Implementation of SSA based two-degree-of freedom fractional order PID controller for AGC with diverse source of generations

Tapas Kumar Mohapatra, Asim Kumar Dey, *Binod Kumar Sahu

Abstract*: This article presents a novel salp swarm algorithm (SSA) to design optimal controllers for automatic generation control of a multi-area, multi-source power system. Every area of the power system has a thermal, a hydro and a gas unit. Initially conventional PID controllers are designed using SSA. Results obtained are compared with that of conventional controller based on Differential Evolution (DE), Teaching Learning Based Optimization (TLBO) and Imperialist Competitive Algorithm (ICA). After ensuring superior performance with SSA based conventional PID controller, the study is extended to design two-degree of freedom conventional PID (2DOF-PID) and two-degree of freedom fractional order PID (2DOF-FOPID) controller for the same power system implementing SSA techniques. It is proved that SSA based 2DOF-FOPID controller demonstrates better dynamic response as compared to other controllers. The study is carried out by applying a step load disturbance of 1 pu in area-1 and integral time absolute error (ITAE) is chosen as objective function in designing the controllers. Robustness analysis is carried out by varying the systems' parameters and applying a randomly changing loading pattern in area-1. In both the cases the proposed SSA based 2DOF-FOIPD controller is found firmly robust.

***Index Terms*: Automatic generation control (AGC); Fractional order PID (FOPID) controller; Salp Swarm Algorithm (SSA), Two degree of freedom FOPID (2DOF-FOPID)..**

I. INTRODUCTION

A multi-area interconnected power system is basically developed to generate, transmit and distribute power with nominal system frequency and voltage. Frequency of power system depends on the equilibrium between power generation and actual load demand (Kundur P, 1994). If power demanded by loads is more than the generated power, generator speed reduces resulting in reduced system frequency and vice versa. So automatic generation control (AGC) plays a significant role to regain the system nominal frequency and tie-line power flow at their predefined scheduled values, under both normal and perturb condition. Maintaining a constant frequency profile is very much essential for a healthy energy system and good power quality.

Performance and Stability of a power system is considerably affected by the type and suitable design of controller. Since the dimension, structure and load demand of power system is gradually increasing; the task of AGC is becoming more challenging. Literature survey reveals that a number of control strategies have been presented in various research articles for AGC study in power system. Control techniques like classical, optimal, fuzzy logic based, ANFIS based etc. and many metaheuristic algorithms like genetic algorithm, particle swarm optimization (PSO), DE, TLBO, etc. have been projected for controller design to study the dynamic behaviour of AGC systems. So, now a day's researcher are paying more attention in proposing innovative optimization and control techniques to tackle problems associated with AGC of power system.

Nanda et al. (1983) implemented integral (I) controller based AGC scheme for a hydrothermal system in both continuous and discrete mode considering generation rate constraint (GRC). They also recommended an optimum sampling period for discrete mode. Nanda et al. (2006) investigated AGC issues in hydrothermal system using I- and proportional-integral (PI) controllers. Dynamic responses are analyzed by taking mechanical & electric governor for hydro unit and single & double stage reheat turbine for thermal unit. Abraham et al. (2007) studied AGC issues in hydrothermal interconnected power system considering superconducting magnetic energy storage (SMES) and thyristor controlled phase shifter (TCPS) units respectively. Nanda et al. (2009) optimized various important parameters of a three unequal area thermal power system for AGC studies using Bacteria Foraging (BF) algorithm. (Tan.W, 2010) proposed a combined tuning method based on 2-DOF internal model control (IMC) and PID approximation approach for LFC of interconnected power system. Bacteria Foraging based I-controller (BFIC) and multilayer perception neural network (MLPNN) controllers are implemented by Saikia et al. (2011) for AGC of a three unequal area hydrothermal power system. They proved that MLPNN controller yields better transient performance as compared to BFIC controller. GA based integral controller for AGC of a three area interconnected realistic thermal power system considering GRC, governor dead band (GDB) and time delay imposed by thermodynamic process, governor, turbine, filters and communication channels is implemented by Golpira et al. (2011). DE based 2DOF-PID controller for AGC of a two area thermal power system incorporating GDB,

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GRC, time delay and reheat type turbine is presented by (Sahu et al., 2013).

Panda and Yegireddy presented design of PI and PID controller using multi-objective NSGA-II technique for AGC of a two area linear and non-linear power system in (Panada et.al 2013), (Mohanty et al. 2014) presented an optimally tuned DE algorithm to design I, PI and PID controllers for AGC of a single and two area multi-source power system consisting of a thermal, a hydro and a gas unit in each area. (Sahu et al., 2015) hybridized Firefly Algorithm and Pattern Search technique (hFA-PS) to design PID controllers to deal with AGC issues in a multi-area multi-source hydrothermal system considering GRC, GDB and time delay. (Kumar et al. 2016) designed a dual mode fuzzy controller to tackle the LFC issue in power system with parallel AC/DC tie-lines and SMES unit. ICA tuned PID controller is implemented by (Kumar et al. , 2016) to study the AGC related issues in a restructured power system. (Padhy and Panda, 2017) implemented hybrid Stochastic Fractal Search and Pattern Search (hSFS-PS) algorithm to optimally design cascade PI-PD controller for AGC of multi-source power system in presence of Plug in Electric Vehicles (PEVs). In (Arya and Kumar, 2017) BFOA based fuzzy PI and PID controllers to deal with AGC related issues in both traditional and deregulated electrical power system.

