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Regular paper

LUS-TLBO Optimized Load Frequency Control for EV-Thermal-Hydro System Using Cascaded 3DOFPID-FOPID-FOPD-TID Controller

This study unveils the application of cascaded- three degree of freedom proportional integral derivative - fractional order proportional integral derivative- fractional order proportional derivative- tilted integral derivative (CC-3DOFPID-FOPID-FOPD-TID) controller optimized by local unimodal sampling –teaching learning based optimization (Lus-TLBO) algorithm for frequency stability. Conventional controller under reformed operating situations, are not giving reasonable performances as compared to cascaded controller in terms of robustness towards system non-linearities. Hence, a novel optimal 3DOFPID-FOPID-FOPD-TID controller is exploited for 4-area hydro thermal power systems considering system non linearities. Further batteries of electric vehicles (EVs) are conformed here in the control areas to speedily incarcerated frequency oscillations following load demands to improve the stability of the system. Frequent simulations are directed to substantiate the robustness and superiority of EVs and the recommended control strategy over prevailing approaches. A hybrid Lus-TLBO algorithm is introduced here to optimize the controller parameters. The supremacy of dynamic performances of Lus-TLBO optimized controller is accomplished with teaching learning based optimization (TLBO) based for EV with system and without system through extensive simulations. Moreover the preeminence of cascade 3DOFPID-FOPID-FOPD-TID controller is executed in comparison with 3DOFPID-FOPID-TID, 3DOFPID-FOPID and 3DOFPID-TID controllers. Finally the robustness of this cascade is performed under random load fluctuation.

Keywords: Electric vehicle, area control error, fractional order controller, cost function, nonlinear constraints

1. *Introduction*

It is overbearing to sustain the power steadiness between the generation and demand for an immense and complex power system. Hence the foremost apprehension to deliver eminence power to the customer in contradiction of load variations, dispersion of renewable energy resources and large number of interconnected power system network. With the advancement of technology Now days, EV is the widely emerging research area due to lower noise pollution and greenhouse emissions. After the permeation of PHEV in the grid, rigorous work has been enumerated concerning LFC [1–4]. In [1, 2], exploitation of electric vehicle for deregulated power system using fractional order controller optimized by flower pollination algorithm (FPA) has discussed. In [3], the effect of electric vehicle for an interconnected thermal and hydro thermal power system using cascade fuzzy-fractional order integral derivative with filter (CF-FOIDF) controller has expounded. Robust frequency control for three area thermal systems incorporated with EV using 2DOF-PID controller has discussed in [4]. Primary control action by governor mechanism is not adequate to abolish the steady state error sharply which demands a secondary controller. Easiness execution of PID controller is frequently used in power system industries for last few periods. Different conventional controllers such as PID [5], degrees of freedom PID controller [6, 7] and fuzzy PID controller [8] are employed in different structures of LFC issues. However, these conventional controllers cannot give satisfactory performances

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when considering large interconnected power system with non-linearities. Hence fractional order controllers such as FOPID [9], tilted integral derivative (TID) controller [10] are widely used because of most robustness toward parameter variations and non linearities. Now days, various cascade controllers are employed across process industries [11-13]. Cascade of 3DOF-FOPIDN controller for two area LFC system has particularized in paper [11]. In [12], hydro thermal LFC system using cascade of Fuzzy-FOPI-FOPD controller has explained. The basis of conniving of the fuzzy controller entails dense involvement for power system stability by considering the input and output scaling factors to articulate the fuzzy rules. But fuzzy controllers needs more processing time because of designing membership functions and fuzzy rules. In [13], cascade of 3DOF-FOPIDN-FOPDN controller designed for two area multi source AGC system optimized by wild goat algorithm (WGA) has exposed. However, the application of TID controller for improvement of dynamic stability has not discussed in that paper which needs further study. Hence, an endeavour is taken to design cascade of three degree of freedom PID controller with fractional order controllers. To progress the enactment of power system, computational technique and proper objective function are essential for estmation of gain and controller parameters. The existing AC transmission system has the disadvantages such as frequency tripping in case of large power oscillations, increase in the fault current and disturbance transmission from one control area to other that deteriorates the entire system performance [14]. The HVDC transmission system controls the power flow and also reduces the problems associated with AC transmission through converter control [15]. The DC flow is highly adjustable in HVDC transmission. Various optimization techniques such as differential evolution [16], grey wolf optimization (GWO) [17], symbiotic organism search algorithm [18], apdaptive symbiotic search optimization (ASOS) [19], cuckoo search [20], teaching learning based optimization (TLBO) algorithm [21-22], etc. conferred for tuning of controllers with suitable index. In this paper an application of local unimodal sampling- teaching learning based optimization (LUS-TLBO) [23] is applied to design the 3DOFPID-FOPID-FOPD-TID controller governed by an ITAE function. The key contributions of this paper

