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Load Frequency Control Using Hybrid Intelligent Optimization Technique for Multi-Source Power Systems

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Abstract: The automatic load frequency control for multi-area power systems has been a challenging task for power system engineers. The complexity of this task further increases with the incorporation of multiple sources of power generation. For multi-source power system, this paper presents a new heuristic-based hybrid optimization technique to achieve the objective of automatic load frequency control. In particular, the proposed optimization technique regulates the frequency deviation and the tie-line power in multi-source power system. The proposed optimization technique uses the main features of three different optimization techniques, namely, the Firefly Algorithm (FA), the Particle Swarm Optimization (PSO), and the Gravitational Search Algorithm (GSA). The proposed algorithm was used to tune the parameters of a Proportional Integral Derivative (PID) controller to achieve the automatic load frequency control of the multi-source power system. The integral time absolute error was used as the objective function. Moreover, the controller was also tuned to ensure that the tie-line power and the frequency of the multi-source power system were within the acceptable limits. A two-area power system was designed using MATLAB-Simulink tool, consisting of three types of power sources, viz., thermal power plant, hydro power plant, and gas-turbine power plant. The overall efficacy of the proposed algorithm was tested for two different case studies. In the first case study, both the areas were subjected to a load increment of 0.01 p.u. In the second case, the two areas were subjected to different load increments of 0.03 p.u and 0.02 p.u, respectively. Furthermore, the settling time and the peak overshoot were considered to measure the effect on the frequency deviation and on the tie-line response. For the first case study, the settling times for the frequency deviation in area-1, the frequency deviation in area-2, and the tie-line power flow were 8.5 s, 5.5 s, and 3.0 s, respectively. In comparison, these values were 8.7 s, 6.1 s, and 5.5 s, using PSO; 8.7 s, 7.2 s, and 6.5 s, using FA; and 9.0 s, 8.0 s, and 11.0 s using GSA. Similarly, for case study II, these values were: 5.5 s, 5.6 s, and 5.1 s, using the proposed algorithm; 6.2 s, 6.3 s, and 5.3 s, using PSO; 7.0 s, 6.5 s, and 10.0 s, using FA; and 8.5 s, 7.5 s, and 12.0 s, using GSA. Thus, the proposed algorithm performed better than the other techniques.

Keywords: optimization techniques; multisource power system; automatic generation control; controllers; load frequency control

1. Introduction

An interconnected power network regulates the frequency to lie within the nominal range and it also controls the exchange of power. Both the active and the reactive demands are changing continuously with the dynamic change in the load, thereby, producing oscillations. The oscillations of the system can be quickly adjusted to the normal range using the Automatic Generation Control (AGC). The frequency of the power system fluctuates due to the losses in the system and the generation-load mismatch. This can also cause fluctuations in the tie-line power between the areas of the test system. The system dynamics must be stable which, can be achieved by controlling the generators and the tie-line power. This control is commonly known as the area control error (ACE). There are three key objectives of AGC, which are as follows [1–3]:

- (1) The fluctuations in the system's frequency must lie within the acceptable limit.
- (2) The fluctuations in the tie-line power must lie within the acceptable limit.
- (3) Economical operation of the generation system.

In the paradigm of the multi-area power system (MAPS), numerous research studies have been reported for the load frequency control (LFC) of the system under varying operating conditions. The issue of LFC in MAPS was presented by Cohn [4]. Elgerd and Fosha reported the challenges of designing an optimal controller for the LFC [5]. Kothari presented the seminal concept of AGC for power system, in [6]. A self-tuning algorithm for the AGC of an interconnected power system was proposed by Lee et al., in [7]. Parmar et al. [8] discussed the LFC for a single-area power system containing thermal, hydro, and gas turbine power plants along with Generation Rate Constraint (GRC). Barisal reported a Teaching Learning-Based Optimization (TLBO) algorithm for the optimal tuning of a Proportional-Integral-Derivative (PID) controller that regulates the frequency as well as the tie-line power with respect to both the AC and DC tie-lines [9]. To achieve the LFC for a Multi-Source Power System (MSPS), a fuzzy Proportional Integral Derivative (PID) controller was developed by Sahu et al., which uses hybrid Local Unimodal Sampling (LUS)-TLBO optimization technique [10]. This novel method was applicable with and without the High Voltage Direct Current (HVDC) network. In [11], a cascade tilt-integral-tilt-derivative controller was proposed for the LFC of a MSPS. A tilt-integral derivative controller was introduced by Topno et al. for a two-area power system [12]. In general, the constrained nonlinear optimization techniques can be used for optimal tuning of the controller for effective operation of power system. Mehdi Tavakoli et al. considered the challenges of wind farm integration in the power grid in the context of LFC [13]. Kangdi Lu et al. reported a population extremal optimization technique with Proportional-Integral (PI) controller in the paradigm of MAPS [14]. In this, the effectiveness of the proposed algorithm was studied across several test systems and the results were compared with those achieved using its counterparts. Furthermore, a novel fuzzy PID controller in combination with a fractional order integrator and a filtered derivative action was developed in the context of AGC for the power system [15]. Recently, Multi-Verse Optimization technique was shown to achieve better tuning of the fractional order Proportional Derivative Proportional Integral (PDPI) controller for LFC, both with and without the HVDC link [16]. Nature-inspired stochastic evolutionary algorithm was proposed in [17] to achieve optimum LFC. The power quality of a two-area power system can be improved by using an interphase power controller [18] or a Flexible Alternating Current Transmission System (FACTS) controller [19].

The novelty of the proposed technique is that it combines three well-known optimization techniques, namely, the Particle Swarm Optimization (PSO), the Gravitational Search Algorithm (GSA), and Firefly Algorithm (FA), for improved performance. Although these techniques have been used for tuning the parameters of the PID controllers for the LFC applications, the solutions are not optimum and provide slow convergence [20–22]. The proposed technique overcame these limitations by combining the advantages of all these three algorithms. It combined the attraction mechanism of fireflies in FA and mixed it with the properties of swarm intelligence of PSO, along with law of gravity of the GSA.

