Comparative performances evaluation of FACTS devices on AGC with diverse sources of energy generation and SMES

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Abstract: This paper deals with automatic generation control of multi area power system using a Fuzzy PID controller. The controller parameters are optimized by Grey Wolf Optimizer (GWO) algorithm. Initially, Hydro-Thermal-Gas two area power systems is considered and superiority of the proposed controller is verified by comparing the results with GWO optimized classical PID controller as well as recently published optimal controller, such as DE-PID and TLBO-PID controllers. The proposed methodology is also verified with a modified power system with a nuclear plant and HVDC link and reveals better performance when compared with sliding mode controller tuned by TLBO algorithm. The proposed controller is designed to stabilize the frequency deviations of nonlinear power system considering FACTS devices and SMES. The results reveal that IPFC seems to be a promising alternative for frequency and tie-line power stabilization. Also the proposed controller is robust and satisfactory towards random step and sinusoidal load patterns.

Subjects: Intelligent Systems; Power Engineering; Systems & Controls

Keywords: automatic generation control; flexible AC transmission system; generation rate constraint; grey wolf optimization algorithm; nuclear power plant

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PUBLIC INTEREST STATEMENT

Automatic generation control (AGC) plays an important role to maintain a desired operating point. In an interconnected system, the function of AGC is to exchange and regulate power produced from various power generation units in each area so that the system frequency and the tie-line power interchanges between different control areas are maintained at their scheduled values. With the passage of time new ideas are emerging for the design of AGC controller to improve the system dynamics under the occurrence of the load perturbation. Flexible AC Transmission Systems (FACTS) are capable of enhancing power system stability by controlling the power flow in an interconnected power system. Further, improvement of system dynamics have been revealed with inclusion of storage devices along with FACTS based controller. A comparative study of FACTS devices on AGC have been analyzed in coordination with SMES, which further enhances system dynamics performance to a large extent.
1. Introduction

In a large interconnected power system, the generation of power is normally done by hydro, thermal and nuclear power plants. However, gas power generation is a small percentage of the total power generation which is suitable to meet the varying load demand. In the field of power system operation and control, automatic generation control (AGC) plays an important role in order to maintain a desired operating level characterized by nominal frequency, voltage profile and load flows in power system. In multi area interconnected power system all the generating units are connected together synchronously and work with the same frequency. A small load perturbation in the system will cause the deviations of frequencies of the areas and tie line power deviations from their nominal values (Elgerd, 2008). Therefore, the function of AGC is to exchange and regulate power produced from various sources in each area so that the system frequency and the tie-line power interchanges between different control areas are maintained at their scheduled values (Bevrani, 2009; Elgerd, 2008; Kothari & Nagrath, 2011). Initially, Elgerd and Fosha have done the pioneering works on AGC for solving regulator design problem (Elgerd & Fosha, 1970a, 1970b). By the passage of time, various controllers such as classical control (Das, Nanda, Kothari, & Kothari, 1990), optimal control (Bhatti, 2014; Elgerd & Fosha, 1970a; Yamashita & Taniguchi, 1986; Yazdizadeh, Ramezani, & Hamedrahmat, 2012), adaptive controls (Oysal, Yilmaz, & Koklukaya, 2005; Pan & Liaw, 1989; Rubaai & Udo, 1994) and robust control (Azam & Mohamed, 2002; Toulabi, Shiroei, & Ranjbar, 2014; Wang, Zhou, & Wen, 1993) are proposed in AGC study. Though, significant improvements of new controllers in recent years, Proportional Integral Derivative (PID) controller is still an attractive and simple option in AGC. Hence, PID controller is most widely employed in many power industries (Bevrani & Hiyama, 2008; Yu & Tomsovic, 2004). In past decades following the advent of modern intelligent techniques such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Fuzzy Logic (FL) and Artificial Neural Network (ANN), new ideas have been emerged for the design of AGC controller to improve the system dynamics under the occurrence of the load perturbation. The gains of PI and PID controllers are optimized through real coded genetic algorithm in a two area power system (Pingkang, Hengjun, & Yuyun, 2002). A PSO based controller parameter tuning of interconnected reheat thermal system is proposed for AGC in Abdel-Magid and Abido (2003). Artificial Bee Colony (ABC) algorithm has been proposed to tune PI and PID controller’s parameters for interconnected reheat thermal power system and its superiority is tested by comparing the dynamic performance of the system having PSO tuned controllers (Gozde, Taplamacioglu, & Kocaarslan, 2012). The optimal output feedback controller is proposed to the multi-source multi area power system having thermal, hydro and gas power plant in each area (Parmar, Majhi, & Kothari, 2012). Similarly, Teaching Learning Based Optimization (TLBO) algorithm is proposed for the same system for AGC in (Barisal, 2015) and the potential and effectiveness is compared with that of Differential Evolution (DE) and optimal output feedback controller proposed in (Mohanty, Panda, & Hota, 2014; Parmar et al., 2012). Few authors proposed hybrid intelligent techniques such as hybrid Bacterial Foraging Optimization Algorithm—PSO (hBFOA-PSO), hybrid Firefly Algorithm—Pattern Search (hFA-PS), hPSO-PS and hDE-PSO for the study of AGC and achieved excellent dynamic performance of the system (Panda, Mohanty, & Hota, 2013; Sahu, Panda, & Padhan, 2015; Sahu, Panda, & Sekhar, 2015; Sahu, Pati, & Panda, 2014). The success of fuzzy logic controllers for AGC of nonlinear power system are reported by many researchers. A self tuning fuzzy PID type controller for AGC of two area interconnected power system is proposed by Yeşil, Güzelkaya, and Eksin (2004). Various heuristic optimization techniques have been incorporated successfully for tuning of fuzzy PID controllers (Sahu, Panda, & Padhan, 2015; Sahu, Panda, & Sekhar, 2015). Similarly, variable structure fuzzy gain scheduling based controller tuned by GA is reported for multi source two area hydro thermal system (Chandrakala, Balamurugan, & Sankaranarayanan, 2013) and output feedback sliding mode controller (SMC) tuned by TLBO algorithm is proposed for multi source two area hydro thermal system with addition of gas plant in one area and nuclear plant in other area (Mohanty, 2015). Distributed optimization and control methods have been applied for economic load dispatch in smart grid (Li, Yu, Yu, Chen, & Wang, 2017; Li, Yu, Yu, Huang, & Liu, 2016). Remodeling of demand side management and development of bidirectional framework for quickly solving problem and getting customers best response is quite encouraging. Due to quite popularity, distributed optimization and control methods are emerging techniques for solving LFC problem. Different level of coordinated communications may be established between the different
controllers. This will lead to establish distributed control mechanism of interconnected realistic power system, which tackles GRC, GDB and load reference set-point constraints.

