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FOSSMC for AGC of Multi-Area Power System in Open Market Environment

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Abstract*: This paper presents a Fractional Order based Second Order Sliding Mode Controller (FOSSMC) for Load Frequency Control (LFC) of Deregulated Multi Area Power System (DMAPS). In this paper a new control strategy have been proposed to improve dynamic response of multi area power system under one possible contract scenario by considering bilateral contracts. This proposed new FOSSMC strategy capable of dealing with frequency deviations for sudden change of load on DISCOs. The advantage of FOSSMC in terms of exhibiting dynamic response compared to group of factional order controllers such as Fractional Order PI(FOPI), Fractional Order Fuzzy Controller(FOFLC) and Fractional Order Sliding Mode Controller(FOSMC) and conventional PI controller.

Index Terms*: Fractional Order based Second Order Sliding Mode Controller, Load Frequency Control, Deregulated Multi Area Power System, Fractional Order PI Controller, Fractional Order Fuzzy Controller, Fractional Order Sliding Mode Controller

I. INTRODUCTION

In power system frequency and voltage are two major control parameters. The control of frequency and voltage put together is called Automatic Generation Control (AGC).LFC is an integral part of AGC. In power system frequency deviation occurs due to mismatch between generation and load demand [1]-[6].In Power System (PS) frequency oscillations minimised by changing tie line power fluctuations. Suddenly load on power system increases, frequency decreases due to generator give-up its kinetic energy to the load [1]-[6]. The LFC is very much complex problem in DPS due to sudden fluctuation of load demand among different DISCOMS [2].The design of load frequency controller for DPS compared to conventional power system due to rapidly varying load demands [3][6]. In [7], [8] presented a modern feedback controller and observer for LFC of competitive electricity market. A robust H infinity and chattering free SMC presented [9], [10]. In present day scenario there is significant contribution by the researchers with soft computing techniques such as DE optimized fuzzy PID,ANFIS controller tuning with ACS presented[11]-[13].An intelligent controllers presented for LFC[14], [15].An code algorithm with PID, imperialist ,quasi-oppositional harmony search and optimal firefly algorithms were implemented for LFC parameters tuning[12]-[16]. The impact of TCSC,TCPS and SSSC FACTs devices were presented[17], [18].The variation of tuning parameters of FACTs devices of TCSC with quasi-oppositional harmony search algorithm presented[19], [20].The combination of SSSC, SMES for simultaneous LFC control in deregulated electricity market presented[21].The role of AC tie line parallel with HVDC link and controller tuning with HPSO Algorithm presented for LFC[26].A PI controller optimized with PSO,TCPS parameters optimization with PSO to improve dynamic performance presented[27], [28]. A Fuzzy PID tuning with HBMO presented [29].

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II. STRUCTURE OF POWER SYSTEM IN OPEN MARKET ENVIRONMENT

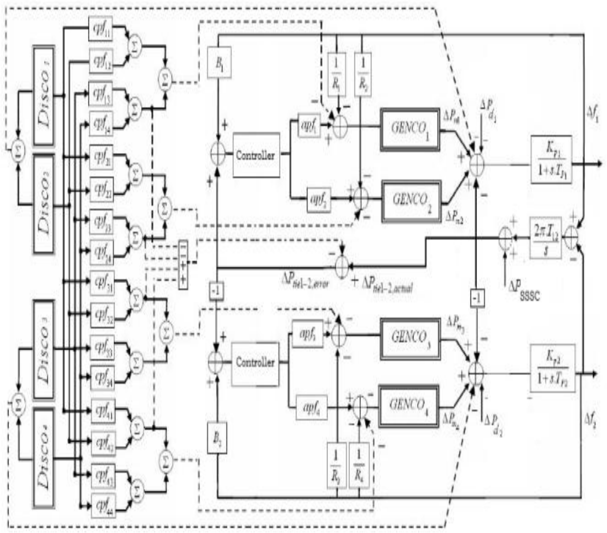

Fig.1. Block diagram of DMAPS with (thermal-thermal)

In the structure of deregulated PS each area consisting of thermal-thermal combination. The modelling of DMAPS presented in [1], [2].

