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Load Frequency Control of Two-Area Interconnected Network using Multi-Stage Controller

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Research Article

Abstract

This paper presents the application of structural optimization technique; grasshopper optimization algorithm (GOA) for load frequency control (LFC) in a two-area power system. The LFC is carried out based on multistage proportional derivative filter type (PD_F) with 0.85 plus Proportional Integral (0.85+PI) controller for obtaining better dynamic system responses. The two control areas consist of thermal power plant units. The nonlinearities of the system have been carried out by introducing (GDB) Governor Dead-Band and GRC (Generation Rate Constraint) to both control areas. A performance comparison was carried out with several objective functions, and the integral time absolute error (ITAE) was proven to perform better. The ITAE performance index has advantage of producing smaller overshoots and oscillations than the integral absolute error (IAE) or integral squared error (ISE) performance indices. The effectiveness of GOA-PD_F+(0.85+PI) controller was compared with other optimization methods like Salp swarm algorithm with Proportional Integral Derivative (SSA-PID) controller and Genetic Algorithm (GA) with PID. The proposed technique outperformed SSA-PID in terms of undershoot, overshoot and settling with a percentage improvement of 58.47 %, 59.79 % and 21.97 % respectively in frequency deviation in area 1. With the proposed controller, the LFC dynamic responses of two-area power systems shall be further enhanced.

Keywords

Load Frequency control; Grasshopper Optimization Algorithm; Multi-stage controller, Power system.

Article History

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1. Introduction

In today's world, the capacity of electric utilities increases and the number of their interconnections increases, which results in a complex power system. These power systems are subdivided into a set of control areas that are interconnected among others via tie-lines based on the principle of coherency. The rated power capacity of such areas is based on their synchronous generator ratings (Hasanien & El-Fergany, 2019). The coherent areas are interconnected through tie lines which are used for contractual energy exchange between areas and provide inter-area support during abnormal operations (Sudha & Vijaya Santhi, 2012). For large scale power systems which consists of interconnected control areas, load frequency is critical in view to keep the frequency and inter area tie power near to the scheduled values (Saxena, 2019). In an interconnected power system, load frequency control (LFC) is necessary to keep the frequency of each area and the tie-line power exchange within the specified limit. The main objective of LFC is to regulate the frequency and tie-line power flow within the control area. The main control challenges in LFC are system model parametric uncertainty, non-linearity present in a realistic power system, and load-disturbances (Kumar *et al.*, 2021) Power system frequency regulation or load frequency control (LFC) has been one of the major challenges in interconnected electrical networks. Therefore, the interest in LFC is growing up rapidly due to the interest in large, interconnected power systems (Nour *et al.*, 2016).

Operation of power system control is an important task for reliable and secure operation because of increasing system size and varying loads (Sivachandran et al., 2016). Changes in the power system load affects mainly the system frequency, while the reactive power is less sensitive to changes in frequency and is mainly dependent on fluctuations of voltage magnitude, so the control of the real and reactive power in the power system is dealt separately as a result in dependence in frequency and voltage respectively (Sivachandran *et al.*, 2016).

LFC is an application of a controller incorporated in the interconnected system to keep the frequency and tie line power within their specified limits in case of load disturbance (Ahmed et al., 2018). The control of the system frequency and real power is dealt with mainly by LFC and is the basis of many advanced concepts of the large-scale control of the power system (Prakash & Sinha, 2018).

LFC has been one of the core issues in interconnected power systems. As a result of this challenge, many researchers have come up different techniques for solving LFC problem by using classical PID controller (Konar *et al.*, 2014), (Krishna *et al.*, 2016), (Kouba *et al.*, 2017), (Regar *et al*., 2017), (Abd-Elazim & Ali, 2018) and (Sarath & Monica, 2018). The tuning of the control parameters was achieved by using a swarm artificial intelligent technique, such as Genetic Algorithm (GA) (Konar et al., 2014), (Regar *et al*., 2017), particle Swarm optimization technique (Krishna *et al*., 2016), firefly algorithm (FA) (Abd-Elazim & Ali, 2018) and Bacteria Forging Optimization

