Firefly Optimization Based Control Strategies for Combined Load Frequency Control and Automatic Voltage Regulation for Two-Area Interconnected Power System

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Abstract: In this research work the combined Load Frequency Control (LFC) and Automatic Voltage Regulation (AVR) of a two-area interconnected power system has been considered. Each control area consists of linearized model of thermal and hydropower system. PID controller has been used as the secondary controller for the combined LFC-AVR of the proposed system. A powerful meta-heuristic algorithm Firefly optimisation technique is used for the optimisation of the proposed controller. Comparison of the system dynamics with and without proposed controller is investigated to show effectiveness of the proposed control scheme. Also, a comparison of the proposed control scheme with other popular meta-heuristic techniques shows the superiority of the proposed control scheme. Moreover, small signal stability analysis of the proposed system has been done using the state space representation of the proposed system.

Keywords: AVR, FA, LFC, PID, PSO.

1. Introduction

Maintenance of reliable and quality power is becoming an ever-increasing challenge in this modern and dynamic world. Generally, when the load side demand changes, a breach in the frequency and voltage subsequent to the load is also witnessed. for the regulation of power frequency load frequency control (LFC) is used, while the machine power output is controlled by the automatic voltage regulator (AVR) by regulating the voltage [1]. Most of the research in literature is generally focussed on the LFC and AVR problem separately. But, when demand changes, there is a deviation in both the frequency and voltage simultaneously from their nominal values respectively. Thus, there is a need to investigate on the combined LFC-AVR problem. Chandrakala et al. used simulated annealing based PID controller for the combined LFC-AVR of the two-area multi-source power system [2]. Qin et al. have used non-linear programming for the AVR of power systems with limited continuous voltage control capability to minimize operational cost [3]. Abd-Alazim et al. have used firefly algorithm based PI controller for LFC of a system including PV grid [4]. Guha et al. have used symbiotic organism search based PID controller for the LFC of a two area thermal reheat system [5]. Mostly researchers have focussed on single, two or three area systems having conventional or non-conventional generation sources to study the LFC problem in different environments [6][7][8][9][10]. Essentially, in this research work the authors have tried to investigate the LFC and AVR problem in a combined manner since very few literature are available in this field.

Various types of controller are discussed in the literature. Conventional controllers are generally preferred by both the researchers and the industry due to their low cost and simple construction. Conventional controllers like integral (I), proportional-integral (PI) and proportional-integral-derivative (PID) are readily used in the literature [11][12][13]. A conventional controller performs satisfactorily only when its parameters are optimised according to the system conditions. For this both manual and automatic techniques are available in literature, though automatic techniques are generally preferred. Intelligent techniques based on modern optimisation algorithms are generally used for the tuning of controller parameters according to the system requirements. Some of the intelligent algorithms used in the literature for the tuning of controller parameters are genetic algorithm (GA) [14], particle swarm

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optimisation (PSO) [15], quasi-oppositional harmonic search (QOHS) algorithm [16], fruitfly optimisation algorithm (FOA) [17], bacteria foraging algorithm (BFA) [18], whale optimisation algorithm (WOA) [19] and interactive search algorithm (ISA) [20].

The main highlights of the current research work are:

a) Combined LFC-AVR model of a two-area interconnected hybrid power system.
b) Investigate the effect of AVR loop in LFC of the proposed system.
c) Investigate the effect of the secondary controller on the dynamics of the system.
d) Investigate the small signal stability of the proposed model.
e) Implementation of the efficacy of FireFly Algorithm (FA) and Particle Swarm Optimization (PSO) for the optimization of the proposed controller.
f) Comparison of the effects of FA-based PID controller and PSO-tuned PID controller on the dynamics of the proposed model to show the dominance of the proposed controller.
g) Comparison of convergence profile of proposed scheme with PSO, WOA and ISA based control scheme

The rest of this research work is divided into the subsequent parts. Section-2 discusses the detailed modelling of the combined LFC-AVR model of a two-area interconnected power system. Section-3 deals with the FA technique and the formulation of the objective function. Section-4 investigates the small signal stability analysis of the proposed model. Section-5 gives the simulation results and analysis of the proposed model. Finally, section-6 concludes the present research work.