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix}$$

$$\sum cpf_{ij} = 1 \quad (1)$$

$$\sum_{j=1}^{M} apf_{ij} = 1 \quad (2)$$

M is number of GENCOs in each area, ACE participation factors (*apf'*s)'' and exchange of tie power flow is a function of *Contract Participation Factor (cpf)[7].*

$$\sum_{j=1}^{M} apf_{ij} = 1 \quad (3)$$

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$$\Delta P_{tie1-2error} = \Delta P_{tie1-2scheduled} - \Delta P_{tie1-2actual} \quad (4)$$

III. THEORY OF FRACTIONAL CALCULUS

The non-integer order (Fractional Order) operator $a^{D_t^\alpha}$ are represented as

$$a^{D_t^\alpha} \begin{cases} \frac{d^\alpha}{dt^\alpha} & for\ \alpha>0 \\ 1 & for\ \alpha = 0 \\ \int_a^t (d\tau)^\alpha & for\ \alpha<0 \end{cases} \quad (5)$$

The fractional order derivative originate as defined by R-L

$$a^{D_t^\alpha} f(t) = \frac{1}{\Gamma(m-\alpha)} \left(\frac{d}{dt}\right)^m \int_a^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}} d\tau \quad (6)$$

The Laplace transform of fractional derivative as suggested by R-L

$$\{0^{D_t^\alpha} f(t); s\} = s^\alpha F(s) - \sum_{k=0}^{(m-1)} s^k \, [o^{D_t^{(\alpha-k-1)}} f(t)]_{t=0} \quad (7)$$

Laplace transform of fractional order derivative under initial condition

$$G(s) = s^\alpha \quad \alpha \in R \quad (8)$$

The fractional Order derivative obtained in terms of filter response

$$\hat{G}(s) = K \prod_{k=-N}^{N} \frac{s+\acute{\omega}_k}{s+\omega_k} \quad (9)$$

The poles and zeros are established by the

$$\acute{w}_k = w_{b.}(w_h/w_b)^{(k+N+0.5(1-\alpha))/(2N+1)} \quad (10)$$

$$w_k = \omega_{b.}(\omega_h/\omega_b)^{(k+N+0.5(1+\alpha))/(2N+1)} \quad (11)$$

The order of the filter is 2N+1 and w_b, ω_h are the lower and higher cut-off frequencies[13]

$$K = w_h^\alpha \quad (12)$$

Fractional Order derivative and integral are linear operator as given in equation (13),(14)

$$a^{D_t^\alpha}(f(t) + g(t)) = a^{D_t^\alpha} f(t) + a^{D_t^\alpha} g(t) \quad (13)$$

$$a^{D_t^{-\alpha}}(f(t) + g(t)) = a^{D_t^{-\alpha}} f(t) + a^{D_t^{-\alpha}} g(t) \quad (14)$$

A. FOPI Controller for LFC of DMAPS

The general form of FOPI is PI^λ, where λ is a real integer [28]

The FOPI input/output model as (19)

$$G(s) = Kp + \left(\frac{Ki}{s^\lambda}\right) \quad (15)$$

The control law of non-integer order controller is represented as(20)

$$u(t) = Kp\, e(t) + Ki\, D^{-\lambda} e(t) \quad (16)$$

B. Design of Oustaloup Filter

The approximated transfer function model [56]

$$K(s) = \left(\frac{1+\frac{bs}{d\omega_b}}{1+\frac{ds}{b\omega_h}}\right)^\lambda \quad (17)$$

Where *0 <* $\boldsymbol{\lambda}$ *< 1, s = jω, b > 0, d >0*, and

$$K(s) = \left(\frac{bs}{d\omega_b}\right)^\lambda \left(1 + \frac{-ds^2+d}{ds^2+b\omega_h}\right)^\lambda \quad (18)$$

