Path Finder Optimization Algorithm Tuned 3DOFPID Controller for Frequency Stabilization in Wind Integrated Realistic Power System with HVDC line

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Abstract- In this paper, a novel controller is suggested for the stabilization of the frequency of wind integrated realistic power system (WIRPS) during load uncertainties. 3-degree-of-freedom PID (3DOFPID) based on the pathfinder optimization algorithm (PFOA) is proposed in this paper. Initially, the performance of PFOA-tuned 3DOFPID is tested on a widely implemented model of dual area hydro-thermal power system (DAHTPS) for 10% step load perturbation in area-1. Later, the suggested controller performance is analyzed on WIRPS for 10%SLP on area-1. Investigation of WIRPS is carried out by considering and omitting the non-linearity constraint of communication time delays (CTDs). The efficacy of the presented controller efficacy is showcased with the other control techniques. Moreover, the impact of CTDs on WIRPS is demonstrated and a further high voltage DC (HVDC) line is laid with the WIRPS for improvement in the performance. The robustness of the implemented strategy is established finally with the robustness test.

Keywords 3DOFPID controller, Path finder optimization algorithm, 10%SLP, CTDs, HVDC line.

1. Introduction

The continuous fluctuations in load demand from the consumer end greatly affect the frequency of the interconnected power system. It is important to maintain the load fluctuations within the limits to ensure the delivery of quality power. The frequency of IPS is one of the key parameters that influence the quality of power and hence becomes the crucial parameter. On the other hand, the stability of IPS also requires the matching of real power demand generation along with the accompanying transmission losses. The continuous fluctuation in load demand disturbs the real power balance and thereby the variations in system frequency. A large deviation in IPS frequency may lead to system collapse and hence an

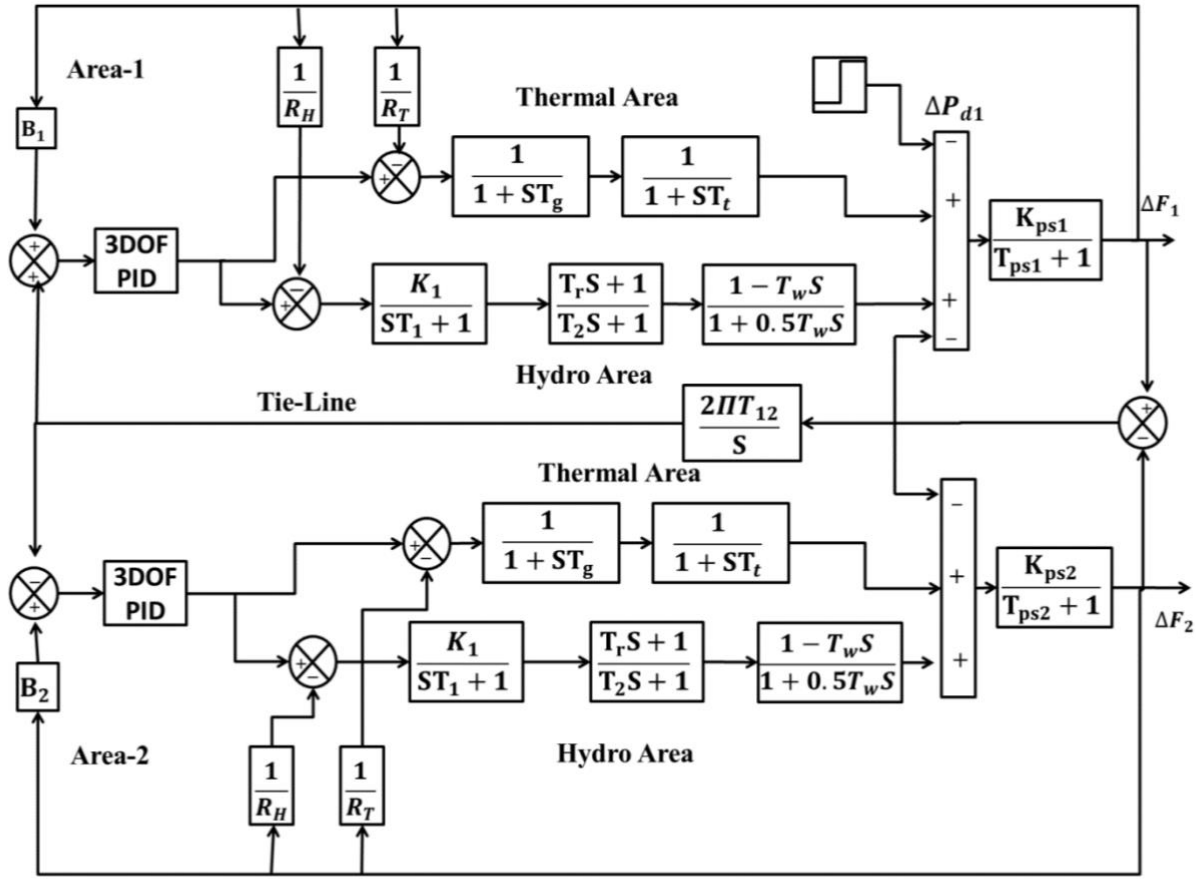


Fig. 1. Transfer function of DAHTPS model.

an effective controller such as a load frequency controller (LFC) is necessitated [1].

The most commonly implemented regulators are PI/PID in the industrial sector as well as in the LFC study. The simplicity in design and efficacy in the operation of PID [2] and the modified versions of PID like PID plus double derivative (PIDD) and adaptive PID are employed extensively. However, the efficacy of these controllers needs optimization techniques to find the parameters optimally. Optimization approaches like selfish-herd optimization (SHO) [3], sine-cosine technique (SCT) [4], falcon optimization method (FOM) [5], mine blast algorithm (MBA), social spider optimizer (SSO) [6] technique, grey wolf optimization (GWO) [7], krill herd algorithm (KHA), multiverse optimization (MVO) [8], firefly algorithm (FA) [9], water cycle algorithm (WCA) [10], hunger game search (HGS) approach, slap swarm algorithm (SSA) [11], Harris hawks algorithm (HHA), harmony search algorithm (HSA) [12], bacteria foraging optimizer (BFO), grasshopper optimization (GHO) [13], cuckoo search technique (CST) [14], quasi-opposition GWO, differential evolution (DE) [15], modified group search (MGS), honey bee algorithm (HBA), marine predator algorithm (MPA) [16] etc. are utilized.

Further, fractional order (FO) and fuzzy (F) FPI, and FPID too are implemented extensively. The complexity in designing FLC and assumptions in the selection of fuzzy rules, and its implementation in realistic practice is not convincing. Moreover, the FO involves too many parameters and is to be found optimally using soft computing approaches to operate more effectively. Algorithms like improved GWO (IGWO) [17], volleyball premier league (VBPL) [18], butterfly optimization approach (BOA) [19], imperialist competitive approach (ICA) [20], constrained population extremal (CPE) [21], artificial sheep algorithm (ASA), wind-driven optimizer (WDO) [22], stochastic fractal search (SFS) [23],hybrid-genetic fuzzy (HGF), adaptive SOS (ASOS) [24], lightning search algorithm (LSA), ant lion technique (ALT) [25], etc. are implemented. The tuning of too many knobs for shifting the IPS operating point to ensure the real power mismatch (RPM) reduction is not convenient.

