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Robustness Analysis for *hy*GWO-PS Optimized FOPID-Controllers in AGC of Interconnected Hydro-Thermal Power System

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Abstract: It has already been found in the literature that the hybrid grey wolf optimization- pattern search (*hy*GWO-PS) tuned fractional order PID (FOPID)-controllers in three area interconnected hydro thermal power system (TAIHTPS) with nonlinearities, multiple tie lines and reheat turbines has produced the far better performance than some recent published approaches. In that study, the settling times and overshoots of frequency & tie line power deviations and ITAE values were obtained by proposed approach called *hy*GWO-PS/FOPID under the nominal condition and are evaluated as: Settling time of Δf_1 = 8.50s; Settling time of Δf_2= 8.50s; Settling time of Δf_3= 8.10s; Settling time of ΔP_{Tie12} = 19.31s; Settling time of ΔP_{Tie23}= 15.23s; Settling time of ΔP_{Tie31}=13.01s; ITAE=1.1243. In this regard, it has become necessary to study the variation in the performance of TAIHTPS consisting of *hy*GWO-PS optimized FOPID-controllers with parametric variations, i.e. with varying load conditions and system parameters (T_G, T_T, T_R, $T_W$and T_{12}). In the present work, the robustness analysis or the sensitivity analysis of *hy*GWO-PS optimized FOPID-controllers under parametric variations for AGC of same interconnected power system has been carried out. The robustness analysis shows that the behaviour or the system dynamic responses of TAIHTPS consisting of *hy*GWO-PS optimized FOPID-controllers hardly alters under the variations in operating load conditions and system parameters over the range [-50%, +50%], i.e. *hy*GWO-PS optimized FOPID is far better robust for the same.

Keywords: *GWO, PS, hyGWO-PS, FOPID Controllers, TAIHTPS, Sensitivity Analysis, Parametric Variation.*

1Introduction

AGC provides the control mechanism for multi area interconnected power system (MAIPS) in preserving the tie- line power and system frequency near about nominal values (Kundur,P., 1994) and for enhanced interconnected AGC, numerous control schemes have been proposed like; MCT (Kumar, P.B. and Kothari, D.P., 2005; Shoults, R.R. and Ibarra, J.A.J., 1993), NN (Chaturvedi, D.K., et al., 1999), FST (Ghosal, S.P., 2004), RL (Ogata., K., 1990) and ANFIS approach (Khuntia, S.R. and Panda., S, 2012) with complex structure of controllers (Saikia, L.C., et al., 2011).

Now a days, trying to develop a new nature inspired optimization algorithms for fine tuning of numerous controllers' parameters has become the popular area of research for improved MAIPS such as BFOA/PI, GA optimized controllers (Nanda, J., et al., 2009; Ali, E.S. and Abd-Elazim, S.M., 2011), Gain Scheduling PI-controller (Gozde, H. and Taplamacioglu, M.C., 2011), ICA/PID (Shabani, H., et al., 2012), TDE & TLBO/P-, PI- & PID- (Mohanty, B., et al., 2014; Barisal, A.K., 2015), Emotional Learning tuned controller (Farhangi, R., et a l., 2012), FA with online wavelet filter (Naidu, K., et al., 2014), ABC/ PI- & PID- (Gozde, H., et al., 2012) and GSA/PI- & PIDF (Sahu, R.K., et al., 2014). In continuation, hybrid algorithms provide further improvement in performance of MAIPS like *h*BFOA-PSO/PID (Sahu, R.K.,Panda, S., 2014), *h*PSO-PS/fuzzy PI (Sahu, R.K., et al., 2015) and *h*GWO-PS/2DOF-PID (Soni, V., et al., 2016a, 2016b, 2017, 2020).

In Soni, V., et al, 2020, it has already been proved that the *hy*GWO-PS tuned fractional order PID controllers (FOPID) for AGC of TAIHTPS produces the far better performance in terms of less settling times, less oscillations, better & fast dynamic response and less ITAE value as compared to some recently published approaches using minimization of ITAE as an objective function. Now, in the present work, the performance of the same power system using the proposed approach *hy*GWO-PS/FOPID has been studied with parametric variations over the range [-50%, +50%]. The simulation results demonstrate that the *hy*GWO-PS tuned FOPID for AGC of same power system is more robust.

The rest of paper is organized as follows: Section 2 describes the basic background about the literature (Details of Soni, V., et al., 2020) which elaborates the standard TAIHTPS, FOPID controller's structure, ITAE (objective function) and *hy*GWO-PS algorithm in brief. Section 3 demonstrates the robustness/sensitivity analysis of the *hy*GWO-PS tuned FOPID controllers for AGC of TAIHTPS. Section 4 provides the results and discussion about the robustness of the same. In Section 5, the conclusions of present work is given followed by acknowledgement and references.

