Decentralised Sliding Mode Load Frequency Control for an Interconnected Power System with Uncertainties and Nonlinearities

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Abstract – *In this paper decentralized sliding mode load frequency control is constructed for multi area power system with matched and mismatched parameter uncertainties. The proportional and integral switching surface is designed for each area to enhance the dynamic performance through reducing the chattering and overshoot during reaching phase. The controller design process has been theoretically proved based on Lyapunov stability theorem. Robustness of the proposed controller is illustrated by implementing it on the three area interconnected power system.*

***Keywords*: Load Frequency Control, Uncertainties, Nonlinearities, Sliding mode control (SMC), Integral switching surface, multi area power system.**

1. INTRODUCTION

Load Frequency Control (LFC) has two major duties, which are to maintain the desired value of frequency and also to keep the tie line power exchange under schedule in the presence of any load changes [1]. Centralized and Decentralized control strategies for LFCs have been introduced in the literature. The LFC design based on an entire power system model is considered to be a centralized control method. Since the 1960s, centralized control methods have been used for LFC. Though centralized control method has advantages of low cost and high reliability, it can also cause communication delays for interconnected power systems. To solve this problem, decentralized control method [2] was first proposed in the 1980s. Each area executes its decentralized control based on locally available state variables. The most traditional decentralized control methods for LFC are PI control and PID control. Sliding mode controller (SMC) is an another method to solve LFC problem. SMC is a nonlinear control strategy that is well known for its fast response and robust performance. The SMC can greatly improve the system transient performance and is insensitive to changes of plant parameters. Recently, the sliding mode load frequency controller (SMLFC) has been applied to solve the problems of power system with uncertainties. In this paper decentralised SMLFC with PI switching surface is proposed to solve the problem of LFC. In this SMC is combined with PI controller to assure the stable operation of the system around wide range of operating points.

2. MULTI AREA SYSTEM MODEL

Linearized model of the power system is considered for the Load Frequency control (LFC) problem because only small changes in the load are excepted during its normal operation.

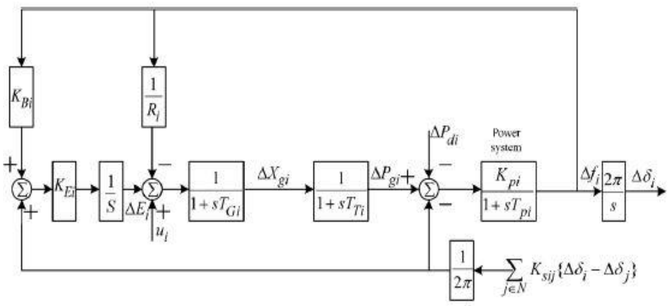

Fig1: Block diagram of *ith area of interconnected power system*

Dynamic equations of *i*th area of multi area system

$$\Delta\dot{f}_i(t) = -\frac{1}{T_{Pi}}\Delta f_i(t) - \frac{K_{Pi}}{T_{Pi}}\Delta P_{di}(t) + \frac{K_{Pi}}{T_{Pi}}\Delta P_{gi}(t) - \frac{K_{Pi}}{2\pi T_{Pi}}\sum_{\substack{j\in N\\ j\neq i}} K_{sij}\{\Delta\delta_i(t) - \Delta\delta_j(t)\} \quad (1)$$

$$\Delta\dot{P}_{gi}(t) = \frac{1}{T_{Ti}}\Delta X_{gi}(t) - \frac{1}{T_{Ti}}\Delta P_{gi}(t) \quad (2)$$

$$\Delta\dot{X}_{gi}(t) = -\frac{1}{R_i T_{Gi}}\Delta f_i(t) - \frac{1}{T_{Gi}}\Delta E_i(t) - \frac{1}{T_{Gi}}\Delta X_{gi}(t) + \frac{1}{T_{Gi}}u_i(t) \quad (3)$$

$$\Delta\dot{E}_i(t) = K_{Ei}K_{Bi}\Delta f_i(t) + K_{Ei}\frac{1}{2\pi}\sum_{\substack{j\in N\\ j\neq i}} K_{sij}\{\Delta\delta_i(t) - \Delta\delta_j(t)\} \quad (4)$$

$$\Delta\dot{\delta}_i(t) = 2\pi\Delta f_i(t) \quad (5)$$

Where i=1,2,3…*N* and *N* is number of areas. The matrix form of dynamic equations can be written as

