Fractional Order Sliding Mode Controller Fed Load-Frequency Control of Multi-Area Deregulated Power System Network

K. Vimala Kumar, V. Ganesh

Abstract: ***This paper presents a Fractional Order Sliding Mode Controller (FOSMC) for load frequency control of multi area power system in deregulated environment. In deregulated power system the design of controller is more complicated due to contracted and un-contracted load demands. This proposed controller shall take care of system nonlinearities and uncertainties under bilateral contract scenario for sudden load disturbances. The performance of proposed controller compared to PI controller and without any controller.***

Keywords: ***Load Frequency Control, Multi-Area Deregulated Power System, Fractional Order Sliding Mode Controller, PI Controller***

I. INTRODUCTION

In power system frequency is one of the parameters for healthy operation under sudden load disturbances [1].The change in frequency varies with kinetic energy stored in the machine, load increases machine give up kinetic energy to the load, load decreases machine barrow kinetic energy [2]. In conventional power system design of load frequency controller is easier and insensitive to tie line power flow [3]. In deregulated power system design of controller is sensitive to tie line power flow [3]. In [4], presented ACS algorithm tuned with ANFIS trained with online data. A FOPID controller presented and investigations reveals that the performance of FOPID controller better than IO controller [5]. A DE optimized [6] fuzzy PID controller presented for restructured power system connected with AC/DC line. A coordinated control [7] strategy of TCPS-SMES presented with penetration of DFIG for LFC. A SPHBMO tuned FLC-PID controller presented for LFC [8].A H-infinity controller [9] presented for restructured power system connected with HVDC link and performance compared to OSMC under various operating conditions and larger load demands. A Fuzzy PID controller with derivative filter optimized by FA presented UPFC and SMEC [10].

A nonlinear SMC [11] presented with matched and unmatched uncertainties for LFC and performance compared to linear SMC, through simulation results the dynamic parameters such as overshoot and settling time reduced by 30 percent. A QOHS [12] presented for AGC of multi area power system in coordination with TCSC. In [13], CS optimized 2DOF-IDD controller demonstrated with different FACTS devices on multi area LFC. A hGSA-PS suggested for LFC of restructured power system and superiority of the controller compared to FA,DE and BFOA [14]. A hybrid FA-PS Fuzzy PID controller [15] presented and performance compared to DE, CPSO. An ACS algorithm based controller for simultaneous control of multi area power system interconnected with AC Tie line parallel with DC link[16].A type-2 FLC presented with error feedback learning proposed[17].

A DMPC presented [18] for multi area deregulated power system by considering bilateral contacts. A [19] newly developed QOGWO tested on two area LFC and effectiveness of optimization algorithm compared to intelligent controllers. In [20] integral controller tuned with ICA algorithm and effectiveness of the ICA tested with SSSC and CES to enhance the dynamic performance of restructured power system. A hybrid DEPS[21]optimized Fuzzy PID controller presented and effectiveness of the methodology compared to BFOA, GA. The ABC algorithm [22] presented for optimizing gains of PI3D controller and performance compared to EP, GA, GSA and PSO. A QOSOS algorithm presented for effective solution for LFC[23]. A DE optimized fuzzy PID controller with derivative filter tested on multi area deregulated power system [24]. A combination of IPFC, RFB connected in series with tie line presented and a hybrid DEPS and FLC Optimized PID controller presented [25].

An optimized LFC with IPFC and RFB demonstrated [26].The performance of FACTs devices tested on two area power system with CSA optimized 2DOF presented [27].An ACS algorithm tuned with ANFIS tested on multi-source deregulated power system[28].A new FSMC presented proposed for LFC of multi area power system[29]. A FLC tuned with PSO presented for LFC of multi area deregulated power system [30]. A Second Order Sliding Mode Controller presented for LFC of thermal-thermal power system[31]. H-Infinity loop shaping, BFOA tuning of PID[32,33].A FLC gain scheduling based LFC controller, a FFA tuning of PID controller presented[34,35]. Intelligent controllers such as ANN, ANFIS presented for three area hydro-thermal power system [36], [37]. A MOSHA based FLC controller, BBBC tuned several classical controllers presented for LFC of deregulated power system [38], [39].