2. Integrated LFC-AVR model for multi-area power system

In this research work, a two-area system, each having a thermal and a hydro system, is considered. The LFC-AVR loop has been integrated into the proposed model. Though the loop acts slowly, it helps in minimizing the system disturbance. The thermal system is composed of the hydraulic amplifier, speed governor, boiler and non-reheat turbine while the hydro system comprises of the hydro-speed governor and hydro turbine. When a disturbance occurs in the system, the speed governor adjusts the input of the turbine so as to compensate the extra demand. The transfer function for the governor can be written as:

$$\Delta P_G = \Delta P_{Ref1} - \frac{1}{R_1}\Delta f_1 \tag{1}$$

Also to fulfill the demand, the boiler transmits the control action to the turbine control valves by sensing the deviation in the steam-flow and pressure drum. The model of the boiler system is shown in Figure 1.

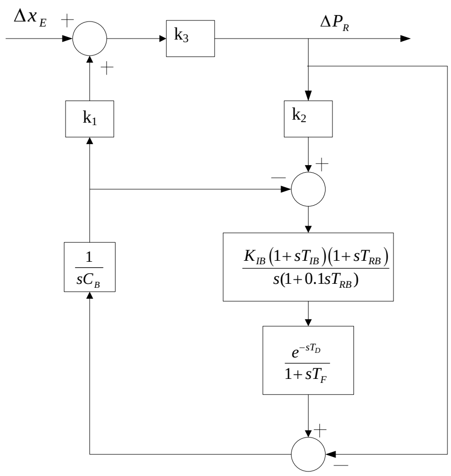

Figure 1. Detailed Model of the Boiler System

The boiler is coupled to the output of the hydraulic amplifier and the turbine input, so as to control its valve power 'ΔP_V' w.r.t. 'ΔP_R'. The turbine power output, 'ΔP_T' driving the generator is given as:

$$\Delta P_T = \frac{1}{1+sT_T}\Delta P_R \quad (2)$$

Likewise, hydro-power plant is composed of the hydro turbine and speed governor. The role of the speed governor in a hydropower plant is same as that in a steam power plant. The reset time of a hydro governor system is given as:

$$T_R = [5 - 0.5(T_W - 1)]T_w \quad (3)$$

Where T_W is the water time constant having the range of 1 s and 4 s. The hydro governor constant (T_1) can be written as:

$$T_1 = \frac{R_{TD}}{R_{PD}}T_R \quad (4)$$

Where,
R_{TD} = Temporary droop characteristic of the hydro governor
R_{PD} = Permanent droop characteristic of the hydro governor

$$R_{TD} = [2.3 - 0.15(T_w - 1)]\frac{T_W}{T_M} \quad (5)$$

Where T_M is the time constant of the machine is equal to 2H; H being the inertia constant. The change of frequency is sensed by the governor indirectly when there is some discrepancy between the generation and demand. The water input to the turbine is then controlled by the governor according to Eqn. (6).

$$\Delta P_{HT} = \frac{(1-sT_W)}{(1+0.5sT_W)}\Delta P_{HV} \quad (6)$$

The tie-line power interchange is governed by (7)

$$\Delta P_{tie12} = \frac{2\Pi T}{s}(\Delta f1 - \Delta f2) \quad (7)$$

For an AVR system, the effect of small deviation in terminal voltage on the real power, ΔP_{real} is governed by the (8)

$$\Delta P_{real} = P_s\Delta\delta + K_1V_F \quad (8)$$

Thus, the effect of small change in power angle, $\Delta\delta$ on the terminal voltage deviation is given by (9)

$$\Delta V_t = K_2\Delta\delta + K_3V_F \quad (9)$$

The detailed model of the AVR loop or the exciter is shown in Figure.2.