(Cao & Cao, 2006) designed and tested the effectiveness of fractional order PID (FOPID) controller over conventional PID controller. They implemented PSO algorithm to design various parameters of the controllers. (Hamamci, 2008) implemented FOPID controller to study the stability of fractional dynamic system. Auto-tuning method for FOPID controller is presented by (Monje et al., 2008). (Alomoush, 2010) implemented FOPI and FOPID controllers for load frequency control of both isolated and interconnected power system. (Li et al., 2010) presented a novel tuning method for FOPID controller for a second order plant to obtain better dynamic performance and robustness. Optimal design of fractional order fuzzy-PID (FOFPID) controller, fuzzy-PID (FPID) controller and PID controller for a closed loop feedback system is presented by (Liu et al., 2014). They compared the simulation result and proved that FOFPID controller exhibits superior dynamic performance as compared to other controllers. (Martin et al., 2015) optimally designed FOPID controller employing DE algorithm to carryout both simulation & experimental study on a DC motor and proved that FOPID controller exhibits superior dynamic performance as compared to conventional PID controller. (Saha and Agashe, 2016) presented a review paper on fractional order controllers investigating their progress in the field of control system engineering.

Literature review reveals that performance and stability of any plant to be controlled is considerably affected by the type and appropriate design of controller. Critical analysis of various literatures related to AGC studies in interconnected power system reveals that,

i. Basically electrical power generation is from various sources in a definite control area. So the study of dynamic behavior of more realistic power system consisting of different energy sources in each area is essential for reliable and good quality electric power supply.

ii. 2-DOF controllers are superior to conventional controllers (Sahu et al., 2013). .

iii. Fractional order controllers exhibit superior dynamic performance as compared to integer order controllers.

iv. Innovative control techniques and implementation of new optimization techniques to solve the problems related to AGC issues are always encouraged.

Critical analysis of literature survey also reveals that only few articles have dealt with study of AGC systems implementing 2-DOF-FOPID controllers. Therefore this research article deals with development of SSA technique to optimally design conventional, fractional order, 2-DOF conventional and 2-DOF fractional PID controllers. Main contributions of the article are as follows:

i. Application of SSA technique in the field of AGC.

ii. Development of a two area interconnected power system with various sources of generation in each area in MATLAB Simulink environment.

iii. Optimal design of PID, FOPID, 2DOF-PID and 2DOF-FOPID controller using SSA optimization techniques.

iv. Study of convergence characteristic of PID, FOPID, 2DOF-PID and 2DOF-FOPID controllers tuned by both SSA techniques to show the effectiveness of SSA based 2DOF-FOPID controller.

v. Comparison of the proposed results with DE based PID controller (Cao & Cao, 2006), hybrid Stochastic Fractal Search-Pattern Search (hSFS-PS) based PID controller (Padhy and Panda, 2017), Teaching Learning Based Optimization tuned PID (TLBO-PID) (Barisal, 2015), Imperialist Competitive Algorithm optimized fractional order fuzzy PID controller (ICA-FOFPID) (Arya, 2017).

vi. Robustness analysis of the proposed SSA based two degree FOPID controller (SSA-2DOFOPID) against systems' parametric variation.

II. SYSTEM UNDER INVESTIGATION

The system under investigation involves a two-area interconnected power system. Each area of the power system consists of a non-reheat type thermal unit, a hydro unit with mechanical governor and a gas power unit. Transfer function model of the power system is shown in Figure 1.

Rating of each generating unit is taken as 2000 MW and the considered power system model is simulated in MATLAB Simulink environment with zero initial conditions. Initial loading on the power system is taken as 1740 MW. Nominal values of all the systems' parameters are depicted in appendix. Inputs to proposed controllers are their respective area control error (ACE) and outputs are ΔPTg, ΔPHg and ΔPGg which acts as actuating signals for the governors of thermal, hydro and gas generating unit respectively. ACE is a linear combination of frequency & tie-line power error of corresponding area and for a two area system expressed as:

$$ACE_1 = B_1 \Delta f_1 + \Delta P_{tie,12} \qquad (1)$$

$$ACE_2 = B_2 \Delta f_2 + \Delta P_{tie,21} \qquad (2)$$

Where, ΔP_{tie12} is the tie-line power deviation from area-1 to area-2, β_1 and β_2 are the frequency bias factor of area-1 and area-2 and Δf_1 and Δf_2 are the frequency deviations in area-1 and area-2, respectively. When the system is subjected to a small disturbance, ACE is used as an actuating signal to the controller for damping out systems' oscillation and reducing the steady state error to zero. In this article SSA based conventional, fractional order, 2DOF-PID and 2DOF-FOPID PID controllers are implemented to enhance the transient behaviour of AGC system. From the profound analysis, results clearly show the dominance of SSA based 2DOF-FOPID controller over other controllers.

III. OVERVIEW OF PID, FOPID AND 2DOF-FOPID CONTROLLER

A. PID controller

As the name suggests, a PID controller basically consists of three modes of operations, i.e. proportional mode, integral mode and derivative mode. It is by far the most commonly used controller in almost all controller design studies because of its simple structure which needs few empirical rules. Structure of the PID controller implemented for thermal unit of the power system under consideration is shown in Figure 2. Output of PID controller in time and in Laplace domain can be expressed as:

$$u_1(t) = K_p ACE_1(t) + K_i \int_0^t ACE_1(t)dt + K_d \frac{dACE_1(t)}{dt} \tag{3}$$

$$U_1(s) = K_p ACE_1(s) + \frac{K_i}{s} ACE_1(s) + K_d sACE_1(s) \tag{4}$$

B. Fractional Order PID (FOPID) controller

Fractional Order PID (FOPID) controller is accepted as an efficient controller in industrial applications and research in comparison to conventional PID controller. Alomoush (2010) attempted implementation of FOPID controller in AGC study for the first time. Several other literatures also deals with fractional order controllers in various fields of science and engineering. The concept of fractional order controller deals with differential equations having fractional calculus. So, FOPID controller is the extension of conventional PID controller incorporating fractional calculus i.e. the derivative and integral order are not integers but are taken as fractions. Incorporation of non-integer order controllers for integer order plants provides higher degree of flexibilities to adjust the gain and phase characteristics as compared to that of integer order controllers. These flexibilities make fractional order control strategy more powerful in designing robust control system. The most frequently used definition for fractional differentiation and integration proposed by Riemann-Liouville (R-L) are given in equations (5) and (6) respectively.

$${}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \frac{d^n}{dt^n} \int_a^t (t-\tau)^{n-\alpha-1} f(\tau)d\tau \tag{5}$$

$${}_aD_t^{-\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_a^t (t-\tau)^{\alpha-1} f(\tau)d\tau \tag{6}$$

Where, ${}_aD_t^{\alpha}$ is the fractional operator, 'α' is the calculus order, 'n' is the first integer greater then 'α', i.e. $n-1 \le \alpha < n$ and $\Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1} e^{-t} dt$ is the gamma function.