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + F_i \Delta P_{di}(t) + \sum_{\substack{j\in N \\ j\neq i}} E_{ij} x_j(t) \quad (6)$$

where

$x_i(t) \in R^{ni}$ is a state vector, $x_j(t) \in R^{nj}$ is a neighboring state vector of $x_i(t)$, $u_i(t) \in R^{(mi)}$ is the control vector, $\Delta P_{di}(t) \in R^{ki}$ is the vector of load disturbance

$$A_i = \begin{bmatrix} -\frac{1}{T_{Pi}} & \frac{K_{pi}}{T_{Pi}} & 0 & 0 & \frac{-K_{pi}}{2\pi T_{pi}} \sum_{\substack{j\in N \\ j\neq i}} K_{sij} \\ 0 & -\frac{1}{T_{Ti}} & -\frac{1}{T_{Ti}} & 0 & 0 \\ -\frac{1}{R_i T_{Gi}} & 0 & -\frac{1}{T_{Gi}} & -\frac{1}{T_{Gi}} & 0 \\ K_{Ei} K_{Bi} & 0 & 0 & 0 & \frac{K_{Ei}}{2\pi} \sum_{\substack{j\in N \\ j\neq i}} K_{sij} \\ 2\pi & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B_i = \begin{bmatrix} 0 & 0 & \frac{1}{T_{Gi}} & 0 & 0 \end{bmatrix}^T \quad F_i = \begin{bmatrix} \frac{-K_{Pi}}{T_{Pi}} & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$E_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{K_{Pi}}{2\pi T_{Pi}} K_{sij} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-K_{Ei}}{2\pi} K_{sij} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad x_i(t) = \begin{bmatrix} \Delta f_i(t) \\ \Delta P_{gi}(t) \\ \Delta X_{gi}(t) \\ \Delta E_i(t) \\ \Delta \delta_i(t) \end{bmatrix}$$

State variables $\Delta f_i(t)$, $\Delta P_{gi}(t)$, $\Delta X_{gi}(t)$, $\Delta E_i(t)$ *and* $\Delta\delta_i(t)$ are changes in frequency, power output, governor value position, integral control and rotor angle deviation respectively. T_{Pi}, T_{Ti}, and T_{Gi} are the time constants of power system, turbine, governor respectively. K_{Ei}, K_{Bi}, K_{Pi}, and R_i are the integral control gain, frequency bias factor, power system gain, and speed regulation coefficient respectively. K_{sij} is the interconnection gain between *i* and *j* ($i \neq j$).

Consider the dynamic model of the system with parameter uncertainty

$$\dot{x}_i(t) = (\bar{A}_i + \Delta A_i)x_i(t) + (\bar{B}_i + \Delta B_i)u_i(t) + (\bar{F}_i + \Delta F_i)\Delta P_{di}(t) + \sum_{\substack{j\in N \\ j\neq i}}^{N} E_{ij} x_j(t) \quad (7)$$

Where $\bar{A}_i \in R^{n_i \times n_i}, \bar{B}_i \in R^{n_i \times m_i}$ *and* $\bar{F}_i \in R^{n_i \times k_i}$ are matrices of nominal parameters;$\Delta A_i, \Delta B_i$ *and* ΔF_i represent parametric uncertainties.

Defining $g_i(t) = \Delta A_i x_i(t) + \Delta B u_i(t) + (\bar{F}_i + \Delta F_i)\Delta P_{di}(t)$ as the aggregated uncertainty, equation(7) becomes

$$\dot{x}_i(t) = \bar{A}_i x_i(t) + \bar{B}_i u_i(t) + \sum_{\substack{j\in N \\ j\neq i}}^{N} E_{ij} x_j(t) + g_i(t) \quad (8)$$

SMLFC with PI switching surface is designed based on the following assumptions to ensure the asymptotic stability of entire system

Assumption 1: $\bar{A}_i$, and $\bar{B}_i$ are fully controllable.

Assumption 2: The following condition is true for matched uncertainty (i.e. uncertainty which is in the range space of the input distribution matrix $\bar{g}_i(t)$).

$$g_i(t) = \bar{B}_i \bar{g}_i(t) \quad (9)$$

Where $\bar{g}_i(t) \in R^{m_i}$

Assumption3: It is assumed that the aggregated disturbance $\bar{g}_i(t)$ is bounded, i.e. there exists a known scalar d_i such that $\|\bar{g}_i(t)\| \leq d_i$ where $\|\cdot\|$ is matrix norm.

3. INTEGRAL SWITCHING SURFACE

SMC with Integral switching surface is also called as Integral Sliding mode controller (ISMC). To improve the dynamic performance and robustness during the reaching phase against the matched and unmatched parameter uncertainty, the proportional and integral (PI) switching surface [4] is selected as

$$\sigma_i(t) = G_i x_i(t) - G_i x_i(0) - \int_0^t G_i(\bar{A}_i - \bar{B}_i K_i) x_i(\tau) d\tau \quad (10)$$

Where K_i and G_i are constant matrices. K_i is designed through pole placement such that the Eigen values of matrix ($\bar{A}_i - \bar{B}_i K_i$) are less than zero.

The term $-G_i X_i(0)$ ensures that $\sigma_i(0) = 0$, so the reaching phase is eliminated. The sliding mode will exist from time t=0 and the system will be robust through the entire closed-loop system response against matched uncertainty.

