Optimal Automatic Generation Control in Multi-Area Power Systems with Diverse Energy Sources

Ashwini Kumar and Omveer Singh

1 Introduction

1.1 General Study and Motivation

For modern power systems, frequency must be constant. The frequency variation is not acceptable in current power system for world wide. The quality power supply can be achieved for power systems with the help of AGC for more area interconnected with diverse energy sources. As robust power demand is a need of mankind globally, when load penetrates from its defined value with perturbation, the state of the grid system condition may appear abnormal from normal state. AGC must identify the deviation in frequency and maintained it to constant system frequency.

As the operation of interconnected power systems should be balanced between generated powers with total load demand plus system losses. If operating point differ the system frequency can deviates, cumulative cause shows unbalanced power in the exchange of areas, result may undesirable effect [1–3].

1.2 Literature Review

ACE used as a single variable is a combination of two variables one is frequency, another is tie-line power exchange. Many good ideas reflected by researchers for AGC problem, through the design of AGC regulators for uncertainty or variation, load characteristics, excitation control and other link like Alternating Current (AC)/Direct Current (DC) [4–8]. In research article, Singh et al. [8, 9] showed as the load demand for different loading scenarios, the generators are interconnected by power line which

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increases the complexity of power system. Authors have been categorized the huge power systems with the principle of coherency for different control areas.

In the last decade, the modern concept for AGC like Genetic Algorithm (GA), Artificial Neural Network (ANN), and Fuzzy Logic Algorithm (FLA) are used to make our AGC simple and robust, as thermal power plant associating with solar energy in Photovoltaic (PV) modules, wind turbine, Electric Vehicle (EV), micro-grid, smart grid, and Super Conducting Magnetic Energy Storage (SMES). This research paper [10] gives a brief exploration of recent research articles written by various authors/researchers/technocrats used different techniques of Artificial Intelligence (AI) and Soft Computing (SC) techniques. The modern AI and SC techniques used for AGC in which different algorithms are like Differential Evolution Particle Swarm Optimization (DEPSO) [11], Firefly Algorithm (FA) [12–14], Grey Wolf Optimizer (GOW) Algorithm [15–21], Ant Colony Optimization (ACO) [22]. These algorithms are justified by its authors with certain parameters, acceptability and also with their limitations.

1.3 Contribution to the Present Research Work

- Design and development of mathematical model of diverse energy sources used in multi-area power systems.
- Modify the proposed model with/without parallel EHVAC/DC links.

2 Power System Model (Two Areas)

Mohanty et al. [23] concreted two unequal areas with multiple hybrid-sources interconnected power system. In Fig. 1 shows the model of non-reheat thermal system and PID controller used in power system.

For generator the output frequency Δf and area control error is given by Eq. (1). In this B denotes the parameter of frequency bias.

$$\text{ACE} = \Delta P_{\text{Tie}} + B\,\Delta f \tag{1}$$

The transfer function shows the analysis in frequency-domain as it represents each component of the area. The transfer function of turbine is shown in Eq. 2.

$$G_T(s) = \frac{\Delta P_T(s)}{\Delta P_V(s)} = \frac{1}{1 + sT_T} \tag{2}$$

With Elgerd [1], a governor is represented for its transfer function in Eq. (3).