DOF controllers from the past few years are gaining momentum in various engineering fields. DOF controllers like 2DOFPID, 3DOFPID are available in literature and optimizations like teaching learning based optimization (TLBO) [26] approach, gravitational search technique (GST) [27] approach (JOA), WCA [28], seagull optimization technique (SOT) [29], DE [30], quasi-oppositional JAYA [31], Equilibrium optimization technique (EOT) [32] are utilized. The evolution of nature-inspired meta-heuristic optimization methods day by day directly finds their application as a solution to engineering optimization problems. A literature survey disclosed that no algorithm is suitable for all optimization problems. Thus, the new optimization techniques will always have a scope in the study of IPS LFC for controller optimization. Thus, PFOA is implemented for optimal tuning in this work on the 3DOFPID controller.

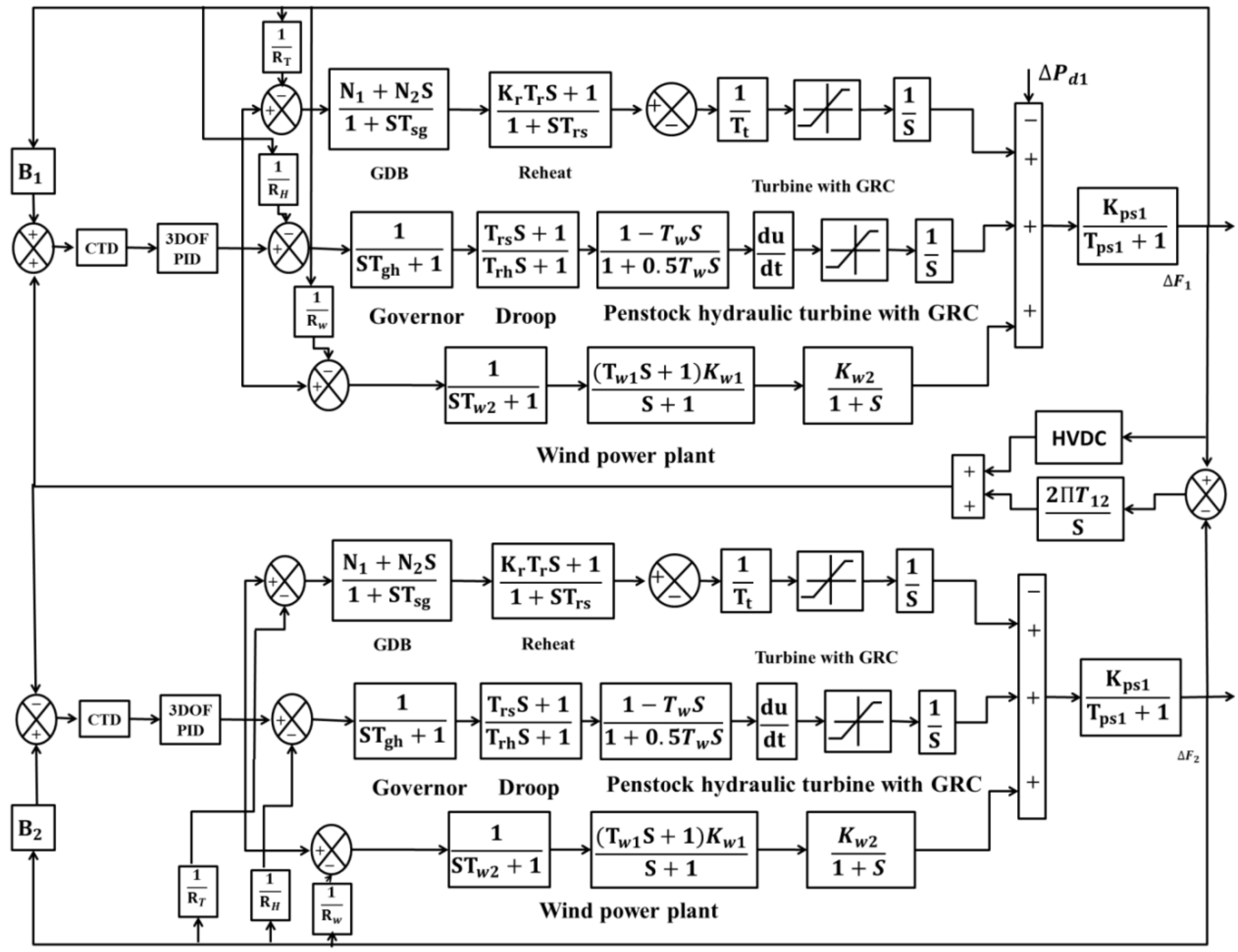


Fig. 2. Transfer function of WIRPS model.

The contributions of this paper are

a) 3DOFPID using PFOA is implemented to LFC of IPS as a secondary controller.
b) The design of the PFOA-based frequency regulator is a maiden attempt in the domain of LFC.
c) The efficacy of PFOA-based 3DOFPID is exhibited with other available control techniques in the literature by testing it on DAHTPS.
d) Performance of PFOA optimized 3DOFPID is analyzed on WIRPS without and considering CTDs.
e) Demonstrated the predominance of CTDs on WIRPS performance.
f) The supremacy of 3DOFPID is showcased in performance comparison with PID and 2DOFPID.
g) WIRPS is laid with an HVDC line and attained performance improvement.
h) Suggested control technique robustness is validated by laying the WIRPS with the uncertainties in loading and system parameters.

2. Investigative Power System

Two different IPS models are taken in this work to test the performance efficacy of the suggested control. At first, the investigation is performed on DAHTPS which is widely accepted by the researchers in literature. DAHTPS has two areas of unique generation capacity with hydro-thermal units and the analysis is done for 10%SLP. Later, the analysis is stretched on to a WIRPS comprised of two areas of unique capacity in real power generation. Each area has hydro-wind-thermal units of power generation and carried out the analysis by impressing area-1 with 10%SLP. Both the DAHTPS and WIRPS are built in the SIMULINK platform and the parameters are chosen from [33-34]. The transfer function models of DAHTPS and WIRPS are depicted in Fig.1 and Fig.2 respectively.

The investigation of the WIRPS model is further extended to the implementation of the HVDC tie-line as an additional line to facilitate the power exchange. HVDC line can carry bulk power and thereby the oscillations might be damped out quickly during large perturbations. The modelling of HVDC [35-37] employed is given in Equation (1).

$$G_{HVDC} = \frac{K_{HVDC}}{1 + sT_{HVDC}} \tag{1}$$

3. Communication Time Delays

In realistic widespread IPS, multiple remote terminal units (RTUs) have been employed at distant places. The measured data by the RTUs are transferred to the control centre and based on that data the error signal will be generated.