Algorithm (Sarath & Monica, 2018) and hybrid approach combining Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) (Kouba et al., 2017). More to that, several smart control strategies have been presented for LFC problem. Some of them were implemented using concept of two-degree freedom controller inter model control IMC (Saxena, 2019), Artificial neural network (ANN) controller (Kassem, 2010), a fuzzy logic-based controller (Khedkar & Nagarale, 2015), fractional-order (FO) controller via internal model control (IMC) technique (Saxena, 2019), Robust control techniques (Jood et al., 2019) and active disturbance rejection control (ADRC) (Liu et al., 2020).

In order to fulfil modern stringent quality requirements; more precise tools base on real time structures with high swiftness competency, high degree of accuracy and reliability is required. The multistage Proportional Derivative filter type (PD_F) with 0.85 plus Proportional Integral (0.85+PI) meet all the design criteria in satisfactory mode. This represents the authors' motivation to use the grasshopper optimization algorithm (GOA) to fine-tune PD_F+(0.85+PI) controllers for a two-area interconnected network. The effectiveness of GOA-PD_F+(0.85+PI) controller is compared with other optimization methods based-PID controller under several operating conditions. A comprehensive study is based on simulation results that are carried out using the powerful MATLAB program.

The paper is organized as follows: Section 2 introduces the system description. Section 3 present the problem formulation and GOA model. Section 4 presents simulation results and discussion. Finally, section 5 presents the conclusion.

2. System Description

In this work, a two-area interconnected power system is presented as shown in Figure 1. An extended power system can be divided into a number of load frequency control areas interconnected by means of tie lines. The two-area system is based on thermal power plants including their control loops. Each control area consists of a principal component such as governor, turbine, reheater, and power system which can be expressed mathematically by first order transfer functions as illustrated in table 1. The system components are adopted from (Hasanien & El-Fergany, 2019). Symbols used with suffix 1 refer to area 1 and those with suffix 2 refer to area 2. Figure 1 demonstrates the complete model of the system, where, R represents speed regulation or droop due to governor action and it contributes to feedback of the primary LFC loop. Moreover, B is area frequency bias parameter, which helps in completing feedback of the secondary LFC loop to generate the error signal that feeds the Multistage Derivative Proportional Filter with 0.85 Plus Proportional Integral controller. T_g, T_t, T_R and T_p are time constant for the governor, turbine, reheater and power system respectively. K_R and K_p are the gains of the reheater and power system. $T12$ represents the synchronization time between the two control area.