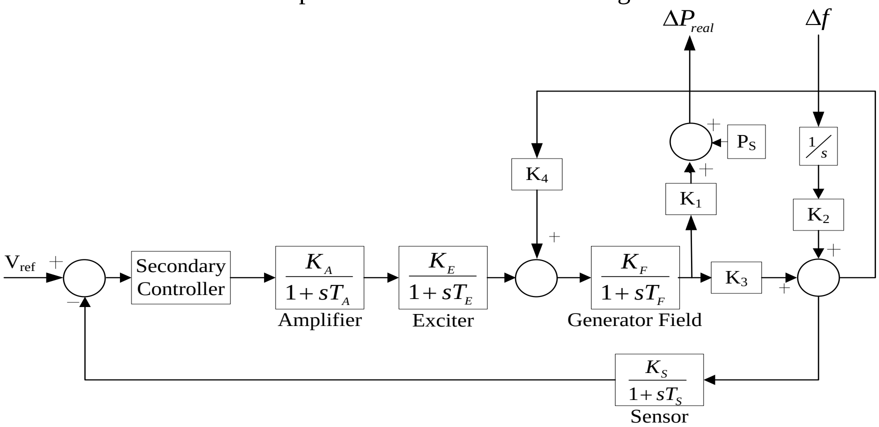

Figure 2. Detailed Model of the AVR loop as the Exciter

The two-area interconnected power system incorporating both LFC and AVR loop under investigation has been shown in Figure 3.

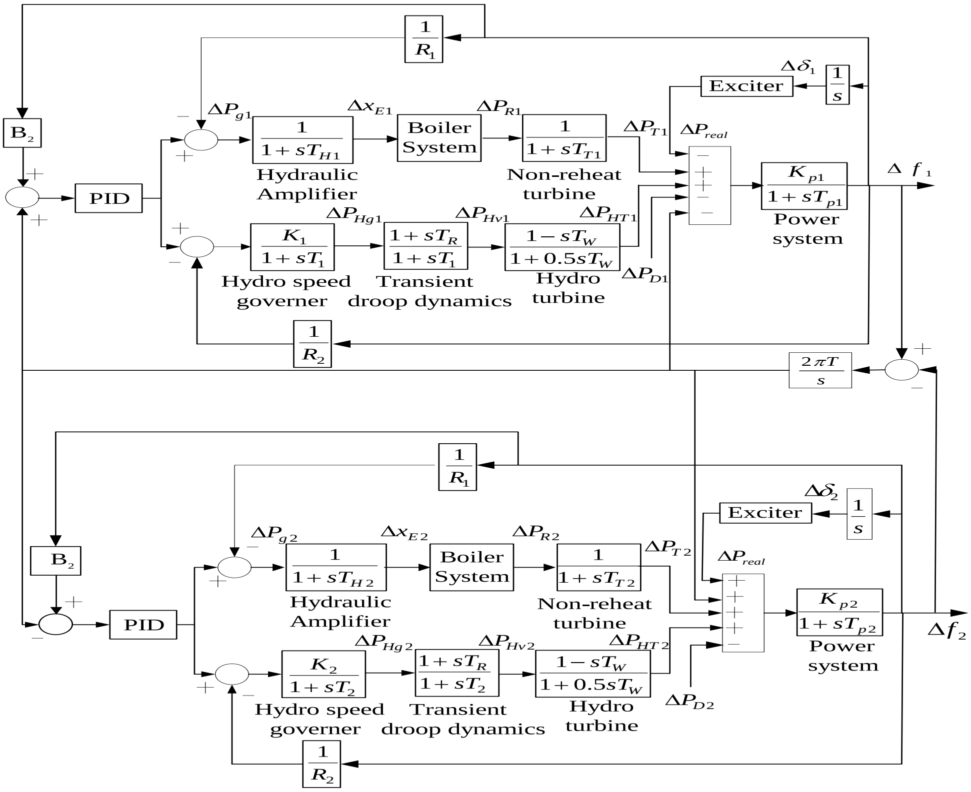

Figure 3. Proposed Model of a Two-area Interconnected Model Incorporating LFC-AVR Loop