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2 Basic Background

In the present work, the same AGC of TAIHTPS (shown in Figure 1) with nonlinearities, multiple tie lines, reheat turbines and three FOPID controllers of dissimilar characteristics as taken in Soni, V., et al, 2020, has been considered. The FOPID controller (shown in Figure 2) has been defined by the following equation Soni, V., et al, 2020:

$$G_{fopid}(s) = K_{Pf} + \frac{K_{If}}{s^{\lambda}} + K_{Df}s^{\mu} \quad (1)$$

The nomenclature of all symbols and parameters of the above equation are given in Soni, V., et al, 2020. The parameters: K_{Pf} , K_{If} , K_{Df} , λ and μ of FOPID in TAIHTPS-AGC have been optimized or tuned using *hy*GWO-PS (shown in Figure 3) algorithm by minimizing the ITAE (OF) given in (2) over the constrained optimization problem defined in (3).

$$J = \int_0^{t_{simulation}} \left(|\Delta w_1| + |\Delta w_2| + |\Delta w_3| + |\Delta Pt_{13}| + |\Delta Pt_{12}| + |\Delta Pt_{23}| \right) \cdot t \cdot dt \quad (2)$$

Minimize J

Subject to

$$\begin{cases} K_{Pfmin} \le K_{Pf} \le K_{Pfmax} \\ K_{Ifmin} \le K_{If} \le K_{Ifmax} \\ K_{Dfmin} \le K_{Df} \le K_{Dfmax} \\ \lambda_{fmin} \le \lambda_f \le \lambda_{fmax} \\ \mu_{fmin} \le \mu_f \le \mu_{fmax} \end{cases} \quad (3)$$

The upper and lower bounds for parameters are defined as:

$$\begin{cases} -2 \le K_{Pf} \le 2 \\ -2 \le K_{If} \le 2 \\ -2 \le K_{Df} \le 2 \\ 0 \le \lambda_f \le 1 \\ 0 \le \mu_f \le 1 \end{cases} \quad (4)$$

The following results of settling times and ITAE are obtained as: ST of Δf_1 = 8.5s; ST of Δf_2= 8.5s; ST of Δf_3= 8.1s; ST of ΔP_{Tie12} = 19.31s; ST of ΔP_{Tie23}= 15.23s; ST of ΔP_{Tie31}=13.01s; ITAE=1.1243.

The more details about used standard test system, GWO algorithm, PS algorithm, *hy*GWO-PS algorithm and the procedure to implement the algorithm for tuning the FOPID controllers' parameters in the considered system, structure of FOPID controllers and its working can easily be found in Soni, V., et al., 2020. The dynamic behavior, settling times, overshoots, value of ITAE of standard power system aforesaid and the relative comparison with others had also been discussed and given in Soni, V., et al., 2020.

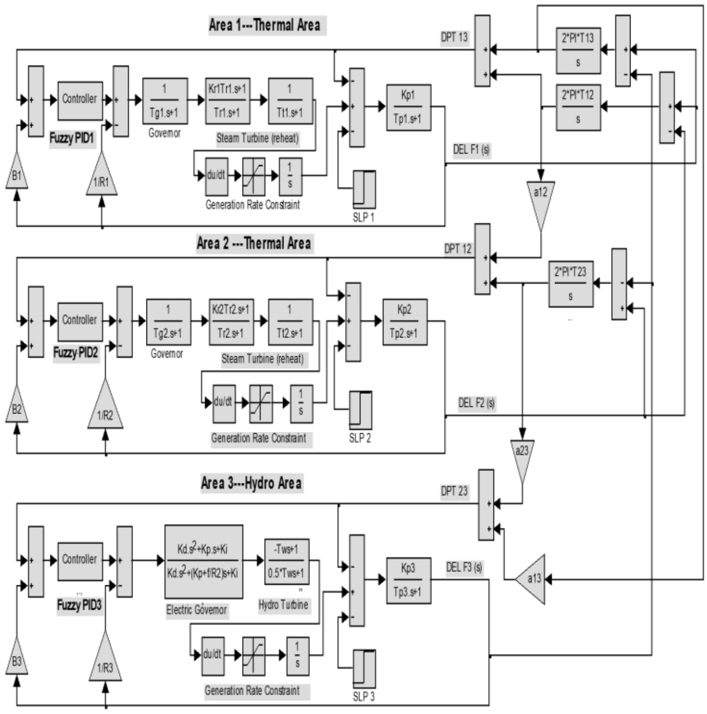

Fig. 1 AGC of TAIHTPS (Soni, V., et al., 2020)

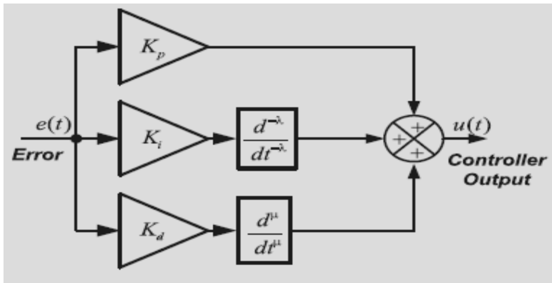

Fig. 2. Structure of FOPID (Soni, V.,*et al.*, 2020)