Further, improvement of system dynamics have been revealed with inclusion of Flexible AC Transmission Systems (FACTS) based controller. These FACTS devices are capable of enhancing power system stability by controlling the power flow in an interconnected power system (Hingorani & Gyugyi, 2000). Several FACTS devices, such as Thyristor Controlled Phase Shifter (TCPS), Static Synchronous Series Compensator (SSSC), Thyristor Controlled Series Compensator (TCSC), Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC), have been developed and proposed for AGC (Abraham, Das, & Patra, 2007; Chidambaram & Paramasivam, 2012; Lal, Barisal, & Tripathy, 2016; Ngamroo, Taeratanachai, Dechanupaprittha, & Mitani, 2007; Padhan, Sahu, & Panda, 2014; Ponnumamy, Banakara, Dash, & Veerasamy, 2015; Pradhan, Sahu, & Panda, 2016; Shankar, Bhushan, & Chatterjee, 2016; Zare, Hagh, & Morsali, 2015). Energy storage devices have been widely accepted by many researchers for AGC in coordination with FACTS devices. The control performance enhancement of two areas multiple unit power system in coordination with Redox Flow Battery (RFB) and IPFC have been introduced in (Chidambaram & Paramasivam, 2012). Bhatt, Roy, and Ghoshal (2011) compared and described the performance of SMES-SMES, TCPS-SMES and SSSC-SMES controllers in AGC for a two area interconnected power system. The system dynamics in coordination with SSSC and TCPS for two area power system has been studied (Subbaramaiah, 2011).

The literature review reveals that the performance of the power systems not only depend on various controllers but also on the intelligent techniques used for controller parameters optimization. Also the improvements of system dynamics have been achieved with inclusion of FACTS and energy storage devices. In perspective of the above, the ongoing work proposes Fuzzy PID controller for AGC. The controller parameters have been optimized by recently developed powerful optimization technique i.e. Grey Wolf Optimizer (GWO) algorithm (Mirjalili, Mirjalili, & Lewis, 2014). The main advantages of selecting GWO algorithm in the present work is that, the algorithm provides very promising results in various engineering optimization problems. It may be noted that the GWO algorithm requires least number of controlling parameter, which make it simple concept for implementation, effective, faster convergence due to inherent randomness for optimum global solutions. Also, Guha, Roy, and Banerjee (2016) tested the superiority and effectiveness of the GWO algorithm by optimizing the classical controllers such as PI/PID controllers for AGC and compared transient responses of the power system with GA, DE, BFOA, hBFOA-PSO, FA and TLBO optimized classical controllers. Also the comparisons have been done with hPSO-PS and hFA-PS optimized Fuzzy PID controllers.

The motivation behind the present work is that efficient AGC of a complex interconnected power system with FACTS devices coordinated with storage facility greatly improves the dynamic stability of the system when subjected to small load perturbation. In the present work the GWO optimized Fuzzy PID controller is proposed on a two area multi-source interconnected power system and its performance is compared with recently published results such as TLBO-PID, DE-PID and optimal controller for the same power system. Furthermore, proposed controller performance is compared in the modified power system having the output feedback sliding mode controller (SMC) (Mohanty, 2015). Finally, the present work is extended with inclusion of several FACTS devices for AGC and a comparative performance of the system have been analyzed in coordination with SMES. Furthermore, three unequal area thermal power system has been considered to verify the potential of FACTS based controller with the proposed algorithm.

In view of the above discussion, the following are the main objectives of the present work:

(I) Initially, the work is started with AGC of multi-area multi-source hydro-thermal-gas power system to investigate the superiority of the proposed GWO optimized Fuzzy PID control technique. Then, the work is extended to hydro-thermal-gas in one area and hydro-thermal-nuclear in another area with Super Conducting Magnetic Energy Storage (SMES). Also, to make the system
more realistic nonlinearities like Generation Rate Constraint (GRC) and Governor Dead Band (GDB) is considered for analysis.

(II) To incorporate different types of FACTS devices for AGC of power system and compare their effectiveness to system performance.

(III) To check the stability of different power system models as proposed in this paper, Eigen value analysis has been done.

(IV) To conduct sensitivity analysis for the proposed GWO optimized Fuzzy PID controller for the proposed model and to investigate its robustness to wide changes in loading patterns.

2. Modeling of the interconnected power system
The system under study is a two area multi source interconnected power system. First the power system model taken into consideration for dynamic behaviour study includes reheat thermal, hydro and gas generating units in each area. Subsequently the study is extended to power system model which includes reheat thermal, hydro and gas generating units in one area. The other area consists of reheat thermal, hydro and nuclear units. The non-linearity such as GRC and GDB is included in the system to make it more realistic power system. The transfer function model of the proposed system is shown in Figure 1 for simulation and AGC study. The system parameters are given in Appendix A.
3. Modeling of FACTS devices
FACTS devices are one aspect of the power electronics revolution that is taking place in all areas of electric energy. The principal role is to enhance controllability and power transfer capability in ac system. In this section modeling of the FACTS devices are presented for AGC study.

3.1. Modeling of SSSC for AGC
The SSSC belongs to the family of FACTS devices. It is installed in series with the transmission lines. It has the capability to shift its reactance characteristic from capacitive to inductive and effectively control the power flow. The SSSC is implemented by a voltage sourced converter operated as a synchronous voltage source and to provide effective voltage and power flow control in an independent way by internally generated series reactive compensation. It is installed in series with the tie-line for frequency stabilization of interconnected power system. The schematic diagram of SSSC connected in series with the tie-line is shown in Figure 2.