3. Implementation of Firefly Algorithm for proposed work

Initially, when a step load perturbation is applied to the system, the primary LFC-loop gets into the action to mitigate the effect of disturbance. Although, due to its limitation, primary controller is not sufficient for the complete removal of the effects. Hence, PID controller has been used as a secondary controller to overcome this problem. The different gains of the PID controller must be optimized according to the proposed system condition to get the desired results. Integral Square Error (ISE) has been taken as the performance index of the proposed system, which is defined by the Eqn. (10),

$$ISE = \int_0^t (\Delta f_1^2 + \Delta P_{tie12}^2 + \Delta f_2^2 + \Delta V_1^2 + \Delta V_2^2) t.dt \tag{10}$$

The three idealized rules of the Firefly Algorithm are as follows:

- All fireflies are unisex so that one firefly will be attracted to other fireflies regardless of their sex.
- Attractiveness is proportional to their brightness, thus for any two flashing fireflies, the less bright one will move towards the brighter one.
- The brightness of a firefly is affected or determined by the landscape of the objective function.

The attractiveness function can be calculated as

$$\beta = \beta_0 e^{-\gamma r^2} \tag{11}$$

Where,

ß0 is attractiveness at r=0.

r is Cartesian or Euclidian distance between fireflies.

The movement of a firefly i is attracted to another more attractive (brighter) firefly j is determined by

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2}(x_i - x_j) \tag{12}$$

Steps involved when Firefly optimisation is applied to proposed model

- Step-1: Initialize the population size of fireflies with predefined constants and the number of iteration.
- Step-2: Locate fireflies within their limits ($K_p(1)$,$K_i(1)$,$K_d(1)$).
- Step-3: Evaluate the performance index i.e. ISE for each set of fireflies.
- Step-4: For two fireflies i and j if ISE(i)<ISE(j) then move firefly j towards i.
- Step-5: Find Cartesian or Euclidian distance between fireflies i and j.
- Step-6: Calculate brightness of each firefly.
- Step-7: Update the position of each firefly.
- Step-8: If end criterion is satisfied. Print the values of K_p,K_i,K_d.

The flowchart for the FA algorithm is shown in Figure.4. The firefly optimization technique employed for the tuning of the proposed controller by subjecting to the ISE as an objective function for the proposed AGC mechanism. The proposed optimization shown merits in terms of settling time and undershoot compared with other optimization technique like PSO, details discussion will carried out in results and discussion section. The improved Figureure of Demerits (FOD) is obseved with firefly algorithm among the other optimization techniques like PSO,WOA and ISA as depicted in Figure 10.