The Taylor series expansion of input/output model [28],

$$K(s) = \left(\frac{bs}{d\omega_b}\right)^\lambda \left(1 + \lambda p(s) \frac{\lambda(\lambda-1)}{2} p^2(s) + \right. \ldots \quad (19)$$

$$p(s) = \frac{-ds^2+d}{ds^2+b\omega_h s}$$

The fractional order derivative (s^λ) obtained as

$$s^\lambda = \frac{(d\omega_b)^\lambda b^{-\lambda}}{\left[1+\lambda p(s)+\frac{\lambda(\lambda-1)}{2}p^2(s)+\cdots\right]} \left(\frac{1+\frac{bs}{d\omega_b}}{1+\frac{ds}{b\omega_h}}\right)^\lambda \quad (20)$$

The fractional derivative (s^λ) written as

$$s^\lambda \approx \frac{(d\omega_b)^\lambda}{b^\lambda(1+\lambda p(s))} \left(\frac{1+\frac{bs}{d\omega_b}}{1+\frac{ds}{b\omega_h}}\right)^\lambda \quad (21)$$

The non-integer order differential operator is a filter transfer function mode [28]

$$s^\lambda \approx \frac{(d\omega_b)^\lambda}{b^\lambda(1+\lambda p(s))} \left(\frac{1+\frac{bs}{d\omega_b}}{1+\frac{ds}{b\omega_h}}\right)^\lambda \quad (22)$$

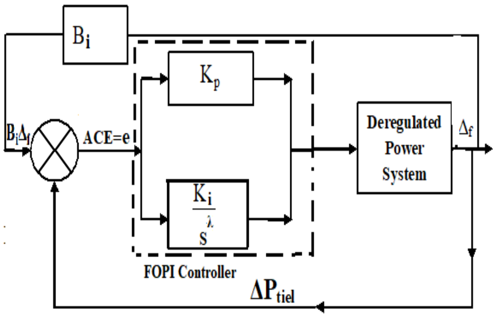

Fig.2. Implementation of non-integer order PI(FOPI) controller for LFC of DMAPS.

The fractional order transfer function is stable if poles of the transfer function located at left of the s plane.

$$d(1-\lambda)s^2 + a\omega_{hs} + d\lambda = 0 \quad (23)$$

The fractional-order part of expression approximated as

$$k(s) = \lim_{n-\infty} \prod_{K=-N}^{N} \frac{1+s/\omega_k'}{1+s/\omega_k} \quad (24)$$

The recursive transfer function model [28]

$$\omega_K' = \left(\frac{d\omega_b}{b}\right)^{\frac{\alpha-2k}{2N+1}}, \omega_b = \left(\frac{b\omega_h}{d}\right)^{\frac{\alpha+2k}{2N+1}} \quad (25)$$

Thus, the continuous rational transfer function model can be obtained as realized in terms of transfer function model of Oustaloup Filter

$$s^\lambda \approx$$

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$$\left(\frac{d\omega_h}{b}\right)^{\lambda}\left(\frac{ds^2+b\omega_h s}{d(1-\alpha)s^2+b\omega_h s+d\alpha}\right)\prod_{k=-N}^{N}\frac{s+\omega_k'}{s+\omega_k} \quad (26)$$

IV. FOFLC FOR LFC OF DEREGULATED POWER SYSTEM

In the design of FOFLC, the gains of FOPI tuned with a set of Fuzzy rules. The inputs to the FLC controller are ACE and derivative of ACE.

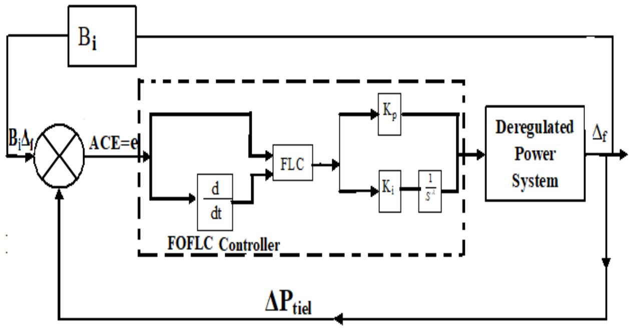

Fig.3 Implementation of FOFLC for control area of DEPS.

