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# LOAD FREQUENCY CONTROL OF MULTI AREA SYSTEM INCORPORATING DISTRIBUTED GENERATION RESOURCES USING CLOSED LOOP CASCADE OF 3DOFPID-FPID-TID CONTROLLER

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**Abstract**: This study emphasis on load frequency control (LFC) to retains the deviations of system frequency and tie line power at their preferred values by maintaining the steadiness between power generation and demand. It defines the importance of integrating distributed generation (DG) resources with existing power system in terms of system dynamic performance. A maiden attempt has been taken to apprehend and deliver CC-3DOFPID-FPID-TID controller with DG resources for frequency and power stabilisation of an interconnected power systems. Cascaded two loop controllers are used here as a substitute to relieve the closed loop system by means of secondary feedback planning. The suggested controller incorporates both the value of cascade (CC) and fractional order (FO) controls for restored eradication of system insecurities. In this recommended cascade –three degree of freedom proportional integral derivative-fuzzy proportional integral derivative –tilted integral derivative (CC-3DOFPID-FPID-TID) controller, slave controller action is performed by tilted integral derivative (TID) and foremost action is governed by three degree of freedom proportional integral derivative-fuzzy proportional integral derivative (3DOFPID-FPID) controller. The controlled parameters are optimized by adaptive symbiotic organism search (ASOS) algorithm for intense outcomes of difficulties in LFC. To persist in ecosystem, adaptive symbiotic relations are expectable by organism through ASOS imitators. Further the dynamic behaviours of proposed controller optimized by ASOS,

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symbiotic organism search (SOS) and ant lion optimization (ALO) are compared by extensive simulations. Moreover the sovereignty of suggested controller is executed through system dynamics comparison among 3DOFPID, TID, CC-3DOFPID-TID, CC-FPID-TID and CC-3DOFPID-FPID-TID controllers. Sensitivity of proposed controller has proven though random load perturbation and variation in system parameters.
***Keywords:***Load frequency control (LFC), Proportional integral derivative (PID), Adaptive symbiotic organism search (ASOS), Area control error (ACE), Integral time absolute error (ITAE), Step load perturbation (SLP).

**摘要**：**本研究**强调负载频率控制 (LFC)，**通**过保持发电量和需求量之间的稳定性，将系统频率和联络线**功率的偏差保持在其首**选值。它定义了在系统动态性能方面将分布式发电 (DG) 资源与现有电力系统集成的重要性。首次尝试使用 DG 资源来理解和交付 CC-3DOFPID-FPID-TID **控制器**，**以**实现互连电力系统的频率和功率稳定。这里使用级联的双回路控制器作为替代，通过二次反馈规划来缓解闭环系统。建议的控制器结合了级联 (CC) **和分数**阶 (FO) **控制的**值，以恢复消除系统不安全性。在这个推荐的级联-**三自由度比例**积分微分-**模糊比例**积分微分-倾斜积分微分（CC-3DOFPID-FPID-TID）**控制器中**，**从控制器**动作由倾斜积分微分（TID）执行，最重要的动作由三自由度比例积分微分-**模糊比例**积分微分(3DOFPID-FPID)**控制器。受控参数通**过自适应共生生物搜索 (ASOS) **算法**优化，用于 LFC **困**难的强烈结果。为了在生态系统中持续存在，生物体通过 ASOS **模仿者可以**预期适应性共生关系。此外，通过广泛的模拟比较了由 ASOS、**共生生物搜索** (SOS) **和**蚁狮优化 (ALO) 优化的拟议控制器的动态行为。此外，建议控制器的主权是通过3DOFPID、TID、CC-3DOFPID-TID、CC-FPID-TID**和** CC-3DOFPID-FPID-TID**控制器之**间的系统动态比较来执行的。尽管随机负载扰动和系统参数的变化已经证明了所提出的控制器的灵敏度。
**关**键词：负载频率控制（LFC）、**比例**积分导数（PID）、**自适**应共生生物搜索（ASOS）、**区域控制**误差（ACE）、积分时间绝对误差（ITAE）、阶跃负载扰动（SLP）。

## 1. Introduction

Discrepancy between power generation and loading of an interconnected system is ensued due to increasing demand of electricity. This unbalance causes eccentricity in system frequency and power interchange and overcome by the closed control of active powers with suitable secondary controllers. Load frequency control (LFC) is accountable for regulating the frequency in power systems. The literature analysis exposes the study in the arena of LFC (Ibraheem et al., 2005).The foremost goal of LFC is to sustain the frequency into scheduled value and controlling the tie-line power exchange in this interconnected system (Elgerd et al. 1970; Saikia et al., 2011). The upgrading of frequency stability by LFC has stated in various research articles for an isolated and multiple interconnected system. However, there are some limitations in terms of system nonlinearities considering generation rate constraint (GRC) (Guha et al., 2016) of3% per minute with reheat turbineand governor dead band (GDB) (Sahu et al., 2013) to the anticipated system.However this is not focused on further truthful power system model in view of physical restraints. In the past decade, power generation is mostly depends on thermal and hydro power plants. With increase in population, industries demanding more power but the availability of coals are going to exhaust within very petite duration of time. As the fossil fuels exhausted with growing demand, integration of conventional units with distributed energy resources located closer to load centres are termed microgrids. Now a day's hybrid interconnected power system comprising of conventional units and renewable energy sources is the extensive research areas in LFC. This organization diminishes the transmission losses, delivers improved controllability by filling their power demands. However, irregular flora of the renewable sources along with microgrids the system frequency divergences are significantly high (Hussain et al., 2017). A microgrid could be designed in the form of distributed generation sources such as wind turbine generator (WTG), fuel cell (FC), aqua electrolyser (AE), diesel engine generator (DEG) and battery energy storage system (BESS) (Pandey et al., 2014).To sustain a suitable steadiness between real power and demand, suitable control strategy needed for power generation from these microgrid resources. Microgrid frequency deviates due to the interconnection of these energy resources. Since the wind power generation is intermittent in nature, a faction WTG power is used for hydrogen production in AE (Mirazimi et al., 2011; Abdul et al., 2012). The system behaviour of WTG is differs from conventional thermal unit due to intermittent power curve. Hence WTG and BESS are harmonized to regulate the frequency eccentricities. For long duration, fuel cell and fly wheel can condensed the frequency fluctuations whereas energy storage devices are considered for short duration of time (Vidyanandan et al., 2016). BESS (A. Pritam et al., 2017) with multi sources are used to soothe system frequency deviation by levelling the load with respect to generation. BESS discharges if the system frequency is higher than scheduled value and charges at the state of lesser value as compared to nominal value.

Nonlinear nature of LFC can be solved by designing suitable secondary controllers. Conventional controller PID (Mohanty et al., 2014) is mostly used in process industry because; it is simple to design in Simulink. However, transient behaviour is worse due to large value of overshoot and not settles quickly. Fuzzy Logic PID control (Pahadasingh et al., 2019) for LFC has better robustness as compared to conventional PID. However such methods suffer limitations of large computational time due to design process of membership function. Through multiple control loops, control action is achieved which are basically degrees of freedom. Concept of 2DOF-PID controller (Dash et al., 2014; Raju et al., 2017)has discussed which has improved response as compared to conventional one. Hence when the tuning knobs present in a controller are more, the performance of the latter is better in LFC. Multi degree-of-freedom PID

(3DOF-PID) controller can also be experimented (Patel et al., 2018) for this proposed system. The dominance of 3DOF-ID controller (Ganthia. B.P. et al., 2018) over 2DOF-ID and single degree freedom PID using BBO technique has discussed for this LFC system. The effect of 3DOF-PID (Debnath et al., 2017) controller over frequency stabilization has analysed for multi area LFC system. Above discussed controllers are mostly numeral controllers, but there are several somatic systems apprehended by fractional order calculus. Fractional order controllers (Debbarma S, et al. 2014) have greater flexibility and stability towards parameter variations as compared to conventional controller. The exploitation of FOPID controller (Pahadasingh et al., 2020) has studied for four area LFC system incorporating EV with HVDC link. TID-based (Morsaliet al., 2017) GCSC damping controller has elaborated in coordination with AGC system. LFC of multi area system using TID (Sahu et al., 2016) controller has presented with filter controller. Load frequency control of multi area system incorporated with distributed generation resources optimized tilted integral derivative (Pahadasingh et al., 2021) controller has deliberated.Now,cascade controllers are mostly used in the power system to enlighten the frequency stability by engaging a secondary loop along with feedback measurement loop. LFC of four area system using PI-PD (Dash et al., 2016)controller has studied. The assistances of expending cascade controllers (Sharma et al., 2015)with respect to single-loop controllers have been recognised with this LFC system. Design of CC-3DOF-ID controller (Rahman et al., 2015) for LFC of an interconnected power system has discussed. Cascade of two degree of freedom PID (Raju et al., 2018) controller is debated for three-area LFC system. However the effect of extra disturbance tuning factor has not discussed. Application of CC-TID controller (Guha et al., 2019) considering non linearity has elaborated for multi area power system. However the effect of extra tuning factor to PID controller in cascade with TID controller has not discussed. Hence this needs further study.

Present power systems ultimatum rich astuteness and precise collection of controller gains for healthier frequency and tie-line power steadiness alongside variation of load. However conformist alterations for getting best standards of controller sceneries are ineffective for system uncertainties and nonlinearities. Furthermore, traditional tuning algorithms are distress from local targets stings, clarified accuracy and demand of derived search space. Hence, deployment of numerous evolutionary algorithms for the perfection of controller gains has been recognized as an intense research topic for LFC study. Hence many evolutionary optimization techniques are explored for this proposed LFC system. In LFC, differential search algorithm (DSA) (Guha et al., 2017), ant lion optimizer (ALO) (Raju et al., 2019),flower pollination algorithm (FPA) (Debbarma et al. 2017), teaching learning based optimization TLBO (Sahu et al., 2015), symbiotic organism search (SOS) (Cheng et al., 2014; Guha et al., 2018).