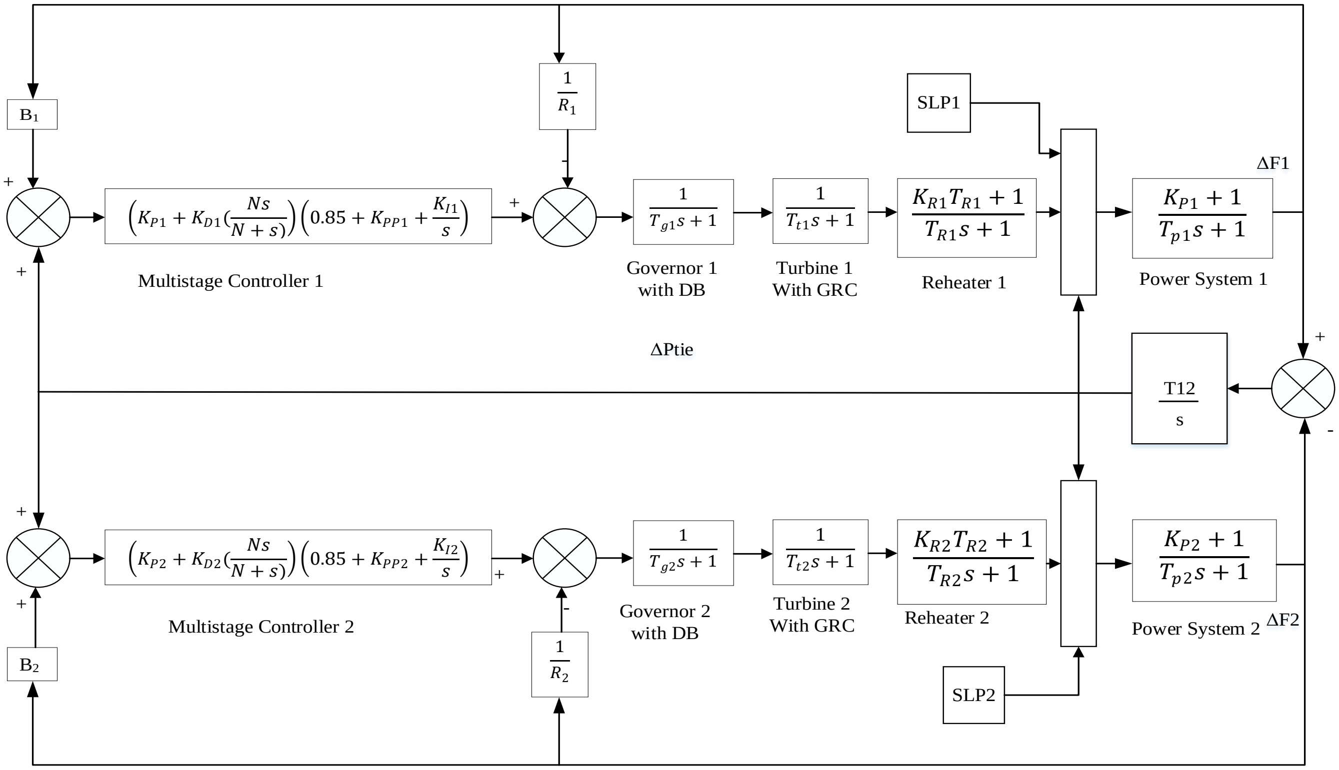

Figure 1: Two-area network integrated with renewable energy sources model

To keep the power system with its nonlinearity, the GDB is implemented. This deadband reveals a signal band interval that no action is required from the governor. An intentional GDB or deadzone with a band of 0.0006 p.u is chosen based on the

AIEE-ASME standards (Tan et al., 2017). Moreover, the GRC of 5% per minute is employed with the turbine model to indicate the rate of change of turbine power and its limitations.

Table 1: Transfer function of component system

Components	**Transfer function**
Governor	$\frac{1}{T_g s + 1}$
Turbine	$\frac{1}{T_t s + 1}$
Reheater	$\frac{K_R T_R s + 1}{T_R s + 1}$
Power system	$\frac{K_P + 1}{T_P s + 1}$

3. Problem formulation

The generalized expression for PID controller in transfer function form is as given in equation (1). K_P, K_I a K_D are the gains of the PID controller. In steady state analysis of transient response PID controller are unable to provide optimal results in many applications, whereas the steady-state-error minimized by integral gain but creates oscillations exhibiting dynamic behaviour. During transient state, integral gain scale-down the speed of the response and reduces steady state stability. For the betterment of transient response, it is customary to turn off the integral parameter. This is easily possible by PD_F+(0.85+P1) controller. It has two phases, in the first section there is a filter connected PD controller and in the next section a PI controller so it can maintain the speed of response by overcoming steady-state error and establishes system stability. During the exchange of active and reactive power across tie-line noise are introduced in the power system network. Hence the net input of the system increases by derivative controller due to presence of noise. These high frequency noise can be easily eliminated with the help of a filter enabled derivative controller (Nayak et al., 2020). The objective function is tuned to minimize the controller gains subject to the following constraints given by (2). Where, K_P, K_I, K_D, K_{PP} and N are the proportional-gain, integral-gain, derivative-gain, second stage proportional-gain and filter coefficient respectively. The controller parameters were optimized using the ITAE performance criteria and the performance criterion are defined in (3), where ΔF_1 and ΔF_2 are the system frequency deviation of area 1 and 2 respectively; ΔP_{tie} is the incremental change in tie line power; t_s is the simulation time.