The optimized parameters have been given in Table 1 [24] as:

Table 1 Optimized parameters of *hy*GWO-PS tuned FOPID for TAIHTPS (Soni, V., et al, 2020)

Prescribed area	K_P	K_I	K_D	λ	μ
Area 1	1.7315	1.7135	0.2595	0.8200	0.0110
Area 2	1.8920	1.3062	0.4512	0.8456	0.9954
Area 3	0.0894	1.4313	0.0553	0.9121	0.1810

The more details about used standard test system, GWO algorithm, PS algorithm, *hy*GWO-PS algorithm and the procedure to implement the algorithm for tuning the FOPID controllers' parameters in the considered system, structure of FOPID controllers and its working can easily be found in Soni, V., et al., 2020. The dynamic behavior, settling times, overshoots, value of ITAE of standard power system aforesaid and the relative comparison with others had also been discussed and given in Soni, V., et al., 2020.

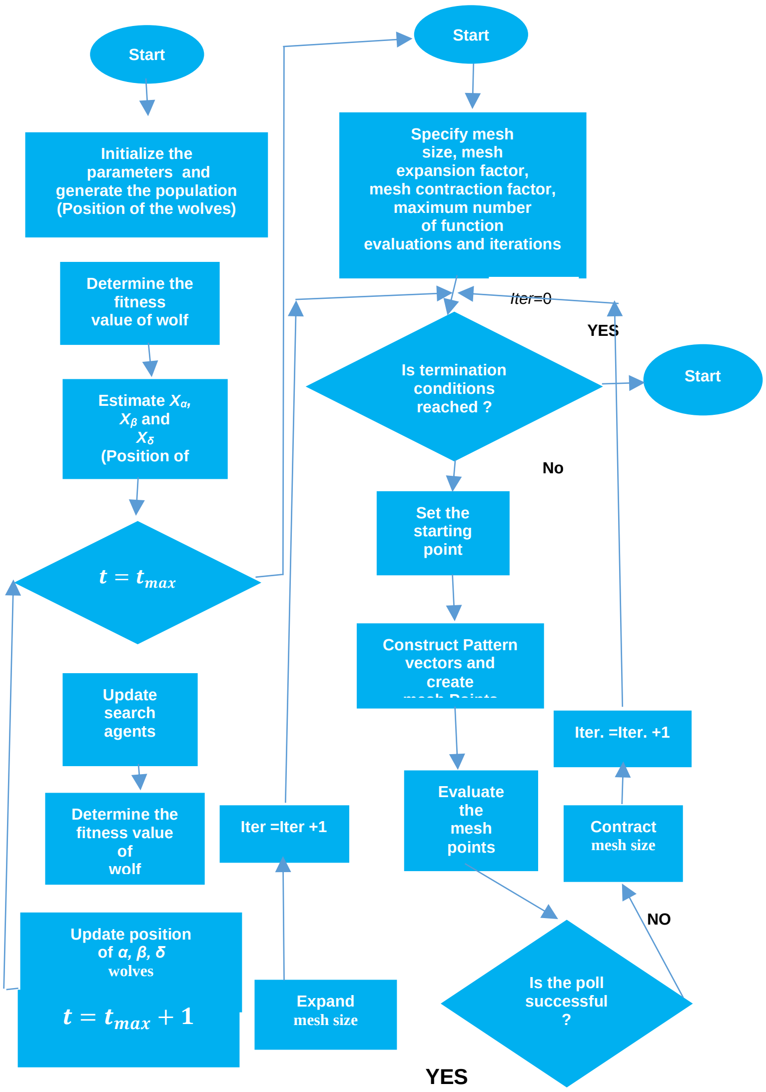

Fig. 3 *hy*GWO-PS algorithm (Soni, V., et al., 2020)

3 Robustness/sensitivity analysis of *hy*GWO-PS optimized FOPID Controllers for AGC of TAIHTPS

Robustness/Sensitivity of TAIHTPS is the ability to provide the approximately constant system dynamic responses with altered operating load conditions and system variables within a certain tolerable range. In the present work, the robustness/sensitivity analysis of TAICHTPS using *hy*GWO-PS/FOPID has been carried out over wide range from -50% to +50% with varying operating load conditions and system parameters. The operating load condition means application of load disturbance in any area and the system parameters are T_G, T_T, T_R, T_W and T_{12} (Saikia, et al., 2011;Nanda, et al., 2009).