Hence encouraged from the above investigation, this paper presents the novel cascade control scheme- CC-3DOFPID-FPID-TID optimized by ASOS for lessening frequency oscillation in hybrid power systems of LFC. Adaptive symbiotic organism search (ASOS) (Ghanshyam et al., 2016; Nayak et al., 2018)is the advanced version of SOS technique to enhance its dynamic performances by maintaining a proper balance between the exploration and exploitation through adaptive benefit factors. The main contribution of this paper is:

i) Modelling of three area thermal hydro LFC system with DGR considering SLP of 1% in area1.

ii) The supremacy and viability of cascaded two loop of 3DOFPID-FPID and TID controller have been recognized over single loop 3DOFPID, TID, cascaded two loop FPID–TID, and cascaded two loop 3DOFPID-TID controller.

iii) Solicitation of ASOS has been explicated for dynamic assessment of CC-3DOFPID-FPID-TID controller gains equated with SOS and ALO algorithms.

iv) To uphold the worth of proposed cascaded controller, different variation of step load perturbation (VSLP) for control areas are projected.

The rest of the paper is structured as follows: section 2 offerings and deliberate the mathematical modelling of LFC system incorporating with DG resources. Section 3 offerings the design of closed loop cascade controller. Section 4 depicts the implementation of ASOS algorithm for tuning of controller parameters. Section 5 presents and discusses the time domain simulation results. Section 6 concludes with the summary of work presented.

## 2. Problem Analysis

*2.1 Three-Area Power System Model:* This paper presents LFC of multi area hybrid power system. This model presents thermal unit for area1 and area2, DGR system for area 1 and hydro power unit for area 3. A step load perturbation (SLP) of 0.01 pu is realistic only for control area1. Power flow for control area can be stated as in equation 1(PrabhaKundur1994).Transfer function for this proposed power system is mentioned in Table 1.

$$P_{TL_1} = \frac{|E_1||E_2|}{X_{TL}} \sin(\delta_1 - \delta_2) \quad (1)$$

Where $|E_1|$ and $|E_2|$are voltage magnitudes of area 1 and area2 respectively.

$X_{TL}$ : Tie-line reactance and $\delta_1$, $\delta_2$ are power angles of respective area

**Table 1** Transfer function of different elements in three area system

| Components | Response Functions |
|---|---|
| Governor | $TF_g = \frac{1}{1+sT_g}$ |
| Steam turbine | $TF_{st} = \frac{1}{1+sT_t}$ |
| Hydro turbine | $TF_{ht} = \frac{1-sT_w}{1+0.5sT_w}$ |
| Rotating mass machine | $\frac{1}{Ms+D}$ |
| Diesel engine generator (DEG) | $\frac{K_{DEG}}{1+ST_{DEG}}$ |
| Wind turbine generator (WTG) | $\frac{K_{WTG}}{1+ST_{WTG}}$ |

| | |
|---|---|
| Fuel cell (FC) | $\frac{K_{FC}}{1+ST_{FC}}$ |
| Aqua electrolyser (AE) | $\frac{K_{AE}}{1+ST_{AE}}$ |
| Battery energy storage system (BESS) | $\frac{K_{BESS}}{1+ST_{BESS}}$ |
| High voltage direct current link | $\frac{K_{DC}}{1+ST_{DC}}$ |

Here the input of controller in each area is the area control error (ACE). It is the summation of frequency deviation with biasing coefficient (B) and tie-line power flow fluctuation.

Area control error can be expressed as in equation (2,3and 4)(PrabhaKundur1994).

$$ACE_1 = \Delta P_{12} + B_1 \Delta w_1 (2)$$
$$ACE_2 = \Delta P_{21} + B_2 \Delta w_2 (3)$$
$$ACE_3 = \Delta P_{31} + B_3 \Delta w_3 (4)$$

$\Delta P_{12}, \Delta P_{21}$, $\Delta P_{31}$ are the tie-line power oscillations of individualzones

$B_1$,$B_2$,$B_3$ are the frequency biasing constant of individual zones

## 2. Cascade Controller Design

Generally PID controller(Mohanty et al.2014)has three parameters for optimization($K_P, K_I, K_D$). However it has severe oscillations with peak overshoot and large settling time causes damage in the system performance. Control action can be achieved by multiple control loops which are basically called as degrees of freedom. So 2DOFPID controller (Raju et al., 2017) is implemented to this system which is more preferable than PID controller in terms of dynamic response. The improvement of responses can be achieved by using 3DOFPID controller(Patel et al., 2018)which contains additional three control loops to enhance the stability of the system, proper response curves and eradication of instabilitieshappening in the power system due to the extra loop D(S) in 3DOF controller.

Tilted integral derivative (TID) controller(Guha et al., 2019)is the fractional order controller having extra tilt component $S^{-n}$ give satisfactory performance for considering non-linearities in large interconnected power systems. However single loop controller may not offer robust performance in system uncertainties. Hence cascade of two loop controllers are considered giving better flexibility and stability towards parameter variations. Again fuzzy PID (Pahadasingh et al., 2019) controller has better robustness and is used as secondary control loop cascaded with the tilted integral derivative controller as primary control loop to minimize the ACE effectively. Further cascade of two loops 3DOFPID is considered as master loop and TID controller is considered as slave loop to achieve zero steady state error. Finally for better tuning and rejection of disturbances, cascade of two loops 3DOFPID-FPID is taken as inner loop for frequency regulation and TID controller is taken as outer loop to retain generation-demand balance. The structure of cascaded 3DOFPID-FPID controller and TID controller are shown in Figure 1 and Figure 2 respectively.

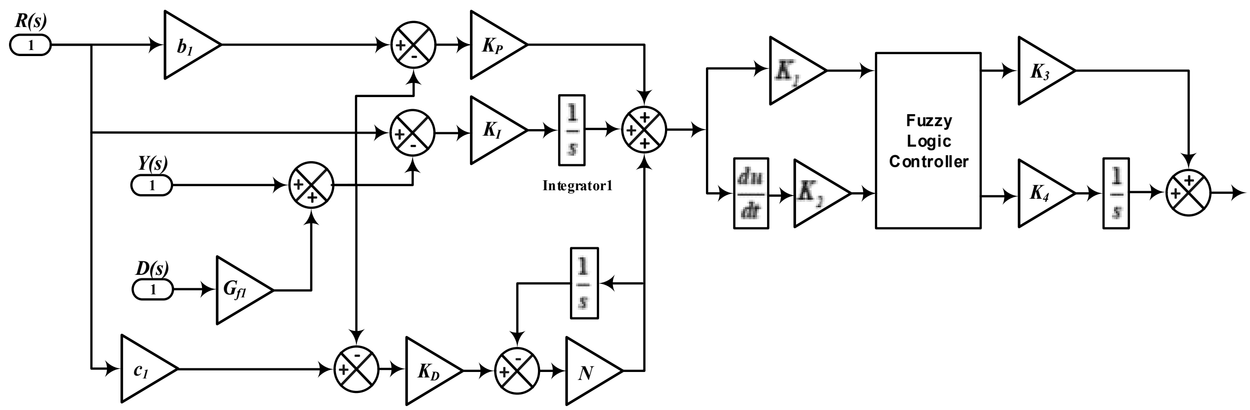
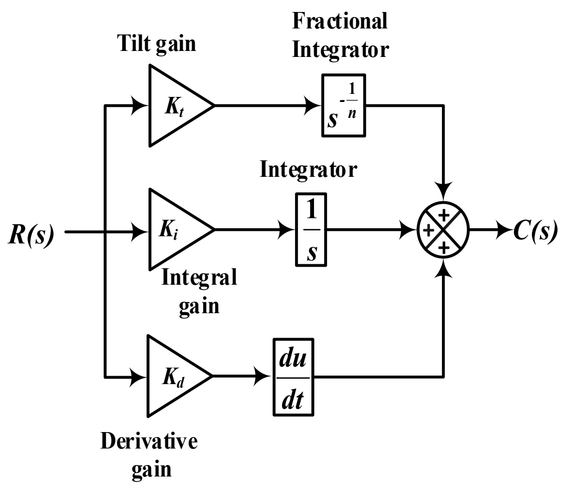



**Fig. 1** Basic structure of cascaded 3DOFPID-FPID Controller

The overall power provided to the load from hybrid microgrid system is expressed in Eq. (5)

$$P_S = P_{WTG} + P_{FC} + P_{AE} - P_{DEG} \pm P_{BESS} (5)$$



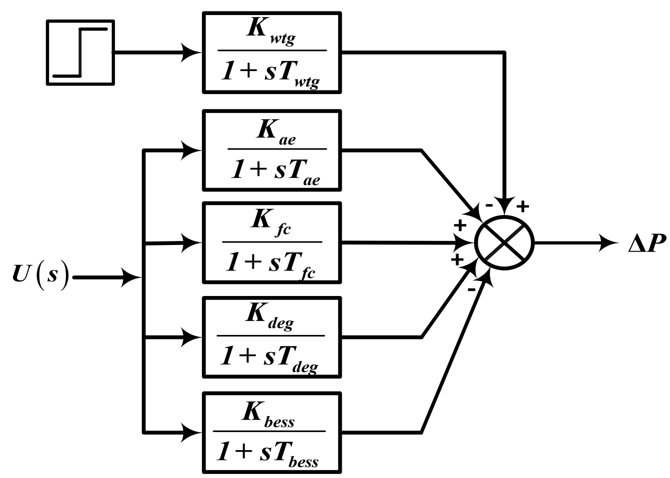




**Fig. 2** Model of TID controller**Fig. 3** Model of DG resources

Where Ps: total power supplied

$P_{WTG}$: output power of wind turbine generator

$P_{FC}$: output power of fuel cell

$P_{AE}$: output power of aqua electrolyser

$P_{DEG}$: output power of diesel generator

$P_{BESS}$: output power of battery energy storage system

The transfer function model of DG resources is presented in Figure 3 and proposed power system is presented in Figure 4.

## 3. Adaptive Symbiotic Organisms Search (ASOS) Algorithm:

This algorithm is the current, vigorous and commanding meta-heuristic algorithm. In this technique no specific algorithm parameters are needed, it only mimics the symbiotic relationships among different organisms for persisting in the ecosystem as in symbiotic organism search method. In ASOS, based on population space ecosystem is considered and the through biological interaction among organisms, new populations can be generated. There are three phases in ASOS algorithm namely mutualism, commensalism and parasitism as similar to SOS algorithm. However the rebellion of organisms in mutualism phase immensely depends on the BFs. For better exploration, generally the organism is far away from best one and adjusts the location with large value.