More exploitation and exploration components were introduced in order to explore the best possible solution in search space. It also increased the diversity and flexibility of the proposed algorithm.

In this paper, a two-area power system with multiple sources was considered. The proposed technique was used to tune the PID controller's parameters by minimizing the Integral Time Absolute Error (ITAE). System performance was examined considering the perturbation step load change in both the areas. The performance of the algorithm was compared to the other three optimization techniques and the results demonstrated the effectiveness of the proposed novel algorithm.

The organization of the rest of the article can be summarized as follows. The state of the art is reviewed in the Section 2. The PID controller and objective function are described in the Section 3, along with the details of the MSPS and MAPS. Development of the proposed hybrid intelligent optimization technique is given in Section 4. The case study along with the discussion is explained in Section 5 and, finally, the conclusion of the proposed work is discussed in Section 6. The various parameters of the algorithms are included in the Appendix A section.

2. State of the Art

This section addresses the state of the art on the LFC that considers different energy sources with multiple power systems along with different controllers.

2.1. LFC in a Single-Area Power System with Conventional Sources

Several articles have dealt with the issue of LFC in a single-area system with conventional energy sources. Luo X. Wang discussed the overview of the technologies evolved in the context of the applications and the energy storage for the power system [23]. A similar work through demand response with thermostatically controlled loads was given in [24]. The issues of data latency were discussed by Hui H Ding in [25] for the LFC under dynamically varying loads. Paliwal Nihkil et al. reported Jaya algorithm for the optimal tuning of the Linear Quadratic Regulator (LQR) controller in a single-area power system for the LFC [26].

2.2. LFC in a Two-Area Power System with Conventional Sources

The LFC of a two-area power system comprised of hydro and thermal plants was carried out using the PI controller by Jha et al., in [27]. Law et al. addressed the issue of LFC for minimizing the risk [28]. For a MAPS with renewable energy sources, a whale optimization algorithm was developed to achieve the load frequency management [29]. Rahman et al. reported the issues of LFC for hybrid power system consisting of Photo-Voltaic (PV) and wind turbine systems [30]. The problem of integrating an electric vehicle in the power system and optimally dispatching its participation in the LFC was discussed in [31]. A. Dutta has considered the LFC of a MSPS with electric vehicles, interconnected using transmission links [32]. In the case of AGC of a two-area power system (TAPS), the challenges of designing an intelligent controller were shown in [33].

2.3. LFC in a MAPS with Conventional Sources

Gondaliya Snehal reported advanced controllers for the LFC of a MAPS [34]. For nonlinear MAPS, the use of flower pollination algorithm gives fascinating results [35]. Alhelou et al. utilized wind-driven optimization algorithm for the LFC of MAPS [36]. They also considered GRC with nonlinearity in their work. Saha et al. reported the use of stochastic fractional search algorithm for the LFC of MAPS that included a thermal power plant [37]. Raju et al. reported the issue of LFC of MAPS with distributed generation resources, using a hybrid Ant-Lion Optimizer (ALO) pattern search optimization technique [38]. The LFC of a power system with electric vehicles was discussed by A. Saha in [39]. Here, electric vehicle system was integrated and the effect of cascade controller was studied. In [40], an optimal strategy was presented for LFC in the presence of cyberattacks.

2.4. Load Frequency Control with Renewable Sources

With the deployment of different renewable energy sources, more consciousness was needed to mitigate the variations in the frequency. The dynamic response of the system mainly depends on the controller action and its proper tuning. In [41], a social spider optimization technique was used to tune the frequency controller for a two-area hybrid micro system. The LFC for a multi-micro grid was reported in [42]. An improved swarm optimization technique with type II fuzzy controller was used for the LFC of an Alternating-Current (AC) micro grid having multi-area islands in [43]. For the LFC of a hybrid micro-grid system, grasshopper optimization technique was used for tuning the PID controller in [44]. Researchers reported the LFC of the power system with hybrid energy sources (including renewable sources) using different intelligent optimization algorithms [45–49].

2.5. Some Recently Developed Controllers

Use of different controllers has been reported by various researchers for MSPS system for conventional power systems as well as those with renewable energy sources. The issue of LFC for MAPS can be handled using direct synthesis approach for tuning the PID controller, as reported in [50]. In case of a deregulated power supply, the coordinated control can be achieved using PI2 controller with redox flow battery and Unified Power Flow Controller (UPFC) [51]. Reduced-order modeling with fractional-order controller was used to achieve the LFC in a MAPS [52]. Further, Lion Algorithm-Based Fractional Order PI (LFOPI) controller was used to achieve the LFC in a MAPS in [53]. Design of a new fractional order PI and Proportional-Derivative (PD) controller was reported in [54] for the AGC of a MAPS. Multi-Objective Uniform Diversity Genetic Algorithm (MUGA) was applied to design a controller for the LFC, in [55]. The comparison of these contemporary literatures based on their approaches and findings are summarized in Table 1.

Table 1. Comparison of the state-of-the-art approaches.