II. DEREGULATED POWER SYSTEM MODEL

The modelling of open market multi-source power system presented in [40-41]. In the structure of deregulated power system each area consisting of thermal-hydro combination. The modelling of multi area deregulated power system presented in [40, 41].

Revised Manuscript Received on February 18, 2020.
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$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix}$$

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

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

Where M represents total number of GENCOs in each area, ACE Participation Factors (APF's)'' and the tie-line power flow is a function of Contract Participation Factor (CPF)

$$\Delta P_{tie1-2scheduled} = \sum_{j=1}^{2}\sum_{j=3}^{4} cpf_{ij}\Delta P_L - \sum_{j=3}^{4}\sum_{j=1}^{2} cpf_{ij} \quad (3)$$

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

$$\sum_{j=1}^{M} apf_{ij} = 1$$

Where M represents total number of GENCOs in each area, Area Control Error (ACE) is a function of tie line power exchange and frequency deviation.

$$ACE_i = B_i \Delta f_{ierror} + \Delta P_{ierror} \quad (5)$$

Where i=1,2

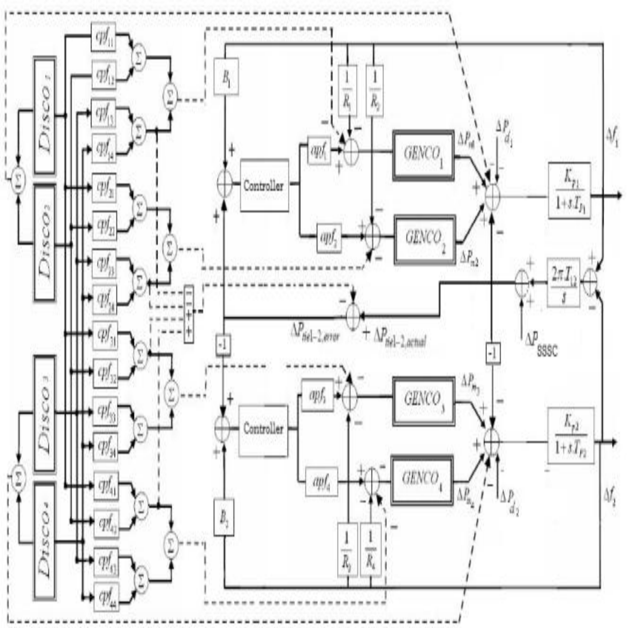

Fig.1 Two area Thermal-Thermal system with AC tie-line in deregulated environment

III. FRACTIONAL ORDER SLIDING MODE CONTROLLER IMPLEMNTATION FOR LFC

A. Theory of Fractional Order Calculus for Design & Implementation of FOSMC

Fractional Order calculus based Fractional (non-integer) order sliding mode controller designed and implemented for different applications but in this paper FOSMC controller implemented for thermal-thermal multi area deregulated power system for load frequency control.

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

$$a^{D_t^\alpha} \begin{cases} \frac{d^\alpha}{dt^\alpha} & for\ \alpha > 0 \\ 1 & for\ \alpha = 0 \\ \int_a^t (d\tau)^\alpha & for\ \alpha < 0 \end{cases} \quad (6)$$

The fractional order derivative originated as defined by R-L[ ]

$$a^{D_t^\alpha} f(t) = \frac{1}{\Gamma(m-\alpha)}\left(\frac{d}{dt}\right)^m \int_a^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}} d\tau \quad (7)$$

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

$$\{0^{D_t^\alpha} f(t); s\} = s^\alpha F(s) - \sum_{k=0}^{(m-1)} s^k \left[o^{D_t^{(\alpha-k-1)}} f(t)\right]_{t=0} \quad (8)$$

Laplace transform of fractional order derivative under initial condition

$$G(s) = s^\alpha \quad \alpha \in R \quad (9)$$

The fractional Order derivative obtained in terms of filter response

$$\hat{G}(s) = K \prod_{k=-N}^{N} \frac{s+\acute{\omega}_k}{s+\omega_k} \quad (10)$$

