Load Frequency Control for Power System of Interconnected Two Area System Using Salp Swarm Algorithm Technique Based 3 DOF-PID Controller for Optimization

Ajay Raja Sinha, Neelesh Kumar Gupta, Ch Sekhar, and A. K. Singh

Abstract In this present work, we develop a model of two-area power grid system for load frequency control (LFC), a three-degree of freedom PID controller is referred and suggested as a special controller. The system under analysis includes a single power system having two control area, each of which comprises reheat type thermal unit generating source. Salp swarm algorithm (SSA) optimization technique is utilized for tuning controller to find the optimal value of the parameter gain of recommended 3DOF-PID control system for each control region or area. The optimization process is preceded using a function Integral time absolute error (ITAE) as an objective function to access the performance measure from simulink model and a 0.01p.u sudden perturbation of load for area-one. For achieving the better dynamic behavior of the system responses, such as time of settling, peak undershoot, and peak overshoot, evaluation of system's dynamic performance. Further comparison of PID, 2DOF-PID and 3DOF-PID controllers are also included in this analysis.

Keywords LFC · 3DOF-PID controller · Two-area power system · Salp swarm algorithm (SSA) optimization · ITAE

1 Introduction

In power system, due to continuous change in load demand results imbalance between generation of real power and demand of load affects the frequency of the power system [1]. An electrical energy supply by the generating system should be kept constant at the desired nominal frequency. It is kept close to the desired value by closed loop control of the reactive power and real power generated in the controllable sources of the system for maintaining power system stability [2]. In interconnected power system, it is also desirable to regulate the tie line power within acceptable limits irrespective of load variations in an area. LFC governs output power from sources within a determined area with respect to variations in frequency of system and power of tie-line. The basic objective of LFC of interconnected power system

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is to achieve desired nominal frequency as possible and is to regulate power flow deviation between two interconnected areas due to step load change.

The appropriate selection and design of controller substantially affected the power system performance and stability. The task of LFC become more challenging because of gradually increase in dimension & load demand of power system. Literature survey review shows that lot of control methods like fuzzy logic, neuro fuzzy etc. have been implemented in various researches in respect to study of LFC related with power system. Many optimization algorithms implemented in various research papers for tuning the controller parameter like grey wolf optimization (GWO), particle swarm optimization (PSO), moth-flame optimization (MFO), ant lion optimization, firefly, ant colony optimization, cuckoo search algorithm. Grasshopper optimization, linearized biogeography algorithm (LBO), teaching learning-based optimization, seeker optimization has been implemented for controller parameter optimization to study the transient nature and steady state response of LFC.

Grasshopper optimization algorithm with FOPID controller is implemented in LFC by D. Guha et al. to improve system dynamics in normal circumstances and in presence of system uncertainties [3]. Load frequency control using SSC with FUZZY, PID and neural network-based controller to control the system dynamics and minimized ACE in two-area power system is explored by Lone et al. [4]. For enhancing load frequency control capability, the ant colony optimization is used in tuning of PID controller of power system is studied by Bernard and Musilek [5]. Fractional order 2DOFPID control using cuckoo search algorithm based AGC scheme for interconnected multi-area power system comprising hydro, thermal and gas unit is employed by Debbarma et al. [6]. The dynamics performance of the LFC system by placing HVDC link between two areas is analyzed by Debanath et al. [7]. M. Raju et al. analyzed the comparative dynamic behavior between various controllers optimized by ant lion optimization technique for LFC [8], they also evaluated the robustness of optimum gain of superlative controller using sensitivity analysis. Gheisamejad [9] proposed a HSCOA optimization to find the optimal gain of Fuzzy PID used in the model of two area system consisting thermal unit for LFC. They also verified the produced effect of non-linearity considering governor dead band in the proposed model of the system. A quasi oppositional GWO based PID controller for load frequency control of a two same hydro-thermal unit in each area is studied by Guha et al. [10]. A. Sahu et al. suggested MFO technique for LFC based 2DOF-PID controller [11]. A. N. A. A. Ibrahim employed LBO based PID-P controller for LFC [12]. J. Seekuka et al. designed two area system model for AGC and optimal value of parameter is found by PSO technique with PID controller [13]. H. Parvnesh et al. studied LFC using SOA based PID controller [14]. P. Panda et al. analyzed 3DOF-PID controller with different optimization algorithm with GWO technique for LFC of two area system [15].

