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Application of Invasive Weed Optimization Algorithm to Optimally Design Multi-Staged PID Controller for LFC Analysis

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Abstract-This article presents the study of frequency regulation of a solar energy based two area integrated power system equipped with multi-staged PID & conventional PID controller. To optimize the parameters of the projected multi-staged PID controllers, invasive weed optimization algorithm (IWOA) is employed. A disturbance to the extent of 0.01 p.u. is injected to the control area 1 to examine the effectiveness of the controllers in maintaining the system stability. Comparison of the results with respect to the magnitude of oscillations and settling time indicates that the proposed multi-staged PID controller outperforms the classical PID controller. The projected multi-staged PID controller optimised by the aforesaid algorithm (IWOA) helps in attaining nominal values of the tie-line power & frequency deviations during large parametric variation of the system and variation of system condition. Robustness of the proposed control strategy is established under various conditions such as (i) inclusion of a time delay of 0.7 s in each control area, (ii) wide variations of the system parameters and (iii) application of a random loading pattern in area 1.

Keywords: Load frequency control, invasive weed optimization algorithm, thermal-solar power system, multi-staged PID controller.

1. Introduction

The complexity of the power system in modern days has increased many folds due to growing energy requirements day by day with population growth and as such the control and operation of power system has become very difficult and challenging. The biggest challenge in current power system is to uphold the tie-line power and frequency at its nominal value. Power system of modern days consists of various control zones interconnected together through tie-lines for exchange of power between these control zones and each control zone may experience disturbance due to randomness and uncertainty of load demand. Any mismatch between the generation and load demand will result in fluctuations of tie-line power and frequency. Load frequency control (LFC) is a mechanism by which a perfect equilibrium between the generation and system load can be achieved thereby upholding the tie-line power and system frequency at a prescribed limit. It facilitates the synchronous generators of each control zone to regulate the power generation according to the load accomplishing zero steady state error so as to retain the synchronism of the system irrespective of any load changes [1-3].

It is found from the study of various literatures that most of the works in the domain of LFC pertain to the use of various optimisation techniques to optimise the parameters of the controller for optimal system performance. Use of Artificial neural network (ANN) and craziness based Particle optimization have been reported in the literature to tune the controller gains for achieving zero steady state error [4-5]. Bacterial foraging optimisation (BFO) technique in this field was first applied by Nanda et al [6]. LFC of a hydro-thermal system was investigated with traditional controllers [7]. Controller plays a vital role in a closed loop control system as it minimizes the error during any sudden disturbance on the system. In recent years, fuzzy logic control method has been employed by several industries for non-linear systems but in such cases, it may not be always possible to get the optimal output. In order to overcome this difficulty, ANFIS controller may be employed for selection of appropriate fuzzy functions to formulate fuzzy rules. Fusion of ANN and fuzzy logic helps in improving the learning capabilities. LFC study of hydrothermal system using ANFIS approach has been proposed by Khuntia et al. [8]. Electrical energy can be stored in the form of magnetic field by use of superconducting magnetic energy storage (SMES). During charging it stores the energy and it releases energy during discharging. Implementation of SMES technology in LFC improves the frequency regulation [9]. LFC study of solar-thermal system with conventional and fuzzy logic controllers has been illustrated in the literature [10-11]. Invasive weed optimisation algorithm (IWOA) was first developed by Mehrabian and Lucas et al. [12]. Parallel PSO was employed for scheduling of energy with penetration of wind energy in power grid [13]. In the literature, fuzzy control based voltage control with photovoltaic source of generation has been illustrated [14] and frequency regulation of microgrid with variable renewable generation output has been investigated [15]. Optimal allocation of distributed generation with renewable energy sources and sizing of storage system in deregulated environment has been proposed [16]. Internal model control (IMC) designed proportional integral (PI) controller has been suggested for frequency regulation of microgrid with different sources of generation [17]. An integrated rural electrification system has been designed with hybridisation of wind and biogas [18]. Effective power control of a standalone hybrid energy system has been proposed [19]. LFC with multi source generation under deregulated environment was studied by using integral controller tuned by imperialistic competition algorithm (ICA) [20]. A fuzzy based proportional integral derivative (PID) controller designed by hybrid optimisation technique has been recommended for LFC study with different source of generation [21]. LFC study with multiple generation sources and energy storage system has been investigated by implementing adaptive fuzzy logic PID controller optimally tuned by modified whale optimisation algorithm [22]. Implementation of multi stage PID controller designed by hybridisation of stochastic fractal search algorithm and local unimodal sampling has been suggested to address the LFC issue of power system [23]. Invasive weed optimisation algorithm hybridised with pattern search technique has been used for optimal design of 2-DOF PID controller in LFC [24]. IWOA optimised multi-staged PID controller has been proposed for LFC of solar-thermal system [25]. In articles [26-27], communication time delay was introduced for LFC analysis in the interconnected system.

In the present analysis, a multi-staged PID controller optimised by IWOA is offered for LFC of a two identical area solar-thermal power system. Main contribution of the work in this article are summarised below.