The robustness/sensitivity analysis for the system can be explained from the Figure 4. The system dynamic responses along with the ITAE value and settling times

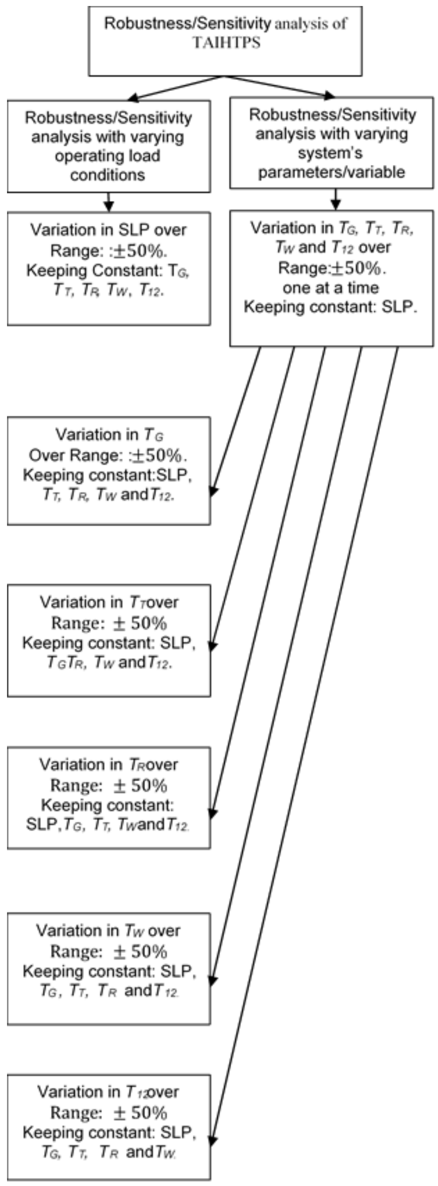

Fig. 4 Complete robustness/sensitivity analysis of TAIHTPS

are observed in each way of performance analysis which decides whether the system is more robust or less. If the variation in system dynamic responses, ITAE values and settling times are very close or near to the respective values of the system response obtained under nominal conditions, the system will be more robust.

4 Results and discussions

4.1 Robustness/sensitivity with variation in operating load conditions

In this analysis, percentage of SPL in area 1 has been varied from its nominal value in wide range of [-50%, +50%] and 10% of SLP has been considered in area 2. During each variation, the system dynamic responses, settling times and ITAE values have been observed. The results have been shown in Figures 5-10.

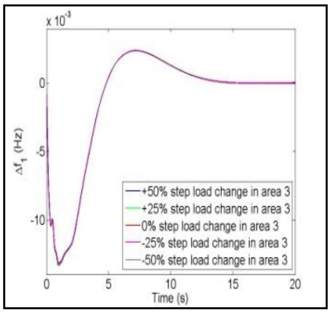

Fig. 5 Variation in Δf_1 with varying load condition (VLC)

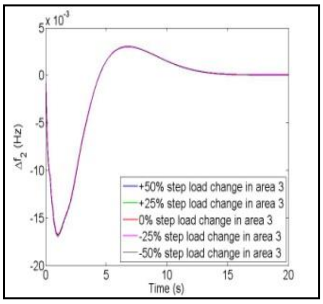

Fig. 6 Variation in Δf_2 with VLC

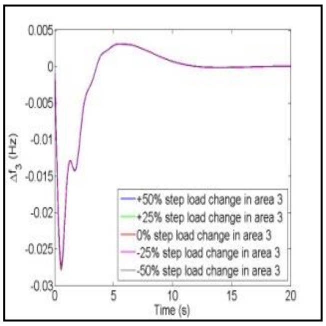

Fig. 7 Variation in Δf_3 with VLC

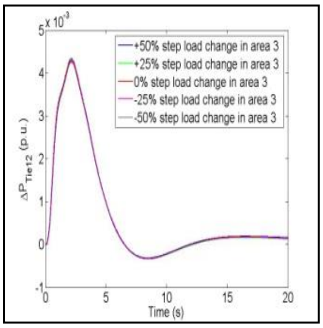

Fig. 8 Variation in ΔP_{Tie12} with VLC

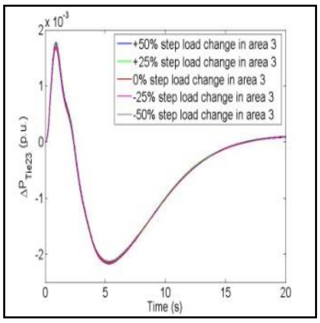

Fig. 9 Variation in ΔP_{Tie23} with VLC

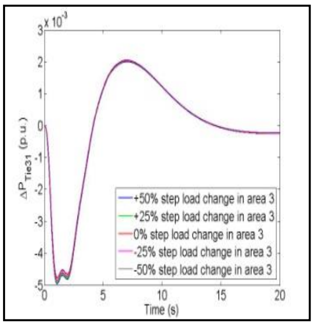

Fig. 10 Variation in ΔP_{Tie31} with VLC

4.2 Robustness/sensitivity with variation in T_G keeping constant operating load conditions, T_T, T_R, T_W and T_{12}

In this analysis, percentage change has been varied in T_G from its nominal value in wide range of [-50%, +50%]. For this analysis, 10% of SLP has been considered in area 2 at time t=0 second. During each variation, the system dynamic responses, settling times and ITAE values have been observed. The results have been shown in Figures 11-16.