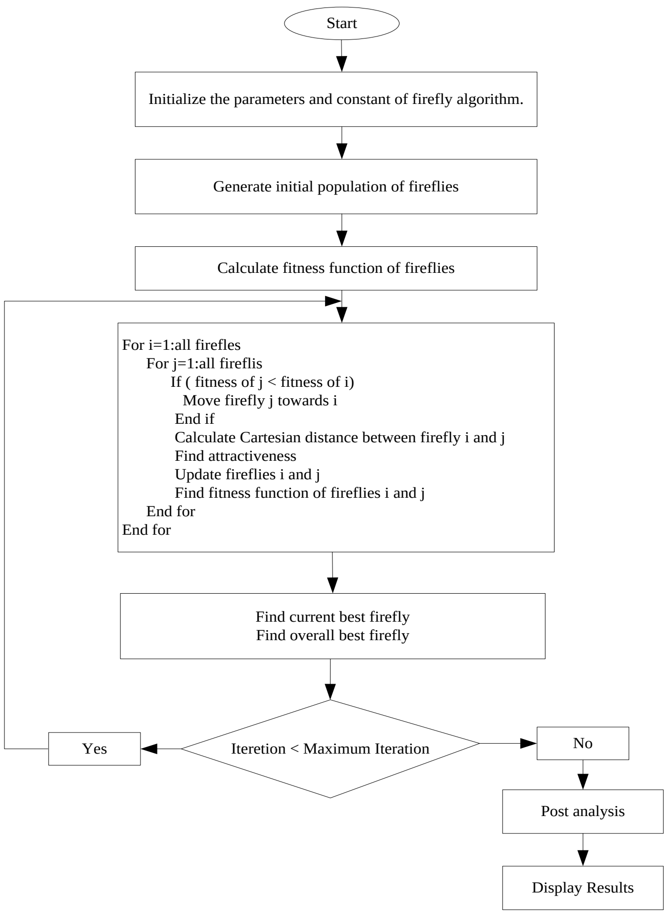

Figure 4. Flowchart for FA algorithm

Table 1. Different optimized value of the PID Controllers.

	First Controller Area			Second Controller Area		
	-Kp	-Ki	-Kd	-Kp	-Ki	-Kd
PSO based Controller	0.8642	3.9465	1.0650	6.5259	8.6860	1.6050
Proposed Based Controller	9.4725	6.0346	5.0515	10.1236	8.3690	4.5659

4. Small Signal Stability Analysis

Table 2. Comparison of Eigenvalue for the Proposed System using Different Tuning Techniques

Eigenvalue parameter with PSO-tuned PID controller	Eigenvalue parameter with Proposed controller
-22.9651533618715 ± 7.00901478655593i	-22.9652120355601 ± 7.00904365351924i
-22.9653389360014 ± 7.00878748498818i	-22.9653524912227 ± 7.00876531311043i
-16.3584086772461	-16.5866375258943
-11.9021173369546 ± 1.18657066022932i	-13.5469479515264 ± 4.09399113424285i
1.46094290833100 ± 6.84703178618107i	3.17713516624120 ± 7.30570130157552i
-2.40046652848984 ± 5.82239205587684i	1.07498160037394 ± 6.57547269368190i
-2.36297989706296 ± 5.81981147410600i	-2.35978637444866 ± 5.82181115438432i
0.549819201903966 ± 3.56492959407652i	-2.37316925750112 + 5.80613706169438i
-3.20669847667353	-4.11915201035780
-2.15664879263664 ± 0.696914905120297i	-2.07605889968972 ± 0.651130486932550i
-2.07404225607422 ± 0.599512330312577i	-2.12679819645581 + 0.680856754668467i
-1.23083371146837	-1.22700518002658
-0.546652452682919	-0.721355854968881
-0.152651571359190	-0.152623686260235
-0.152664080804201	-0.152653116542236
-0.0960195651703970	-0.0960272317500690
-0.0959826631503419	-0.0960080664059280
-0.0376525850704740	-0.0397515778264082
-0.0398955360047818	-0.0388576381582553
-0.0562309322003325	-0.0530957904679813
-0.0509924285256260	-0.0510681196239602
-0.000141767199723264	-0.000141767594070001
-0.000141767648456844	-0.000141767461625939

The proposed system includes diverse generating systems. Figure.3 shows the proposed system having thermal and hydro generating system. Small signal stability is one of the important ways to study the stability of the system. This is done using the eigenvalue analysis. Figure.3 shows the transfer function model of the proposed system. Small signal stability analysis is done using the state space representation governed by the following equations.

$$\dot{X} = AX + BU \tag{13}$$

$$Y = CX \tag{14}$$

$$|\lambda I - A| = 0 \tag{15}$$

Where,

$X = [X_1\ X_2 \ldots X_N]^T$ is the state vector and N is the number of state variables

$U = [U_1\ U_2 \ldots U_L]^T$ is the control vector and L is the number of control variables

$Y = [Y_1\ Y_2 \ldots Y_N]^T$ is the output vector and P is the number of output variables

$\lambda =$ eigenvalue of the proposed system

Table 2 shows the comparison of the eigenvalues of the proposed system for the PSO based PID controller and FA based PID controller. First of all proposed system is represented in state space form of Eq. (13) and eigenvalues from Eq. (15) are calculated. The position of eigenvalue decides stability of the system. For the system to be stable all eigenvalues should lie on the left side of the imaginary axis. The real eigenvalue represents non-oscillatory mode and complex conjugate eigenvalue represent oscillatory mode.