- A four area LFC system encompassing of thermal and EV model designed in MATLAB/SIMULINK environment.
- A novel 3DOFPID-FOPID-FOPD-TID cascade controller is designed. The supremacy of this controller is elucidated in compared to 3DOFPID-FOPID-TID, 3DOFPID-FOPID and 3DOFPID-TID controller.
- Application of local unimodal sampling- teaching learning based optimization (LUS-TLBO) is smeared to establish the controllers parameters.
- Performing robustness analysis of proposed controller using a random load perturbation

2. Notation

System parameters	**Nominal values**
Subscript referred to area i	1 to 4
Damping coefficient D_i	0.0083 pu
Governor time constant T_{gi}	0.08 s
Turbine time constant T_{ti}	0.3 s
Speed regulation constant R_i	2.4 pu
Reheat turbine gain K_{ri} and T_{ri}	0.5 , 0.2 s
Generator gain K_{pi}	120 Hz/MW

Generator time constant T_{pi}	20 s
Inertia constant H_i	5 s
Tie line power coefficient T_{ij}	0.086 MW/rad
Starting hydro time T_w	1 s

3. *Problem Formulation*

3.1 System Modeling

The suggested system comprising of an organized four area thermal power generation having the capacities of 1: 2: 4: 5 and each area equipped with the nonlinearities such as GRC, reheat turbine. To achieve zero steady state error secondary controller is applied in each area with EV-thermal system. Input to the controller is area control error which can be expressed as (1). The transfer function of generator, governor and turbine for thermal system reffered as [24-25].

$$ACE_i = \sum_{j=1}^{N} \Delta P_{ij} + B_i \Delta f_i \qquad i = 1 \dots 4 \tag{1}$$

B_1, B_2 are the frequency bias factor of ith area and
Δf is the frequency for ith area.

Most of the EV's are integrated to the grid; it is quite possible to take part in LFC so as to suppress the load fluctuations rapidly. EVs have its own battery and it has faster response by connection with integrated grid through power electronic devices.

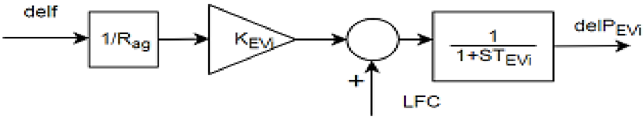

Fig. 1 Arrangement of EVs model

Discharged EVs are smeared in each area to diminish the unsettlement between generation and demand. Basic structure of EV model is shown in Fig. 1. The frequency range lies in between ±10 mHz. Ev's battery has fast response characteristics so as to stabilizing the load fluctuations effectively. In this model R_{ag} is the droop factoring same as to thermal unit and ΔP_{EVi} is the incremental change for ith generations. K_{EVi}, the gain of EV and T_{EVi} is the time constant of EV. The value of K_{EV} is elected conferring to SOC eminence of battery connected into the grid. The vehicle to grid real power added to the network is depends on area control error as (3) where P_g^{max} and P_g^{min} area the maximum and minimum value of vehicle to grid power. Maximum and minimum power output limits of $\Delta P_g^{max}$and ΔP_g^{min} as given follows [13]

$$\Delta P_g^{max} = +\left[\frac{1}{N_{EV}} \times (\Delta P_{EVi})\right] \tag{2}$$

$$\Delta P_g^{min} = -\left[\frac{1}{N_{EV}} \times (\Delta P_{EVi})\right] \tag{3}$$

Where N_{EV} signifies associated number of electric vehicles. Discharged EVs considered for area1, area2, area3 and area4 are 2000, 8400, 14000 and 20000 respectively.

