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تطبيق التحكم بطريقة امالة الاشتقاق والتكامل على نظام ثنائي القدرة

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الخلاصة

هذا ورقة تقدم نهج جديد، يطلق عليه التحكم بإمالة التكامل والاشتقاق، بغرض الحصول على استقرار تردد الاختلافات تحت تغيرات الاحمال في استنتاج التحكم التلقائي. ان تطبيق التحكم بنظام امالة التكامل والاشتقاق على نظام التحكم التلقائي يعتبر أفضل استجابة وأعلى درجة حرية في اختيار متغيرات التحكم. إنه متفوق الصفات مثل ضبط المتغير ببساطة وأفضل نسبة رفض للاضطراب. بالإضافة، أنه يبين تأثير بسيط من تغيير المتغير على السلوك المرغوب. ولبحث هذه السمات، نتعامل مع نظام ذو منطقتين حراريتين يتألف من توربين غير معاد التسخين. وقد تم عمل دراسة لاكتشاف فعالية التحكم بإمالة التكامل والاشتقاق. وقد تم الحصول على مكاسب نظام التحكم بواسطة إيجاد الحل الأمثل المقيد الغيرخطي باستخدام معيار خطأ التكامل المطلق التكامل. المقارنة بين أنظمة التحكم السابقة بين أن أداء التحكم بإمالة التكامل والاشتقاق كان الأفضل.

Application of tilt integral derivative control on two-area power system

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ABSTRACT

This paper presents a new approach, tilt integral derivative (TID) control, to stabilize frequency variations under load changes in automatic generation control (AGC). The TID control is applied to AGC because of its better response and higher degree of freedom in choosing the control parameters. It has superior qualities such as simple parameter tuning and better disturbance rejection ratio. In addition, it shows insignificant effect of parameter variation on the desired response. To examine these attributes, a two-area thermal system consisting of non-reheat turbine is considered for study. Further, sensitivity analysis has been carried out to explore the robustness of the TID controller. The controller gains are obtained by solving a constrained non-linear optimization using an integral time absolute error (ITAE) index. A comparative analysis between integral control, PID control, fractional order PID (FOPID) control and TID control reveals that TID controller can deliver better performance for AGC.

Keywords: Automatic generation control; constrained non-linear optimization; integral control; PID control; FOPID control; TID control.

INTRODUCTION

In an interconnected power system, an adequate amount of power generation is required to meet the fluctuating load demand characteristics. There is a constant need to generate enough power that is delivered to the load so that a balance between generation and load is maintained. It is difficult to maintain a balance between generation and load, due to the occurrence of transient disturbances in the power system. These disturbances cause voltage and frequency instabilities, affecting the smooth operation of the system. There are two control loop mechanism, automatic voltage regulator (AVR) and automatic generation control (AGC), to deal with the voltage and frequency instability respectively. Frequency instability is considered to be an important issue in an interconnected power system and it is vital to keep the system frequency under permissible limits. This action is called load frequency control (LFC) or automatic generation control (AGC) (Kundur, 1994). Therefore, the role of AGC is significant during normal working conditions and in transient disturbances.

AGC has been extensively examined by researchers in the past and still holds a great deal of interest in researchers. The issues of load frequency control were first addressed by Concordia & Kirchmayer, (1953) and Cohn (1957). Since then, many control strategies have been introduced to address the load frequency control problem controllers. The main purpose of all control strategies proposed for LFC was to reduce the steady state errors and to pull the system from the state of instability to normal operating conditions. Classical control (Concordia &, Kirchmayer, 1953) is commonly applied in LFC problem; however, due to increased complexities and non-linearities classical control techniques are not providing desired performance (Van Ness, 1963; Cohn, 1967). As a result, modern control approach based on system identification was introduced to design an optimal control system, (Fosh & Elgerd, 1970; Pan & Liaw, 1989). But, the approach requires identification of model parameters, making the designing process difficult due to increase in computational complexity (Zribi *et al.* 2005). The conditions of various complexities such as extensive computations, multi-variable and non-linearities require a flexible approach for evaluating the performance of system. Therefore, Intelligence control scheme such as ANNs, fuzzy logic, GAs has been introduced for AGC (Cam & Kocaarslan, 2005; Kocaarslan & Cam, 2005). In conclusion, different control strategies have been applied in LFC problem, and there is still much scope to explore new methods and technique for the same.

