

Optimal LFC Regulator for Frequency Regulation in Multi Area Power System



V. Santoshi Raju and P. Venkatesh

Abstract In a power system, frequency control is more sensitive to the variations of load. So, it needs proper balancing of generation and load demand. Linear controllers such as proportional integral (PI) do not account the non-linearity of the system. Their performance with non-linear power system may be ineffective. This project will present Sliding Mode Control (SMC) which has distinguished properties of accuracy, robustness and easy tuning performance. Due to these advantages SMC technique is effectual for LFC and most vigorous to the base parameter and uncertainties. The anticipated controller is set side by side with Proportional-Integral Derivative (PID), Tilt-Integral Controller (TID) and Fractional Order PID (FOPID) controllers for performance analysis and Grey Wolf Optimization (GWO) will be used to tune the parameters of controllers in Load Frequency Control (LFC). The proposed controller is applied to two area single unit LFC power system consist of thermal unit. To validate the usefulness of controllers, Integral of the Time Weighted Absolute Error (ITEA) performance index will be considered and 1% step load change will be applied. The resulting power system will be modelled and simulated in MATLAB/SIMULINK environment. The proposed work is effective in maintaining the frequency deviation, undershoots and overshoots of the power system to zero in a considerably less time with SMC compared to other controllers.

Keywords Proportional-integral-derivative (PID) · Tilt-integral-derivative (TID) · Fractional order-proportional-integral-derivative (FOPID) · Sliding mode controller (SMC) · Grey wolf optimization (GWO)

1 Introduction

Frequency deviation control in the power system is the most general strategy for the efficient operation of power systems [1–5]; hence the power demand should be coordinated to the power generation whenever source and load varies [1]. The Load

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Frequency Control (LFC) will make sure that the steady state errors in the power system will be maintained zero throughout the operation for a two area power system, where the two areas are coupled all the way through a tie-line [6]. The operation of LFC also includes to curtail the unexpected tie-line power flows between interrelated adjacent areas and also to curb the transient variations of multi area frequencies. The most intricate problem in LFC is when power transaction takes place between interconnected multi areas, when uncertainties rises in distributed generator and model parameters [7]. In a conventional LFC, Area Control Error (ACE), also termed as control input signal compromises of multi area tie-line power exchanges and local area frequency [8]. In order to meet up with the grid performance levels, the widely used controller to control the ACE is Proportional-Integral (PI) controllers. In order to tune the parameters of PI controller many intelligent optimization techniques are used which will enhance dynamics of the controller and also used to improve the robustness of the controller in conditions power system function state variations [9] and [10].

In the contemporary days, bunch of recent direct strategy came into existence like optimal control techniques [2], distributed control techniques [3], robust control technique [11] and hybrid control algorithms, are significantly used for LFC design [12]. On comparing all the controllers, Sliding Mode Control (SMC) dynamics has a unique feature which can be modelled regardless of disturbances and system parameters, which will enhance the robustness and response speed of LFC [4]. For a two area single unit LFC, second-order SMC and extended disturbance observer is proposed in [13].

This paper proposes a second-order SMC algorithm with an additional extended disturbance observer for a two area LFC scheme. In order to trim down the intricacy of the power system, the load change and the tie-line power are considered as one single parameter, i.e. lumped disturbance parameter so that the order of the power system will be reduced then the extended disturbance observer is used to estimate the lumped disturbance parameter. SMC requires a sliding surface calculated through state variable transformation which compels the frequency deviation to zero without an integral unit. Here, sliding surface matrix is used to tune the system dynamics and desirable sliding surface matrix can be calculated through optimal sliding manifold design or Eigen value assignment method. During load variations, if the scheduled power requires any changes, the modelled scheme will work more efficiently. In order to eliminate the chattering effect, the second-order sliding mode control technique along with super-twisting algorithm is engaged which will compel the sliding surface to reach the sliding surface, respectively. Therefore, the modelled robust LFC can effectively utilize the benefits of SMC and thus it permits very low real-time computational burden.