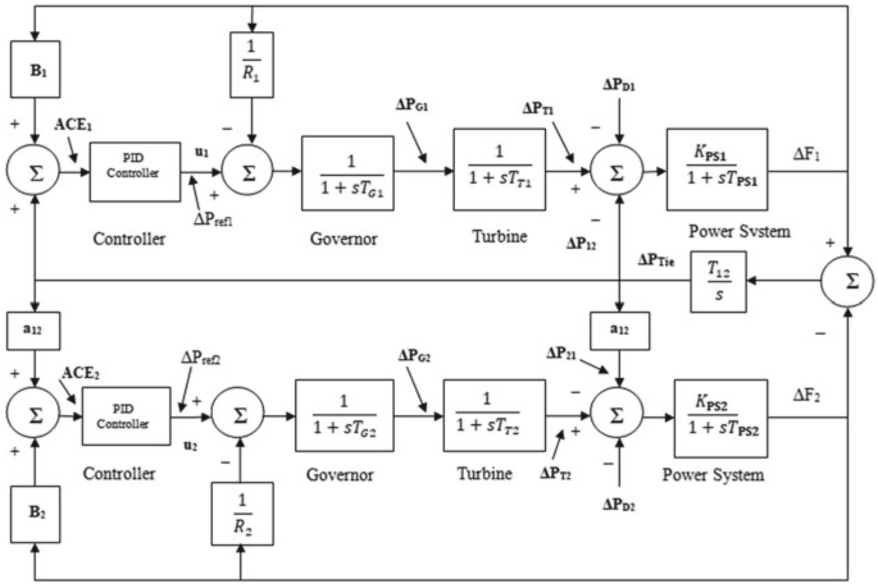


Fig. 1 Transfer function model for power system of 2area non-reheat thermal system ACE with PID controller

$$G_G(s) = \frac{\Delta P_V(s)}{\Delta P_G(s)} = \frac{1}{1 + sT_G} \tag{3}$$

Two inputs used for speed governing system as ΔP_{ref} also $\Delta \mathbf{f}$ for 1 output $\Delta P_G(s)$ shown by [2] as following;

$$\Delta P_G(s) = \Delta P_{\text{ref}}(s) - \frac{1}{R}\Delta f(s) \tag{4}$$

The representation of generator and load shown by the transfer function as [2], as following;

$$G_p(s) = \frac{K_P}{1 + sT_P} \tag{5}$$

In this notation are $T_P = \frac{2H}{fD}$ and $K_P = \frac{1}{D}$.

The load system for generator show 2 inputs $\Delta P_D(s)$ and $\Delta P_T(s)$ with 1 output $\Delta f(s)$ shown by following [2]:

$$\Delta f(s) = [\Delta P_T(s) - \Delta P_D(s)]\, G_p(s) \tag{6}$$

3 Design Controller Structure of AGC

PI controller is used for development of advanced control. Controller has simple design and reliable operation utilized, also not need of higher skills than others. Proportional and integral are two mode of PI controller, it increases the gain of closed loop also improves the transient phenomenon but steady state error remained. The steady state error reduces to with an integral control. For integral controller the response for a transient period is slow. The dynamic and static accuracy not eliminate by proportional—plus—integral control. For

$$\left|\frac{\mathrm{d(ACE)}}{\mathrm{d}t}\right| > \Delta$$

$$\Delta P_C = K_P \mathrm{ACE}(t);$$

While ACE stands for area control error.

$$\left|\frac{\mathrm{d(ACE)}}{\mathrm{d}t}\right| \leq \Delta;$$

$$\Delta P_C = K_I \int \mathrm{ACE}(t)$$

The design a controller is based on constraints and specification. The controller is integral of absolute error (IAE), integral square error (ISE), integral time absolute error (ITAE), and integral time square error (ITSE). Authors [24] considered ITAE as an objective function and parameters of PI controller are optimized using GWO algorithm as given in equation.

$$J = \int (|\Delta f_1| + |\Delta f_2| + |\Delta P_{\mathrm{Tie}}|)$$

The deviations for system frequency are Δf_1 and Δf_2, also a ΔP_{Tie} is the incremental change for tie line power.

3.1 Dynamic Response Analysis

Rout et al. [25] worked for PI controller with DE algorithm used in AGC. A comparative performance assessment enhanced by Shiva et al. [26], examined for QOHS algorithm and internal model control made for AGC (Tables 1; Fig. 2).