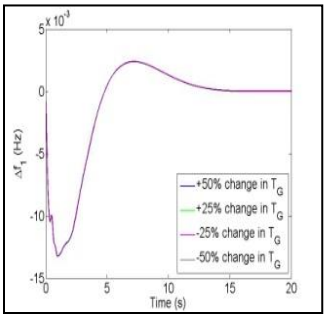

Fig. 11 Variation in Δf_1 with ΔT_G

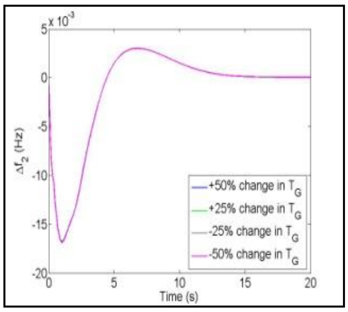

Fig. 12 Variation in Δf_2 with ΔT_G

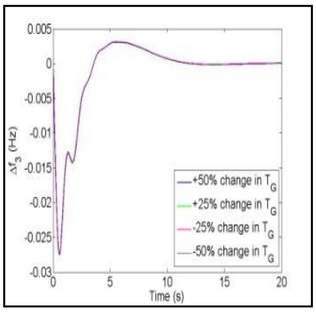

Fig. 13 Variation in Δf_3 with ΔT_G

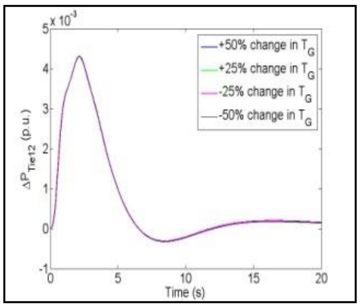

Fig. 14 Variation in ΔP_{Tie12} with ΔT_G

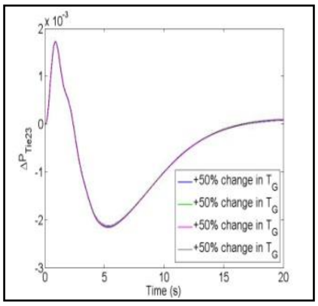

Fig. 15 Variation in ΔP_{Tie23} with ΔT_G

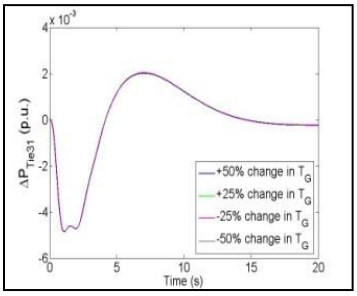

Fig. 16 Variation in ΔP_{Tie31} with ΔT_G

4.3 Robustness/sensitivity with variation in T_T keeping constant operating load conditions, T_G, T_R, T_W and T_{12}

This analysis shows the variation in T_T in percentage from its nominal value for wide range of [-50%, +50%]. A 10% of step load change in area 1 has been considered at time t=0 second. The results are shown in Figure. 17-22.

