optimal control theory. IEEE Trans Power Appar Syst. 1970;PAS-89(4):563-577.
3. Ibraheem, Kumar P, Kothari DP. Recent philosophies of automatic generation control strategies in power systems. IEEE Trans Power Syst. 2005;20(1):346-357.
4. Shankar R, Pradhan SR, Chatterjee K, Mandal RA. A comprehensive state of the art literature survey on LFC mechanism for power system. Renew Sustain Energy Rev. 2017;76:1185-1207.
5. Arya Y, Kumar N and Ibraheem, "AGC of a two-area multi-source power system interconnected via AC/DC parallel links under restructured power environment", Optim Control Appl Methods. vol. 37, no. 4, pp. 590–607, 2016.
6. Nasiruddin I, Hakimuddin N, Bhatti TS. AGC of two area power system interconnected by AC/DC links with diverse sources in each area. Int. J Electr Power Energy Syst. 2014;55:297-304.
7. Arya Y, Kumar N. Optimal control strategy-based AGC of electrical power systems: a comparative performance analysis. Optim Control Appl Methods. 2017;38(6):982-992.
8. Garg JK, Khosla A, Hakimuddin N. Automatic generation control (AGC) of a multi sources power system (PS) with natural choice of power plants. EMITTER Int J Eng Technol. 2019;7(1):105-128.
9. Ibraheem N, Bhatti TS. AGC of two area interconnected power system with diverse sources in each area. Int J Electr Eng. 2013;13(4):202-209.
10. Venkateswarlu K, Mahalanbis AK. Load frequency control using output feedback. J Inst Eng (India). 1978;58(EL-4):200-203.
11. Kawabata H, Kido M. A decentralized scheme of load frequency control of power system. Electr Eng Jpn. 1982;102(4):100-106.
12. Hakimuddin N, Khosla A, Garg JK. Centralized and decentralized AGC schemes in 2–area interconnected power system considering multi source power plants in each area. J King Saud Univ Eng Sci. 2020;32(2):123-132.
13. Aldeen M, Marsh JF. Observability, controllability and decentralized control of interconnected power systems. Int J Comput Electr Eng. 1990;16(4):207-220.
14. Yang TC, Ding ZT, Yu H. Decentralised power system load frequency control beyond the limit of diagonal dominance. Int. J Electr Power Energy Syst. 2002;24(3):173-184.
15. Ibraheem, Kumar P, Hasan N, Nizamuddin. Sub-optimal AGC of interconnected power system using output vector feedback control strategy. Electr Power Compon Syst. 2012;40(9):977-994.
16. Hasan N, Ibraheem, Kumar P, Nizamuddin. Sub-optimal automatic generation control of interconnected power system using constrained feedback control strategy. Int. J Electr Power Energy Syst. 2012;43(1):295-303.
17. Wu QH, Hogg BW, Irwin GW. A neural network regulator for turbogenerators. IEEE Trans Neural Netw. 1992;3(1):95-100.
18. Beaufays F, Abdel-Magid Y, Widrow B. Application of neural networks to load-frequency control in power systems. J Neural Netw. 1994;7(1):183-194.
19. Demiroren A, Sengor NS, Zeynelgil HL. Automatic generation control by using ANN technique. Electr Power Compon Syst. 2001;29(10):883-896.
20. Arya Y, Kumar N, Sinha SK. Fuzzy logic based load frequency control of multi-area electrical power system considering non-linearities and boiler dynamics. Int Energy J. 2012;13(2):97-111.
21. Cam E. Application of fuzzy logic for load frequency control of hydro electrical power plants. Energ Conver Manage. 2007;48(4):1281-1288.
22. Arya Y and Kumar N, “Design and analysis of BFOA-optimized fuzzy PI/PID controller for AGC of multi-area traditional/restructured electrical power systems”, Soft Comput, vol. 21, no. 21, pp. 6435–6452, 2017.
23. Jadhav AM, Vadrajacharya K. Performance verification of PID controller in an interconnected power system using particle swarm optimization. Energy Procedia. 2012;14:2075-2080.
24. Gozde H, Taplamacigolu MC. Automatic generation control application with craziness based particle swarm optimization in a thermal power system. Int J Electr Power Energy Syst. 2011;33(1):8-16.
25. Pathak N, Verma A, Bhatti TS, Nasiruddin I. Modeling of HVDC tie links and their utilization in AGC/LFC operations of multi-area power systems. IEEE Trans Ind Electron. 2019;66(3):2185–2197.
26. Abdel-Magid YL, Dawoud MM. Optimal AGC tuning with genetic algorithms. Electr Pow Syst Res. 1996;38(3):231-238.
27. Al-Hamouz ZM, Al-Duwaish HN. A new load frequency variable structure controller using genetic algorithms. *Electr Pow Syst Res*. 2000;55(1):1-6.

28. Abdennour A. Adaptive optimal gain scheduling for the load frequency control problem. *Electr Power Compon Syst*. 2002;30(1):45-56.

29. Rerkpseedapong D, Hasanovic A, Feliachi A. Robust load frequency control using genetic algorithms and linear matrix inequalities. *IEEE Trans Power Syst*. 2003;18(2):855-861.

30. Ramakrishna KSS, Bhatti TS. Sampled-data automatic load frequency control of a single area power system with multi-source power generation. *Electr Power Compon Syst*. 2007;35(8):955-980.