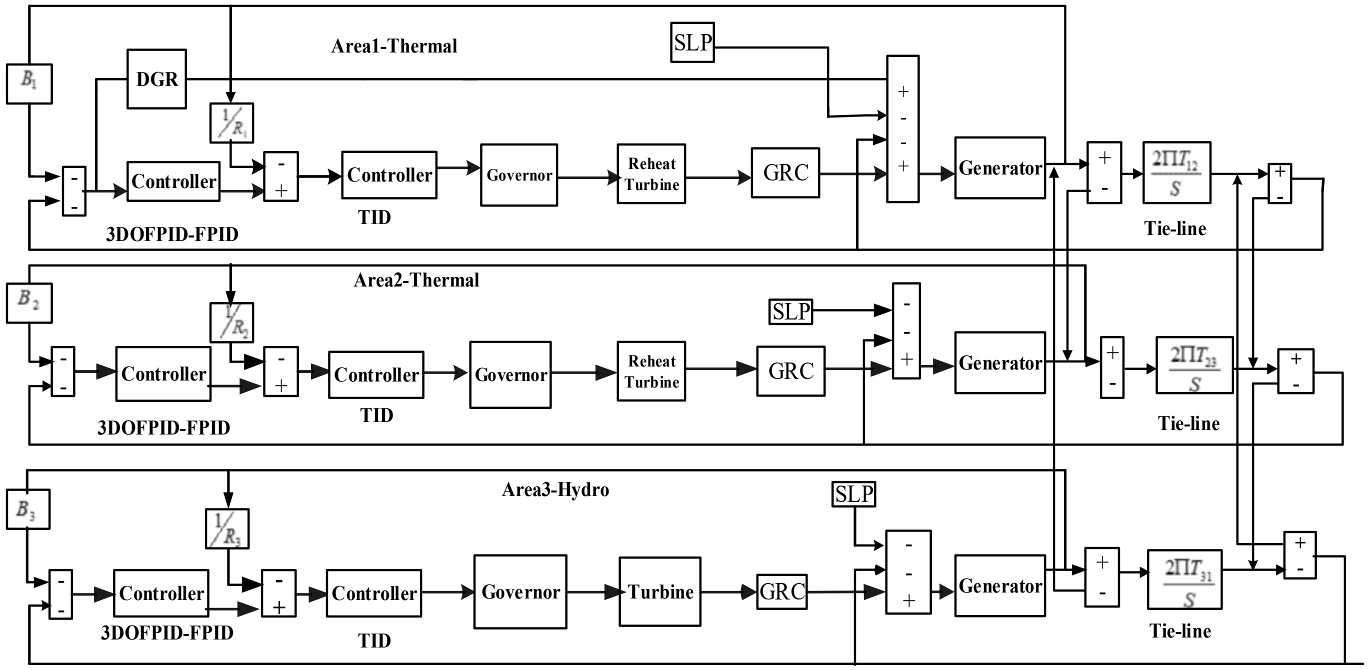



**Fig. 4** Transfer function model for three area power system using cascade loop controller

By this the computational time is less but it may suffer from local minima or skitter from global solution. Whereas, the organism changes its location with a small value (exploitation) needs more computational time. Hence, The ABFs assist a well equilibrium between exploration and exploitation. When the organism is afar from best one, the ABFs augments the diversity factor and consciously lessen this factor.

(i)Mutualism phase: This phase reveals the mutual benefit symbiotic relationship between two different species. In this phase $X_i$ and $X_j$ are the two arbitrary organisms. To enhance the chance of survival, they interact between themselves.

$$X_{i,new} = X_i + rand(0,1) * (X_{best} - Mutual\_vector * ABF_1) \quad (6)$$

$$X_{j,new} = X_j + rand(0,1) * (X_{best} - Mutual_{vector} * ABF_2) \quad (7)$$

where $Mutual\_vector = \frac{X_i+X_j}{2}$ (8)

rand (0,1) is the random numberand $BF_1, BF_2$ are the benefit factor within the range of 1to 2.

Both $i^{th}$ and $j^{th}$ organisms are restored by getting aids from this interface with a probability factors called benefit $BF_1$ and $BF_2$.

The BFs of mutualism phase of SOS algorithm are revised by assuming this technique in [47]. The adaptive benefit factors (ABF) are expressed in equations (9) and (10).

$$ABF_1 = \frac{f(X_i)}{f(X_{best})} \quad if\ f(X_{best}) \neq 0 \quad (9)$$

$$ABF_2 = \frac{f(X_j)}{f(X_{best})} \quad if\ f(X_{best}) \neq 0 \quad (10)$$

(ii) Commensalism phase: Two random organisms $X_i$and $X_j$from the ecosystem are permitted to interrelate in this phase. In this communication organism $X_i$assistances from the interaction, but organism $X_j$neither assistance nor writhes from the connection. The new updated value of $X_i$is calculated

$X_{i,new} = X_i + rand(-1,1) * (X_{best} - X_j)$(11)

(iii) Parasitism phase: In this phase one species get benefits from ecosystem and other is actively harmed. $X_j$is selected as a host for parasite vector (PV) from the ecosystem. This vector tries to replace $X_j$for survival in ecosystem and the fitness values of both are calculated.

If PV has better fitness value then it will kill $X_j$from the ecosystem and consume this place. If $X_j$is better, then it gets immunity from PV. Now this PV will no longer alive in the ecosystem.

***Objective Function***

Performance of optimization process depended on the objective function generally used in time domain. Here integral of time multiplied absolute error (ITAE) is used as objective function because of small overshoot and oscillations. Mathematical expression of ITAE function is

$f = \int|\Delta F_1 + \Delta F_2 + \Delta F_3 + \Delta P_{tie}|.t.dt$ (12)

Where, $dt$ is a very small time interval,$\Delta F_1$,$\Delta F_2$and $\Delta F_3$are frequency deviations for area1, area2 and arae3 respectively. The tie line power deviation for control area is$\Delta P_{tie}$. In area1 step load perturbation is taken as 0.01 p.u.

## 4. Simulation Results and Discussions

### *3.1 Comparison of performances for different algorithms*

In this paper, 3DOFPID-FPID controller is considered as secondary loop of the power system and TID controller is considered as primary loop. The controller and gain parameters are optimized by optimization techniques to regulate the frequency oscillations. At first ant lion optimization (ALO) algorithm is used with an objective function ITAE for 50 numbers of iterations. Then symbiotic organism search based controller has elaborated with same objective functions and that numbers of iterations. After that adaptive symbiotic organism search based controller has taken for the dynamic performances of controller. From the above three optimization techniques, the later one has improved dynamic performances as compared to others in terms of reduced oscillations, overshoots and settling time. Simulations results from Figure 5 to Figure 10show the performances of controller using ALO, SOS and ASOS algorithm. The gain parameters of these algorithm based controller are depicted in Table 2.