Domain	Key Problems Addressed	References
LFC in conventional power system with single area	Contemporary technologies for energy storage; behavior of the load; impact of data latency on LFC; algorithms for optimal tuning of LFC	[23–26]
LFC in conventional power system with two area	Multi-source two area power system with PI controller; reliability concerns; whale optimization algorithm; multi-source power system with PV and wind turbine; electric vehicle with LFC challenges; multiple sources and the related challenges; intelligent controller for AGC	[27–33]
LFC in conventional power system with multiple area	controllers for LFC of MAPS; flower pollination algorithm; wind driven optimization algorithm for LFC; GRC with nonlinearity; stochastic fractional search algorithm for LFC; hybrid ALO pattern search optimization; effect of cascade controller on electric vehicles; security concern related to LFC	[34–40]
LFC in power system with renewable sources	social spider optimizer technique; LFC for multi micro grid power system; improvisation of swarm optimization technique; grasshopper optimization technique; intelligent optimization techniques with renewable sources	[41–49]
Advancements in controllers for LFC of power system	PID controller for MAPS; PI2 controller for MAPS; fractional order controller to achieve LFC in MAPS; LFOPI controller; new fractional order PI and PD controller; MUGA for controller design	[50–55]

3. PID Controller and the Proposed Power System

The proposed work presents a heuristic-based new hybrid optimization technique for automatic LFC of a two-area MSPS. Proposed intelligent technique uses the main features of three different optimization techniques, namely, the Firefly Algorithm (FA), the Particle Swarm Optimization (PSO), and the Gravitational Search Algorithm (GSA). This hybrid technique is used for the parametric tuning of the PID to regulate the fluctuations in the frequency and the tie-line power. The PID is one of the most widely used controllers and is ubiquitous in today's modern industries. Moreover, it is widely applicable in the

systems with single-input, single-output systems. The output of the PID controller can be represented by Equation (1).

$$U(t) = K_{pr}e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

where $e(t)$ and $u(t)$ denote the input and output of the PID controller. Moreover, K_{pr} , K_i and K_d represent the proportional gain, the integral gain, and the derivative gain, respectively.

We considered the ITAE as the objective function. The tuning of the parameters of the PID controller was achieved by minimizing this objective function. The objective function can be described by Equation (2).

$$ITAE = \int_0^{t_{sim}} t \times |e(t)| dt \quad (2)$$

A test system consisting of two areas was considered for the LFC analysis. The test system used multiple sources for power generation, such as the hydro power plant, the gas turbine power plant, and the thermal power plant. The modeling of this test system was done in MATLAB SIMULINK using linearized approach, and the model is depicted in Figure 1. Some of the parameters of this test system are mentioned in the Appendix A. In each area, all the three different plants were connected and one PID controller was used for the AGC. The performance was measured by capturing the dynamic responses of the frequency, tie-line power, and the ACE. The perturbation with step load was considered for both the areas of the power system. The generators in each area may or may not have changed their output power with variation in the load. It depended on their participation rates. The participation rates were not necessarily the same for all the generators. However, the summation of participation factors for all the generators in each area must be unity.

Objective Function for Automatic Generation Control (AGC)

For the proper operation of the power system under varying operating conditions, optimal tuning of the controllers connected in the system are very important. The parameters of the controllers have to be tuned to make it robust against model uncertainty and dynamical changes. It should be able to track the desired point for all the variables and should be sensitive to the fluctuations in the load perturbation.

There have been many performance indices such as integral of absolute error, integral of time weighted squared error, integral of squared error, and integral time absolute error in literature. However, ITAE was found to give satisfactory results for parametric optimization with respect to LFC in terms of settling time and overshoot. Therefore, we considered ITAE as an objective function in our current work.

$$J = ITAE = \int_0^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{tie}|) . t . dt \quad (3)$$

where ΔP_{tie} is the variation in tie-line power and ΔF_1 and ΔF_2 represents variation in frequency corresponding to area 1 and area 2, respectively. The objective function was minimized by the proposed hybrid optimization technique for finding the PID controller's parameters.

The following were the constraints:

$$\begin{aligned} K_{P_{min}} &< K_P < K_{P_{max}} \\ K_{I_{min}} &< K_I < K_{I_{max}} \\ K_{D_{min}} &< K_D < K_{D_{max}} \end{aligned}$$

The differential equation for PID controller is shown in Equation (1). Furthermore, we have

$$U_1 = K_{P1} \cdot ACE_1 + K_{I1} \cdot \int ACE_1 + K_{D1} \cdot \frac{dACE_1}{dt} \quad (4)$$

$$U_2 = K_{P2} \cdot ACE_2 + K_{I2} \cdot \int ACE_2 + K_{D2} \cdot \frac{dACE_2}{dt} \quad (5)$$

where

$$ACE_1 = B_1 \Delta F_1 + \Delta P_{tie} \quad (6)$$

$$ACE_2 = B_2 \Delta F_2 - \Delta P_{tie} \quad (7)$$

From the Figure 1, and from the Equations (6) and (7), it can be understood that the ACE depended on the variations in the frequency and tie-line power for the given test system. Input to the PID controller was ACE. Equations (4) and (5) indicate the importance of properly tuning the parameters of PID controller i.e., the proportional gain constant K_P , the integral gain constant K_I , and the derivative gain constant K_D . The objective function is given by the Equation (3) and the parameters of PID controller were tuned using the proposed hybrid intelligent optimization technique for improving the LFC of the two-area system.