Table 1 Gain of controller, value of objective function, and time of settling

Algorithms	Parameter	ITAE	Settling time (2% Band) Ts, s		
			Δ f_1	Δ f_2	Δ P_{Tie}
Conventional PI [34]	$K_P = -0.7005$	3.7568	45	45	28
	$K_I = 0.3802$				
GA tuned PI [34]	$K_P = -0.2346$	2.745	10.59	11.39	9.37
	$K_I = 0.2662$				
BFOA tuned PI [34]	$K_P = -0.4207$	1.7975	5.52	7.09	6.35
	$K_I = 0.2795$				
DE tuned PI [35]	$K_P = -0.2146$	0.9991	8.96	8.16	5.75
	$K_I = 0.4335$				
MFO tuned PI [25]	$K_P = -0.3735$	0.9704	6.10	6.5	5.76
	$K_I = 0.3645$				

3.2 System Data

See Tables 2 and 3; Fig. 3.

4 Brief Optimization Techniques Used in AGC

4.1 Particle Swarm Optimization Algorithm

Singh et al. [8, 9] showed as the load demand for different loading scenarios; the generators are interconnected by power line which increases the complexity of power system. Authors have been categorized the huge power systems with the principle of coherency for different control areas. Sahu et al. [11] worked for AGC of interconnected power system, like hDEPSO, FLA based PID controller. Investigations have been shown effectiveness of hybrid DEPSO technique over PSO and DE. Pathak et al. [27] worked for dynamic performance with two area AGC of thermal-thermal system also worked for generation schedule trajectories versus time constant of steam chest time constant and re-heater time constant find for various control strategies of power output.

Arya et al. [28] developed AC/DC parallel links interconnected via with two equal control areas with thermal and hydro generating power sources. Authors made the CRAZYPSO and hBFOA-PSO algorithms for optimal PI regulators in AGC with thermal power system of 2-area non-reheat and GDB nonlinearity. In this article, RES uncertainties with penetration for AGC in power system. Authors [14, 15] implemented hybrid DEPSO optimized fuzzy PID controllers, and 2-area power systems with different energy sources like hydro, thermal and gas sources and genetic