Table 1: K_p tuning with linguistic rules

e \ Δ_e	NB	NM	ZO	PM	PB
NB	PB	PB	PM	ZO	ZO
NM	PB	PB	PM	ZO	ZO
ZO	PM	PM	ZO	NM	NM
PM	ZO	ZO	NM	NB	NB
PB	ZO	ZO	NM	NB	NB

Table 2: K_i tuning with linguistic rules.

e \ Δ_e	NB	NM	ZO	PM	PB
NB	PB	PB	PM	ZO	ZO
NM	PB	PB	PM	ZO	ZO
ZO	PM	PM	ZO	NM	NM
PM	ZO	ZO	NM	NB	NB
PB	ZO	ZO	NM	NB	NB

V. FOSMC MODELING FOR IMPLEMENTATION AS CONTROLLER FOR LFC

The FOSMC control law obtained by combining fractional calculus with sliding mode,

A. Theory of FOSMC

The FOSMC designed based on sliding surface(S) defined [29]

$$S_1 = D_t^{\alpha} e_1 + \lambda_1.(e_1 - z) \quad (26)$$

Apply derivative both sides

$$\dot{S}_1 = D_t^{(\alpha-1)}\ddot{e}_1 + \lambda_1.(\dot{e}_1 - \dot{z})$$

$$\dot{S}_1 = D_t^{(\alpha-1)}(\ddot{x}_1 - \ddot{x}_{1d}) + \lambda_1.(\dot{e}_1 - \dot{z})$$

$$\dot{S}_1 = D_t^{(\alpha-1)} f_1(x) + b_1(x)u + d_1 - \ddot{x}_1 d) + \lambda_1.(\dot{e}_1 - \dot{z})$$

(29)

The control law defined as

$$u = \frac{-1}{(b_1 - \lambda_1\frac{k_2}{\Phi_2}b_2)}[f_1 - \ddot{x}_{1d} - \lambda_1\frac{k_2}{\Phi_2}.(f_2 - \ddot{x}_{3d}) + D_t^{(1-\alpha)}\left(\lambda_1.\dot{e}_1 - \lambda_1\lambda_2\frac{k_2}{\Phi_2}.\dot{e}_3\right) + D_t^{(1-\alpha)}(k_1.sgn(\frac{S_1}{\Phi_1}))] \quad (30)$$

$$\dot{S}_1 = -D_t^{(\alpha-1)}D_t^{(1-\alpha)}\left(\lambda_1.\dot{e}_1 -\right.$$

$\lambda1\lambda2k2\Phi2.e3-Dt\ \alpha-1Dt$
$1-\alpha k1.sgns1\Phi1+\lambda1.e1-\lambda1\lambda2k2\Phi2.e3+Dt$
$\alpha-1d1-\lambda1k2\Phi2.Dt\ \alpha-1d2$ (31)

$$\dot{S}_1 = -k_1.\left(sgn\left(\frac{s_1}{\Phi_1}\right)\right) + k_1.\left(sgn\left(\frac{s_1(0)}{\Phi_1}\right)\right) + \left(\lambda_1.\dot{e}_1(0) - \lambda_1\lambda_2\frac{k_2}{\Phi_2}.\dot{e}_3(0)\right) - \lambda_1\frac{k_2}{\Phi_2}.D_t^{(\alpha-1)}d_2 \quad (32)$$

$$\dot{S}_1 = -k_1\left(sgn\left(\frac{s_1}{\Phi_1}\right)\right) + D_t^{(\alpha-1)}d_1 - \lambda_1\frac{k_2}{\Phi_2}.D_t^{(\alpha-1)}d_2$$

$$\dot{S}_1 = -k_1\left(sgn\left(\frac{s_1}{\Phi_1}\right)\right) + \Psi_1(sgn(\frac{s_1}{\Phi_1}) - \lambda_1\frac{k_2}{\Phi_2}.\Psi_2(sgn\left(\frac{s_1}{\Phi_1}\right)) \quad (34)$$

$$S_1\dot{S}_1 \le \Phi_1.\left(\Psi_1 - \lambda_1\frac{k_2}{\Phi_2}.\Psi_2 - k_1\right).\left(\frac{s_1}{\Phi_1}\right)$$