The poles and zeros are established by the

$$\acute{w}_k = w_{b.}(w_h/w_b)^{(k+N+0.5(1-\alpha))/(2N+1)} \quad (11)$$

$$w_k = \omega_{b.}(\omega_h/\omega_b)^{(k+N+0.5(1+\alpha))/(2N+1)} \quad (12)$$

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

$$K = w_h^\alpha \quad (13)$$

Fractional Order derivative and integral is linear operator as given in equation (14), (15)

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

$$a^{D_t^{-\alpha}}(f(t) + g(t)) = a^{D_t^{-\alpha}} f(t) + a^{D_t^{-\alpha}} g(t) \quad (15)$$

B. Implementation of FOSMC for LFC of Multi-Area Power System in Deregulated Environment

The FOSMC controller implemented for LFC of thermal-thermal DMAPS. In the implementation of FOSMC control law, initially a fractional order Oustaloup filter designed and derivative applied to the output of the filter then derivative output of filter feed it to the signm function. In the implementation of control law for two area deregulated power system depicted in block diagram as shown in Fig.3

$$e_i = ACE_i = B_i \Delta f_{ierror} + \Delta P_{ierror}, i = 1,2, \quad (15)$$

The switching function of i^{th} control area

$$S_i = k_p e_i + k_d D^{-\lambda} e_i \quad (16)$$

The derivative of switching function

$$\dot{S}_i = k_p \dot{e}_i + k_d D^{1-\lambda} e_i \quad (17)$$

$$\dot{S}_i = k_p \dot{x}_i + k_d D^{1-\lambda} x_i \quad (18)$$

Under steady state condition ACE is zero

$$k_p \dot{x}_i + k_d D^{1-\lambda} x_i = 0 \quad (19)$$

$$\dot{x}_i = x_{i+1} \quad (20)$$

Retrieval Number: C5490029320/2020©BEIESP
DOI: 10.35940/ijeat.C5490.029320

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$$k_p x_{i+1} + k_d D^{1-\lambda} x_i = 0 \quad (21)$$
$$k_p x_{i+1} = -k_d D^{1-\lambda} x_i \quad (21)$$
$$\dot{x}_i = x_{i+1} = -\frac{k_d}{k_p} D^{1-\lambda} x_1 \quad (22)$$
$$u = u_{eq} + k\, sign(s) \quad (23)$$
$$Sgn(s) = \begin{cases} -1 \; if \; s < 0; \\ . \\ 1 \; if \; s > 0; \end{cases} \quad (24)$$

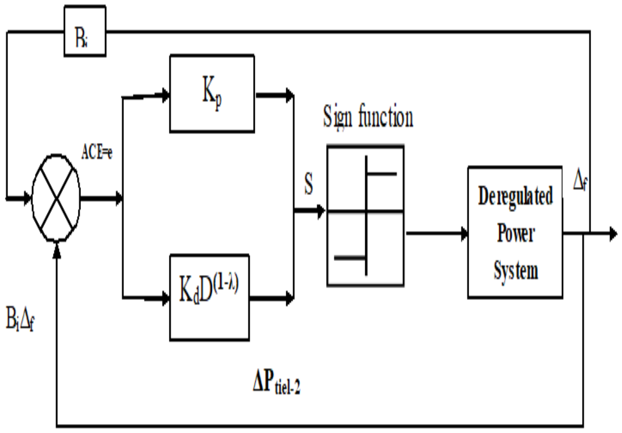

Fig.2 Functional Diagram of FOSMC for Open-Market Power System

IV. SIMULATION RESULTS

Under bilateral lateral transaction scenario simulations are performed and consider that DISCOMs draw a power of 0.1 p.u MW.
The contribution of each GENCO of each control area
apf1= 0.6, apf2 = 1 - apf1 = 0.4
apf3=0.6, apf4= 1 - apf3 = 0.4