2 System Under Analysis

The developed model of two area system under analysis comprises a reheat type thermal generating source for each area for LFC of power system. The analysis of the system has been done with reheat type thermal unit and 3DOF-PID for each control area. The developed transfer function of the interconnected system via tie-line is provided in Fig. 1 and developed system parameters are designed by taking the reference from [2, 15]. In this dynamic model, respective error of control area referred as area control error (ACE) and sudden disturbance of load in area 1 is fed to each of 3DOF-PID controller that is a linear combination of drift in the power at tie-line and drift in frequency where B_1, B_2 are frequency bias of each control area. Each area of ACE is equated in Eq. (4).

In this model of single stage steam turbine of reheat type, required transfer function is shown below.

$$\text{Governor } T/F, \ G_{\text{SG}}(s) = \frac{K_{\text{sg}}}{1 + sT_{\text{sg}}} \tag{1}$$

$$T/F \text{ of reheat type steam turbine, } G_{\text{T}}(s) = \frac{K_{\text{T}}(1 + sK_{\tau}T_{\tau})}{(1 + sT_{\text{T}})(1 + sT_{\tau})} \tag{2}$$

$$\text{Generator load } T/F, \ G_{\text{PS}}(s) = \frac{K_{\text{PS}}}{(1 + sT_{\text{PS}})} \tag{3}$$

$$\text{ACE\_area1} = B_1 * \Delta f_1 + \Delta P_{\text{tie},12}$$
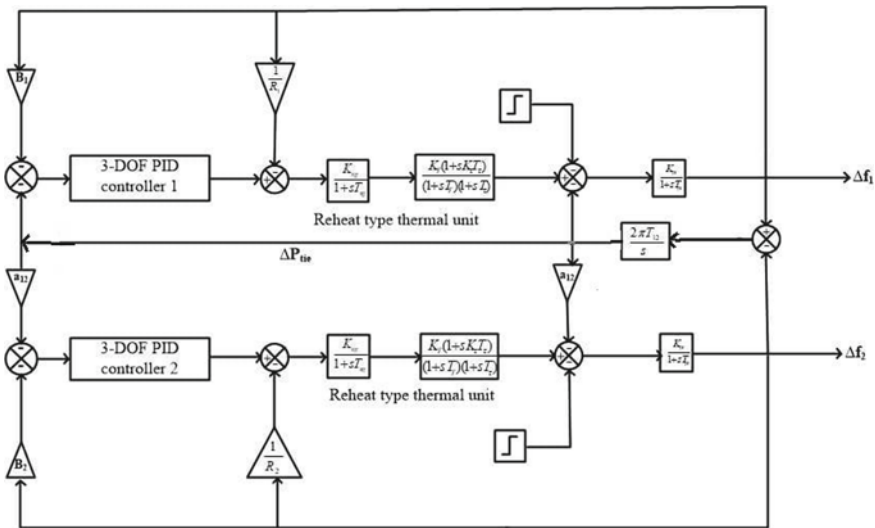

Fig. 1 Transfer function model of two area reheat type thermal unit power system

$$ACE\_area2 = B_2 * \Delta f_2 + \Delta P_{\text{tie},21} \tag{4}$$

where, $K_{\text{sg}}, K_{\text{T}}, K_{\tau}$ and K_{ps} are gain of speed governor, gain of single stage turbine, gain of high-pressure stage and gain of power system respectively. The parameter $T_{\text{sg}}, T_{\text{T}}, T_{\tau}$ and T_{ps} are time constant of speed governor, time constant of turbine, time constant of reheater turbine and the time constant of power system respectively. R_1, R_2 are the speed regulation constant of thermal power plants.