The controller in the plant location receives the error signal and thereby the operating point of IPS will be varied to minimize the gap between real power demand generations. The reception and transmission of data between various devices are possible through communication peripherals. The data exchange through the communication peripherals may not do instantly due to the inheritance of time delays. Thus, CTDs are to be considered to assess the stability of IPS. Most of the researchers in the literature omitted the CTDs consideration and in this paper, it is modelled mathematically as given in Equation (2) [38-40].

$$e^{-s\tau_d} = \frac{1-\frac{\tau_d}{2}s}{1+\frac{\tau_d}{2}s} \tag{2}$$

4. Controller and Objective Function

The implementation of higher-order DOF regulators in the domain of LFC is gaining momentum and is highly efficacious than classical, FLC and FO-type regulators especially for non-linearity models. The order of DOF dictates the individual control loops that the controller might acquire for its operation. Thus, the 3DOFPID has three closed loops that can work independently and facilitates the features of disturbance rejection, fluctuation dampening and quick steady state condition. The detailed mathematical modelling of 3DOFPID is provided in [41]. The structure of 3DOFPID as a damping regulator is rendered in Fig.3.

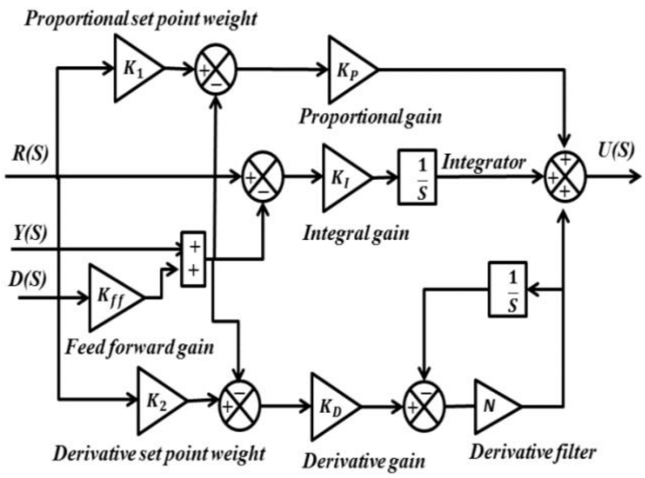


Fig. 3. 3DOFPID regulator

K_P, K_I, K_D, K_{ff}, K_1 and K_2 are the parameters of 3DOFPID that are to be found optimally using nature-inspired meta-heuristic optimization-based search techniques. In this paper, PFOA is utilized and the optimization of the parameters is performed subject to the ISE [42-45] objective function given in Equation (3).

$$J_{ISE} = \int_0^{T_{Sim}} \left(\Delta f_1^2 + \Delta P_{tie12}^2 + \Delta f_2^2\right)dt \tag{3}$$

5. Path Finder Optimization Algorithm

Nowadays the algorithms that are evolved from the hunting, exploiting and searching abilities of the animal swarm are grabbing the attention of researchers over the world to achieve a solution to optimization problems. An individual in the swarm leads the group and the other acts according to it. Based on the abilities in reaching the target, the leader may vary. In an animal swarm, the target is the water, pasture and feeding area. In PFOA, the position of each animal is initialized in d-dimensional space. The leader has coined the name path finder in this PFOA. Equation (4) represents the pathfinder looking for the prey or feeding area.

$$K(j+\Delta j) = K^0(j).\,n + f_i + f_p + \varepsilon \tag{4}$$

Where 'K' indicates position vector, time is indicated with 'j', 'f_i' indicates pair-wise interaction, and pathfinder position is indicated with 'f_p' and 'ε' is vibration vector. The pathfinder position is updated on the other hand as given in Equation (5).

$$K_p(j+\Delta j) = K_p(j) + \Delta K + A \tag{5}$$

'A' indicates the fluctuation vector, and 'ΔK' represents the distance moved by the pathfinder. However, making use of the above equations (4-5) to implement the PFOA is not feasible. Thus, the equations are modified by the researchers in [46] and are modelled as

$$K_i(t+1) = K_i(t) + R_1.\left(K_j(t) - K_i(t)\right) + R_2.\left(K_p(t) - K_i(t)\right) + \varepsilon \tag{6}$$

$$K_p(t+1) = K_p(t) + 2r_3.\left(K_p(t) - K_p(t-1)\right) + A \tag{7}$$

$$\varepsilon = \left(1 - \frac{t}{t_{max}}\right).u_1.D_{ij} \tag{8}$$

$$D_{ij} = \left\|K_i - K_j\right\| \tag{9}$$

$$A = u_2.e^{\frac{-2t}{t_{max}}} \tag{10}$$

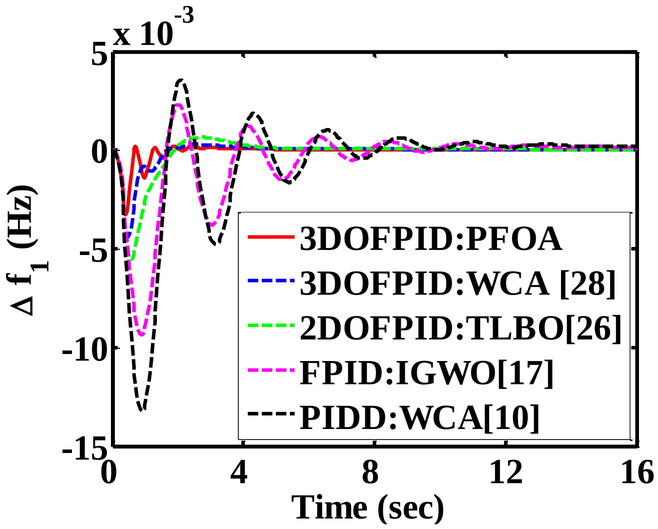
Where 't' indicates present iteration, R_1 and R_2 are random vectors, 'K_i' is the i[th] member position vector. In this algorithm, the path-finder tries to locate the best food location and in this work, it is treated as the global optima. The other animals in the swarm try to follow the path-finder. After initialization of the parameters, the fitness of each individual is calculated and the movement of animals is according to the equation (7). In each iteration, the fluctuation vector is generated using equation (10). The two important parameters in PFOA are αand βcoefficients. The random vectors R1 and R2 are equal to αr1 and βr2 respectively. 'α' indicates the interactive coefficient that measures the togetherness of the animal with the neighbouring animal and 'β' attraction coefficient that evaluates the distance from the animal to the path-finder. In PFOA the path-finder position is treated as the current optima and the position of the animals is upgraded using the coefficients. If the new position is better than the old then the positions are updated. The new fitness values are calculated and if the fitness of any member is better than that of the path-finder then that member is treated as the new path-finder. Later, the vectors of A and ε are updated and finally, the PFOA iterative process terminates when it met the stopping criteria.