- Modelling of a two identical area power system having solar-thermal generation units in each area in MATLB Simulink environment.
- Composing the IWOA in .mfile to minimise the objective function
- Optimal design of PID and multi-staged PID controllers by integrating IWOA algorithm composed in .m file with the designed power system model in simulink environment for LFC.
- Result comparison of the system performance with both the controllers to prove the efficacy of the suggested multi-staged PID controller.
- Validation of the robustness of the proposed control approach by (i) introducing a constant time delay in each area, (ii) widely varying the system parameters and (iii) applying a random system loading.

2. System Configuration

The power system model using transfer functions of the components is designed in Simulink environment and is depicted in Fig. 1. Each area of the designed system consists of solar-thermal unit of 2000 MW. Various parameters of the designed model have been taken from [25]. In the model, T_g denotes time constant of the governor of thermal plant, T_t denotes time constant of the turbine of thermal plant, K_r denotes the reheat constant of thermal plant, T_r denotes the reheat time constant of thermal plant, K_p denotes the power system gain constant of each area, T_p denotes power system time constant of each area, K_S denotes gain of solar unit and T_S denotes the solar unit time constant. The system is equipped with IWOA optimised PID/ multi-staged PID controllers. Integral time absolute error (ITAE) has been selected as the objective function (J) for this work. The optimisation problem is formulated as minimisation of the objective function (J). Mathematical expression of ITAE for the designed model is given below.

$$J = \int_0^t \left(|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}| \right) t\, dt \qquad (1)$$

Where Δf_1 and Δf_2 represents respectively the frequency change of control area 1 and control area 2, ΔP_{tie} represents the change of power flow in the tie-line.

Solar system:

Photovoltaic cells are used to generate electric energy from solar energy with different types of collectors. Collectors captivate the sunlight to heat fluid flowing in the pipe via the heat exchanger. Description of the solar system modelling is given below [25].

$$\frac{dT_0(t)}{dt}=\frac{A\eta_0}{C}I(t)-\frac{U_LA}{C}[T_\alpha(t)-T_e(t)] + \frac{v(t)}{V}[T_0(t)-T_e(t)] \qquad (2)$$

Where $T_\alpha(t)=\frac{T_i(t)+T_0(t)}{2}$ (3)

Equation obtained above signifies the rate of change of temperature in the output. By keeping the output temperature unaltered, the above equation can be modified as

$$\frac{dT_0(t)}{dt}+\left[\frac{U_LA}{2C}+\frac{v}{V}\right]T_0(t)=\frac{A\eta_0}{C}I(t)+ \left[\frac{v}{V}-\frac{U_LA}{2C}\right]T_i(t)+\frac{U_LA}{2C}T_e(t) \qquad (4)$$

Laplace transformation of the above equation yields:

$$T_0(s)=\frac{T_s}{T_s+1}\frac{A\eta_0}{C}I(s)+\frac{T_s}{T_s+1}\left[\frac{v}{V}-\frac{U_LA}{2C}\right]T_i(s) +\frac{T_s}{T_s+1}\times\frac{U_LA}{2C}T_e(s) \qquad (5)$$

