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# A New Optimal Load Frequency Control Based on Hybrid Genetic Algorithm and Particle Swarm Optimization

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*Abstract:* This paper proposes an application of a new hybrid approach combining Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) to optimal Load Frequency Control (LFC) design in interconnected power system. The proposed hybrid GA-PSO technique was applied to obtain the Proportional-Integral-Derivative (PID) controller parameters. The random nature of the GA operators makes the algorithm sensitive to initial population. However the GA algorithm may not converge if the initial population is not well selected. On other hand, PSO was shown to converge rapidly during the initial stages of a global search, but around global optimum, the search process will become very slow. The main idea of this paper is to propose a new algorithm which combines GA and PSO to solve the frequency regulation problem in interconnected power system. Time domain performance of the LFC controller, such as the maximum overshoot and settling time are being optimized based on the performance criteria like the Integral Square Error (ISE), Integral Absolute Error (IAE), Integral Time multiply Absolute Error (ITAE) and Integral Time multiply Square Error (ITSE), or their combination. To verify the effectiveness of the proposed algorithm, initially a two-area power system is used then the proposed approach was extended to the three-area interconnected power system. The obtained simulation results are compared to those yielded by the other classical and heuristic optimization techniques surfaced in the recent state-of-the-art literature. The comparative study demonstrates the validity and the potential of the proposed approach and shows its robustness to solve the optimal LFC problem.

*Keywords:* Load Frequency Control (LFC); Interconnected Power Systems; Optimal Control; Genetic Algorithm (GA); Particle Swarm Optimization (PSO); Hybrid GA-PSO.

## 1. Introduction

In large-scale electrical networks, frequency instability poses a major problem and presents an issue of great importance for operators from the power supply. Increasing size of the interconnected power systems has been accompanied with the appearance of the oscillations frequency problems which may result in disconnection actions, loss of several lines, and zone isolation. However the scheduled power exchange is controlled through local generation dispatch without an automatic control, but with the continuously changing operating points, it has always been difficult to stabilize the scheduled power exchange [1]. From this perspective, the feasibility of Automatic Generation Control (AGC) becomes apparent. As important functions of AGC, power system frequency regulation named load frequency control (LFC) has been one of big challenges in interconnected electrical networks. Therefore, the interest in LFC is growing up rapidly due to the interest in large interconnected power systems [2].

Power supply frequency is considered as a key factor of power supply quality. Frequency stability enhancement of synchronous generator is one of major importance in power system. A single generator unit feeds a power line to various users whose power demand can vary over time. As a consequence of load variations, the frequency of the generator changes over time [3].

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The frequency has an inverse relationship with the load that is changing continually. The change in system load causes a change in the speed of all generator rotor of the system leading to change in system frequency. This power mismatch between load and supply will be compensated by a change in the rotational kinetic energy of the generators ending up with a deviation in the generators speed and hence the frequency. The frequency adjustment is performed by the action on production. Maintaining the frequency at its reference value only be achieved through maintaining the supply-load balance by adjusting the level of production and the demand (supply = consumption). Therefore it is extremely important to keep the system frequency at its nominal value. In case of frequency deviation due to transient conditions or disturbances, nominal frequency must be restored in an acceptable period of time [4]. Power systems regulators usually specify performance indices which must be maintained by the power systems operators. Since the existence of alternating current power systems, different philosophies have been applied to maintain the supply frequency.

Generally the frequency control is spread over three levels: primary control which is carried out by the governor control, secondary control presented by the load frequency control (LFC), and tertiary control or economic dispatching control (EDC) [5]. The aim of this three control systems is to hold the frequency at the nominal value, and maintain the balance between the generated power and the consumed power. The most joint control modes are: the isochronous control, droop control and automatic generation control, in particular load frequency control (LFC). In the isochronous control mode, a big generator will be assigned the task of holding the frequency and the rest of generators will be running at constant power output. In the droop control mode, all generators will respond to the frequency deviation. AGC is achieved by adding a supervisory control loop, which is the LFC loop to the droop control system in order to achieve better performance and improve the frequency control and stability [6]. The main objective of LFC is to maintain zero steady state frequency deviation and to track the load demands. The LFC has been around for the past few decades and it came into practical applications in many power systems around the world. LFC becomes particularly useful in interconnected power systems as it can control the power exchange between the neighboring interconnected areas and enhances the overall system stability [7].

Many works and papers have proposed different control methods and strategies to improve the LFC performance. Proportional-Integral (PI) and Proportional-Integral-Derivation (PID) controllers meet most of the 90% of industrial needs because of their functional simplicity and they provide robust and reliable performance for most systems [6-9]. Some published literature researchers focused on utilizing better tuning methods to tune a PID based load frequency control (LFC). In 1942, Ziegler and Nichols proposed two experimental approaches to quickly adjust the controller parameters without knowing the precise dynamic model of the system to adjust [10-11]. In early 1970, Fosha and Elgerd in their pioneering work applied classical optimal control methodology to solve LFC problem [6-7]. In the 1990s, in order to provide simple rules but more efficient than those of Ziegler- Nichols, Åström, Hagglund and Wittenmark analyzed the adjustment dynamics of a large number of process behavior [10]. This analysis led to the establishment of tables used in the calculation of P, I and D from simple measurements [6]. Several other works have been proposed for tuning the PI and PID controller parameters such as Genetic Algorithm (GA) [12-13], Particle Swarm Optimization (PSO) [14], Bacterial Foraging Optimization Algorithm (BFOA) [15-16], Differential Evolution Algorithm (DEA) [11-17], Firefly Algorithm (FA) [18], H-infinity technique [19] and Gravitational Search Algorithm (GSA) [20]. A significant number of the published works attempted to apply the Fuzzy Logic and multi-stage Fuzzy [21]. Artificial Neural Networks (ANN) controllers [22] were also used by some researchers to solve LFC problem. Many others hybrid methods such as the hybrid algorithm between Bacterial Foraging and Particle Swarm Optimization (BF-PSO) [23], hybrid algorithm between Differential Evolution and Particle Swarm Optimization (DE-PSO) [24] and Neuro-Fuzzy [25] are also used by some researchers.

In this paper, a new hybrid technique combining Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) is proposed to solve the optimal load frequency control (LFC) problem in interconnected power system. This novel algorithm mix the evolution idea of GA with population intellectual technique of PSO algorithm to create a more robust and efficient algorithm. The proposed hybrid GA-PSO algorithm is used to obtain the Proportional-Integral-Derivative (PID) controller parameters for various objective functions such as: ISE, IAE, ITAE, ITSE or their combination. The performance of the proposed method is investigated for the two-area and three-area 9-unit interconnected power systems. Simulation results of the proposed method are compared with the existing approaches in the literature. The results are tabulated as a comparative performance in view of peak overshoot and settling time and the capability of the proposed algorithm to solve LFC problem under different disturbances is confirmed.

The layout of this paper is divided into five sections. Section one comprises this Introduction. Section two presents the interconnected power system model, and is divided in two sub-sections, the first one discusses the frequency stability and control problem and the second presents the dynamic model of a multi-area interconnected power system. Section three illustrates the different stages and steps of the proposed approach. Section four focuses to the presentation and discussion of the results, also a comparative study with existing methods in the literature is presented in this section. Finally, the last section is devoted to the conclusion of this paper.

## 2. Interconnected Power System Model

In an interconnected system, with independently controlled areas, the generation within each area has to be controlled so as to maintain scheduled power interchange. The frequency has an inverse relationship with the load that is changing continually, and the change in real power affects the system frequency. In order to hold the constancy of frequency, the quality of power generation must meet certain minimum standards [5].

### *A. Frequency Stability and Control Problem*

The frequency and the balance between production and demand are strongly related. This requires that all production units can continue to operate and keep synchronization within a certain range of frequency around the rated frequency. It is also necessary that a sufficient number of generators can adapt quickly and flexibly production to load via the reaction to changes in frequency or power set from a central control or a dispatcher. The aim of this regulation is to reduce to zero the frequency difference, always matching the engine torque to the resistive torque by the control of the position of the control valves to the rotating speed. Frequency control is usually divided into three major control levels: primary control (or self control), secondary control (or load frequency control (LFC)) and tertiary control (or economic dispatching control (EDC)) as shown in Figure 1. The purpose of all control systems is to maintain the output of a controlled system such as the frequency at the specified value [26].