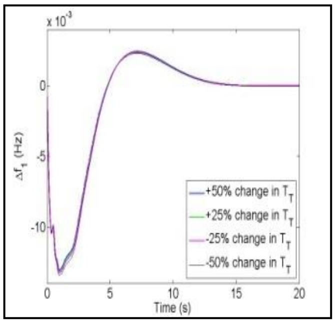

Fig. 17 Variation in Δf_1 with ΔT_T

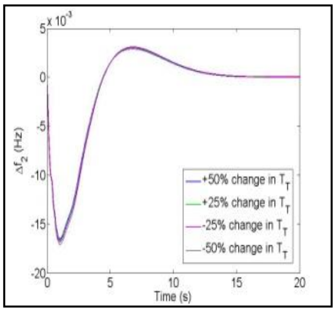

Fig. 18 Variation in Δf_2 with ΔT_T

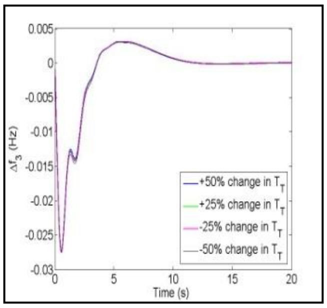

Fig. 19 Variation in Δf_3 with ΔT_T

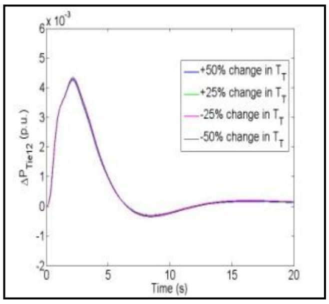

Fig. 20 Variation in tie-line power deviation; ΔP_{Tie12} with ΔT_T

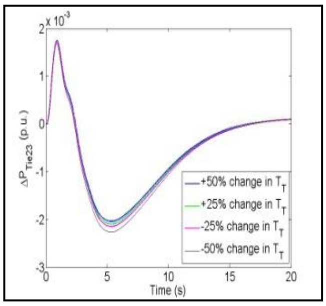

Fig. 21 Variation in ΔP_{Tie23} with ΔT_T

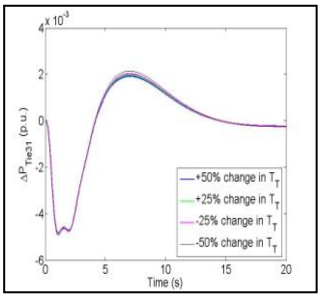

Fig. 22 Variation in ΔP_{Tie31} with ΔT_T

4.4 Robustness/sensitivity with variation in T_R keeping constant operating load conditions, T_G, T_T, T_W and T_{12}

This analysis shows the variation in T_R in percentage from its nominal value for wide range of [-50%, +50%]. A 10% of step load change in area 1 has been considered at time t=0 second. The results are shown in Figures 23-28.

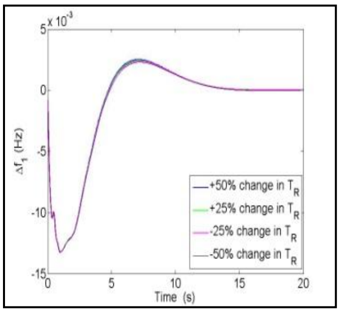

Fig. 23 Variation in Δf_1 with ΔT_R

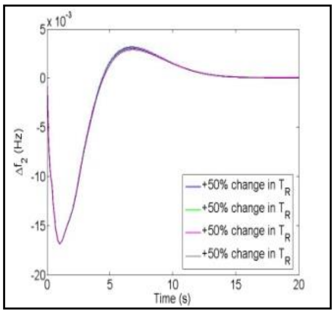

Fig. 24 Variation in Δf_2 with ΔT_R

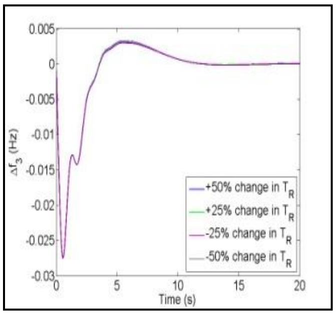

Fig. 25 Variation in Δf_3 with ΔT_R

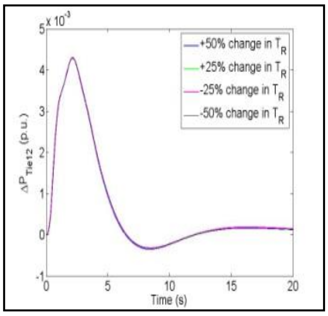

Fig. 26 Variation in ΔP_{Tie12} with ΔT_R

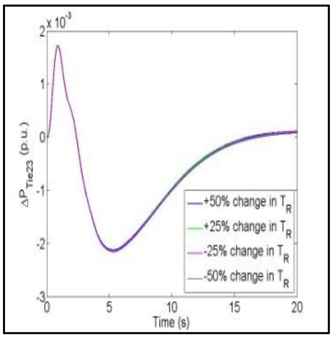

Fig. 27 Variation in ΔP_{Tie23} with ΔT_R

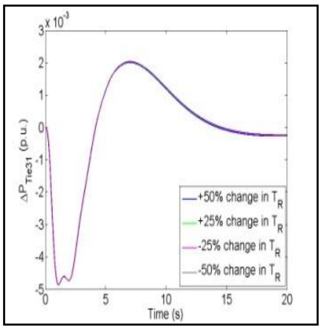

Fig. 28 Variation in ΔP_{Tie31} with ΔT_R

4.5 Robustness/sensitivity with variation in T_W keeping constant operating load conditions, T_G, T_T, T_R and T_{12}

This analysis shows the variation in T_W in percentage from its nominal value for wide range of [-50%, +50%]. A 10% of step load change in area 1 has been considered at time t=0 second. The results are shown in Figures 29-33.