2 Grey Wolf Optimization (GWO)

Grey wolf optimization (GWO) technique is the latest meta-heuristic methods proposed by Mirjalili et al. in 2014 [5]. Grey wolves lives in packs and is considered to be at the peak of the food chain. In Grey wolves, they are further divided into 4 sub-groups, i.e. alpha (α), beta (β), delta (δ), and omega (ω) and alpha (α) category is considered to be the top of all the wolf's in ranking and hence alpha (α) is considered to be the healthy solution and the second, third and fourth best are beta (β), delta (δ) and omega (ω) [14].

Generally, Grey wolf's follow a particular and rare strategy to attack the prey. Initially, they hunt, chase and attack the prey, and then they blockade the prey and finally attack the prey.

The encircling behaviour of Grey wolf can be represented in Eqs. (1) and (2):

$$\vec{D} = \left| \vec{C} \cdot \vec{X}_p(t) - \vec{X}_p(t) \right| \tag{1}$$

$$\vec{X}(t + 1) = \vec{X}_p(t) - \vec{A} \cdot \vec{D} \tag{2}$$

where T is present iteration, C , D and A is vector coefficient, X_p is prey's tracking vector and X is Grey wolf's tracking vector.

The vector A and C can be estimated as shown in Eqs. (3) and (4):

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \tag{3}$$

$$\vec{C} = 2 \cdot \vec{r}_2 \tag{4}$$

r_1 and r_2 are the arbitrary vectors and 'a' decreases from 2 to 0 during the repetition. The chase is leaded by alpha (α), beta (β), delta (δ) and omega (ω). One of the advantages of GWO algorithm is it is simple to apply due to its simplex composition, low required memory and computational necessity [14].

3 Fractional Order Controllers

PI controller is the most conventional controller and is widely used to tune the parameters of LFC in power system. Day by day, as the order of LFC increases and multiple areas are inter-connected through the tie-line which enhances intricacy of the power system and degrading the performances of the orthodox controllers. In order to increase the effectiveness of the power system, a non-integer order control or a fractional order control (FOC) came into existence which is purely based on fractional calculus. There are different kinds of FOC's like Tilt Integral Controller (TID), fractional order PID (FOPID).

3.1 Tilt-Integral-Derivative (TID) Controller

TID controller is the FOC which is used to finely tune the LFC parameters. Since it is a non-linear controller, TID generally works on three controllers (T , I , D) and an additional parameter (n) is used here for tuning purpose. TID controller is almost same like a PID controller, but the proportional characteristics are substituted by tilt a proportional characteristic (represented by the transfer function $(s^{-\frac{1}{n}})$) which provides a frequency function called feedback gain and it is tilted with reference to the gain of the traditional controller. On comparison to PID, TID controller offers high level of flexibility to control variables.

$$g(s, \beta) = \frac{T}{S^{\frac{1}{n}}} + \frac{T}{S} + Ds \quad (5)$$

where

$$\beta = \begin{bmatrix} T \\ I \\ D \\ n \end{bmatrix} \in R^4 \quad (6)$$

and $n \in R$ and $n \neq 0$ and $2 < n < 3$, $u(s)$ is control signal, $r(s)$ is reference signal $e(s)$ is error signal, $y(s)$ is output signal and $g(s, \beta)$ is transfer function of TID controller [$s \in Z$, $\beta \in R$].

3.2 Fractional Order PID (FOPID) Controller

FOPID is the extension of PID controller which is purely based on fractional order differential calculus. FOPID gives better response than conventional controllers due to presence of five parameters that gives good design flexibility to design the derivative and integral components. λ and μ are additional parameters to the conventional PID in FOPID and can be expressed as $PI^\lambda D^\mu$. The two additional parameters λ of integration and μ of derivative also made the tuning of the new FOPID controller more flexible.

The transfer function of FOPID controller can be represented as Eq. (7):

$$G(s) = \frac{U(s)}{E(s)} = K_p + K_I \frac{1}{s^\lambda} + K_D s^\mu \quad (7)$$

where K_p is proportional gain, K_D is differential gain, K_I is integral gain, λ is degree of integration and μ is degree of differentiation.

The $PI^\lambda D^\mu$ controller is more accurate and gives a prospect to further regulate the variations in control system.