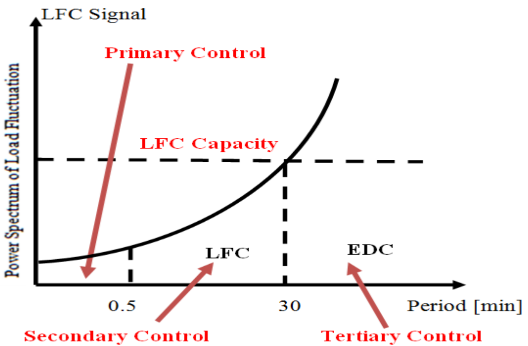


Figure 1. Frequency Control Levels.

- Primary control: is implemented through governor control installed in each generating unit and starts within seconds of a disturbance. The main role of the primary control is to stabilize the frequency system but not return the frequency to its nominal value [26].

- Secondary control: also called supplementary control, LFC is used for the fluctuation with the period of several minutes (about 30 minutes). The main goals of the secondary control (LFC) are to change the valve reference positions of the generating units and take back the system frequency to nominal values [5-6].
- Tertiary control: refers to the economic dispatching control (EDC) of units, and presents a part of the regular market clearing mechanism. Tertiary control acts on minute-to-hours time scale (30 minutes- hours) [26].

*B. Dynamic Model*

Normally a large interconnected electrical network is made up of several control areas tied with each other by tie-lines power flow as shown in Figure 2. In each area, a Load Frequency Controller (LFC) observes and monitors the system frequency and the tie-line power flows between interconnected zones. In interconnected multi-area power system the modeling of a typical control area-*i*, which includes *n* generating units, from a *Z*-control area power system is presented in Figure 3 [9], where each area is represented with three major components: generator, turbine, and governor control system [5].

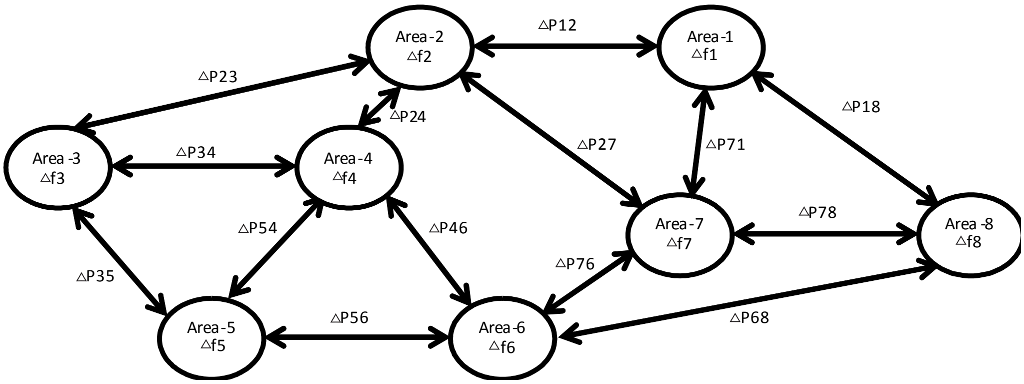


Figure 2. Typical Large Interconnected Multi-Areas Power System.

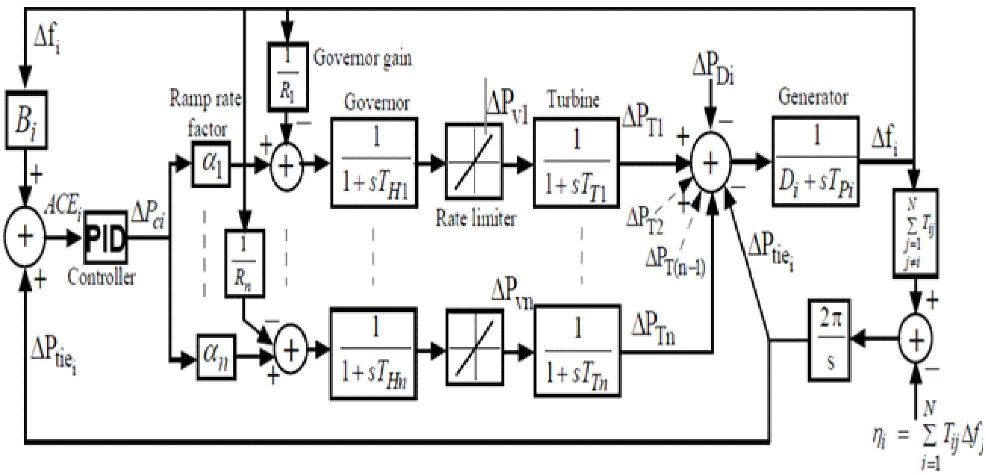


Figure 3. Dynamic Model Representation of Control Area *i*.

*B.1. Power Plant Controls Loops Model*

In the multi-machine interconnected multi-area power system each plant is equipped with governor and excitation system to regulate the frequency and the voltage magnitude. Also each generator is equipped with a power system stabilizer (PSS) which is designed for suppressing low-frequency oscillations in power systems. This work basically focuses on the frequency regulation, and Figure 4 graphically depicts the LFC mechanism.

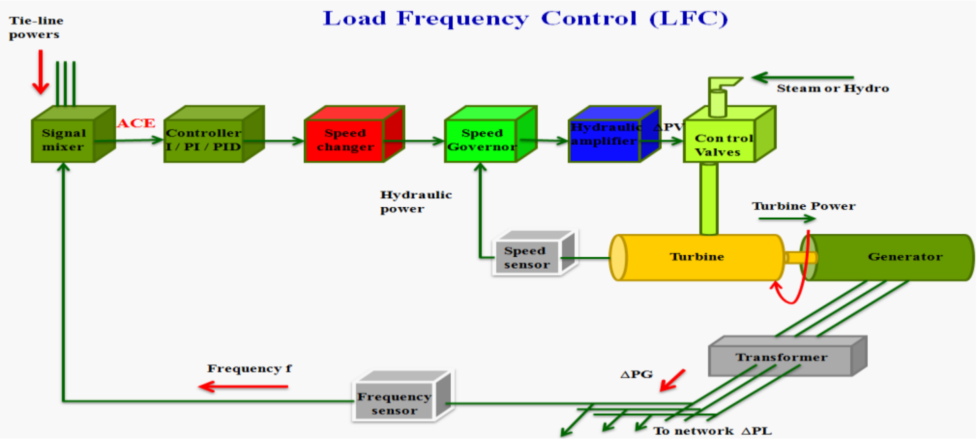

Figure 4. LFC Control Loop of a Synchronous Generator.

The main objective of installed LFC loop is to observe the system and take care of small changes in load demand to hold the system frequency in the nominal value. For the purpose of frequency control study and analysis in the presence of load disturbances, a simple differential mathematical model of area *i* with *n* generating units can be written [5-6]:

$$\frac{d\Delta Pv_{mi}}{dt} = \frac{1}{T_{H_{mi}}}\left(U_{mi} - \left(\frac{1}{R_{mi}} * \Delta f_i\right) - \Delta Pv_{mi}\right) \tag{1}$$

$$\frac{d\Delta P_{T_{mi}}}{dt} = \frac{1}{T_{T_{mi}}}\left(\Delta Pv_{mi} - \Delta P_{T_{mi}}\right);m=1\ldots.n \tag{2}$$

$$\frac{d\Delta f_i}{dt} = \frac{1}{T_{P_i}}\left(\sum_{l=1}^{l=n} \Delta P_{T_{li}} - \Sigma\, \Delta Ptie_i - \Delta P_{D_i} - D_i * \Delta f_i\right) \tag{3}$$