Recently, fractional order control (FOC) has gained the attention of researchers working around LFC problem. Fractional order control is an application of fractional calculus (FC) to control theory. Fractional calculus is a notion based on ordinary integration and differentiation to non-integer order (Samko *et al.*, 1987; Miller & Ross, 1993). FOC is a system described by fractional differential equations. Later, by applying Laplace transformation on the fractional differential equations, a transfer function of given system is obtained, for which a suitable fractional order controller can be designed (Manabe, 1960; Podlubny, 1994). There are four representative fractional order controllers (FOC) in the literature, namely, TID (Tilted Integral Derivative) controller, CRONE controller (*Contrˆole Robuste d'Ordre Non Entier*), $PI^{\lambda}D^{\mu}$ controller and fractional lead-lag compensator (Xue & Chen., 2002). A generalization of the PID controller, namely the $PI^{\lambda}D^{\mu}$ controller, involving an integrator of order λ and a differentiator of order μ has been proposed by Podlubny (1999). Author has also demonstrated better response of this type of controller, in comparison with the classical PID controller, when used for the control of fractional-order systems. A frequency domain approach by using fractional-order PID (FOPID or $PI^{\lambda}D^{\mu}$) controllers was also studied by Vinagre *et al.* (2000). In the LFC problem, the effect of fractional order PID

(FOPID) controller under a conventional environment with non-reheat turbine was first introduced by Alomoush (2010). The fractional order PID (FOPID) controller was then applied to an interconnected power system using imperialist competitive algorithm for parameter tuning (Taher *et al.*, 2010). However, none of the fractional order controller other than FOPID has been proposed in the load frequency control problem.

In this paper, TID controller has been applied on the load frequency control problem of interconnected power system. The optimal value of TID controller parameters is obtained by minimizing the performance index, ITAE- Integral of time-weighted absolute error. Also, comparison between the dynamic response obtained from Integral controller, PID controller, FOPID controller and TID controller has been presented in this paper. The integral controller, PID controller and FOPID controller are taken as a benchmark for comparative analysis. For a uniform comparative analysis, all the controllers are optimized using same optimization technique i.e. interior point algorithm and their performance has been analyzed based on system response. As a result, by improving the system stability and response, the TID controller shows better performance than Integral controller, PID controller and FOPID controller in LFC problem.

SYSTEM INVESTIGATED

The transfer function model of two-area non-reheat thermal system is shown in Figure 1. Each area in the system model consists of transfer function of governor, turbine (non-reheat) and combined inertia of rotating mass plus load of that area. The interconnecting weak link between the two-area is called tie line. Each control area in the system, monitors the system frequency and tie line deviation and tries to restore the normal operating state of the system.

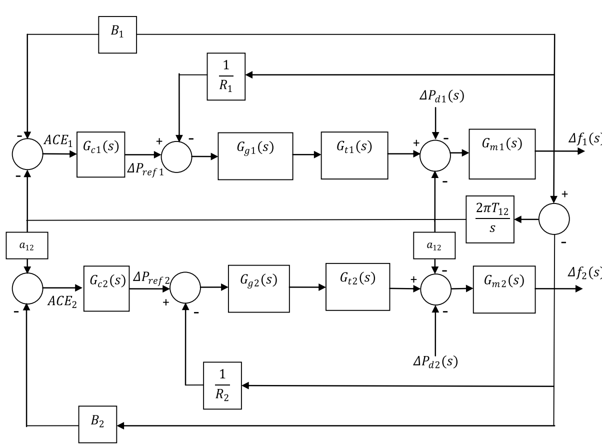

Fig. 1. Block diagram model of a two-area non-reheat thermal system

The deviation between desired and actual system frequency combined with the deviation from the scheduled net interchange in a control area is called area control error (ACE) given by,

$$ACE_i = \sum\nolimits_j (\Delta P_{tie,i,j} + B_i \Delta f_i) \tag{1}$$

Where ACE_i is area control error of ith area also acting as an input to the respective controllers of ith area, $\Delta P_{tie,i,j}$ is tie-line power flow error between ith and jth area, Δf_i is frequency error of ith area, B_i is frequency bias coefficient of ith area, which is given by,

$$B_i = \frac{1}{R_i} + D_i \tag{2}$$

Here, D_i is damping co-efficient of ith area and $1/R_i$ is the droop characteristics of ith area. The two-area system may be represented in transfer function form as:

For Area-1

$$\frac{\Delta f_1(s)}{\Delta \mathrm{P}_{ref1}(s)} = G_1(s) = \frac{G_{m1}(s)G_{t1}(s)G_{g1}(s)}{1 + G_{m1}(s)G_{t1}(s)G_{g1}(s)/R_1} \tag{3}$$

$$\Delta \mathrm{P}_{ref1}(s) = G_c(s) \cdot ACE_1 \tag{4}$$

For Area-2

$$\frac{\Delta f_2(s)}{\Delta \mathrm{P}_{ref2}(s)} = G_2(s) = \frac{G_{m2}(s)G_{t2}(s)G_{g2}(s)}{1 + G_{m2}(s)G_{t2}(s)G_{g2}(s)/R_2} \tag{5}$$

$$\Delta \mathrm{P}_{ref2}(s) = G_c(s) \cdot ACE_2 \tag{6}$$

For Tie-line

$$\frac{\Delta \mathrm{P}_{Tie}(s)}{\Delta f_1(s) - \Delta f_2(s)} = G_{Tie}(s) = \frac{2\pi \mathrm{T}_{12}}{s} \tag{7}$$

Where, machine plus load dynamics are shown by transfer function $G_{mi}(s) = \frac{K_{mi}}{1 + sT_{mi}}$, Governor dynamics by $G_{gi}(s) = \frac{1}{1 + sT_{gi}}$, Turbine dynamics by $G_{ti}(s) = \frac{1}{1 + sT_{ti}}$. The transfer function of tie line power deviation response is given by $G_{Tie}(s)$ and T_{12} is the synchronizing co-efficient of tie-line connecting the ith and jth area. The transfer function of Integral controller is $G_{ci}(s) = \frac{K_{INi}}{s}$, PID controller is $G_{ci}(s) = K_{Pi} + \frac{K_{Ii}}{s} + K_{Di}s$.

For FOPID controller transfer function is given by,

$$G_{ci}(s) = K_{PFi} + \frac{K_{IFi}}{s^{\lambda}} + K_{DFi} s^{\mu} \tag{8}$$

And for TID controller transfer function is given by,

$$G_{ci}(s) = \frac{KT_i}{s^{\frac{1}{n_i}}} + \frac{KI_i}{s} + KD_i s \tag{9}$$

Here i = 1, 2, 3...are the number of control areas in a power system. For two area system, control area-1 is represented by subscript i = 1 and control area-2 is represented by subscript i = 2 as shown in Figure.1.

CONTROLLER METHODOLOGY

TID controller

The TID control is a closed loop tunable compensator having three control parameters (*KT, KI, KD*) and a tuning parameter (*n*). The structure of TID is similar to PID, except the proportional behavior is replaced by a tilted proportional behavior having transfer function $1/s^{1/n}$ or $s^{-1/n}$. The tilted behavior provides a feedback gain as a function of frequency which is tilted with respect to the gain/frequency of conventional compensator. So, the entire compensator is referred to as Tilt-Integral-Derivative (TID) compensator. A block diagram representation of the TID control is shown in Figure 2.

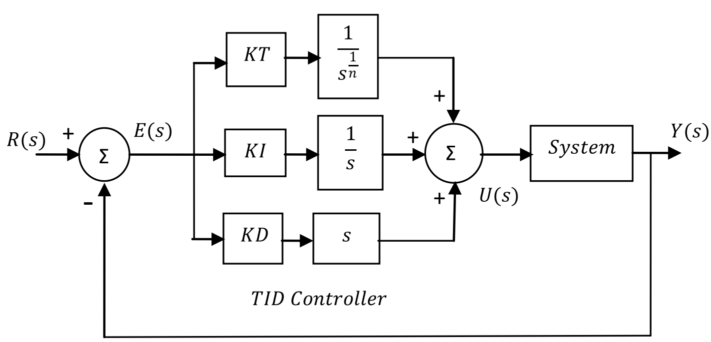

Fig. 2. Structure of TID controller in a closed loop system

And mathematically may be expressed as:

$$U_{TID}(s) = G_{TID}(s, \theta) E_{TID}(s) \tag{10}$$

$$E_{TID}(s) = R_{TID}(s) - Y_{TID}(s) \tag{11}$$

Where $G_{TID}(s,\theta)$ is the transfer function of the TID controller in complex variable $s \in \mathbb{C}$ and parameterized by $\theta \in \mathbb{R}^4$. The mathematical description of transfer function $G_{TID}(s,\theta)$ is:

$$G_{TID}(s,\theta) = \frac{KT}{s^{\frac{1}{n}}} + \frac{KI}{s} + KDs \tag{12}$$

Where $\theta^T = \begin{bmatrix} KT & KI & KD & n \end{bmatrix}$ (13)

And $\theta \in \mathbb{R}^4$, here θ is a vector of four control parameters KT, KI, KD and n where $n \in \mathbb{R}$ & $n \neq 0$. The range of n is preferably between 2 and 3.

TID control offers high degree of freedom in control parameters and likely to have superior properties like simpler tuning, higher rejection ratio, and smaller effects of plant parameter variations on closed loop response (Lurie, 1994). However, TID control has never been explored before in the area of automatic generation control other than FOPID controller.

Both TID control and FOPID control are types of fractional order control, emerged from fractional calculus applied to control theory. Therefore, sometimes TID controller is thought of being a special case of FOPID. However, TID controller is not a special case of FOPID controller because TID controller has significantly different structure than FOPID controller as shown in Equation (8) and Equation (9). According to Lurie (1994), the TID controller is similar to PID controller except the proportional behavior is replaced by a tilt behavior having transfer function $1/s^{1/n}$, where n is a non-zero real number, preferably between 2 and 3. As it can been seen from Equation (8), the structure of TID controller the term n cannot be zero and for TID controller to be a special case of FOPID controller, the term $1/n$ must be zero, which is restricted by the inventor. Therefore, it can be concluded that TID control is not a special case of FOPID control.

PARAMETER OPTIMIZATION

Formulation of optimization problem

In this paper, the optimum value of controller parameters is obtained by minimizing the objective function formulated using performance indices. A suitable performance index examined here is the integral of time multiplied by the absolute error (ITAE) and is given as:

$$ITAE = \int_0^\infty t \cdot |e(t)| \cdot dt \tag{14}$$

Where $e(t)$ is the error variable defined as the difference of set value $y(set)$ and actual value $y(t)$ in time domain. For two-area LFC model $e(t)$ may be expressed as:

$$e(t) = (|\Delta f_1(t)| + |\Delta f_2(t)| + |\Delta P_{Tie}|) \tag{15}$$

$$J = ITAE = \int_0^{t_{sim}} t \cdot (|\Delta f_1(t)| + |\Delta f_2(t)| + |\Delta P_{Tie}|) \cdot dt \tag{16}$$

Where $\Delta f1(t)$ and $\Delta f2(t)$ are the system frequency deviation of two-area LFC model and J is the objective function for two-area LFC system used for solving the optimization problem. An identical two-area system is considered for the study, which reflects identical controllers. Therefore the optimal values of TID controller constants (*KT, KI, KD, n*) are obtained by solving the optimization problem formulated by means of Equation (16) under the restriction of the range (θ) may be represented as:

$$\text{Minimize}(J) \tag{17}$$

Subject to $\theta(x) \geq 0$,

Equation (17) is a constrained non-linear optimization problem where $\theta(x)$ is a function of upper and lower bound with the optimization variables (*KT, KI, KD, n*) and x is given by, $x = [KT_{\min} \quad KT_{\max} \quad KI_{\min} \quad KI_{\max} \quad KD_{\min} \quad KD_{\max} \quad n_{\min} \quad n_{\max}]^T$ where $x \in \mathbb{R}^8$. The subscripts *min* and *max* denotes minimum bound and maximum bound respectively. To change the problem into Lagrangian equivalent function, a slack variables v is added to Equation (17) and may be written as;

$$\text{Minimize}(J) \tag{18}$$

Subject to $\theta(x) - v = 0$

where v is a vector given by, $v = [v_1 \quad v_2 \quad v_3 \quad v_4 \quad v_5 \quad v_6 \quad v_7 \quad v_8]^T \in \mathbb{R}^8$ such that $v \geq 0$ and $\theta(x)$ is a function of upper and lower bound with the optimization variables *KT*, *KI*, *KD*, and *n* which are to be tuned so for optimization problem become a variable.