Here, the solar field time constant is given by

$$T_s=1/\frac{U_LA}{2C}+\frac{v}{V} \qquad (6)$$

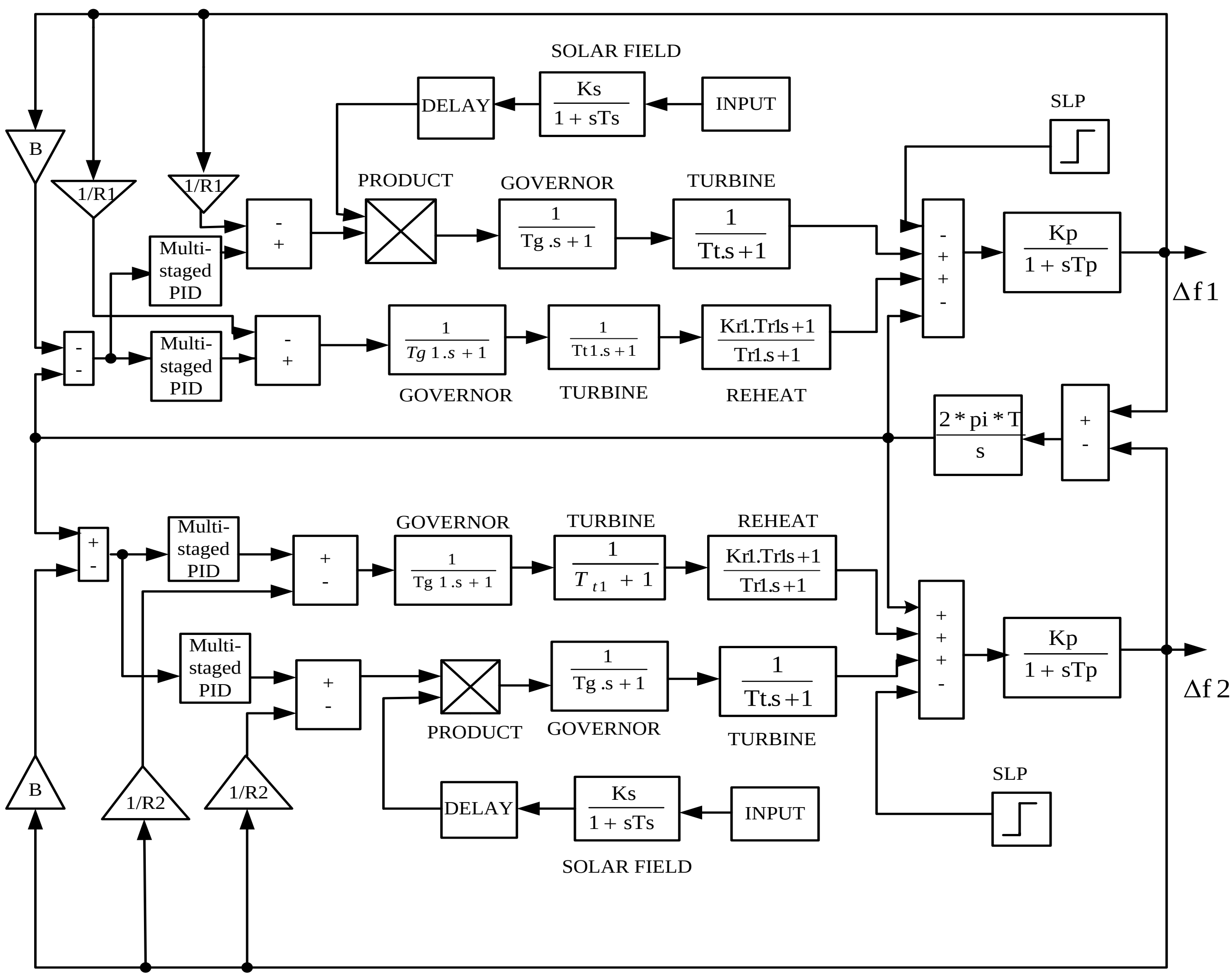

Fig. 1. Transfer function model of power system under consideration

Neglecting the inlet temperature and environmental temperature change, the solar field can be mathematically modelled as:

$$G(s) = \frac{K_s}{1+T_s s} \tag{7}$$

Where K_s is the gain of the solar field.

3. Controllers Outline (PID/Multi-staged PID Controller)

PID controller is the most popular traditional controller. Structural configuration of PID controller is depicted in Fig. 2. Transfer function for this controller is given by

$$TF_{PID} = L_p + \frac{Li}{s} + L_d s \tag{8}$$

Where, L_p, L_d & L_i are the controller gains associated with proportional, derivative and integral actions of the controller respectively.

PID controller is simple in design and it is robust. However, it suffers from the disadvantage of catching the optimal solution during the transient state as well as during the steady state. The integral term helps to remove the error during steady state but it results in poor transient performance of the system and also it makes the system sluggish. Hence, to enrich the transient performance and stability of the system and for faster system response, a double staged PD-PI controller including a PD controller in the first phase supervised by a PI controller in the second phase is proposed in this paper. A first order derivative filter is incorporated with the PD controller to eliminate the high frequency noise produced due to sensors and tie-line telemetry system. Structural configuration of the controller is depicted in Fig. 3. Mathematical expression of the transfer function for the controller is given below.

$$TF_{MPID} = \left(L_{P1} + L_D\left(\frac{N_1 s}{N_1 + s}\right)\right)\left(1 + L_{P2} + \frac{L_I}{s}\right) \tag{9}$$

Where L_{P1}, L_D & N_1 are respectively the first phase proportional gain, derivative gain and filter coefficient and L_{P2} & L_I are respectively the proportional gain and integral gain in second phase of the controller. Area control error (ACE) acts as error signal input to the controller.

4. Invasive Weed Optimization Algorithm

For the first time, IWOA was proposed by Mehrabian et al for solving optimisation problem [12]. The algorithm simulates the ecological colonization and distribution process of weeds. Weeds are robust and adaptive to environmental changes. They possess with invasive habits of growth. As the algorithm is derivative free, it has high convergence. Algorithms for traditional IWOA is summarised by the following steps.

i. Initialisation of solution: A set of initial solution i.e. seeds are randomly generated within the search space. The dimension of the search space is determined by the numbers of variables.

ii. Reproduction: The fitness values of the seeds are evaluated. At this stage, the seeds have grown to become weeds. These weeds are ranked on the basis of their fitness values in the colony. Now each weed is capable of producing new seeds according to its rank. Higher is the fitness of the weed, more is the numbers of seeds produced by the weed. The number of seeds produced by each weed is given by:

$$\text{Number of seeds} = \frac{F - F_{lowest}}{F_{highest} - F_{lowest}}(S_{\max} - S_{\min}) + S_{\min} \tag{10}$$

Where, F is the fitness of the current weed, F_{lowest} and $F_{highest}$ are respectively the least fitness and maximum fitness of the current population, $Seed_{\min}$ and $Seed_{\max}$ are respectively the least and maximum value of a weed.