In the interconnected multi-area power system, different areas are attached with each other by tie-lines, and the power flows between the areas are allowed by these tie-lines. The power deviation $\Delta P_{Tij}$ between area *i* and area *j* can be expressed by [6-7]:

$$\frac{d\Delta P_{Tij}}{dt} = T_{ij}(\Delta f_i - \Delta f_j) \tag{4}$$

In order to maintain the system frequency and power interchange with neighbouring control areas at the scheduled values, a control error signal named the Area Control Error (ACE) is measured. This signal is a linear combination of net interchange and frequency deviation and represents the real power unbalance between supply and load of power. The area control error (ACE) is given by [9-10]:

$$ACE_i = \Delta P_{Tij} + \beta_i \Delta f_i \tag{5}$$

Where: $\beta_i$ is the frequency response characteristic for area *i*.
The frequency bias factor is given by:

$$\beta i = \sum_{i=1}^{i=n} \frac{1}{R_i} + \sum_{i=1}^{i=n} D_i \tag{6}$$

A number of control strategies to solve LFC problem have been reported in the literature [7-25]; the most extensively used is based on classical PI and PID controllers. In this paper, each generator is generated by PID controllers. The controller parameters are tuning with the proposed hybrid GA-PSO algorithm using different objective functions. The simulation results are compared through existing methods in several published papers and works. The diagram of the PID controller used is shown in Figure 5 and the PID model is given by [6]:

$$K(S)=K_p+\frac{K_i}{S}+K_d S \tag{7}$$

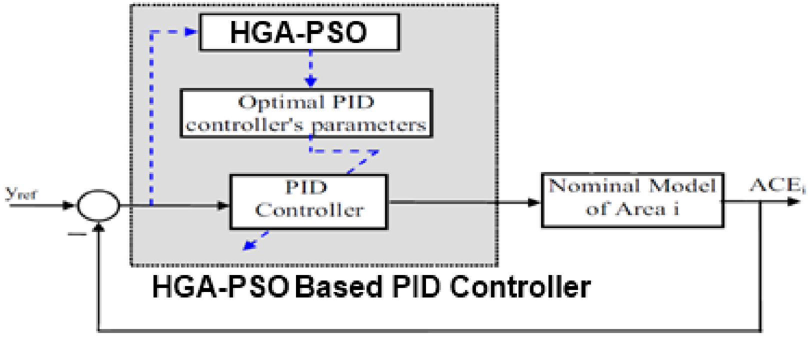


Figure 5. PID Controller Model.

The error inputs to the controllers are the respective Area Control Errors (ACEs) given in equation (5), and the outputs of the controllers are the control area function $U_i$ given by:

$$U_i=K_p.ACE_i+K_i.\int ACE_i\,dt+K_d.\frac{dACE_i}{dt} \tag{8}$$

In order to study the optimal load frequency control using a novel technique more robust for obtain the optimal PID controller parameters in the aim to improve the performances of the LFC controller and hold the frequency at the nominal value, the proposed hybrid GA-PSO algorithm is discussed in the next section.

*B.2. Systems Under Study*

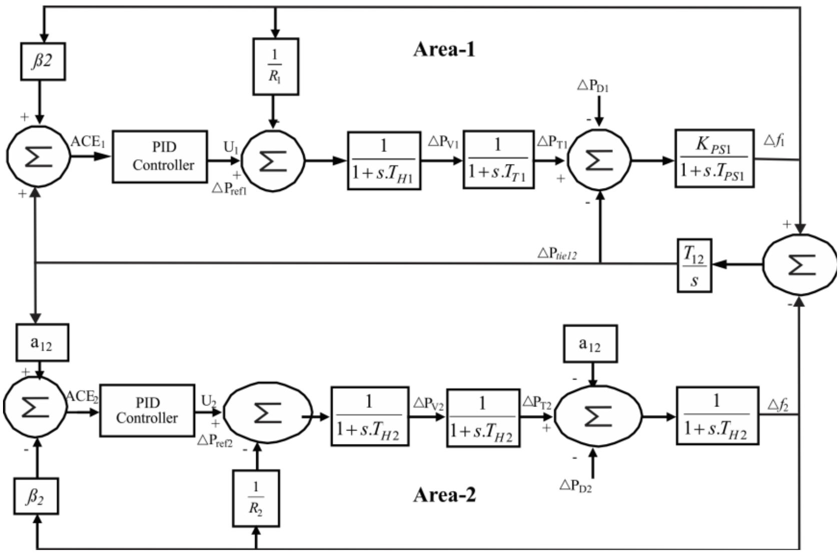


Figure 6. Two-Area Non-Reheat Thermal System.

The system under investigation consists of two-area interconnected power system of non-reheat thermal plant as shown in Figure 6. The system is widely used in literature for the design and analysis of automatic load frequency control of interconnected power systems [15-16]. To prove the capability of the proposed approach, the hybrid GA-PSO algorithm is tested on large interconnected three-area 9-unit power system, where each zone has three parallel-operating generating units that are owned by various generation companies (GenCos), and every generating unit has non-reheat thermal power plant [9].

In the general case of interconnected multi-area power system, the state space model is given by [5]:

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX \end{cases} \tag{14}$$

Where:

$$\begin{cases} U = \left[\Delta P_{D1} \quad .... \quad \Delta P_{Di} \quad u_1 \quad ... \quad u_i\right]^t \\ Y = \left[Y_1 \quad Y_2\right]^t = \left[\Delta f_1 \quad ... \quad \Delta f_i \quad \Delta P_{tie_{12}} \quad ... \quad \Delta P_{tie_{ij}}\right]^t \\ X = \left[X_{D11} \quad .. \quad X_{D1n} \quad \Delta f_1 \quad .. \quad X_{Di1} \quad .. \quad X_{Din} \quad \Delta f_i \quad X_Z\right]^t \\ X_{D11} = \left[\Delta P_{T11} \quad \Delta P_{V11}\right], \quad X_{Din} = \left[\Delta P_{T_{in}} \quad \Delta P_{Vin}\right] \\ X_Z = \left[\Delta P_{tie12..} \quad ... \quad \Delta P_{tie_{ij}}\right] \end{cases} \tag{15}$$

$n$: number of generating unit and $i$: number of area.

## 3. Hybrid Genetic Algorithm and Particle Swarm Optimization "HGA-PSO"

Among the optimization methods GA and PSO are the most used; these techniques are global optimization algorithms and are suitable for solving optimization problems with linear or non-linear objective functions. The objective of this paper is to use a combined algorithm between GA and PSO to solve LFC problem in an interconnected power system. In this work, various kinds of intelligent algorithms, namely GA, PSO, BFOA, ABC, hybrid BF-PSO and hybrid GA-PSO are used for finding the optimal PID controller parameters. The capability of the proposed hybrid GA-PSO method is proven through a comparative study with other published papers.

### *A. Genetic Algorithm*

GA is a heuristic global searching algorithm based on the mechanisms of biological evolution and natural genetics developed by J.H. Holland in early 1970s [27]. By the generational evolution of the population (selection, crossover and mutation), it solves the optimal solution and satisfactory solution. In generally GA comprises three basic phases [27-28]:

1- Creating an initial population.
2- Evaluating a fitness function.
3- Producing a new population.

As with any search algorithm, the optimum solution is obtained only after much iteration named also generation. The speed of the iterations is determined by the length of the chromosome and the size of the populations. There are two main methods for GA to generate itself, namely generational or steady state. In generational, an entire population is replaced after iteration. However, little members of the population are discarded at each iteration in steady state, along with the population size remains constant. Among the drawbacks of GA are [29]:

- It's possibility to converge prematurely to a sub-optimal solution.
- It's high sensitivity to initial population.

However, the GA application to solve optimization problems is generated by the following limits [29]:

- The objective function must be well written; Based on the stochastic search; It is a blind search and non-oriented; High sensitivity to initial parameters; It is computationally expensive; the stopping criterion.

The basic algorithm of GA shown in Figure 7 can be resumed by these 7 steps [29-31]:
1. Initialize a population of chromosomes.
2. Evaluate each chromosome in the population.
3. Create new chromosomes by mating current chromosomes.
4. Apply mutation and recombination as the parent chromosomes mate.
5. Delete member of the population to, accommodate room for new chromosomes.
6. Evaluate the new chromosomes and insert them into the population.
7. If time is up, stop and return the best chromosomes; if not, go to 3.