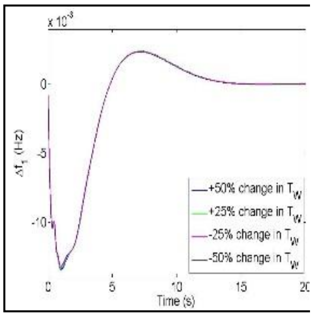

Fig. 29 Variation in Δf_1 with ΔT_R

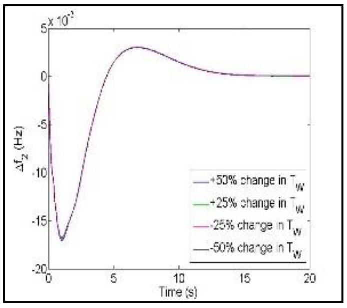

Fig. 30 Variation in Δf_2 with ΔT_R

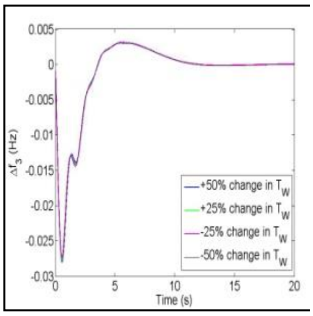

Fig. 31 Variation in Δf_3 with ΔT_R

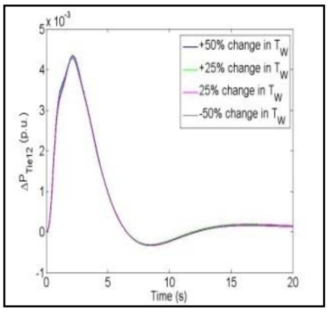

Fig. 32 Variation in ΔP_{Tie12} with ΔT_R

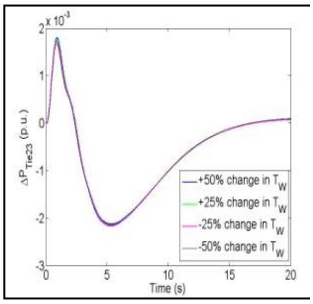

Fig. 33 Variation in ΔP_{Tie23} with ΔT_R

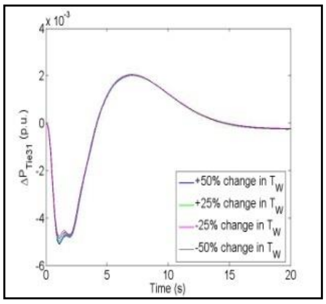

Fig. 34Variation in ΔP_{Tie31} with ΔT_R

4.6 *Robustness/sensitivity with variation in T_W keeping constant operating load conditions, T_G, T_T, T_R and T_{12}*

This analysis shows the variation in T_{12} in percentage from its nominal value for wide range of [-50%, +50%]. A 10% of step load change in area 1 has been considered at time t=0 second. The results are shown in Figure. 34-39.

From simulation results shown in Figures 5-39, the variation in ITAE values and settling times of frequency and tie-line power deviations have been tabulated in Tables 2-3. Simulation results show that there are slight or negligible variations observed in ITAE values, settling times of frequency and tie-line power deviations, i.e. the behaviour of the system under consideration hardly alters with parametric variation means once the parameters of *hy*GWO-PS optimized FOPID-controllers for TAIHTPS have been set, i.e. there is no need to reset again over the range of [-50%, +50%].

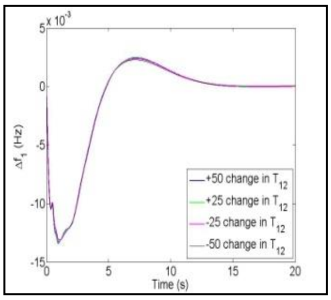

Fig. 34 Variation in Δf_1 with ΔT_{12}

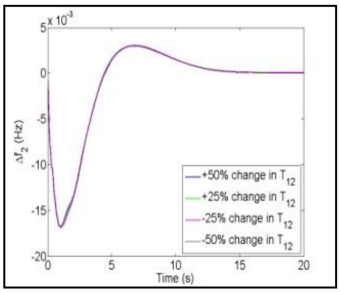

Fig. 35 Variation in Δf_2 with ΔT_{12}

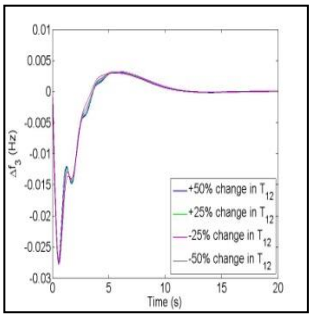

Fig. 36 Variation in Δf_3 with ΔT_{12}

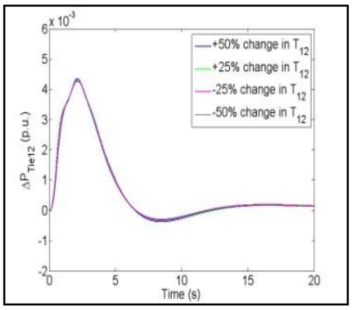

Fig. 37 Variation in ΔP_{Tie12} with ΔT_{12}

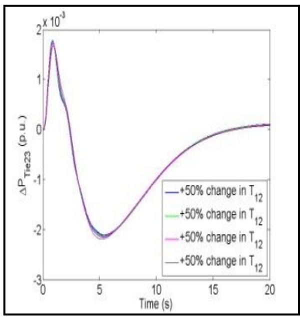

Fig. 38 Variation in ΔP_{Tie23} with ΔT_{12}

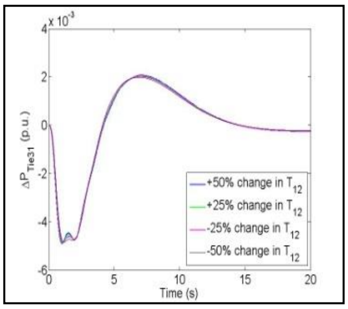

Fig 39 Variation in ΔP_{Tie31} with ΔT_{12}

Table 2 Robustness/Sensitivity analysis of *hy*GWO-PS optimized FOPID-controllers for TAIHTPS