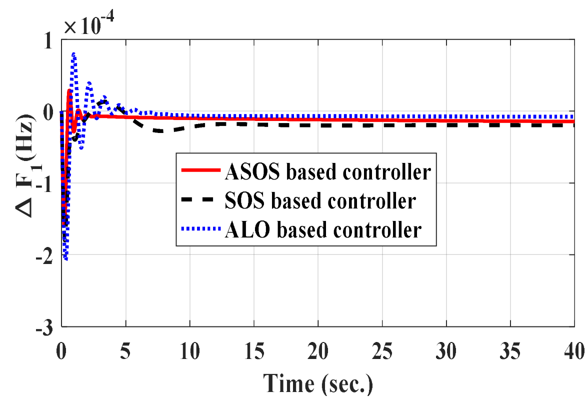



**Fig. 5**System frequency deviation for area1

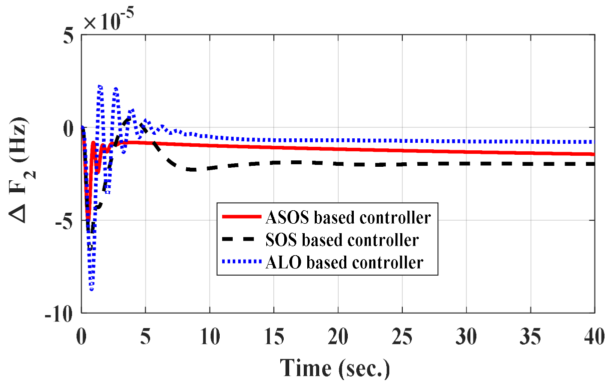



**Fig. 6**System frequency deviation for area2

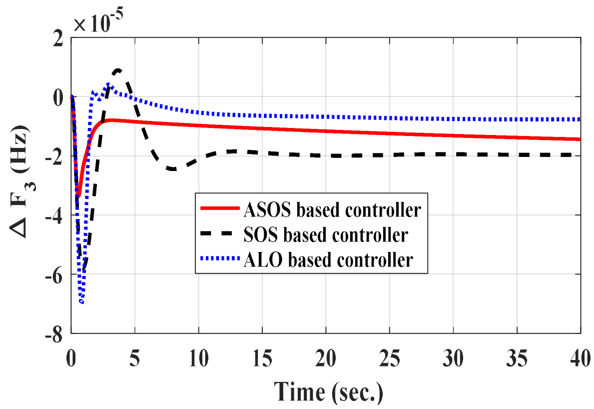



**Fig. 7** System frequency deviation for area3

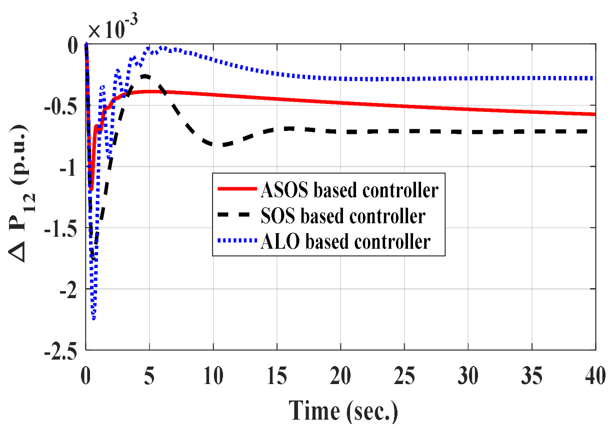



**Fig. 8**Power interchange between area 1 and area 2

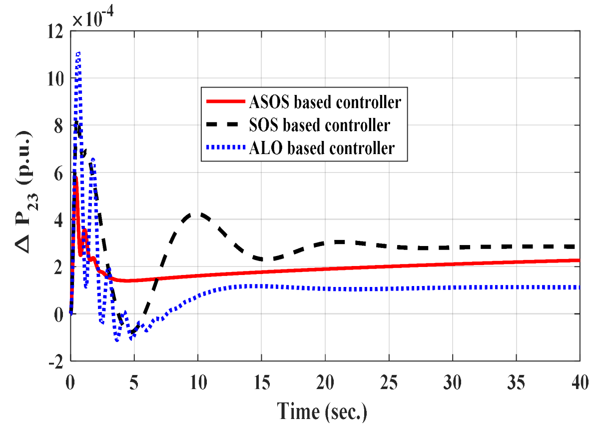



**Fig. 9** Power interchange between area 2 and area 3

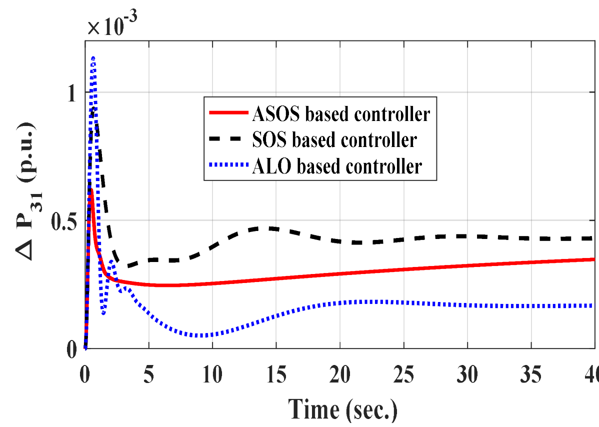



**Fig. 10** Power interchange between area 1 and area 2

From the above figure, ASOS based 3DOFPID-FPID-TID controller has minimum value of settling time (4.16 sec) as compared to SOS based (7.35 sec) and ALO based (9.29 sec) method for frequency variation in control area 1. The computational time of ASOS algorithm, SOS algorithm and ALO algorithm are 331.0156s, 398.4063s and 423.0271s respectively. The dynamic response of ALO based controller has large oscillations as compared to SOS and ASOS based controller.The gain parameters of 3DOFPID-FPID-TID controller (14) for each area are optimized by three different algorithms such as

ASOS, SOS and ALO. These values are depicted in Table 2.

**Table 2** Gain parameters of 3DOFPID-TID controller optimized by different algorithms

| Gain parameters | ASOS based controller | SOS based controller | ALO based controller |
|---|---|---|---|
| $K_1$ | 2.0000 | 0.9692 | 1.0329 |
| $K_2$ | 0.1000 | 1.0579 | 0.4145 |
| $K_3$ | 1.4851 | 1.3649 | 0.9457 |
| $b_1$ | 2.0000 | 0.9852 | 1.1142 |
| $c_1$ | 1.1798 | 1.2742 | 0.8163 |
| $Gf_1$ | 0.1000 | 0.0100 | 0.0392 |
| $N_1$ | 300.0000 | 122.9281 | 138.6478 |
| $K_4$ | 0.1000 | 0.0100 | 0.7193 |
| $K_5$ | 2.0000 | 1.3130 | 1.4981 |
| $K_6$ | 1.1984 | 0.9511 | 0.8879 |
| $K_7$ | 0.7016 | 1.6212 | 0.4572 |
| $K_8$ | 2.0000 | 1.4584 | 0.2497 |
| $K_9$ | 0.1000 | 1.6810 | 0.3643 |
| $b_2$ | 2.0000 | 0.4251 | 0.2314 |
| $c_2$ | 1.6278 | 0.1391 | 1.1144 |
| $Gf_2$ | 0.1000 | 1.2046 | 0.3257 |
| $N_2$ | 100.0000 | 299.1426 | 127.7086 |
| $K_{10}$ | 0.1000 | 0.1000 | 1.2168 |
| $K_{11}$ | 0.1000 | 1.7784 | 0.6481 |
| $K_{12}$ | 0.1000 | 0.9473 | 0.0299 |
| $K_{13}$ | 0.4894 | 0.4133 | 0.8505 |
| $K_{14}$ | 0.1000 | 1.8936 | 0.7791 |
| $K_{15}$ | 04084 | 1.7912 | 0.0179 |
| $b_3$ | 0.1000 | 1.9337 | 1.8753 |
| $c_3$ | 1.1254 | 1.4030 | 0.4389 |
| $Gf_3$ | 0.1000 | 1.1079 | 0.5867 |
| $N_3$ | 100.0000 | 210.1914 | 138.5578 |
| $K_{16}$ | 1.5216 | 1.8280 | 1.1187 |
| $K_{17}$ | 0.7447 | 0.1000 | 0.5258 |
| $K_{18}$ | 0.8428 | 0.2729 | 0.7593 |

***3.2****Comparison of dynamic performances for all controllers*

At first 2DOFPIDN controller is used for this proposed system in which two extra control loops R(s), Y(s) and filter coefficient N are taken and six parameters are optimized for one area.

After that a 3DOFPIDN controller is used in which three control loops are taken in addition of disturbance D(s) to 2DOFPIDN where seven parameters are optimized. Further cascade of fuzzy PID and TID controller are utilized for this proposed system having 10 parameters to be optimized for single area. Then cascade of 3DOFPIDN and TIDcontroller areconsidered for tuning of 10 controlled parameters. Finally cascade of 3DOFPIDN-FPID and TID controller are reserved for tuning of 14 parameters in one area through simulations. For TID controller the value of (n) is taken as 0.5 for each area.

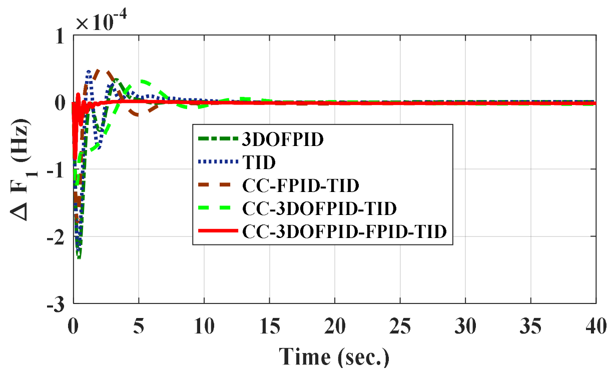



**Fig. 11** System frequency deviation for area1

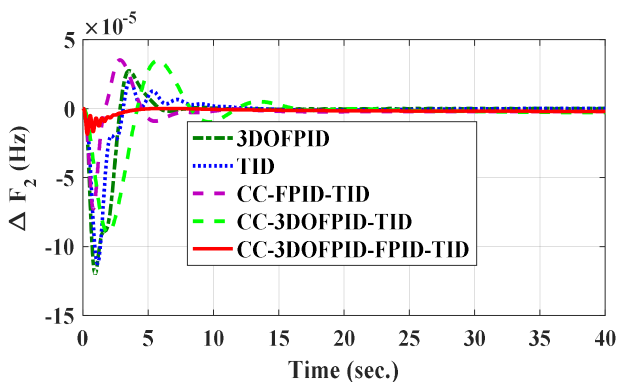



**Fig. 12** System frequency deviation for area2

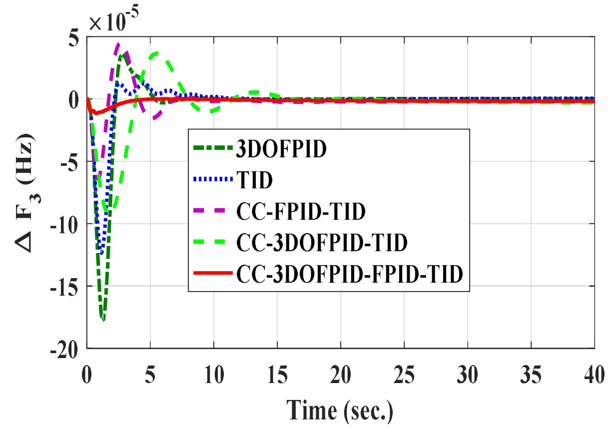



**Fig. 13** System frequency deviation for area2

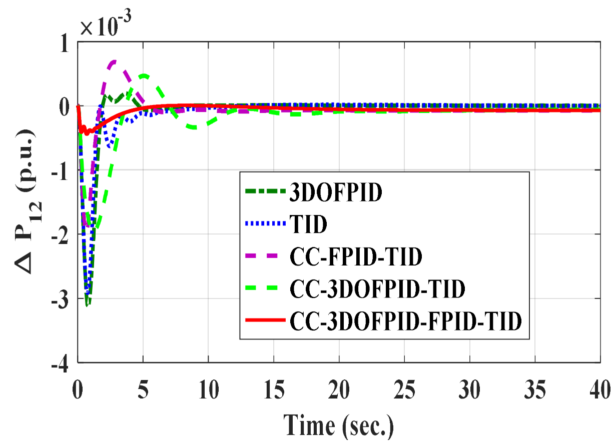



**Fig. 14** Interchanging power between area1 and area 2

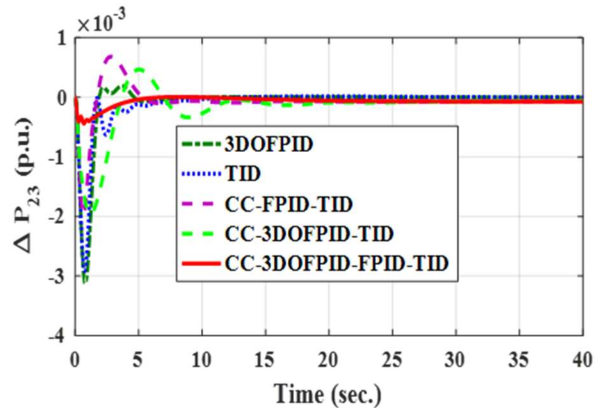



**Fig. 15** Tie power between area2 and area 3

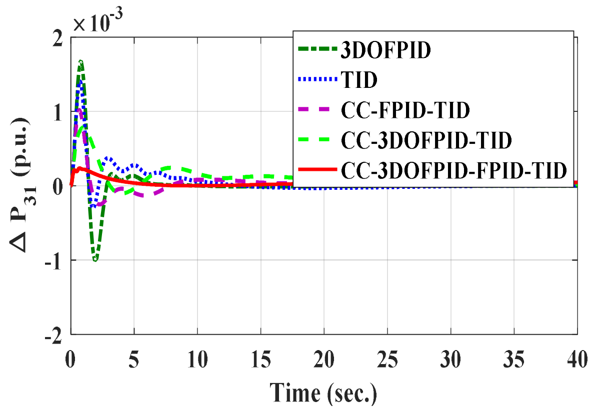



**Fig. 16**Tie power between area 3 and area 1

The controller cascaded-three degree of freedom–tilted integral derivative (CC-3DOF-TID), in which 3DOF-PID controller is used as secondary loop and TID controller is used as primary loop with governor action for this proposed three area LFC system. The controller parameters are optimized by ASOS algorithm to diminish the frequency oscillations. Also the cascade of 3DOF-PID, 3DOF, 2DOF and PID controllers are optimized by ASOS algorithm.