$$Tf_{PID} = K_P + \frac{K_i}{s} + K_D s \quad (1)$$

$$\left.\begin{aligned} K_{P\,min} \le K_P \le K_{P\,max} \\ K_{D\,min} \le K_D \le K_{D\,max} \\ K_{I\,min} \le K_I \le K_{I\,max} \\ K_{PP\,min} \le K_{PP} \le K_{PP\,max} \\ N_{min} \le N \le N_{max} \end{aligned}\right\} \quad (2)$$

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

3.1 Multistage Controller PD_F+(0.85+PI)

This controller has two sections; the proportional derivative filter type (PD_F) with the 0.85 plus proportional integra part (PI). The 0.85 plus proportional integra part helps to reduce the transient response for a two-area network. For the steady state analysis of electric network, the major objective is to minimize the steady-state error. The gain Ki, i.e., integral controller gain must be increased, but this introduces disturbance in the performance. For the stability of the electric network, transient response and steady-state error must be minimized by actuating the integral controller accurately in various dynamic states. This can easily be achievable with the help of a multistage Proportional Derivative filter type (PD_F) with the 0.85 plus proportional integra part (PI). In order to obtain an optimal performance, the gains of the controller are optimized using GOA. The controller detailed model is shown in Figure 2. The overall transfer function of PD_F+(0.85+P1) controller is given by (4).

$$Tf_{multistage-PID} = \left(K_P + K_D\left(\frac{Ns}{N+s}\right)\right)\left(0.85 + K_{PP} + \frac{K_I}{s}\right) \quad (4)$$

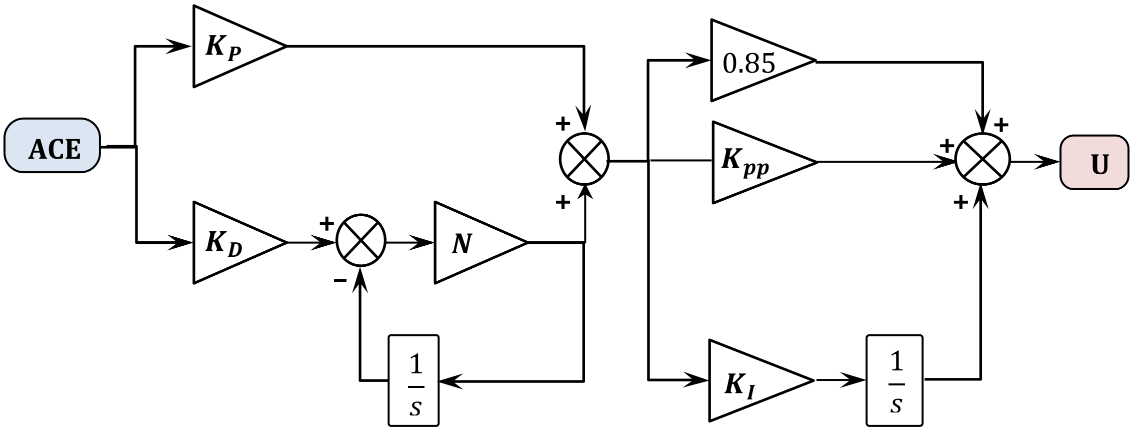

Figure 2: Structure of $PD_F + (0.85 + P1)$

4. Results and discussion

The complete framework has been carried out by MATLAB R2019a platform. The PC with 2.5 GHz, core i5, 8GB RAM has been used for performing the programming. The formation of simulation model of the power system network is done in SIMULINK platform and the GOA codes are in script & function file of MATLAB. The GOA algorithm executed for 100 times to get value of optimized controller gains. The base target-oriented solution is obtained by compiling the Simulink model with each iteration results for global optimum. The system performance is assessed under different operating conditions during the following scenarios:

4.1 Performance Assessment of the Two-area Network without Nonlinearities

This performance assessment introduces an optimal procedure to fine tune PD_F + (0.85+PI) controllers of the system under study using the GOA. In this performance assessment, all the system nonlinearities such as GDB and GRC are deactivated. The main reason for this component deactivation is to test the effectiveness of the proposed controller with other heuristic-based controllers. To check the power system dynamic responses, a step load perturbation (SLP) of +1% is applied to area 1 at time t = 0 s, as a network disturbance. The optimal controller gains (same both control areas) of the system is summarized Table 2.