iii. Spatial dispersion: The seeds so produced are distributed in the solution space around their parent unit. To ensure this, the produced seeds are dispersed randomly over the solution space by normally dispersed random numbers having zero mean but changing variance. But the standard deviation of random function goes on decreasing as the numbers of iteration increases. For a given iteration, the standard deviation of the random function is given by:

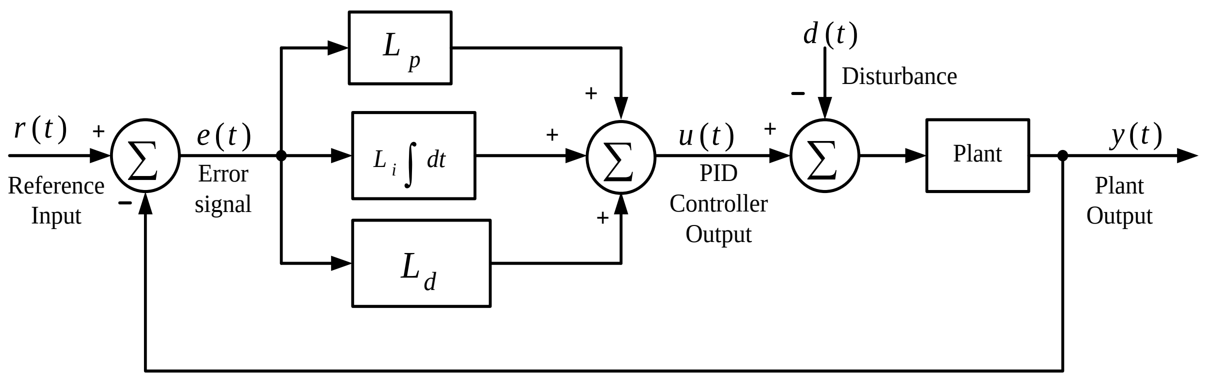

Fig. 2. Configuration of PID controller.

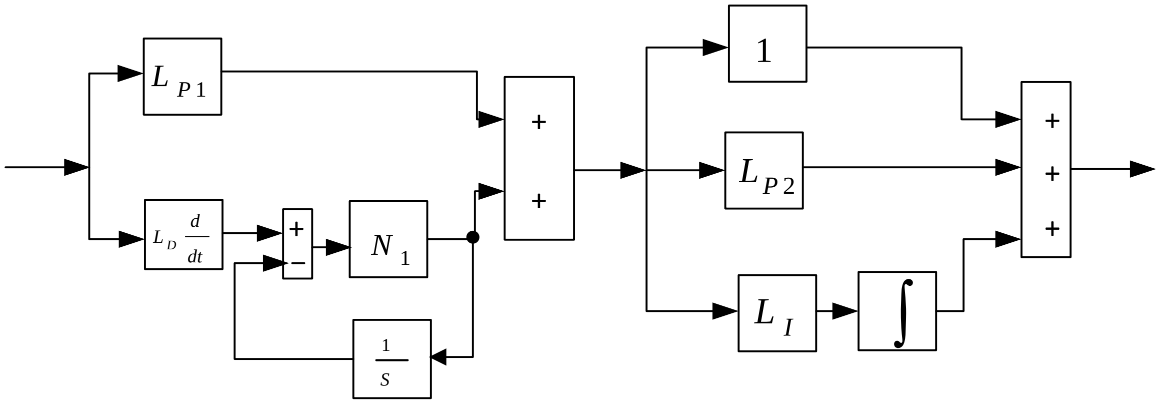

Fig. 3. Configuration of Multi-staged PID controller.

$$SD_{Iter} = \left(\frac{Iter_{\max} - Iter}{Iter_{\max}}\right)^n (SD_i - SD_f) + SD_f \qquad (11)$$

Where $Iter$ represents the current iteration, $iter_{\max}$ represents the maximum number of iterations, SD_i represents the initial standard deviation, SD_f represents the final standard deviation and n represents the nonlinear modulation index having the value in the range [2, 3].

iv. Competitive exclusion: In this step, the seeds are ranked together with their parents and then weeds possessing inferior fitness are removed till the maximum population is reached.

v. The above steps are repeated until the stopping criterions are met.

In this work, both the number of solutions as well as the number of iterations have been taken as 100 for the simulation study and the stopping criteria is met when the total numbers of iterations is reached. The time taken for one complete run of the optimization process is 8 min 41 sec with the PC having configuration: windows 10, MATLAB 2016a, 4GB RAM, Core i3 processor.

5. Result And Analysis:

Simulation study of the considered power system was carried out in MATLAB Simulink environment by implementing IWOA optimised PID and multi-staged PID controller separately. The performance of the controllers was evaluated by performing different case studies as mentioned below. Simulation results obtained with both the controllers in their individual presence were contrasted for comparison and are presented in this section.