**Table3**. $U_{sh}$and$O_{sh}$ for 4-area hybrid power system at 1% SLP using different controllers

| **Performances** | Controller | $\Delta f_1$ *in Hz* | $\Delta f_2$ *in Hz* | $\Delta f_3$ *in Hz* | $\Delta P_{12}$ *in pu* | $\Delta P_{23}$ *in pu* | $\Delta P_{31}$ *in pu* |
|---|---|---|---|---|---|---|---|
| Undershoot ($U_{sh}$) in pu | 3DOFPID-FPID-TID | -0.0827 | -0.0148 | -0.0111 | -0.4421 | -0.0014 | -0.0005 |
| | FPID-PID | -0.1285 | -0.0699 | -0.0424 | -1.9523 | -1.8145 | -1.1900 |
| | 3DOFPID-TID | -0.1780 | -0.0726 | -0.0680 | -1.9799 | -1.9404 | -1.5024 |
| | TID | -0.2149 | -0.1103 | -0.1322 | -2.8962 | -2.2021 | -2.0317 |
| | 3DOFPID | -0.2333 | -0.1201 | -0.1772 | -3.1243 | -2.3076 | -2.5051 |
| Overshoot ($O_{sh}$) in pu | 3DOFPID-FPID-TID | 0.0115 | 0.0002 | 0.0000 | 0.0053 | 0.2044 | 0.2370 |
| | FPID-PID | 0.0326 | 0.0033 | 0.0037 | 0.1258 | 0.8590 | 0.8500 |
| | 3DOFPID-TID | 0.0382 | 0.0291 | 0.0293 | 0.2013 | 1.1135 | 1.1461 |
| | TID | 0.0453 | 0.0303 | 0.0324 | 0.2148 | 1.3113 | 1.4025 |
| | 3DOFPID | 0.0486 | 0.0408 | 0.0529 | 0.2271 | 1.4701 | 1.6748 |

The dynamic assessments of all these controllers are compared through extensive simulations. From the simulation results Figure 11 to Figure 16, the cascaded 3DOF-TID controller has reduced overshot and undershoot as compared to others. The cascaded 3DOF-TID controller optimized by ASOS algorithm settles quickly as compared to others. Further the performance of these controllers tuned by ASOS technique is mentioned in Table 3. Also the gain parameters of all these controllers optimized by ASOS algorithm are depicted in Table 4. There are 15 gain parameters such as ( $K_1, K_2, K_3, b_1, c_1, Gf_1, N_1$) for 3DOFPID controller, ($K_4, K_5, K_6, K_7$) for fuzzy PID controller and ( $K_8, K_9, K_{10}, n$) for TID controller for each area. Hence for three areas proposed system, 45 parameters are to be optimized by ASOS algorithm.

**Table 4** Gain values of controllers optimized by ASOS algorithm

| Control Areas | Gain parameters | 3DOFPID-FPID-TID controller | 3DOFPID-TID controller | FPID-TID controller | 3DOFPID controller | TID controller |
|---|---|---|---|---|---|---|
| Area 1 | $K_1$ | 1.5248 | 0.6454 | ------- | 2.0000 | 0.8790 |
| | $K_2$ | 0.3176 | 2.0000 | ------- | 2.0000 | 1.1269 |
| | $K_3$ | 1.6003 | 1.9353 | ------- | 0.3216 | 1.2097 |
| | $b_1$ | 1.4506 | 0.9169 | ------- | 0.8434 | ------- |
| | $c_1$ | 1.2033 | 1.2052 | -------- | 1.7969 | ------- |
| | $Gf_1$ | 0.0012 | 0.0100 | -------- | 1.8114 | ------- |
| | $N_1$ | 137.4861 | 100.0000 | -------- | 300.0000 | ------- |
| | $K_4$ | 1.5374 | ------- | 0.4025 | ------- | ------- |
| | $K_5$ | 1.5907 | ------- | 1.7167 | ------- | ------- |
| | $K_6$ | 1.9611 | ------- | 0.6517 | ------- | ------- |
| | $K_7$ | 1.5235 | ------- | 1.7273 | ------- | ------- |
| | $K_8$ | 0.9339 | 1.2354 | 1.1751 | -------- | ------- |
| | $K_9$ | 0.5160 | 0.6522 | 2.0000 | -------- | ------- |
| | $K_{10}$ | 0.7321 | 0.3715 | 0.0100 | ------- | ------- |
| | $n$ | 0.4232 | 0.2331 | 0.3765 | ------- | 0.3994 |
| Area 2 | $K_1$ | 0.4623 | 0.6676 | ------- | 0.9292 | 2.0000 |
| | $K_2$ | 0.8477 | 0.0611 | ------- | 1.0903 | 0.1000 |
| | $K_3$ | 0.5136 | 0.0100 | ------- | 1.9177 | 0.0100 |
| | $b_1$ | 0.0344 | 0.0100 | ------- | 1.3401 | ------- |
| | $c_1$ | 0.5464 | 1.3999 | -------- | 0.1051 | ------- |
| | $Gf_1$ | 0.5084 | 0.0100 | -------- | 1.3811 | ------- |
| | $N_1$ | 1.0895 | 100.000 | ------- | 118.4932 | -------- |
| | $K_4$ | 0.0100 | ------- | 0.2683 | ------- | ------- |
| | $K_5$ | 0.4314 | ------- | 1.0123 | ------- | ------- |
| | $K_6$ | 1.9773 | ------- | 1.2835 | ------- | -------- |

| | | | | | | |
|---|---|---|---|---|---|---|
| | $K_7$ | 0.1610 | ------- | 0.5922 | ------- | ------- |
| | $K_8$ | 0.7965 | 1.2263 | 1.8754 | ------- | ------- |
| | $K_9$ | 1.7372 | 1.1079 | 0.9757 | ------- | -------- |
| | $K_{10}$ | 0.2404 | 0.1465 | 0.0332 | ------- | ------- |
| | $n$ | 0.3443 | 0.0100 | 0.3243 | ------- | 0.1668 |
| Area 3 | $K_1$ | 1.5331 | 2.0000 | ------- | 1.4811 | 0.0632 |
| | $K_2$ | 1.2630 | 0.2298 | ------- | 1.0859 | 2.0000 |
| | $K_3$ | 0.5896 | 0.3027 | ------- | 0.0100 | 0.0100 |
| | $b_1$ | 0.2530 | 0.0100 | ------- | 0.1163 | ------- |
| | $c_1$ | 0.2334 | 0.6254 | ------- | 0.5479 | ------- |
| | $Gf_1$ | 1.0692 | 1.2436 | ------- | 1.5623 | ------- |
| | $N_1$ | 100.4839 | 103.1329 | ------- | 218.8336 | ------- |
| | $K_4$ | 0.7454 | ------- | 1.8754 | ------- | ------- |
| | $K_5$ | 1.0331 | ------- | 0.9757 | ------- | ------- |
| | $K_6$ | 1.2630 | ------- | 0.0100 | ------- | ------- |
| | $K_7$ | 0.6237 | ------- | 1.2992 | ------- | ------- |
| | $K_8$ | 1.2143 | 1.3551 | 1.6768 | ------- | ------- |
| | $K_9$ | 0.9632 | 0.6730 | 0.5439 | ------- | ------- |
| | $K_{10}$ | 0.6227 | 0.5433 | 0.2303 | ------- | ------- |
| | $n$ | 0.2505 | 0.3520 | 0.1522 | ------- | 0.4112 |

***5.3****SensitivityScrutiny*

This analysis is conceded to study the robustness of the system when the effectivesettings and system parameters vary within a definiteeasiness. Robustness of the power system is checked by varying the loading circumstances and system parameters from their nominal values in the range of +50% to -50% with 25% step size without changing the optimum values of CC-3DOFPID-FPID-TID controller parameters. A step load perturbation of 10% is applied to area 1 and robustness has tested for optimum CC-3DOFPID-FPID-TID parameters attained from ASOS algorithm. Result attained from sensitivity analysis for frequency deviations and tie line power deviations are given in Table 5 and Table 6 respectively. From Table 5 and Table 6, it is perceived that ASOS optimized cascaded 3DOFPID-FPID-TID controlled LFC system is fairly robust towards parametric distinction over an inclusive series.

