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New approach in two-area interconnected AGC including various renewable energy sources using PSO

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Abstract: This paper presents a novel approach for automatic generation control (AGC) as an integrated two-area thermal-hybrid power generation system (THPGS) where thermal generators are interconnected with various renewable power generators (RPGs) like a solar power generator (SPG), wind power generator (WPG), fuel cell, and aqua electrolyzer. A comparison is carried out between the THPGS and a normal thermal power system considering proportional integral and derivative controllers. Particle swarm optimization (PSO) is used for optimizing the gain parameters of the controller. Investigation of dynamic responses is carried out considering step load perturbation as well as random load perturbation (RLP). Problems are formulated considering the variation in SPG and WPG power output in the presence of RLP in area 1 and the change in generation of SPG and WPG power in both areas for analyzing system stability and robustness. The investigation proves that PSO-optimized controllers are so robust that it is not necessary to change the parameter values of the controllers for a wide variation in SPG and WPG output power. Thus, integration of RPGs in AGC is properly applied for investigating the dynamic behaviors of the system. All the simulation works are implemented in MATLAB/Simulink software.

Key words: Automatic generation control, renewable power generators, wind power generator, solar power generator, fuel cell, aqua electrolyzer, thermal-hybrid power generation system, particle swarm optimization

1. Introduction

Loads in modern power systems vary continuously and generators should follow the variation of loads to maintain the load–generation balance. Load–generation mismatch creates frequency deviation in the system. Automatic generation control (AGC) maintains an automatic balance between the load demand and generation [1]. In present days, the interest in integrating renewable power generators (RPGs), especially solar power generators (SPGs) and wind power generators (WPGs) along with fuel cells (FCs) and aqua electrolyzers (AEs), has experienced a huge growth due to detrimental environmental conditions caused by the tremendous use of fossil fuel. Indeed, the unlimited use of fossil fuel raises questions about sustainability and our future existence on earth. Now thermally integrated RPGs in AGC are considered as a preferred solution to reduce the usage of fossil fuel [2].

To date, many articles have focused on several interesting facts about AGC. Nehrir [3] presented a detailed study on power management, system configuration-sizing, and effective control strategies of RPGs working as a multiple generators. These RPGs can be utilized in stand-alone mode as well as grid-connected

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mode. Effective control strategies and system configuration were presented for healthy operation of systems in [4,5]. Moreover, Lopes et al. [6] proposed a proper control strategy that provides an effective solution in stand-alone mode operation of RPGs. Proper state-space equations and optimal control strategy of thermally integrated linearized AGC models were presented in [7,8]. Moreover, in [9] an effective control strategy for system stability and proper system dynamics was established. New approaches towards designing an improved controller and proper system modeling for RPGs in integrated thermal AGC were elaborated in [10]. Kumar et al. drew attention to the detailed application of a wind generator-based AGC system and its effective control strategies in [11]. In the previous articles, most of the stand-alone approaches were described considering the energy storage devices, whereas Zarina et al. [12] proposed a novel control technique for system frequency regulation in the presence of solar PV panels in a conventional multibus system without using any kind of energy-storing elements because inclusion of these energy-storing elements raises the overall cost of the system. Rahman et al. [13] investigated the dynamic behavior of an AGC system considering a dish-Stirling type solar thermal system and WPGs with proper GDB and GRC. Investigation proved that a solar and wind integrated AGC system in the presence of a suitable control strategy is one of the suitable power balancing approaches in modern power systems. Application of FACTS devices in the power tie line was investigated in the presence of a thermally integrated AGC model with an improved proportional integral and derivative (PID) controller for effective dynamic responses and better power quality [14]. For proper system operation, investigation of system behavior was carried out considering all the linearity as well as nonlinearity present in an AGC [15]. In general, the design of a suitable controller is necessary for healthy system operation. The gain parameters of the controller must be properly designed and optimized for stable system operation. Moreover, Sanki et al. [16] reported the superiority of PID controllers in the context of the stability of the system. For optimum design of PID controllers several nature-based metaheuristic techniques have been incorporated over the years. In [17,18] results proved the effectiveness of particle swarm optimization (PSO) in terms of better dynamic response and fast convergence compared to the genetic algorithm (GA) in many engineering applications. Moreover, [19] described the dominancy of PSO over differential evolution in a two-area interconnected thermal power system.

Based on the above discussion, the contributions of this paper are as follows:

1) To date, studies on AGC are carried out only using SPGs and WPGs. In this paper a novel approach is presented for an AGC system considering SPGs, WPGs, FCs, and AEs.

2) Several authors presented their work without considering proper GDB and GRC. In this paper, for a realistic approach to the system, proper GDB and GRC are implemented considering 50% system loading with 1% step load perturbation (SLP) as the nominal loading condition.

3) Practically, the output powers of WPGs and SPGs are not always constant. For analyzing system performance, investigation is carried out considering constant power as well as variation in power output of RES units.

4) For a simple algorithm and fast convergence, PSO is utilized for optimizing the gain parameters of the controller.

