Load Frequency Control in Deregulated Environment based on Fuzzy PID and SPGSA

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ABSTRACT

The Strength Pareto Gravitational Search Algorithm (SPGSA) based on Fuzzy PID controller is proposed in this paper to solve the Load Frequency Control (LFC) problem in a deregulated environment. In multi area electric power systems, if a large load is suddenly connected (or disconnected) to the system, or if a generating unit is suddenly disconnected by the protection equipment, there will be a long-term distortion in the power balance between that delivered by the turbines and that consumed by the loads. This imbalance is initially covered from the kinetic energy of rotating rotors of turbines, generators and motors and, as a result, the frequency in the system will change. This paper applied a fuzzy controller to solve this problem. The results of the proposed controller are compared with the classical fuzzy PID type controller and classical PID controller through ITAE and FD performance indices.

Keywords: SPGSA, Load Frequency Control, Two-Area Power System, Deregulated Environment

INTRODUCTION

For large scale electric power systems with interconnected areas, Load Frequency Control (LFC) is important to keep the system frequency and the inter-area tie power as near to the scheduled values as possible. The input mechanical power to the generators is used to control the frequency of output electrical power and to maintain the power exchange between the areas as scheduled. A well designed and operated electric power system must cope with changes in the load and with system disturbances, and it should provide acceptable high level of power quality while maintaining both voltage and frequency within tolerable limits. Many control strategies for Load Frequency Control (LFC) in electric power systems have been proposed by researchers over the past decades[1]

The foremost task of LFC is to keep the frequency constant against the randomly varying active power loads, which are also referred to as unknown external disturbance[2]. Another task of the LFC is to regulate the tie-line power exchange error. A typical large-scale power system is composed of several areas of generating units. In order to enhance the fault tolerance of the entire power system, these generating units are connected via tie-lines. The usage of tie-line power imports a new error into the control problem, i.e., tie-line power exchange error. When a sudden active power load change occurs to an area, the area will obtain energy via tie-lines from other areas. But eventually, the area that is subject to the load change should balance it without external support. Otherwise there would be economic conflicts between the areas. Hence each area requires a separate load frequency controller to regulate the tie-line power exchange error so that all the areas in an interconnected power system can set their set points differently [3]

There are lots of techniques to solve the LFC problem in power system [4] The Proportional Integral (PI) controllers have been broadly used for the load frequency controllers [5] The LFC design based on an entire power system model is considered as centralized method. In [6] and [7] this centralized method is introduced with a simplified multiple-area power plant in order to implement such optimization techniques on the entire model. However, the simplification is based on the assumption that all the subsystems of the entire power system are identical while they are not. In this paper, to overcome these problems, SPGSA is proposed for the solution of tuning the fuzzy controller parameters. Its main advantage is the fact that it uses mainly real random numbers, and as a result, it seems appropriate technique to use LFC problem solution. The effectiveness of the proposed method is tested on a three-area deregulated power system. Also the result of the proposed technique is compared with classical fuzzy PID type controller and classical PID controller [9] through Integral of the Time multiplied Absolute value of the Error (ITAE) and the Figure of Demerit (FD) performance indices.

Power System Description
Power systems have variable and complicated characteristics and comprise different control parts and also many of the parts are nonlinear [1]. These parts are connected to each other by tie lines and need controllability of frequency and power flow [4]. Deregulated power system consists of GENCOs, TRANSCOs and DISCOs with an open access policy. This is obvious that all transactions have to be cleared via Independent System Operator (ISO) or other responsible infrastructure. In this latter environment, it is appropriate that a new model for LFC scheme is improved to account for the effects of possible load following contracts on the system’s dynamics [10].