In general the integro-differential operator ${}_aD_t^{\alpha}$ is expressed as:

$${}_aD_t^{\alpha} = \begin{cases} \dfrac{d^{\alpha}}{dt^{\alpha}} & for\ \alpha > 0 \\ 1 & for\ \alpha = 0 \\ \displaystyle\int_a^t (d\tau)^{-\alpha} & for\ \alpha < 0 \end{cases} \tag{7}$$

Laplace transformation of fractional differential equation expressed in (5) is given by:

$$L\left\{ {}_aD_t^{\alpha} f(t) \right\} = s^{\alpha} F(s) - \sum_{k=0}^{n-1} s^k \, {}_aD_t^{\alpha-k-1} f(t) |_{t=0} \tag{8}$$

With zero initial condition equation (8) becomes:

$$L\left\{ {}_0D_t^{\alpha} f(t) \right\} = s^{\alpha} F(s) \tag{9}$$

From equation (9) it is clear that, with zero initial condition, the fractional derivatives and fractional integrations make the transfer functions of a dynamic systems fractional order of $'s'$. Structure of FOPID controller is shown in Figure 3 and its output in time and Laplace domain are expressed in equations (10) and (11) respectively.

$$u_1 = K_{p1} ACE_1(t) + K_{i1} \frac{d^{-\lambda}}{dt^{-\lambda}} ACE_1(t) + K_{d1} \frac{d^{\mu}}{dt^{\mu}} ACE_1(t) \tag{10}$$

$$U_1(s) = K_{p1} ACE_1(s) + \frac{K_{i1}}{s^{\lambda}} ACE_1(s) + K_{d1} s^{\mu} ACE_1(s) \tag{11}$$

Where, $K_{p1}, K_{i1} \& K_{d1}$ are the controller gains, λ is the order of integrator and μ is the order of differentiator of thermal units. ACE_1 is the area control error of area1.

Equations (10) and (11) clearly depicts that all conventional controllers (PID) are specific cases of fractional controller, where λ and μ are equal to one. Various points of classical PID controller and the plane of FOPID controller are shown in Figure 4.

In Figure 4 it is seen that,
If $\lambda = 1$ and $\mu = 1$, then it is classical PID controller.
If $\lambda = 0$ and $\mu = 1$, then it is classical PD controller.
If $\lambda = 1$ and $\mu = 0$, then it is classical PI controller.
If $\lambda = 0$ and $\mu = 0$, then it is classical P controller.
If λ = fraction and μ = fraction, then it is FOPID controller.