5. Result and Discussions

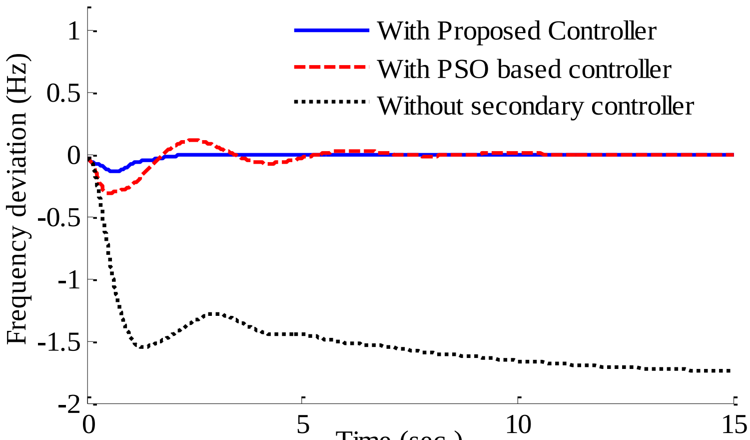

Figure 5. Frequency Deviation in Area-1

The proposed control scheme of the two-area interconnected power system incorporating LFC-AVR loop has been simulated in the MATLAB/SIMULINK environment. The proposed model is shown in Figure 3 and the detailed model of the boiler and exciter has been depicted in the Figure 1 and Figure 2 respectively. PID controller is used as the controller for the LFC of the proposed system. In this research work, FA and PSO optimization techniques have been used for the optimization of the proposed controller and their effects on the system dynamics have been compared. Small signal stability analysis of the system has been performed for the proposed model given in Figure 3. Eigenvalues of the proposed control scheme has been compared with PSO based PID controller to show the effectiveness of the proposed model. Table 1 compares the eigenvalues of both the cases which shows that the system becomes more stable when the proposed controller has been used. To study the system dynamics, a step load perturbation (SLP) of 0.1 pu is applied in area-1. The effect of SLP on the frequency deviation and terminal voltage in area-1 are shown in Figure 5 and Figure.6 respectively. While on the other hand, corresponding frequency deviation and terminal voltage for area-2 are depicted in Figure 7, Figure 8 respectively. The tie-line power flow deviation for the proposed system is shown in Figure 9. The comparison of percentage improvement of the proposed control scheme over PSO based PID controller is given in Table 3. Moreover, the superiority of the proposed scheme is further validated by comparison of convergence profile of proposed scheme with PSO, WOA and ISA based control scheme as shown in Figure 10.