In the restructured power system, Generation Companies (GENCOs) may or may not participate in the LFC task. On the other hand, distribution Companies (DISCOs) have the liberty to contract with any available GENCOs in their own or other areas. Thus, there will be various combinations of the possible contracted scenarios between DISCOs and GENCOs [1-3]. The concept of an Augmented Generation Participation Matrix (AGPM) is introduced to express these possible contracts in the generalized model. The dimension of the AGPM matrix in terms of rows and column is equal the total number of GENCOs and DISCOs in the overall power system, respectively. Consider the number of GENCOs and DISCOs in area i be ni and mi in a large scale power system with N control areas. The structure of the AGPM is given by:

\[
AGPM = \begin{bmatrix}
AGPM_{i1} & \cdots & AGPM_{iN} \\
\vdots & \ddots & \vdots \\
AGPM_{iN} & \cdots & AGPM_{NN}
\end{bmatrix}
\]  

(1)

Where, ni and mi define the number of GENCOs and DISCOs in area i and gpfij refers to the ‘generation participation factor’ and displays the participation factor of GENCO i in total load following requirement of DISCO j based on the possible contracts. The sum of all inputs in each column of AGPM is univalent. The block diagram of a generalized LFC model with AVR loop in a deregulated power system to control area i, is presented in Fig.1. These new information signals are considered as disturbance channels for the decentralized LFC design [4].

As there are many GENCOs in each area, ACE signal has to be distributed among them due to their ACE participation factor in the LFC task and \( \sum_{i=1}^{N} \eta_{ij} = 1 \). It can be written that [5]:

\[
d_i = \Delta P_{tie,ij} + \Delta P_{tie,0}, \quad \Delta P_{tie,ij} = \sum_{k=1}^{N} gpf_{ik} \Delta P_{tie,ik,
s}\]

(2)

\[\eta_{ij} = \sum_{j=1, j\neq i}^{N} \frac{T_{ij}}{\sum_{j=1, j\neq i}^{N} T_{ij}} \Delta f_j, \quad \zeta_{ij} = \sum_{k=1, k\neq i}^{N} \Delta P_{tie,ik, sch}\]

\[\Delta P_{tie,ij} = \sum_{j=1, j\neq i}^{N} \sum_{i=1}^{N} \sum_{k=1}^{N} gpf_{ik} \Delta P_{L}(z_i + y_j, z_i + y_j) \]

\[\Delta P_{tie,ij} = \Delta P_{tie,ij, error} + \zeta_{ij}\]

\[\Delta P_{tie,ij} = \sum_{j=1}^{N} gpf_{ij} \Delta P_{tie,ij} + \eta_{ij} \sum_{j=1}^{N} \Delta P_{tie,ij, k = 1, 2, ..., n_i}\]

Where, \( \Delta P_{tie,ij} \) is the desired total power generation of a GENCO k in area i and must track the demand of the DISCOs in contract with it in the steady state. Two GENCOs and DISCOs are assumed to each control an area for which the system parameters are given in [3].

To make the visualization of contracts easier, the concept of a “DISCO Participation Matrix” (DPM) will be used. Essentially, DPM gives the participation of a DISCO in contract with a GENCO. In DPM, the number of rows has to be equal to the number of GENCOs and the number of columns has to the number of DISCOs in the system. Any entry of this matrix is a function of the total load power contracted by a DISCO toward a GENCO.

The Strength Pareto Gravitational Search Algorithm (SPGSA)

The Gravitational Search Algorithm (GSA) is constructed based on the law of gravity and the notion of mass interactions. GSA is one of the newest heuristic algorithms which have been inspired by the Newtonian laws of gravity and motion. In GSA a set of agents called masses are introduced to find the optimum solution by simulation of Newtonian laws of gravity and motion [11]. Also, each mass agent has four specifications: position, inertia mass, active gravitational mass, and passive gravitational mass. The position of the mass corresponds to a solution of the problem, and its gravitational and inertial masses are determined using a fitness function. In other words, each mass presents a solution, and the algorithm is navigated by properly adjusting the gravitational and inertia masses. By lapse of time, we expect that masses be attracted by the heaviest mass. This mass will present an optimum solution in the search space [12].

The GSA could be considered as an isolated system of masses. It is like a small artificial world of masses obeying the Newtonian laws of gravitation and motion. More precisely, masses obey the following laws:

- Law of gravity: Each particle attracts every other particle and the gravitational force between two particles is directly proportional to the product of their masses...
and inversely proportional to the distance between them, \( R \).