It is approved in the next section that that the designed switching surface of the sliding mode can assure system asymptotic stability under both matched and unmatched uncertainty.

3.1. Uncertainty with matching condition:

During sliding $\sigma(t) = \dot{\sigma}(t) = 0$ and therefore

$$\dot{\sigma}_i(t) = G_i \bar{A}_i x_i(t) + G_i \bar{B}_i u_i(t) + G_i \sum_{\substack{j=1 \\ j\neq i}}^{N} E_{ij} x_j(t) + G_i g_i(t) - G_i(\bar{A}_i - \bar{B}_i K_i) x_i(t) = 0 \quad (11)$$

If $g_i(t)$ satisfies the matching condition i.e., $g_i(t) = \bar{B}_i \bar{g}_i(t)$ the equivalent controller is derived as (12)

$$u_{ieq}(t) = -K_i x_i(t) - (G_i \bar{B}_i)^{-1} G_i \sum_{\substack{j=1 \\ j \neq i}}^{N} E_{ij} x_j(t) - \bar{g}_i(t) \quad (12)$$

It provides compensation for matched uncertainty.

When the system enters in to sliding mode operation, the state trajectory can be controlled to be $\sigma_i(t) = 0$ by using $u_{ieq}(t)$

Substituting the (12) in to (8), the equivalent dynamic equation in sliding mode is as

$$\dot{x}_i(t) = (\bar{A}_i - \bar{B}_i K_i) x_i(t) + [I_n - \bar{B}_i (G_i \bar{B}_i)^{-1} G_i] \sum_{\substack{j=1 \\ j \neq i}}^{N} E_{ij} x_j(t) \quad (13)$$

where I_n is an identity matrix

$$\tilde{A}_i = \bar{A}_i - \bar{B}_i K_i, \quad \tilde{E}_{ij} = [I_n - \bar{B}_i (G_i \bar{B}_i)^{-1} G_i] E_{ij}$$

Equation (13) becomes

$$\dot{x}_i(t) = \tilde{A}_i x_i(t) + \sum_{\substack{j=1 \\ j \neq i}}^{N} \tilde{E}_{ij} x_j(t) \quad (14)$$

K_i is selected such that the $\tilde{A}_i$ satisfy the constraint

$$\|\exp(\tilde{A}_i t)\| \leq \gamma_i \exp(-\delta_i t) \quad (15)$$

Where γ_i and δ_i are positive constants

The following lemma is used to prove the theorem

Lemma 1 (Gronwall) [4] : Assuming that $e(t)$ and $q(t)$ are positive continuous function

$$e(t) \leq k + \int_0^t q(s) e(s) ds \quad \text{for} \quad t \geq 0 \quad (16)$$

$$e(t) \leq k \exp \int_0^t q(s) ds \quad (17)$$

Theorem 1: Equation (14) is asymptotically stable if (15) and the following inequality holds:

$$\gamma_i \tilde{c}_i < \frac{\tilde{\delta}}{N} \quad (18)$$

$$\tilde{c}_i = \max \left\{ \|\tilde{E}\|_i, j = 1, \ldots, N \right\}, \; \tilde{\delta} = \min \left\{ \delta_i, i = 1, \ldots, N \right\}$$

Proof: Solving (14) equation gives

$$x_i(t) = \exp(\tilde{A}_i t) x_{io} + \int_0^t \exp\left[(\tilde{A}_i (t - w) \right] \times \sum_{\substack{j=1 \\ j \neq i}}^{N} \tilde{E}_{ij} x_j(w) dw \quad (19)$$

Taking the norm for both sides of Eq.(19), considering (15), and defining maximum Euclidean norm of $\tilde{E}_{ij}$ as $\tilde{c}_i$ then multiplying both sides of that Eq. by $\exp(\tilde{\delta} t)$, gives

$$\| x_i(t) \| \exp(\tilde{\delta} t) \leq \gamma_i \| x_{io} \| + N \gamma_i \tilde{c}_i \int_0^t \exp(\tilde{\delta} w) \| x_j(w) \| dw \quad (20)$$

From Lemma 1, we have

$$\| x_i(t) \| \exp(\tilde{\delta} t) \leq \gamma_i \| x_{io} \| \exp\left(\int_0^t N \gamma_i \tilde{c}_i dw \right) \quad (21)$$

Then

$$\| x_i(t) \| \leq \gamma_i \| x_{io} \| \exp\left(-(\tilde{\delta} - N \gamma_i \tilde{c}_i) t \right) \quad (22)$$

Equation (22) clearly shows that the overall power system with matched uncertainty is asymptotically stable under condition (15).