However, the PFOA is used to optimize the 3DOFPID by finding the optimal parametric values concerning the constraint of ISE in this work. Adoption of PFOA in LFC study for regulator optimization is a maiden attempt and in this work, the code for PFOA is written in the format of (.m file) for maximum iterations and populations of 100.

6. Simulation Results

6.1. Case-1: Performance of DAHTPS Under Various Control Approaches

At first, a rigorously implemented IPS model of DAHTPS is chosen for analysis to prove the effectiveness of the suggested approach. The area-1 of DAHTPS is repressed with 10%SLP and the system dynamic behaviour under various controllers like PIDD using WCA [10], FPID using IGWO [17], 2DOFPID using TLBO [26], 3DOFPID using WCA [28] and 3DOFPID using PFOA is compared in Fig.4. The DAHTPS system behaviour under different control techniques are assessed numerically in the aspect of settling time given in Table 1. Noticing the Fig.4 responses, it is confirmed that the proposed PFOA tuned 3DOFPID outperforms the other control techniques that are reported in literature recently in terms of diminishing the peak-under-shoots (PUS) and peak-over-shoots (POS). Moreover, the responses very quickly attain a steady position with the presented controller. Further, the objective function is minimized effectively by the PFOA-based 3DOFPID and is enhanced by 35.88% with 3DOFPID using WCA, 46.31%with 2DOFPID using TLBO, 59.07%with FPID using IGWO, and 81.38%with PIDD using WCA. The optimal controller gains employed in this work for the DAHTPS are noted in Table 2.



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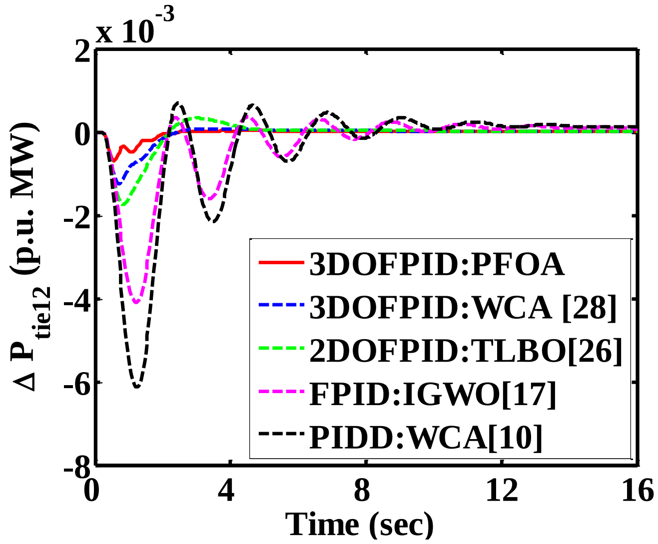

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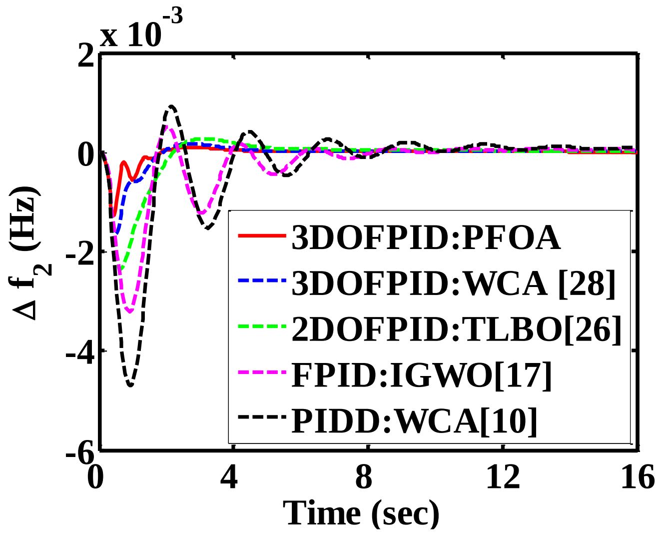

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Fig. 4. Case-1 responses on DAHTPS. a.Δf_1 b.ΔP_{tie12} c.Δf_2.

6.2. Case-2: Performance of WIRPS Without CTDs Under PFOA-based Controllers

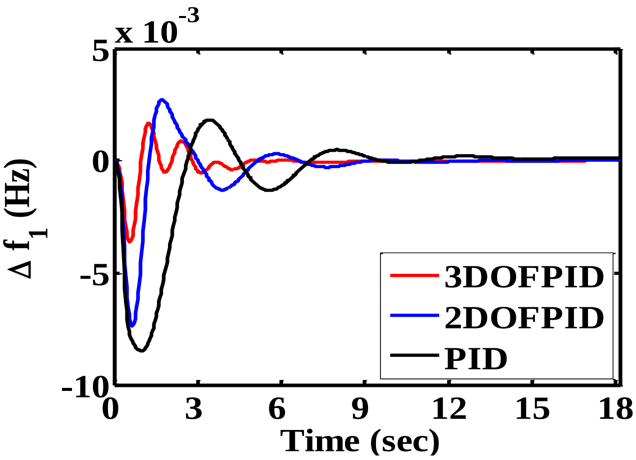
Later, the analysis is stretched out to another realistic IPS model of WIRPS. Regulators such as PID, 2DOFPID and 3DOFPID are enacted on WIRPS in both areas one after the other and are rendered optimally using PFOA. Carried out the investigation on WIRPS for 10%SLP on area-1 and the CTDs are not considered in this subsection. WIRPS dynamic behaviour for this case is compared in Fig.5 and interpreted numerically in terms of time conceded to reach the steady condition as provided in Table 3. it has been enlightening that the developed PFOA tuned 3DOFPID dominates the 2DOFPID and PID in mitigating the PUS, POS and the oscillations in tie-line flow are damped out effectively. Moreover, the 3DOFPID exhibits more efficacy in bringing down the ISE index value and is improvised by 69.72%with PID and 39.65%with 2DOFPID.