Interior point algorithm

The constrained optimization problem in Equation (18) is solved using interior point algorithm. The advantage of using interior point algorithm over other algorithms is that it always satisfies bound constraints in all intermediate iterations. The algorithm attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate. The solution begins when a logarithmic barrier term α is introduced in the objective function, which replaces the non-negativity constraints of Equation (18) resulting in a problem given by:

$$\text{Minimize}\,(J - \alpha\sum_{p=1}^{k}\ln v_p\,) \tag{19}$$

Subject to $\theta(x) - v = 0\,, v \geq 0$

Here, k is the number of constraint equations given by, $k = [\,KT_{min} \leq KT \leq KT_{max},\ KI_{min} \leq KI \leq KI_{max},\ KD_{min} \leq KD \leq KD_{max},\ n_{min} \leq n \leq n_{max}] \in \mathbb{R}^8$. Now, to determine the unconstrained solution of Equation (19), the Lagrangian function is defined as:

$$L_\alpha(x, v, y) = J - \alpha\sum_{p=1}^{k}\ln(v_p) - y^{\mathrm{T}}(\theta(x) - v) \tag{20}$$

Here $y \in \mathbb{R}^4$ is the Lagrange multiplier. The minimization problem (20) is not computationally attractive as it requires finding k variables. It is then wise to use a single Lagrangian multiplier which reduces the computation cost significantly. However, $\theta(x)$ is a vector equality constraint therefore; if the objective function J is a strictly positive function such that $J(\bullet) : \mathbb{R}^N \to \mathbb{R}^+$ (ITAE is strictly positive), then $(\theta(x) - v)$ must be replaced with a function $(f(\bullet) : \mathbb{R}^k \to \mathbb{R})$ for a single Lagrangian multiplier problem such that $(\theta(x) - v)$ changes to $\| \theta(x) - v \|_1$ which is well defined when using single Lagrangian multiplier. Equation (20) is the required unconstrained function to optimally evaluate the parameters of respective controllers with respect to first order optimality conditions. Several algorithms have been presented for the numerical solution of optimality conditions see as (Byrd *et al.*, 1999; Waltz *et al.*, 2006).

RESULT AND ANALYSIS

The AGC model under study is an identical two-area system (area-1: 2000MW and area-2: 2000MW). The system comprises of two thermal units and is subjected to step load disturbance (SLD) of 0.01 pu. The nominal value of system parameters are taken from Elgerd (1983) and are presented in Appendix. Two cases have been considered to study the previously mentioned properties of TID controller, (i) At normal operating condition, (ii) Effect of parameter variations. Simulation results are obtained using MATLAB.

At normal operating condition

When area-1 is subjected to $\Delta P_{d1} = 0.01pu$ under a load equivalent to 50% of system rating, the frequency deviation in area-1 (Δf_1), frequency deviation in area-2 (Δf_2) and tie line power deviation (ΔP_{Tie}) are shown in Figure 3(a), Figure 3(b) and Figure 3(c) respectively. The optimal value of the controller parameters are: *Integral gain* $K_{IN} = 0.497$. *PID gains;* $K_P = 1.042$, $K_I = 2.150$, $K_D = 0.386$. *FOPID gains;* $K_{PF} = 1.499$, $K_{IF} = 2.151$, $K_{DF} = 1.370$, $\lambda = 0.99$, $\mu = 1.03$. *TID gains; KT = 31.745, KI = 49.702, KD = 4.652, n = 2.987.*