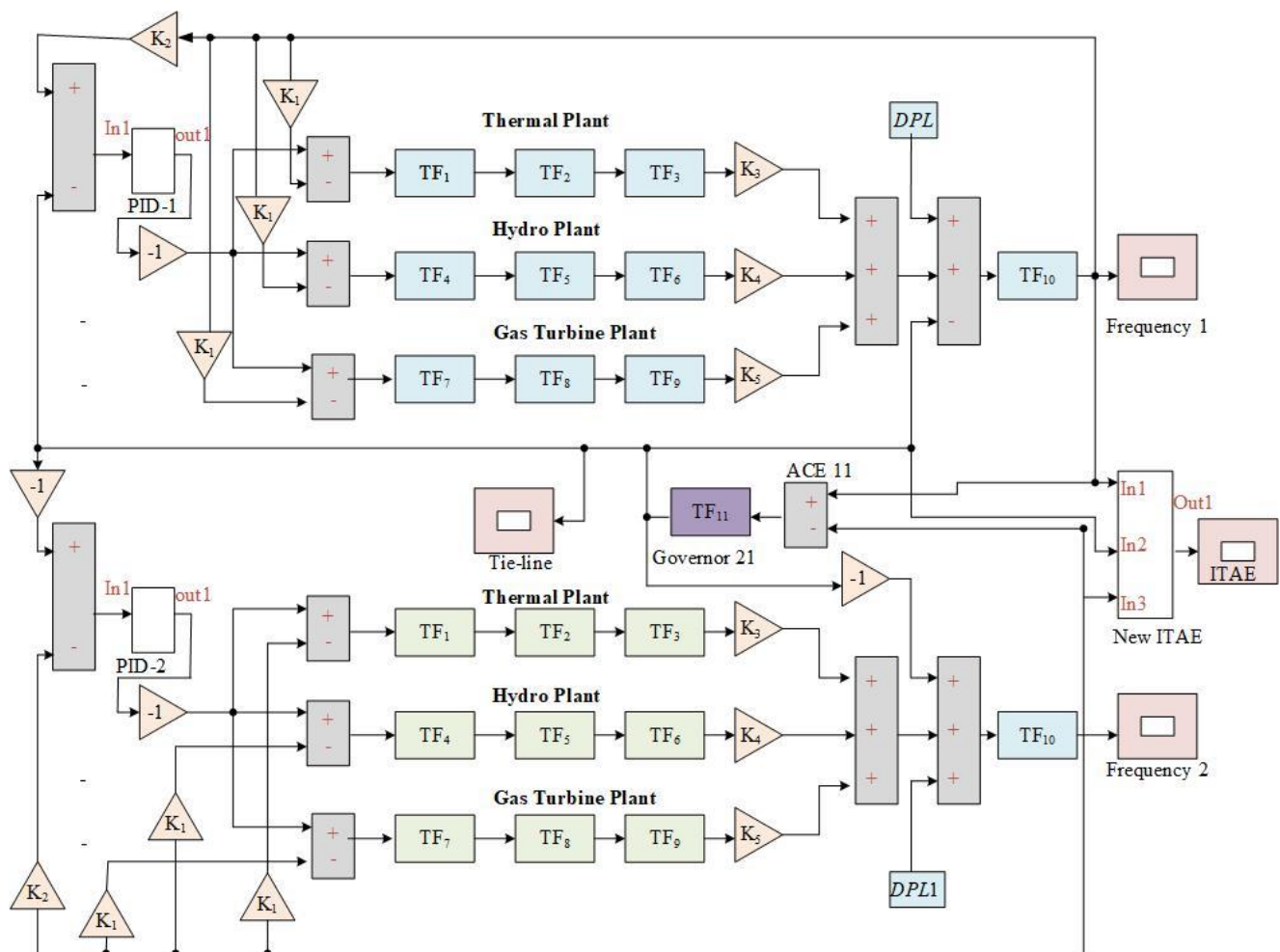


Figure 1. Simulink implementation of a two-area MSPS.

4. Hybrid Intelligent Optimization Technique

The proposed hybrid intelligent optimization (HIO) technique is a combination of three well-known optimization techniques, namely, the FA, the PSO, and the GSA. The possible candidate solutions were regarded as objects. Further, the position of every object was updated depending upon the properties of all the three optimization techniques.

The FA is basically based on the behavior of flashing light. This flashing light attracts the potential prey and also helps in communication with the other fireflies [56]. Further, the GSA optimization technique is motivated by Newton's gravitational law. Without loss of generality, the performance of each object is measured in terms of their corresponding mass. A linear relationship exists between the masses and the objective function [57]. PSO is used to update the particle's position (candidate solution) depending upon the particle's velocity. Each particle's velocity is decided by the current particle's best position and particle's global best [58].

The hybrid intelligent optimization technique takes the properties of all the three algorithms and updates the values of its object (candidate solution) by integrating all the three algorithms' updated equations [59].

$$x_i = (x_i^1, \dots, x_i^{d-1}, x_i^d, \dots, x_i^m) \forall i \in \{1, 2, \dots, N\} \quad (8)$$

Here x_i^d denotes position i th of agent in d th dimension.

$$x_i^d(t+1) = x_i^d(t) + \beta_0 e^{-\gamma r_{ij}^2} (x_j - x_i) + a_i^d(t) + v_i^d(t+1) + \alpha \varepsilon \quad (9)$$

Here, $x_i^d(t)$ is the current position of object for iteration t .

The second term of the Equation (9) denotes the property of firefly algorithm (FA) where objects attract each other based on the attractiveness β_0 .

If the positions of the i th and the j th fireflies are known to be as x_i and x_j , respectively, then the Euclidian distance r_{ij} can be used to estimate distance between them.

$$r_{ij} = \sqrt{\sum_{k=1}^d (x_{i,k} - x_{j,k})^2} \quad (10)$$

The attraction between the fireflies is given by:

$$\beta = \beta_0 e^{-\gamma r^2} \quad (11)$$

The third term of the Equation (9) shows the acceleration of the object by which it will update its position to the new one using the property of the GSA optimization technique.

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \quad (12)$$

where $a_i^d(t)$ is the acceleration in the dimension d of the object i for iteration t and $F_i^d(t)$ is the force that acts on a single object.

$$F_i^d(t) = \sum_{j=1: j \neq i}^N \text{rand}_j F_{ij}^d(t) \quad (13)$$

Now, the resultant force due to mass j on mass i is:

$$F_{ij}^d(t) = G(t) \frac{M_{pi}(t) \cdot M_{aj}(t)}{R_{ij}(t) + \varepsilon} (x_j^d(t) - x_i^d(t)) \quad (14)$$

where R_{ij} is the Euclidian distance between agent i and agent j . M_{aj} is the active gravitational mass of agent j and $G(t)$ is gravitational constant. Further, the masses of each agent are updated by:

$$m_i(t) = \frac{\text{worst}(t) - \text{fit}_i(t)}{\text{worst}(t) - \text{best}(t)}$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)} \quad (15)$$

The fourth term of Equation (9) shows the velocity of each object, which is updated based on the PSO optimization technique.

$$v_i^d(t+1) = v_i^d(t) + r1 \cdot c1 \cdot (pbest(t) - x_i^d(t)) + r2 \cdot c2 \cdot (gbest(t) - x_i^d(t)) \quad (16)$$

where r_1 and r_2 are random numbers in the limit $[0, 1]$, p_{best} and g_{best} are personal best and global best of particles, and c_1 and c_2 are the acceleration coefficients. The new direction with respect to the search space is characterized by the random movement, which is captured in the last term of the equation.