Paramete rs	**% Change**	**Performance Index with Proposed Approach; *hy*GWO-PS/FOPID**

Variation (PV)		Settling time T_s (Sec.)		
		Δf_1	Δf_2	Δf_3
Nominal	0	8.50	8.50	8.10
Operating Load Conditions (OLC)	+50	8.50	8.50	8.10
	+25	8.50	8.50	8.10
	-25	8.50	8.50	8.10
	-50	8.50	8.50	8.10
T_G	+50	8.50	8.51	8.10
	+25	8.51	8.51	8.10
	-25	8.51	8.50	8.10
	-50	8.50	8.50	8.09
T_T	+50	8.51	8.51	8.11
	+25	8.49	8.51	8.11
	-25	8.49	8.48	8.13
	-50	8.49	8.48	8.12
T_R	+50	8.48	8.49	8.13
	+25	8.49	8.49	8.13
	-25	8.49	8.48	8.12
	-50	8.49	8.48	8.12
T_W	+50	8.48	8.47	8.13
	+25	8.48	8.47	8.13
	-25	8.48	8.47	8.11
	-50	8.48	8.47	8.12
T_{12}	+50	8.49	8.46	8.12
	+25	8.49	8.46	8.12
	-25	8.49	8.46	8.12
	-50	8.49	8.46	8.12

Table 3 Robustness/Sensitivity analysis of *hy*GWO-PS optimized FOPID-controllers for TAIHTPS

PV	% Change	Performance Index with Proposed Approach; *hy*GWO-PS/FOPID			ITAE Value
		Settling time T_s (Sec.)			
		ΔP_{Tie12}	ΔP_{Tie23}	ΔP_{Tie31}	
Nom.	0	19.31	15.23	13.01	1.1243
OLC	+50	19.31	15.24	13.01	1.1243
	+25	19.31	15.24	13.01	1.1243
	-25	19.31	15.24	13.01	1.1256
	-50	19.31	15.24	13.01	1.1257
T_G	+50	19.31	15.23	13.01	1.1262
	+25	19.32	15.23	13.01	1.1260
	-25	19.31	15.25	13.01	1.1260
	-50	19.33	15.25	13.01	1.1262
T_T	+50	19.32	15.25	13.01	1.1309
	+25	19.32	15.25	13.01	1.1298
	-25	19.32	15.26	13.01	1.1298
	-50	19.32	15.24	13.01	1.1297
T_R	+50	19.33	15.25	13.01	1.1255
	+25	19.33	15.25	13.01	1.1254
	-25	19.33	15.25	13.02	1.1254
	-50	19.33	15.24	13.02	1.1254
T_W	+50	19.30	15.25	13.02	1.1254
	+25	19.30	15.24	13.02	1.1254
	-25	19.30	15.24	13.02	1.1254
	-50	19.30	15.24	13.02	1.1254
T_{12}	+50	19.35	15.24	13.02	1.1255
	+25	19.34	15.24	13.02	1.1255
	-25	19.34	15.24	13.02	1.1248
	-50	19.34	15.24	13.02	1.1246

5 Conclusions

In this paper, the performance of the FOPID controllers of dissimilar characteristics tuned by *hy*GWO-PS algorithm for TAIHTPS has been studied with the parametric variation over the range from -50% to +50%. The parametric variation has been applied in two ways: first is the variation in the operating load condition over the range of [-50%, +50%] by keeping system parameters constant and second is the variation in the system parameters over the range of [-50%, +50%] by keeping the operating load conditions constant. This study is known as the sensitivity analysis of the of the *hy*GWO-PS tuned FOPID controllers used in the aforesaid interconnected power system. This is also called as the robustness analysis of the same. In whole analysis, the objective function is ITAE. The simulation results of sensitivity analysis show that very less or the negligible change is observed in the dynamic responses of the TAIHTPS with both ways of parametric variations over the range of [-50%, +50%] which shows that the *hy*GWO-PS tuned FOPID controller is more robust for the same means once the parameters of the controllers are set, there is no need to reset again for the broad range [-50%, +505] of parametric variations. Finally, it is concluded that the *hy*GWO-PS algorithm provides the better robustness for FOPID controllers in AGC of the aforesaid power system.

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