$$S_1\dot{S}_1 \le \Phi_1.\left(\Psi_1 - \lambda_1\frac{k_2}{\Phi_2}.\Psi_2 - k_1 + \xi\right).\left(\frac{s_1}{\Phi_1}\right)$$

$$u = \frac{-1}{(b_1 - \lambda_1\frac{k_2}{\Phi_2}b_2)}[f_1 - \ddot{x}_{1d} - \lambda_1\frac{k_2}{\Phi_2}.(f_2 - \ddot{x}_{3d}) + D_t^{(1-\alpha)}\left(\lambda_1.\dot{e}_1 - \lambda_1\lambda_2\frac{k_2}{\Phi_2}.\dot{e}_3\right) + D_t^{(1-\alpha)}k_1.sat(\frac{S_1}{\Phi_1}))] \quad (37)$$

5.2 LFC of DMAPS with FOSMC

In the design of a FOSMC, the ACE is a error signal. The error signal as an input to the controller.

$$e_i = ACE_i = B_i\Delta f_{ierror} + \Delta P_{ierror}, i = 1, 2, \quad (38)$$

e_i is a state variable ($e_i = x_i$)

The sliding surface of i^{th} control area

$$S_i = k_p e_i + k_d D^{-\lambda} e_i$$

The derivative of sliding surface

$$\dot{S}_i = k_p \dot{e}_i + k_d D^{1-\lambda} e_i \quad (40)$$

$$\dot{S}_i = k_p \dot{x}_i + k_d D^{1-\lambda} x_i \quad (41)$$

under steady state Condition ACE is zero

$$k_p \dot{x}_i + k_d D^{1-\lambda} x_i = 0 \quad (42)$$

$$\dot{x}_i = x_{i+1}$$

$$k_p x_{i+1} + k_d D^{1-\lambda} x_i = 0 \quad (43)$$

$$k_p x_{i+1} = -k_d D^{1-\lambda} x_i$$

$$\dot{x}_i = x_{i+1} = -\frac{k_d}{k_p} D^{1-\lambda} x_1 \quad (44)$$

$$u = u_{eq} + k\ sign(s) \quad (45)$$

$$Sgn(s) = \begin{cases} -1\ if\ s < 0; \\ . \\ 1\ if\ s > 0; \end{cases} \quad (46)$$

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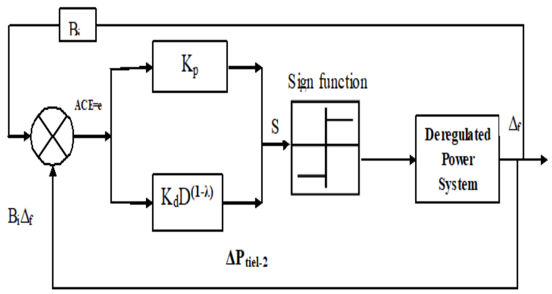

Fig.4. Block diagram model of FOSMC implementation for control area deregulated power system

VI. DESIGN OF FOSSMC FOR LFC OF DMAPS

The FOSSMC is fast response controller developed based on non-integer calculus [30]. The error dynamics of nonlinear power system is given as

$$e(t) = [e_1(t), e_r(t), \ldots\ldots, e_n(t)] = x(t) - x_r(t). \quad (47)$$

The fractional-order sliding variable $\sigma(t)$ is function of error

$$\sigma(t) = I^{(1-\alpha)}[e_n(t) - \textstyle\sum_{i=0}^{n-1} c_i e_i(t)] \quad (48)$$

where the constants $c_{1,}c_2, \ldots\ldots, c_{n-1}$ are selected in such a way that all the roots pi of the polynomial

$$P(s) = s^{(n-1)} + \textstyle\sum_{i=0}^{n-2} c_{i+1} s^i = \prod_{i=1}^{n-1}(S - p_i) \quad (49)$$