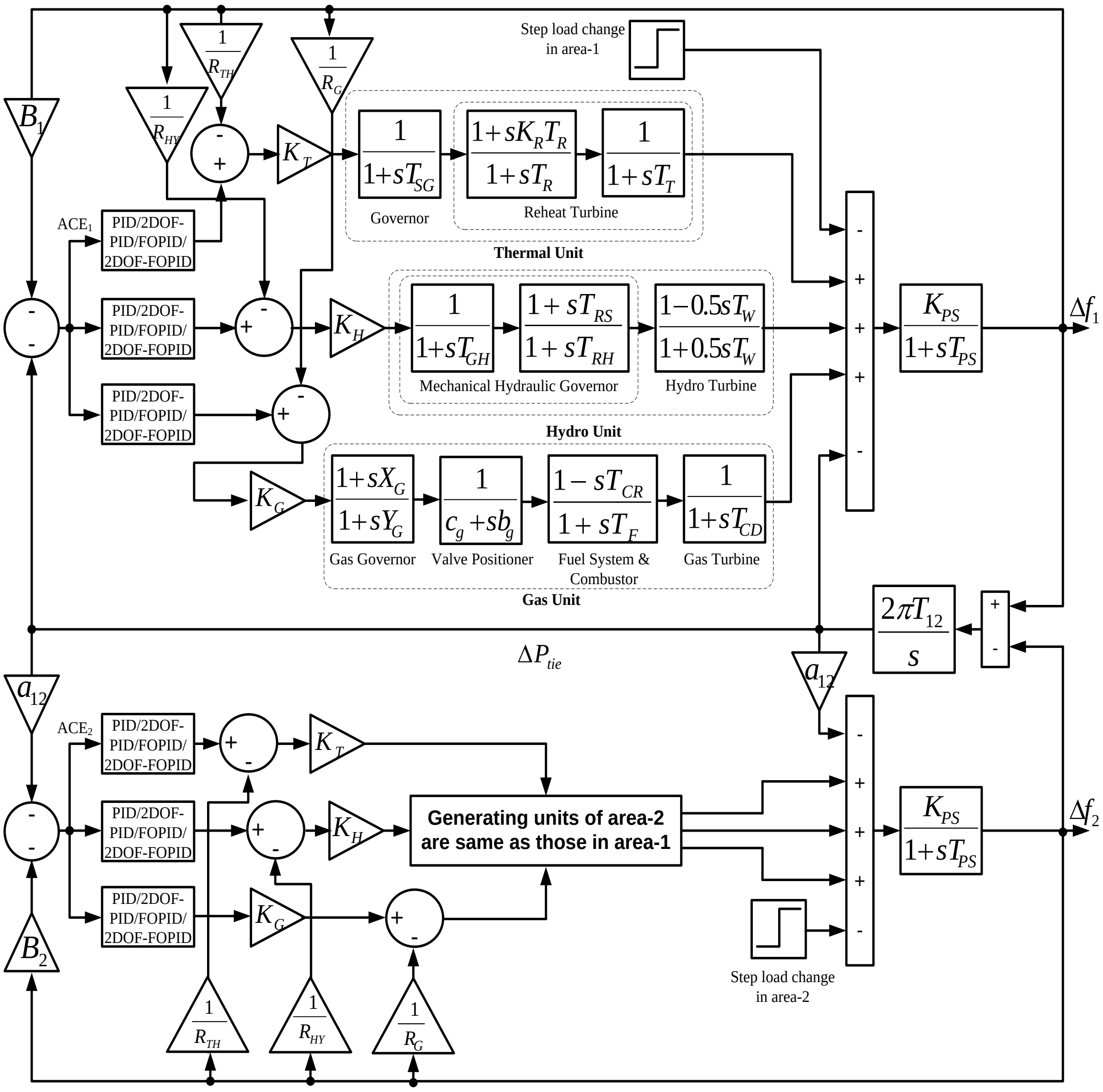

Figure 1. Transfer function model of two area multi-source power system.

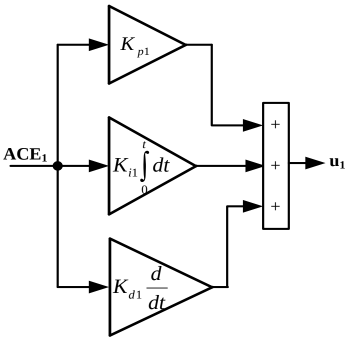

Figure 2. Structure of PID controller

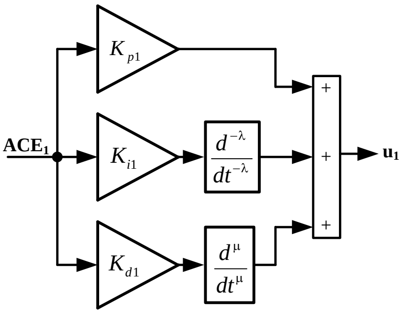

Figure 3. Structure of FOPID controller

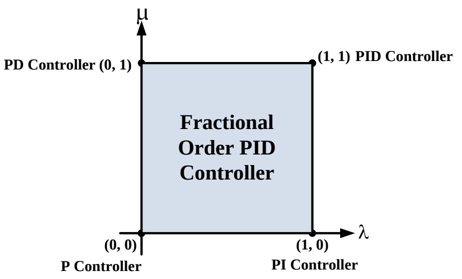

Figure 4. Points of classical PID controller and plane of FOPID controller.

FOPID controller has better performance due to the following reasons:

1. It is more robust and stable than conventional PID controller.
2. For systems having large time delays, it provides better results than conventional PID controller.
3. It can easily accomplish the property of iso-damping, in comparison to PID controller.
4. It provides five different operating conditions as stated above, which is not possible in the case of conventional PID controller.
5. It can attain improved response for non-minimum phase system.
6. It provides better results for higher order systems as compared to conventional PID controller.

C. Two degree of freedom PID (2DOF-PID) controller.

The degree of freedom of a control system is characterized as the quantity of closed-loop transfer functions that can be adjusted independently. A two degree of freedom PID (2DOF-PID) controller has the ability of smooth set point tracking and good disturbance rejection as compared to PID controller. Its output signal is based on the difference between the reference signal and the system output. In general, a 2DOF-PID controller improves the overall closed loop dynamic performance of the system to be controlled. Figure 5 shows structure of a 2DOF-PID controller for the thermal units of the power system shown in Figure 1. So, in a 2DOF-PID controller, in addition to the PID controller gains (K_p, K_i, K_d), two more parameters like proportional set point weight (P_W) and derivative set point weight (D_W) are to be optimally designed.

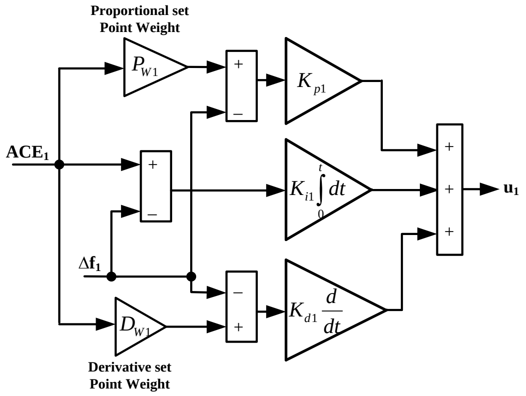

Figure 5. Structure of 2DOF-PID controller for thermal units.

Output of 2DOF-PID controller shown in Figure 5 in time and Laplace domain are expressed in equations (12) and (13).

$$u_1(t) = K_{p1}\left\{ACE_1(t)\times P_{W1} - \Delta f_1(t)\right\} + K_{i1}\int_0^t \left\{ACE_1(t) - \Delta f_1(t)\right\} dt$$
$$+K_{d1}\frac{d}{dt}\left\{ACE_1(t)\times D_{W1} - \Delta f_1(t)\right\} \tag{12}$$

$$U_1(s) = K_{p1}\left\{ACE_1(s)\times P_{W1} - \Delta F_1(s)\right\} + K_{i1}\frac{ACE_1(s) - \Delta F_1(s)}{s}$$
$$+K_{d1}s\left\{ACE_1(s)\times D_{W1} - \Delta F_1(s)\right\} \tag{13}$$

D. Two degree of freedom fractional order PID (2DOF-FOPID) controller

It is evident from recently published research articles that 2DOF-PID controller can effectively control and enhance the dynamic performances while dealing with complicated control related problems. However, it is also proved in literatures that, incorporation of fractional order calculus instead of integer order calculus in control system design lengthens the prospect of additional performance enhancement. Therefore in this article a two-degree of freedom fractional order PID (2DOF-FOPID) controller is implemented in the field of AGC. Structure of 2DOF-FOPID controller is shown in Figure 6 and input and output relationships in time and Laplace domain are given in equations (14) and (15).