![Figure 2. Schematic diagram of SSSC connected in series with the tie-line.](image)

The controller to change the SSSC voltage can be expressed as (Ngamroo et al., 2007; Ponnusamy et al., 2015; Pradhan et al., 2016):

$$\Delta V_S = \left( \frac{1 + T_1 s}{1 + T_2 s} \right) \left( \frac{1 + T_3 s}{1 + T_4 s} \right) \left( \frac{K_2}{1 + T_{SSSC} s} \right) \Delta \text{Error}(s) \quad (1)$$

If the frequency deviation $\Delta F_1(s)$ is sensed, it can be used as the control signal (i.e. $\Delta \text{Error} = \Delta F_1(s)$) to the SSSC unit to control $V_S$, which will alter the tie-line power flow between two areas and assist in stabilizing the frequency oscillation. Thus:

$$\Delta P_{tie}(s) = \frac{2\pi T_{12}}{s} \left[ \Delta F_1(s) - \Delta F_2(s) \right] + K_1 \left( \frac{1 + T_1 s}{1 + T_2 s} \right) \left( \frac{1 + T_3 s}{1 + T_4 s} \right) \left( \frac{K_2}{1 + T_{SSSC} s} \right) \Delta F_1 \quad (2)$$
where, $K_{SSSC} = K_1 \cdot K_2$

$$\Delta P_{tie} = \frac{2\pi T_{12}}{s} \left[ \Delta F_1(s) - \Delta F_2(s) \right] + \left( \frac{1 + T_1 s}{1 + T_2 s} \right) \left( \frac{1 + T_3 s}{1 + T_4 s} \right) \left( \frac{K_{SSSC}}{1 + T_{SSSC} s} \right) \Delta F_1(s)$$

(3)

where, $K_{SSSC} = K_1 \cdot K_2$

$$\Delta P_{tie}(s) = \Delta P_{12}(s) + \Delta P_{SSSC}(s)$$

(4)

where $\Delta P_{SSSC}(s) = \left( \frac{1 + T_1 s}{1 + T_2 s} \right) \left( \frac{1 + T_3 s}{1 + T_4 s} \right) \left( \frac{K_{SSSC}}{1 + T_{SSSC} s} \right) \Delta F_1(s)$

(5)

The detailed structure of SSSC in series with tie line is provided in Figure 3. The input signal of SSSC controller is the frequency deviation p.u. Hz in Area 1. The structure of SSSC frequency stabilizers consists of the stabilization gain ($K_{SSSC}$) block and the phase compensation block with time constants $T_1$, $T_2$, $T_3$ and $T_4$ which provides the appropriate phase-lead characteristics to compensate the lag between input and the output signals.

3.2. Modeling of the TCPS for AGC

The TCPS is a device that changes the relative phase angle between the system voltages. Therefore, the real power flow can be controlled to mitigate the frequency oscillations and improve power system stability (Abraham et al., 2007). A schematic of the two area interconnected power system with TCPS in series with the tie line is shown in Figure 4. TCPS is placed near Area 1. Resistance of the tie-line is neglected. Without TCPS, the incremental tie-line power flow from Area 1 to Area 2 can be expressed as:

$$\Delta P_{tie12} = \frac{2\pi T_{12}}{s} (\Delta f_1 - \Delta f_2)$$

(6)

where $T_{12}$ is the synchronizing constant without TCPS and $\Delta f_1$ and $\Delta f_2$ are frequency deviations of Area 1 and Area 2 respectively. The detail derivations are presented in Abraham et al. (2007).

The phase shifter angle $\Delta \phi(s)$ with inclusion of TCPS can be represented as:

$$\Delta \phi(s) = \frac{K_\phi}{1 + sT_{PS}} \Delta \text{Error}(s)$$

(7)

where $K_\phi$ and $T_{PS}$ are the gain and time constant of the TCPS. Now the tie-line power flow deviation can be written as:
If the frequency deviation $\Delta F_1(s)$ is sensed and used as the control signal to the TCPS unit to control the TCPS phase angle which in turn, control the tie-line power flow, then Equation (7) becomes:

$$\Delta P_{Tie12}(s) = 2\pi T_{12} \left[ \Delta F_1(s) - \Delta F_2(s) \right] + \frac{K_{\phi}}{1 + sT_{PS}} \Delta Error(s)$$  \hfill (8)

Also the tie-line power flow becomes:

$$\Delta \phi(s) = \frac{K_{\phi}}{1 + sT_{PS}} \Delta F_1(s)$$  \hfill (9)

The detail derivations of UPFC based controller for AGC study is given in (Shankar et al., 2016). Thus the UPFC based controller can be represented as follows.

**Figure 6. Schematic diagram of two area interconnected power system with UPFC.**

![Diagram of two area interconnected power system with UPFC.](https://doi.org/10.1080/23311916.2017.1318466)
where \( T_{UPFC} \) is a time constant of UPFC.

The structure of UPFC as frequency stabilizer is shown in Figure 7.

### 3.4. Modeling of IPFC for AGC

The IPFC provides a path for the cost-effective utilization of individual transmission lines by encouraging the autonomous control of both the real and reactive power flow. The IPFC which belongs to FACTS family proposed by Gyugyi with Sen and Schauder in 1998 provides attractive option for compensation and power flow management of multiple transmission lines at a given substation (Hingorani & Gyugyi, 2000). The IPFC employs a number of dc-to-ac converters and each provides series compensation for a different line. The schematic of IPFC is shown in Figure 8. It facilitates not only compensation of each transmission line separately but also provides compensation of all at the same time. The IPFC not only provides independent control of reactive series compensation of each individual line, but also provides a capability to directly transfer of real power between the compensated lines through dc link. In this way it controls both the real and reactive power transfer through the common dc link from over-loaded lines to under-loaded lines.

To understand the impact of IPFC in the power system during the steady state the mathematical derivation is presented in Chidambaram and Paramasivam (2012). The IPFC based controller can be represented in AGC as:

\[
\Delta P_{IPFC}(s) = \left\{ \frac{1}{1 + sT_{IPFC}} \right\} \Delta F_1(s) \tag{12}
\]

\[
\Delta P_{IPFC}(s) = \left\{ \frac{1}{1 + sT_{IPFC}} \right\} \left\{ k_1 \Delta F_1(s) + k_2 \Delta P_{12}(s) \right\} \tag{13}
\]

where \( T_{IPFC} \) is a time constant of IPFC.
Figure 9. Structure of IPFC as a frequency controller.

\[ \Delta F_1(s) \xrightarrow{K_1} \Delta F_2(s) \xrightarrow{\frac{2\pi T_{12}}{s}} \Delta P_{12} \xrightarrow{K_2} \Delta P_{IPFC} \xrightarrow{\frac{1}{1+sT_{IPFC}}} \Delta P_{tie} \]

\[ \Delta P_{tie}(s) = \Delta P_{IPFC}(s) + \Delta P_{12}(s) \]

Figure 10. SMES circuit diagram.