$$\Delta P_{EVi} = \begin{cases} P_g^{max}, & |K_{EV}.ACE| > P_g^{max} \\ P_g^{min}, & |K_{EV}.ACE| < P_g^{min} \\ K_{EV}.ACE, & |K_{EV}.ACE| \le P_g^{max} \end{cases} \tag{4}$$

Evs charging and discharging capability is siupposed whin range of ±5 kW. Here, K_{EV}= 1 is considered for SOC range of 50–70%

3.2. *Gain Scheduling Control*

Three degrees of freedom PID controller has extra four adjustment factors with greater flexibility. K_{pi}, K_{Ii} and K_{Di} are the gain of single order degree of freedom from C(s). N_i is the filter constant for derivative gain. $R_C(s)$ consists of proportional set point weightings b_i and derivative set point weightings respectively. The feed forward controller $FF_C(s)$ has gain parameter g_i. Conventional controller cannot give satisfactory performance when system loading or system parameter changes. Also considering the nonlinearity such as GRC and GDB these inter controller cannot cope widely. Therefore fractional order concept is introduced for better adjustment of system dynamics. FOPID controller is similar to PID controller(K_p, K_i, K_d), with integral-differential orders (λ, µ)
The transfer function of the FOPID controller is expressed in equation (5)

$$G_c(s) = K_p + K_i/S^{\lambda} + K_d S^{\mu} \qquad (5)$$

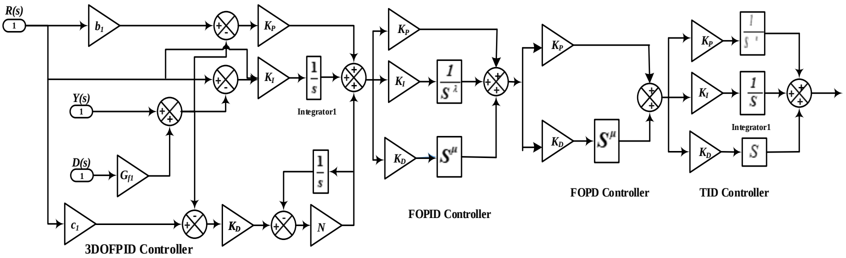

Fig. 2 Casacdestructure of 3DOFPID-FOPID-FOPD-TID controller

Then fractional order tilted integral derivative (TID) cascaded with the above two controllers. TID controller is similar to PID with extra tilt component of transfer function$S^{-(1/n)}$. Tis improved the feedback repose for better stability towards external/internal disturbances. The transfer function of TID controller is given in equation (6)

$$G_c(s) = K_p S^{-(1/n)} + K_i/S + K_d S \qquad (6).$$

Finally transfer function model of the 3DOFPID-FOPID-FOPD-TID controller is represented in Fig 2. This controller formationn has ultimately seven tuning factors for 3DOFPIDccontroller, five tuning parameters for FOPID controller, four tuning parameters of FOPD controller and four tuning factors for TID controller. The transfer function modelling of four area system is shown in Fig. 3.

3.3 Optimization Technique

Though local search algorithms are uncomplicated, more dynamic and applied broadly in the area of hard computational problems they go through the local minima. Generally global techniques are not suitable when requiring more/less fitness evaluations for large/small search dimensions for tuning parameters. Hence to get returns of both local and global techniques, LUS algorithm is hybridised with TLBO algorithm here. The basic steps for LUS-TLBO algorithm are:

- Initialize the population x_k
- Add x_k with another vector $a_k$and update the position vector
- Compare fitness values of $x_{k,new}$andx_k. Set new as the best values otherwise the previous one. Decrease the sampling range r.

- Then $x_{k,new}$ is assumed as initial population.
- Compute $x_{diff} as\ x_{diff} = rand.(x_{teacher} - (T_F x_{mean}))$
- Update $x_{k,new}$by adding it with x_{diff} which is
- Accept $x_{k,new1}$ for better solution else$x_{k,new}$.
- Further learner interacts with other learners to generate new solution$x_{k,new}$2.
- Then select either $x_{k,new2}$ or $x_{k,new1}$according to performance.
- Repeat above steps until stopping criterion is obtained.