5.1. Case 1: Application of a step load of 1% in area 1

A load perturbation of 1% is applied in control area 1 and the system response with individual presence of both the controllers under this condition is contrasted in Figs. 4-6. IWOA optimised parameters of the controllers are recorded in Table 1. Table 2 shows the comparative performance analysis of the two controllers. It shows the comparison of settling time (T_s), peak overshoot (O_{sh}) and peak undershoot (U_{sh}) of the transient response. Figures 4-6 and Table 2 illustrate the dominance of the proposed controller over the conventional PID controller. It is evident that the frequency deviations of both areas as well as the tie-line power deviation attain the least value of settling time, undershoot and overshoot with the proposed multi-staged PID controller in comparison to the traditional PID controller.

The percentage improvement in peak overshoot, peak undershoot and settling time of frequency deviation in area 1 in case of multi-staged PID controller is respectively 89.41 %, 28.37 % and 40.58 % as compared to conventional PID controller. The percentage improvement in peak overshoot, peak undershoot and settling time of frequency deviation in area 2 in case of multi-staged PID controller is respectively 92.66 %, 74.21 % and 25.98 % as compared to conventional PID controller. Similarly, the percentage improvement in peak overshoot, peak undershoot and settling time of tie-line power deviation in case of multi-staged PID controller is respectively 90 %, 63.75 % and 23.5 % as compared to conventional PID controller. Hence, it is observed that there is significant improvement in peak overshoot, peak undershoot and settling time of Δf_1, Δf_2 & ΔP_{tie} with the proposed controller.

5.2. Case 2: Inclusion of Time Delay.

In this case, a time delay of 0.7s is introduced prior to the controller block to reflect the delay of control signal [26-27]. This time delay is accounted for different delays in the system. Figures 7-9 illustrate the transient response of the system under this circumstance. These figures reveal the supreme performance of the suggested controller over the conventional PID controller. Least values of settling time, peak undershoots and peak overshoot is witnessed with multi-staged PID controller when compared with the PID controller. As evident from Figs. 7-9, these values are considerably less for multi-staged PID controller as compared to the PID controller.

As a further extension of the study, the following cases were considered to validate the robustness of the recommended controller.

5.3. *Case 3: Variation of system parameters*

The system will be treated as robust if it is able to handle the system stability during abnormal variations of the system parameters. The system parameters may not remain constant throughout the operation of the system. The parameters may vary abnormally due to many factors. Here the robustness of the system is examined due to parameters discrepancy. The parameters (bias constant B and frequency regulation coefficient R) of the Simulink model are varied from −30% to +30% in a step of 15%. During these conditions, the performance specifications of the time response of Δf_1 & Δf_2 are recorded and grouped in Table 3. Comparison of Table 2 and Table 3 shows that there is no significant variation in peak overshoot, peak undershoot and settling time of Δf_1 & Δf_2. Hence, the intactness of performance stability of the system in spite of wide range of variation of system parameters is evidenced with the proposed controller. Thus the suggested multi-staged PID controller shows robust behavior during the abnormal situation of parameter variation.

5.4. *Case 4: Application of random loading on the system*

In this case, the performance of the suggested controller was investigated by varying the loading of control area 1 in a random manner. This investigation is performed to prove the capability of the designed controller to maintain frequency stability during any types of abnormal loading conditions. The nature of arbitary loading applied in control area 1 is depicted in Fig. 10. With this abnormal loading pattern, transient responses of Δf_1, Δf_2 & ΔP_{tie} are plotted in Figs. 11-13 respectively. These figures reveal that the overshoot and undershoot spikes of Δf_1, Δf_2 & ΔP_{tie} are much less in multi-staged PID controller than the PID controller. This proves that the recommended multi-staged PID controller exhibits supreme performance in comparison to other controller during the abnormal conditions of random loading.