5. Results and Discussion

The model for the MSPS was developed using the concepts of controls' systems. Different plants, such as thermal, hydro, and gas turbine, were represented using their equivalent transfer functions. Two different areas were considered with these power plants. Using Equation (1) and Equations (4)–(7), the test system was designed to evaluate the performance. On the other hand, the proposed hybrid intelligent optimization technique was designed using Equations (2), (3), and (8)–(16).

The test system was implemented as a Simulink model using the MATLAB (R2016a) software on an i5-6200 CPU@ 2.30 GHz with 8 GB RAM. Also, the proposed algorithm was implemented using MATLAB. Furthermore, the other optimization techniques such as PSO, FA, and GSA were also implemented using the MATLAB. All these four algorithms were integrated with MATLAB Simulink model of the test system to obtain a comparative performance evaluation. Some other key parameters of the test system and parameters related to the optimization techniques are elaborated in the Appendix A of the manuscript.

Based on several case studies, the effectiveness of the proposed controller was analyzed under dynamic system operating conditions. Based on the four optimization techniques, the parameters of PID controller was tuned by minimizing the ITAE. Specifically, the optimization techniques were used to find the optimal parameters of PID controller, which are used for the LFC of the MSPS. To elucidate the efficacy of the proposed optimization techniques, we considered two cases, which are described below.

Case Study I: Both the areas of the test system were subjected to a load increment of up to 0.01 p.u. The proposed hybrid intelligent optimization algorithms FA, PSO, and GSA were used for the parametric tuning of the PID controller. Their performances were compared in terms of settling time and overshoot for the ΔF_1 , ΔF_2 , and ΔP_{12} variables, where ΔP_{12} is the variation in tie-line power and ΔF_1 and ΔF_2 represent the variation in frequency corresponding to area 1 and area 2, respectively. Table 2 represents the tuned PID controller parameters. Table 3 reports the peak overshoot and the settling time for variables of interests. The dynamic responses are depicted in Figure 2. The overshoot/undershoot phenomena could not be avoided in MSPS with perturbation step load change. However, minimum settling time was of the utmost importance for the proper operation of the MSPS. Thus, the minimum settling time was the most desirable metric in comparison to the overshoot/undershoot. Conclusively, the efficacy of the proposed algorithm was measured in terms of settling time. The settling times (frequency deviation in area-1, frequency deviation in area-2, and tie-line power flow, respectively) obtained for case study I were 8.5 s, 5.5 s, and 3.0 s, using the proposed algorithm, which was better against the results of

8.7 s, 6.1 s, and 5.5 s using PSO; 8.7 s, 7.2 s, and 6.5 s using FA; and 9.0 s, 8.0 s, and 11.0 s using the GSA.

Table 2. PID controller tuned parameters using different optimization techniques—case study I.

O.T.	K_{p1}	K_{i1}	K_{d1}	K_{p2}	K_{i2}	K_{d2}	ITAE
FA	6.797	7.964	3.24	8.976	7.6	4.39	0.075
PSO	8.474	9.80	3.25	6.35	8.4	1.92	0.069
GSA	5.514	8.680	5.81	7.462	6.4	3.17	0.089
HIO (Proposed)	10.00	10.00	3.26	10.00	9.9	3.3	0.054

Table 3. Effect of different optimization techniques on system state variables- case study I.

O.T.	States Variables	Over-Shoot	Settling Time
HIO (Proposed)	ΔF_1	−0.0134	8.5
	ΔF_2	−0.013	5.5
	ΔP_{12}	−0.000013	3.0
PSO	ΔF_1	−0.0135	8.7
	ΔF_2	−0.017	6.1
	ΔP_{12}	0.0007	5.5
FA	ΔF_1	−0.0135	8.7
	ΔF_2	−0.012	7.2
	ΔP_{12}	−0.0004	6.5
GSA	ΔF_1	−0.0115	9.0
	ΔF_2	−0.0135	8.0
	ΔP_{12}	0.0005	11.0

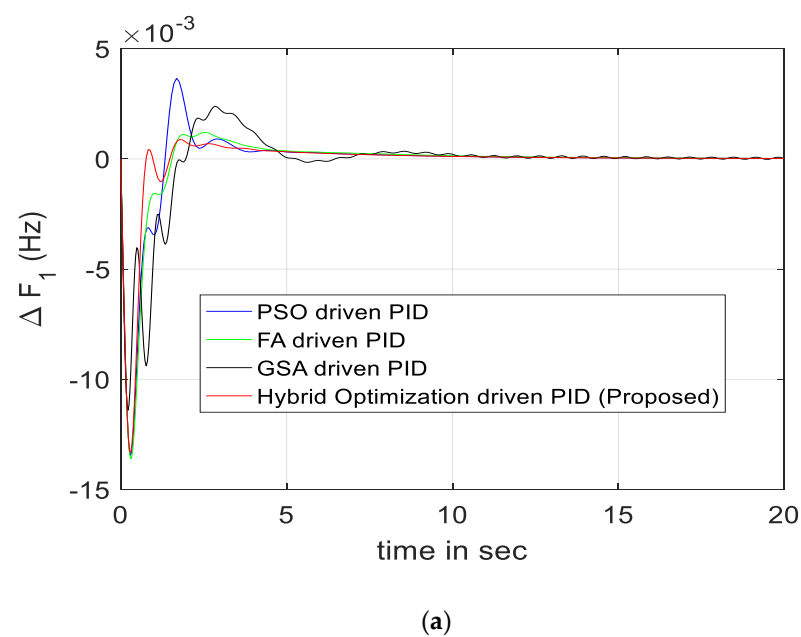


Figure 2. Cont.