Figure 11. Structure of SMES as frequency stabilizer.

\[ \Delta F_i(s) \xrightarrow{1+sT_1} \xrightarrow{1+sT_2} \xrightarrow{1+sT_3} \xrightarrow{1+sT_{SMES}} \Delta P_{SMES} \]

and

\[ \Delta P_{tie}(s) = \Delta P_{IPFC}(s) + \Delta P_{12}(s) \] (14)

where \( T_{IPFC} \) is a time constant of IPFC.

The structure of IPFC as a frequency controller is shown in Figure 9.

4. Modeling of the SMES system for AGC

Figure 10 shows the basic transfer function model of SMES unit in power system. An SMES unit has high efficiency and fast response. An SMES unit is designed to store electric power in the low loss superconducting magnetic coil. Its storage capability in addition to kinetic energy of the generator rotor enhances the damping of the electromechanical oscillation in power system. In view of the above, two SMES units are incorporated in Area 1 and Area 2 in order to stabilize frequency oscillations as shown in Figure 1.

The structure for SMES as frequency stabilizer is modeled as the second order lead-lag compensator as shown in Figure 11. The input signals of the SMES units are p.u. frequency deviations in respective areas where those are connected. The parameters of SMES frequency stabilizers in each area such as, the stabilization gain \( K_{SMES} \) and time constants \( T_1, T_2, T_3 \) and \( T_4 \) are to be optimized for optimal design of SMES frequency stabilizer.
5. Controller structure and objective function

The structure of the Fuzzy PID controller is shown in Figure 12 (Sahu et al., 2014; Yeşil et al., 2004). An identical controller is employed in each area. The error inputs to the controllers are the respective area control error (ACE). For the two areas interconnected power system, the ACE signal made by frequency and tie-line power deviations is represented by Equations (15) and (16),

\[
e_1(t) = ACE_1 = B_1 \Delta F_1 + \Delta P_{\text{Tie}}
\]

\[
e_2(t) = ACE_2 = B_2 \Delta F_2 + a_{12} \Delta P_{\text{Tie}}
\]

Fuzzy controller uses error \(e\) and derivative of error \(\dot{e}\) as input signals. The outputs of the Fuzzy controllers \(U_L\), \(U_H\) and \(U_G\) are the control inputs of the generating units. Fuzzy PID controller is a combination of fuzzy proportion-integral (PI) and fuzzy proportional-derivative (PD) controllers. The input scaling factors are \(K_1\) and \(K_2\) and the output scaling factors are \(K_3\) and \(K_4\). Triangular membership functions are used with five fuzzy linguistic variables such as NB (negative big), NS (negative small), Z (zero), PS (positive small) and PB (positive big) for both the inputs and the output. Membership functions for error, error derivative and FLC output are shown in Figure 13. Mamdani fuzzy inference engine is selected for the present work. The two-dimensional rule base for error, error derivative and FLC output are given in Table 1.

In the selection process of the controller parameters, the objective function is first defined based on the desired specifications and constraints. The output specifications in time domain are peak overshooting, rise time, settling time and steady state errors. In Integral of Time Multiplied Absolute Error (ITAE), time is multiplied with the absolute value of errors so that oscillations die out quickly and results in minimum of settling time (Ogata, 2010). Therefore, it is used as objective function for controller parameters tuning. The objective function \(J\) for controller parameters optimization of the interconnected power system is depicted below.
where, $\Delta F_1$ and $\Delta F_2$ are the frequency deviations in Area 1 and Area 2 respectively; $\Delta P_{tie}$ is the incremental change in tie line power; $t_{sim}$ is the time range of simulation. The problem constraints are the minimum and maximum limits of Fuzzy PID controllers scaling factors $K_1$, $K_2$, $K_3$ and $K_4$. Thus, the design problem can be formulated as follows:

Minimize $J$ 

Subject to:

$K_{min}^1 \leq K_1 \leq K_{max}^1$, $K_{min}^2 \leq K_2 \leq K_{max}^2$, $K_{min}^3 \leq K_3 \leq K_{max}^3$ and $K_{min}^4 \leq K_4 \leq K_{max}^4$ (19)

6. Grey Wolf Optimizer algorithm

The meta-heuristic optimization techniques have been successfully implemented in many engineering fields. Those have produced excellent results and have many advantages over conventional methods such as simplicity, flexibility, derivative free mechanism and local optima avoidance (Mirjalili et al., 2014). The Grey Wolf Optimizer (GWO) algorithm is one of the meta-heuristic algorithms inspired by grey wolves ($Canis lupus$) (Mirjalili et al., 2014). Grey wolf, also known as timber wolf or western wolf belongs to Canidae family.

The advantage of GWO algorithm over most of the optimization algorithm is that the algorithm requires no specific input parameters. Also, it is straightforward and free from computational complexity. The flowchart of GWO algorithm is presented in Figure 14.

The group hunting is an important social behaviour apart from the surviving and living in a pack. The main phases of group hunting are as follows:

(i) Tracking, chasing and approaching the prey.
(ii) Pursuing, encircling and harassing the prey until it stops moving.
(iii) Attack towards the prey.

The mathematical model of social hierarchy of wolves, tracking, encircling and attacking prey are given in Mirjalili et al. (2014).
Finally, the steps of GWO algorithm may be summarized as follows (Guha et al., 2016):

(a) The search process is started with random initialization of candidate solutions (wolves) in the search space.
(b) Alpha, beta and delta wolves are estimated based on the position of prey.
(c) To find the optimum location of prey, each wolf updates its position.
(d) A control parameter \( \vec{a} \) linearly decreases from 2 to 0 for better exploitation and exploration of candidate solutions.
(e) Candidate solutions tend to diverge and at the end the optimum solution is stored.