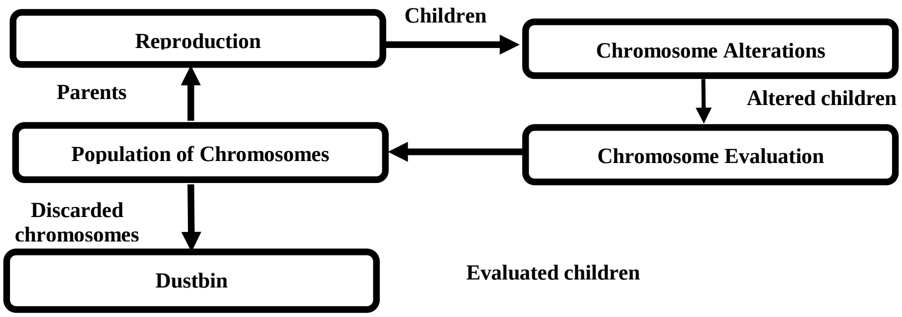


Figure 7. Different Procedures of GA

*B. PSO Algorithm*

The Particle Swarm Optimization (PSO) is a heuristic optimization method based on swarm intelligence. It comes from research on the bird and fish flock movement behavior. PSO is a population-based optimization method developed in 1995 by Dr. Kennedy and Dr.Eberhart [6]. It has become one of the most popular techniques applied in various optimization problems due to its easiness and capability to find near optimal solutions [13]. It belongs to the class of direct search methods that can be used to find a solution to an optimization problem in a search space. In the PSO method, a swarm consists of a set of individuals, with each individual specified by position and velocity vectors *(xi(t), vi(t))* at each time or iteration. Each individual is named as a "particle" and the position of every particle represents a potential solution to the under study optimization problem. The basic algorithm of PSO is given by these 7 steps [32]:
1. Create a population of agents (called particles) uniformly distributed over *X*.
2. Evaluate each particle's position according to the objective function.
3. If a particle's current position is better than its previous best position, update it.
4. Determine the best particle (the particle's previous best positions).
5. Update particles velocities according to:

$$V_i^{t+1} = V_i^t + C_1 rand_1 \left( Pbest - X_i^t \right) + C_2 rand_2 \left( gbest - X_i^t \right) \tag{11}$$

6. Move particles to their new positions according to:

$$X_i^{t+1} = X_i^t + V_i^{t+1} \tag{12}$$

7. Go to step 2 until stopping criteria are satisfied.

The general algorithm of PSO is shown in Figure 8 [10]:

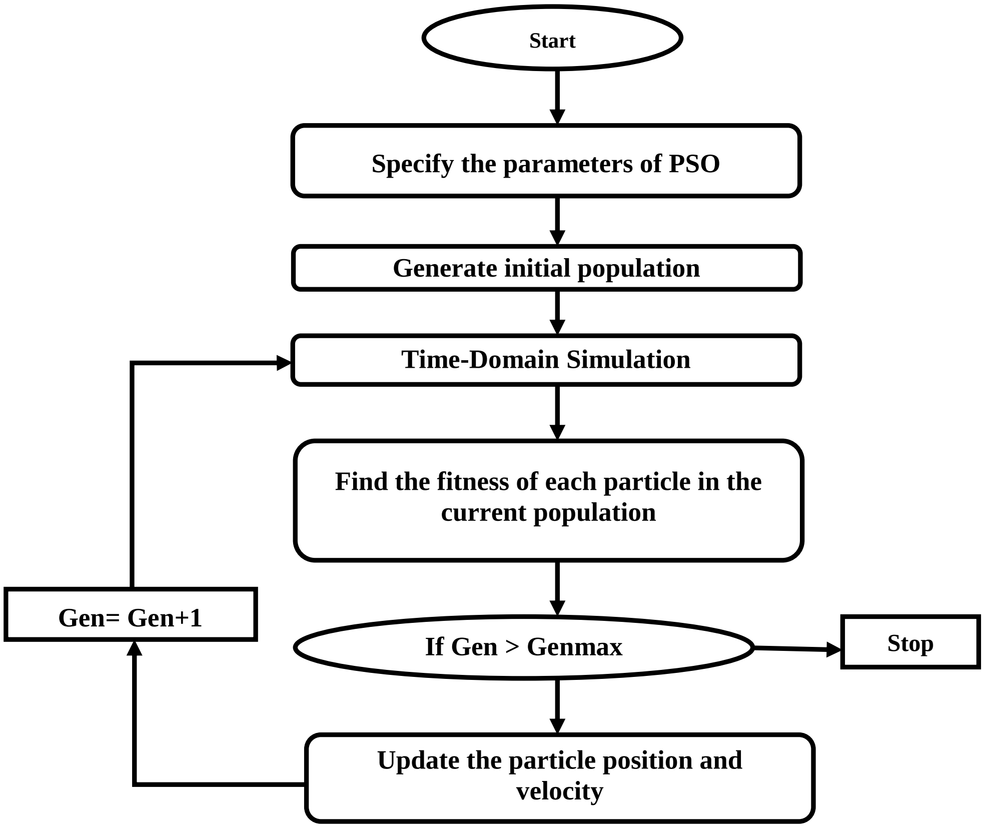


Figure 8. PSO Algorithm

*C. Proposed Hybrid GA-PSO Algorithm*

As with any search algorithm, GA and PSO have benefits, disadvantages and critical issues. In other hand GA and PSO have the complementary performance. The standard GA suffers from a slow convergence speed. Moreover, there are two critical issues in this algorithm, first is its premature convergence, and second is its weak local searching ability. Unlike the GA, PSO has no evolution operators such as crossover and mutation, but at the same time PSO begins with a random population matrix just like the continuous GA, also PSO uses a few parameters and is easy to implement and can often locate nearly optimal solutions with a fast convergence speed and presents an efficient optimization algorithm for solving complicated problems, which present the simplicity of this algorithm over GA. In contrast, PSO is inferior in the global convergence than GA but has the characteristic with easiness, flexibility and memorability. The major problem in PSO is to adjust its velocity step size for fine tuning in the search space, which often leads to premature convergence [27-34]. The main idea behind this work is combining the advantages of PSO and GA and creates a hybrid algorithm which can finds time-optimal solutions simultaneously.

The proposed hybrid GA-PSO combines the evolution concept of GA with population intellectual strategy of PSO algorithm. This algorithm is divided into two levels, the PSO level and the GA level. Using this new approach combines the advantages of PSO and GA, and during searching process, some individuals find the optimization with PSO searching strategy and others find the optimization with GA, and the whole population information is shared by each agent. Only the individual with high fitness could have the chance of entering next generation's optimization. Therefore, this method inherits the valuable evolution information, improves the searching efficiency of particle swarm, and also guarantees the global convergence of algorithm. The proposed hybrid GA-PSO algorithm can be described as follows [27]:

Step 1: Set up the initial parameters:

1.1 The population number of GA: $N_{GA}$,

2.1 The population number of PSO: $N_{PSO}$,

3.1 The population number of hybrid GA-PSO algorithm is: $N_{HGA\text{-}PSO} = N_{GA} + N_{PSO}$;

4.1 Then set up the various parameters in the GA and PSO.

Step 2: initialize randomly the population of GA and PSO.

Step 3: Calculate each population's fitness; Find out the solution when fitness is highest in the current population, and store this solution as the globally optimal solution.

Step 4: According to the step 3, survive individuals with the high fitness and eliminate other individuals with low fitness.

Step 5: Carry on the genetic evolution and particle swarm searching to the survival individual according to the step 4.

- PSO stage: Particles update their velocities and positions according to (16) and (17).
- GA stage: GA has three operators, namely selection, crossover, and mutation.
-

Step 6: Inspect the suspension conditions. If it satisfies the condition of convergence, it will terminate iterations and put out final result, or else go to step 3.

In the aim to choose the best objective function that give the better performances to solve optimal LFC problem using the proposed HGA-PSO algorithm, various objective functions were tested in this paper.

These objective functions are given by:

$$J1:\ ITAE = \int_0^{tsim} t.\left(|\Delta f_1| + |\Delta f_2| + |\Delta Ptie_{12}|\right).dt \tag{13}$$

$$J2:\ ITSE = \int_0^{tsim} t.\left((\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta Ptie_{12})^2\right).dt \tag{14}$$

$$J3:\ IAE = \int_0^{tsim} \left(|\Delta f_1| + |\Delta f_2| + |\Delta Ptie_{12}|\right).dt \tag{15}$$

$$J4:\ ISE = \int_0^{tsim} \left((\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta Ptie_{12})^2\right).dt \tag{16}$$

$$J5=J1+J2 \tag{17}$$

$$J6=J3+J4 \tag{18}$$

$$J7=J3+J2 \tag{19}$$

$$J8=J4+J1 \tag{20}$$

The Flowchart of the proposed HGA-PSO algorithm employed in the present paper is shown in Figure 9:

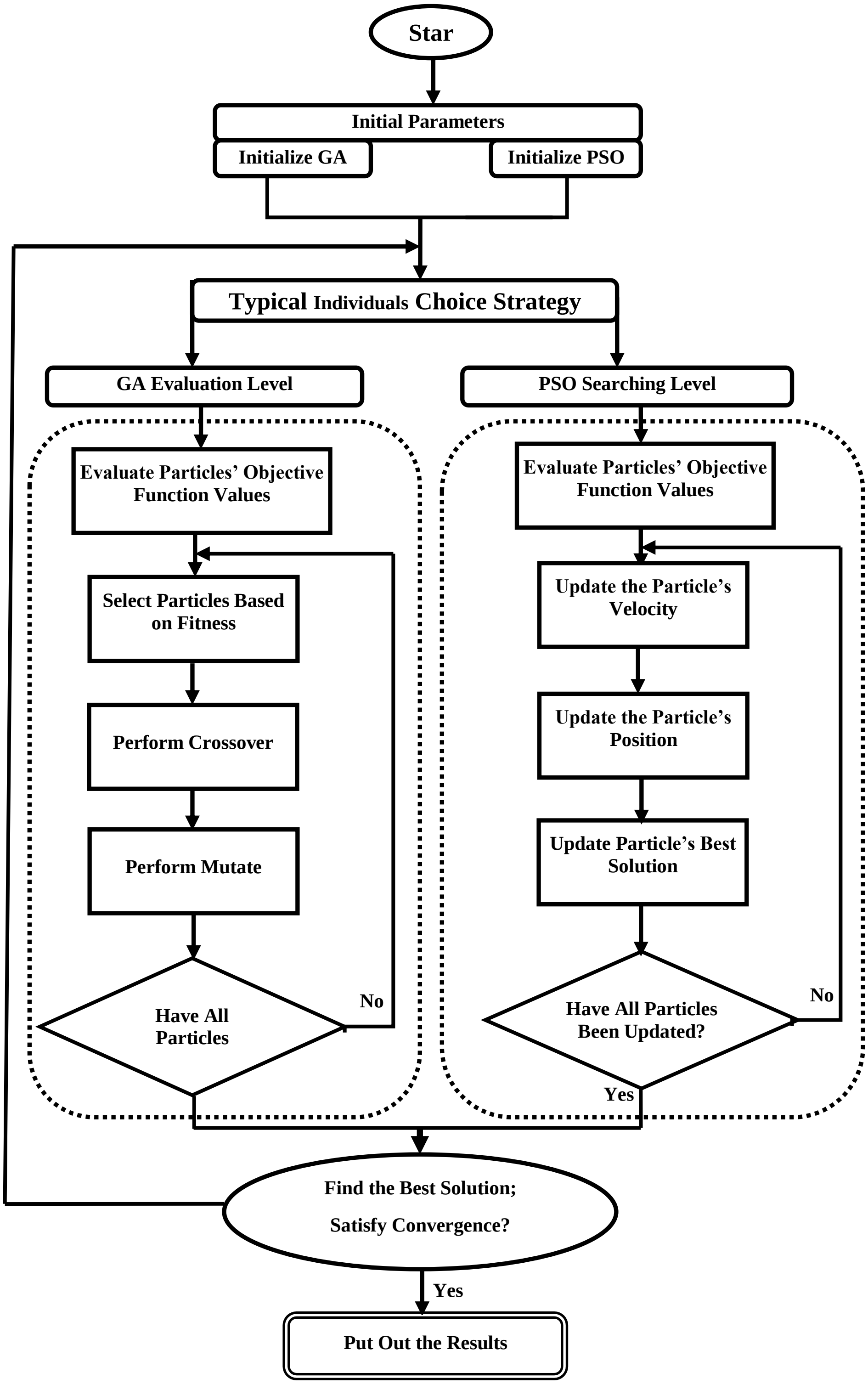


Figure 9. Flowchart of Proposed Hybrid GA-PSO Algorithm.

## 4. Simulation Results

This section presents the simulation results of the proposed approach hybrid GA-PSO. Two-area and three-area interconnected power systems are considered for the simulation and the values of the different parameters of the test systems are given in Appendix. This section is divided into two parts, the first one is devoted to present the simulation results of the two-area interconnected power system, and the second is dedicated to present the simulation results of the three-area interconnected power system.

### *A. Two-Area Interconnected Power System*

The two-area interconnected system shown in Figure 6 is simulated for 0.1 pu step load perturbation in area-1. The simulation results are compared with two ways, citing that the second comparison depends on the results of the first comparison. The first one is based on a comparison of the proposed HGA-PSO algorithm using different objective functions in order to choose the right objective function to solve LFC problem. After that the objective function is selected based on the comparative study presented before, the second comparison presents a comparative study between the proposed algorithm with other methods and works published in the literature in the aim to prove the effectiveness of the proposed approach.

#### *A.1. Results of Selection of the Objective Function*

This sub-section presents the results of the first comparative study for the selection of good objective function using the eight functions presented in section 3.3. The PID controller parameters of the first comparative study are given in Table 1, and the fluctuations in the system frequency and the tie-line power flow are shown in Figures 10, 11, and 12 respectively.
PID Controller Parameters.

| ***Objective functions*** | ***Parameters*** | ***Kp*** | ***Ki*** | ***Kd*** |
|---|---|---|---|---|
| *J1* | *ITAE* | 6.14 | 3.73 | 2.8345 |
| *J2* | *ITSE* | 4.8752 | 4.0960 | 4.5470 |
| *J3* | *IAE* | 4.1679 | 8.2558 | 6.0243 |
| ***J4*** | *ISE* | 7.8011 | 8.6599 | 6.1941 |
| *J5* | *ITAE+ITSE* | 6.7200 | 4.4107 | 4.2291 |
| *J6* | *IAE+ISE* | 1.1528 | 1.1406 | 0.9101 |
| *J7* | *IAE+ITSE* | 9.1308 | 4.2744 | 5.7063 |
| *J8* | *ISE+ITAE* | 3.3352 | 7.6609 | 6.1528 |

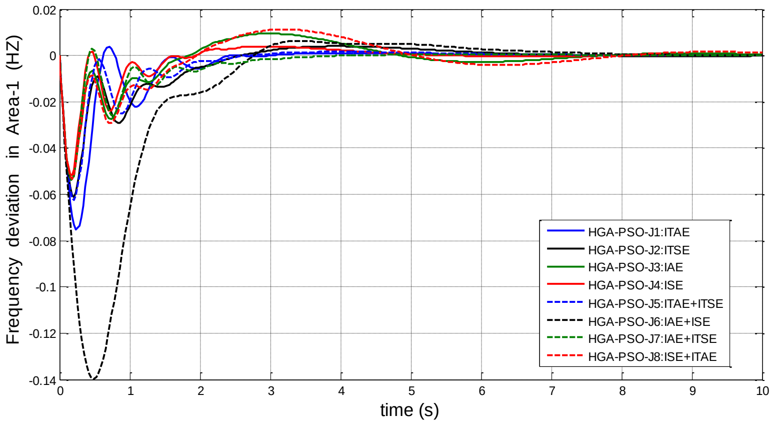


Figure 10. Frequency Deviation in Area-1.

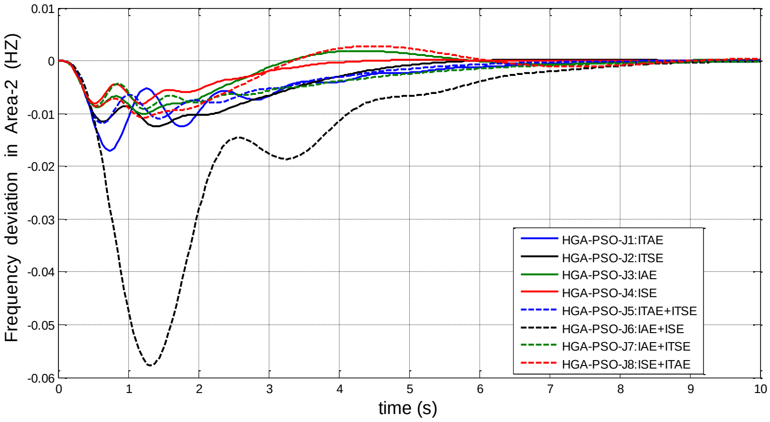


Figure 11. Frequency Deviation in Area-2.

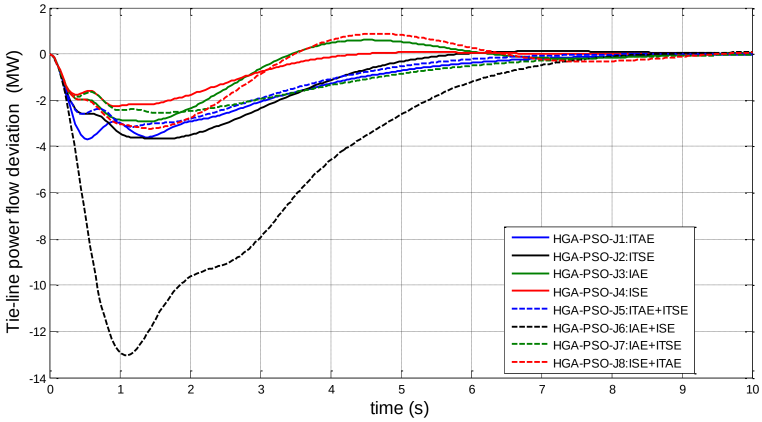


Figure 12. Tie-Line Power Flow Deviation.

