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INTEGRATING SSSC WITH VARIABLE STRUCTURE OBSERVER BASED OPTIMAL CONTROLLER FOR DAMPING FREQUENCY OSCILLATIONS OF DEREGULATED POWER SYSTEM

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ABSTRACT

In this paper design of integrated static synchronous series capacitor (SSSC) and variable structure system observer (VSSO) based optimal controller for damping of frequency oscillations in Multi Area Power System (MAPS) under deregulated environment is presented. A Thermal-Thermal power system is considered for simulation study. SSSC is a series connecting device which is connected with tie line of the system. The low frequency oscillations of system are minimized by designing the gain of SSSC. The high frequency oscillations are minimized by designing observer based optimal controller. The design of VSSO matrix is a function of transformed System matrix obtained from optimal sliding mode control law. The performance of deregulated system with integrated control strategy (SSSC+ VSSO based Controller) is tested and simulation results are presented and compared to Neuro Fuzzy Sliding Mode Controller (NFSMC) and PI controller.

Keywords: deregulated power system, static synchronous series capacitor, Neuro fuzzy sliding mode controller, variable structure system observer.

INTRODUCTION

The change in load initiates tie line power flow results deviations in frequency. For proper trade of power in the Tie lines control of frequency [1-24] is a great challenge to a power system engineer particularly in a deregulated Environment. These days' series FACT devices in tie line are commonly used for damping frequency oscillations [25, 26]. One kind of series controlled FACT device, Static Synchronous Series capacitor (SSSC) is used to suppress these power oscillations effectively and also controls the Tie-line power flow in specified limits [27-30].

Many authors studied these coordinated control strategies with different combinations. Few of them are, coordinated control of $H_\propto$ controller and SSPS [31]. A TCPS and PSO based fine turning PID controller, this method suppress frequency oscillations effectively [32]. The frequency response of each CA can be improved by adjusting parameters of SSSC and SMES using Probabilistic Methods Applied to Power Systems [33]. A dual mode control strategy with FABFM plus SSSC and TCPS is demonstrated for LFC [34]. Performance improvement by employing TCPS for AGC of a hydrothermal system under deregulation is presented in [35] and Redox Flow Batteries (RFB) with IPFC presented [36]. The authors earlier have proposed Neuro Fuzzy Sliding Mode Controller (NFSMC) for LFC Problem of MAPS in Deregulated Environment [37]. All these popular strategies were designed with a basic assumption that, all the system variables are available for execution of control law. As the system behaviour is uncertain and model wise it is highly nonlinear, the performance of system with designed controllers is doubtful [38].

Under these limitations, there is a necessity for design of a robust Load Frequency Controller to minimize the settling time, also to mitigate both the high frequency and low frequency oscillations. This is the main objective of this proposed control strategy. The name of the proposed control strategy is "Variable Structure Observer based Optimal Controller (VSSOC)". The integral parts of VSSOC are an observer and an optimal controller. This strategy assumes a SSSC is cascaded with tie line. The feature of the designed sliding mode observer [39-46] is to estimate all the state variables by taking Δf_1 & Δf_2 as inputs. Then system is converted in to state space model with observed states. These observer states are given as input to design control law using an optimal sliding mode controller. The desired response of the system with optimal controller is obtained by setting the gain through minimization of performance index.

The remaining paper presented the following. Section II discusses overview of the modeling of open access Thermal-Thermal system, SSSC and NFSMC. Algorithm of proposed VSSOC and flow chart were described in section III. Results of simulation were presented in section IV. Finally concluding remarks were presented in the last section.

Dynamic Model of Restructured Power System for AGC, SSSC and NFSMC

To address load frequency control problem a Thermal-Thermal system was considered and its dynamic model in deregulated environment is mentioned in Figure-1 [4, 5].