7. Results and discussion of the simulated test system

7.1. Two area test system

The simulation of system under study has been done in MATLAB/Simulink environment and GWO algorithm has been written in (.m file). The developed model is simulated using initial gain scheduling parameters considering an 1% step load perturbation (SLP) in Area 1 at time \( t = 0 \) s. The objective function is calculated in .m file and used in optimization algorithm for tuning the gains of Fuzzy PID controller for power system. Series of experiments were conducted to choose the appropriate controller parameters. The simulation was repeated for 30 times and the best final solution among the 30 runs is selected as proposed controller parameters. The best final solutions obtained in the 30 runs are considered as optimal solution shown in Table 2 for the system under study.
Table 2. GWO optimized Fuzzy PID controller parameters of power system-1 without physical constraints

| Methods                | Area 1 = Thermal | Area 2 = Hydro | Area 3 = Gas |
|------------------------|------------------|----------------|-------------|
| GWO optimized controller | $K_1 = 1.6974$   | $K_1 = 0.5428$ | $K_1 = 1.5258$ |
|                        | $K_2 = 1.8336$   | $K_2 = 0.0605$ | $K_2 = 0.1659$ |
|                        | $K_3 = 0.4935$   | $K_3 = 1.0157$ | $K_3 = 0.3308$ |
|                        | $K_4 = 1.0103$   | $K_4 = 1.1712$ | $K_4 = 1.0340$ |

Figure 15. (a) Frequency deviation in Area 1 subjected to a step load change of 0.01 p.u. in Area 1, (b) Frequency deviation in Area 2 subjected to a step load change of 0.01 p.u. in Area 1 and (c) Tie-line power flow deviation subjected to a step load change of 0.01 p.u. in Area 1.
Figure 16. (a) Frequency deviation in Area 1 subjected to a step load change of 0.01 p.u. in Area 1 and their comparison for proposed GWO optimized Fuzzy PID control scheme with TLBO optimized Output feedback SMC scheme, (b) Frequency deviation in Area 2 subjected to a step load change of 0.01 p.u. in Area 1 and their comparison for proposed GWO optimized Fuzzy PID control scheme with TLBO optimized Output feedback SMC scheme and (c) Tie-line power flow deviation subjected to a step load change of 0.01 p.u. in Area 1 and their comparison for proposed GWO optimized Fuzzy PID control scheme with TLBO optimized Output feedback SMC scheme.

Table 3. GWO optimized Fuzzy PID controllers parameters of power system-2 with HVDC link, GRC and reheat turbine

| Methods                        | Area 1 = Area 2 |
|--------------------------------|----------------|
| GWO optimized controller       |                |
| Fuzzy PID controller           |                |
| $K_1$ = 0.2393                  | $K_1$ = 1.1126 |
| $K_2$ = 0.5789                  | $K_2$ = 0.4438 |
| $K_3$ = 1.8669                  | $K_3$ = 1.3002 |
| $K_4$ = 1.4068                  | $K_4$ = 1.4014 |
|                                | $K_s = 1.8334$ |
|                                | $K_s = 1.4036$ |
|                                | $K_s = 0.3902$ |
|                                | $K_s = 1.3604$ |
The predominance of the proposed GWO optimized Fuzzy PID controller is verified in Figure 15(a)–(c), when compared with optimal controller, DE-PID controller, TLBO-PID controller and GWO optimized PID controller for the multi-source two area power system having Hydro-Thermal-Gas in each area considering a 1% SLP in Area 1 at time, $t = 0$ s. The controller parameters values are given in Table 2. Then, a gas unit in Area 2 is replaced by nuclear unit along with HVDC link, GRC and reheat turbine in each area. The model is simulated with the proposed controller and controller parameters are optimized. Results in terms of frequency deviations in each area and tie-line power deviation are shown in Figure 16(a)–(c) by comparing with recently published paper on TLBO optimized output feedback sliding mode controller (SMC). The optimized values for the proposed controllers are presented in Table 3. The performance index values in terms of maximum undershoot (MUS), maximum overshoot (MOS), settling time with 2% tolerance band and different errors are shown in Table 4. The present work is extended considering GDB with GRC and reheat turbine with inclusion of SMES units in both areas. The comparative analysis of the considered system with proposed controller is done with and without SMES units in each area. It is clear from Figure 17(a)–(c) that system performance further improves with SMES units. Also the Eigen values and minimum damping ratio (MDR) are presented in Table 5. As we know the closed loop system is said to be stable if all the eigen values are located to the left half of the s-plane. From Table 5, it is clear that all eigen values are lying in the left half of s-plane for which the system is stable. The MDR value with SMES and proposed controller is found to be higher than without SMES. The settling time, maximum overshoot (MOS) and minimum undershoot (MUS) are better with SMES as shown in Table 6.
Further the present work is extended to verify the improvements in system performance with incorporation of different FACTS devices such as SSSC, TCPS, UPFC and IPFC along with SMES units as shown in Figure 1. The optimal gains of the proposed GWO based Fuzzy PID controller with FACTS devices are reported in Table 7. The comparison of the performance of the system with different FACTS devices are shown in Figure 18(a)–(c). It is clear from Figure 18(a)–(c) that UPFC and IPFC providing good results. If only frequency deviation of Area 1 is considered UPFC performs better than IPFC. But IPFC performs better than UPFC when frequency deviation in Area 2 and tie-line power deviations are also considered. The performance of IPFC is dominating to all FACTS members considered. The performance index values with different FACTS devices are given in Table 8. The overall
### Table 5. System modes, minimum damping ratio, for multi-source multi area power system with HVDC link, GDB, GRC and Reheat turbine without and with SMES

| Methods             | GWO Fuzzy PID without SMES | GWO Fuzzy PID with SMES |
|---------------------|-----------------------------|--------------------------|
| System Modes        |                             |                          |
| −2.0000             | −2.0000                     |                          |
| −0.0348             | −2.0000                     |                          |
| −5.0000             | −0.0348                     |                          |
| −2.0000             | −3.3333                     |                          |
| −0.0348             | −3.3333                     |                          |
| −3.3333             | −0.1000                     |                          |
| −3.3333             | −12.5000                    |                          |
| −0.1000             | −5.0000                     |                          |
| −12.5000            | −0.1000                     |                          |
| −0.1000             | −12.5000                    |                          |
| −12.5000            | −0.0348                     |                          |
| −5.0000             | −0.0348                     |                          |
| −19.9809            | −36.7400 +23.9350i          |                          |
| −2.2222 + 5.1856i   | −36.7400 −23.9350i          |                          |
| −2.2222 −5.1856i    | −36.6879 +23.9109i          |                          |
| −2.4483 +4.9497i    | −36.6879 −23.9109i          |                          |
| −2.4483 −4.9497i    | −20.0148                    |                          |
| −4.5159             | −4.5858                     |                          |
| −2.1734             | −3.4205 +1.3882i            |                          |
| −1.0459             | −3.4205 −1.3882i            |                          |
| −0.4667             | −3.3076 +1.3945i            |                          |
| −0.1084             | −3.3076 −1.3945i            |                          |
| −0.1435             | −0.1431                     |                          |
| −5.0000             | −0.1098                     |                          |
| −2.0000             | −0.1431                     |                          |
| −2.0000             | −1.0409                     |                          |
| −2.0000             | −2.2554                     |                          |
| −2.0000             | −1.5745                     |                          |
| −1.5505             | −5.0000                     |                          |
| −5.0000             | −2.0000                     |                          |
| MDR                 | 0.3939                      | 0.8378                   |