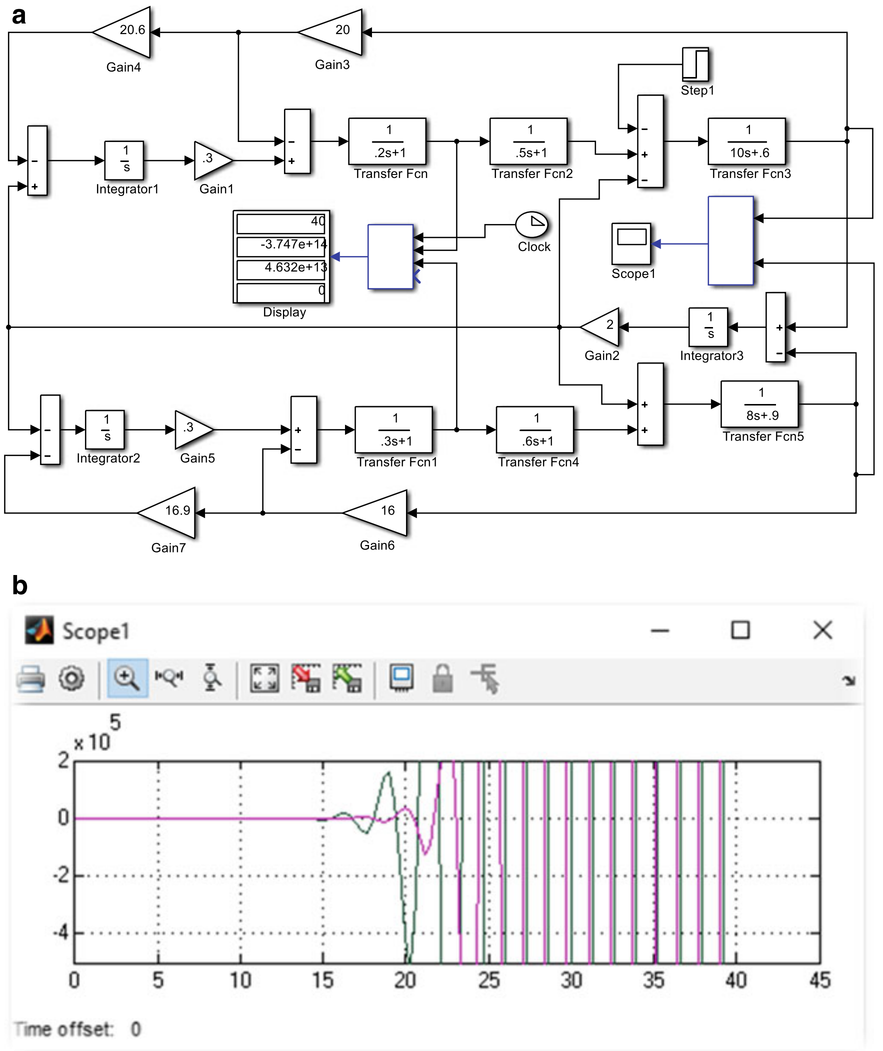


Fig. 2 **a** Simulation of two-area system, **b** step response of simulation for two-area system

algorithm has utilized for gain of optimal PID also for various test had been done with cases using ISE plus ITAE performance.

Table 2 The values of the power system constants with steam turbine and hydro turbine

Steam turbine	Hydro turbine	Power system
Time constant of speed governor *Tg* = 0.08 s	Rest time of speed governor TRH = 5.0 s	Rated area capacity Pr1 = Pr2 = 2000 MW Inertia constant H = 5 MW-s/MVA
Time Constant of Turbine *Tt* = 0.3 s	Time constant of transient droop TGH = 0.2 s	Rated frequency fr = 60 Hz Load frequency characteristic, *D* = (dPL/df)*(1/Pr) pu MW /Hz
Time Constant of re-heater *Tr* = 10 s	Main servo time constant Tw = 1.0 s	Gain Constant for Power System Kps = (1/D) Hz/pu MW
Coefficient of re-heat steam turbine *Kr* = 0.3	Speed governor regulation parameter Rhy = 2.4 Hz/pu MW	Power System Time Constant Tps = (2H/fr*D) s Frequency bias constant B1 = B2 = 0.425 puMW/Hz
Regulation parameter for Speed governor Rth = 2.4 Hz/pu MW		Tie-line: P12max = 100 MW (*d*1–*d*2) = 30°

Table 3 The power system constants of values for different nominal loads and corresponding scheduled power generation

Load (MW) in each area	Area-1 Generation		Ptie,12 (MW) Thermal MW)	Area-2 Generation		Power system constants	
	Thermal (MW)	Hydro (MW)		Thermal (MW)	Hydro (MW)	Kps (Hz/pu/MW)	Tps (sec)
1600	1000	600	100	1000	600	68	11
1500	900	600	100	1000	500	75	13

4.2 *Firefly Algorithm*

Pradhan et al. [12] used FA for optimization of PID in AGC where comparison shows the better one over GSA and GA, Authors also mention the impact of unified power flow controller and super conducting magnetic energy storage system. Padhana et al. [13] proposed a FA for LFC of multi-area power systems and compare it with other intelligent technique like BFOA, DE, and hBFOA-PSO optimized PI controller's performance developed FA-optimized PID controller.

Jagatheesan et al. [14] developed FA for optimizing the PID controller in more than one area power system for reheat thermal and compared with genetic algorithm and particle swarm optimize based PID controller.