The outline of the paper is as follows: Section 2 describes the detailed linearized model of system components. Section 3 describes the problem formulation, followed by Section 4, which presents a brief discussion of the PSO technique, and Section 5 presents simulated dynamic responses as well as a detailed discussion of the system behavior. Section 6 gives the concluding remarks of this work.

2. System design

In this work, a two-area interconnected power system has been investigated where each area consists of one thermal unit, one SPG unit, one WPG unit, one FC unit, and one AE unit considering 50% system loading with 1% SLP as the nominal loading condition. The two areas are connected by a tie line, which helps in power sharing between the areas. In this work the interconnected system is designed in MATLAB/Simulink by using the transfer function of each power-generating unit. The basic model of the thermal-hybrid power generation system (THPGS) is shown in Figure 1. Each power-generating unit is described in later sections. All the RPGs here are taken as first-order transfer functions. For detailed design of the generating units, readers may refer to [20,21]. All the system gain constants and time constants are indicated in the nomenclature. The values of gain parameters and time constants are given in the Appendix.

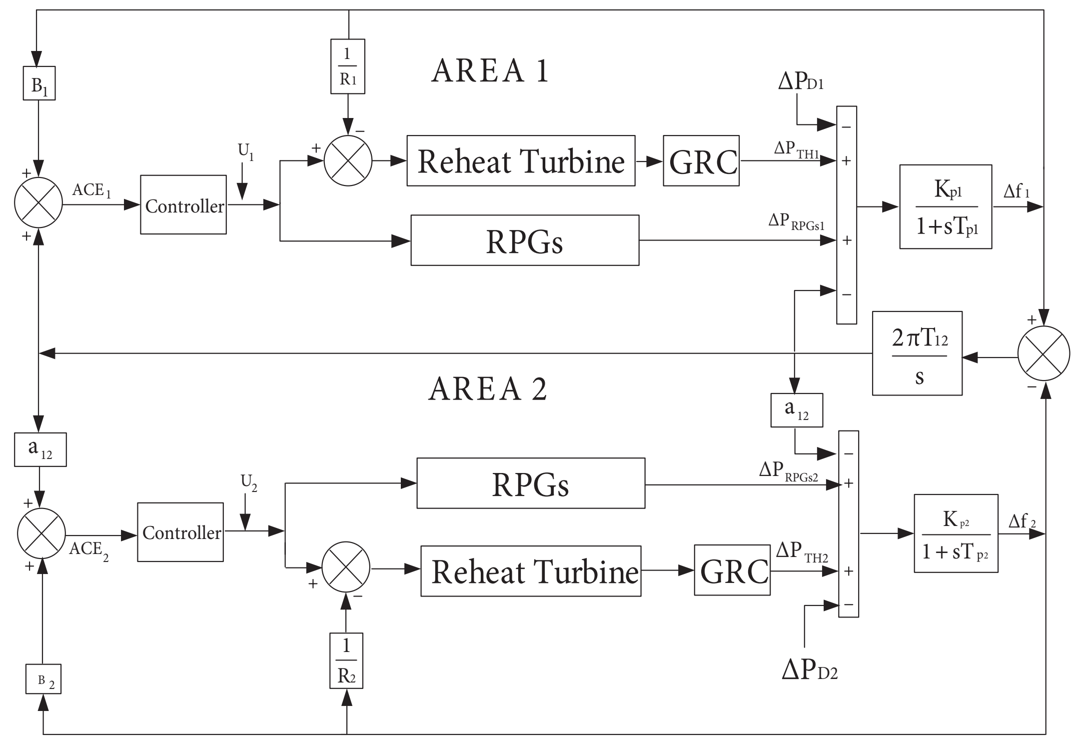

Figure 1. Basic model of two-area THPGS.

2.1. Modeling of reheat turbine

At present, most countries depend on thermal power generation in terms of mitigating the load demand. In this work, a reheat turbine model is considered in the presence of 3% per minute GRC and the fly-ball governor system. The linearized transfer function model of the reheat turbine is shown in Figure 2.

2.2. Modeling of SPG

The SPG is one of the promising renewable energy sources. They have recently gained huge interest among researchers and industrialists due to their flexibility, abundance, and CO_2-free power production. Continuous research and development in this area lowers the price of solar power to such an extent that the present price of solar power falls below the rate of thermally generated power. SPG-produced power is dependent on solar

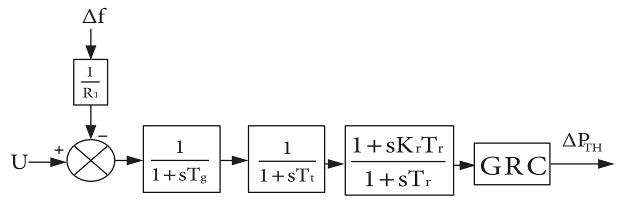

Figure 2. Linearized model of reheat turbine.

irradiance (φ) and ambient temperature (T_a). When the SPG is considered with thermal generation, it gives better performance in load-generation power balancing. The basic equation of solar power is:

$$P_{SPG} = \eta\phi A\{1 - 0.005(T_a + 25)\}, \tag{1}$$

where η is the efficiency, ϕ is solar irradiance (W/m^2), A is the effective solar array area, and T_a is ambient temperature ($^\circ$C). The basic transfer function model is shown in Figure 3.