4 Sliding Mode Controller (SMC)

The i th area system dynamics of a multi area inter-connected power system can be represented as shown below (Eqs. 8–11) [4]. The frequency and the power exchange between the LFC's of inter-connected areas in a multi area power system should be maintained constant throughout the operation [4].

$$\Delta \dot{f}_i = \frac{1}{2H_i} \Delta P_{mi} - \frac{1}{2H_i} \Delta P_{Li} - \frac{D_i}{2H_i} \Delta f_i - \frac{1}{2H_i} \Delta P_{tie,i} \quad (8)$$

$$\Delta \dot{P}_{mi} = \frac{1}{T_{ii}} \Delta P_{gi} - \frac{1}{T_{ii}} \Delta P_{mi} \quad (9)$$

$$\Delta \dot{P}_{gi} = \frac{1}{T_{gi}} \Delta P_{ci} - \frac{1}{R_i T_{gi}} \Delta f_i - \frac{1}{T_{ti}} \Delta P_{gi} \quad (10)$$

$$\Delta \dot{P}_{tie,i} = 2\pi \sum_{j=1, j \neq i}^N T_{ij} (\Delta f_i - \Delta f_j) \quad (11)$$

This LFC model is as it is taken from [4] because the research studies reveal that this LFC model is more practical and reliable and will give results without disturbing the accuracy of the system.

Where i is the area of the system, Δf_i is fluctuations in system frequency, ΔP_{mi} is output of synchronous machine, ΔP_{gi} is position of valve, ΔP_{ci} is output of the controller, ΔP_{Li} is load variations, T_{ij} is tie-line coefficient, H_i is synchronous machine inertia, D_i is damping coefficient of machine, T_{gi} is the governor time constant, T_{ti} is the turbine time constant, R_i is the speed drop, $\Delta P_{tie,i}$ is the deviation between the actual and the scheduled power flows.

$\Delta P_{tie,i}$ Can be evaluated as:

$$\Delta P_{tie,i} = \sum_{j=1, j \neq i}^N (\Delta P_{tie,actj} - \Delta P_{tie,schedj}) \quad (12)$$

In the classical matrix form, the system changes can be written as:

$$\dot{x}_i(t) = \bar{A}_i x_i(t) + \bar{B}_i u_i(t) + \bar{F}_i \Delta P_{Li} \quad (13)$$

where

$$\text{State variable matrix: } x_i(t) = [\Delta f_i \ \Delta P_{mi} \ \Delta P_{gi} \ \Delta P_{tie,i}]^T,$$

Control input: $u_i = P_{ci}$,

$$\bar{A}_i = \begin{bmatrix} -\frac{D}{2H_i} & \frac{1}{2H_i} & 0 & -\frac{1}{2H_i} \\ 0 & -\frac{1}{T_{ii}} & \frac{1}{T_{ii}} & 0 \\ -\frac{1}{R_i T_{gi}} & 0 & -\frac{1}{T_{gi}} & 0 \\ 2\pi \sum_{j=1, j \neq i}^N T_{ij} & 0 & 0 & 0 \end{bmatrix}, \bar{B}_i = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{gi}} \\ 0 \end{bmatrix}, \text{ and } \bar{F}_i = \begin{bmatrix} -\frac{1}{2H_i} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The transfer function for hydro turbine is

$$G_{\text{hydro}} = \frac{1 - T_{ti}s}{1 + 0.5T_{ti}s}$$

Now the LFC model of a multi area power system can be inscribed as:

$$\dot{x}_i(t) = \hat{A}_i x_i(t) + \hat{B}_i u_i(t) + \hat{F}_i \Delta P_{Li} \tag{14}$$

where

The state variable matrix: $x_i(t) = [\Delta f_i \ \Delta P_{mi} \ \Delta P_{gi} \ \Delta P_{tie,i}]^T$,