- Law of motion: The current velocity of any mass is equal to the sum of the fraction of its previous velocity and the variation in the velocity.

\[
AGPM_{ij} = \begin{bmatrix}
gpf(s_i+1)(z_j+1) & \cdots & \cdots \\
& \ddots & \ddots \\
gpf(s_i+n_i)(z_j+m_j) & \cdots & \cdots
\end{bmatrix}
\]

\[
s_i = \sum_{k=1}^{i-1} n_i, z_j = \sum_{k=1}^{j-1} m_j, i, j = 2, \ldots, N \text{ & } s_1 = z_1 = 0
\]

Figure 1. Generalized LFC model in the restructured system

Variation in the velocity or acceleration of any mass is equal to the force acted on the system divided by mass of inertia.

To describe the GSA consider a system with \( s \) masses in which position of the \( i \)th mass is defined as:

\[
X_i = (x_i^1, \ldots, x_i^d, \ldots, x_i^s), i = 1, 2, \ldots, s
\] (7)
Where, xid is position of the ith mass in the dth dimension and n is the dimension of the search space. According to [19] mass of each agent is computed after calculating current population’s fitness as:

$$M_i(t) = \frac{q_i(t)}{\sum_{j=1}^{s} q_j(t)}$$  \hspace{1cm} (8)

Where, Mi(t) is the mass value of the agent i at t.

$$q_i(t) = \frac{fit_i(t) - \text{worst}(t)}{\text{best}(t) - \text{worst}(t)}$$  \hspace{1cm} (9)

Where, fiti(t) is the fitness value of the agent i at t, and worst (t) and best (t) are defined as follows for the minimization problem:

$$\text{best}(t) = \min_{j \in \{1, \ldots, s\}} fit_j(t) \quad \text{worst}(t) = \max_{j \in \{1, \ldots, s\}} fit_j(t)$$

To compute acceleration of an agent, total forces from a set of heavier masses that apply on it should be considered based on the law of gravity, which is followed by calculation of agent acceleration using the law of motion. Afterwards, next velocity of an agent is calculated as a fraction of its current velocity added to its acceleration. Then, its next position can be calculated using:

$$F_i^d(t) = \sum_{j \in \text{best}, j \neq i} \text{rand}_j G(t) \frac{M_j(t)}{R_{ij}(t) + \varepsilon} (x_j^d(t) - x_i^d(t))$$

$$a_i^d(t) = \frac{F_i^d(t)}{M_i(t)} = \sum_{j \in \text{best}, j \neq i} \text{rand}_j G(t) \frac{M_j(t)}{R_{ij}(t) + \varepsilon} (x_j^d(t) - x_i^d(t))$$

$$v_i^d(t + 1) = rand_i \times v_i^d(t) + a_i^d(t)$$

$$x_i^d(t + 1) = x_i^d(t) + v_i^d(t + 1)$$  \hspace{1cm} (10)

Where, randi and randj are two uniformly distributed random numbers in the interval [0, 1], ε is a small value, Rij(t) is the Euclidean distance between two agents i and j, defined as Rij(t)=||Xi(t), Xj(t)||2, kbest is the set of first K agents with the best fitness value and biggest mass, which is a function of time, initialized to K0 at the beginning and decreasing with time. Here K0 is set to s (total number of agents) and is decreased linearly to 1.

In GSA, the gravitational constant, G, will take an initial value, G0, and it will be reduced with time:

$$G(t) = G(G_0, t)$$  \hspace{1cm} (11)

Also some differences and advantages of this technique are consisting of [13]:

- In GSA, the agent direction is calculated based on the overall force obtained by all other agents.
- In GSA the force is proportional to fitness value and so agents see the search space around themselves in the influence of force.
- GSA is memory-less and only current position of the agents plays a role in the updating procedure.
- In GSA the force is inversely proportional to the distance between solutions.

Fig. 2 shows the flowchart of the proposed intelligent algorithm.

4. SPGSA

If we plot the objective values f1 and f2 of these optimal solutions against each other in one plot. A multi-objective optimization algorithm tries to approximate these solutions but uses a different approach to obtain these solutions. The supposed algorithm sorts the population based on non-dominated fronts. The first front found is ranked the highest and the last one the lowest. This ranking is used in the mating flight selection process. In addition to, for assure diversity in a population (honey bee) employed crowding distance measure.