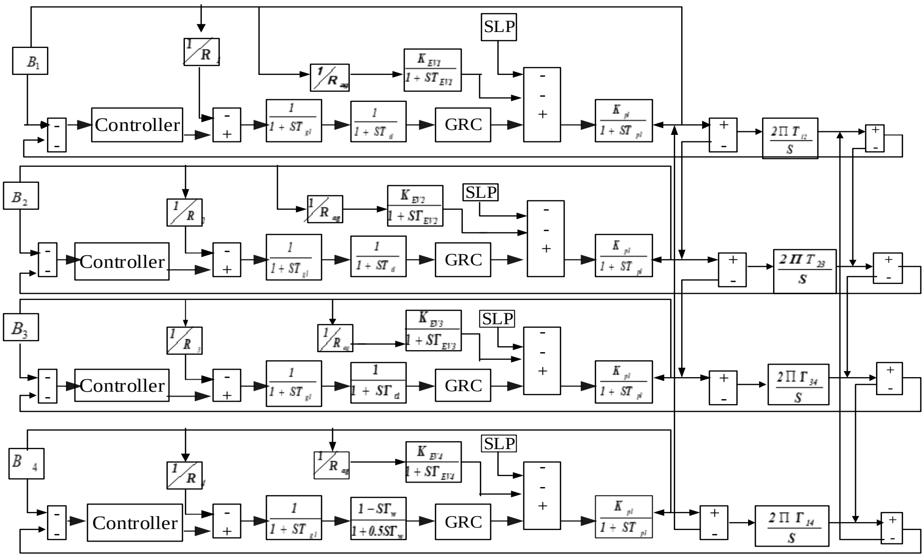

Fig. 3 Modelling structure of four area EV-thermal-hydro system using cascade controller

4. *Simulation Results*

4.1 Comparison of controllers using LUS-TLBO algorithm

In this study LFC of unequal four area hydro thermal units has equipped in Matlab/Simulink environment. At first, cascade of 3DOFPID-TID controller and then cascade of 3DOFPID-FOPID controller is pragmatic with SLP of 1% for area 1. Further cascade of 3DOFPID-FOPID-TID controller has considered for better tuning and rejection of oscillations. Finally cascade of 3DOFPID-FOPID-FOPD-TID controller is chosen for faster response with improved stability of frequency and power interchange among control areas. An assessment is ended among 3DOFPID-FOPID-FOPD-TID, 3DOFPID-FOPID-TID, 3DOFPID-FOPID and 3DOFPID-TID controllers through numerous simulatio ns individually shown in Fig. 4to Fig. 7.

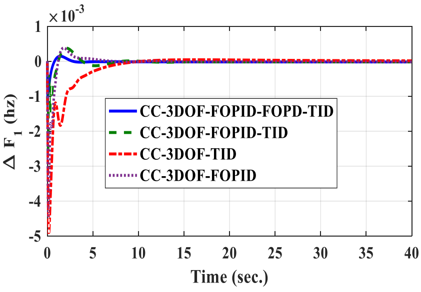

Fig. 4 Frequency variation for area 1

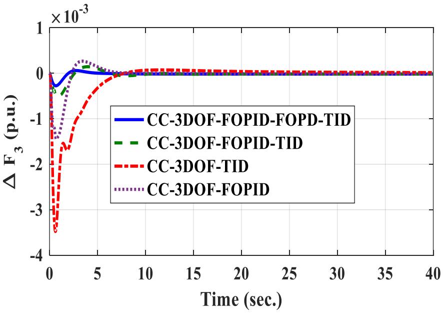

Fig. 5 Frequency variation for area 3

Fig.4 and Fig. 5 show the frequency variations and Fig. 6 and Fig. 7 show the tie line power deviations of power system under study. The proposed controller has reduced undershoot and overshoot as compared to other cascade controllers