Table 2. Comparative Study with Different Objective Functions.

| | | *HGA-PSO ITAE* | *HGA-PSO ITSE* | *HGA-PSO IAE* | *HGA-PSO ISE* | *HGA-PSO ITAE+ITSE* | *HGA-PSO IAE+ISE* | *HGA-PSO IAE+ITSE* | *HGA-PSO ISE+ITAE* |
|---|---|---|---|---|---|---|---|---|---|
| *Area-1* | *Peak overshoot [Hz]* | 0.07526 | 0.05906 | 0.05323 | 0.05183 | 0.06057 | 0.1396 | 0.05323 | 0.05320 |
| | *Settling time [s]* | 5.628 | 7.453 | 7.491 | 1.6085 | 5.977 | 8.928 | 5.611 | 8.128 |
| *Area-2* | *Peak overshoot [Hz]* | 0.01693 | 0.01156 | 0.08656 | 0.008045 | 0.01186 | 0.05771 | 0.008456 | 0.008511 |
| | *Settling time [s]* | 8.558 | 6.176 | 8.826 | 3.489 | 8.396 | 9.125 | 6.881 | 6.758 |
| *Tie-line* | *Peak overshoot [MW]* | 3.66 | 3.642 | 2.875 | 2.182 | 3.122 | 13.02 | 2.488 | 3.224 |
| | *Settling time [s]* | 7.346 | 6.01 | 7.681 | 3.98 | 6.916 | 8.143 | 7.317 | 7.051 |

### *A.2. Comparative Study with Different Approaches*

After the Integral Square Error (ISE) choice as objective function for the proposed HGA-PSO algorithm to solve LFC problem based on the results presented before, in this second sub-section the performance of proposed HGA-PSO approach is compared with individual GA and

PSO techniques and other recently conventional and meta-heuristic techniques such as: the classical Ziegler-Nichols method, BFOA, ABC, and HBF-PSO in order to show the effectiveness and robustness of this novel algorithm through other methods. The fluctuations in the system frequency and the tie-line power flow are shown in Figures 13, 14, and 15 respectively.

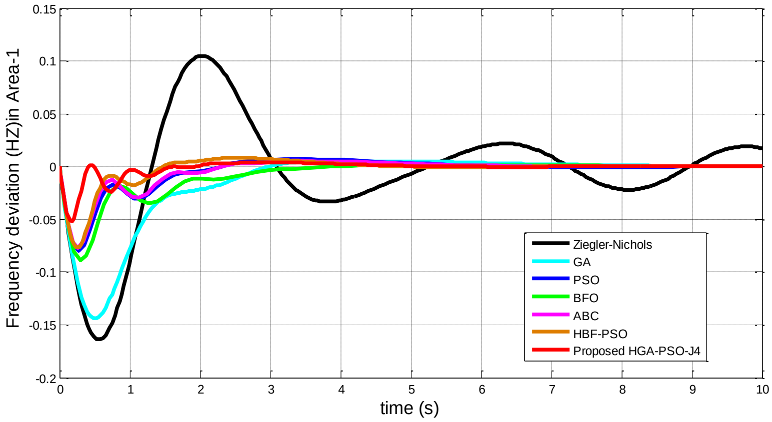


Figure 13. Frequency Deviation in Area-1.

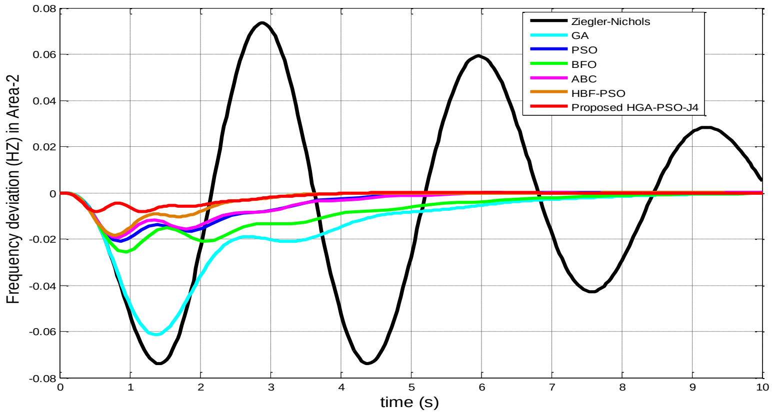


Figure 14. Frequency Deviation in Area-2.

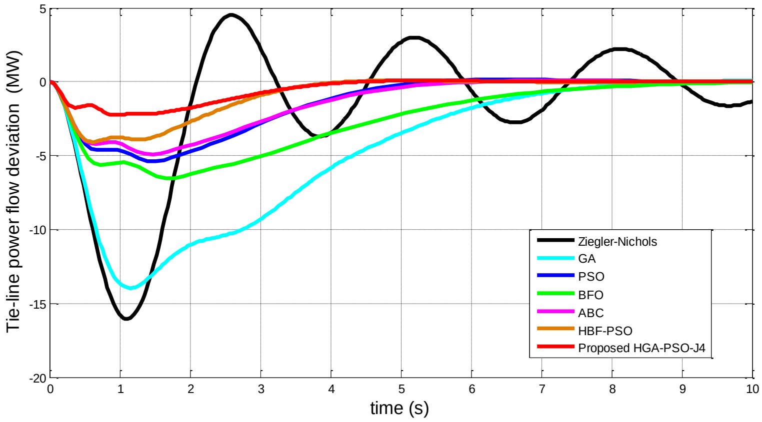


Figure 15. Tie-line Power Flow Deviation.

A step increase in demand of 0.1 pu is applied at t = 0 s in area-1. The controller parameters were obtained using the proposed HGA-PSO algorithm based on the objective function J4: ISE due to its superior performance. The results obtained are depicted and compared in Table 3. To show the superiority of the proposed method for optimizing PID controller parameters, results of some recently published modern optimization methods for the same interconnected power system are provided in Table 4.

The system frequency and the tie-line power flow are suppressed if both areas adopt classical or optimal LFC controller. Using optimal PID parameters the fluctuations of the system are suppressed better then the case of classical PID controller. From the results shown in Figures 13, 14 and 15, it can be observed that the proposed HGA-PSO algorithm is able to give best results in view of minimizing fluctuations of frequency and interconnected power flow, when compared to the other applied methods as shown in Table 3.

Table 3. Comparative Study with Different Approaches.

| | | *Ziegler-Nichols* | *GA (ITSE)* | *PSO (ITAE)* | *BFO (ITAE)* | *ABC (ITSE)* | *HBF-PSO (ITAE)* | *Proposed HGA-PSO J4 :ISE* |
|---|---|---|---|---|---|---|---|---|
| ***Area-1*** | *Peak overshoot [Hz]* | 0.1525 | 0.1436 | 0.0799 | 0.08924 | 0.076 | 0.0713 | 0.05183 |
| | *Settling time [s]* | 19.14 | 6.028 | 4.239 | 5.122 | 4.75 | 3.942 | 1.6085 |
| ***Area-2*** | *Peak overshoot [Hz]* | 0.07372 | 0.0614 | 0.02095 | 0.02489 | 0.01926 | 0.01807 | 0.008045 |
| | *Settling time [s]* | 20 | 8.731 | 4.688 | 7.766 | 4.614 | 4.47 | 3.489 |
| ***Tie-line*** | *Peak overshoot [MW]* | 15.98 | 13.95 | 5.36 | 6.529 | 4.934 | 4.038 | 2.182 |
| | *Settling time [s]* | 17.06 | 8.659 | 6.454 | 9.622 | 6.022 | 4.322 | 3.98 |