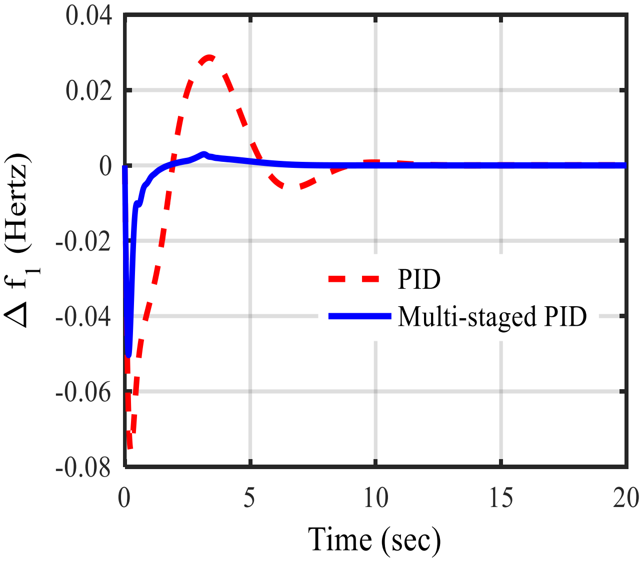

Fig.4. Frequency oscillation of area 1

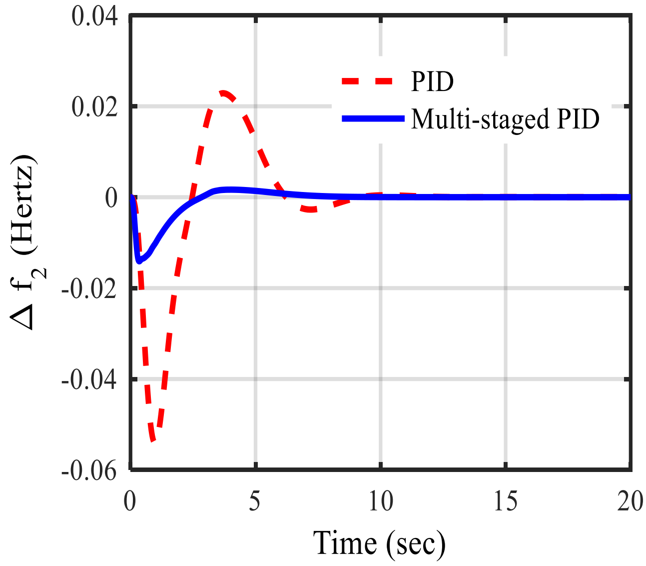

Fig.5. Frequency oscillation of area 2

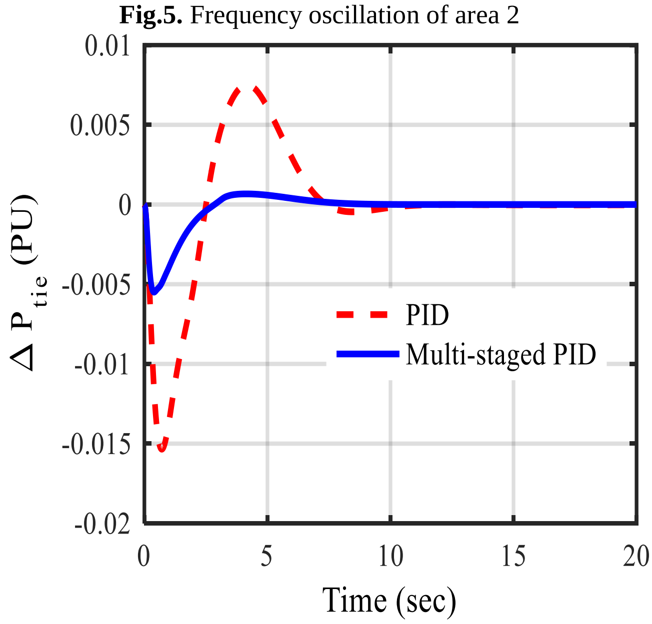

Fig.6. Tie-line power oscillation

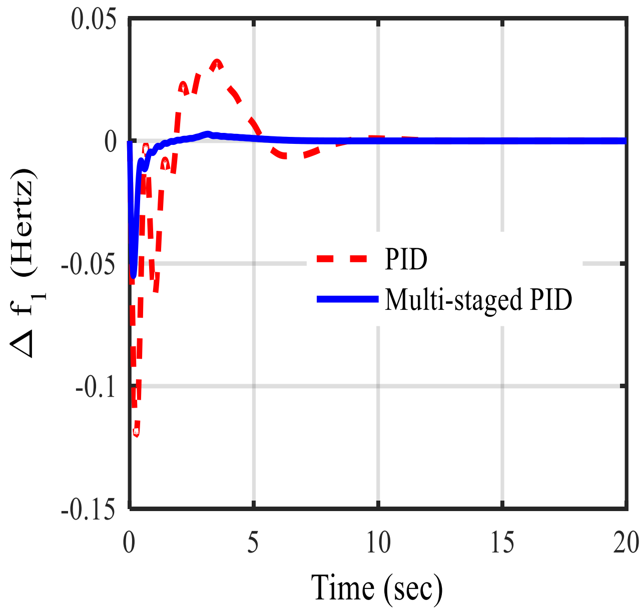

Fig.7. Frequency oscillation of area 1 with time delay

Table 1. IWOA Optimized parameters of the controllers

Projected Controller (Multi-Staged PID)									
Solar-thermal Area 1					Solar-thermal Area 2				
N_1	L_I	L_{P2}	L_D	L_{P1}	N_1	L_I	L_{P2}	L_D	L_{P1}
96.325	3.0000	1.0241	2.8975	2.9835	65.6241	0.03141	1.0214	1.4598	2.8541

Conventional Controller (PID)					
L_d	L_i	L_p	L_d	L_i	L_p
1.8756	2.9423	2.3124	0.2478	0.02875	2.2478

Table 2. Transient response specifications with IWOA optimised PID/Multi-staged PID controller

Controller	Δf_1			Δf_2			ΔP_{tie}		
	$O_{sh}\times10^{-3}$ in Hz	U_{sh} Hz	T_s in sec	$O_{sh}\times10^{-3}$ in Hz	U_{sh} Hz	T_s in sec	$O_{sh}\times10^{-3}$ in Hz	U_{sh} Hz	T_s in sec
Multi-staged PID	0.0029	-0.0510	7.3985	0.0016	-0.0139	9.229	0.00069	-0.0054	8.3910
PID	0.0274	-0.0712	12.4512	0.0218	-0.0539	12.469	0.0069	-0.0149	10.969

Table 3. Transient response specifications under variation of system parameters.