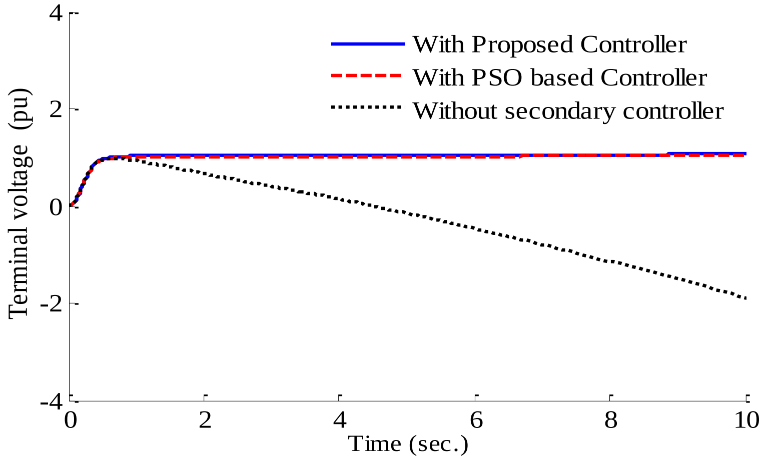

Figure 6. Terminal Voltage Profile of Area-1

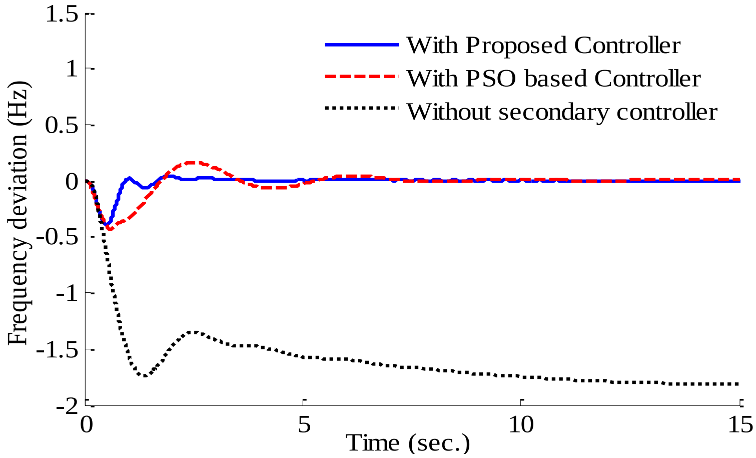

Figure 7. Frequency Deviation in Area-2

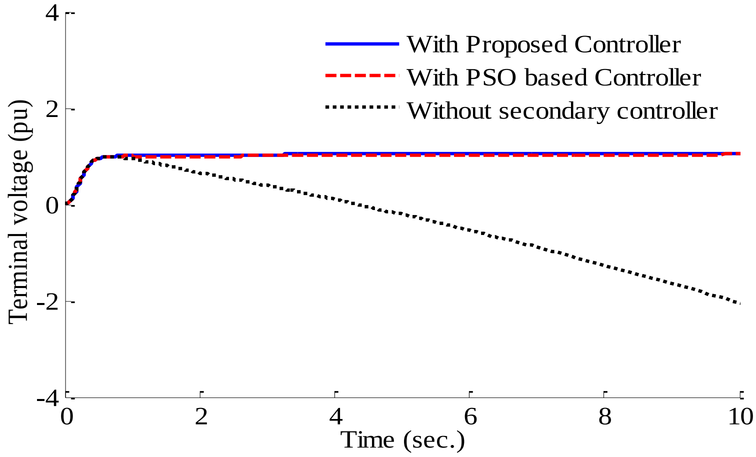

Figure 8. Terminal Voltage Profile of Area-2

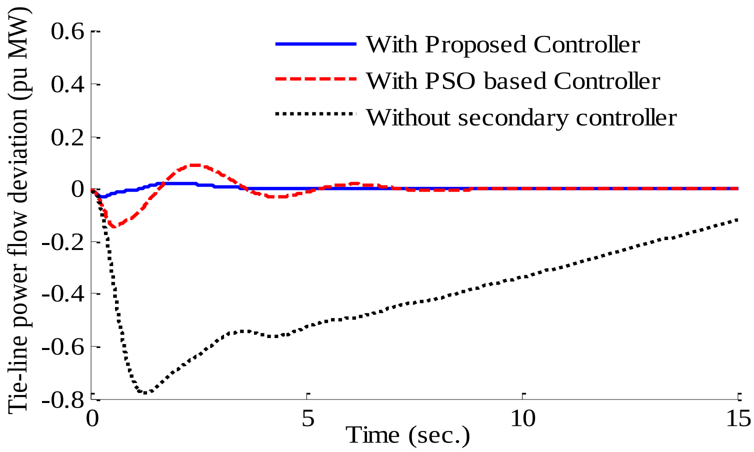

Figure 9. Tie-line Power Flow Deviation

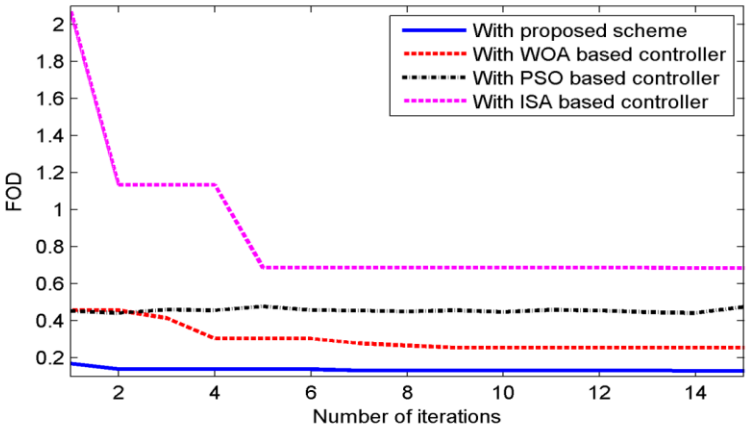

Figure 10. Comparison of convergence profile of proposed scheme with PSO, WOA and ISA based control scheme

Table 3. Comparison of percentage improvement with the proposed controller and with PSO based controller.

Maximum Deviation in	PSO based controller	With Proposed controller	Improvement (%)
Frequency of Area-1 (Hz)	-0.3144	-0.1405	55.31
Frequency of Area-2 (Hz)	-0.4337	-0.3994	7.9
Tie-line power (Hz)	-0.1423	0.0310	78.21

It is observed from Table – 3 that there is improvement in terms of maximum frequency deviation of 55.31% and 7.9% in area-1 and area-2 respectively. Moreover, improvement in maximum tie-line power flow deviation is 78.21% for the proposed power system. Therefore, the comparative study justifies the superiority of the proposed control scheme over other modern optimisation based control techniques. Thus, the proposed LFC-AVR configuration of two-area inter-connected power system using FA-based PID controller performs efficiently and is able to reduce the frequency and tie-line power flow deviation effectively.

6. Conclusion