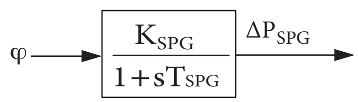

Figure 3. Linearized model of SPG.

2.3. Modeling of WPG

The WPG emerges as one of the promising alternative energy sources. After solar energy, it is a more effective and available energy producer. Recently many countries choose WPGs as alternative power producers. In the case of WPGs, output power is dependent on the velocity of the wind (ν_ϖ) and the basic equation is as follows:

$$P_{WT} = \frac{1}{2}\rho A_S C_P(\nu_\varpi)^3. \tag{2}$$

The basic transfer function model is shown in Figure 4.

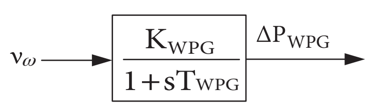

Figure 4. Linearized model of WPG.

2.4. Modeling of FC

The FC evolves as one of the reliable RPGs and acts as an electrochemical device. FCs produce electrical energy from chemical reactions without ejecting CO_2 into the environment. It has gained much interest due to its modular and flexible design. It arises as a very prominent RPG along with SPGs and WPGs. The linearized model is shown in Figure 5.

2.5. Modeling of AE

Frequency deviation as well as power fluctuation are very common in interconnected systems. In implementing a suitable control strategy, an AE can be utilized as one of the appropriate RPGs. AEs actually get some

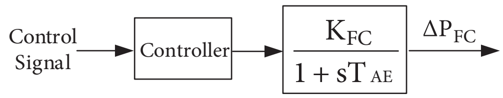

Figure 5. Linearized model of FC.

extra power from WPGs or SPGs to produce hydrogen and this hydrogen can be used as an energy producer in FCs. By sensing the frequency deviation signal, AEs help to control power fluctuations in interconnected power systems. The basic linearized model is given in Figure 6. The SPG, WPG, FC, and AE are combined to form RPGs as in Figure 1.

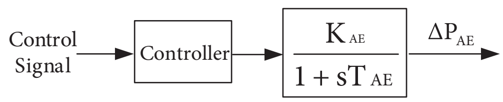

Figure 6. Linearized model of AE.

3. Problem formulation

In this study the problem has been formulated considering several case studies. The detailed problem formulation is given in Table 1. The analysis is addressed in detail in Section 5.

Table 1. Problem formulation.

Scenario	Problem formulation	Simulation time	Disturbance parameter
1	Comparison between two thermal and two-area THPGS	100	1% SLP in area 1
2	Analysis system dynamics of THPGS	200	RLP in area 1
3	Varying ΔP_{WPG} and ΔP_{SPG} in area 1	200	RLP in area 1
4	Varying ΔP_{WPG} and ΔP_{SPG} in both areas	200	1% SLP in area 1

For analyzing the system dynamics, the cost function (J) is determined by using the integral square error (ISE) technique. The following equation describes the cost function of the system:

$$J_{ISE} = \int_{0}^{T} \{(\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta P_{tie})^2\} dt. \tag{3}$$

4. PSO optimization

The concept of PSO was first introduced by Kennedy and Eberhart in 1995 [22]. The idea was adopted from the social behavior and movement dynamics of insects, birds, and fish. This is basically a global gradientless stochastic search method that is mostly suited to continuous-variable problems. The performance of PSO is versatile and flexible in nature. In the last few years the idea of PSO has successfully been applied to a wide variety of problems like neural networks, structural optimization, and shape topology optimization.

In this study, the gain parameters of PID controllers are optimized by PSO technique. This optimization technique provides easy implementation and gives fast convergence criteria compared to other methods. In this regard, basic terminologies of this algorithm are presented in Table 2.

Table 2. PSO parameters.

x_k^i– Particle position	p_k^g– Best "remembered" swarm position
v_k^i– Particle velocity	C_1, C_2 – Cognitive and social parameters
p_k^i– Best "remembered" individual particle position	$r_1 r_2$ – Random numbers between 0 and 1

Positions of individual particles are updated as follows:

$$x_{k+1}^i = x_k^i + v_{k+1}^i, \tag{4}$$

while the velocity is calculated as follows:

$$v_{k+1}^i = v_k^i + C_1 r_1 \left(p_k^i - x_k^i\right) + C_2 r_2 \left(p_k^g - x_k^i\right). \tag{5}$$

In this work, the cost function given in Eq. (3) is minimized by using PSO-optimized values of Kp, Ki, and Kd. The constraint of the optimization problem in this system is given below:

$K_{j,\min} < K_j < K_{j,\max}$, where K_j is parameter values of the controller.

Over the years, PSO has gained more interest and diversified areas of application. The flow chart of PSO is given in Figure 7.