3.2. Uncertainty with unmatched condition:

Uncertainties in practical power systems are not always satisfies the ideal matching condition. Therefore, a new theorem is proposed to assure that system dynamic trajectory with mismatched uncertainty in sliding mode is stable, and it is theoretically proved in this section based on Lyapunov stability theorem considering the uncertainties satisfy the following two assumptions.

Assumption 4: $\text{rank}[\bar{B}_i, g_i(t)] \neq rank[\bar{B}_i]$

Assumption 5: $\|g_i(t)\| \leq h_i$ where $\| \cdot \|$ is matrix norm and h_i is a known positive constant.

Under assumption (4), the equivalent controller with unmatched uncertainty is derived from (10) as

$$u_{ieq}(t) = -K_i x_i(t) - (G_i \bar{B}_i)^{-1} G_i \sum_{\substack{j=1 \\ j \neq i}}^{N} E_{ij} x_j(t) - (G_i \bar{B}_i)^{-1} G_i g_i(t) \quad (23)$$

Substituting (23) in (8), the equivalent dynamic equation with unmatched uncertainty in sliding mode is as

$$\dot{x}_{ieq}(t) = (\bar{A}_i - \bar{B}_i K_i) x_i(t) + [I_n - \bar{B}_i (G_i \bar{B}_i)^{-1} G_i] g_i(t) + [I_n - \bar{B}_i (G_i \bar{B}_i)^{-1} G_i] \sum_{\substack{j=1 \\ j \neq i}}^{N} E_{ij} x_j(t) \quad (24)$$

where $\tilde{A}_i = \bar{A}_i - \bar{B}_i K_i$, $\tilde{E}_{ij} = [I_n - \bar{B}_i (G_i \bar{B}_i)^{-1} G_i] E_{ij}$, $\tilde{F}_i = [I_n - \bar{B}_i (G_i \bar{B}_i)^{-1} G_i] g_i(t)$

Because there is a gain matrix K_i for stable $\tilde{A}_i$, a symmetric positive definite matrix Q_i exists for the following Lyapunov equation:

$$\tilde{A}_i^T P_i + P_i \tilde{A}_i = -Q_i \quad (25)$$

Where P_i is the solution of (23) for a given positive definite symmetric matrix Q_i.

Theorem 2: For $x \in Bc(\eta)$, system dynamic performance in sliding mode is stable at any time. Where $Bc(\eta)$ is the complement of the closed ball centered at $x = 0$ with radius

$$\eta = \frac{2\tilde{c}_i \|P_i\| + 2\tilde{h}_i \|P_i\|}{\lambda_{\min}(Q_i)} \tag{26}$$

Proof: considering the positive definite function $v(t) = x_i^T(t)P_i x_i(t)$ as a Lyapunov candidate function and substituting (24) into the derivate of $v(t)$, gives

$$\dot{v}(t) = x_i^T(\tilde{A}_i^T P_i + P_i\tilde{A})x_i(t) + \tilde{F}^T(t)P_i x_i(t) + x^T{}_i(t)P_i\tilde{F}$$
$$x^T{}_i(t)P_i\left(\sum_{j=1}^{N}\tilde{E}_{ij}x_j(t)\right) + \left(\sum_{j=1}^{N}\tilde{E}_{ij}x_j(t)\right)^T P_i x_i(t) \tag{27}$$

$$\dot{v}(t) = x_i^T Q_i x_i(t) + \tilde{F}^T(t)P_i x_i(t) + x^T{}_i(t)P_i\tilde{F}_i$$
$$+\left(\sum_{j=1}^{N}\tilde{E}_{ij}x_j(t)\right)^T P_i x_i(t) + x^T{}_i(t)P_i\left(\sum_{j=1}^{N}\tilde{E}_{ij}x_j(t)\right) \tag{28}$$

Based on assumption 5, $\|\tilde{F}\| \le \tilde{h}_i = \|[I_n - B_i(G_iB_i)^{-1}G_i\|h_i$ and $\left\|\tilde{E}_{ij}\right\| \le \tilde{c}_i$, $\dot{v}(t)$

$$\dot{v}(t) \le -\lambda_{\min}(Q_i)\|x_i\|^2 + 2c_i\|P_i\|\|x_i\| + 2\tilde{h}_i\|P_i\|\|x_i\| \tag{29}$$

When the state trajectory enters into the closed ball $B^c(\eta)$ and the Eigen value $\lambda_{\min}(Q_i) > 0$, the Lyapunov function satisfies $\dot{v}(t)$ < 0. Therefore the dynamic system with mismatched uncertainty is stable in the sliding mode.

4. SMLFC Control law Design

For an interconnected power system the Reachability condition for each area is given by

$$\sum_{i=1}^{N}\frac{\sigma_i^T(t)\dot{\sigma}_i(t)}{\|\sigma_i(t)\|} < 0 \tag{30}$$

It is a sufficient condition to ensure that at each time instant, the system state trajectories will converge towards the sliding surface.