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**Flowchart:**

1. Generate initial population
2. Evaluate the fitness for each mass
3. Calculate the G, best, worst, Mi and Mj of the population
4. Update position and velocity
5. Meeting end of criterion?
   - Yes: Return best solution
   - No: Repeat steps 2-4
The main steps of the SPO algorithm are explained in more detail as follows:

### B. Non-Dominated sort

This set of non-dominated solutions is called a Pareto front. A multi-objective algorithm selects and improves solutions based on this domination principle to approximate the real trade-off curve. Non-domination occurs when a candidate cannot be improved any further in one objective while degrading in another objective. Figure 3 explains this in more detail. The figure shows that crowding distance for solution \( y(x4) \) is calculated relative to the solutions from the same front which are all colored blue. The distance is the sum of the length and width of a cubical that can be drawn through these two closest neighbours.

![Flowchart of GSA](image)

**Figure 2.** Flowchart of GSA

![Crowding distance measure](image)

**Figure 3.** Crowding distance measure

### C. SPGSA-based PID type controller

This paper applied the PID controller for the solution of LFC problem [7]. Actually, the PID controller in wide range of operating conditions which provides robust performance. It is clear that, transient performance of the power system with respect to the control of the frequency and tie-line power flows obviously depends on the optimal tuning of the PID controller’s parameters. In order to overcome the backwashes of conventional method and supply optimal control performance, SPGSA technique is proposed to optimal tune of PID controllers parameters under different operating conditions. The block diagram of proposed technique for PID controller is presented in Fig. 4. Also the equation of load frequency control for PID in each control area is:

\[
\text{PID} = k_p + \frac{k_i}{S} + k_d
\]  

(6)

Actually, in industrial PID controller is applied for low pass filter which is necessary to omit high frequency noise in entry of differentiator. Therefore in this paper for PID controller, conversion function of differentiator is:

\[
k_0 S(1+T_dS), T_d=100, k_0=10^{-5}
\]  

(7)

By taking Area Control Error (ACEi) as the input of PID controller in two case studies, the control vector for PID controller in each control area is given by:

\[
u_i = k_{pi} \cdot ACE_i + k_{ii} \int ACE_i dt + k_{di} \cdot ACE_i
\]  

(8)

According to equation 8, in this paper the KPi, KII and KDI gains are tuned by proposed SPGSA technique. The design problem can be formulated as the following constrained optimization problem, where the constraints are the PID controller parameter bounds:

\[
K_{min} \leq \begin{bmatrix} K_{pi} & K_{ii} & K_{di} \end{bmatrix} \leq \begin{bmatrix} K_{max} & K_{max} & K_{max} \end{bmatrix}
\]

Accordingly, the PID controller generates the control signal that applies to the governor set point in each area where the SPGSA module works offline. For testing the robustness of the proposed technique, the power system is analyzed through some performance indices as ITAE and FD which are based on ACEi and system responses characteristic, respectively [14]. The formulation of ITAE and FD are described as:
In other words, the concept of appropriate situation for LFC problem is based on overshoot (OS), undershoot (US) and settling time of frequency deviation in comparison of other techniques. It is clear that, the lower value of this objective functions is the best situation for system. The result of PID parameters are shown in Table 1. Also, the numerical results of these indices are presented in Table 2.

To improve the overall system dynamic performance in a robust way and optimization synthesis, SPGSA technique is employed to solve the above mentioned optimization problem and search for optimal or near optimal set of off-nominal PID controller parameters (KPi, KIi and KDi for i=1, 2, ..., N) where, N introduce the number of control areas [4]. Hence, the proposed method finds appropriate PID parameters with considering objective functions optimization. The convergence trend of proposed technique is presented in Fig. 5.