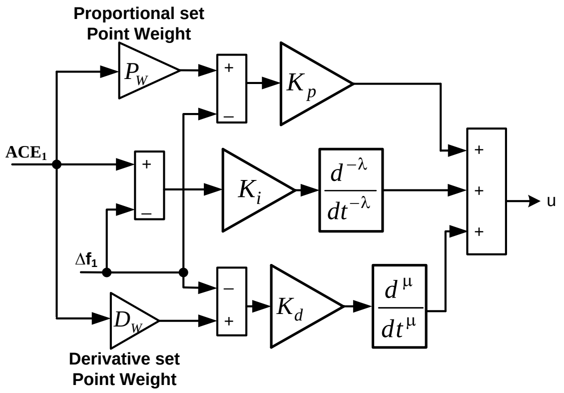

Figure 6. Structure of 2DOF-FOPID controller for thermal units

$$u_1(t) = K_{p1}\left\{ACE_1(t)\times P_{W1} - \Delta f_1(t)\right\} + K_{i1}\frac{d^{-\lambda}}{dt^{-\lambda}}\left\{ACE_1(t) - \Delta f_1(t)\right\}$$
$$+K_{d1}\frac{d^{\mu}}{dt^{\mu}}\left\{ACE_1(t)\times D_{W1} - \Delta f_1(t)\right\} \tag{14}$$

$$U_1(s) = K_{p1}\left\{ACE_1(s)\times P_{W1} - \Delta F_1(s)\right\} + K_{i1}\frac{ACE_1(s)-\Delta F_1(s)}{s^{\lambda}} + K_{d1}s^{\mu}\left\{ACE_1(s)\times D_{W1} - \Delta F_1(s)\right\} \qquad (15)$$

From the above discussion it is clear that a PID controller has three gains (K_p, K_i, K_d), an FOPID controller has five parameters ($K_p, K_i, K_d, \lambda, \mu$), a 2DOF-PID controller has five parameters (K_p, K_i, K_d, P_W, D_W) and a 2DOF-FOPID controller has seven parameters ($K_p, K_i, K_d, \lambda, \mu, P_W, D_W$). All these gains are optimally designed using Salp Swarm Algorithm (SSA) by considering integral time absolute error (ITAE) expressed in equation (16) as objective function. Overviews of proposed SSA algorithms are discussed in Figure 7 depicts strategy adopted in this article to optimally design various gains of the controllers.

$$ITAE = \int_0^{t_{sim}} \left(|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|\right) t\, dt \qquad (16)$$

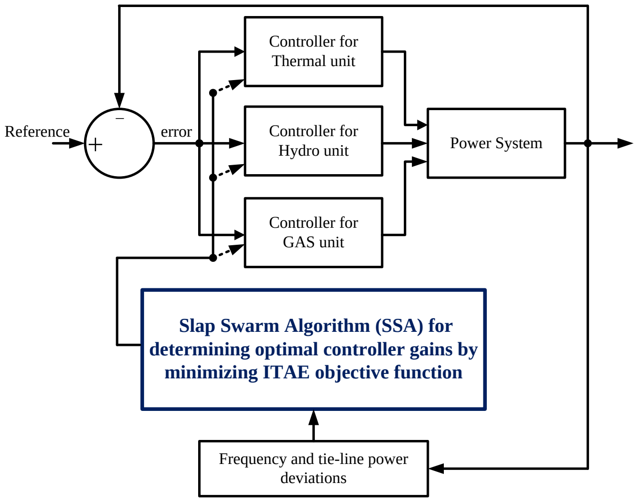

Figure 7. Strategy adopted to optimally design controllers' gains.

IV. OVERVIEW OF PROPOSED OPTIMIZATION ALGORITHMS

Swarm Algorithm (SSA)

Salps have their place in the family of Salpidae. Their tissues are very similar to those of jelly fish also they move in a very similar manner to jelly fish. Figure 8 (a) shows an individual salp and 8 (b) depicts a group of salp forming a chain. Swarming behaviour of salps is one interesting activity and is mathematically modelled by (Mirjalili et al., 2017) to develop Salp Swarm Algorithm (SSA). To mathematically model the salp chains the entire population is divided into two groups namely leader and followers. The leader salp is considered to be at the front of the chain and rest of the salps are considered to be the followers. The leader guides entire swarm and the other salps follow the salp ahead of it.

Various steps involved in SSA algorithm are:

i. ***Initialization:*** - In this stage initial population is randomly generated in the predefined range using the relation:

$$X_i = X_{min} + (X_{max} - X_{min}) \times rand \qquad (17)$$

Where, X_{min} & X_{max} are the minimum and maximum values of the variables to be optimally designed and rand is a random number in the range [0-1]. After evaluation of the fitness, the solution vector of size [NP x D] are sorted keeping the best solution in 1st position called the leader, 2nd best solution in 2nd position and so on.