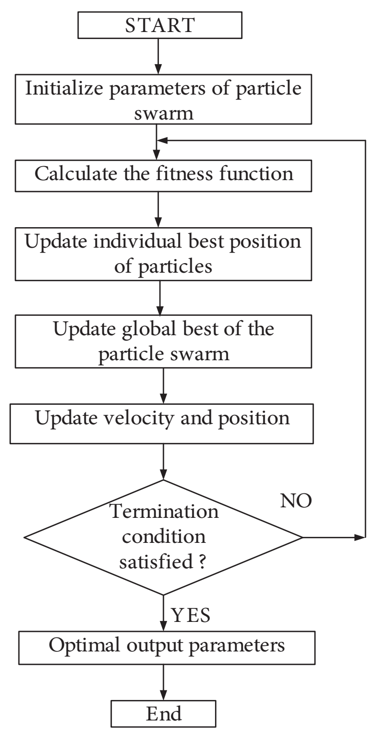

Figure 7. Flow chart of PSO.

5. Simulation results and discussion

This section presents the analysis of dynamic responses and a detailed discussion of the case studies. In Figure 8, the convergence curve between the cost function and number of iterations proves its effectiveness. It is clear that the system cost function converges to its minimum value in between 10 and 20 iterations. Several case studies are implemented and a detailed discussion of the cases is presented in later sections.

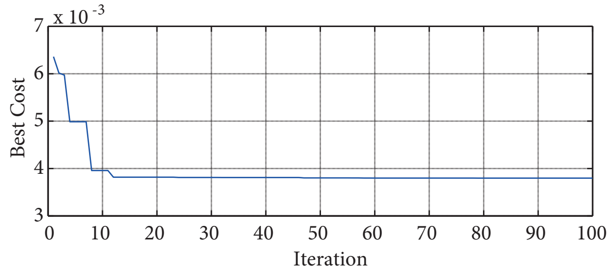

Figure 8. Convergence curve.

5.1. Comparison between THPGS and thermal generating system

In this case study, a comparison is done between a two-area THPGS and two-area thermal power generation system. Analyzing Tables 3 and 4, it is clear that the presence of RPGs gives promising results in terms of power demand mitigation and fast stability. Figures 9A and 9B clearly present that the THPGS is better compared to the normal thermal system in terms of peak time, peak overshoot, and settling time. Integration of RPGs with a conventional power system is very effective and that is also verified from the given tables. In the case of the THPGS, $\Delta Pg1$ and $\Delta Pg2$ are also settling down quickly compared to the other case. Dynamic responses also prove the fast stability and power balance between the generation and load side when the THPGS is considered.

Table 3. Optimum values of PID controllers.

PSO optimized system	K_{p1}	K_{p2}	K_{i1}	K_{i2}	K_{d1}	K_{d2}	Cost function
PID-thermal	2.053	0.058	3.327	1.023	2.547	0.056	4.107×10^{-3}
PID-THPGS	1.0235	2.034	3.524	0.472	2.047	0.872	3.804×10^{-3}

Table 4. Comparison of the dynamic responses.

PSO optimized system	Δf1			Δf2			ΔP_{tie}		
	OS (pu) $\times 10^{-3}$	US (pu) $\times 10^{-3}$	ST (s)	OS (pu) $\times 10^{-3}$	US (pu) $\times 10^{-3}$	ST (s)	OS (pu) $\times 10^{-3}$	US (pu) $\times 10^{-3}$	ST (s)
PID-thermal	12.54	–57.86	29.98	11.93	–52.40	27.69	0.81	–9.2	38.22
PID-THPGS	12.49	–27.48	18.23	10.45	–34.83	16.91	0.66	–8.9	34.4

OS = Overshoot, US = undershoot, ST = settling time.

5.2. Random load perturbation (RLP)

In this case, system performance is investigated using RLP in area 1. Detailed responses are shown in Figures 10A–10E and the PID parameters are considered similar to the previous case. It is observed that the frequency deviations in both areas are in the prescribed limits and change of sudden random load does not affect $\Delta Ptie$. From Figure 10D, it can be stated that, as the disturbance is given in area 1 only, the FC and AE continuously