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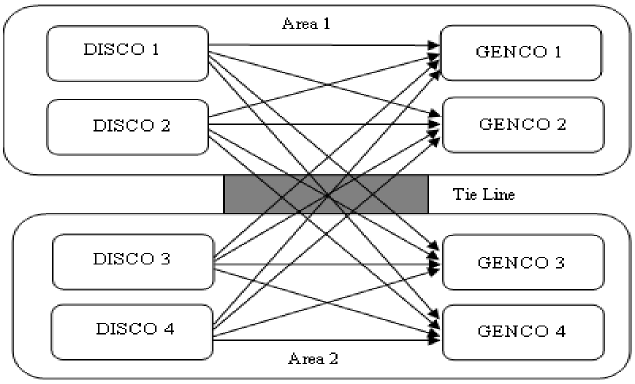

Figure-1. Dynamic model of MAPS with AC Tie-line.

The change in Tie-line power and frequency deviation has a combined effect on Area Control Error (ACE) [4, 5] and is given by

$$ACE_i = B_i \Delta f_{ierror} + \Delta P_{ierror} \quad i = 1, 2,$$

In deregulated power system contract participation factor (cpf) [5] will affect the tie line power flow and these two are related by the following equation.

$$P_{tie-scheduled} = \sum_{i=1}^{2} \sum_{j=3}^{4} cpf_{ij}\ \Delta P_{Lj} - \sum_{i=3}^{4} \sum_{j=1}^{2} cpf_{ij}\ \Delta P_{Lj}$$

$$\Delta P_{tie-error} = \Delta P_{tie-sched.} - \Delta P_{tie-act.}$$

The transaction between the DISCOMs and GENCOs are related by DPM [4, 5]. The ACE is distributed among all the GENCOs and is called ACE participation factor, given by

$$\sum_{i=1}^{NGENCO_j} \propto_{ji} = 1.0$$

where, $\propto_{ji}$ is the ACE participation factor of the G|ENCO No. "i" in the area No. "j". Number of GENCOs in area "j" is $NGENCO_j$.

In open market environment a two control area power system having Thermal plants was shown in Figure-2.

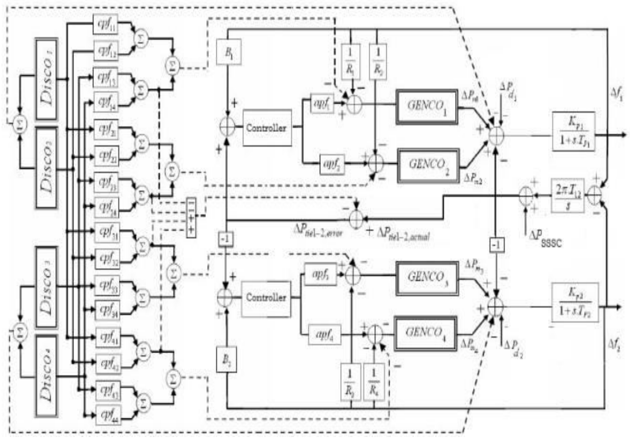

Figure-2. MAPS integrated with SSSC for AGC in a Deregulated Environment.

Mathematical Modelling of SSSC

The mathematical model of SSSC is available in various publications. The reader can refer [27-30]. The basic equations can be referred in [27-30] and the power supplied by SSSC is given by:

$$\Delta P_{SSSC} = \left(\frac{V_m V_n}{X_T} \sin\theta_{mn} + \frac{V_m V_n}{X_T} \sin\theta_{mn} \times \frac{V_s}{\sqrt{{V_m}^2 + {V_n}^2 - 2 V_m V_n \cos\theta_{mn}}} \Delta V_s \right)$$

The dynamic model of SSSC for LFC problem is shown in the Figure-3.

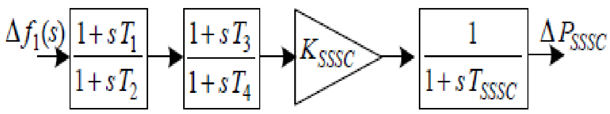

Figure-3. Dynamic model of SSSC for power oscillation damping.

Overview of NFSMC

The design procedure of NFSMC proposed by the same authors can be referred in [37]. This controller combines the features of Fuzzy logic and Neural Networks. The main objective is to adjust the sliding surface to achieve good dynamic response. The block diagram representation is given in Figure-4.