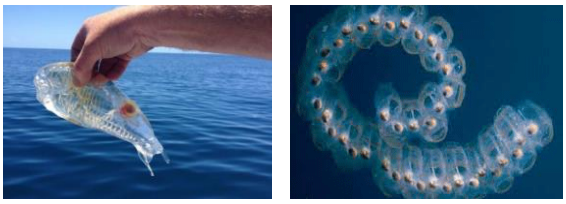
(a) (b)

Figure 8 (a) An individual salp, (b) Salp chain.

ii. Updation of leader:- Position of the leader is updated using the relation:

$$x_i^1 = \begin{cases} F_i + (c_1(x_{i,max} - x_{i,min})c_2 + x_{i,\min}) & if\ c_3 \geq 0 \\ F_i - (c_1(x_{i,max} - x_{i,min})c_2 + x_{i,\min}) & if\ c_3 < 0 \end{cases} \qquad (18)$$

Where, x_i^1 is the updated position of the leader, $x_{i,max}$ & $x_{i,min}$ are the maximum and minimum values of various variables respectively and c_1, c_2 and c_3 are random numbers. 'c_1' is one of the very important parameter in SSA since it balances both exploration and exploitation. It is updated in every iteration using the relation:

$$c_1 = 2e^{-\left(\frac{4iter}{itermax}\right)^2} \qquad (19)$$

Where, 'iter' is the current number and 'itermax' is the maximum number of iteration. c_2 and c_3 are random numbers in the range [0-1].

iii. Updation of followers:- Position of the followers are updated using the relation:

$$x_i^m = \frac{1}{2}\left(x_i^m - x_i^{m-1}\right) \qquad (20)$$

Where, $m \geq 2$ is the position of mth follower.

iv. Imposition of limits and evaluation of newly generated population after updation:-

In this stage limits on the newly generated population are imposed based on the upper and lower bounds. Then fitness of newly generated population is evaluated and the best performing solution is stored.

v. Steps 'ii-iv' are repeated until stopping criteria are met.

V. RESULT AND DISCUSSION

This paper presents a comparative performance analysis of Salp Swarm Algorithm (SSA) tuned PID, FOPID, 2DOF-PID and 2DOF-FOPID controllers to analyse the frequency stabilization capability of an AGC system. Each area of the two-area power system considered for the study has a thermal unit, a hydro unit and a gas unit. The power system model is simulated in MATLAB Simulink environment and SSA techniques are written in .m file which calls the Simulink model and run it to design the optimal controller gains. Number of populations and maximum number of iterations both are considered as 100. ITAE expressed in equation (16) is selected as objective function and minimized to obtain the optimal gain parameters for the controllers. Step load perturbation of 0.01 pu is applied in area-1 to analyse the dynamic performance of the system. Optimal gains of various controllers obtained with SSA techniques are given in Table 1.

Objective function (ITAE) values for different controllers are shown in the last row of Table 1. It is seen that a minimum value of ITAE (=0.0305) is obtained with SSA based 2DOF-FOPID controller in comparison with other controllers. An improvement of 7.54 %, 10.76 %, 14.29 %, 59.54 %, 64.26 %, 72.83 %, 78.36 %, 92.61 % and 95.64 % in ITAE is obtained with SSA optimized 2DOF-FOPID controller in comparison with SSA-2DOF-PID, SSA-2DOF-PID, SSA-FOPID, SSA-PID, hSFS-PS-PID and DE-PID respectively. Undershoots, overshoots and settling times (with a band of 0.0005 %) of frequency deviations in both the areas and tie-line power deviations with proposed controllers and with some of the controllers recently proposed by researchers are depicted in Table 2. Frequency deviations in area-1 and area-2 and tie-line power deviations are depicted in Figure 9-14. Figure 9-11 shows the deviations with PID and FOPID controllers whereas Figures 12-14 depicts the deviations with two-degree of freedom PID and FOPID controllers.

From Table 2 and Figures 9-14 it is obvious that a significant improvement is achieved with SSA based controllers in comparison with other controllers. Again it is seen that 2-DOF fractional order controllers are better than fractional order controllers and fractional controllers are performing better as compared to conventional controllers. The results obtained are compared with recently published articles and found to be superior. It is observed that SSA based PID controller outperforms DE based PID, TLBO-PID, hSFS-PS based PID. It is also seen that SSA optimized 2-DOF-FOPID and 2-DOF-PID controllers are superior to ICA-FOFPID controller. It is also evident that SSA designed 2-DOF-FOPID is yielding better transient performance amongst all the controllers.

Robustness analysis of the proposed SSA based 2-DOF-FOPID controller is carried out by varying all the systems' parameters from -20 % to + 20 % in steps of 10 % and by applying randomly varying loads in both area-1 and area-2 as shown in Figure 15. Deviations in frequency of area-1, area-2 and tie-line power due to random load variations are shown in Figure 16.

From Figures 15-16 it is seen that there is no significant change in dynamic behavior of the system i.e. the proposed controller is robust enough to tackle any change in systems' parameter and random change in load variation. So finally the above discussion manifests that the proposed SSA designed 2DOF-FOPID controller is yielding better dynamic response in all aspects as compared to other proposed controllers and controllers reported in some recently published articles.

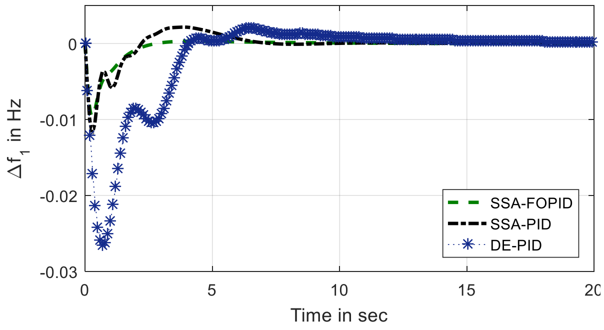

Figure 9 Frequency deviation in area-1 with PID and FOPID controllers.

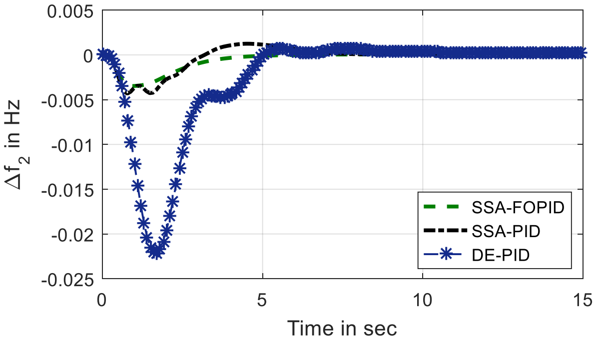

Figure 10 Frequency deviation in area-2 with PID and FOPID controllers.