Table 2: Optimal values of proposed controller gain

Kp	Kd	Kpp	Ki	N
10.88	9.57	0.9967	0.9088	98

Figure 4 shows the transient response in change in frequency deviation in area 1 (ΔF_1) without nonlinearities. It is clearly seen that GOA-PD_F +(0.85+PI) controller outperformed SSA-PID and GA-PID controllers in terms of settling time at 1% step load pertubation. Figure 5 depicts the transient response in change in frequency deviation in area 2 (ΔF_2) without nonlinearities. It is seen that GOA-PD_F +(0.85+PI) controller outperformed SSA-PID and GA-PID controllers in term of undershoot, overshoot and settling time at 1% SLP. Figure 6 shows the transient response in change in tie-line power (ΔP_{tie}) without nonlinearities. It is seen that GOA-PD_F +(0.85+PI) controller outperformed SSA-PID and GA-PID controller in terms of undershoot, overshoot and settling time at 1% step load pertubation. Table 3 shows the transient response of the multi-area network without the nonlinearities considering a SLP of 1%. The ITAE criterion is chosen as a single objective function. The optimal settings of the GOA include 50 population size and 100 iterations. This optimization process is repeated more than 25 times to test the algorithm robustness. The tables also show the minimal error obtain from the simulation using the integral squared error criteria.