4.1 Control law for matched uncertainty

Theorem 3: According to assumptions 1 and 2, a decentralized switching control law (31) can be designed to assure the hitting/Reachability condition (30)

$$u_i(t) = K_i x_i - (G_i\bar{B}_i)^{-1}\|G_i\|\|\tilde{c}_i\|\|x_i(t)\|\operatorname{sgn}(\sigma_i(t)) - d_i$$
$$-(G_i\bar{B}_i)^{-1}\lambda_i\operatorname{sgn}(\sigma_i(t)) \tag{31}$$

K_i is the state feedback controller which is responsible for the performance of the nominal system.

where $\lambda_i > 0$, and

$$\operatorname{sgn}(\sigma_i(t)) = \begin{cases} 1, & \text{if } \sigma_i(t) > 0 \\ 0, & \text{if } \sigma_i(t) = 0 \\ -1, & \text{if } \sigma_i(t) < 0 \end{cases}$$

proof: constructing a Lyapunov function $v(t) = \sum_{i=1}^{N}\|\sigma_i(t)\|$ the derivative of $v(t)$ is as

$$\dot{v}(t) = \sum_{i=1}^{N}\frac{\sigma_i^T(t)\dot{\sigma}_i(t)}{\|\sigma_i(t)\|} < 0 \tag{32}$$

Substitute (11) into (32), gives

$$\dot{v}(t) = \sum_{i=1}^{N}\frac{\sigma_i^T}{\|\sigma_i\|}\left[-G_i\bar{B}_iK_ix_i(t) + G_i\bar{B}_iu_i(t) + G_i\sum_{j=1}^{N}E_{ij}x_j(t) + G_i\bar{B}_i\bar{g}_i\right] \tag{33}$$

When the uncertainty satisfied the matching condition (9), and controller $u_i(t)$ satisfies (30), $\dot{v}(t)$ becomes

$$= \sum_{i=1}^{N}\frac{\sigma_i^T}{\|\sigma_i\|}\left\{\left[G_i\sum_{j=1}^{N}E_{ij}x_j(t) + G_i\bar{B}_i\bar{g}_i\right] - \sum_{i=1}^{N}[\|G_i\|\|\tilde{c}_i\|x_i(t) + G_i\bar{B}_id_i] - \lambda_i\operatorname{sgn}\sigma_i(t)\right\} \tag{34}$$

Based on $\tilde{c}_i$ definition and assumption 5, it is obvious that $\dot{v}_i(t) < -\lambda_i < 0$. Therefore the hitting condition (30) is assured by the designed controller (31).

This theorem shows that control law (31) can drive system (8) to sliding surface (10) and maintain a sliding motion thereafter.

4.2 Control law for unmatched uncertainty

When the uncertainty is unmatched, the decentralized switching control law (33) can be designed to assure the hitting condition (28)

$$u_i(t) = K_ix_i - (G_i\bar{B}_i)^{-1}\|G_i\|\|\tilde{c}_i\|\|x_i(t)\|\operatorname{sgn}(\sigma_i(t)) - (G_i\bar{B}_i)^{-1}\|G_i\|h_i$$
$$(G_i\bar{B}_i)^{-1}\lambda_i\operatorname{sgn}(\sigma_i(t)) \tag{35}$$

Theorem 4 can be similarly proved as theorem 3.

5. SIMULATION RESULTS:

In order to test the robustness of the controller five different cases without and with controller are considered.

Case-1: Three area system with 0.1p.u step disturbance:

In this base case nominal parameters without considering uncertainties are considered for three areas.

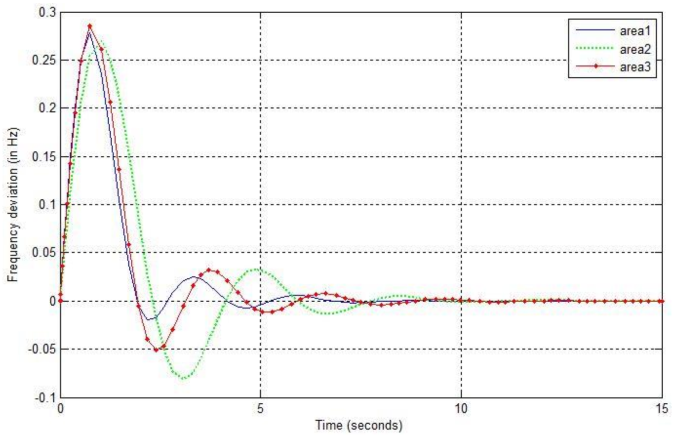

Fig-2: Frequency deviation of three area system for case1

Fig.2 shows that Frequency deviation of three areas approaches to zero within 10sec because the PI controller performs the basic LFC function

Case-2: Three area system with matched uncertainty

In order to test the robustness of the designed SMLFC same matched parameter uncertianity(represented by cosine functions around nominal values) is considered for three areas.