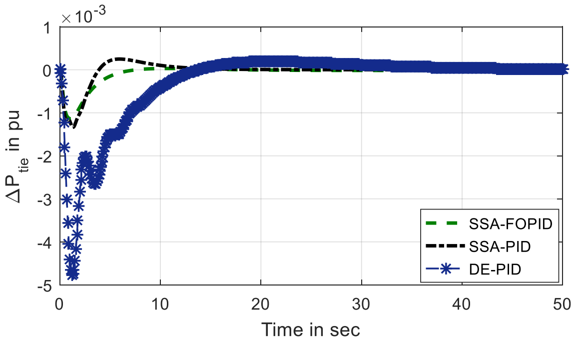

Figure 11 Tie-line power deviation with PID and FOPID controllers.

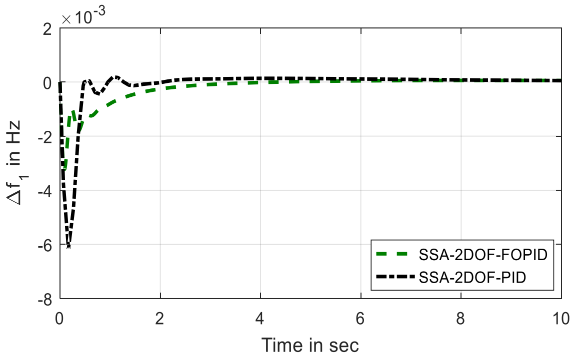

Figure 12 Frequency deviation in area-1 with FOPID and 2DOF-FOPID controllers.

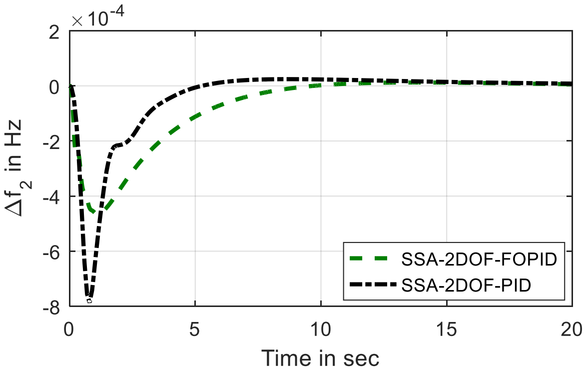

Figure 13 Frequency deviation in area-2 with FOPID and 2DOF-FOPID controllers.

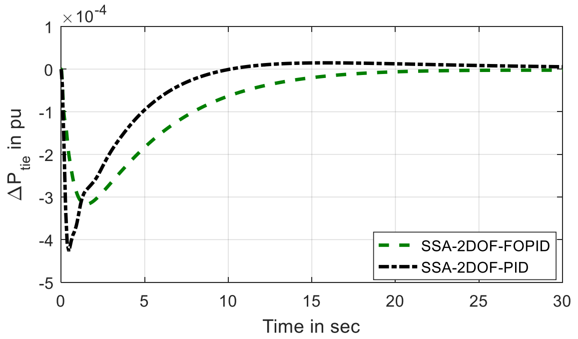

Figure 14 Tie-line power deviation with FOPID and 2DOF-FOPID controllers.

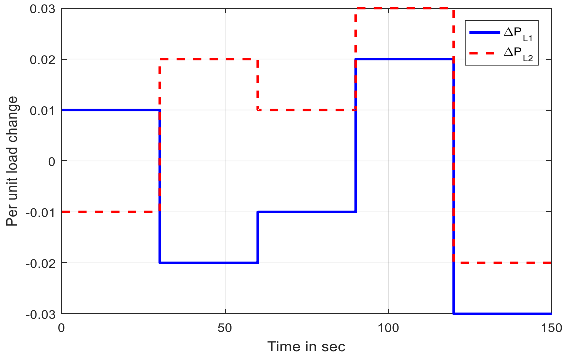

Figure 15 Randomly varying loading pattern in area-1 and area-2.

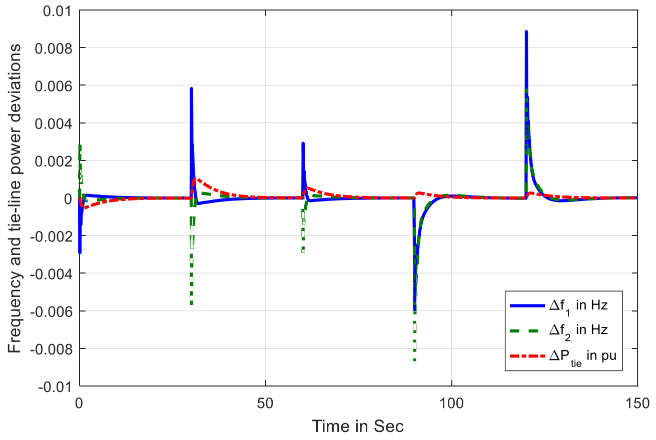

Figure 16 Frequency and tie-line power deviations due to randomly varying load shown in figure 17.

VI. CONCLUSION

In this research article, fractional order PID (FOPID) and 2DOF-FOPID controllers are optimally designed employing Salp Swarm Optimization Algorithm (SSA) to tackle the AGC related issues in two area interconnected power system. Each area of the power system consists of a thermal unit, hydro unit and a gas unit. Comparative performance analysis is done to validate the efficacy of SSA based 2DOF-FOIPD controller over SSA based PID, SSA based FOPID controllers and DE, TLBO, hSFS-PS PID controllers and ICA tuned fractional order fuzzy-PID controller. Sudden step load change of 1% is applied in area-1 and ITAE is taken as objective function to optimally design the controllers. It is observed that SSA based 2DOF-FOPID controller outperforms other controllers by exhibiting less undershoot, overshoot and settling time Finally robustness analysis of SSA based 2DOF-FOPID controller is performed by varying all the systems' parameters and by applying randomly varying loads to both the areas. It is observed that the projected SSA designed 2DOF-FOPID controller is robust against parametric variations and random load variations.