**Table 5**Dynamic assessment due to parameter variations for frequency deviations of control areas

| Parameters | %age deviation | $T_s in\ sec$ | $\Delta f_1$ | | $\Delta f_2$ | | $\Delta f_3$ | |
|---|---|---|---|---|---|---|---|---|
| | | | $O_{sh}\ in\ pu$ | $U_{sh} in\ pu$ | $O_{sh}\ in\ pu$ | $U_{sh} in\ pu$ | $O_{sh}\ in\ pu$ | $U_{sh} in\ pu$ |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $D_1$ | +50 | 10.18 | 0.0175 | -0.1727 | 0.0233 | -0.0929 | 0.0319 | -0.0962 |
| | +25 | 11.69 | 0.0206 | -0.1382 | 0.0228 | -0.0733 | 0.0217 | -0.0833 |
| | -25 | 12.02 | 0.0186 | -0.1533 | 0.0193 | -0.0892 | 0.0198 | -0.0742 |
| | -50 | 13.19 | 0.0203 | -0.1596 | 0.0208 | -0.0816 | 0.0221 | -0.1092 |
| $D_2$ | +50 | 13.96 | 0.0744 | -0.2385 | 0.0370 | -0.1368 | 0.0124 | -0.0995 |
| | +25 | 14.92 | 0.1507 | -0.2127 | 0.3507 | -0.3651 | 0.0870 | -0.1092 |
| | -25 | 15.67 | 0.0195 | -0.2030 | 0.0236 | -0.1120 | 0.0281 | -0.1175 |
| | -50 | 16.83 | 0.0108 | -0.1617 | 0.0109 | -0.0781 | 0.0119 | -0.0756 |
| $D_3$ | +50 | 8.29 | 0.0112 | -0.1794 | 0.0102 | -0.0780 | 0.0099 | -0.1004 |
| | +25 | 7.07 | 0.0341 | -0.2127 | 0.0029 | -0.0918 | 0.0027 | -0.0970 |
| | -25 | 8.15 | 0.0126 | -0.2021 | 0.0099 | -0.0838 | 0.0095 | -0.1262 |
| | -50 | 10.54 | 0.0229 | -0.1625 | 0.0266 | -0.0991 | 0.0325 | -0.0943 |
| $M_1$ | +50 | 6.22 | 0.0355 | -0.2945 | 0.0332 | -0.1107 | 0.0316 | -0.1429 |
| | +25 | 7.06 | 0.0317 | -0.3936 | 0.0300 | -0.0995 | 0.0361 | -0.1326 |
| | -25 | 7.12 | 0.3464 | 0 | 0.0143 | 0 | 0.0115 | 0 |
| | -50 | 7.23 | 0.6958 | 0 | 0.0578 | 0 | 0.0487 | 0 |
| $M_2$ | +50 | 8.02 | 0.0544 | -0.2287 | 0.0403 | -0.1032 | 0.0594 | -0.1642 |
| | +25 | 8.87 | 0.0571 | -0.2291 | 0.0402 | -0.1026 | 0.0640 | -0.1665 |
| | -25 | 9.53 | 0.0079 | -0.0000 | 0.4710 | 0 | 0.0085 | -0.0000 |
| | -50 | 9.94 | 0.0139 | -0.0000 | 2.4770 | 0 | 0.0958 | -0.0000 |
| $M_3$ | +50 | 8.07 | 0.0469 | -0.2282 | 0.0312 | -0.1317 | 0.0318 | -0.1616 |
| | +25 | 9.10 | 0.0424 | -0.2293 | 0.0311 | -0.1432 | 0.0274 | -0.1500 |
| | -25 | 9.23 | 0.0745 | -0.0000 | 0.0922 | -0.0000 | 1.4220 | 0 |
| | -50 | 9.65 | 0.1162 | -0.0000 | 0.1339 | -0.0000 | 1.0730 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $R_1$ | +50 | 8.06 | 0.0525 | -0.2279 | 0.0271 | -0.0765 | 0.0675 | -0.1408 |
| | +25 | 8.73 | 0.0638 | -0.2289 | 0.0164 | -0.0483 | 0.0859 | -0.1290 |
| | -25 | 9.07 | 0 | -0.0710 | 0 | -2.2367 | 0 | -0.0730 |
| | -50 | 9.39 | 0 | -0.0759 | 0 | -0.6470 | 0 | -0.0779 |
| $R_2$ | +50 | 8.29 | 0.0525 | -0.2279 | 0.0271 | -0.0765 | 0.0675 | -0.1408 |
| | +25 | 7.80 | 0.0638 | -0.2289 | 0.0164 | -0.0483 | 0.0809 | -0.1290 |
| | -25 | 8.96 | 0 | -0.0710 | 0 | -2.2367 | 0 | -0.0730 |
| | -50 | 9.24 | 0 | -0.0759 | 0 | -0.6470 | 0 | -0.0779 |
| $R_3$ | +50 | 9.17 | 0.0515 | -0.2276 | 0.0443 | -0.1134 | 0.0546 | -0.1502 |
| | +25 | 11.69 | 0.0539 | -0.2275 | 0.0470 | -0.1129 | 0.0566 | -0.1460 |
| | -25 | 12.86 | 0.0610 | -0.2275 | 0.0551 | -0.1119 | 0.0636 | -0.1371 |
| | -50 | 14.28 | 0.0660 | -0.2275 | 0.0609 | -0.1113 | 0.0688 | -0.1324 |
| $B_1$ | +50 | 11.02 | 0.0788 | -0.2770 | 0.0503 | -0.1449 | 0.0589 | -0.1976 |
| | +25 | 12.24 | 0.1117 | -0.3088 | 0.0583 | -0.1656 | 0.0674 | -0.2239 |
| | -25 | 13.58 | 0.2541 | -0.3982 | 0.0957 | -0.2233 | 0.1484 | -0.3001 |
| | -50 | 14.02 | 1.6185 | -1.6762 | 0.3291 | -0.3438 | 0.9191 | -0.8682 |
| $B_2$ | +50 | 8.5 | 0.0522 | -0.2276 | 0.0490 | -0.1537 | 0.0489 | -0.1744 |
| | +25 | 10.81 | 0.0595 | -0.2279 | 0.0733 | -0.1841 | 0.0474 | -0.1866 |
| | -25 | 11.61 | 0.0907 | -0.0679 | 0.3008 | -0.2250 | 0.0603 | -0.0629 |
| | -50 | 11.92 | 0.0721 | -0.0404 | 0.2094 | -0.3879 | 0.0811 | -0.0441 |
| $B_3$ | +50 | 8.6 | 0.0380 | -0.2276 | 0.0328 | -0.1158 | 0.0453 | -0.1713 |
| | +25 | 9.07 | 0.0306 | -0.2276 | 0.0274 | -0.1164 | 0.0393 | -0.1788 |
| | -25 | 12.55 | 0.0116 | -0.2276 | 0.0111 | -0.1175 | 0.0222 | -0.1949 |
| | -50 | 15.23 | 0.0030 | -0.2276 | 0.0030 | -0.1181 | 0.0099 | -0.2040 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $R_t$ | +50 | 7.79 | 0.0394 | -0.2276 | 0.0306 | -0.1138 | 0.0306 | -0.1341 |
| | +25 | 8.44 | 0.0289 | -0.2277 | 0.0182 | -0.1128 | 0.0142 | -0.1077 |
| | -25 | 9.22 | 0 | -0.1394 | 0 | -0.1533 | 0 | -0.8495 |
| | -50 | 9.67 | 0 | -0.0454 | 0 | -0.0465 | 0 | -0.1319 |
| $T_1$ | +50 | 9.27 | 0.0504 | -0.2573 | 0.0560 | -0.1527 | 0.0844 | -0.2137 |
| | +25 | 10.57 | 0.0514 | -0.2803 | 0.0690 | -0.1908 | 0.1022 | -0.2542 |
| | -25 | 17.04 | 0.0431 | -0.3915 | 0.0501 | -0.3512 | 0.0738 | -0.4098 |
| | -50 | 17.53 | 0 | -0.1048 | 0 | -0.0908 | 0 | -0.0896 |
| $T_2$ | +50 | 8.91 | 0.0466 | -0.2264 | 0.0268 | -0.0782 | 0.0609 | -0.1352 |
| | +25 | 9.78 | 0.0578 | -0.2264 | 0.0159 | -0.0481 | 0.0809 | -0.1224 |
| | -25 | 14.69 | 0.1772 | -0.2262 | 0.0872 | -0.0136 | 0.2144 | -0.0981 |
| | -50 | 14.91 | 36.7488 | -0.2261 | 42.3473 | 0 | 36.2271 | -0.0882 |
| $T_3$ | +50 | 8.87 | 0.0368 | -0.2272 | 0.0390 | -0.1030 | 0.0528 | -0.1090 |
| | +25 | 9.81 | 0.0617 | -0.2270 | 0.0278 | -0.0974 | 0.0395 | -0.0668 |
| | -25 | 10.08 | 0.1828 | -0.2267 | 0.1487 | -0.1272 | 0.1456 | -0.1445 |
| | -50 | 10.69 | 0.3530 | -0.0909 | 0.3525 | -0.0909 | 0.4355 | -0.0973 |
| $T_{g1}$ | +50 | 9.69 | 0.0445 | -0.2066 | 0.0395 | -0.1082 | 0.0523 | -0.1512 |
| | +25 | 9.67 | 0.0430 | -0.1968 | 0.0392 | -0.1062 | 0.0531 | -0.1492 |
| | -25 | 11.22 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -50 | 11.36 | 0 | 0 | 0 | 0 | 0 | 0 |
| $T_{g2}$ | +50 | 9.2 | 0.0481 | -0.2279 | 0.0410 | -0.1113 | 0.0532 | -0.1585 |
| | +25 | 9.64 | 0.0479 | -0.2290 | 0.0415 | -0.1109 | 0.0546 | -0.1590 |
| | -25 | 10.32 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -50 | 10.61 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $T_{g3}$ | +50 | 8.33 | 0.0441 | -0.2276 | 0.0385 | -0.1141 | 0.0482 | -0.1528 |
| | +25 | 8.90 | 0.0427 | -0.2276 | 0.0377 | -0.1137 | 0.4076 | -0.1502 |
| | -25 | 9.01 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -50 | 9.39 | 0 | 0 | 0 | 0 | 0 | 0 |
| $T_{CH1}$ | +50 | 9.54 | 0.0371 | -0.1811 | 0.0336 | -0.0951 | 0.0423 | -0.1366 |
| | +25 | 11.08 | 0.0341 | -0.1533 | 0.0319 | -0.0932 | 0.0405 | -0.1299 |
| | -25 | 12.31 | 0 | -0 | 0 | 0 | 0 | 0 |
| | -50 | 12.82 | 0 | -1.2424 | 0. | -0.0353 | 0 | -0.0285 |
| $T_{CH2}$ | +50 | 9.18 | 0.0476 | -0.2282 | 0.0391 | -0.1055 | 0.0512 | -0.1573 |
| | +25 | 9.63 | 0.0455 | -0.2288 | 0.0382 | -0.1040 | 0.0510 | -0.1570 |
| | -25 | 10.37 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -50 | 11.54 | 0.0094 | -0.0000 | 0.6476 | -0.0000 | 0.0101 | -0.0000 |
| $T_r$ | +50 | 9.03 | 0.0531 | -0.2276 | 0.0446 | -0.1448 | 0.0574 | -0.1571 |
| | +25 | 9.57 | 0.0597 | -0.2276 | 0.0495 | -0.1147 | 0.0632 | -0.1546 |
| | -25 | 10.30 | 0.0000 | -0.1234 | 0.0000 | -0.1234 | 0.0000 | -0.1791 |
| | -50 | 10.68 | 0.0000 | -0.2365 | 0.0000 | -0.2364 | 0.0000 | -0.2969 |
| $T_w$ | +50 | 9.89 | 0.0515 | -0.2276 | 0.0445 | -0.1149 | 0.0584 | -0.1618 |
| | +25 | 10.24 | 0.0554 | -0.2276 | 0.0478 | -0.1150 | 0.0644 | -0.1658 |
| | -25 | 10.97 | 0 | -0.0881 | 0 | -0.1112 | 0 | -2.1969 |
| | -50 | 11.33 | 0.0249 | -0.0000 | 0.0278 | -0.0000 | 0.1758 | --0.0000 |
| $T_{12}$ | +50 | 9.82 | 0.0486 | -0.2276 | 0.0408 | -0.1148 | 0.0529 | -0.1583 |
| | +25 | 9.82 | 0.0486 | -0.2276 | 0.0408 | -0.1148 | 0.0529 | -0.1583 |
| | -25 | 9.82 | 0.0486 | -0.2276 | 0.0408 | -0.1148 | 0.0529 | -0.1583 |
| | -50 | 9.82 | 0.0486 | -0.2276 | 0.0408 | -0.1148 | 0.0529 | -0.1583 |