31. Ramakrishna KSS, Bhatti TS. Discrete data load frequency control of two-area power system with multi-source power. *Int. Energy J*. 2008;9(2):145-154.

32. Ramakrishna KSS, Sharma P, Bhatti TS. Automatic generation control of interconnected power system with diverse sources of power generation. *Int J Eng Sci Technol*. 2010;2(5):51-65.

33. Ramakrishna KSS, Bhatti TS. Automatic generation control of single area power system with multi-source power generation. *Proc Inst Mech Eng Part A*. 2008;222:1-11.

34. Gözde H, Taplamacıoğlu MC, Kocaarslan İ. Comparative performance analysis of artificial bee colony algorithm in automatic generation control for interconnected reheat thermal power system. *Int. J Electr Power Energy Syst*. 2012;42(1):167-178.

35. Safi SJ, Tezcan SS, Eke I, Farhad Z. Gravitational search algorithm (GSA) based pid controller design for two area multi-source power system load frequency control (LFC). *Gazı Univ J Sci*. 2018;31(1):139-153.

36. Sahu RK, Panda S, Padhan S. Optimal gravitational search algorithm for automatic generation control of interconnected power systems. *Ain Shams Eng J*. 2014;5(3):721-733.

37. Abd-Elazim SM, Ali ES. Parameter optimization of automatic generation controller for interconnected power systems using BAT algorithm. Paper presented at: Proceedings of the National Conference on Emerging Trends in Electrical and Electronics Engineering, Jamia Millia Islamia, New Delhi, India; 2015.

38. Pradhan B, Bhende CN. Online load frequency control in wind integrated power systems using modified JAYA optimization. *Eng Appl Artif Intell*. 2019;77:212-228.

39. Gupta N, Kumar N, Chitti Babu B. JAYA optimized generation control strategy for interconnected diverse source power system with varying participation. *Energy Sources, Part A*. 2019;1-17. https://doi.org/10.1080/15567036.2019.1646354.

40. Guha D, Roy PK, Banerjee S. Whale optimization algorithm applied to load frequency control of a mixed power system considering nonlinearities and PLL dynamics. *Energy Syst*. 2019;1-30. https://doi.org/10.1007/s12667-019-00326-2.

41. Shankar R, Kumar A, Raj U, Chatterjee K. Fruit fly algorithm-based automatic generation control of multiarea interconnected power system with FACTS and AC/DC links in deregulated power environment. *Int Trans Electr Energy Syst*. 2019;26(1):12-20.

42. Passino KM. Biomimicry of bacterial foraging for distributed optimization and control. *IEEE Control Syst Mag*. 2002;22(3):52-67.

43. Paramasivam B, Chidambaram IA. Bacterial foraging optimization based load frequency control of interconnected power systems with static synchronous series compensator. *Int J Latest Trends Comput*. 2010;1(2):7-13.

44. Paramasivam B, Chidambaram IA. Design of a load-frequency controller using bacterial foraging optimization algorithm for an interconnected power system with facts. *Int J Res Rev Electr Comput Eng*. 2011;1(2):45-54.

45. Ali ES, Abd-Elazim SM. Bacteria foraging optimization algorithm based load frequency controller for interconnected power system. *Int. J Electr Power Energy Syst*. 2011;33(3):633-638.

46. Nanda J, Mishra S, Saikia LC. Maiden application of bacterial foraging-based optimization technique in multiarea automatic generation control. *IEEE Trans Power Syst*. 2009;24(2):602-609.

47. Nasiruddin I, Bhatti TS, Hakimuddin N. Automatic generation control in an interconnected power system incorporating diverse source power plants using bacteria foraging optimization technique. *Electr Power Compon Syst*. 2015;43(2):189-199.

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**APPENDIX A**

Nominal system data\(^\text{48}\):

\[
P_i = 2000 \text{ MW}, H = 5 \text{ MW-s/MVA}, T_{gl} = 0.08 \text{ second}, T_u = 0.3 \text{ second}, T_R = 10 \text{ seconds}, K_H = 0.3, T_{RHI} = 41.6 \text{ seconds}, T_{GH} = 0.513 \text{ second}, T_{RI} = 5 \text{ seconds}, T_W = 0.3 \text{ second}, X_1 = 0.6 \text{ second}, Y_1 = 1 \text{ second}, b_i = 0.05 \text{ second}, c_1 = 1, T_{FI} = 0.23 \text{ second}, T_{CFI} = 0.01 \text{ second}, T_{CDI} = 0.2 \text{ second}, K_{PSI} = 120, T_{PSI} = 20 \text{ seconds}, T_{12} = 0.0433 \text{ pu MW/rad}, \text{ and } \alpha_{12} = -1.
\]
APPENDIX B

The value of upper and lower Limits of PID Controller considered for the simulation studies are given in Table 7 as below.

TABLE 7 Lower and upper limits of gains of the PID Controllers

| Gains  | Limits of PID controller parameter | Minimum | Maximum |
|--------|-----------------------------------|---------|---------|
| $-K_{P1}$ |                                   | 0.0     | 5.0     |
| $-K_{I1}$ |                                   | 0.0     | 5.0     |
| $-K_{D1}$ |                                   | 0.0     | 5.0     |
| $-K_{P2}$ |                                   | 0.0     | 5.0     |
| $-K_{I2}$ |                                   | 0.0     | 5.0     |
| $-K_{D2}$ |                                   | 0.0     | 5.0     |