3   The 3DOF-PID Controller

We developed and designed a completely unique controller here, where several control loops accomplish the control operation. A PID controller and 2DOFPID controller is initially used in each control area, and then tested by using the 3DOFPID controller for LFC. As we increased the degree of freedom of PID controller i.e. no. of independent control loops, the control action of controller change and each control loop execute their control work independently in the system. The architecture of controller implemented in proposed system is shown in Figs. 2 and 3. Two control loops are obviously included in the 2DOF-PID controller, while three control loops are included in the 3DOF-PID controller. The 3DOF-PID is more dynamic than PID and 2DOF-PID to eliminate the system oscillations. The actions of three closed loops in the 3DOF-PID controller are responsible for enhancing stability, modeling the closed loop responses and minimizing the disturbances. The architecture of 2DOF-PID and 3DOF-PID controller is shown in Figs. 2 and 3 respectively.

Here, ACE is input for each PID controller, 2DOF-PID controller and 3DOF-PID controller and is represented by $R(s)$. The output of the system denoted by $V(s)$
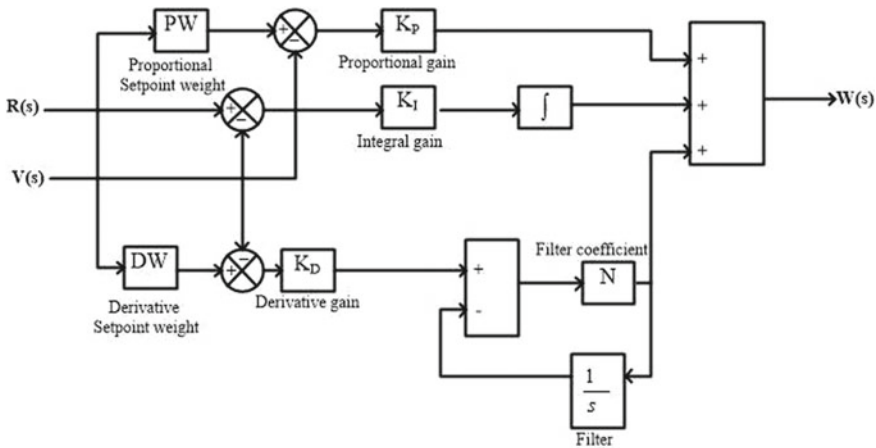

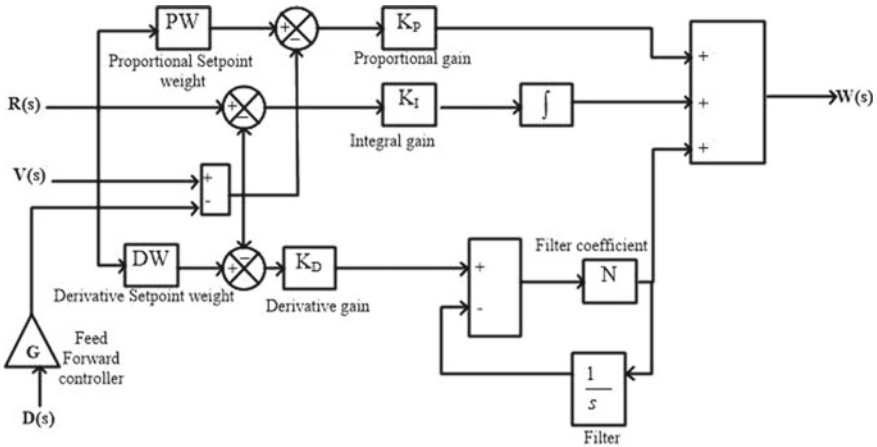**Fig. 2** 2DOF-PID controller architecture

Fig. 3 3DOF-PID controller architecture

indicates the frequency deviation in each area. The controller output, i.e. signal W(s) is input to each control area generating units. $D(s)$ is the sudden variation in load in area 1 which is fed to the controller independently. The basic differences between 2DOF-PID and 3DOF-PID controller is the $D(s)$ which is disturbances occurring in the power system, i.e. provided in 3DOF-PID as feedback and is not present in 2DOF-PID controller.