Parameters	**%age deviation**	$O_{sh}\times10^{-3}$ **for** Δf_1 **(in p.u.)**	U_{sh} **for** Δf_1 **(in p.u.)**	T_s **for** Δf_1 **(in sec)**	$O_{sh}\times10^{-3}$ **for** Δf_2 **(in p.u.)**	U_{sh} **for** Δf_2 **(in p.u.)**	T_s **for** Δf_2 **(in sec)**
B	**-30%**	0.0032	-0.071	7.7417	0.0027	-0.0162	9.512
	-15%	0.0030	-0.0521	7.4120	0.0018	-0.0141	9.321
	+15%	0.0031	-0.0526	7.4321	0.0020	-0.0141	9.332
	+30%	0.0033	-0.064	7.7784	0.0026	-0.0165	9.561
R	**-30%**	0.0040	-0.0579	8.6521	0.0019	-0.0144	9.879
	-15%	0.0033	-0.0524	7.457	0.0017	-0.0140	9.352
	+15%	0.0034	-0.0526	7.485	0.0017	-0.0141	9.354
	+30%	0.0042	-0.0587	8.2145	0.0019	-0.0145	9.945

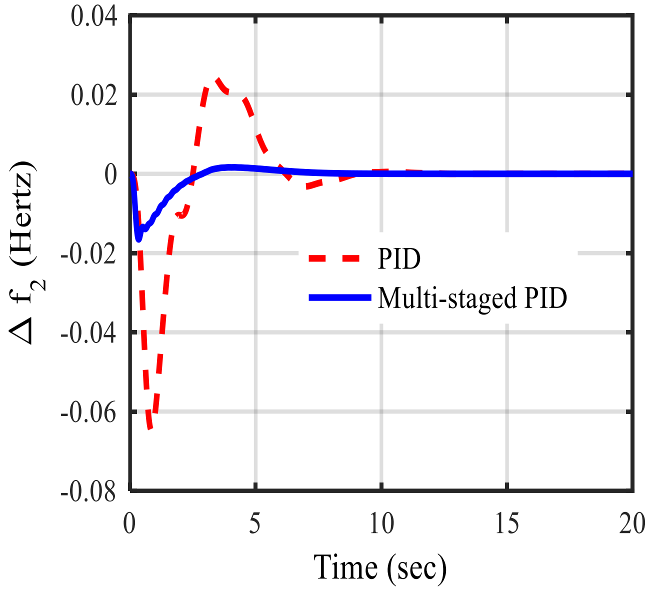

Fig.8. Frequency oscillation of area 2 with time delay

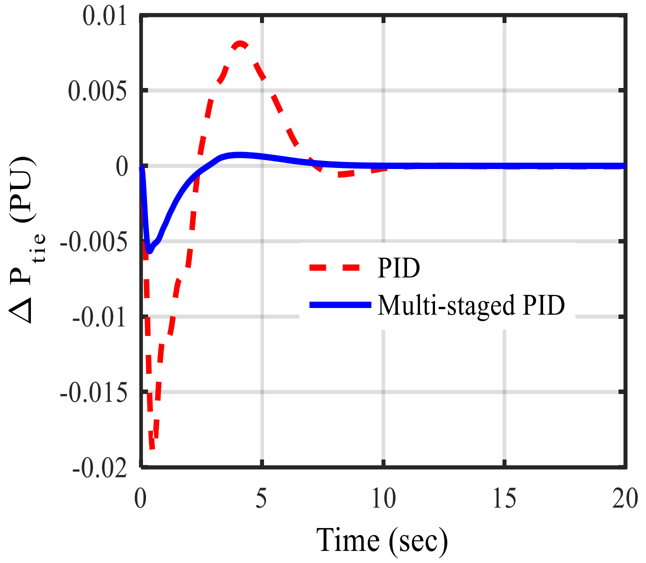

Fig.9. Tie-line power oscillation with time delay

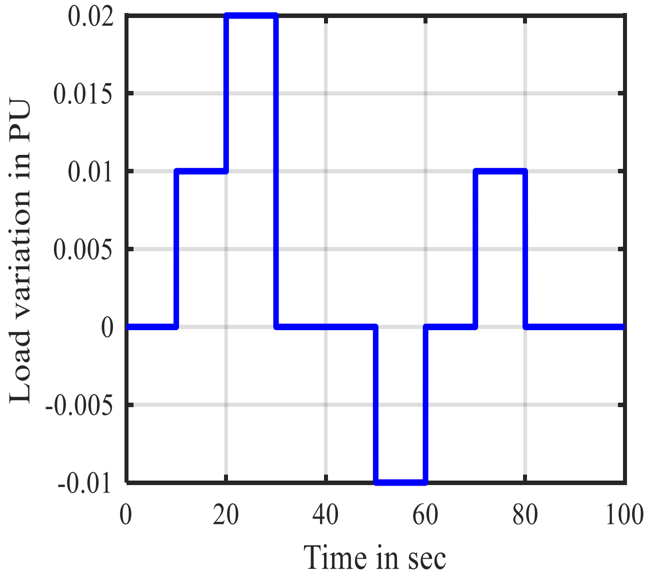

Fig. 10. Nature of random loading applied to control area 1

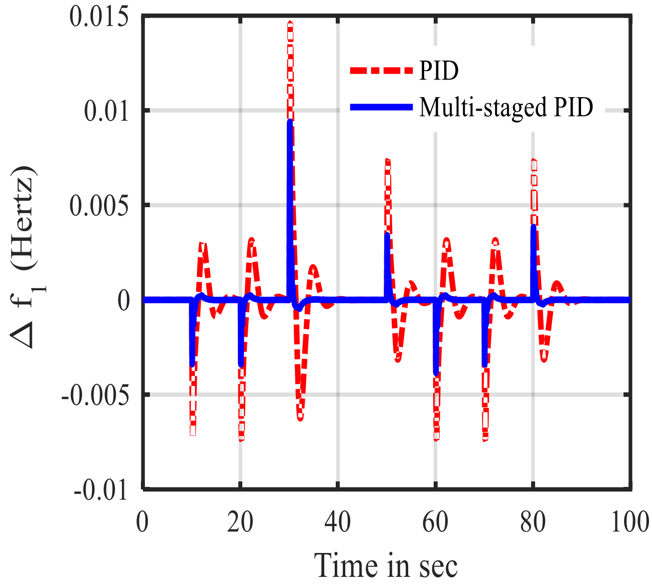

Fig. 11. Frequency oscillation of area 1 (random load)

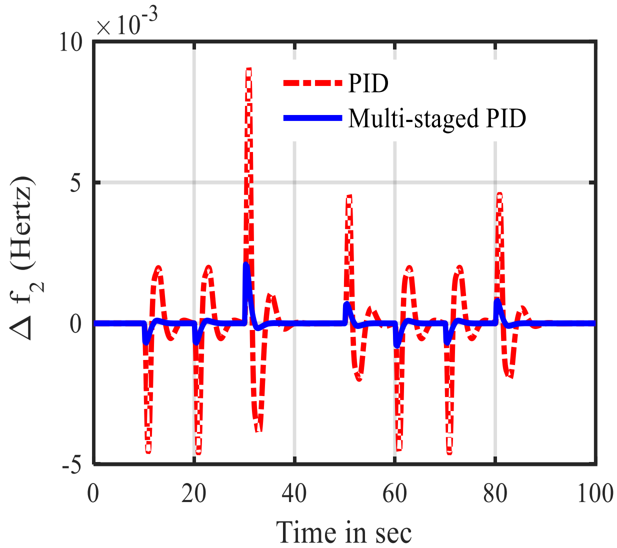

Fig. 12. Frequency oscillation of area 2 (random load)

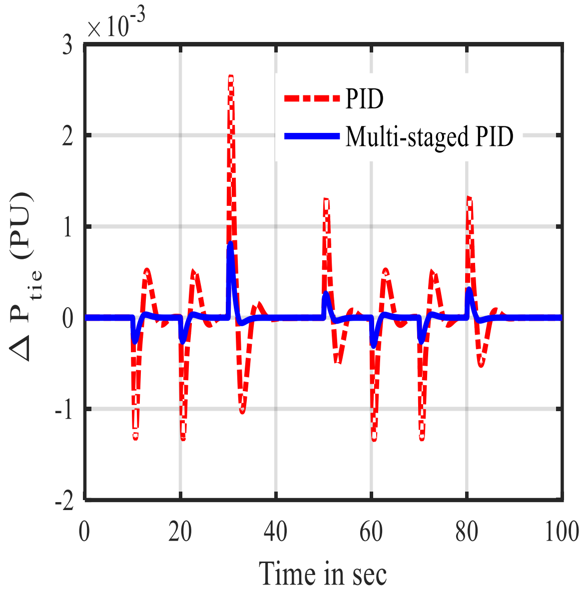

Fig. 13. Tie-line power oscillation (random load)

From the above result analysis with various case studies, it is found that the proposed multi-staged PID controller exhibits superior performance than the PID controller as expected. The multi-staged PID controller essentially performs better due to the two fold control actions in the two stages. In the first stage, it reaps the benefit of PD controller giving faster response and improving the transient performance of the system. In the second stage, it reaps the benefit of PI controller thereby eliminating the steady state error.

6. Conclusion

A model of two identical area solar energy based integrated power system equipped with projected multi-staged PID and conventional PID controller has been designed for frequency regulation. Invasive weed optimisation algorithm was employed to obtain suitable values of controller parameters for optimal system performance. In the first instance, area 1 was subjected to a load perturbation of 1% for performance evaluation of the controllers and it was witnessed that the proposed multi-staged PID controller outperforms the PID controller. Thereafter, the robustness of the proposed control technique was validated by (i) introducing a delay time of 0.7s in all control areas, (ii) widely varying the system parameters and (iii) applying an arbitrary loading pattern in control area 1. It was found that the projected multi-staged PID controller tuned by IWOA technique is quite superior in terms of settling time and swinging magnitude in comparison to the PID controller.

Acknowledgement

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