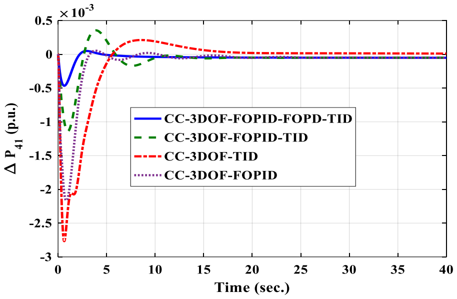

Fig. 6 Tie power variation T_{14}

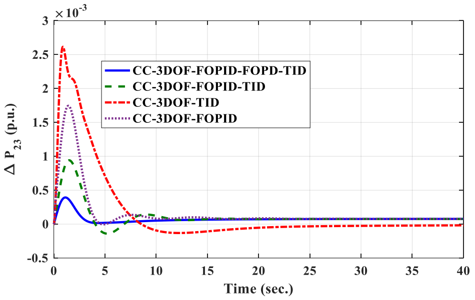

Fig. 7 Tie power variationT_{23}

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Table1 Performance values of controllers optimized by LUS-PSO algorithm

Performances	Controller	Δf_1 *in Hz*	Δf_2 *in Hz*	Δf_3 *in Hz*	Δf_4 *in Hz*	ΔP_{12} *in pu*	ΔP_{23} *in pu*	ΔP_{34} *in pu*	ΔP_{41} *in pu*
Undershoot (U_{sh}) in pu	3DOF-FOPID- FOPD-TID	-1.186	-0.171	-0.276	-0.130	-0.466	-0.000	-0.229	-0.000
	3DOF-FOPID-TID	-2.567	-0.299	-0.508	-0.263	-1.139	-0.100	-0.566	-0.046
	3DOF-FOPID	-4.478	-0.733	-1.450	-0.713	-2.165	-0.113	-0.940	-0.055
	3DOF-TID	-4.952	-2.593	-3.478	-2.039	-2.766	-0.230	-0.989	-0.069
Overshoot (O_{sh}) in pu	3DOF-FOPID- FOPD-TID	0.146	0.170	0.059	0.006	0.049	0.393	0.088	0.142
	3DOF-FOPID-TID	0.376	0.252	0.143	0.040	0.255	0.941	0.153	0.347
	3DOF-FOPID	0.381	1.140	0.165	0.136	0.553	1.744	0.283	0.735
	3DOF-TID	0.445	1.303	0.183	0.149	0.411	2.614	0.378	0.819

The dynamic performances of all controllers are accessed by using LUS-TLBO algorithm with 0.01 SLP for area1.The performance values of these controllers are depicted in Table 1. The supremacy of dynamic performances for 3DOF-FOPID-FOPD-TID controller over other cascade controller has elucidated in terms of reduced overshoot and peak value.Table 2 shows the gain parameter values of proposed cascade of 3DOFPID-FOPID-FOPD-TID controller for power system under study.

4.2 Comparison of LFC system with and without EV model

Tuning of 3DOFPID-FOPID-FOPD-TID controller for four area thermal system is simulated again with EV system. A comparison has made between the system with and without EV through numerous simulations which are shown in Fig. 8 to Fig. 9.

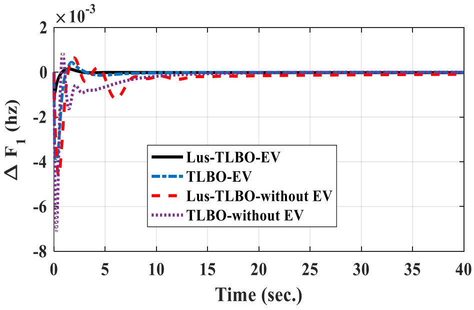

Fig. 8 Frequency variation with EV system

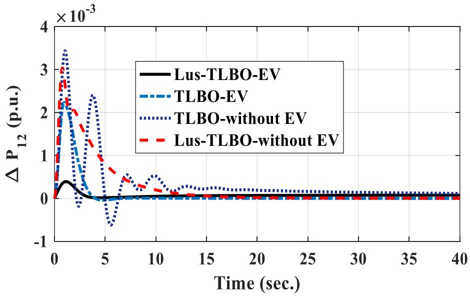

Fig. 9 Tie power variation with EV system

It is observable that addition of EV parameters with the proposed LFC system has faster ability to damp out oscillations as compared to conventional units only proposed systemwithout EV as shown in Fig. 8 and Fig. 9