Table 1. DAHTPS responses settling time

Settling time (Sec)	PIDD: WCA	FPID: IGWO	2DOFPID: TLBO	3DOFPID: WCA	3DOFPID: PFOA
Δf_1	15.85	14.32	6.84	5.07	4.42
ΔP_{tie12}	15.88	14.56	8.12	5.87	4.62
Δf_2	14.81	13.88	7.90	5.16	4.35
ISE*10^{-3}	197.450	89.814	68.463	57.322	36.754

Table 2. Controller optimal gains for DAHTPS

Parameters		PIDD: WCA	FPID: IGWO	2DOFPID: TLBO	3DOFPID: WCA	3DOFPID: PFOA
Area-1	K_P	0.639	0.712	0.656	0.946	0.722
	K_I	0.395	0.242	0.187	0.724	0.518
	K_D	0.188	0.831	0.074	0.561	0.296
	K_{DD}	0.178	-	-	-	-
	K_1	-	-	0.122	0.174	0.172
	K_2	-	-	0.034	0.095	0.099
	K_{ff}	-	-	-	0.086	0.206
Area-2	K_P	0.607	0.728	0.496	0.829	0.634
	K_I	0.217	0.367	0.178	0.722	0.627
	K_D	0.114	0.578	0.219	0.694	0.307
	K_{DD}	0.199	-	-	-	-
	K_1	-	-	0.019	0.109	0.209
	K_2	-	-	0.027	0.034	0.212
	K_{ff}	-	-	-	0.025	0.199



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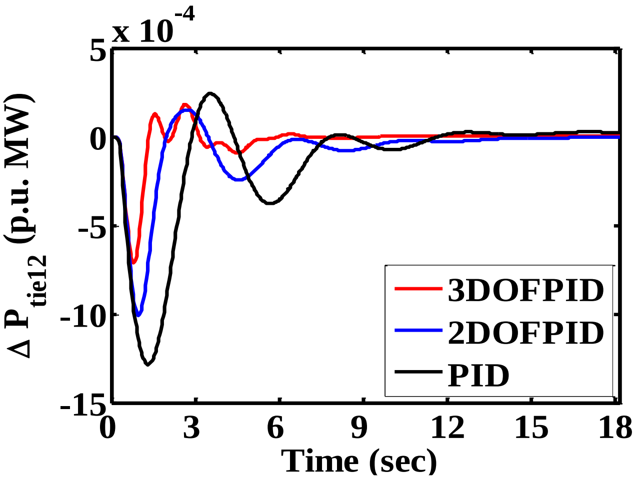

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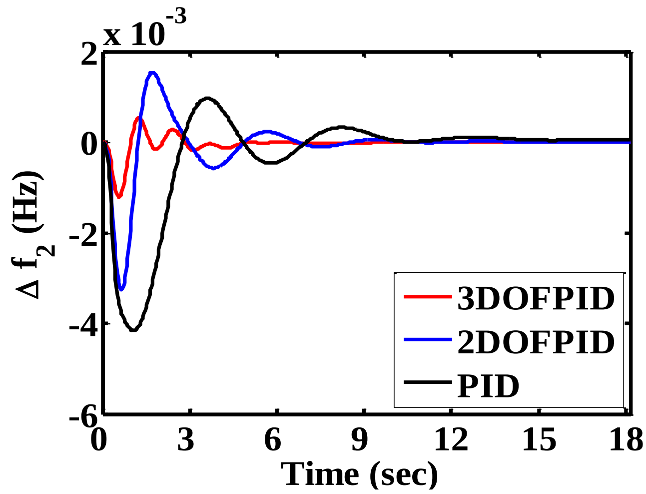

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Fig. 5. Case-2 responses on WIRPS. a.Δf_1 b.ΔP_{tie12} c.Δf_2.

The optimal parameters of PID, 2DOFPID and 3DOFPID for WIRPS without conceiving CTDs using PFOA are noted in Table 4.

6.3. Case-3: Performance of WIRPS With CTDs Under PFOA-based Controllers

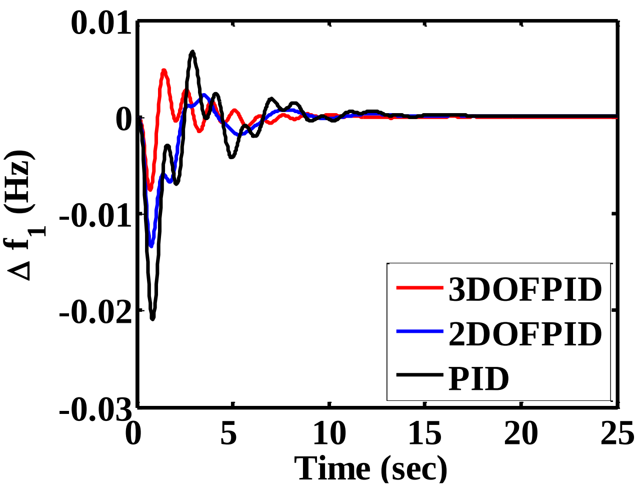
Further, the WIRPS is conceived with CTDs for analysis and the practical time delay parameter of 0.12seconds is deliberated in this paper. PFOA-based 3DOFPID; 2DOFPID and PID are kept in each area and observed the system dynamic behaviour for 10%SLP on area-1. Dynamic responses of WIRPS believing the CTD are shown in Fig.6 and the settling time is placed in Table 3.

Table 3. WIRPS responses settling time for case-2 and case-3.

Settling time (Sec)	Case-2			Case-3		
	PID	2DOFPID	3DOFPID	PID	2DOFPID	3DOFPID
Δf_1	14.11	9.55	6.746	17.89	13.85	11.84
ΔP_{tie12}	16.30	14.39	9.28	21.89	16.78	13.56
Δf_2	14.59	9.84	8.30	17.27	13.95	11.69
ISE*10^{-3}	81.183	40.736	24.581	448.197	217.221	73.548

Table 4. Controller optimal gains in WIRPS

Parameters		Case-2			Case-3		
		PID	2DOFPID	3DOFPID	PID	2DOFPID	3DOFPID
Area-1	K_P	0.599	0.531	0.898	0.858	0.540	0.511
	K_I	0.069	0.493	0.415	0.621	0.146	0.078
	K_D	0.163	0.514	0.219	0.435	0.154	0.142
	K_1	-	0.067	0.097	-	0.082	0.176
	K_2	-	0.107	0.189	-	0.116	0.134
	K_{ff}	-	-	0.132	-	-	0.311
Area-2	K_P	0.683	0.670	0.866	0.762	0.489	0.614
	K_I	0.161	0.562	0.468	0.528	0.261	0.216
	K_D	0.210	0.651	0.116	0.726	0.167	0.173
	K_1	-	0.045	0.058	-	0.048	0.096
	K_2	-	0.069	0.078	-	0.009	0.128
	K_{ff}	-	-	0.092	-	-	0.266



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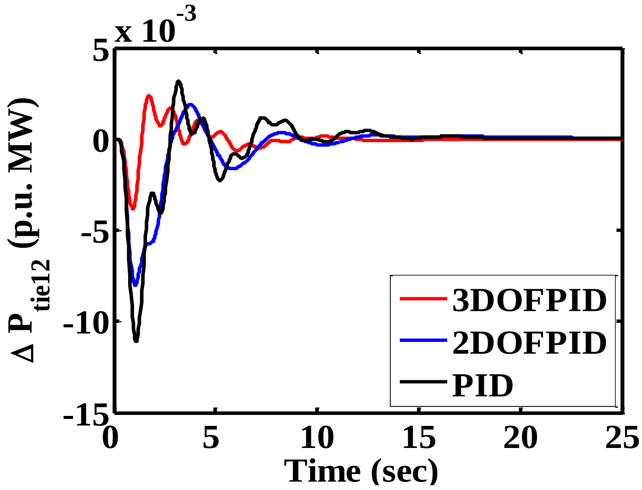