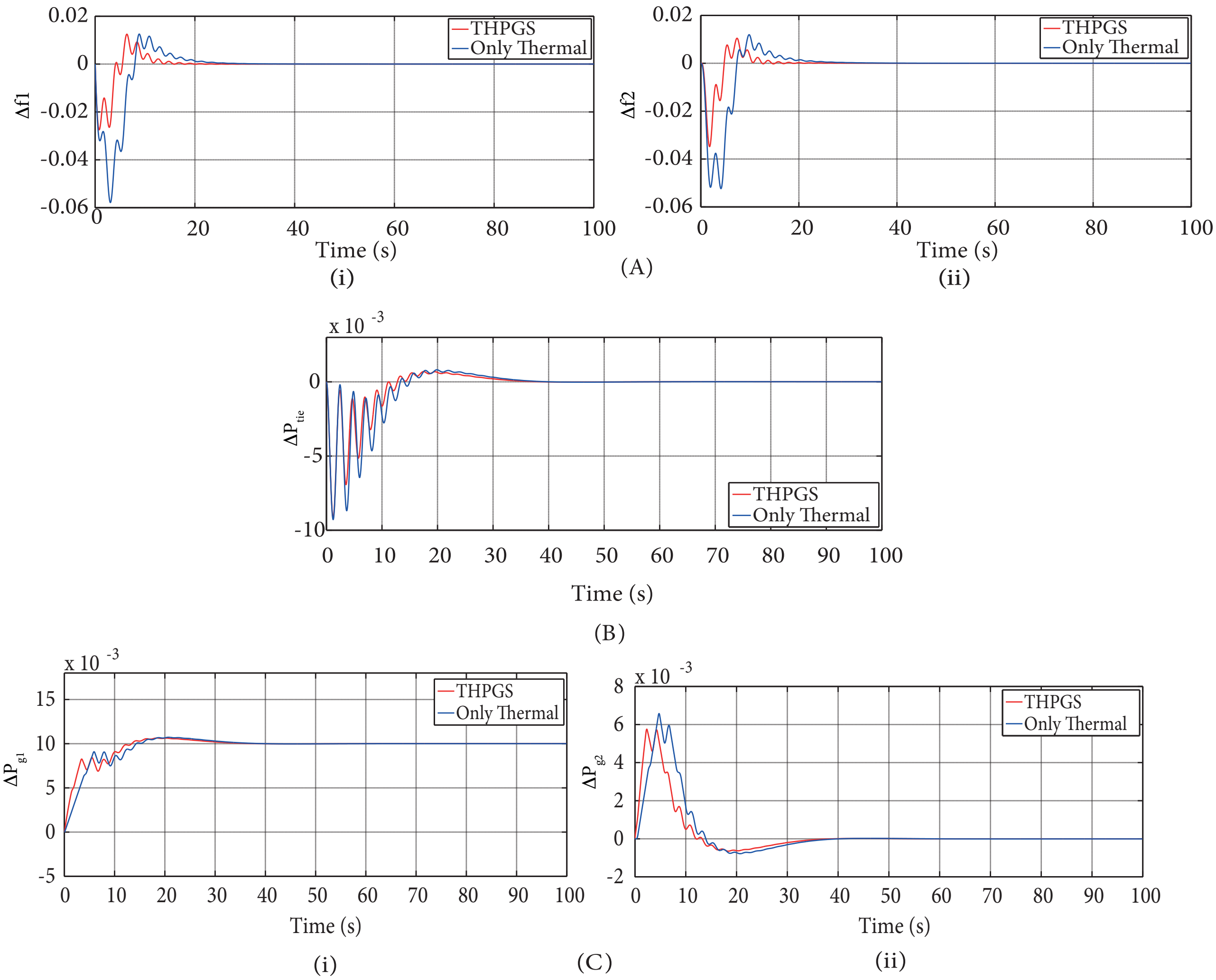

Figure 9. Comparison between THPGS and thermal generating system. A) Frequency deviation in (i) area 1 and (ii) area 2. B) Tie-line power exchange. C) Generated power deviation at (i) area 1 and (ii) area 2.

adjust the output power to maintain the power balance in the same area. The FC and AE units present in area 2 do not vary in a wide range because no such disturbance is introduced in that area. Figure 10E clearly shows no noticeable changes in the dynamic responses in power output of the FC and AE units in area 2.

5.3. Varying WPG and SPG in area 1, with RLP in the same area

In this section an investigation is carried out considering variation in wind power and solar power with RLP in area 1. In Figure 11 dynamic responses are presented. Critical observation shows that frequency deviation and the tie line power exchange vary within permissible limits, although RLP is applied with variation of the WPG and SPG units in area 1. Again from Figure 11, it is observed that the FC and AE help in balancing the power demand. As RLP is applied to area 1 only, no noticeable change is found in the output power of the FC and AE in area 2. The dynamic responses given in Figure 11 clearly show the effectiveness of the FC and AE for balancing power between the generation and load demand. As PID parameters remain unaltered, the following responses also prove the sensitivity, robustness, and stability of the system.