Control input: $u_i = P_{ci}$,

$$\hat{A}_i = \begin{bmatrix} -\frac{D}{2H_i} & \frac{1}{2H_i} & 0 & -\frac{1}{2H_i} \\ \frac{2}{R_i T_{gi}} & -\frac{2}{T_{ii}} & \frac{2}{T_{ii}} + \frac{2}{T_{gi}} & 0 \\ -\frac{1}{R_i T_{gi}} & 0 & -\frac{1}{T_{gi}} & 0 \\ 2\pi \sum_{j=1, j \neq i}^N T_{ij} & 0 & 0 & 0 \end{bmatrix}, \hat{B}_i = \begin{bmatrix} 0 \\ -\frac{2}{T_{gi}} \\ \frac{1}{T_{gi}} \\ 0 \end{bmatrix} \text{ and } \hat{F}_i = \begin{bmatrix} -\frac{1}{2H_i} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The ultimate purpose of the LFC is to uphold the system frequency invariable, i.e. the change in frequency $\Delta f_i = 0$. Equations (13) and (14) shows when there are alteration in the system load, ΔP_{Li} , and scheduled tie-line power, $\Delta P_{tie,i}$, Δf_i should be driven to zero by regulating the generator control output $\Delta P_{ci} = \Delta P_{Li} + \Delta P_{tie,i}$ and therefore the alteration in the system, load frequency and the scheduled tie-line power together dumped into the single parameter, i.e. extended disturbance. The power system variations can be expressed as (Fig. 1):

$$\dot{x}_i(t) = A'_i x_i(t) + B'_i u_i(t) + F'_i \Delta P_{Li} \tag{15}$$

where

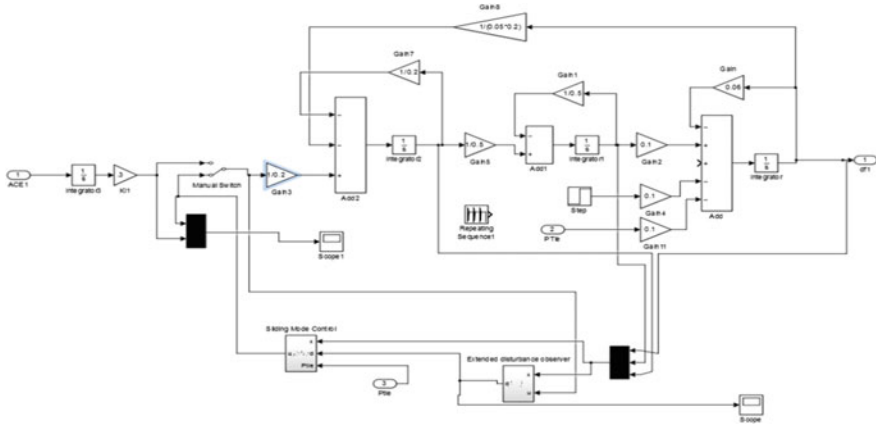


Fig. 1 Thermal unit with extended disturbance observer and SMC

$$A'_i = \begin{bmatrix} -\frac{D}{2H_i} & \frac{1}{2H_i} & 0 \\ T_{g1i} & -T_{t1i} & -T_{t2i} \\ -\frac{1}{R_i T_{gi}} & 0 & -\frac{1}{T_{gi}} \end{bmatrix}, B'_i = \begin{bmatrix} 0 \\ T_{g2i} \\ \frac{1}{T_{gi}} \end{bmatrix}, B''_i = \begin{bmatrix} 0 \\ T_{g2i} \\ \frac{1}{T_{gi}} \end{bmatrix} \text{ and } \Delta P_{di} = \Delta P_{Li} + \Delta P_{tie,i}$$

On the basis of the new LFC system proposed in Eq. (15) and the estimated disturbance observer obtained from disturbance observer, a novel sliding mode is proposed using system state variable transformation.

4.1 Disturbance Observer to Estimate Extended Disturbance

From Eq. (8), the state variables can be modelled as Eq. (16):

$$\dot{x}_i(t) = A'_i x_i(t) + B'_i u_i(t) + F'_i \hat{d}_i + L(y_i - \hat{y}_i) \tag{16}$$

$$\hat{y}_i = C \hat{x}_i \tag{17}$$

where L = feedback matrix and C = output matrix [4].

A disturbance observer vector can predict the disturbance using the estimated states as in Eq. (18):

$$\begin{cases} \hat{d}_i = \beta_i + M \hat{x}_i \\ \dot{\beta}_i = -M \left(A'_i x_i + B'_i u + F'_i \hat{d}_i \right) + \hat{d}_i \end{cases} \tag{18}$$

where β_i is a supplementary variable and M is a gain matrix constant [4].

Here, the first order derivative of disturbance is negligible, i.e. zero due to the slow system load changes during the LFC operation.