**Table 6**Dynamic assessment due to parameter variations for tie power deviations among control areas

| Parameters | %age deviation | $\Delta P_{12}$ | | $\Delta P_{23}$ | | $\Delta P_{31}$ | |
|---|---|---|---|---|---|---|---|
| | | $O_{sh}$ *in pu* | $U_{sh}$*in pu* | $O_{sh}$ *in pu* | $U_{sh}$*in pu* | $O_{sh}$ *in pu* | $U_{sh}$*in pu* |
| $D_1$ | +50 | 0.0174 | -2.0820 | 1.0729 | -0.2576 | 1.0091 | -0.1082 |
| | +25 | 0.1503 | -1.7556 | 0.9975 | -0.2873 | 0.8464 | -0.0258 |
| | -25 | 0.0409 | -1.8858 | 1.0607 | -0.2916 | 0.8441 | -0.0650 |
| | -50 | 0.1537 | -1.9465 | 1.1210 | -0.2227 | 1.0377 | -0.0303 |
| $D_2$ | +50 | 0.4408 | -3.1908 | 1.7198 | -0.4516 | 1.4710 | -0.4216 |
| | +25 | 1.8981 | -2.7542 | 3.4296 | -3.3607 | 1.8445 | -1.8822 |
| | -25 | 0.2128 | -2.8299 | 1.4697 | -0.1039 | 1.3602 | -0.2895 |
| | -50 | 0.0177 | -1.8611 | 0.9452 | -0.1336 | 0.9381 | -0.0731 |
| $D_3$ | +50 | 0.0146 | -2.1683 | 1.0868 | -0.1318 | 1.0815 | -0.0293 |
| | +25 | 0 | -2.5622 | 1.2073 | -0.0390 | 1.3550 | -0.0319 |
| | -25 | 0.0192 | -2.4851 | 1.1328 | -0.1642 | 1.3523 | -0.3805 |
| | -50 | 0.2756 | -2.2047 | 1.2238 | -0.3061 | 0.9899 | -0.2411 |
| $M_1$ | +50 | 0.0137 | -3.0313 | 1.4129 | -0.4020 | 1.6355 | -0.1964 |
| | +25 | 0.0142 | -2.7274 | 1.3231 | -0.3597 | 1.4238 | -0.1196 |
| | -25 | 1.1656 | 0 | 0 | -0.5755 | 0 | -0.5901 |
| | -50 | 3.3990 | 0 | 0 | -1.6632 | 0 | -1.7359 |
| $M_2$ | +50 | 0.1161 | -3.0793 | 1.3168 | -0.4829 | 1.7948 | -0.4894 |
| | +25 | 0.1306 | -3.0749 | 1.3057 | --0.4861 | 1.8072 | -0.5238 |
| | -25 | 0 | -0.5862 | 1.1704 | 0 | 0.0000 | -0.5842 |
| | -50 | 0 | -4.5519 | 9.9027 | 0 | 0.0000 | -4.5408 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $M_3$ | +50 | 0.1435 | -2.9393 | 1.6702 | -0.3782 | 1.3191 | -0.0258 |
| | +25 | 0.1237 | -2.7630 | 1.8153 | -0.3754 | 1.0006 | -0.0254 |
| | -25 | 0 | -3.0957 | 0.0000 | -2.9756 | 6.0713 | 0 |
| | -50 | 0 | -3.4031 | 0.0000 | -3.2172 | 6.6209 | 0 |
| $R_1$ | +50 | 0.2552 | -3.2999 | 1.8719 | -0.6142 | 1.5739 | -0.6323 |
| | +25 | 0.3876 | -3.4629 | 2.3503 | -0.7184 | 1.4690 | -0.8585 |
| | -25 | 3.7692 | -0.0000 | 0.0000 | -7.5281 | 3.7589 | 0 |
| | -50 | 2.1281 | -0.0000 | 0.0000 | -4.2339 | 2.1057 | 0 |
| $R_2$ | +50 | 0.2552 | -3.2999 | 1.8719 | -0.6142 | 1.5739 | -0.6323 |
| | +25 | 0.3876 | -3.4629 | 2.3503 | -0.7184 | 1.4690 | -0.8588 |
| | -25 | 3.7692 | -0.0000 | 0.0000 | -7.5281 | 3.7589 | 0 |
| | -50 | 2.1281 | -0.0000 | 0.0000 | -4.2339 | 2.1057 | 0 |
| $R_3$ | +50 | 0.0228 | -3.1796 | 1.4372 | -0.5408 | 1.7425 | -0.2576 |
| | +25 | 0.0310 | -3.1883 | 1.4290 | -0.5777 | 1.7593 | -0.1632 |
| | -25 | 0.0703 | -3.2060 | 1.4124 | -0.6860 | 1.7936 | -0.1403 |
| | -50 | 0.1221 | -3.2149 | 1.4039 | -0.7619 | 1.8110 | -0.2440 |
| $B_1$ | +50 | 0.3417 | -3.9757 | 1.8363 | -0.6094 | 2.1394 | -0.6545 |
| | +25 | 0.6543 | -4.5304 | 2.1006 | -0.7086 | 2.4298 | -0.8675 |
| | -25 | 2.3160 | -6.0558 | 2.8422 | -1.1783 | 3.2266 | -1.5490 |
| | -50 | 19.2958 | -20.2101 | 4.3595 | -4.1516 | 16.0066 | -15.4990 |
| $B_2$ | +50 | 0.0428 | -3.0673 | 1.3011 | -0.4483 | 1.8169 | -0.3826 |
| | +25 | 0.1501 | -3.0071 | 1.2450 | -0.6345 | 1.9083 | -0.4201 |
| | -25 | 1.0417 | -1.4008 | 3.0036 | -2.2466 | 1.2335 | -1.6639 |
| | -50 | 1.7684 | -1.0694 | 2.4259 | -3.7697 | 2.0013 | -1.3802 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $B_3$ | +50 | 0.1219 | -3.1509 | 1.4644 | -0.3911 | 1.6865 | -0.8081 |
| | +25 | 0.2271 | -3.1449 | 1.4701 | -0.3214 | 1.6748 | -1.0209 |
| | -25 | 0.5299 | -3.1326 | 1.4819 | -0.1089 | 1.6506 | -1.5325 |
| | -50 | 0.7168 | -3.1262 | 1.4881 | -0.0396 | 1.6381 | -1.8365 |
| $R_t$ | +50 | 0.1614 | -3.1746 | 1.4410 | -0.3682 | 1.7336 | -0.0144 |
| | +25 | 0.2310 | -3.1976 | 1.4198 | -0.2139 | 1.7986 | -0.0435 |
| | -25 | 3.3708 | -0.0000 | 3.1760 | 0 | 0.0000 | -6.5468 |
| | -50 | 0.7965 | -0.0000 | 0.7659 | 0 | 0.0000 | -1.5625 |
| $T_1$ | +50 | 0.0345 | -2.0356 | 1.9628 | -0.6805 | 2.1651 | -0.4760 |
| | +25 | 0.0244 | -1.2030 | 2.4632 | -0.8353 | 2.5019 | -0.3883 |
| | -25 | 1.9485 | -0.0668 | 4.5346 | -0.5394 | 3.6703 | -0.2019 |
| | -50 | 1.4211 | 0 | 1.2336 | 0 | 1.6085 | 0 |
| $T_2$ | +50 | 0.2514 | -3.3846 | 0.9995 | -0.3240 | 1.5040 | -0.5894 |
| | +25 | 0.3920 | -3.5181 | 0.6159 | -0.1908 | 1.4031 | -0.8271 |
| | -25 | 0.6499 | -3.9214 | 0.1491 | -1.1265 | 1.2248 | -2.0182 |
| | -50 | 0 | -498.190 | 0 | -575.007 | 1.1371 | -651.824 |
| $T_3$ | +50 | 0.1456 | -3.3566 | 1.3012 | -0.4827 | 1.0788 | -0.1526 |
| | +25 | 0.2593 | -3.4999 | 1.2286 | -0.3453 | 0.6291 | -0.0434 |
| | -25 | 1.4624 | -3.8771 | 1.6174 | -1.9067 | 0.7697 | -1.0551 |
| | -50 | 1.1637 | -4.6524 | 1.1055 | -4.7566 | 1.1760 | -4.7050 |
| $T_{G1}$ | +50 | 0.0749 | -2.9707 | 1.3748 | -0.4813 | 1.5982 | -0.3679 |
| | +25 | 0.0672 | -2.9068 | 1.3553 | -0.4771 | 1.5557 | -0.3527 |
| | -25 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -50 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $T_{G2}$ | +50 | 0.1057 | -3.1792 | 1.4716 | -0.5223 | 1.7076 | -0.4374 |
| | +25 | 0.1104 | -3.1981 | 1.4927 | -0.5399 | 1.7156 | -0.4513 |
| | -25 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -50 | 0 | 0 | 0 | 0 | 0 | 0 |
| $T_{G3}$ | +50 | 0.0777 | -3.1694 | 1.4465 | -0.4676 | 1.7229 | -0.3994 |
| | +25 | 0.0690 | -3.1752 | 1.4407 | -0.4583 | 1.7345 | -0.4015 |
| | -25 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -50 | 0 | -3.0535 | 0.0000 | -3.0034 | 0.0570 | 0 |
| $T_{CH1}$ | +50 | 0.0225 | -2.6029 | 1.2192 | -0.4076 | 1.4007 | -0.1962 |
| | +25 | 0.0136 | -2.4521 | 1.2025 | -0.3841 | 1.3020 | -0.1484 |
| | -25 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -50 | 0 | -3.4721 | 1.7214 | 0 | 1.7507 | 0 |
| $T_{CH2}$ | +50 | 0.1184 | -3.1601 | 1.4612 | -0.5454 | 1.7135 | -0.4274 |
| | +25 | 0.1304 | -3.1631 | 1.4830 | -0.5742 | 1.7097 | -0.4303 |
| | -25 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -50 | 0 | -0.7507 | 1.4988 | 0 | 0.0000 | -0.7481 |
| $T_r$ | +50 | 0.0819 | -3.1626 | 1.4532 | -0.5430 | 1.7093 | --0.3628 |
| | +25 | 0.1021 | -3.1627 | 1.4531 | -0.6090 | 1.7096 | -0.2593 |
| | -25 | 1.7924 | -0.0000 | 1.7313 | -0.0000 | 0.0000 | -3.4606 |
| | -50 | 3.2354 | -0.0032 | 3.2437 | -0.0003 | 0.0017 | -6.4791 |
| $T_w$ | +50 | 0.0660 | -3.1619 | 1.4539 | -0.5438 | 1.7080 | -0.5338 |
| | +25 | 0.0620 | -3.1609 | 1.4550 | -0.5856 | 1.7059 | -0.6081 |
| | -25 | 4.1815 | -0.0000 | 4.0457 | 0 | 0.0000 | -8.2273 |
| | -50 | 0 | -0.6433 | 0.0000 | -0.6063 | 1.2497 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $T_{12}$ | +50 | 0.0971 | -3.1625 | 1.4533 | -0.4946 | 1.7092 | -0.4265 |
| | +25 | 0.0971 | -3.1625 | 1.4533 | -0.4946 | 1.7092 | -0.4265 |
| | -25 | 0.0971 | -3.1625 | 1.4533 | -0.4946 | 1.7092 | -0.4265 |
| | -50 | 0.0971 | -3.1625 | 1.4533 | -0.4946 | 1.7092 | -0.4265 |