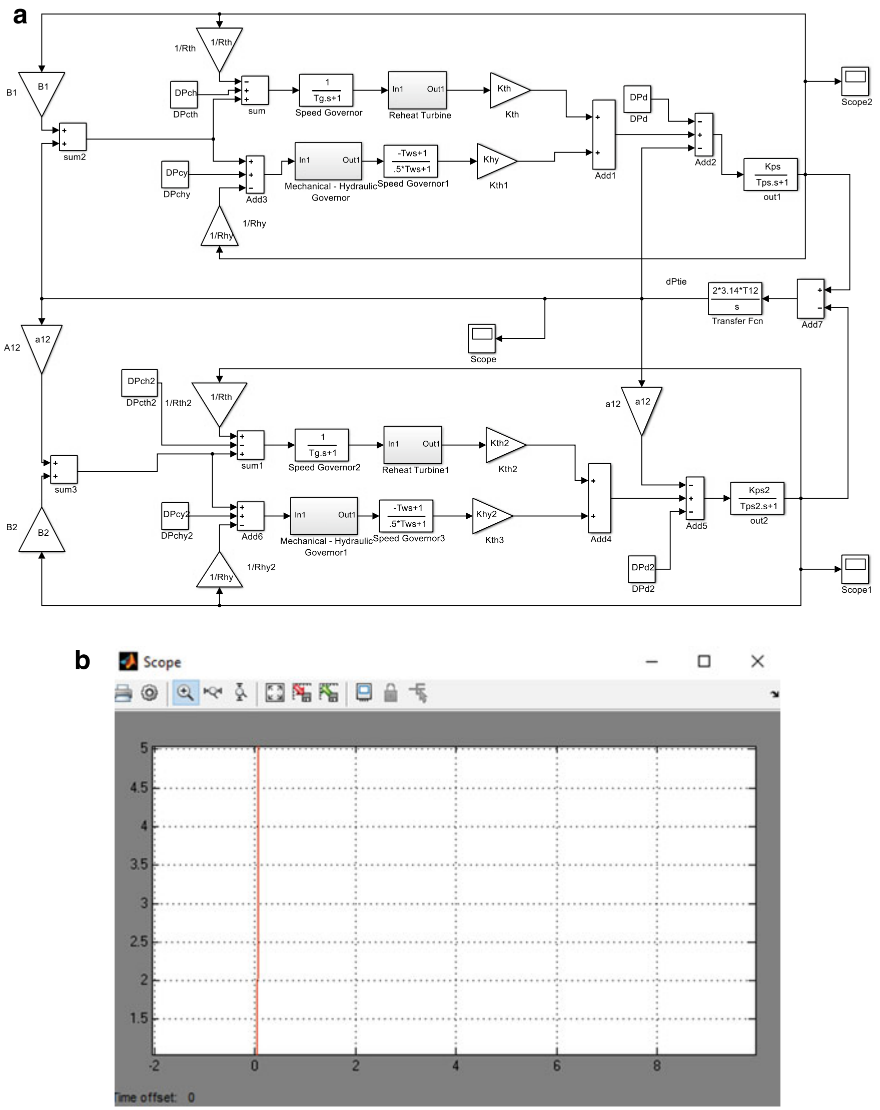


Fig. 3 **a** Simulation of two-area with diverse energy source, **b** Simulation result of power system for two-areas with ACE

4.3 Grey Wolf Optimization Algorithms

Y. Sharma et al. [15] made PID controller with GWO optimization also used data like peak overshoot, settling time, and magnitude of oscillations in the system, with or without solar thermal power plant (STPP). Guha et al. validated the QOGWO

Table 4 Diverse Energy Sources in Multi-Area Power Systems with

Area-1	Solar; Thermal
Area-2	Wind; Diesel
Area-3	Hydro; Nuclear
Area-4	Electric Vehicle; SMES; HVDC link

method [16] compared with its simulation with GWO and other AI techniques. Srinivasarathnam et al. [17] analyzed Grey Wolf Optimization (GWO) algorithm for PID controller gains of optimal tuning in secondary frequency control as the multi micro grid system and autonomous micro grid system operates in isolation. Padhy et al. [18] developed Modified GWO based optimal cascade PI-PD controller in plug-in EVs for AGC of power systems also algorithm qualified its superiority. Singh et al. [19] used GWO technique to optimize gains of three unequal area of AGC with reheat thermal system also doubly fed induction generator wind turbine. GWO algorithm used by Lal et al. [20] for interconnected hydro-thermal power system with fuzzy based PID controllers in AGC. Soni et al. [21] represented system robustness of 2DOF-PID controller optimized by varying the parameters with standard test system, operating load, by size and location at unbalanced area (Table 4; Fig. 4).