In this research work, the combined LFC-AVR model of a two-area hydro-thermal interconnected power system has been proposed. For practical purposes, boiler dynamics of thermal system is included in the proposed model. The system is subjected to a 1% SLP in area-1. Firefly algorithm based PID controller has been used for the LFC-AVR control of the system. The superiority of the proposed control scheme has been validated from the simulation results which also show improvement in voltage profiles in both the areas. Comparison of proposed control scheme with other popular meta-heuristic techniques shows its superiority. The effectiveness of FA over other popular meta-heuristic techniques have been shown by comparing their convergence profiles. Thus, the FA based PID controller performs efficiently and effectively for the proposed control algorithm.

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Thermal System: R1 = 2 Hz/p.u. MW, TH = 0.08 s, TT = 0.3 s, KP1 = 80, KP2 = 133.33, TP1 = 16 s, TP2 = 26.67 s, B1 = B2 = 0.425 p.u. MW/Hz.
Hydro System: R2: 2 Hz/p.u, K1 = 1, T1 =48.7 s, TR = 5 s, T2 = 0.513 s, TW = 1 s.
Exciter: PS = 0.145 p.u.MW/rad, KE = 1, KA = 10, TA = 0.1 s, TF = 1.4, KF = 0.8, KS = 1, TS = 0.05 s, K1 = 1, K2 = -0.1, K3 = 0.5, K4 = 1.4.
Tie-line: T = 0.1.
Boiler: k1, k¬2, k3 = 0.85, 0.095, 0.92 respectively, CB = 200, TD = 0, TF = 10 s, KIB = 0.03, TIB = 26 s, TRB = 69 s.

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