In this case, a random load form is considered as disturbance for electrical system. Gains and other parameters of cascaded 3DOFPID-FPID-TID controller are optimised using the ASOS technique. With acquired optimal standards, the dynamic responses for frequency and interchange power deviations are plotted and compared in Figure 17 and Figure 18. It is realized from the responses that the cascaded 3DOFPID-FPID-TID controller delivers the system responses with shortened fluctuations as compared to single loop controllers and two loop cascaded FPID-TID and 3DOFPID-TID controller.

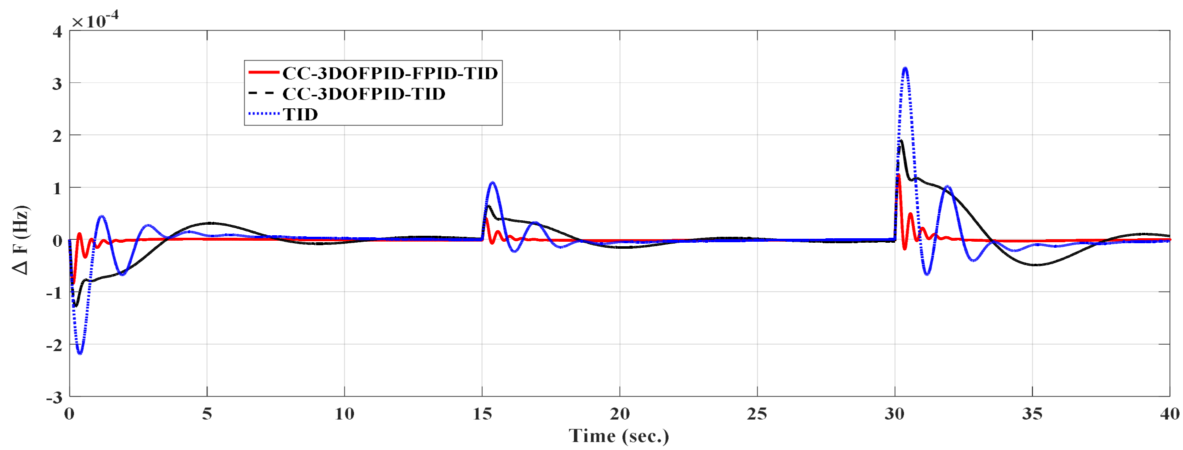



**Fig. 17** Effect of random load perturbation for frequency deviation using secondary controller

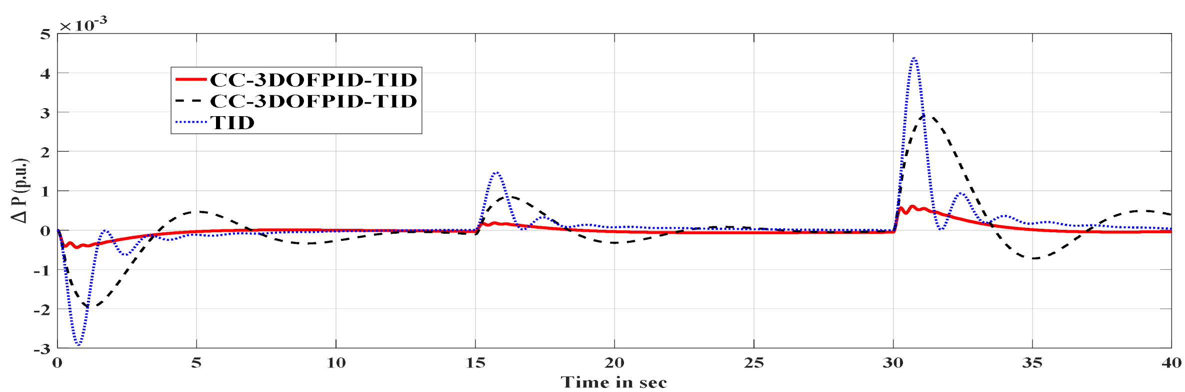



**Fig. 18** Effect of random load perturbation for tie power deviation using secondary controller

## 5. Conclusion:

A novel 3DOFPID-FPID controller cascaded with TID controller is applied to three area hybrid power system. Hybrid power is the combination of conventional thermal and hydro with distributed generation resources. Here area 1, area 2 are the thermal generating units and area 3 is the hydro generating unit. DGR is applied to only area 1. The controller parameters are optimized by a recent heuristic optimization technique ASOS. This technique has better dynamic response as compared to other algorithms such as SOS and ALO. The ASOS based controller has minimum oscillation and peak overshoot as compared to ALO based and SOS based controller.ASOS based 3DOFPID-FPID-TID controller has minimum value of settling time (4.16 sec) as compared to SOS based (7.35 sec) and ALO based (9.29 sec) controller for frequency variation in control area 1. The dynamic performances of this proposed system has compared for all the controllers like 3DOFPID, TID, cascaded 3DOFPID with TID, cascaded FPID with TID and cascaded 3DOFPID-FPID with TID controller. The later one has better stability criteria and also better dynamic performances such as less overshoot and undershoots with less settling time. Sensitivity analysis also reveals that 3DOFPID-FPID-TID controller gains are quite reorganized for changed loading settings. The future scope of this paper is to the study the effect of cascaded fractional order controller with advanced heuristic optimization techniques.

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**Nomenclature**

| System parameters | Values | Time constant (sec) | Gain coefficient |
|---|---|---|---|
| Frequency (f) in Hz | 50 | | |
| Steam turbine ($T_{CH}$) | ------ | 0.3 | ------ |
| Speed Governor for thermal unit ($T_G$) | ------ | 0.1 | ------ |
| Speed Governor for hydro unit($T_G$) | ------ | 0.2 | ------ |
| Inertia constant (M) for thermal unit | ------ | 10 | ------ |
| Inertia constant (M) for hydro unit | ------ | 6 | ------ |
| Wind turbine generator (WTG) | ------ | 1.5 | 0.000833 |
| Fuel cell (FC) | ------ | 0.5 | 0.02 |
| Aqua electrolyser (AE) | ------ | 4 | 0.01 |
| Diesel engine generator (DEG) | ------ | 2 | 0.0003 |
| Battery energy storage system (BESS) | ------ | 0.1 | -0.0003 |
| Frequency bias coefficient (B) | 0.425 | ------ | ------ |
| System damping (D) | 1 | ------ | ------ |
| Speed regulation (R) | 0.08 | ------ | ------ |
| Transient droop regulation ($R_t$) | 0.38 | ------ | ------ |
| Reset time ($T_r$) | | 5 | ------ |
| Start time of water ($T_w$) | | 1 | |

| | | | |
|---|---|---|---|
| Synchronizing power coefficient ($T_i$) | 15 | ------ | ------ |
| Tie line power deviation ($\Delta P_{tie}$) | 0.06 | ------ | ------ |