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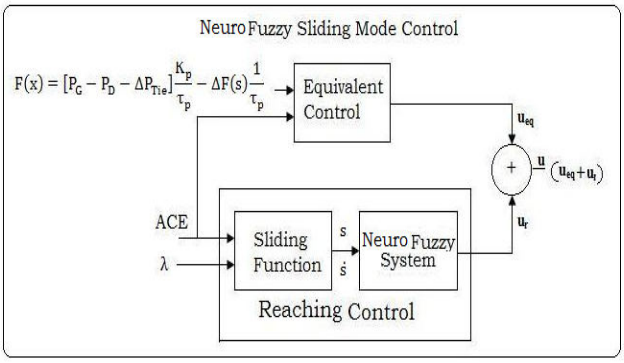

Figure-4. Schematic diagram of NFSMC.

Design of proposed VSSOC with SSSC

Design and implementation of proposed VSSOC is discussed in this section. SSSC connected in series with tie for the purpose of minimizing low frequency oscillations. Using the deviations in frequencies in two areas the observer states are estimated. These states are used as inputs for sliding mode optimal controller. The control law is designed using optimal control theory by minimizing performance index which in turn adjusts the weight matrix Q and R matrices. Figure-5 describes the process of implementation VSSOC on a deregulated power system.

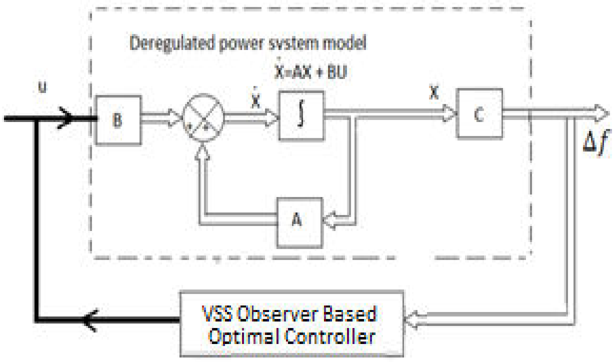

Figure-5. Implementation of proposed VSSOC.

Algorithm for the implementation of VSSOC

1. Convert the system into state space model.
2. Let us consider observer gain matrix $L = I_n$
3. The observer gain matrix is partitioned into
$$L_1 = [I_p \quad O_{p\times(n-p)}]$$
$$L_2 = [O_{(n-p)\times p} \quad I_{(n-p)}]$$
$$M = [I_p \quad O_{p\times(n-p)}]$$
4. While designing observer system matrix these are he approximations made by Utkin [45]
5. $M_1 = L_1; M_2 = L_2; F_{11} = A_{11}; F_{12} = A_{12}; F_{21} = A_{21}; F_{22} = A_{22}$
$$G_1 = \begin{bmatrix} A_{11} \\ I_p \end{bmatrix}; \; G_1 = \begin{bmatrix} I_{(n-p)} \\ A_{12} \end{bmatrix}$$
6. The observer system matrix N reduced to Utkin's matrix
$$N_{11} = A_{11} - Z_1G_1; \; N_{12} = A_{12} - Z_1G_2;$$
$$N_{21} = A_{21} - Z_2G_1; N_{22} = A_{22} - Z_2G_2;$$
7. In VSSOC observer Z_1 and Z_2 approximated as
$$Z_1 = 0; \; Z_2 = [0 \;\; Z_{22}]$$
8. N matrix is minimized as
$$N = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} - Z_{22}A_{12} \end{bmatrix}$$
9. Sliding poles obtained from sliding mode control law by using pole placement method and Z_{22} is obtained.
10. The other observer parameters *J, E* and *H are* reduced to
$$J = \begin{bmatrix} 0 & 0 \\ 0 & Z_{22} \end{bmatrix};$$
$$E = 0;$$
$$H = B$$

The flow chart for VSSOC is given in Figure-6.