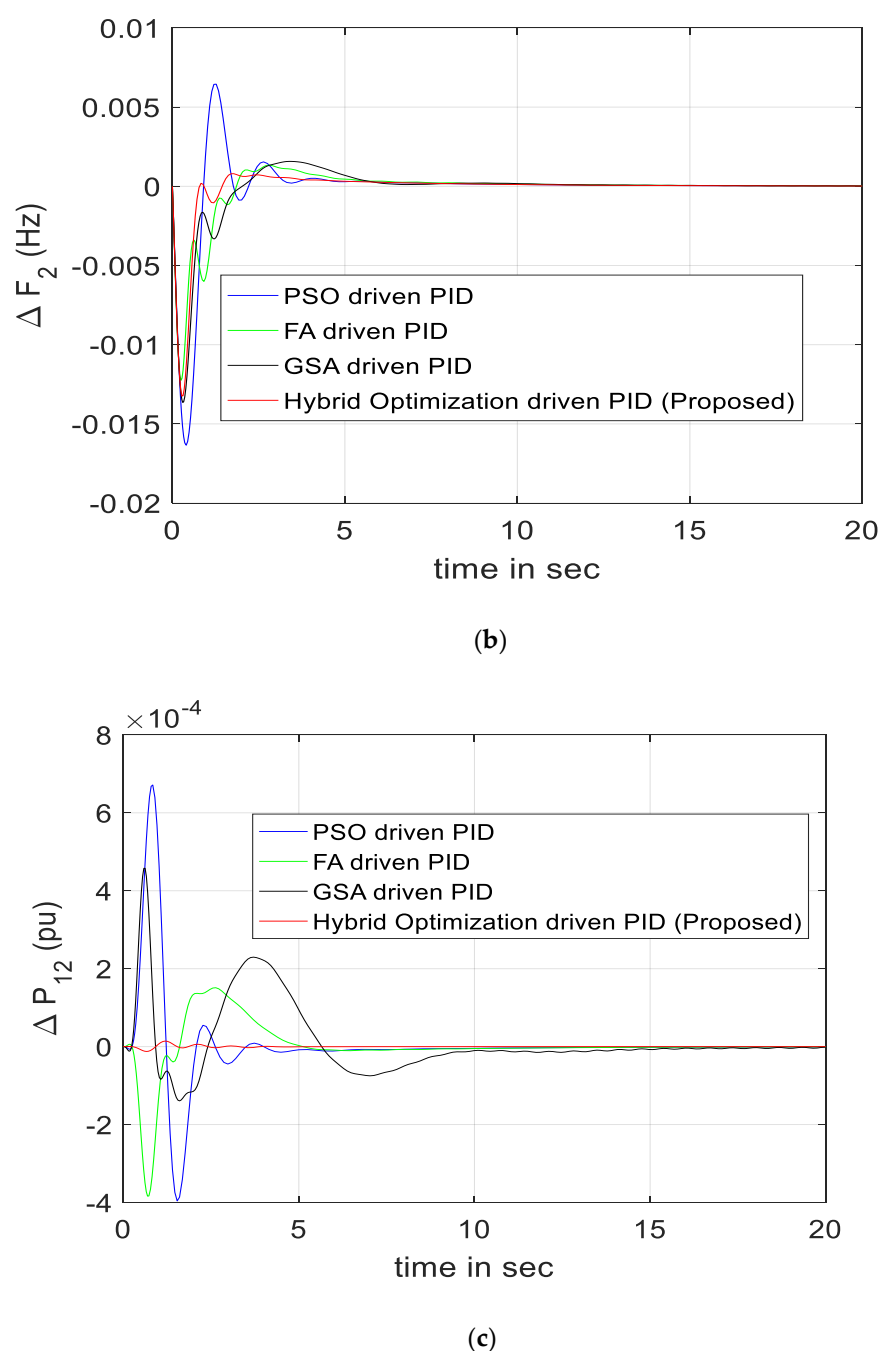


Figure 2. Dynamic response of a two-area MSPS for case study I. (a) ΔF_1 , (b) ΔF_2 , and (c) ΔP_{12} .

It can be clearly seen that the proposed optimization technique completely outperformed the other three well-known optimization techniques (PSO, FA, and GSA) in terms of settling time. Moreover, the overshoot was also seen to be minimum with the proposed algorithm for tie-line power flow, which is an added advantage of the proposed algorithm.

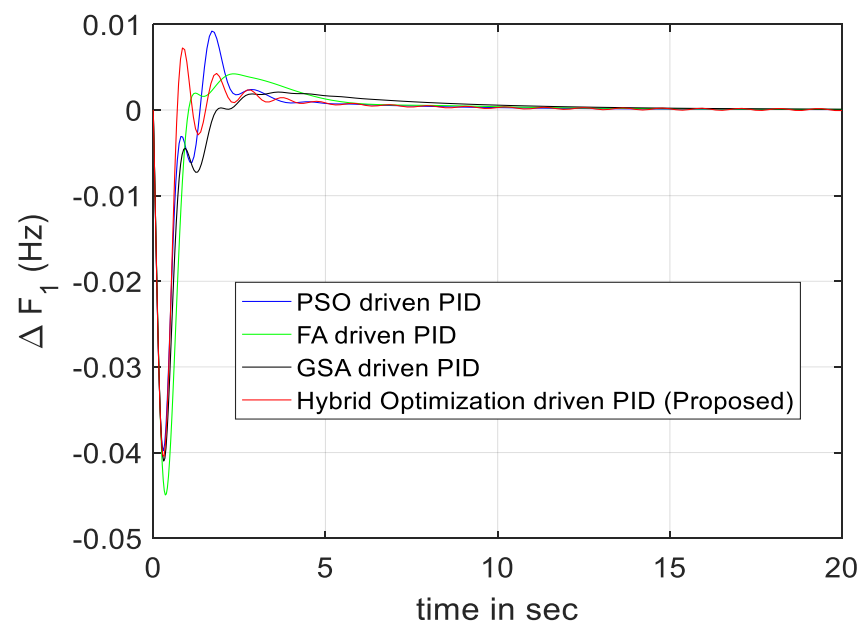
Case Study II: In this case, we considered area 1 with increments in load up to 0.03 p.u. and in area 2 with increments in load up to 0.02 p.u. All four techniques were used to obtain the tuned parameters of the PID controller. In response to the perturbation step load change, the performance was evaluated for all three system variables ΔF_1 , ΔF_2 , and ΔP_{12} using proposed techniques. The tuned parameters of PID controller is summarized in Table 4. Further, for system variables the peak overshoot and settling time are summarized in Table 5. The dynamic response to perturbation step load is shown in Figure 3 for each system variable.