![Figure 5. Variations of fitness function.](image)

### TABLE I. OPTIMUM PID CONTROLLER GAINS

<table>
<thead>
<tr>
<th>SPGSA PID</th>
<th>Area 1</th>
<th>Area 2</th>
<th>Area 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>2.772</td>
<td>1.781</td>
<td>1.672</td>
</tr>
<tr>
<td>$K_i$</td>
<td>3.756</td>
<td>1.468</td>
<td>1.458</td>
</tr>
<tr>
<td>$K_d$</td>
<td>1.789</td>
<td>1.145</td>
<td>1.045</td>
</tr>
</tbody>
</table>

In this paper, a nonlinear model with ±0.1 replaces the linear model of turbine $\Delta P_{ki}/\Delta T_{ki}$ is considered which is shown in “Fig. 6”. The proposed controller reduces the Frequency Deviance ($\Delta F$) in dynamic status Per Load variations ($\Delta P_{L}$). This is to take Generation Rate Constraints (GRC) in to account, i.e. the practical limit on the rate of the change in the generating power of each GENCO.

![Figure 6. Nonlinear turbine model with GRC](image)

### Scenario 1

The GENCOs participate only in load following control of their areas. It is assumed that a large step load of 0.1 p.u. is demanded by each DISCO in areas 1 and 2. Assume that a case of Poolco based contracts between DISCOs and available GENCOs are simulated based on the following AGPM. Also the GENCOs of area 3 do not participate in the AGC task [9]. Essentially, DPM gives the participation of a DISCO in contract with a GENCO. The deviation of frequency and tie lines power flows for +25% changes is presented in Fig. 7. The element of DPM matrix and desired values for this scenario are:

\[
\Delta P_{M1,1} = 0.11 \text{ pu MW, } \Delta P_{M2,1} = 0.09 \text{ pu MW, } \\
\Delta P_{M3,2} = 0.1 \text{ pu MW, } \Delta P_{M2,2} = 0.1 \text{ pu MW}
\]
In this Scenario, it is assumed that in addition to the specified contracted load demands and 25% increase in parameters, DISCO 1 in area 1, DISCO 1 in area 2 and DISCO 2 in area 3 demand 0.05, 0.04 and 0.03 pu MW as large un-contracted loads, respectively [9]. Using Eq. (2), the total local load in all areas is obtained as:

\[ p_{\text{loc,1}} = 0.25, p_{\text{loc,2}} = 0.24, p_{\text{loc,3}} = 0.23 \text{ MW} \quad (10) \]

**Figure 7.** Frequency deviation and tie line power flows; solid (SPGSAPID), dashed (CFPID) and dotted (PID)

**Figure 8.** The simulation results of scenario 2 are presented in Fig. 8.

**Figure 9.** ITAE and FD performance Indices

<table>
<thead>
<tr>
<th>Change parameters</th>
<th>ITAE Scenario 1</th>
<th>ITAE Scenario 2</th>
<th>FD Scenario 1</th>
<th>FD Scenario 2</th>
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<tbody>
<tr>
<td></td>
<td>SPGSAP ID</td>
<td>CPI D</td>
<td>PID</td>
<td>SPGSAP ID</td>
</tr>
<tr>
<td>25%</td>
<td>283</td>
<td>340</td>
<td>378</td>
<td>429</td>
</tr>
<tr>
<td>20%</td>
<td>265</td>
<td>293</td>
<td>356</td>
<td>408</td>
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<tr>
<td>15%</td>
<td>248</td>
<td>269</td>
<td>346</td>
<td>384</td>
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<td>10%</td>
<td>237</td>
<td>258</td>
<td>340</td>
<td>366</td>
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<td>5%</td>
<td>226</td>
<td>256</td>
<td>334</td>
<td>354</td>
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<tr>
<td>Nominal</td>
<td>214</td>
<td>259</td>
<td>329</td>
<td>334</td>
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<tr>
<td>-5%</td>
<td>226</td>
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<td>-25%</td>
<td>304</td>
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Conclusion
This paper presents a SPGSA to solve the LFC problem in power system. It is well known that the conventional method to tune gains of the PID controller with numerical analysis may be tedious and time consuming. This control strategy was chosen because of the increasing complexity and changing structure of the power systems. Also, it is easy to implement without additional computational complexity. The effectiveness of the proposed method is tested on a three-area restructured power system for a wide range of load demands and disturbances under different operating conditions in comparison with CPID and PID through ITAE and FD. Simulation results demonstrate its superiority and robustness.

Reference
8. Mohammadi, Mohsen, and Noradin Ghadimi. "Designing controller in order to control micro-turbine in island mode using EP