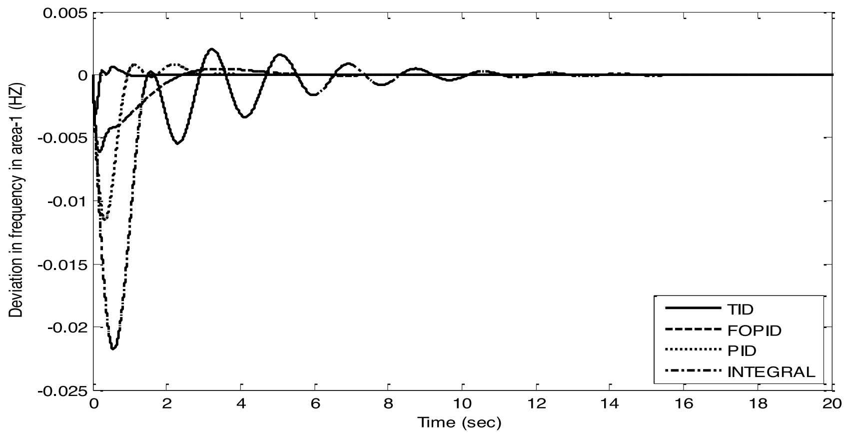

Fig. 3(a). Frequency deviation response in area-1 at $\Delta P_{d1} = 0.01pu$

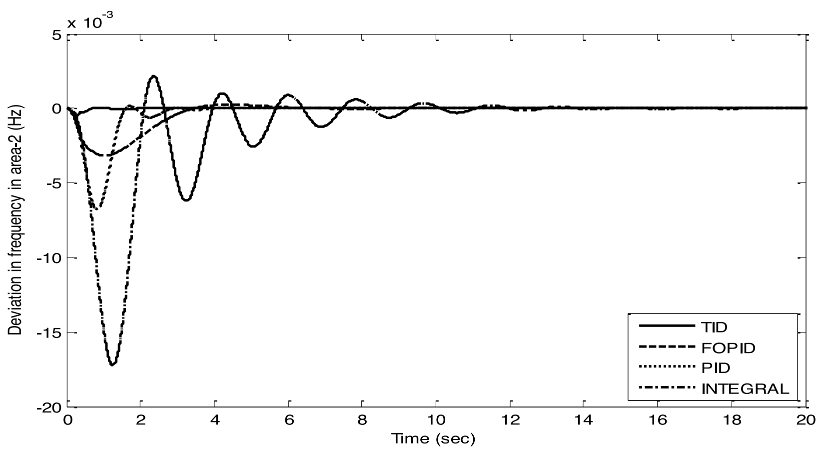

Fig. 3(b). Frequency deviation response in area-2 at $\Delta P_{d1} = 0.01pu$.

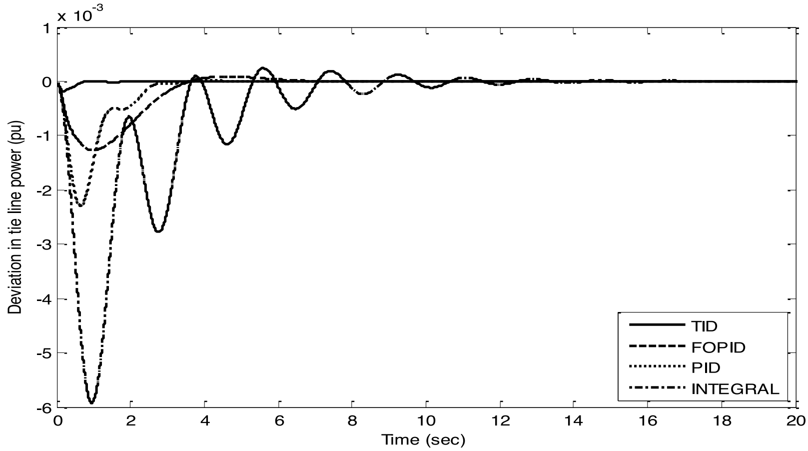

Fig. 3(c). Tie line power deviation response at $\Delta P_{d1} = 0.01pu$.

Effect of parameter variations

To study the robustness property of the proposed TID controller, all the system parameters are subjected to ±15% change from its nominal value and system response is obtained using the same value of controller parameter, as used for normal operating conditions. For this study, the response of TID and FOPID controller has been taken into consideration, as it can be seen in previous section (normal operating conditions) that TID and FOPID controller excels integral and PID controller in terms of performance. So, the frequency deviation in area-1 (Δf_1), frequency deviation in area-2 (Δf_2) and tie line power deviation (ΔP_{Tie}), due to ±15% change in system parameters are shown in Figure 4(a), Figure 4(b) and Figure 4(c) respectively.