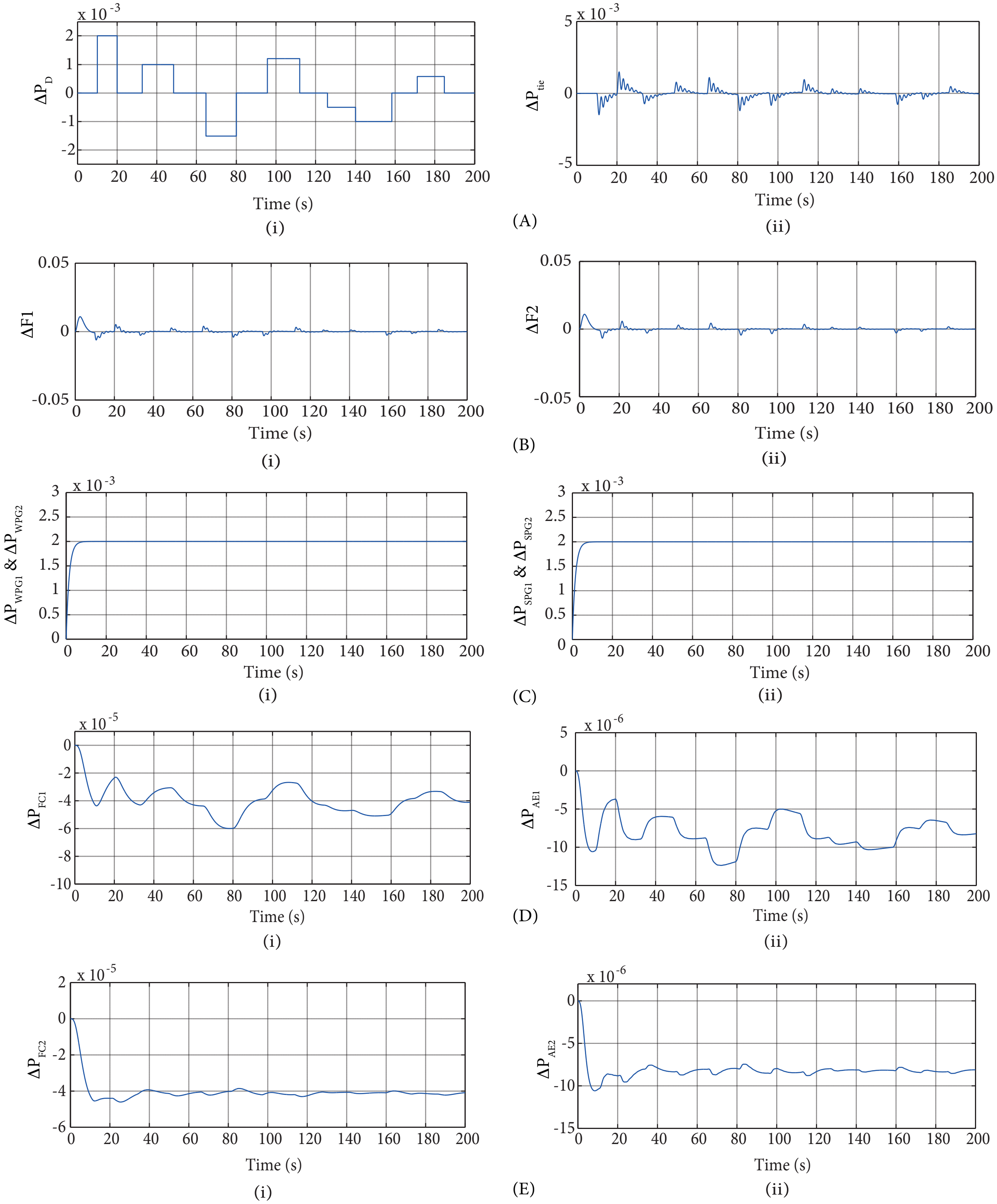

Figure 10. Considering RLP: A) (i) variable load and tie line power exchange (ii); B) frequency deviation in (i) area 1 and (ii) area 2; C) generated power in both areas for (i) wind power and (ii) solar power; D) generated power deviation in area 1 for (i) fuel cell and (ii) aqua electrolyzer; E) generated power deviation in area 2 for (i) fuel cell and (ii) aqua electrolyzer.