Table 1 Optimal gain of different controllers.

For Thermal Units							
	P_W	D_W	K_p	K_i	K_d	λ	μ
SSA-2DOF-FOPID	5.0000	4.6732	5.0000	3.7649	5.0000	0.9678	1.0000
	P_W	D_W	K_p	K_i	K_d		
SSA-2DOF-PID	4.2655	0.0100	4.9181	4.9976	4.6698		
	K_p	K_i	K_d	λ	μ		
SSA-FOPID	4.8847	5.0000	4.8884	0.8418	0.9913		
	K_p	K_i	K_d				
SSA-PID	5.0000	4.8652	5.0000				
For Hydro Units							
	P_W	D_W	K_p	K_i	K_d	λ	μ
SSA-2DOF-FOPID	0.6200	3.6043	0.0100	4.0737	3.7327	0.7197	0.3404
	P_W	D_W	K_p	K_i	K_d		
SSA-2DOF-PID	5.0000	1.2229	4.8719	4.8401	0.0262		
	K_p	K_i	K_d	λ	μ		
SSA-FOPID	1.3362	0.0100	2.4515	0.8771	0.5549		
	K_p	K_i	K_d				
SSA-PID	4.2323	2.0128	2.5646				
For Gas Units							
	P_W	D_W	K_p	K_i	K_d	λ	μ
SSA-2DOF-FOPID	1.7449	3.2356	4.8321	4.7251	4.8181	0.8062	0.0328
	P_W	D_W	K_p	K_i	K_d		
SSA-2DOF-PID	2.6385	2.1094	5.0000	5.0000	0.8384		
	K_p	K_i	K_d	λ	μ		
SSA-FOPID	4.5825	4.6676	5.0000	0.6788	1.0000		
	K_p	K_i	K_d				
SSA-PID	0.0100	2.4760	2.5756				
ITAE with different control approach							
	SSA-2DOF-FOPID	SSA-2DOF-PID	SSA-FOPID	SSA-PID	hSFS-PS-PID [16]	DE-PID [12]	
	0.0305	0.0329	0.0789	0.1303	0.3818	0.6464	

Table 2 Undershoot, Overshoot and settling time in frequencies and tie-line power deviations.

Parameters	Δf_1				Δf_2				ΔP_{tie}		
	($U_{sh}\times10^{-3}$) in Hz	($O_{sh}\times10^{-3}$) in Hz	T_s in sec		($U_{sh}\times10^{-3}$) in Hz	($O_{sh}\times10^{-3}$) in Hz	T_s in sec		($U_{sh}\times10^{-3}$) in p.u.	($O_{sh}\times10^{-3}$) in p.u.	T_s in sec
SSA-2DOF-FOPID	**-3.2273**	**0.0579**	10.9401		**-0.4650**	**0.0123**	6.6276		**-0.3169**	**0**	11.0435
SSA-2DOF-PID	-6.1642	0.1870	10.0586		-0.7865	0.0244	**3.8599**		-0.4268	0.0147	6.4586
ICA-FOFPID [26]	-8.6	--	5.4542 (with 0.00005 band) 1.7907 (0.0005 band)		-2.6	--	10.1536 (with 0.00005 band) 3.343 (with 0.0005 band)		-0.8	--	**6.6908** (with 0.00005 band) **2.2248** (0.0005 band)
SSA-FOPID	-9.5679	0.3115	11.2262		-3.4750	0.0652	11.8101		-1.1391	0.0303	6.2940
SSA-PID	-11.8862	2.1601	13.4073		-4.3189	1.2512	14.8073		-1.3381	0.2498	12.3073
hSFS-PS: PID [16]	−20.2	4.0577	15.2937		−13.4	2.1471	19.7937		−3.25	0.2481	18.3937
TLBO-PID [27]	−13.9	3.7600	19.0180		−5.5	2.2955	19.5790		−1.46	0.2541	14.2154
DE-PID [12]	-26.5801	2.0342	36.8446		-22.1397	0.7714	42.8446		-4.7585	0.1935	38.6446

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Appendix: Nominal values of power systems' parameters.

Parameters	Symbols	Values	Parameters	Symbols	Values
Area rated Capacity	P_{rt}	2000 MW	Hydro turbine governor time constant	T_{RH}	28.749 sec
Nominal area load	P^0_L	1740 MW	Resetting time	T_R	4.9sec
Nominal system frequency	f_s	60 Hz	Governor time constant	T_{GH}	0.2sec
Power system gain	K_{PS}	68.9655 Hz/puMW	Water starting time	T_W	1.1sec
Power system time constant	T_{PS}	11.49 sec	Lead time constant of gas turbine governor	X	0.6sec
Steam Turbine time constant	T_T	0.3 sec	Lag time constant of gas turbine governor	Y	1.1sec
Steam Turbine Reheat time constant	T_r	10.2 sec	Valve positioner gains	a = c	1
Steam Turbine Reheat constant	K_r	0.3	Valve positioner time constant	b	0.049sec
Governor speed regulation parameters of thermal, hydro and gas units	R	2.4 Hz/puMW	Gas turbine combustion reaction time delay	T_{CR}	0.01sec
Frequency bias coefficient	β	0.4312 puMW/Hz	Gas turbine fuel time constant	T_F	0.239sec
Synchronisation coefficient	T_{12}	0.0433	Compressor discharge volume time constant	T_{CD}	0.2sec
Gain	α_{12}	-1	Participation factors of thermal, gas, and hydro units	K_T, K_G, K_H,	0.5747, 0.1380, 0.2873
Governor time constant in steam plant	T_G	0.06 sec	Gain of RFB	K_{RFB}	1.8

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