4 The Implementation of SSA in This Study

The idea or motivating factors of using SSA optimization technique as well as its mathematical model, are presented in this section. Mirjalili et al. proposed the SSA, a nature-inspired optimizer [16]. The goal of SSA is to construct a population-based optimizer that mimics salps natural swarm behavior. The swarming behavior of salps is modeled mathematically, the random introduction of salp locations is performed as shown in Eq. (5).

$$X_1^{1:n} = \text{Rand}(\ldots)(ub_k - lb_k) + lb_k, \forall k \in \text{ number of variables} \qquad (5)$$

$X_1^{1:n}$ indicates the salps' initial locations, ub_k denotes the upper limit, and lb_k denotes the lower limit. Rand($\ldots$) is expression for generating the number between zero and one. Secondly, a group leader and followers must be decided to mimic the salp swarming process. The leader of the swarm is a single salp who is leading the group, while the rest of the swarm are followers. With each successive step, the leader is accountable for leading the group into a safer position in this formation. The mathematical version of the leader in a salp swarm is Eq. (6), where P represents

the position vector of target food and X represents position of each salp in two dimensions.

$$X_k^1 = \left\{ \begin{array}{l} P_i + c_1((uh_k - lh_k)c_2 + lh_k)c_3 \geq 0 \\ P_i + c_1((uh_k - lh_k)c_2 + lh_k)c_3 < 0 \end{array} \right\} \tag{6}$$

X_k^1 represents the leader's position in the kth dimension, P_i represents the position vector for the source of food in the kth dimension, uh_k represents the upper limit of the kth dimension, lh_k represents the lower limit of the kth dimension, and c_1, c_2, and c_3 represent random numbers. SSA describes a long spiral chain of salps in the ocean; as a result, this style of algorithm will avoid immature convergence to localized maximum and minimum optimal solutions. Equation (7) depicts the leading salps food perusing method by equating its motion toward the position of food target. This is a critical SSA parameter that directs the follower salps to effectively capture food sources,

$$c_1 = 2e^{-\left(\frac{4m}{M}\right)^2} \tag{7}$$

where (m/M) indicate the ratio of the ongoing present iteration (m) to the maximum number of considered iteration (M). Furthermore, random guess in the range of *0–1* are assigned to c_2 and c_3, depending on the step size, this approximation is responsible for the orientation of the corresponding location for any kth dimensions. The law of motion given by Newton plays a vital role in characterizing the successive locations of followers as presented in the Eq. (8).

$$X_k^1 = \frac{1}{2}bt^2 + v_0t^2 \tag{8}$$

The location of the followers is defined by $X_k{}^1$ and $i \geq 2$. The expression in Eq. (8) indicates the path in the kth dimension. In the following Eq. (8), t denotes time, and v_0 denotes the salp follower's initial velocity, which is considered to be zero. In most optimization analysis, time is denoted by the iteration number; hence, a step size of one is picked for the time variable. Equation (9) is a modified type version of Eq. (8).

$$X_k^1 = \frac{X_k^i + X_k^{i-1}}{2} \tag{9}$$

It's worth noting that the salp spiral chain has the unique feature to move toward the continuous-changing target food source position in order to get optimal solution by searching and utilizing the feature search space.