$$\Delta A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -2.26\cos(t) & 2\cos(\text{t}) & -2.604\cos(\text{t}) & 3\cos(\text{t}) & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

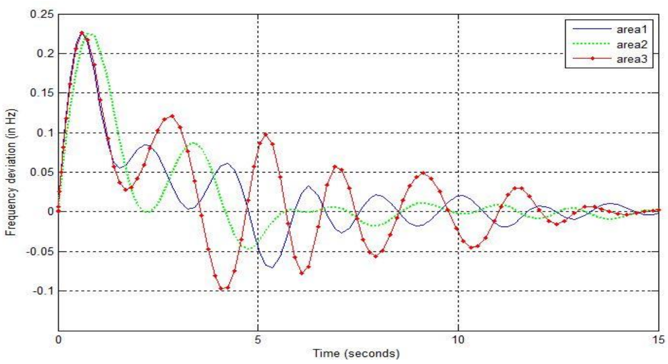

Fig-3: Frequency deviation of three area system without SMLFC for the matched uncertainty

Fig.3 shows that Frequency deviation for three areas without SMLFC have large overshoots within 15sec and cannot approach to zero

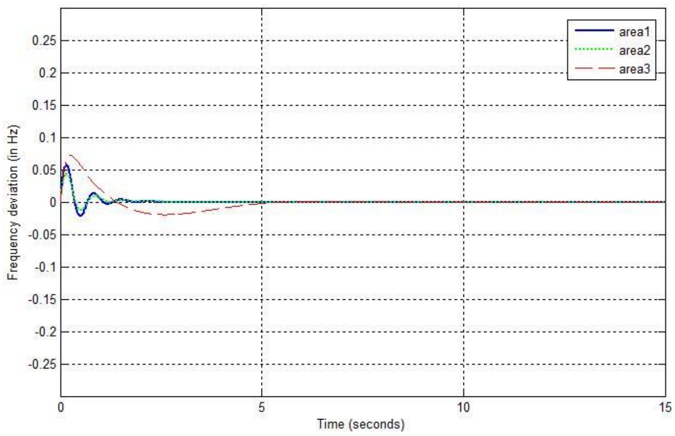

Fig-4: Frequency deviation of three area system with SMLFC for the matched uncertainty

Fig.4 shows that frequency deviation approaches to zero within 10sec, which has the faster response speed than that in Fig.3 because the matching uncertainty is compensated by the SMLFC.

Case3:Three area system with unmatched uncertainty

The performance of the three area system for different unmatched uncertainty($\Delta P_{d1} = 0.02\ pu, \Delta P_{d2} = 0.015\ pu$, $\Delta P_{d3} = 0.01\ pu$) is shown in fig. 5.

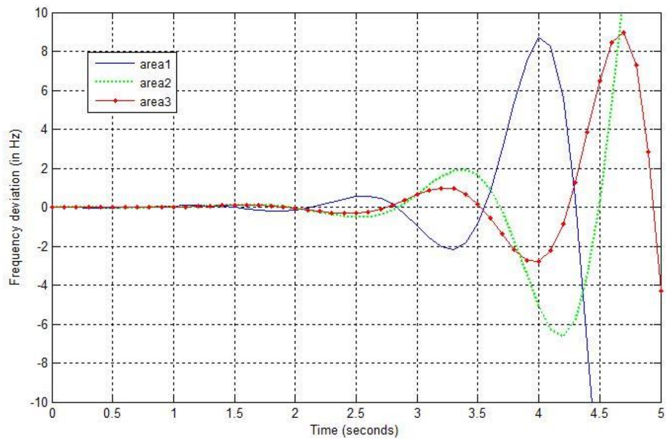

Fig-5: Frequency deviation of three area system without SMLFC for the unmatched uncertainty

Fig.5 shows that frequency deviation of three areas without SMLFC cannot approach to zero after the disturbances.

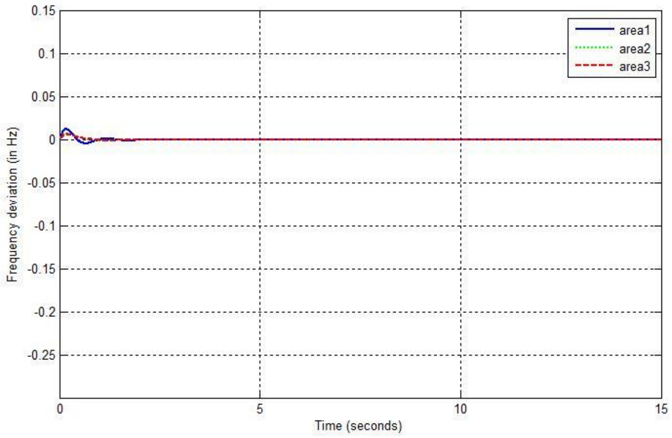

Fig-6: Frequency deviation of three area system with SMLFC for the unmatched uncertainty