Table2 System gain parameters of differnt controllers

Controller Structure	**Control Areas**	K_P	K_i	K_d	λ	μ	b_i	c_i	Gf_i	N
3DOFPID-FOPID-FOPD-TID	Area 1	0.6199 1.7958 1.6591 1.5632	0.3988 1.6832 1.7242	0.7289 1.2101 0.1987 1.2031	1.9879	0.3114 0.3024	0.3214	1.6193	0.5710	163.1592
3DOFPID-FOPID-FOPD-TID	Area 2	0.9240 1.7893 0.2450 1.6048	0.4956 0.2967 0.9347	0.8392 0.1250 0.7486 0.3401	1.7310	1.2010 1.7031	1.4790	1.8458	1.8217	185.6457
3DOFPID-FOPID-FOPD-TID	Area 3	0.9266 0.8473 1.5216 1.3278	1.0036 0.1773 0.7447	1.5843 0.1079 0.2729 1.0327	1.7057	1.6901 1.3902	0.6754	0.5769	1.5925	224.7166
3DOFPID-FOPID-FOPD-TID	Area 4	0.1634 1.6083 1.1486 0.2710	0.3621 1.4579 0.5350	0.8970 0.7910 0.7652 0.3189	1.8983	1.5127 1.6043	1.6203	1.3462	0.3573	279.6427

Table 3 indicates the performance values of 3DOFPID-FOPID-FOPD-TID controller optimized by Lus-TLBO and TLBO algorithm. Further Lus-TLBO based optimized controller with EV system and TLBO based proposed controller with EV system has compared in terms of diminshed value of undershoot and overshoot. Hence the EV system has reduced oscillation with faster response as compred to power system under sstudy without EV model.

Table3 Performance values of poewer system with and without EVmodel

Performances	Controller	Δf_1 *in Hz*	Δf_2 *in Hz*	Δf_3 *in Hz*	Δf_4 *in Hz*	ΔP_{12} *in pu*	ΔP_{23} *in pu*	ΔP_{34} *in pu*	ΔP_{41} *in pu*
Undershoot (U_{sh}) in pu	Lus-TLBO-EV	-1.1865	-0.1713	-0.2761	-0.1303	-0.4662	-0.0000	-0.2291	-0.0000
	TLBO-EV	-4.4786	-0.7335	-1.4509	-0.7135	-2.1651	-0.0034	-0.9404	-0.0450
	LusTLBO-without EV	-4.6205	-4.3192	-3.8017	-2.7186	-3.0845	-0.6154	-1.2106	-0.1010
	TLBO-without EV	-7.3772	-4.4311	-4.9020	-2.8821	3.1123	-0.7096	-1.3813	-0.1142
Overshoot (O_{sh}) in pu	Lus-TLBO-EV	0.1464	0.1706	0.0591	0.0065	0.0496	0.3933	0.0883	0.1427
	TLBO-EV	0.3810	0.2400	0.2658	0.1351	0.0536	1.7448	0.3834	0.7532
	LusTLBO-without EV	0.6403	2.1469	0.3327	0.1400	0.1842	3.4405	0.4825	1.1552
	TLBO-without EV	1.2182	2.2314	0.4954	0.1512	0.2226	3.6965	0.6818	1.9662

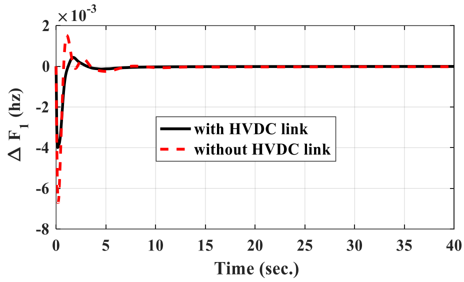

Fig. 10 Frequency variation with HVDC

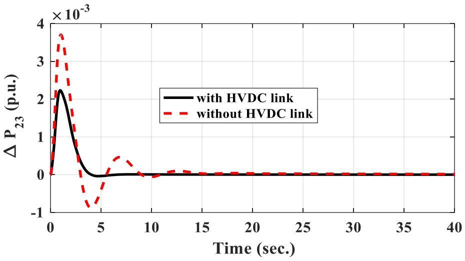

Fig. 11 Tie power variation with HVDC

4.2 Comparison of LFC system with and without HVDC link

In this case, the HVDC link [14] is placed parallel with all the tie lines. Lus-TLBO technique is used to otimize the gain prameters of casacde 3DOFPID-FOPID-FOPD-TID controller. The dynamics with and without HVDC link of this proposed systemare are compared in Fig. 10 and Fig. 11.