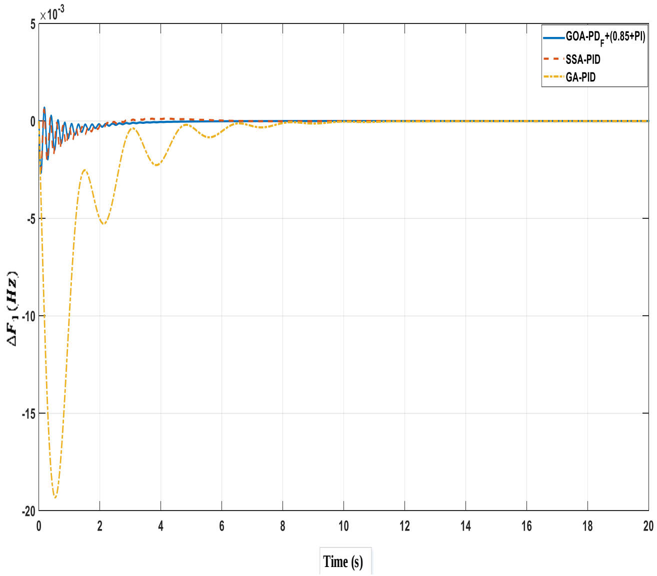

Figure 4: ΔF_1 for 1% SLP

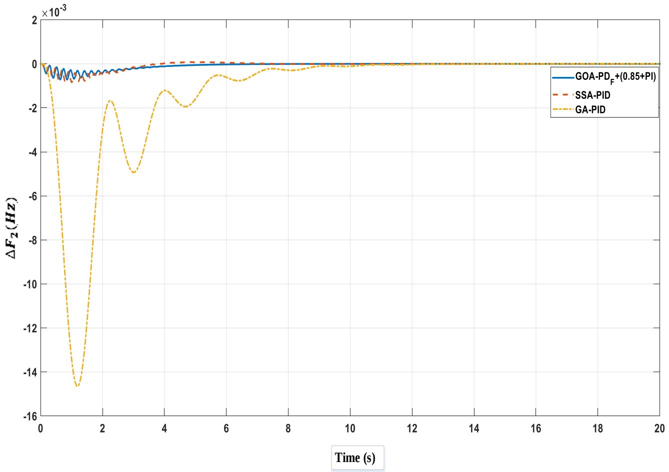

Figure 5: ΔF_2 for 1% SLP

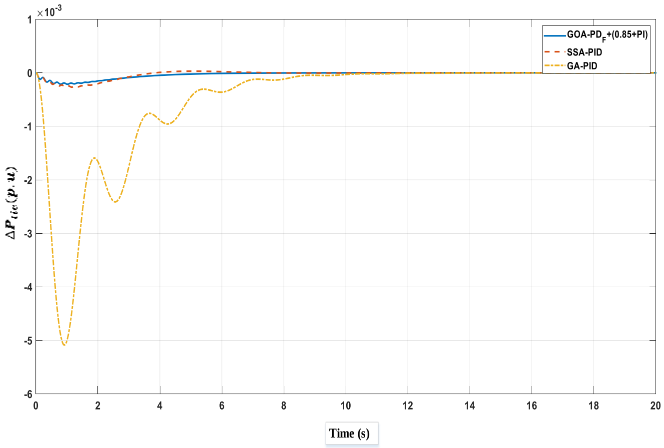

Figure 6: ΔP_{tie} for 1% SLP

Table 3: Performance analysis of system response without nonlinearities

Algorithms	**Response**	**MUS**	**MOS**	**T_s(s)**
GOA-PD$_{F+}$(0.85+PI)		2.66e-3	6.803e-4	6.50
SSA-PID	$\Delta F_1(s)$	2.52e-3	5.95e-4	9.57
GA-PID		1.93e-2	3.84e-3	12.84
GOA-PD$_{F+}$(0.85+PI)		7.29e-4	4.27e-5	9.58
SSA-PID	$\Delta F_2(s)$	8.33e-4	7.77e-5	12.14
GA-PID		1.46e-2	5.22e-4	13.93
GOA-PD$_{F+}$(0.85+PI)		2.21e-4	1.61e-5	9.38
SSA-PID	$\Delta P_{tie}(p.$	2.67e-4	3.08e-5	13.94
GA-PID		5.08e-3	1.34e-4	14.14

4.2. Performance Assessment of the Two-area Network with Nonlinearities

In this performance assessment, the proposed interconnected power system is evaluated subjecting the system non-linearities such as GDB and GRC. Therefore, to test the power system dynamic responses with all it nonlinearities, a SLP of +1% p.u is applied to area-1 at time t =0s, as a network disturbance. The power system responses such as ΔF_1, ΔF_2 and ΔP_{tie} are depicted in Figure 7 to Figure 9. The optimal controller gain and the transient response specification are shown in table 4 and 5 respectively. Figure 7 shows the transient response in ΔF_1 with nonlinearities. It is seen that GOA-PD$_F$+(0.85+PI) controller outperformed SSA-PID in terms ofundershoot, overshoot and settling time at 1 % step load pertubation. Figure 8 depict the transient response in ΔF_2 with nonlinearities. It is clearly seen that GOA-PD$_F$ +(0.85+PI) controller outperformed SSA-PID in terms of undershoot, overshoot and settling time at 1 % step load pertubation. Figure 9 shows the transient response in ΔP_{tie} with nonlinearities. It is clearly seen that GOA-PD$_F$ +(0.85+PI) controller outperformed SSA-PID in terms of undershoot, overshoot and settling time at 1% step load pertubation.