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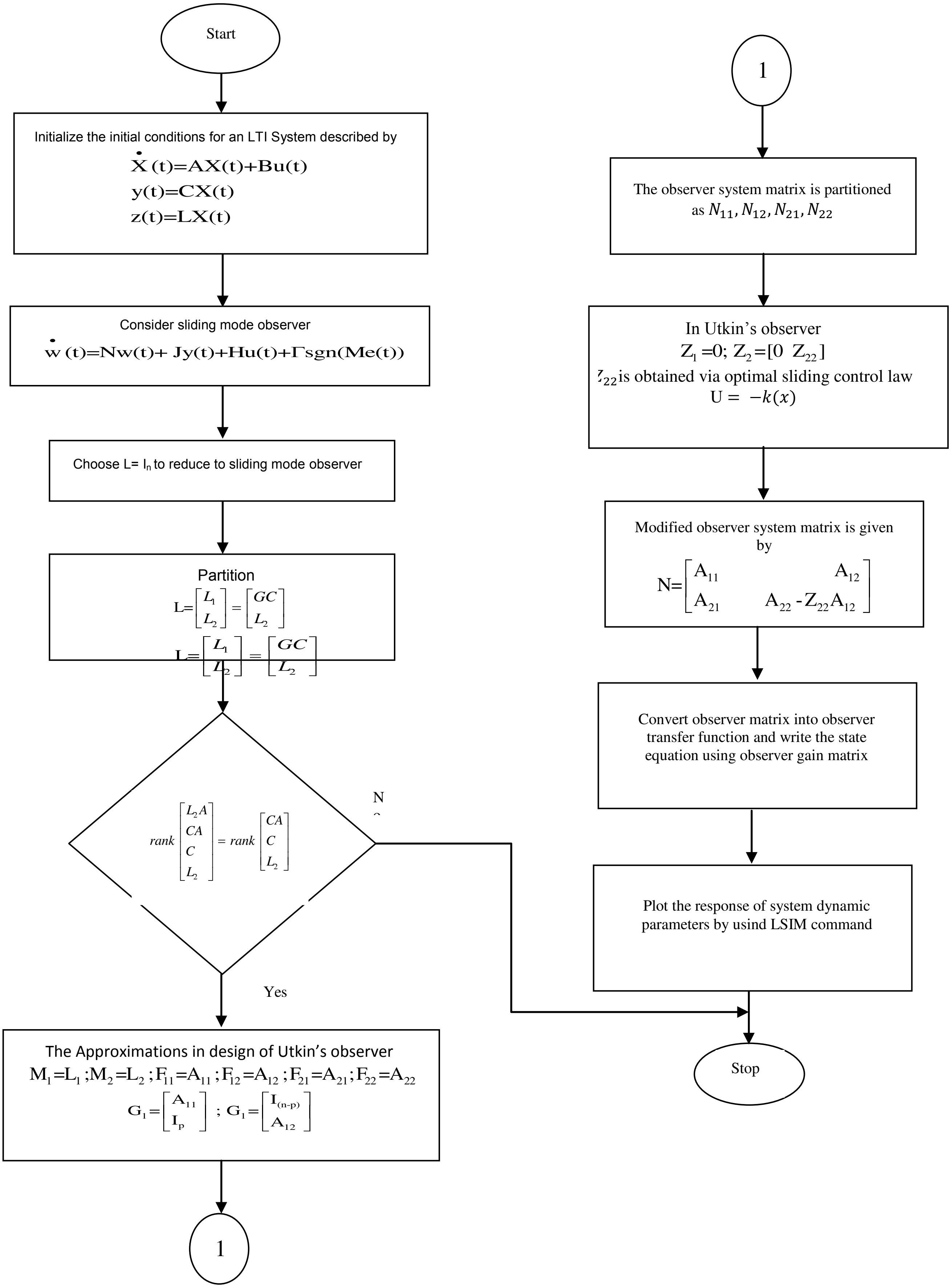

Figure-6. Flow chart for sliding mode observer based optimal controller.