Define the quantity

$$\xi(t) = e_n(t) + \textstyle\sum_{i=1}^{n-1} c_i e_i(t). \quad (50)$$

$e_n(t)$ is given as

$$e_n(t) = -\textstyle\sum_{i=1}^{n-1} c_i e_i(t) + \xi(t) \quad (51)$$

Where $\lim_{t\to 0} \xi(t) = 0$

The reduced order equivalent representation is given as

$$C\ D^\alpha e_i = e_{i+1,} \quad i = 1,2, \ldots., n-2, \quad (52)$$

$$C\ D^\alpha e_i = \textstyle\sum_{i=1}^{n-1} c_i e_i(t) + \xi(t) \quad (53)$$

$u(t)$ is the control output of super twisting algorthem

$$u(t) = u_1(t) + u_1(t) \quad (54)$$

$$\dot{u_1} = -\Upsilon sgn(S) \quad (55)$$

$$u_2 = \begin{cases} -\lambda |s_0|^\rho sgn(S) & if|y|>s_0 \\ -\lambda |y|^\rho sgn(S) & if|y| \le s_0 \end{cases} \quad (56)$$

A. Υ, and $\boldsymbol{s_0}$ are design parameters.

ρ should be between 0.5 to 1.

The second control law of $u_2(t)$ becomes a linear function of the output sliding function at small departures ($|y| \le s_0$).

A. Implementation of FOSSMC for LFC of Deregulated Power System

The FOSSMC control methodology for multi area deregulated power system implemented. The control methodology implemented in two stages. The ACE is an error signal is an input to the first stage. The output of first stage is input to the second stage while implementation of control law.

$$e_i = ACE_i = B_i \Delta f_{ierror} + \Delta P_{ierror}, i = 1, 2 \quad (57)$$

e_i is a state variable ($e_i = x_i$)

The sliding surface of i^{th} control area

$$S_i = k_p e_i + k_d D^{-\lambda} e_i \quad (58)$$

The derivative of sliding surface is the output of first stage

$$\dot{S}_i = k_p \dot{e}_i + k_d D^{1-\lambda} e_i \quad (59)$$

$$\dot{S_i} = k_p \dot{x_i} + k_d D^{1-\lambda} x_i$$

Sliding surface is input while implementation of second stage of the control methodology, this is known as Second Order Sliding Mode Controller is given as two components

$$u(t) = u_1(t) + u_2(t) \quad (60)$$

$$\begin{cases} \dot{u_1} = -\gamma sign(S), u_1(0) = 0 \\ u_2 = -\lambda |\sigma|^{\frac{1}{2}} sign(S) \end{cases} \quad (61)$$

λ,γ are the modelling parameters are positive. The implementation of first and second stage combined together a fractional second order sliding mode controller obtained[60,61].

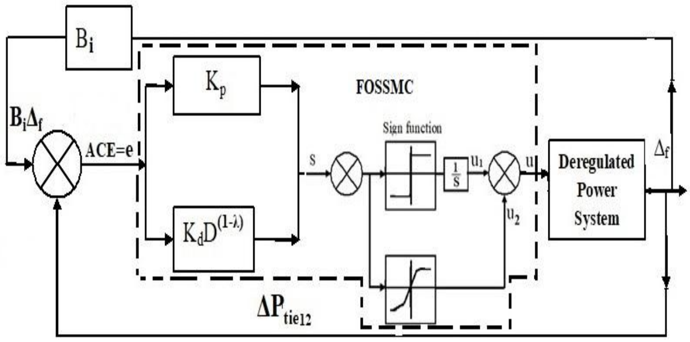

Fig.5. Block diagram model for implementation of FOSSC to LFC of Deregulated Power System

VII. SIMULATION RESULTS

Simulations are performed under bilateral transaction scenario under various operating condition and larger load demands. DISCOMs draw a mega watt capacity of 0.1 pu MW.

GENCOs participates in AGC based on the following *apfs*.

apf1= 0.6, apf2 = 1 - apf1 = 0.4

apf3=0.6, apf4= 1 - apf3 = 0.4

A. Thermal-Thermal power system with bilateral Transactions

The DPM matrix for the power transaction between GENCO and TRANSCO is give as

$$\text{DPM} = \begin{bmatrix} 0.5 & 0.3 & 0.1 & 0.3 \\ 0.1 & 0.2 & 0.6 & 0.2 \\ 0.4 & 0.0 & 0.2 & 0.1 \\ 0.0 & 0.5 & 0.1 & 0.4 \end{bmatrix} \Delta P_{mi} = \textstyle\sum_i^j cpf_{ij} \Delta P_{Lj}$$