Table 4. Controller Parameters and Settling Time

| | ***Controller Parameters*** | | | ***Settling Time [s]*** | | |
|---|---|---|---|---|---|---|
| | *Kp* | *Ki* | *Kd* | $\Delta f_1$ | $\Delta f_2$ | $\Delta P_{tie12}$ |
| ***NSGA-II-PI [12]*** | -0.428 | 0.2967 | _ | 6.87 | 3.48 | 6.08 |
| ***NSGA-II-PID [12]*** | -0.2346 | 0.2662 | 0.6146 | 4.3 | 5.75 | 5.39 |
| ***GA-PI [16]*** | -0.2346 | 0.2662 | _ | 11.39 | 10.59 | 9.37 |
| ***BFOA-PI [16]*** | -0.4207 | 0.2795 | _ | 7.09 | 5.52 | 6.35 |
| ***HBFOA-PSO (ITAE) [15]*** | -0.3317 | 0.4741 | 0.1795 | 7.39 | 7.65 | 5.73 |
| ***HBFOA-PSO [15]*** | -0.4383 | 0.3349 | 0.2374 | 5.17 | 6.81 | 4.59 |
| ***PSO (ITAE) [15]*** | -0.3597 | 0.4756 | 0.1887 | 7.37 | 7.82 | 5 |
| ***Conventional design [16]*** | -0.3317 | 0.4741 | _ | 45 | 45.01 | 27.27 |
| ***DE-PI-$J_3$ [11]*** | -0.4233 | 0.2879 | _ | 6.39 | 6.69 | 4.85 |
| ***DE-PI-$J_2$ [11]*** | -0.4741 | 0.3047 | _ | 8.96 | 8.15 | 5.75 |
| ***DE-PI-$J_1$ [11]*** | -0.2146 | 0.4335 | _ | 45 | 45 | 28 |
| ***GSA-PI [20]*** | -0.4383 | 0.3349 | _ | 5.17 | 6.81 | 4.59 |
| ***PS tuned fuzzy PI [32]*** | 0.4509 | 0.5470 | _ | 6.05 | 7.10 | 5.56 |
| ***PSO tuned fuzzy PI [32]*** | 0.8176 | 0.7948 | _ | 5.13 | 6.22 | 4.83 |
| ***HPSO-PS tuned fuzzy PI [32]*** | 0.9336 | 0.7203 | _ | 2.26 | 3.74 | 2.94 |
| ***Ziegler-Nichols*** | 0.4713 | 2.63 | 0.6575 | 19.14 | 20 | 17.06 |
| ***GA (ITSE)*** | 0.9971 | 0.9775 | 0.8729 | 6.028 | 8.731 | 8.659 |
| ***PSO (ITAE)*** | 3.1205 | 2.7821 | 2.4641 | 4.239 | 4.568 | 6.454 |
| ***BFO (ITAE)*** | 2.8718 | 1.7219 | 1.9680 | 5.122 | 7.698 | 9.622 |
| ***ABC (ITSE)*** | 3.8648 | 5.2572 | 2.8802 | 4.75 | 4.614 | 6.022 |
| ***HBFO-PSO (ITAE)*** | 3.3173 | 3.2453 | 2.5977 | 3.4942 | 4.47 | 4.322 |
| ***Proposed HGA-PSO (J4:ISE)*** | 7.8011 | 8.6599 | 6.1941 | 1.6085 | 3.489 | 3.98 |

From Table 3, compared with the single GA and PSO algorithms, the hybrid GA-PSO algorithm shows the best performance: shorter searching time, higher calculating efficiency, and easier to find the optimal solution. Using this novel HGA-PSO algorithm, the settling time is very short compared to the time given by other modern methods published in the literature. The results of the proposed approach are also compared to other published papers such as: Ziegler-Nichols [16], NSGA-II [12], GA [16], PSO [15], ABC, BFO [16], HBF-PSO [15], GSA-PI [20], DE-PI [11] and HPSO-PS fuzzy PI [32] as shown in Table 4.

It can be observed that the proposed technique is superior compared to all existing methods and gives better results in terms of the settling time and peak overshoot. The results also show the superiority of the proposed approach and confirm its potential to LFC problem over disturbances comparing to other methods. Seen from the results and the comparative study depicted in Table 3 and Table 4, this novel algorithm could rapidly converge to the correct optimal solution and give the best PID controller parameters to solve the optimal load frequency control problem.

*B. Extension to Three-Area Interconnected Power System*

To demonstrate the capability of the proposed approach and their ability to solve optimal LFC problem in large power systems which have several interconnected areas equipped with multi generating units, the study is extended to a three-area 9-unit system [9] considering thermal unit in each area. The system parameters are given in Appendix [9]. The interconnected three-area 9-unit system under study is shown in Figure 16. The same procedure as presented in Section 4.1 is followed to tune the PID controller parameters. The final PID controller parameters for each area are obtained using the proposed hybrid GA-PSO algorithm employing J4: ISE as objective function. It is noted that the LFC signals are inputted to the governors of each units. The three-area power system is simulated for multi step load disturbances: 0.1 pu in area-1, 0.1 pu in area-2, and 0.1 pu in area-3, thereby the system responses are shown in Figures 17-22.

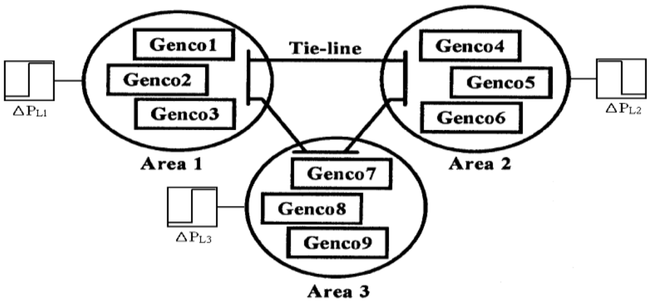


Figure 16. Three-Area 9-Unit Interconnected Power System.

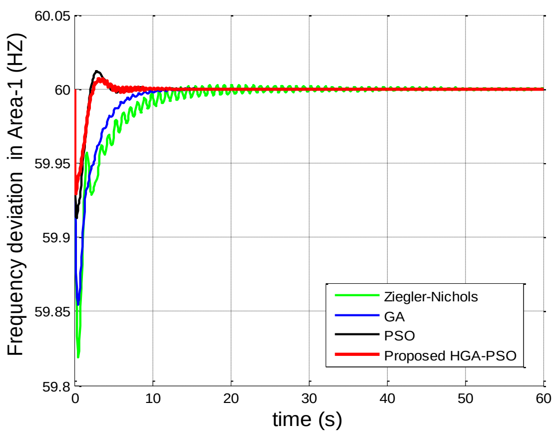


Figure 17. Frequency Deviation in Area-1.

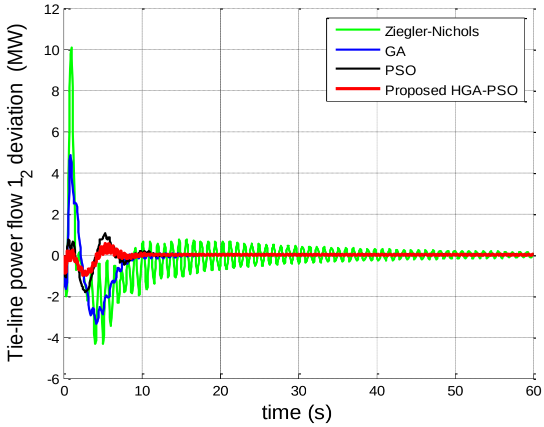


Figure 18. Tie-line Power Deviation in Area-1.

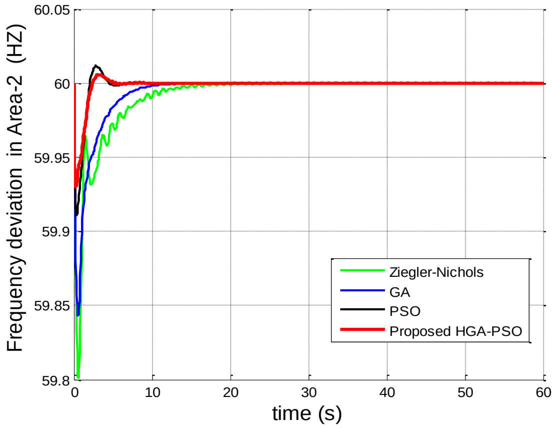


Figure 19. Frequency Deviation in Area-2.