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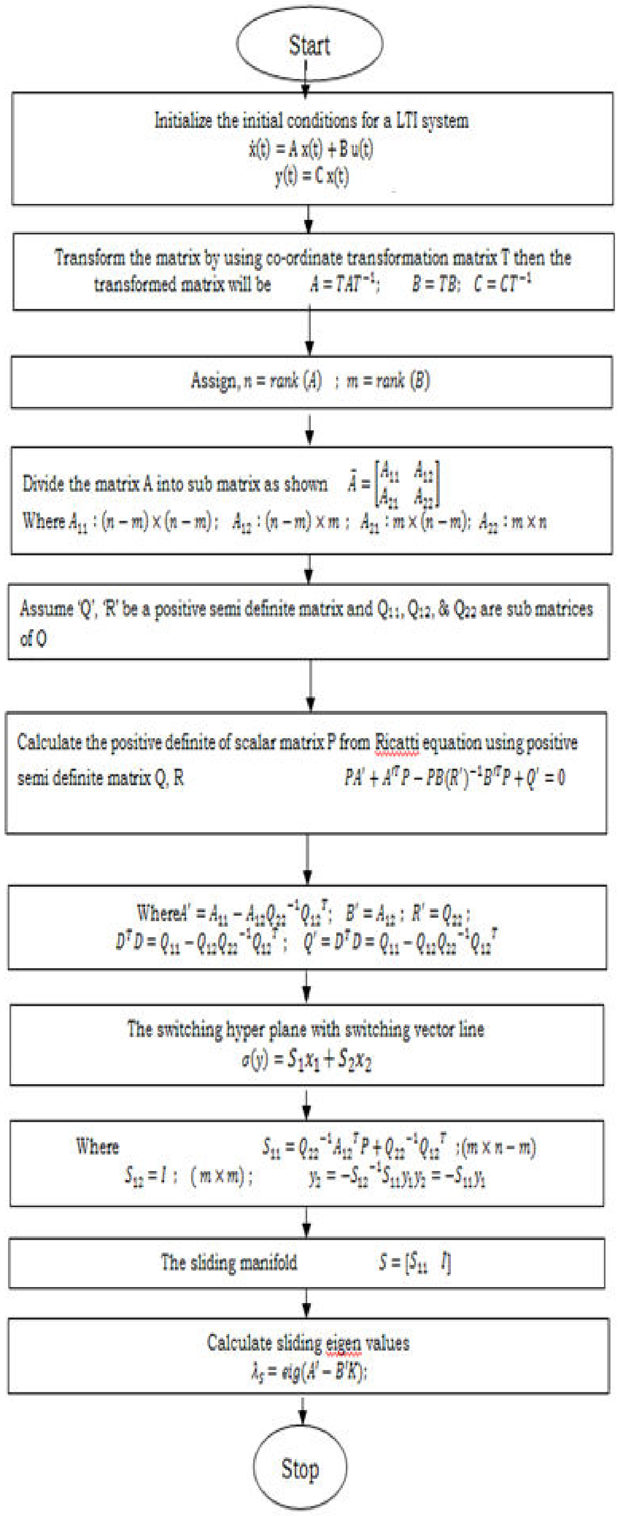

Figure-7. Flow chart for design of sliding poles.

Algorithm for the Design of sliding poles:

Step-1: Canonical transformation is used to transform system state.

$$\bar{A}=TAT^{-1};\ \bar{B}=TB\ ;\bar{C}=CT^{-1}$$

Step-2: The hyper plane is given as $\sigma(y)$

$$\sigma(y)=S_1x_1+S_2x_2=0$$

Step-3: optimize the PI.

$$J_1=\frac{1}{2}\int_{t_s}^{\infty}x^TQx.\,dt\ ;\ x\in R^{(n\times1)}\ ;\ Q\in R^{(n\times n)}$$

To optimize J1 the problem is considered as quadratic regulator.

$$J_1=\frac{1}{2}\int_{t_s}^{\infty}[x_1^T(Q_{11}-Q_{12}Q_{22}Q_{12}^T).x_1+v^TQ_{22}v]dt\ ;$$

$$v = x_2 + Q_{22}^{-1}Q_{12}^{T}x_1\ ;$$

$$x_2 = -Q_{22}^{-1}(A_{12}^{T}P+Q_{12}^{T}).x_1\ ;$$

$$Q = (M^{-1})^T Q\, M^{-1} = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix};$$

$$\bar{X}_2^T\bar{Q}_{21}\bar{X}_1=\bar{X}_1^T\bar{Q}_{12}\bar{X}_2$$

Step-4: Matrix Riccati equation is solved and P matrix evaluated.