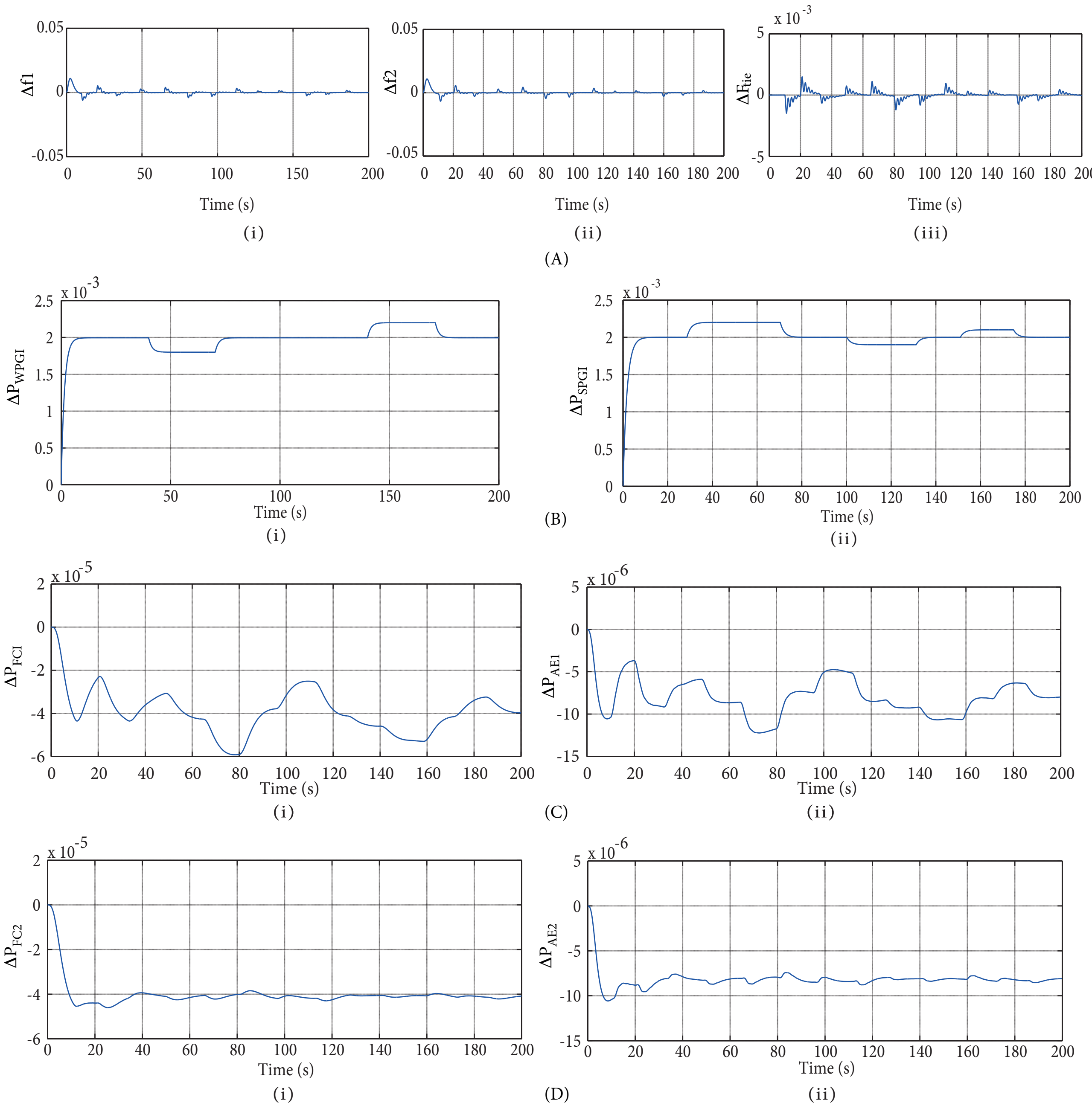

Figure 11. Varying WPG and SPG in area 1 with RLP in the same area: A) (i) frequency deviation in area 1, (ii) frequency deviation in area 2, and (iii) tie line power exchange; B) change in generated power in area 1 for (i) wind power and (ii) solar power; C) generated power deviation in area 1 for (i) fuel cell and (ii) aqua electrolyzer; D) generated power deviation in area 2 for (i) fuel cell and (ii) aqua electrolyzer.

5.4. Varying WPG and SPG in both areas 1 and 2

In this case, system performance is analyzed with varying wind power and solar power in both areas with SLP in area 1. Although the system is considered under varying wind and solar power generation, dynamic responses of frequency deviation and tie line power exchange show stable responses in Figure 12A. Figure 12B proves that the total power generation is equal to the load power demand in area 1. From this study, once again the robustness and stability of the system are established. A summary of the above case studies is furnished in Table 5.