$\Delta P_{m1} = 0.5(0.1) + 0.3(0.1) + 0.1(0.1) + 0.3(0.1)$=0.12pu MW;

ΔP_{m2}=0.11 pu MW

ΔP_{m3}=0.07 pu MW;

ΔP_{m4}=0.1 pu MW;

The dynamic response of two area thermal-thermal power system

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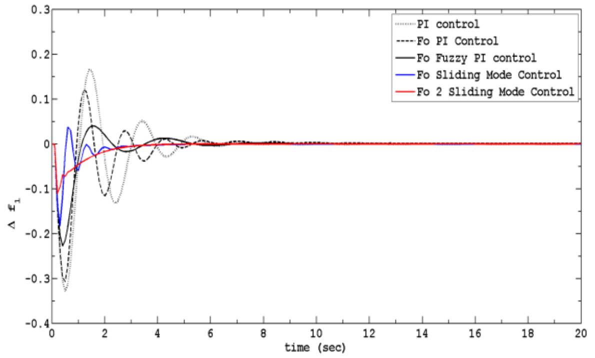

Fig.6. Control Area-1 frequency response with thick red line with FOSSMC

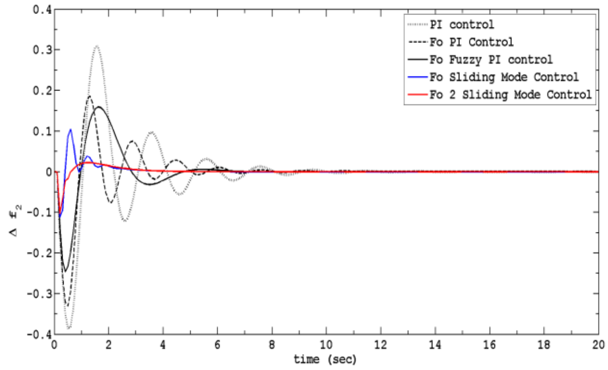

Fig.7. Control Area-2 frequency response with thick red line with FOSSMC

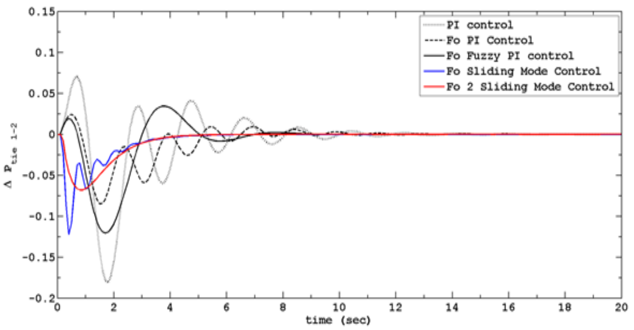

Fig.8. Power deviation in tie line with thick red line with FOSSMC

The performance of the controllers presented in terms of time domain parameters such as overshoot and settling time is given below Table.3.

Table.3 Performance of Several Controllers on Various terms

Name of the controller	% overshoot in Δf_1 of Control Area-1	% overshoot in Δf_2 of Control Area-2	Settling time of Δf_1 of Control Area-1	Settling time of Δf_2 of Control Area-2
PI Controller	-35%	30%	12 Sec	14 Sec
FOPI	-30%	19%	6 Sec	8 Sec
FOFLC	-24%	15%	5.0 Sec	4 Sec
FOSMC	-18%	10%	3.0 Sec	2.5 Sec
FOSSMC	-10%	01%	2.0 Sec	1.0 Sec

VIII. CONCLUSION

This paper presents design of FOSSMC to reduced load frequency oscillations of DMAPS.The performance of the controller compared to normal PI , FOPI,FOFLC and FOFSMC controllers under various operating conditions and larger load distrabances by considereing bilateral contract scenario.The dynamic performance of FOSSMC performance is good by observing diminishing overshoot and settling time and fast dynamic response compared to Fractional Order Sliding Mode Controller(FOSMC), FOFLC,FOPI and conventional PI controller.

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