Table 4: Optimal values of proposed controller gain

Kp	**Kd**	**Kpp**	**Ki**	**N**
8.91	9.23	0.9967	0.9788	80.7

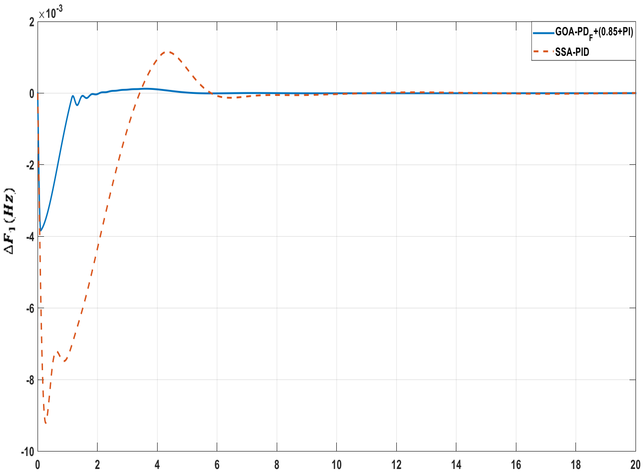

Figure 7: ΔF_1 for 1% SLP with nonlinearities

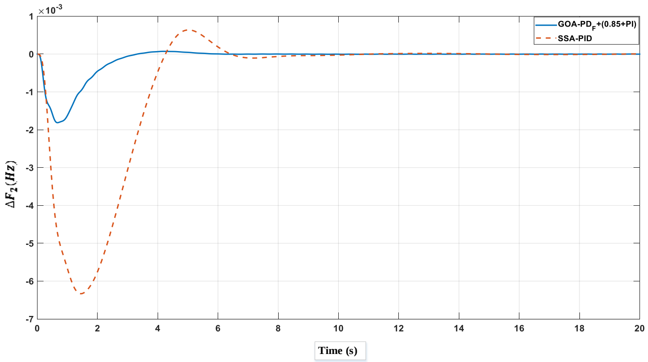

Figure 8: ΔF_2 for 1% SLP with nonlinearities

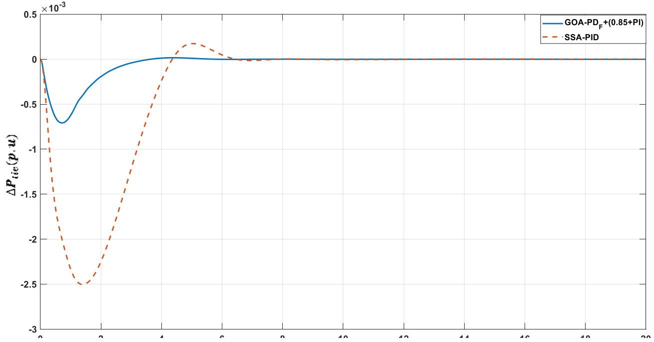

Figure 9: ΔP_{tie} for 1% SLP with nonlinearities

Table 5 shows the transient response of the two-area network with the nonlinearities, GDB and GRC considering a SLP of 1%. It is observed that the results of GOA-PD$_F$+(0.85+PI) performed best in terms of undershoot, overshoot and setting time using the ITAE performance criterion. The optimal settings of the GOA include 50 population size and 100 iterations. This optimization process is repeated more than 25 times to test the algorithm robustness using the ITAE criteria.

Table 5: Performance analysis of system responses with nonlinearities

Algorithms	**Response**	**MUS**	**MOS**	**T_s(s)**
GOA-PD$_F$-(0.85+PI)		3.82e-3	9.44e-5	7.99
SSA-PID	$\Delta F_1(s)$	9.20e-3	1.15e-3	10.24
GOA-PD$_F$-(0.85+PI)	$\Delta F_2(s)$	1.81e-3	6.73e-5	8.32
SSA-PID		6.34e-3	6.38e-4	10.01
GOA-PD$_F$-(0.85+PI)		7.08e-4	1.52e-5	6.71
SSA-PID	$\Delta P_{tie}(p.u)$	2.50e-3	1.74e-4	9.32

5. Conclusion

This paper has introduced an application of GOA to fine tune the PD$_F$+(0.85+PI) controllers for LFC of a two-area interconnected network. The GOA was used to obtain the various controller gains. The integral time absolute error (ITAE) is taken as the objective function for the stabilization in frequency and tie line power deviation of all control areas with and without the presence of nonlinearities like GDB, and GRC. The simulation result clearly justify that the proposed technique delivers better result in terms to overshoot, undershoot, and settling time in frequency response analysis and tie-line power deviation when compared with SSA-PID and GA-PID. Therefore, the GOA-PD$_F$ +(0.85+PI) controller can be applied to enhance the dynamic responses of different power systems.

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