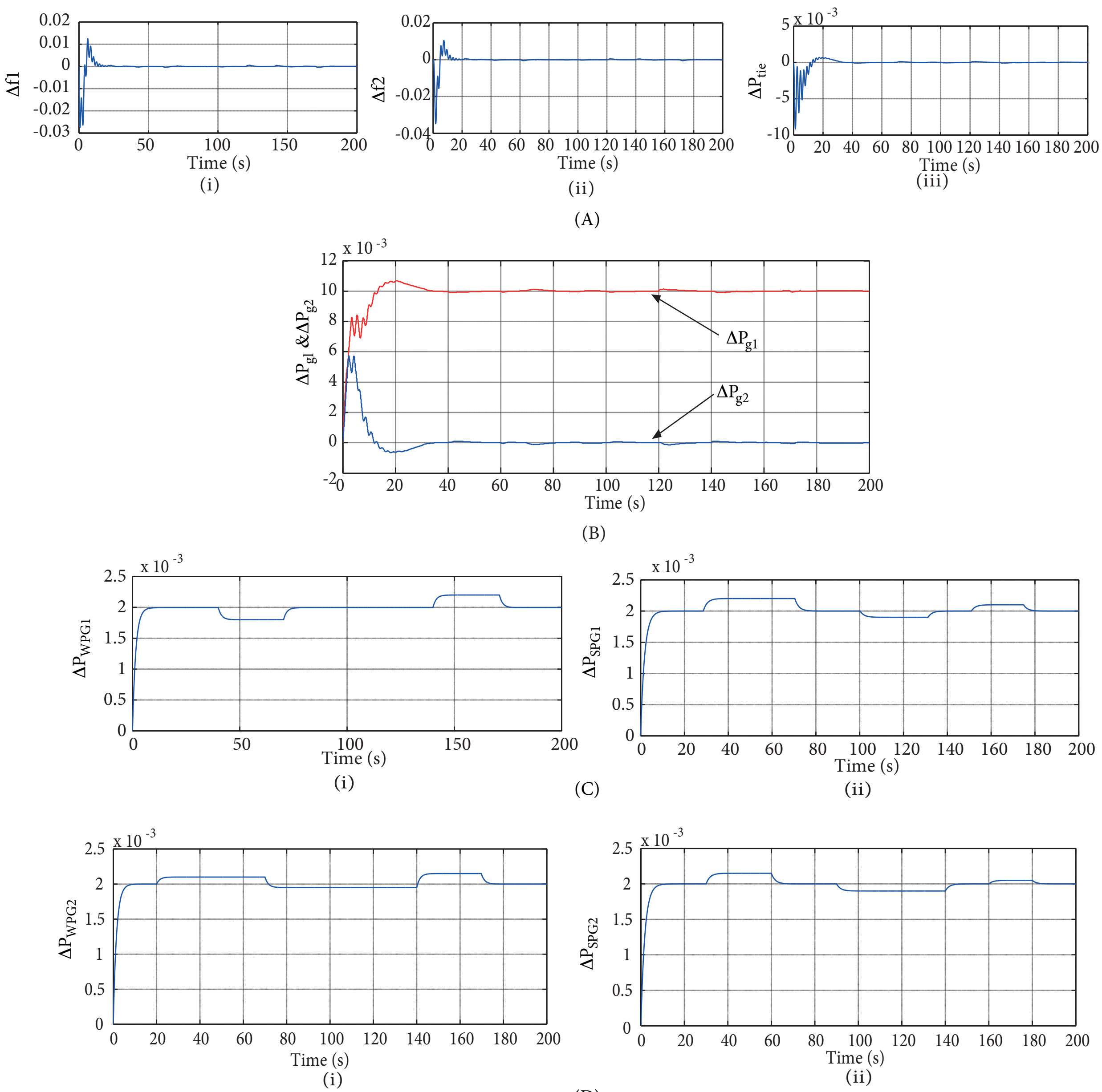

Figure 12. Varying WPG and SPG in both area 1 and area 2: A) (i) frequency deviation in area 1, (ii) frequency deviation in area 2, and (iii) tie line power exchange; B) change in generated thermal power in both areas; C) change in generated power in area 1 for (i) wind power and (ii) solar power; D) change in generated power in area 1 for (i) wind power and (ii) solar power.

Table 5. Summary of result analysis.

Scenario	Problem formulation	Disturbance parameter	Controller parameters	Remark
1	Comparison between two thermal and two-area THPGS	1% SLP in area 1	PID controller optimized	THPGS shows better results compared to normal thermal system.
2	Analysis system dynamics of THPGS	RLP in area 1	Optimized values unaltered	System frequency and tie line power vary in permissible limits. As perturbation is introduced in area 1, the RPGs present in that area help to manage the power balance. The optimized values of PID parameters are not altered. The proposed system shows robust nature and stable responses.
3	Varying ΔP_{WPG} and ΔP_{SPG} in area 1	RLP in area 1	- DO -	
4	Varying ΔP_{WPG} and ΔP_{SPG} in both areas	1% SLP in area 1	- DO -	

6. Conclusion

A novel approach is incorporated to examine a two-area interconnected reheat thermal power system considering a SPG, WPG, FC, and AE. System modeling and detailed analysis are performed using MATLAB/Simulink software. In this work the PSO technique is implemented to optimize the gain parameters of the controller. A synopsis of the detailed analysis of results is presented in Table 5. Based on the case studies it can be stated that load–generation balance is maintained by controlling the power output of the thermal units as well as the FC and AE. Dynamic responses of PSO-optimized PID controllers prove its superiority in terms of system oscillation, overshoots, undershoots, and settling time. PSO-optimized controllers also prove its robustness and sensitivity, considering variation in the power output of SPG and WPG units. Detailed investigations of the above-mentioned cases assure the proper system operation and load-balancing scheme of the proposed model. Detailed system investigation also confirms the suitability and healthy system operation of this proposed model. Based on the above results, it can be concluded that the integrated THPGS system is highly recommended for future power system design for better power management and load–generation power balance.

Nomenclature

T_G	Governor time constant
T_T	Steam chest time constant
K_R	Reheat gain
T_R	Reheat time constant
K_P	Power system gain
T_P	Power system time constant
R	Speed regulation
T_{12}	Tie line stiffness coefficient
B	Frequency bias characteristics
K_p	Proportional gain
K_i	Integral gain

K_d	Derivative gain
K_{SPG}	Gain parameter of SPG
T_{SPG}	Time constant of SPG
K_{WPG}	Gain parameter of WPG
T_{WPG}	Time constant of WPG
K_{FC}	Gain parameter of FC
T_{FC}	Time constant of FC
K_{AE}	Gain parameter of AE
T_{AE}	Time constant of AE

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Appendix

$T_G = 0.08$ s	$T_R = 10$ s	R = 2.4 Hz/pu	$K_{SPG} = 1$	$T_{WPG} = 1.5$ s	$K_{AE} = 1/500$
$T_T = 0.3$ s	$K_P = 20$	$T_{12} = 0.0866$	$T_{SPG} = 1.8$ s	$K_{FC} = 1/100$	$T_{AE} = 0.5$ s
$K_R = 0.5$	$T_P = 120$ s	B = 0.425 pu	$K_{WPG} = 1$	$T_{FC} = 4$ s	