### Table 6. Performance evaluation of proposed GWO optimized Fuzzy PID controller by settling time, minimum undershoot and maximum overshoot of multi-source multi area nonlinear power system without and with SMES

| Controllers and parameters | Without SMES | With SMES |
|----------------------------|--------------|-----------|
| Settling times (2% tolerance band) (s) | $\Delta F_1$ | 4.42 | 1.75 |
|                             | $\Delta F_2$ | 4.54 | 3.68 |
|                             | $\Delta P_{\text{tie}}$ | 3.5 | 2.38 |
| MOS (p.u.)                  | $\Delta F_1 \times 10^{-4}$ | 20.0607 | 1.846 |
|                             | $\Delta F_2 \times 10^{-4}$ | 1.0095 | 1.0521 |
|                             | $\Delta P_{\text{tie}} \times 10^{-4}$ | 0.5726 | 0.6377 |
| MUS (p.u.)                  | $\Delta F_1 \times 10^{-1}$ | −9.83358 | −3.60876 |
|                             | $\Delta F_2 \times 10^{-1}$ | −1.75890 | −0.88572 |
|                             | $\Delta P_{\text{tie}} \times 10^{-1}$ | −0.78422 | −0.44698 |
The performance of IPFC is found to be better than others. The eigen values evaluated for the system with coordinated operation of different FACTS devices with an SLP of 1% in Area 1 are presented in Table 9. All eigen values are lying in the left half of s-plane, because of which the system is stable. The MDR value of IPFC based controller is found to be 0.5881, which is higher than others. To approve the adequacy of the proposed approach the analysis is carried out for the system subjected to different load patterns such as random step load and sinusoidal load. A random step load pattern is presented in Figure 19 and is applied in Area 1. The system responses are given in Figure 20(a)–(c).

Figure 18. (a) Frequency deviation of Area 1 with SMES and FACTS subjected to a step load change of 0.01 p.u. in Area 1, (b) Frequency deviation of Area 2 with SMES and FACTS subjected to a step load change of 0.01 p.u. in Area 1 and (c) Tie-line power flow deviation with SMES and FACTS subjected to a step load change of 0.01 p.u. in Area 1.
### Table 7. Optimal gains of controller for different FACTS devices

| Methods                        | Area 1 = Area 2 | Area 1 = Area 2 | SMES constants | FACTS constants |
|--------------------------------|----------------|----------------|----------------|-----------------|
| GWO optimized fuzzy PID controller |                |                |                |                 |
| SSSC                           | $K_1 = 1.6291$ | $K_2 = 0.5978$ | $K_3 = 1.8000$ | $T_s = 0.0048$  | $T_x = 0.2933$  |
|                                | $K_4 = 0.3561$ | $K_5 = 0.1037$ | $K_6 = 0.7356$ | $T_s = 0.0178$  | $T_x = 0.0516$  |
|                                | $K_7 = 1.6633$ | $K_8 = 0.7323$ | $K_9 = 0.9476$ | $T_s = 0.2393$  | $T_x = 0.5041$  |
|                                | $K_{10} = 0.1372$ | $K_{11} = 0.2603$ | $K_{12} = 1.6671$ | $T_s = 0.0295$  | $T_x = 0.7684$  |
|                                |                |                |                | $K_{\text{smes}} = 0.3649$ | $K_{\text{SSSC}} = 0.2830$ |
|                                |                |                |                | $T_{\text{smes}} = 0.0405$ | $T_{\text{SSSC}} = 0.2254$ |
| TCPS                           | $K_1 = 1.8279$ | $K_2 = 1.7430$ | $K_3 = 0.2655$ | $T_s = 0.4554$  | $K_{\phi} = 1.9004$ |
|                                | $K_4 = 0.3036$ | $K_5 = 0.4515$ | $K_6 = 0.1037$ | $T_s = 0.0509$  |                 |
|                                | $K_7 = 1.8793$ | $K_8 = 1.7688$ | $K_9 = 1.8824$ | $T_s = 0.4097$  | $T_x = 0.0172$  |
|                                | $K_{10} = 1.9604$ | $K_{11} = 0.5784$ | $K_{12} = 0.1095$ | $T_s = 0.0265$  |                 |
|                                |                |                |                | $K_{\text{smes}} = 0.8695$ | $T_{\text{smes}} = 0.2268$ |
| UPFC                           | $K_1 = 1.9347$ | $K_2 = 1.8720$ | $K_3 = 0.2627$ | $T_s = 0.5942$  | $T_{\text{spec}} = 0.0201$ |
|                                | $K_4 = 0.3568$ | $K_5 = 0.3125$ | $K_6 = 0.6757$ | $T_s = 0.0587$  |                 |
|                                | $K_7 = 1.2961$ | $K_8 = 1.3503$ | $K_9 = 1.7661$ | $T_s = 0.4635$  |                 |
|                                | $K_{10} = 1.9822$ | $K_{11} = 0.5819$ | $K_{12} = 0.3135$ | $T_s = 0.0280$  |                 |
|                                |                |                |                | $K_{\text{smes}} = 0.8872$ | $T_{\text{smes}} = 0.1571$ |
| IPFC                           | $K_1 = 1.9669$ | $K_2 = 1.5336$ | $K_3 = 0.2389$ | $T_s = 0.5766$  | $K_{\text{spec}} = 0.0270$ |
|                                | $K_4 = 0.3811$ | $K_5 = 0.4944$ | $K_6 = 0.5364$ | $T_s = 0.0683$  | $K_{\text{spec}} = 0.0016$ |
|                                | $K_7 = 1.5876$ | $K_8 = 1.9892$ | $K_9 = 1.6987$ | $T_s = 0.4558$  | $T_{\text{spec}} = 0.0450$ |
|                                | $K_{10} = 1.8540$ | $K_{11} = 0.6728$ | $K_{12} = 0.3353$ | $T_s = 0.0220$  |                 |
|                                |                |                |                | $K_{\text{smes}} = 0.8149$ | $T_{\text{smes}} = 0.4599$ |