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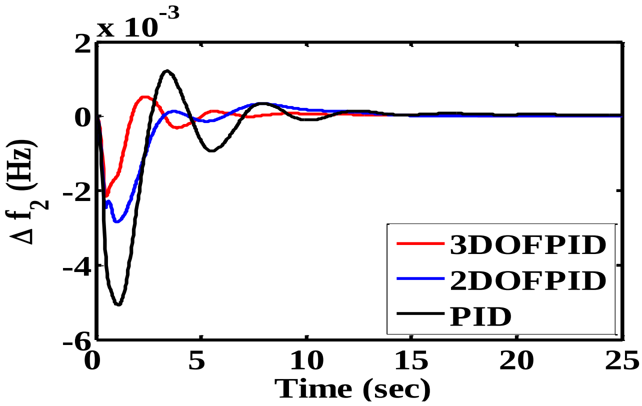

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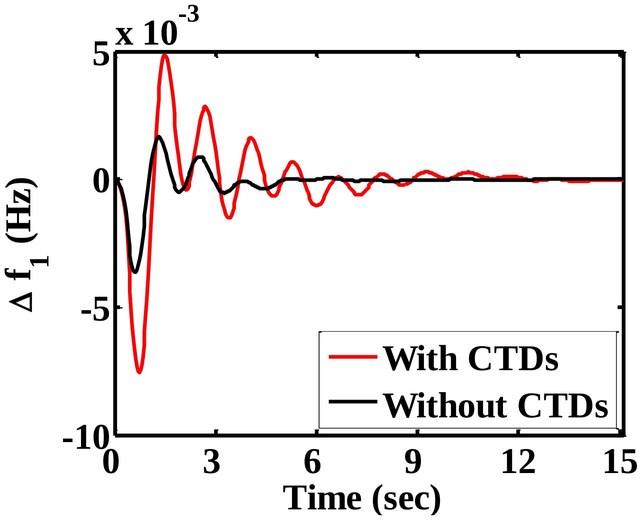
Fig. 6. Case-3 responses on WIRPS. a.Δf_1 b.ΔP_{tie12} c.Δf_2.

It is remarked from Fig.6 that the 3DOFPID optimized with PFOA is superior to PID and 2DOFPID in reducing the peak deviations. From Table 3 it is clear that the responses of WIRPS with CTDs under load disturbances are dragged down to stable conditions in less time by the 3DOFPID controller. The significant improvement in objective function minimization is noticed with 3DOFPID and is improved by 83.59%with PID and 66.14%with 2DOFPID. The optimal gains of 3DOFPID, 2DOFPID and PID that are located with PFOA are noted in Table 4.

6.4. Case-4: Exhibiting the Impact of CTDs on WIRPS Performance

In this case, the WIRPS dynamical behaviours are compared for the cases of considering and not believing the CTDs with the system. The responses only under the regulation of PFOA tuned 3DOFPID are likened in Fig.7 to elevate the predominance of CTDs on the behaviour. The 3DOFPID is demonstrated as the best from the above analysis, so the dynamical behaviour of WIRPS under 3DOFPID is chosen to be compared to showcase the impact of CTDs on the LFC performance. Responses compared in Fig.7 are the dynamic behaviour of WIPS for 10%SLP for believing and not believing the CTDs. From Fig.7 it has been depicted that the fluctuations in system dynamic behaviour for the case of taking CTDs have slightly more deviated when compared to that of not taking the CTDs with WIRPS. Further, the responses concede more time to settle down the deviations and also to reach a steady position. Thus, it is concluded that the dynamic behaviour of WIRPS with CTDs is more disturbed. This is because of the control signal generation delay to shift the IPS operating point and thereby the minimization of RPM might be done with some delay. The RPM has a direct analogy to the system control area frequency and hence in the case of CTDs the responses are more fluctuated.



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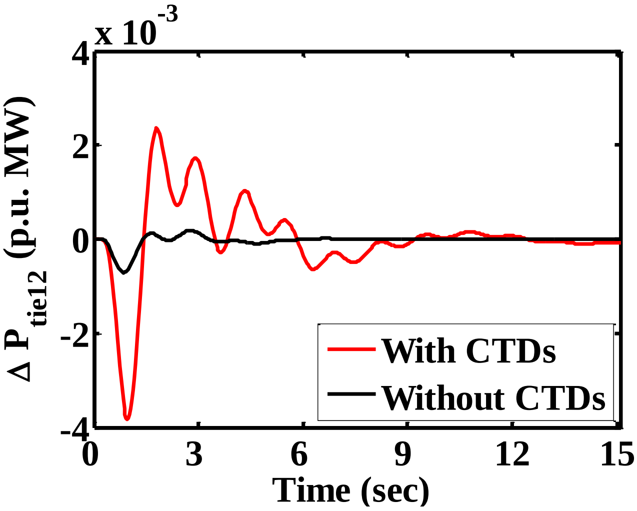

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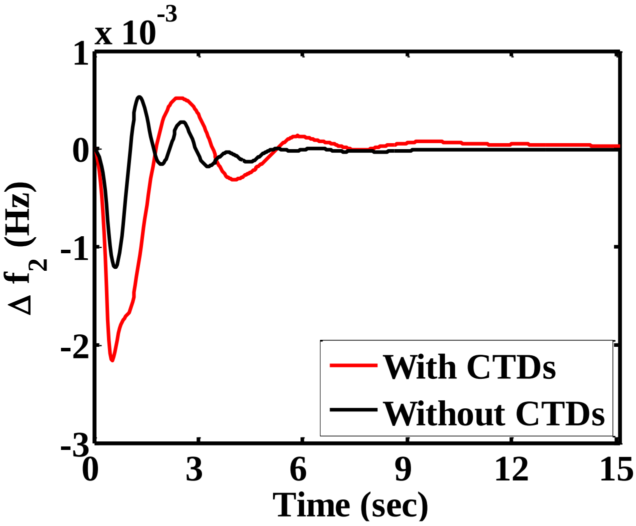

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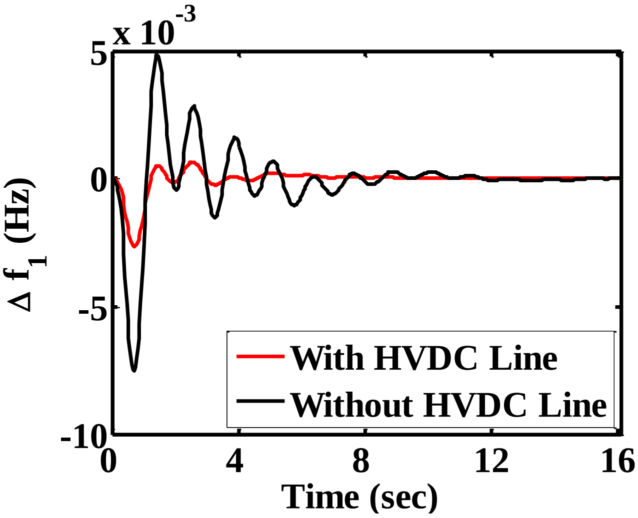
Fig. 7. Case-4 responses on WIRPS. a.Δf_1 b.ΔP_{tie12} c.Δf_2.