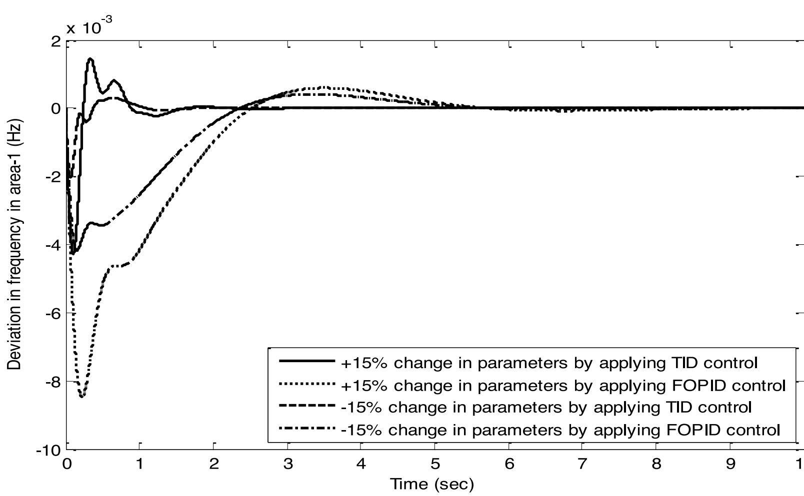

Fig. 4(a). Frequency deviation response in area-1 due to ±15% change in all system parameters.

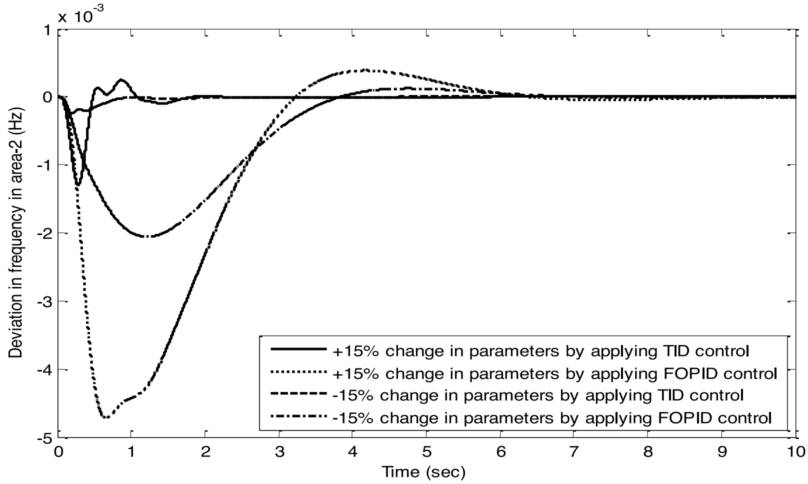

Fig. 4(b). Frequency deviation response in area-2 due to ±15% change in all system parameters.

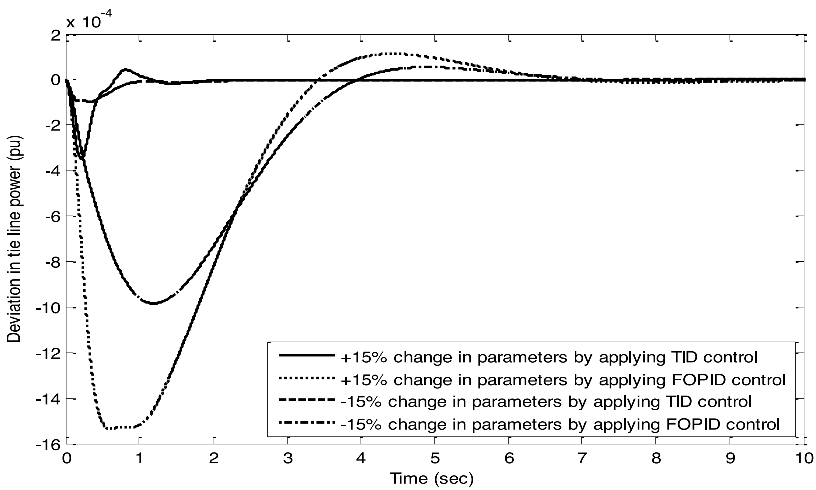

Fig. 4(c). Tie line power deviation response due to ±15% change in all system parameters.