5 Objective Function Formulation and Implementation

Error based criteria like integral absolute error, integral squared error, ITAE are the most commonly used error function as objective functions in literature. In comparison to other function Integral square error (ISE), Integral absolute error (IAE), Integral time square error (ITSE) and ITAE. The ITAE based error criteria is mostly used as objective function to achieve desired response of system and because of its smoother work. Therefore, the implemented SSA algorithm optimizes the system controller parameter by using ITAE as the objective function. The function ITAE is shown in Eq. (10).

$$\text{ITAE} = \int_{0}^{\infty} t * |e_0(t)| * \mathrm{d}t \tag{10}$$

$$\text{ITAE} = \int_{0}^{t_{\text{sim}}} |\Delta f_1 + \Delta f_2 + \Delta P_{\text{tie}}| * t * \mathrm{d}t \tag{11}$$

Here Δf_1 is the frequency drift from nominal value in area 1, Δf_2 is the drift of frequency from nominal in area 2, ΔP_{tie} is the drift of power in tie-line and t_{sim} is the simulation run time. The advantages of ITAE as objective function is the reduction of peak overshoot, settling time and give the optimum gain parameter. The objective function must be minimized using the following constraints described below.

$$k_{\text{P minimum}} \leq k_{\text{p}} \leq k_{\text{P maximum}}$$
$$k_{\text{I minimum}} \leq k_{\text{I}} \leq k_{\text{I maximum}}$$
$$k_{\text{D minimum}} \leq k_{\text{D}} \leq k_{\text{D maximum}}$$
$$p_{\text{w minimum}} \leq p_{\text{w}} \leq p_{\text{w maximum}}$$
$$d_{\text{w minimum}} \leq d_{w} \leq d_{\text{w maximum}}$$
$$N_{\text{minimum}} \leq N \leq N_{\text{maximum}}$$

Here K_{p} is the proportional gain, k_{I} is the integral gain and K_{D} is the derivative gain whereas $p_{\text{w}}, d_{\text{w}}$ are the proportion set-point weight, derivative set-point respectively and N is the derivative filter coefficient of 3DOF-PID controller.

6 Result Analysis

The developed robust 3DOF-PID controller is used in system includes single generating source of thermal unit. For determining the frequency and tie-line responses sudden load variation of 0.01 per unit is implemented in area-1. The obtained

responses such as frequency drift in area 1, drift in tie-line power and frequency drift in area 2 of proposed system are displayed in Figs. 4, 5 and 6 respectively.

For tuning the controller parameters of PID, 2DOF-PID, 3DOF-PID, SSA optimization technique is implemented and mentioned in Table 1. System performances are tabulated in Table 2. The ITAE value of controllers optimized by SSA technique is tabulated in Table 3.
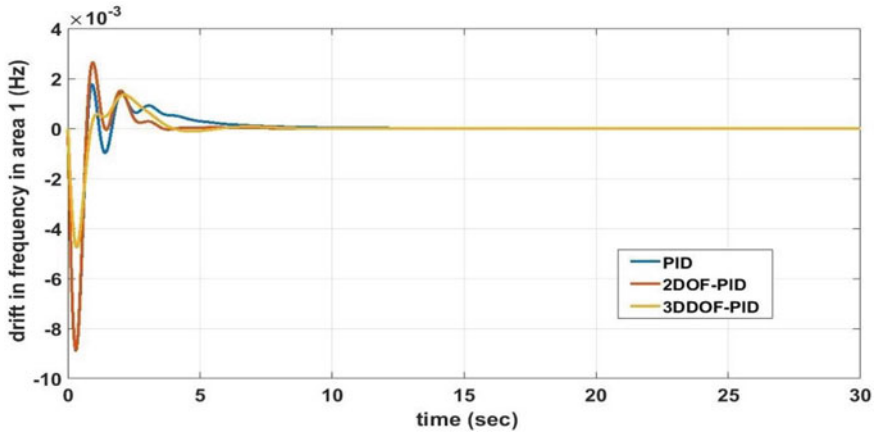