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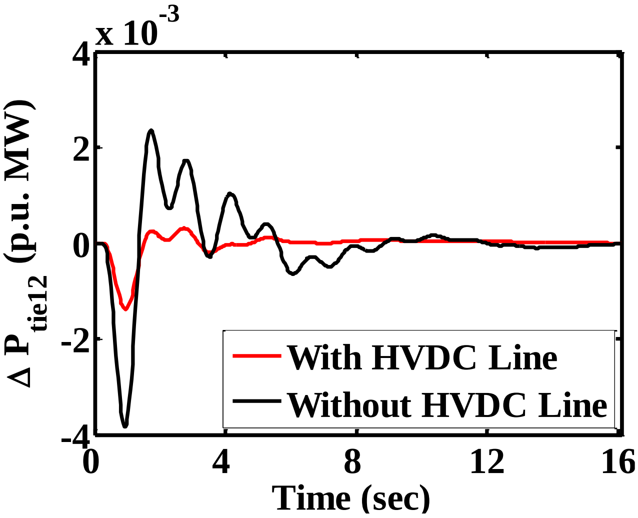

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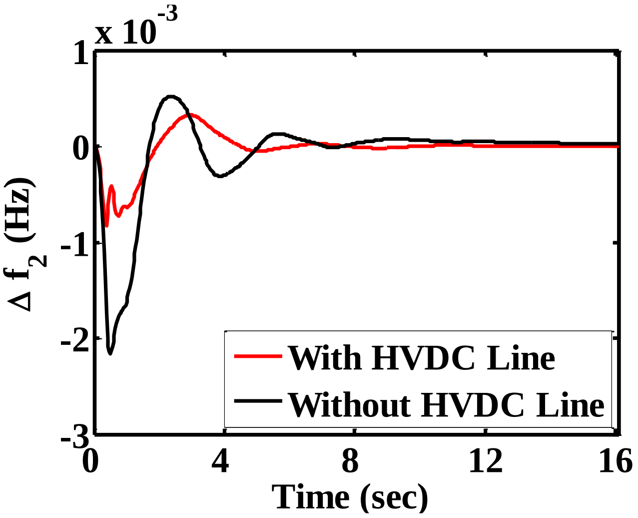

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Fig. 8. Case-5 responses on WIRPS. a.Δf_1 b.ΔP_{tie12} c.Δf_2.

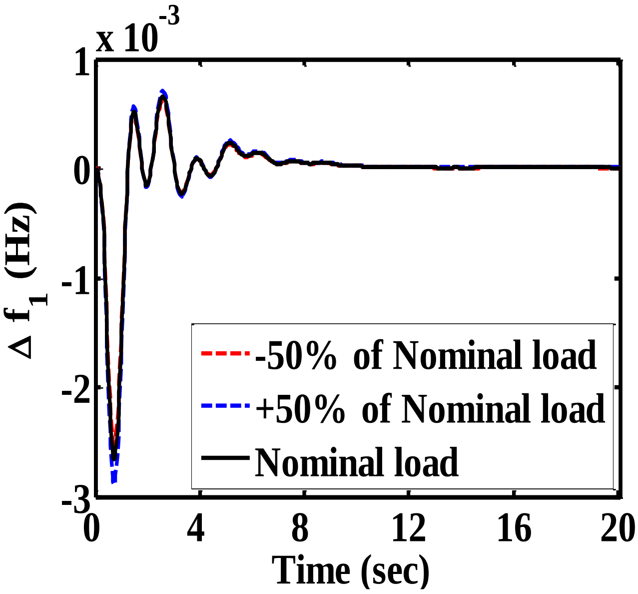
In realistic practice, the IPS is vast and employs many devices and the data exchange is done through the communication peripherals which inherit the time delay property. The exchange of data between the devices located at various points is not done instantly. Thus, researchers should consider the delay in data acquisition that is taken out for generating the control signal. Hence this paper recommends considering the CTDs while developing the soft computing techniques-based regulator for LFC study to ensure system stability.

6.5. Case-5: Performance of WIRPS with CTDs Under PFOA-based 3DOFPID and HVDC Line.

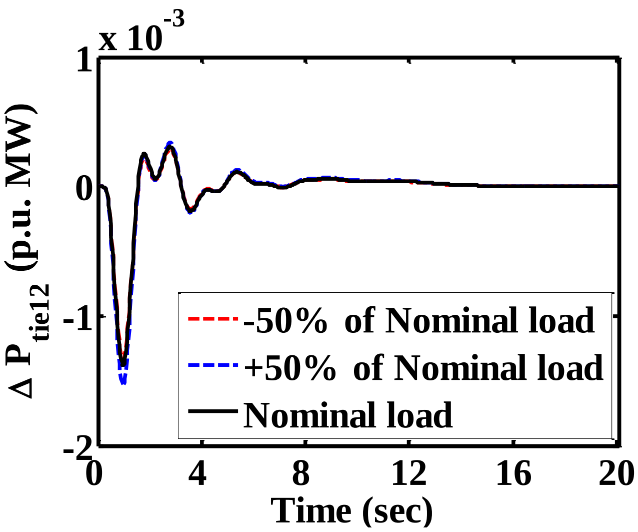
Furthermore, the WIRPS considering CTDs is laid with an HVDC line to obtain better frequency regulation. The WIRPS with HVDC as an additional tie-line is governed and monitored under PFOA-based 3DOFPID for 10%SLP on area-1. WIRPS dynamical variations are likened in Fig.8 and are concluded that the variations are further mitigated with the implementation of an HVDC line addition. Moreover, the responses concede less time to reach a stable position and the PUS is very much enhanced. Also, the time of 8.71, 9.26 and 8.29 seconds conceded for Fig.8 (a, b, c) respectively this is substantially low to that of the AC line alone. Thus, the adoption of an additional HVDC tie-line is the powerful territorial control approach to further attain system stability, especially under load uncertainty conditions.