4.2 Design of Sliding Surface

The main objective of the sliding mode control is to regulate the system and further arrive at the sliding surface. Designing of sliding surface is completely dependent on the control objective. The desired conditions of control objective is $\Delta f_i = 0$, $\Delta P_{mi} = \Delta P_{di}$, $\Delta P_{gi} = \Delta P_{di}$ and $\Delta P_{ci} = \Delta P_{di}$. In order to satisfy the requirements, the new state variables are derived:

$$\left. \begin{aligned} \Delta f_i &= \Delta f_i - 0 \\ \Delta \eta_i &= \Delta P_{mi} - \Delta P_{di} \\ \Delta \xi_i &= \Delta P_{gi} - \Delta P_{di} \end{aligned} \right\} \quad (19)$$

By substituting (19) in (15), the power system dynamic equation can be rewritten as:

$$\begin{aligned} \begin{bmatrix} \Delta \dot{f}_i \\ \Delta \dot{\eta}_i \end{bmatrix} &= \begin{bmatrix} -\frac{D_i}{2H_i} & \frac{1}{2H_i} \\ T_{g1i} & -T_{t1i} \end{bmatrix} \begin{bmatrix} \Delta f_i \\ \Delta \eta_i \end{bmatrix} + \begin{bmatrix} 0 \\ T_{t2i} \end{bmatrix} \Delta \xi_i \\ \Delta \dot{\xi}_i &= \begin{bmatrix} -\frac{1}{R_i T_{gi}} & 0 \end{bmatrix} \begin{bmatrix} \Delta f_i \\ \Delta \eta_i \end{bmatrix} - \frac{1}{T_{gi}} \Delta \xi_i + \frac{1}{T_{gi}} u_i - \frac{1}{T_{gi}} \Delta P_{di} \end{aligned} \quad (20)$$

The state variable $\Delta \xi_i$ is directly proportional to the input variable u_i . In order to derive the sliding surface, the sliding variable can be selected as:

$$s_i = \Delta \xi_i - k \begin{bmatrix} \Delta f_i \\ \Delta \eta_i \end{bmatrix}, \quad K \in R^{1 \times 2} \quad (21)$$

When the system changes are only limited to the sliding surface $s_i = 0$, the modified reduced model can be given as Eq. (22):

$$\begin{bmatrix} \Delta \dot{f}_i \\ \Delta \dot{\eta}_i \end{bmatrix} = \left(\begin{bmatrix} -\frac{D_i}{2H_i} & \frac{1}{2H_i} \\ T_{g1i} & -T_{t1i} \end{bmatrix} + \begin{bmatrix} 0 \\ T_{t2i} \end{bmatrix} K \right) \begin{bmatrix} \Delta f_i \\ \Delta \eta_i \end{bmatrix} \quad (22)$$

The parameters of K can be calculated with propose methods i.e. Eigen value assignment method [4].

4.3 The Control Law Based on Super-Twisting Algorithm

The super-twisting algorithm based LFC have 2 objectives: an Equivalent controller to compensate the power system dynamics and the sliding mode control to compensate the unmodelled dynamics and disturbance arising due to errors present in the modelled parameter.

The equivalent controller can be given in Eq. (23):

$$u_i = \left(\left[-\frac{1}{R_i} \ 0 \right] + K + T_{gi} K (A_{11} + A_{12}K) \right) \begin{bmatrix} \Delta f_i \\ \Delta \eta_i \end{bmatrix} + T_{gi} \left(-\frac{1}{T_{gi}} - K A_{12} \right) s_i - T_{gi} v_i \quad (23)$$

Equation (20) is transformed to Eq. (24) as:

$$\begin{bmatrix} \Delta \dot{f}_i \\ \Delta \dot{\eta}_i \end{bmatrix} = (A_{11} + A_{12}K) \begin{bmatrix} \Delta f_i \\ \Delta \eta_i \end{bmatrix} + A_{12} s_i \quad (24)$$

$$\dot{s}_i = v_i + \tilde{f}(\Delta f_i, \Delta \eta_i, t) \quad (25)$$

where $\tilde{f}(\Delta f_i, \Delta \eta_i, t)$ = the system disturbance, unmodelled changes and system uncertainties. The sliding mode controller based on the super-twisting algorithm is given by Eq. (26):

$$v = -k_1 \vartheta_1(s) - \int_0^t k_2 \vartheta_2(s) dt \quad (26)$$

$$\vartheta_1(s) = |s|^{\frac{1}{2}} \text{sign}(s) \quad (27)$$

$$\vartheta_2(s) = \vartheta_1'(s) \vartheta_1(s) = \frac{1}{2} \text{sign}(s) \quad (28)$$

where

$$\text{sign}(s) = \begin{cases} 1, & s > 0 \\ 0, & s = 0 \\ -1, & s < 0 \end{cases}$$