### Table 8. Performance criteria for multi-source multi area nonlinear power system with SMES and FACTS

| Objective function and parameters | SSSC       | TCPS       | UPFC       | IPFC       |
|-----------------------------------|------------|------------|------------|------------|
| ITAE                              | 0.0086     | 0.0072     | 0.0098     | 0.0077     |
| ISE                               | $4.5798 \times 10^{-6}$ | $4.2021 \times 10^{-7}$ | $1.8377 \times 10^{-6}$ | $7.7629 \times 10^{-7}$ |
| ITSE                              | $9.7544 \times 10^{-6}$ | $1.4507 \times 10^{-8}$ | $2.6448 \times 10^{-8}$ | $1.5436 \times 10^{-8}$ |
| IAE                               | 0.0068     | 0.0028     | 0.0043     | 0.0029     |
| Settling times (2% band)           | $\Delta F_1$ | $\Delta F_2$ | $\Delta F_3$ | $\Delta F_4$ |
|                                   | 2.34       | 1.55       | 1.59000    | 1.29       |
|                                   | 3.5        | 2.01       | 4.51000    | 2.25       |
|                                   | 2.9        | 0.66       | 1.41000    | 1.41       |
|肌炎 (MUS)                        | $\Delta F_1$ | $\Delta F_2$ | $\Delta F_3$ | $\Delta F_4$ |
|                                   | $-0.00500375$ | $-0.00182222$ | $-0.00118080$ | $-0.00217230$ |
|                                   | $-0.00266690$ | $-0.00050430$ | $-0.00175894$ | $-0.00036766$ |
|                                   | $-0.00125826$ | $-0.00026595$ | $-0.00117744$ | $-0.00018922$ |
|平均 (MOS)                        | $\Delta F_1$ | $\Delta F_2$ | $\Delta F_3$ | $\Delta F_4$ |
|                                   | 0.00000014191 | 0.0000234079 | 0.0000357620 | 0.00001321079 |
|                                   | 0.0000005316 | 0.000021740 | 0.00005974 | |
|                                   | 0.000000991 | 0.00002438 | 0.00011378 | 0.00002815 |
Figure 19. Random load pattern with respect to time.

![Graph showing random load pattern with respect to time.]

Figure 20. (a) Frequency deviation in Area 1 subjected to random load in Area 1 with GWO optimized Fuzzy PID controller, (b) Frequency deviation in Area 2 subjected to random load in Area 1 with GWO optimized Fuzzy PID controller and (c) Tie line power deviation obtained subjected to random load in Area 1 with GWO optimized Fuzzy PID controller.

![Graph showing frequency deviation in Area 1.]

![Graph showing frequency deviation in Area 2.]

![Graph showing tie line power deviation.]

The sinusoidal load perturbation represented by Equation (20) with varying amplitude as shown in Figure 21 is applied in Area 1. The expression for sinusoidal load change is as follows:

\[ \Delta P_D = 0.03 \sin(44.36t) + 0.05 \sin(5.3t) - 0.1 \sin(6t) \]  

(20)

Figure 22(a)–(c) show the system response subjected to sinusoidal varying load in Area 1.
Figure 21. Sinusoidal load pattern with respect to time.

Figure 22. (a) Frequency deviation in Area 1 subjected to sinusoidal load pattern in Area 1 with GWO optimized Fuzzy PID controller with and without FACTS, (b) Frequency deviation in Area 2 subjected to sinusoidal load pattern in Area 1 with GWO optimized Fuzzy PID controller with and without FACTS and (c) Tie line power deviation subjected to sinusoidal load pattern in Area 1 with GWO optimized Fuzzy PID controller with and without FACTS.
Figure 23. Transfer function model of interconnected three area thermal power system.
It is clear from Figures 20(a)–(c) and 22(a)–(c) that the system oscillation greatly decreased with incorporation of FACTS controller. It is proved that the IPFC performs better among all FACTS devices for the considered power system.

| Table 10. Optimal gains of controller for different FACTS devices for three area thermal power system |
|---------------------------------------------------|-----|-----|-----|-----------------|
| Methods                                           | Area 1 | Area 2 | Area 3 | FACTS constants |
| GWO optimized fuzzy PID controller without FACTS  | $K_1 = 0.6293$ | $K_1 = -0.276$ | $K_1 = -0.4377$ | $K_1 = -0.1808$ | $K_1 = 0.7097$ | $K_1 = 0.6156$ | $K_1 = -0.217$ | $K_1 = 0.0711$ | $K_1 = -0.1324$ | $K_1 = 0.7757$ | $K_1 = -0.2862$ | $K_1 = -0.6008$ |
| GWO optimized fuzzy PID controller with UPFC      | $K_1 = 0.9979$ | $K_1 = 0.3061$ | $K_1 = 0.6104$ | $T_{UPFC_1} = 0.0302$ | $K_1 = 0.0456$ | $K_1 = 0.0737$ | $K_1 = 0.0368$ | $T_{UPFC_2} = 0.0044$ | $K_1 = 0.9998$ | $K_1 = 0.1513$ | $K_1 = 0.052$ | $T_{UPFC_3} = 0.9999$ | $K_1 = 0.2096$ | $K_1 = 0.8659$ | $K_1 = 0.5553$ |
| GWO optimized fuzzy PID controller with IPFC      | $K_1 = 0.7572$ | $K_1 = 0.7655$ | $K_1 = 0.5097$ | $T_{IPFC_1} = 0.0442$ | $K_1 = 0.0843$ | $K_1 = 0.3992$ | $K_1 = 0.1513$ | $T_{IPFC_2} = 0.0452$ | $K_1 = 0.9997$ | $K_1 = 0.3735$ | $K_1 = 0.0098$ | $T_{IPFC_3} = 0.2809$ | $K_1 = 0.2232$ | $K_1 = 0.7232$ | $K_1 = 0.5523$ |

It is clear from Figures 20(a)–(c) and 22(a)–(c) that the system oscillation greatly decreased with incorporation of FACTS controller. It is proved that the IPFC performs better among all FACTS devices for the considered power system.