6.6. Case-6: Robustness test

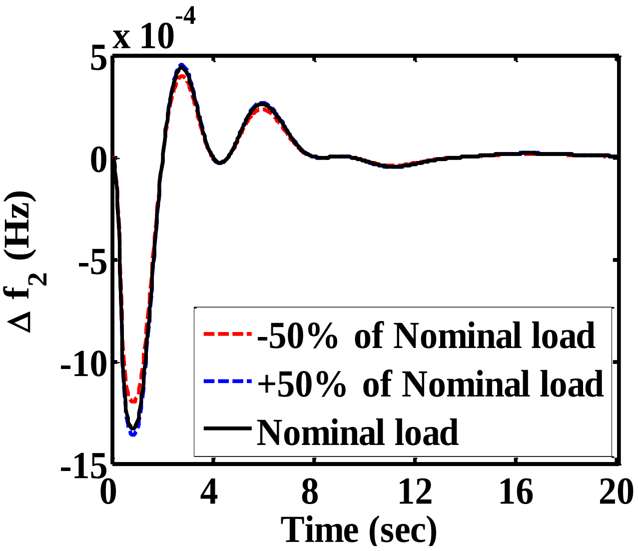
In the study of LFC, it is mandatory to check the robustness of the suggested technique. Hence, the WIRPS having CTDs under PFOA-based 3DOFPID and the adoption of an additional HVDC line is subjected to load uncertainty and parameter uncertainty. Initially, the system is targeted with uncertainty in the load of ±50% from nominal loading and for a parametric uncertainty of ±50% in the tie-line coefficient. The system responses for uncertainty in loading and tie-line coefficient are depicted in Fig.9 and Fig.10 Noticing from Fig.9 and Fig.10 that the responses have hardly deviated even though the system is prone to the uncertainty in loading and tie-line coefficient.



(a)

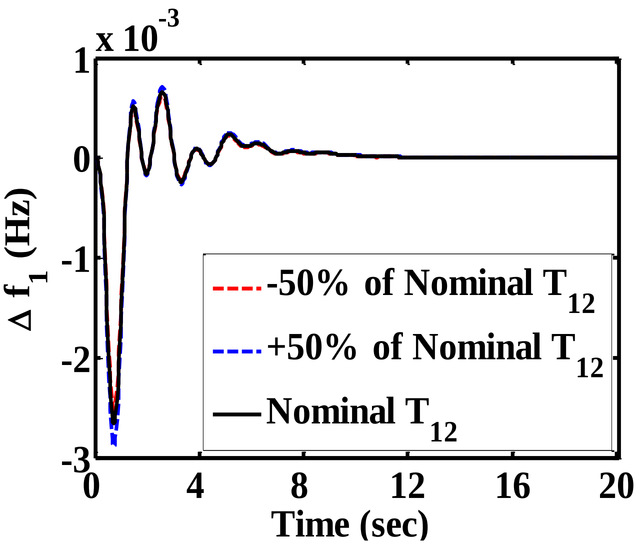


(b)

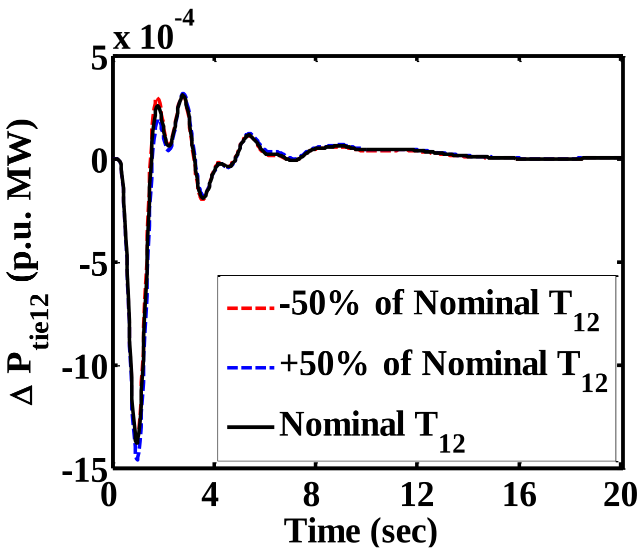


(c)

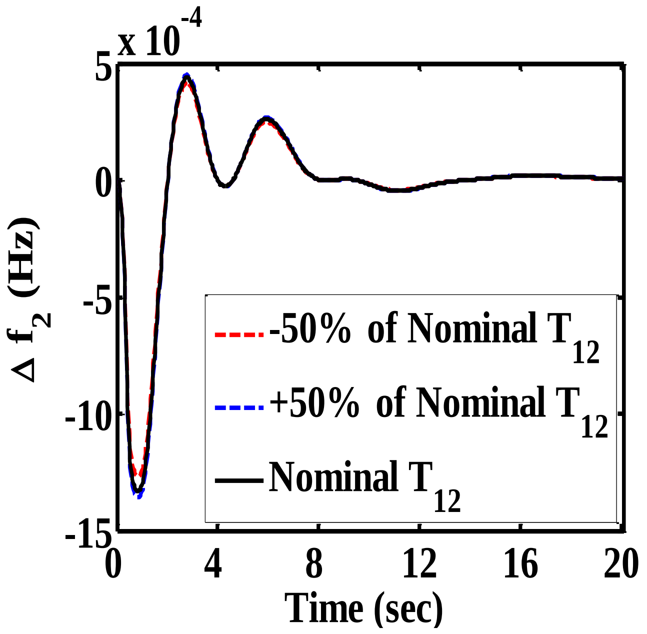
Fig. 9. Case-6 responses on WIRPS for load variation. a.Δf_1 b.ΔP_{tie12} c.Δf_2.



(a)



(b)



(c)

Fig. 10. Case-6 responses on WIRPS for uncertainty in tie-line coefficient. a.Δf_1 b.ΔP_{tie12} c.Δf_2.

It is resolved that the presented mechanism of PFOA tuned 3DOFPID and implementation of additional HVDC line to the WIRPS is robust. Thus, the 3DOFPID parametric is not necessarily to be altered even for further load-altering.

7. Conclusion

3DOFPID optimized with PFOA is established as an effective controller for the LFC of realistic IPS. Implementation of PFOA-based regulator to LFC is a maiden attempt. The efficacy of the presented control approach is demonstrated with different regulatory approaches like PIDD using WCA, FPID using IGWO, 2DOFPID using TLBO and 3DOFPID using WCA being implemented on a widely accepted test system model of DAHTPS. Further, the PFOA tuned 3DOFPID is applied on WIRPS for 10%SLP and the performance supremacy of 3DOFPID is exhibited with the performances of PID and 2DOFPID. Investigation on WIRPS is performed for the cases not believing and believing the CTDs to reveal their impingement on the system behaviour. The dynamic responses of WIRPS exhibit the predominance of CTDs on system performance. The fluctuations in control area frequency and tie-line are more for the case of considering the CTDs. Moreover, this work recommends considering the IPS models with CTDs while designing the frequency regulator. Further, the HVDC line is laid with WIRPS and substantial melioration in dynamical behaviour is noticed. Finally, the WIRPS under PFOA-based 3DOFPID is prone to uncertainty in loading and parameters. The dynamical behaviour of the system during uncertainty is not much affected and hence the robustness is validated. The dynamical nature of WIRPS with only wind penetration in this paper is studied and there is a scope for analysing the system with geothermal integration. Further, the analysis might be extended to the restructured environment in future.

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