If $\left| \tilde{f}(\Delta f_i, \Delta \eta_i, t) \right|$ has a boundary condition $\rho |s|^{\frac{1}{2}}$, where $\rho > 0$, the condition for the globally asymptotic at origin $s_i = 0$ is given in Eqs. (29) and (30):

$$k_1 > 2\rho \quad (29)$$

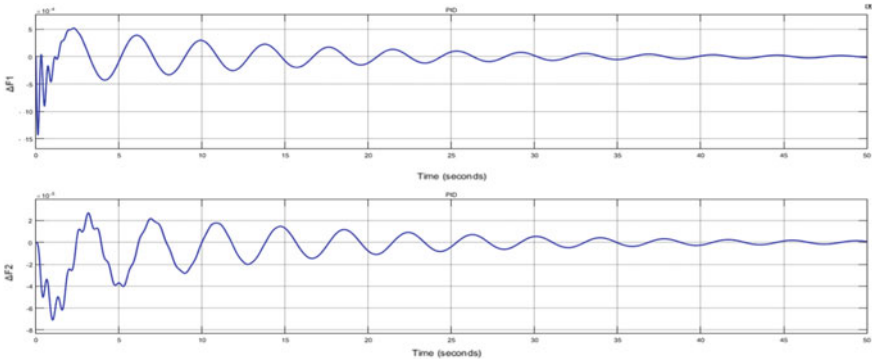


Fig. 2 Frequency deviations of two areas using of PID controller

$$k_2 > k_1 \frac{5\rho + 4\rho^2}{2k_1} \tag{30}$$

5 Results

Parameters of non-reheat turbine of area-1: $T_{i1} = 0.5$ (s), $T_{g1} = 0.2$ (s), $H_1 = 5$ (s), $D_1 = 0.6$ (pu/Hz), $R_1 = 0.05$ (pu/Hz) and $K_{Ii} = 0.3$. Parameters of non-reheat turbine of area-2: $T_{i1} = 0.6$ (s), $T_{g1} = 0.3$ (s), $H_1 = 4$ (s), $D_1 = 0.3$ (pu/Hz), $R_1 = 0.0625$ (pu/Hz) and $K_{Ii} = 0.3$.

Figure 2 shows the obtained graph when PID controller is used to tune the proposed two area power system and Fig. 3 shows the obtained graph when FOPID controller is used to tune the power system and it is showing best results in comparison with PID.

Figure 4 shows the obtained graph when the TID controller is used to tune the two area power system and Fig. 5 shows the obtained graph when SMC controller is used to tune the proposed two area power system.

6 Conclusion and Future Scope

A second-order SMC algorithm with an additional extended disturbance observer for a two area LFC scheme is proposed in this paper. For the proposed two area single unit power system, the overshoot and undershoot of the SMC is less than the PID, FOPID and TID controllers (shown in Table 1) which enables the more efficient operation of LFC. Though the settling time of TID controller is nearby SMC but on comparing the overall overshoots, undershoots and settling times of all the controllers, SMC yields