Extension to Multi-Area Power Systems with Diverse Energy Sources

Arya et al. [28] worked for AC/DC parallel links with 2-equal control areas integrated by thermal and hydro generating power sources. Authors made the CRAZYPSO and hBFOA-PSO algorithms for optimal PI regulators in AGC with 2-area non-reheat

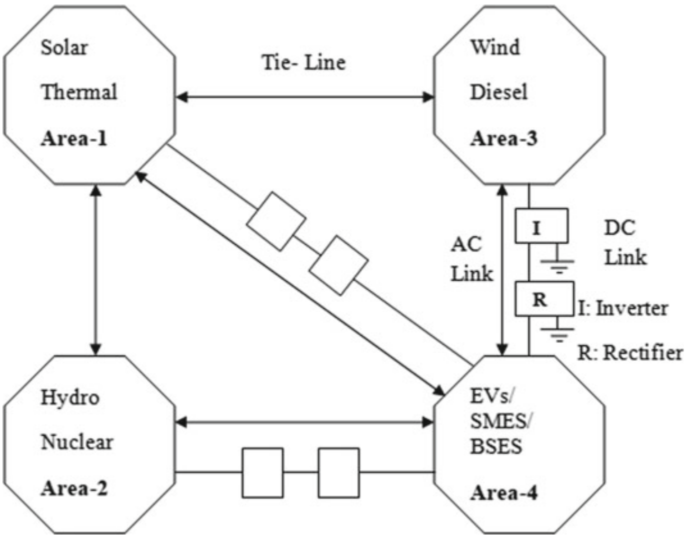


Fig. 4 Power system for 4-area diverse energy. *Source* with HVAC/DC link

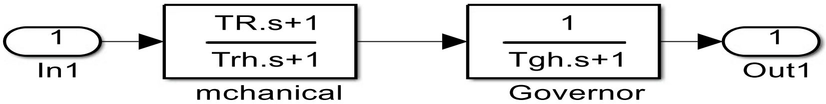
thermal system and the GDB nonlinearity. An equation based AGC regulators developed by Sharma et al. [29] for interconnected for 2-area power system with AC/DC tie-line. McNamara et al. [30] introduced for frequency regulation in AC/Multi-terminal Direct Current (MTDC)-connected grids, proposed article for MPC as a means of implementing AGC, while minimizing DC grid power losses. Almeida et al. [31] worked on EVs to stabilize with AGC. Gaur et al. [32] made a model consisting of a three area system embedded with EVs. The research article [33] Zhang et al. presented a LL algorithm based complementary generation control of integrated power grids for high penetration RESs and EVs. Oshnoei et al. [34] researched for EVs with AGC for perturbation of multi-area. Recently used of EVs with ABCO with tilt ID controller. Mathur et al. [35] explored on integration with wind power and V2G for stable frequency by perturbation. Authors worked for AGC in multi area power system [36–38], so that smooth and stable system developed.

5 Conclusions

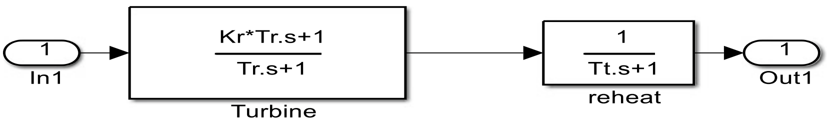
In this research paper investigation has done for PSO, FA, and GWO technique based AGC controllers with diverse energy sources in each areas. Power systems are as thermal, diesel, nuclear, and many more sources interconnected with hybrid resources like solar power, wind energy, hydro power, electric vehicles, micro-grid, and smart grid. The interconnection of different sources with two areas, also for multi area as well as tie-line control with several algorithms and soft computing techniques are shown in brief.

Appendix

Mechanical—Hydraulic Governor



Reheat Turbine



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