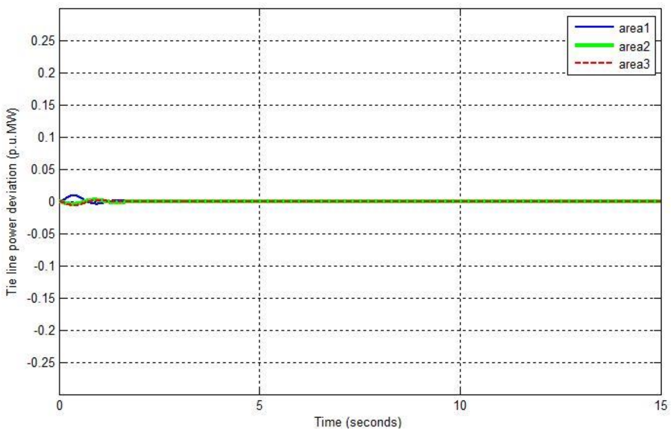

Fig-7: Tie line power deviation of three area system with SMLFC for the unmatched uncertainty

Fig.6 & Fig.7 shows that frequency and the tie line power deviation of each area reaches to zero with the designed SMLFC

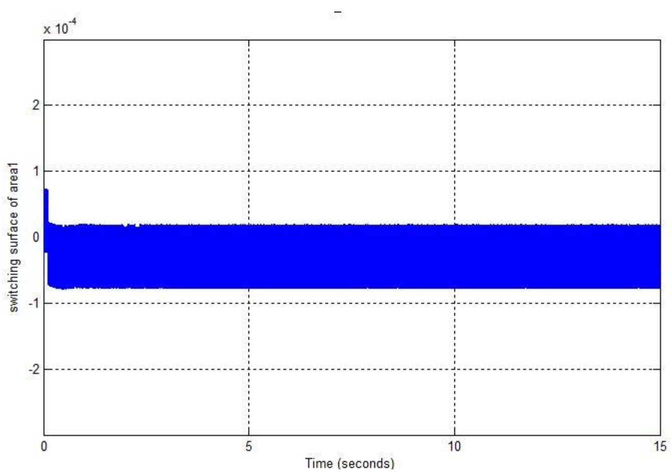

Fig8: switching surface σ_1(t)

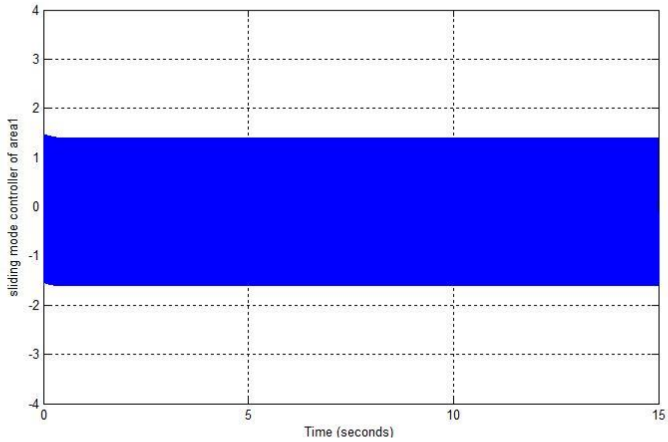

Fig9: sliding mode controller u_1(t)

The switching surface function and the control law of the controller in Area1 of the three area system for the case of unmatched uncertainty is shown in Fig.8 and Fig.9.

Case-4: Three area system with GRC and unmatched uncertainty using SMLFC

The Dynamic response of the three area system with generation rate constraint [4] and unmatched uncertainty is shown in fig.10. For thermal system a generating rate limitation of 0.1pu is considered, the equations of GRC [4] are derived and given below:

$$\Delta\dot{P}_g \leq 0.1\, p.u.MW/min = 0.0017\, p.u.M\, W/s$$

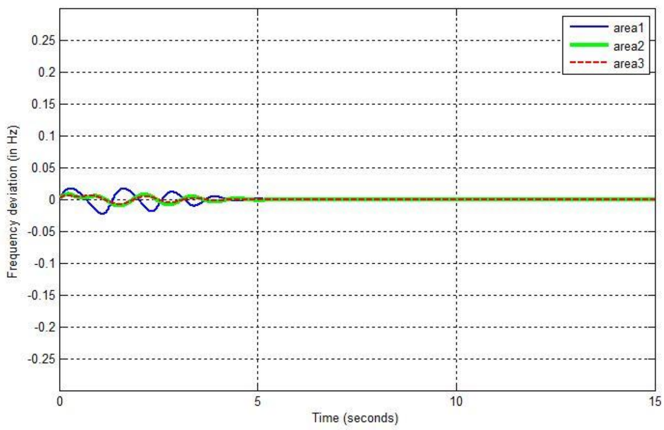

Fig-10: Frequency deviation of three area system with SMLFC for case-4

Fig.10 shows that there is same overshoot, but longer settling time compared with those when GRC is not considered in Fig 6. Therefore the system without the GRC performs better. It also shows that the SMLFC can also make the system stable with the GRC.