Table 4. Percentage improvement of performance indices for frequency and tie line power deviation

Performance	Controller	Δf_1 *in Hz*	Δf_2 *in Hz*	Δf_3 *in Hz*	Δf_4 *in Hz*	ΔP_{12} *in pu*	ΔP_{23} *in pu*	ΔP_{34} *in pu*	ΔP_{41} *in pu*
Overshoot (O_{sh}) in pu	3DOF-FOPID-TID	61.08	32.43	58.92	84.10	80.57	58.22	52.36	58.88
	3DOF-FOPID	61.57	85.03	64.35	95.22	85.97	77.45	68.84	80.59
	3DOF-TID	67.10	86.90	67.72	95.65	87.94	84.95	76.68	82.59
Settling time (T_s) in sec	3DOF-FOPID-TID	62.90	56.45	37.68	43.74	39.88	28.54	23.22	39.06
	3DOF-FOPID	58.44	44.55	23.69	32.86	39.48	28.58	29.28	39.70
	3DOF-TID	32.39	67.21	25.39	67.73	47.42	33.58	32.72	58.20
Undershoot (U_{sh})	3DOF-FOPID-TID	72.04	42.16	61.26	83.25	81.22	60.28	58.61	64.83

in pu	3DOF-FOPID	72.54	85.32	70.14	94.18	83.69	79.31	75.24	80.61
	3DOF-TID	77.15	86.88	71.31	94.06	85.67	83.46	78.29	82.41

Further, robustness of proposed controller has proven by using randomly perturbed load injected to area-1. The expeditions of frequency and tie-line power variations are revealed in Fig. 10 and Fig. 11 respectively. From that figures, it is discernible that the oscillations of frequence and power interchange concludes to zero with slight impetuous response. Hence, robustness of proposed 3DOFPID-FOPID-FOPD-TID controller has remarkable under random load perturbation.

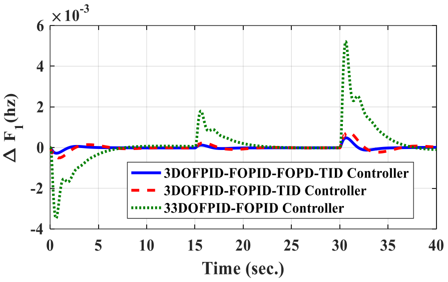

Fig. 10 Frequency variation due to RLP

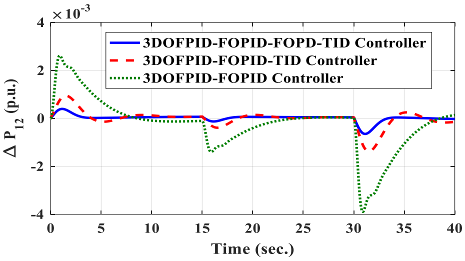

Fig. 11 Power interchange due to RLP

Conclusion

In this work, a novel LUS-TLBO based 3DOFPID-FOPID-FOPD-TID controller is used for four areas LFC with nonlinearities. The system is an interconnected EV-thermal-hydro unit to provide faster response of mitigating the oscillation as compared to conventional one. The submission of hybrid LUS-TLBO technique is used here to augment several gain and controller parameters for cascaded controller to maintain a proper balance between the exploitation and exploration. Considering system non-linearity, GRC in this multi-area LFC with EV system, the projected cascaded controller provides remarkable dynamic response as compared to 3DOFPID-FOPID-TID, 3DOFPID-FOPID and 3DOFPID-TID controllers. The supremacy of proposed LUS-TLBO algorithm based cascaded controller has reduced undershoot and peak transient as compared to TLBO algorithm. The projected controller with electric vehicle has enhanced dynamic responses as compared to system without EV, because of faster response characteristics of EV's battery. Finally robustness of proposed controller has proven by considering random load pertubation to proposed system. Application of EV in distibution network will considered for further study.

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