$$P.(A_{11}-A_{12}Q_{22}^{-1}Q_{12}^{T})+(A_{11}-A_{12}Q_{22}^{-1}Q_{12}^{T})^TP$$
$$-P.A_{12}Q_{22}^{-1}Q_{12}^{T}P+D^TD=0$$

Step-5: The surface is designed using optimal control law.

$$H=\begin{bmatrix}Q_{22}^{-1}(A_{12}^{T}P+Q_{12}^{T} & I\end{bmatrix}\times M$$

$$PA_s+A_s^TP-PB_sR_s^{-1}B_s^TP+Q_s=0$$

Where

$$A_s=A_{11}-A_{12}Q_{22}^{-1}Q_{12}^{T}\ ;\ B_s=A_{12}\ ;\ R_s=Q_{22}\ ;$$

Step-6: The control law for equivalent control

$$K_e=(SB)^{-1}.S.A$$

Step-7: The corrective control law is given by

$$K_r=(SB)^{-1}.S.\delta\ \ (\delta\text{ - sliding margin})$$

Step-8: the cumulative control law

$$u=-KX=-(K_e+K_r)X$$

Step-9: Eigen values of hyper plane λ_H calculated by

$$\lambda_H=eig(A-BK)$$

Step-10: sliding Eigen values λ_s [47] calculated by

$$\lambda_s=eig(A-BK)$$

SIMULATION RESULTS

Contract scenario

In bilateral contract scenario, freedom will be there for the DISCOs to contract with GENCOs of same

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area or other area. The contracted power will be dispatched to the DISCOs based on the following DPM.

$$DPM = \begin{bmatrix} 0.2 & 0.3 & 0.5 & 0.0 \\ 0.3 & 0.2 & 0.0 & 0.7 \\ 0.5 & 0.0 & 0.2 & 0.1 \\ 0.0 & 0.5 & 0.3 & 0.2 \end{bmatrix}$$

It is considered that, each DISCO demands 0.1puMW power from the all other GENCOs. The GENCOs participates in AGC based on the following *ACEpfs.*

$\alpha_1 = 0.6$, $\alpha_2 = 1 - \alpha_1 = 0.4$
$\alpha_3 = 0.5$, $\alpha_4 = 1 - \alpha_3 = 0.5$

In steady state there should not be any mismatch between the generation of a GENCO and the load requirement of a DISCO in contract with it. It is expressed as

$$\Delta P_{mi} = \sum_j cpf_{ij} \Delta P_{Lj}$$

So, for this scenario we have
$\Delta P_1 = 0.2(0.1) + 0.3(0.1) + 0.5(0.1) + 0.0(0.1) = 0.1$puMW
$\Delta P_2 = 0.12$puMW;
$\Delta P_3 = 0.08$puMW;
$\Delta P_4 = 0.1$puMW;

The simulation results for the system under consideration i.e. Thermal - Thermal System were presented. Figure-8 represents deviation of frequency in control area-1, Figure-9 represents deviation of frequency in control area-2 and Figure-10 represents tie-line power exchange deviation.

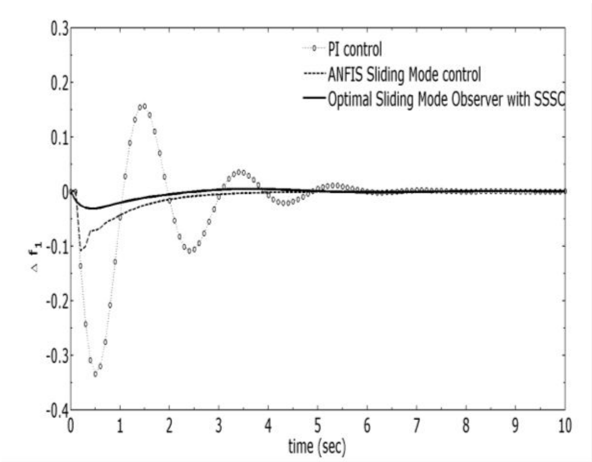

Figure-8. Deviation in frequency in control area 1.