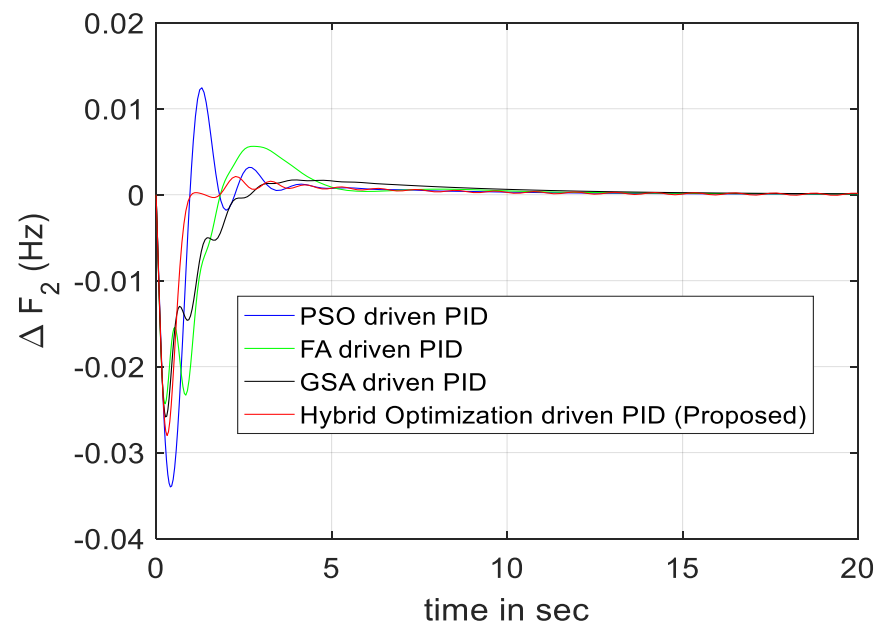
Table 4. PID controller tuned parameters using different optimization techniques—case study II.

O.T.	K _{p1}	K _{i1}	K _{d1}	K _{p2}	K _{i2}	K _{d2}	ITAE
FA	5.37	6.72	2.42	5.84	6.81	4.73	0.238
PSO	8.47	9.80	3.25	6.35	8.4	1.92	0.168
GSA	7.28	5.23	3.02	8.54	5.4	3.84	0.275
HIO (Proposed)	9.79	10.00	2.99	10.00	10	2.99	0.143

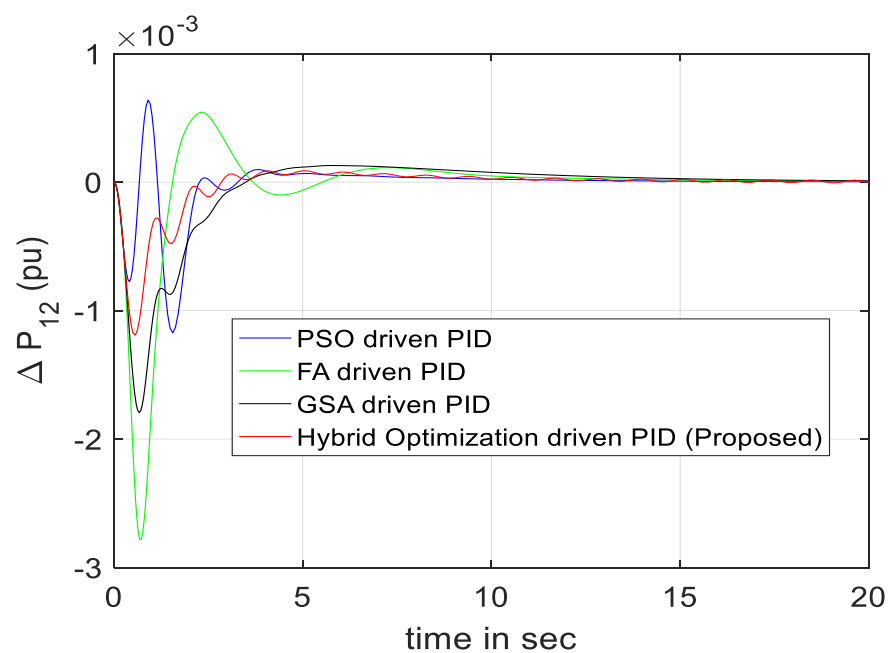
Table 5. Effect of different optimization techniques on system state variables- case study II.

O.T.	States Variables	Over-Shoot	Settling Time
HIO (Proposed)	ΔF_1	−0.040	5.5
	ΔF_2	−0.027	5.6
	ΔP_{12}	−0.0011	5.1
PSO	ΔF_1	−0.039	6.2
	ΔF_2	−0.033	6.3
	ΔP_{12}	−0.0007	5.3
FA	ΔF_1	−0.045	7.0
	ΔF_2	−0.024	6.5
	ΔP_{12}	−0.0027	10
GSA	ΔF_1	−0.041	8.5
	ΔF_2	−0.026	7.5
	ΔP_{12}	−0.0017	12

**(a)****Figure 3.** *Cont.*



(b)



(c)

Figure 3. Dynamic response of a two-area MSPS for case study II (a) ΔF_1 , (b) ΔF_2 , and (c) ΔP_{12} .