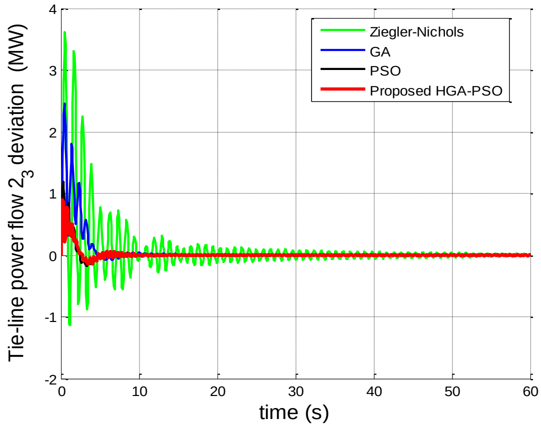


Figure 20. Tie-line Power Deviation in Area-2

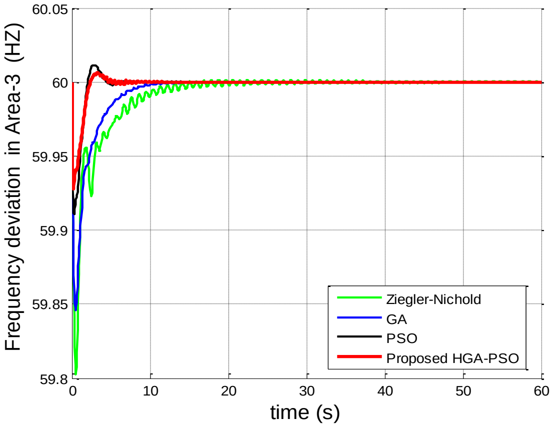


Figure 21. Frequency Deviation in Area-3

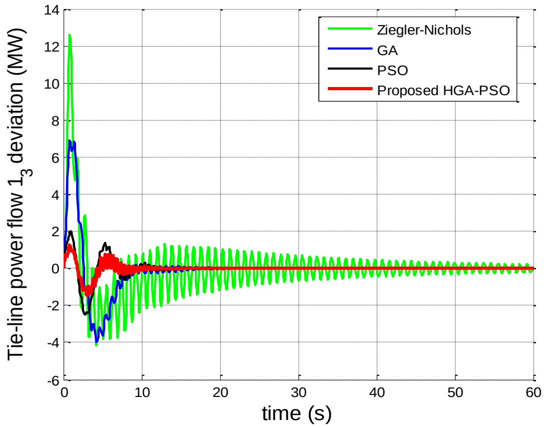


Figure 22. Tie-line Power Deviation in Area-3

Table 5. Comparative Study with Different Approaches.

| *Techniques* | | *Ziegler-Nichols* | *GA (ITSE)* | *PSO (ITAE)* | *HGA-PSO (ISE)* |
|---|---|---|---|---|---|
| *Frequency Area-1* | *Peak overshoot [HZ]* | 0.181 | 0.1442 | 0.08623 | 0.06698 |
| | *Settling time [s]* | 49.57 | 13.71 | 8.12 | 5.92 |
| *Frequency Area-2* | *Peak overshoot [HZ]* | 0.1891 | 0.1551 | 0.08815 | 0.06773 |
| | *Settling time [s]* | 19.54 | 11.76 | 6.616 | 5.658 |
| *Frequency Area-3* | *Peak overshoot [HZ]* | 0.1972 | 0.1527 | 0.08789 | 0.0711 |
| | *Settling time [s]* | 45.69 | 13.3 | 8.322 | 5.864 |
| *Tie-Line* $\Delta P_{tie12}$ | *Peak overshoot [MW]* | 10.08 | 4.793 | 1.031 | 0.4395 |
| | *Settling time [s]* | 108.6 | 15.69 | 12.91 | 10.225 |
| *Tie-Line* $\Delta P_{tie13}$ | *Peak overshoot [MW]* | 12.61 | 6.806 | 1.966 | 1.244 |
| | *Settling time [s]* | 113.42 | 19.76 | 14.38 | 11.61 |
| *Tie-Line* $\Delta P_{tie23}$ | *Peak overshoot [MW]* | 3.621 | 2.454 | 1.087 | 0.9053 |
| | *Settling time [s]* | 91.28 | 16.08 | 13.93 | 9.493 |

These curves indicate the capability of the HGA-PSO in reducing the settling time and damping power system oscillations in large interconnected power system. Furthermore, the mean settling time of these variations reducing effectively. From where, hybrid GA-PSO based PID controller greatly enhances the system stability and improves the characteristics of frequency power supply. Critical analysis of the system responses clearly reveals that dynamic performance of the system is significantly attained with proposed approach. From the results shown in Table 5, it can be concluded that, the proposed control strategy provides a robust and stable control satisfactorily and the optimum values of controller parameters obtained with the proposed hybrid GA-PSO are the best.

From the simulation results, we can conclude that the LFC scheme based on the proposed HGA-PSO approach suppresses the fluctuations of the system successfully. It is clear from the results, the proposed algorithm yields the best performances compared to all types of control strategy.

## 5. Conclusion

In this paper, the optimal load frequency control (LFC) of interconnected power systems is investigated. The impact of LFC control method on the fluctuations caused by step load disturbance is examined; also the effect of LFC controller is analyzed. The Proportional-Integral-Derivative (PID) controller parameters of the investigated LFC model are optimized by different techniques. An application of new approach based on hybrid Genetic Algorithm and Particle Swarm Optimization (HGA-PSO) to solve LFC problem is developed. The proposed hybrid GA-PSO algorithm is first applied to the two-area interconnected power system and then extended to the large three-area 9-unit interconnected power system model. The main objective is to combine the advantages of GA and PSO to create a strong robust algorithm with more excellent performance to solve frequency regulation problem. The interconnected test systems have been simulated for various step load disturbances. To achieve the best performances different objective functions were tested, which are: ISE, IAE, ITAE, ITSE, or their combination. The results of the proposed hybrid GA-PSO algorithm are compared with other classical and intelligent methods such as: Ziegler-Nichols, GA, BFOA, PSO, ABC and hybrid BF-PSO. The simulation results show the high performance of hybrid GA-PSO algorithm which minimizes the frequency fluctuations for the system more than the other methods. The obtained results are very promising and the robustness of the proposed approach is confirmed.

*List of Symbols*

$\Delta f_i$: Frequency Deviation.
$\Delta Ptie$: Tie-lien Power Flow Deviation.
$\beta_i$: Frequency Bias.
$C_1$: PSO Cognitive Coefficient.
$C_2$: PSO Social Coefficient.
$D_i$: Load-Damping.
*gbest*: Global Best Position.
$K_{PS}$: Power System Gain Constant.
*Pbest*: best position for the i$^{th}$ Agent.
$R_i$: Governor Speed Regulation Parameter.
$T_H$: Governor Time Constant.
*Tij*: Tie-line Rigidity Factor.
$T_{Ps}$: Area Aggregate Inertia.
$t_{sim}$: Simulation Time.
$T_T$: Turbine Time Constant.
$U_i$: Control Signal.
*V*: PSO Velocity Vector.
*X*: PSO Position Vector.
$\alpha_{12}$: Constant.

$\Delta P_T$ : Turbine Power.
$\Delta P_V$: Valve Position Variation.

*Abbreviations*
*AGC*: Automatic Generation Control.
*ACE*: Area Control Error.
*ABC*: Artificial Bee Colony.
*BFO*: Bacterial Foraging Optimization.
*DEA*: Differential Evolution Algorithm.
*EDC*: Economic Dispatching Control.
*GA*: Genetic Algorithm.
*GenCos*: Generation Companies.
*GSA*: Gravitational Search Algorithm.
*HBF-PSO*: Hybrid Bacterial Foraging and Particle Swarm Optimization.
*HGA-PSO*: Hybrid Genetic Algorithm and Particle Swarm Optimization.
*HPSO-PS*: Hybrid Particle Swarm Optimization and Pattern Search.
*LFC*: Load Frequency Control.
*NSGA*: Non-dominated Sorting Genetic Algorithm.
*PSO*: Particle Swarm Optimization.

*Appendix*
*A.1 Data of a typical two-area power system:*
$P_R$= 2000 MW (rating), $P_L$= 1000 MW (nominal load-ing); $f$ = 60 Hz, $B_1$, $B_2$= 0.045 pu MW/Hz; $R_1$= $R_2$= 2.4 Hz/pu; $T_{H1}$= $T_{H2}$= 0.03 s; $T_{T1}$= $T_{T2}$= 0.3 s; nominal power system parameters: $K_{PS1}$= $K_{PS2}$= 120 Hz/pu MW; $T_{PS1}$= $T_{PS2}$= 20 s; $T_{12}$= 0.545 pu; $a_{12}$= −1.

*A.2 Data of a typical three-area power system:*
All data of the three-area 9-unit test system are available in [9].

*A.3 Proposed hybrid GA-PSO parameters:*
- *GA parameters:*
  Population size = 30; Maximum number of generation = 100; Crossover probability = 1; Mutaion probability = 0.1.
- *PSO parameters:*
- Population size = 30; Maximum iteration = 100; Correction factor = 0.4; Inertia = 0.2.

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