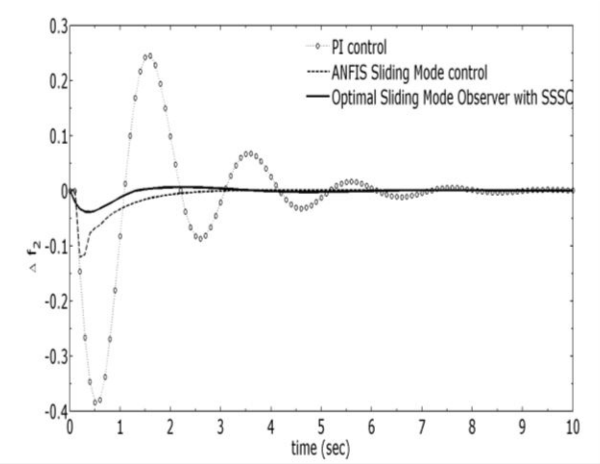

Figure-9. Deviation in frequency in control areas 2.

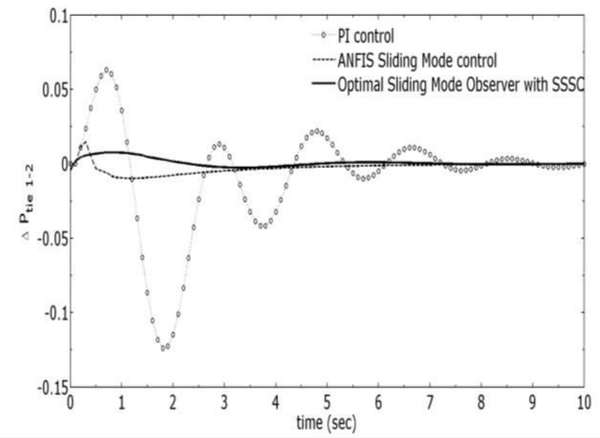

Figure-10. Tie - line power exchange deviation.

Table-1: Deviation in Frequency overshoots in CA-1, CA-2 with introduction of various controllers.

Type of Controller	Percentage overshoot in Δf in Control Area-1	Percentage overshoot in Δf in Control Area-2
PI	100	100
NFSMC	30	30
SMOOC+SSSC	10	10

Table -2: Deviation in Frequency settling time in CA-1 and CA-2

Type of Controller	Settling time of CA-1 (frequency deviation)	Settling time of CA-2 (frequency deviation)
PI	6sec	8sec
NFSMC	2sec	2sec
SMOOC+SSSC	< 2sec	< 2sec

Appendix

The power system parameter values are given in table 3 & 4 for Thermal - Thermal system

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Table 3: GENCO parameters

GENCOs parameters	Area1		Area2	
	Genco-1	Genco-2	Genco-3	Genco-4
T_T(S)	0.32	0.30	0.03	0.32
T_g(s)	0.06	0.08	0.06	0.07
R(Hz/pu)	2.4	2.5	2.5	2.7

Table 4: Control Area parameters

Control Area Parameters	Area-1	Area-2
K_p (pu/Hz)	120	120
T_p(s)	20	25
B(pu/Hz)	0.425	0.396

CONCLUSIONS

Variable structure observer based optimal controller is proposed to reduce tie-line power oscillations as well as to improve frequency response of two area thermal-thermal power system. The nonlinearities in power system model, unpredictable and uncertainty behavior of power system have overcome with this control strategy. The proven sliding mode control strategies are implemented. A Thermal-Thermal power system is considered for simulation study. SSSC is connected in series with tie line of the system. The low frequency oscillations of system are minimized by designing the gain of SSSC. The high frequency oscillations are minimized by designing observer based optimal controller. The performance of deregulated system with integrated control strategy (SSSC+ VSSO based Controller) is tested and simulation results are presented and compared to Neuro Fuzzy Sliding Mode Controller (NFSMC) and PI controller.

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