**Figure 24.** Structure of UPFC as frequency stabilizer for three area power system.
7.2. Three unequal area thermal power system

The system considered is a three unequal area thermal system. Each area of power system consists of speed governor, single stage reheat turbine and generation rate constraint (GRC) of 3%/min. The capacities of different control areas are in the ratio of 2:5:8. The nominal system parameters are presented in Appendix B. The transfer function model of the considered system is shown in Figure 23.

It is concluded from the discussion as presented in Section 7.1 that, overall performance of UPFC and IPFC are superior among others FACTS devices for improvement of power system dynamic performance. In order to verify the potential of the UPFC and IPFC based controller, a three area power system is considered in present study. The Structure of UPFC and IPFC as frequency stabilizers for three area power system are shown in Figures 24 and 25, respectively. The system dynamic responses are evaluated and analyzed with 1% SLP in Area 1. The optimal gains of controllers for different FACTS devices are given in Table 10. The frequency deviations in Area 1, Area 2 and Area 3 are shown in Figure 26(a)-(c) respectively, subjected to SLP of 1% in Area 1 with GWO optimized Fuzzy PID controller with and without FACTS devices. The IPFC is once again exhibiting greater flexibility as far as the dynamics of the system is considered.
8. Conclusion

This paper presents the design and implementation of GWO optimized Fuzzy PID controller in power systems. At first multi-source two area power system having Hydro-Thermal-Gas in each area is considered and the effectiveness and superiority of the proposed GWO optimized Fuzzy PID controller for the power system is verified by comparing the results with GWO optimized classical PID controller as well as recently published optimal controller, DE-PID and TLBO-PID controllers. Then the considered power system model is modified and a gas unit in Area 2 is replaced by nuclear unit along with HVDC link, GRC and reheat turbine in each area. The comparison is made between GWO optimized Fuzzy PID controller and TLBO optimized output feedback with SMC for the same power
system. The study reveals that the dynamic performance of the system improves largely with the proposed controller as compared to TLBO optimized output feedback SMC. Then work is extended considering GDB with GRC and reheat turbine with inclusion of SMES units in both areas. The system dynamics is significantly improved in presence of SMES. A comparative study is also presented with coordinated operation of different FACTS controllers for AGC with the proposed controller. Finally sensitivity analysis is carried out to determine the robustness of the system with proposed controller at different load perturbation like random step load and sinusoidal load in Area 1.

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Appendix

The typical values of system under study are given below:

A.1. Power system-1 (Barisal, 2015; Mohanty et al., 2014; Parmar et al., 2012)

\[ f = 60 \text{ Hz}; \quad B_1 = B_2 = 0.425 \text{ p.u. MW/Hz}; \quad P_R = 2,000 \text{ MW} \quad \text{(rating)}; \quad P_L = 1,740 \text{ MW} \quad \text{(nominal loading)}; \]
\[ R_1 = R_2 = R_3 = 2.4 \text{ Hz/p.u. MW}; \quad p_f_{11} = p_f_{21} = 0.46966; \quad p_f_{12} = p_f_{22} = 0.37814; \quad p_f_{13} = p_f_{23} = 0.1522; \]
\[ T_p = 11.49 \text{ s}; \quad K_p = 68.9566 \text{ Hz/p.u. MW}; \quad T_{12} = 0.0433 \text{ p.u.}; \quad a_{12} = -1. \]

Thermal: \( T_{g1} = T_{g2} = 0.08 \text{ s}; \quad T_{r1} = T_{r2} = 10 \text{ s}; \quad K_{r1} = K_{r2} = 0.3; \quad T_{r1} = T_{r2} = 0.3 \text{ s}. \)

Hydro: \( T_{m1} = T_{m2} = 28.75 \text{ s}; \quad T_{g1} = T_{g2} = 5 \text{ s}; \quad T_{gh1} = T_{gh2} = 0.2 \text{ s}; \quad T_{w1} = T_{w2} = 1 \text{ s}. \)

Gas: \( b_1 = b_2 = 0.5; \quad c_1 = c_2 = 1; \quad X_{c1} = X_{c2} = 0.6 \text{ s}; \quad Y_{c1} = Y_{c2} = 1 \text{ s}; \quad T_{c1} = T_{c2} = 0.03 \text{ s}; \quad T_{t1} = T_{t2} = 0.23 \text{ s}; \quad T_{cd1} = T_{cd2} = 0.2 \text{ s}. \)

A.2. Power system-2 (Mohanty, 2015)

This is the modified system of power system1 with physical constraints, HVDC link, nuclear power plant in Area 2 are given below:

\[ f = 60 \text{ Hz}; \quad B_1 = B_2 = 0.4312 \text{ p.u. MW/Hz}; \quad P_R = 2,000 \text{ MW} \quad \text{(rating)}; \quad P_L = 1,740 \text{ MW} \quad \text{(nominal loading)}; \]
\[ R_1 = R_2 = R_3 = 2.4 \text{ Hz/p.u. MW}; \quad K_T = 0.543478; \quad K_H = 0.326084; \quad K_N = 0.130438; \quad T_{12} = 0.545 \text{ p.u.}; \quad a_{12} = -1. \]

HVDC: \( T_{dc} = 0.2 \text{ s}; \quad K_{dc} = 1. \)

Nuclear: \( K_{HI} = 2; \quad K_{R1} = 0.3; \quad T_{R1} = 0.5 \text{ s}; \quad T_{fHI} = 7 \text{ s}; \quad T_{fH2} = 9 \text{ s}. \)

GRC of thermal 3\% per minute.

GRC of hydro 360\% up and 240\% down per minute.

B. Power system-3 (Raju, Saikia, & Sinha, 2016)

\[ f = 60 \text{ Hz}, \quad T_g = 0.08 \text{ s}; \quad T_a = 0.3 \text{ s}; \quad T_s = 10 \text{ s}; \quad K_a = 0.5; \quad K_g = 120 \text{ Hz/p.u. MW}; \quad T_{p} = 20 \text{ s}; \quad H_I = 5 \text{ s}; \]
\[ D = 8.33 \times 10^{-7} \text{ p.u. MW/Hz}, \quad R = 2.4 \text{ Hz/p.u. MW}, \quad T_{12} = 0.0866 \text{ p.u. MW/\text{rad}}; \quad B_1 = 0.425 \text{ p.u. MW/Hz}, \]
\[ \text{Loading} = 50\%, \quad \text{GRC} = 3 \text{ min in each area}, \quad \text{capacities of different areas are 2:5:8 and SLP = 1 in Area 1}. \]