In order to test the robustness of proposed controller against the system parameter variations, the range of parameter variations -20% to +20% of their nominal value is considered [5]

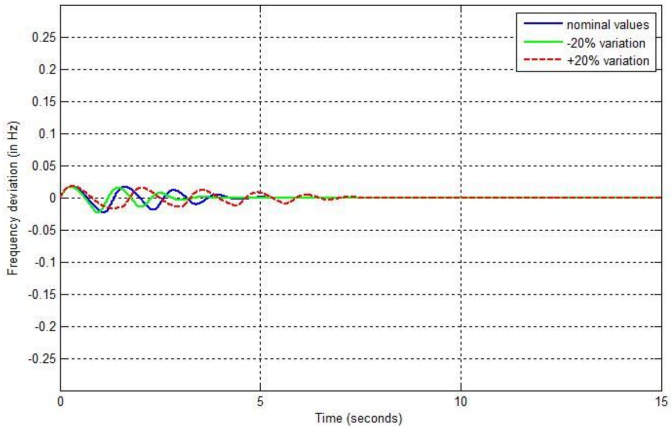

Fig-11: Frequency deviation of area1 with parameter variations for case-4

Case-5: Three area system with GRC, GDB and unmatched uncertainty using SMLFC In this paper 0.1% of dead band nonlinearity is considered.

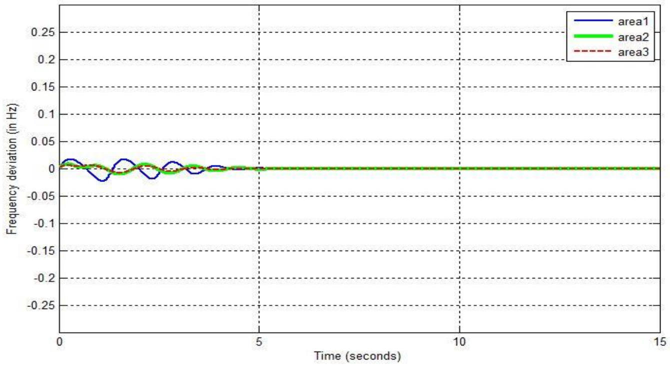

Fig-12: Frequency deviation of three area system with SMLFC for case-5

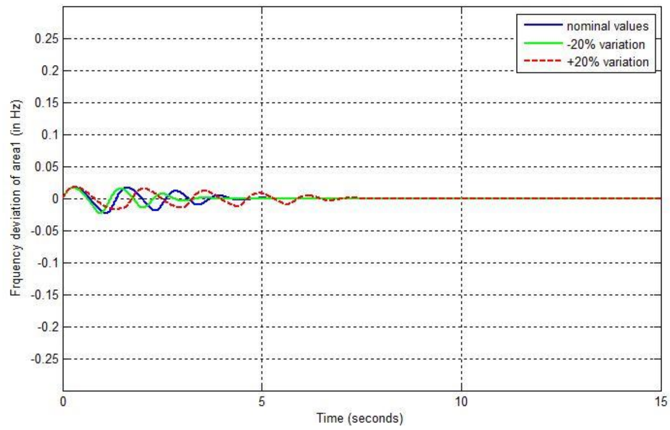

Fig-13: Frequency deviation of area1 with parameter variations for case-5

8. APPENDIX

DATA: Parameters of the three area Interconnected Power system are given below :

Area	K_{Pi}	T_{Pi}	T_{Ti}	T_{Gi}	K_{Ei}	K_{Bi}	K_{Sij}	R_i
1	120	20	0.3	0.08	0.8	0.41	0.055	2.4
2	112.5	25	0.33	0.072	0.8	0.37	0.065	2.7
3	115	20	0.35	0.07	0.8	0.4	0.0545	2.5

Nominal plant models for three areas [6]

6. CONCLUSIONS

In this project, a novel decentralized SMLFC with PI switching surface is designed to solve the Load frequency control (LFC) problem of multi-area interconnected power systems with matched uncertainties and unmatched uncertainties. This controller uses the Local state measurements to regulate the frequency deviation of each area. The controller design process has been theoretically proved in this project based on Lyapunov stability theory to assure that frequency deviation reaches zero. Robustness of the controller against the uncertainties and nonlinearities is tested in the three-area interconnected system. Fast frequency responses and insensitive to parameter variations and load disturbance show that the performance of the proposed control strategy is effective and reliable. In future the proposed controller can be applied to multi area interconnected power system containing renewable energy.

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