The settling times (frequency deviation in area-1, frequency deviation in area-2, and tie-line power flow, respectively) obtained for case study II were 5.5 s, 5.6 s, and 5.1 s, using the proposed algorithm, which was better against the results of 6.2 s, 6.3 s, and 5.3 s using PSO; 7.0 s, 6.5 s, and 10.0 s using FA; and 8.5 s, 7.5 s, and 12.0 s using GSA.

It can be clearly seen that the proposed optimization technique completely outperformed the other three well-known optimization techniques (PSO, FA, and GSA) in terms of settling times. Moreover, the proposed algorithm also offered minimum overshoot compared to the other techniques, excluding PSO.

6. Conclusions

The challenges related to the LFC in a MAPS with multiple sources was addressed in the proposed work. We considered a two-area power system with multiple sources. An intelligent optimization technique was developed by combining and extracting the main features of the three well-known optimization techniques, the PSO, the GSA, and the FA. The proposed technique was used to tune the PID controller's parameters by minimizing ITAE performance indices. System performance was examined considering perturbation step load change in both the areas. Simulation of the test system subjected to perturbation step load was carried out to evaluate the performance and robustness of the novel, proposed algorithm with respect to peak overshoot and settling time performance indices. The settling times (frequency deviation in area-1, frequency deviation in area-2, and tie-line power flow, respectively) obtained for the case study I were 8.5 s, 5.5 s, and 3.0 s using the proposed algorithm against the results of 8.7 s, 6.1 s, and 5.5 s using PSO; 8.7 s, 7.2 s, and 6.5 s using FA; and 9.0 s, 8.0 s, and 11.0 s using GSA. Similarly, the settling times (frequency deviation in area-1, frequency deviation in area-2, and tie-line power flow, respectively) obtained for case study II were 5.5 s, 5.6 s, and 5.1 s using the proposed algorithm against the results of 6.2 s, 6.3 s, and 5.3 s using PSO; 7.0 s, 6.5 s, and 10.0 s using FA; and 8.5 s, 7.5 s, and 12.0 s using GSA. Even though settling time is a more desirable metric compared to overshoot/undershoot, it was found that, for case study I, the overshoot/undershoot was minimum with the proposed algorithm for tie-line power flow. Similarly, for case study II, the proposed algorithm also offered lower overshoot than other techniques, except PSO. Conclusively, it was observed that the proposed technique outperformed the other three well-known techniques, which were PSO, FA, and GSA. Therefore, the proposed controller is effective and convenient for real-time implementation. In spite of comparing the proposed optimization techniques with other well-known optimization techniques, it would be interesting to see the impact of different controllers. Thus, unlike the present work where we used PID controller, the authors are interested in observing the impact of different controllers on the performance of the MSPS in their future work. Furthermore, the authors wish to obtain the system performance in a deregulated environment with power contracts between many generation stations and the consumers.

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Appendix A

In order to simplify the testing and implementation, the values of the parameters used for the power system and for the other optimization techniques are listed below [9].

Rated power (P_R) = 2000 MW; Frequency (f) = 50 Hz; frequency biased constant (B) for area 1 and area 2: $B_1 = B_2 = 0.4312$ p.u. MW/Hz; nominal load power (P_L) = 1840 MW; turbine time constant (T_t) = 0.3 s; reheater gain and time constant: (K_R) = 0.3, T_r = 10 s; speed governor time constant (T_{sg}) = 0.08; participation factor for turbine (K_T) = 0.543478; droop governor constants (R) for thermal (R_1) hydro (R_2) gas (R_3): $R_1 = R_2 = R_3 = 2.4$ Hz/p.u. MW; mechanical hydraulic time constants: $T_{rh} = 28.75$ s, $T_{gh} = 0.2$ s; participation factor for gas (K_G) = 0.130438; participation factor for hydraulic (K_H) = 0.326084; parameters and constant of gas power plant: $Y_c = 1$ s, $b_g = 0.5$, $X_c = 0.6$ s, $c_g = 1$, $T_{cr} = 0.01$ s, $T_{cd} = 0.2$ s; hydro-turbine time constant (T_W) = 1 s; power system time constant (T_{ps}) = 11.49 s; time

constant (T_{rs}) = 5 s; time constant (T_{fc}) = 0.23 s; gain and time constant for DC: $K_{dc} = 1$, $T_{dc} = 0.2$ s; power system gain constant (K_{ps}) = 68.9566 Hz/p.u. MW; tie-line constant: $a_{12} = -1$, $T_{12} = 0.0433$ p.u.

Hybrid Intelligent Optimization Technique: No. of Objects: 20, α (randomness) = 20, β_0 (attractiveness) = 0.2, G_0 (gravitational constant) = 100, γ (absorption) = 1, No. of Iteration: 25.

GSA Parameters: No. of populations: 20, G_0 (gravitational constant) = 100, $\alpha = 20$, No. of iterations: 25.

FA Parameters: No. of fireflies: 20, α (randomness) = 0.5, $\beta_0 = 0.2$, γ (absorption) = 1, No. of Iteration: 25.

PSO Parameters: No. of iterations: 25, No. of particles = 20.

In Figure 1: $TF_1 = \frac{1}{0.08s+1}$, $TF_2 = \frac{3s+1}{10s+1}$, $TF_3 = \frac{1}{0.3s+1}$, $TF_4 = \frac{1}{0.2s+1}$, $TF_5 = \frac{5s+1}{28.75s+1}$, $TF_6 = \frac{-s+1}{0.5s+1}$, $TF_7 = \frac{1}{0.05s+1}$, $TF_8 = \frac{0.6s+1}{s+1}$, $TF_9 = \frac{-0.01s+1}{0.23s+1}$, $TF_{10} = \frac{68.9566}{11.49s+1}$, $TF_{11} = \frac{6.28 \times 0.0433}{s}$, $K_1 = \frac{1}{2.4}$, $K_2 = 0.4312$, $K_3 = 0.543478$, $K_4 = 0.326084$, and $K_5 = 0.130438$.

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