Fig. 4 Frequency drift response in area 1 with respect to PID, 2DOF-PID, 3DOF-PID
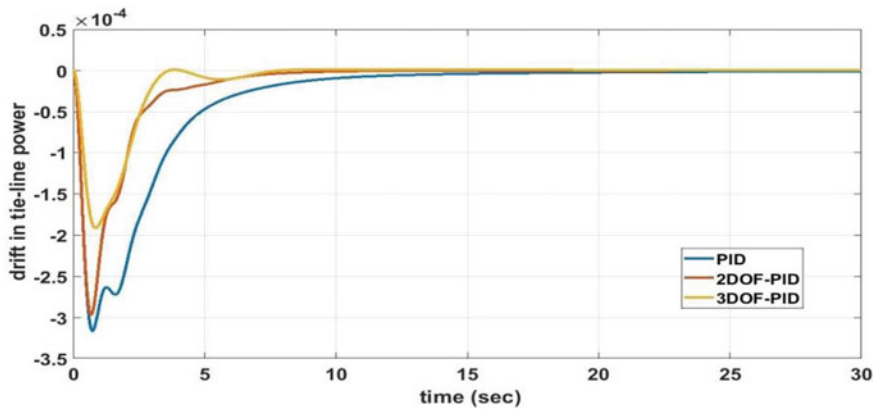

Fig. 5 Deviation of power in tie-line with respect to PID, 2DOF-PID, 3DOF-PID
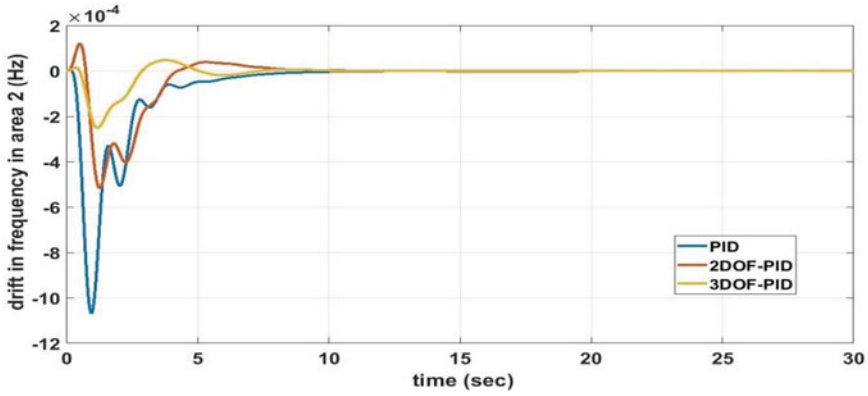
Fig. 6 Frequency drift response in area 2 with reference to PID, 2DOF-PID, 3DOF-PID

Table 1 Tuned parameters of controller obtained from SSA optimization technique

Controller parameter	3DOF-PID controller	2DOF-PID controller	PID controller
K_p	7.27422	9.924576	5.997753
K_i	14.6301	10	10
K_d	5.65144	10	3.456607
P_W	2.52908	3.225151	–
D_W	2.51303	0.005610451	–
G_{ff}	0.0001	–	–
N	65.9841	200	199.889

Table 2 Values of time domain obtained from the responses

Deviation	Time domain factors	PID	2DOF-PID	3DOF-PID
Δf_1	Settling time	8.6334	6.6274	5.6732
	Peak overshoot	0.0026311	0.0017048	0.0013719
	Peak undershoot	0.00877	0.0086919	0.00467
Δf_2	Settling time	11.4137	9.7132	7.6436
	Peak overshoot	0.0	0.0001149	0.00004688
	Peak undershoot	0.0010633	0.0005077	0.000246
ΔP_{tie}	Settling time	18.6513	8.3752	7.5741
	Peak overshoot	0.000000956	0.0	0.000957
	Peak undershoot	0.00031602	0.00029497	0.0002341

Table 3 Optimized ITAE values obtained by SSA technique

SI. No	Types of controller	ITAE
1	PID	0.036586
2	2DOF-PID	0.02474
3	3DOF-PID	**0.015715**

The bold value show the least value of ITAE for the 3-DOF-PID controller and that's why it is superior to the other controllers

7 Conclusion

Here, a SSA optimization based 3DOF-PID controller has been used for the load frequency control of a reheat type thermal unit. The adaptability of the controller proposed is validated and compared to the results with pre-published results. It is concluded from the comparison of responses that the proposed 3DOF-PID controller possess sustainable response when compared with other methods for the same task.

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