For the two cases discussed, the value of objective function i.e. ITAE is given in Table 1. The settling time (ST) (in seconds) and overshoot (OS) (in per unit) based on 2% of steady state error (e_{ss}) is shown in Table 2. As settling time is within the range of 2% of e_{ss} , the result is obtained as zero for controllers except Integral controller. However, the result of overshoot shows that TID controller is more robust.

Table 1 Value of ITAE at different operating conditions with respect to different controllers

	Integral	PID	FOPID	**TID**
Nominal operating condition	0.1647	0.0122	0.0241	**0.0011**
15% increase in system parameters from nominal value	0.5852	0.0319	0.0518	**0.0016**
15% decrease in system parameters from nominal value	0.0794	0.0104	0.0311	**8.39×10^{-4}**

Table 2 Overshoot (in pu) in Δf_1, Δf_2 and ΔP_{Tie} with respect to different controllers

Operating Conditions		Controllers							
		Integral		PID		FOPID		**TID**	
		ST	OS	ST	OS	ST	OS	**ST**	**OS**
Nominal operating condition	Δf_1	8.89	0.021	0	0.011	0	0.006	**0**	**0.003**
	Δf_2	0	0.017	0	0.006	0	0.003	**0**	**6.1×10^{-4}**
	ΔP_{Tie}	0	0.006	0	0.002	0	0.001	**0**	**1.9×10^{-4}**
15% increase in all system parameters	Δf_1	17.26	0.026	0	0.014	0	0.008	**0**	**0.004**
	Δf_2	17.30	0.025	0	0.011	0	0.004	**0**	**0.001**
	ΔP_{Tie}	0	0.007	0	0.003	0	0.001	**0**	**3.4×10^{-4}**
15% decrease in all system parameters	Δf_1	0	0.017	0	0.008	0	0.004	**0**	**0.002**
	Δf_2	0	0.010	0	0.003	0	0.002	**0**	**2.4×10^{-4}**
	ΔP_{Tie}	0	0.004	0	0.001	0	9.8×10^{-4}	**0**	**9.90×10^{-5}**

CONCLUSIONS

In this paper, a tilt integral derivative controller has been applied to two-area non-reheat interconnected thermal system. The objective was to introduce TID controller as a load frequency controller for AGC models and to study the possible improvements that can be achieved using the TID controller. The superiority of TID control is analyzed when system undergoes step load disturbance of 0.01pu and all system parameters are subjected to variations of ±15% from their nominal value. The simulation results obtained from the study provides a comparative analysis between Integral controller, PID controller, FOPID controller and TID controller. It is evident from the results that TID controller is robust in nature and shows better performance than PID and FOPID controller. Therefore, it can be concluded that, TID control shows property of robust control structure and provides a better time response specifications under step load disturbance as well as under parameter variations.

APPENDIX

System parameters: system frequency f = 60 Hz, Rated power of ith area (i = 1,2,3…) P_{ri} = 2000MW, Operating load P_{opi} = 1000MW, Governor speed regulation in ith area (i = 1,2,3…) R_i = 2.4 Hz/pu MW, Frequency bias coefficient B_i = 0.425 pu MW/Hz, H_i = 5s, Damping coefficient D_i = 0.00833 pu MW/Hz, Load change in ith area (i = 1,2,3…) ΔP_{d1} = 0.01pu, ΔP_{d2} = 0, Synchronizing coefficient T_{ij} = 0.866, Governor time constant T_{gi} = 0.08s, Turbine time constant T_{ti} = 0.3 s, T_{mi} = 20s, K_{mi} = 120 Hz/pu MW, a_{12} = -1, Lower bound (LB) = 0 & Upper bound (UB) = 50 (for $K_{IN}, K_P, K_I, K_D, K_{PF}, K_{IF}, K_{DF}, KT, KI, KD$), LB = 0 & UB = 2 (for λ, μ), LB = 2 & UB = 3 (for n)

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