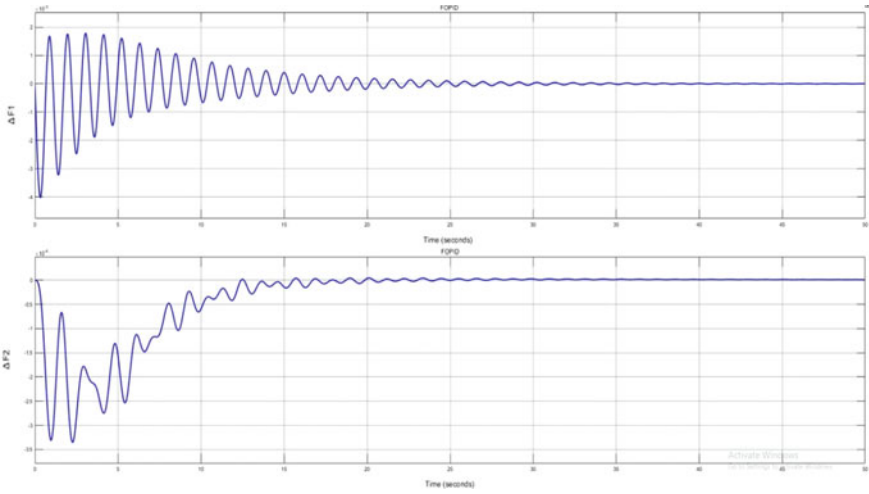


Fig. 3 Frequency deviations of two areas using FOPID controller

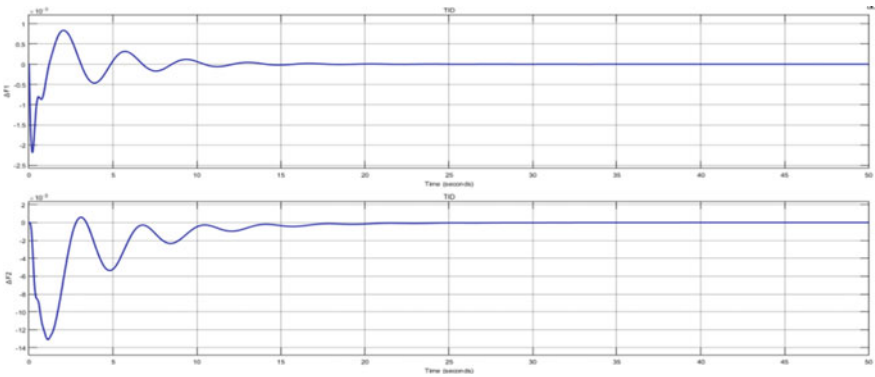


Fig. 4 Frequency deviations of two areas using TID controller

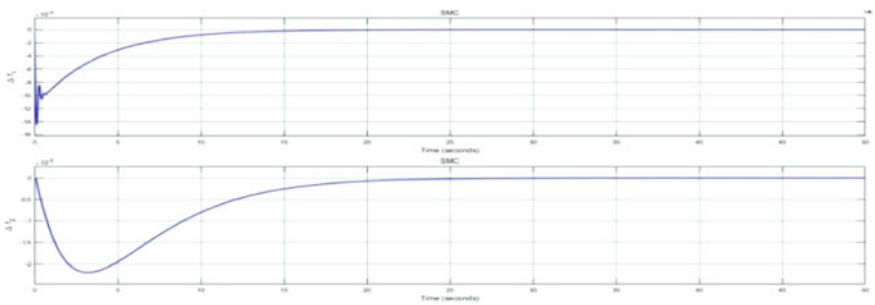


Fig. 5 Frequency deviations of two areas using SMC

Table 1 Controller parameters tuned using GWO algorithm

Controllers	K_P		K_T		K_I		K_D	
	ΔF_1	ΔF_2	ΔF_1	ΔF_2	ΔF_1	ΔF_2	ΔF_1	ΔF_2
PID	5.4062	25.5691	–	–	41.2698	12.864	8.69693	5.06956
FOPID	2.0842	0.53467	–	–	2.6327	6.1092	1.0024	1.4542
TID	–	–	5.4062	25.5691	41.2698	12.864	8.69693	5.06956

Table 2 Comparison of settling times, overshoots and undershoots for various controllers

Controllers	Settling time (in s)		Overshoot		Undershoot	
	ΔF_1	ΔF_2	ΔF_1	ΔF_2	ΔF_1	ΔF_2
PID	48	50	0.0005	– 0.0014	0.00003	– 0.00007
FOPID	40	30	0.0019	– 0.0004	0	– 0.0034
TID	18	24	0.0003	– 0.0022	0.00001	– 0.00013
SMC	16	26	0	– 0.0014	0	– 0.000022

the efficient results. The proposed work is effective for maintaining the frequency deviation of the power system to zero in a considerably less time and also reduces the overshoots and undershoots with SMC compared to other controllers which enables the efficient operation of the power system (Table 2).

Further, FACTS devices can be incorporated and also the proposed work can be applied to the deregulated power system for more efficient operation.

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