A. Thermal Multi-Source Power System in Open-Market Environment with Bilateral Transactions

The DPM matrix for simulation studies

$$DPM = \begin{bmatrix} 0.5 & 0.3 & 0.1 & 0.3 \\ 0.1 & 0.2 & 0.6 & 0.2 \\ 0.4 & 0.0 & 0.2 & 0.1 \\ 0.0 & 0.5 & 0.1 & 0.4 \end{bmatrix}$$

$$\Delta P_{mi} = \sum_i^j cpf_{ij} \Delta P_{Lj}$$

$$\Delta P_{m1} = 0.5(0.1) + 0.3(0.1) + 0.1(0.1) + 0.3(0.1) = 0.12 \text{pu MW};$$
$$\Delta P_{m2} = 0.11 \text{ pu MW}$$
$$\Delta P_{m3} = 0.07 \text{ pu MW};$$
$$\Delta P_{m4} = 0.1 \text{ pu MW};$$

The frequency response with different controllers indicated with different controllers indicated below

Name of the Controller	Type of line indicated
without controller	Doted lines with circles
PI controller	Dotted line
FOPI controller	Thick black line
FOSMC controller	Thick Red line

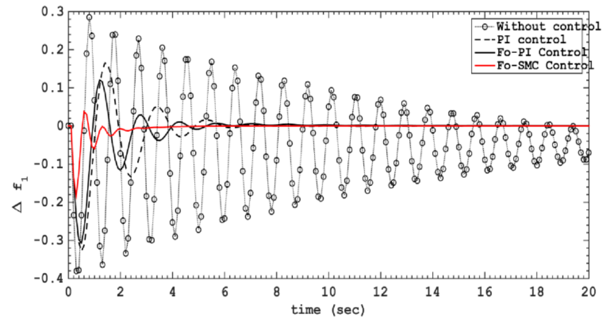

Fig.4 Frequency deviation of Control Area -1

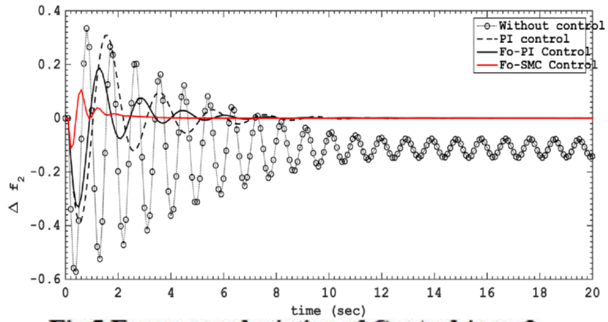

Fig.5 Frequency deviation of Control Area-2

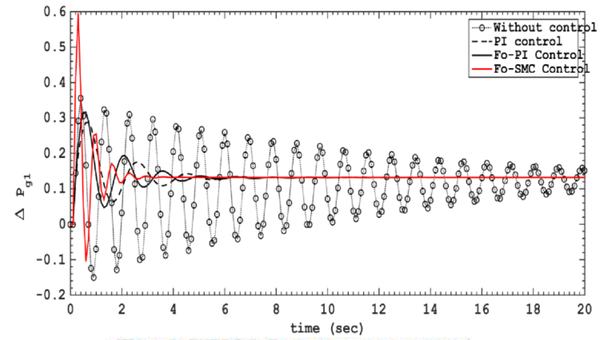

Fig.6 GENCO-1 power output

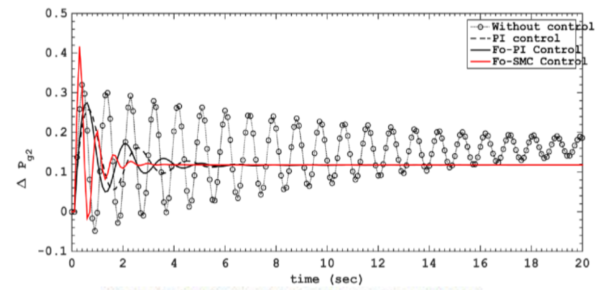

Fig.7 GENCO-2 power output

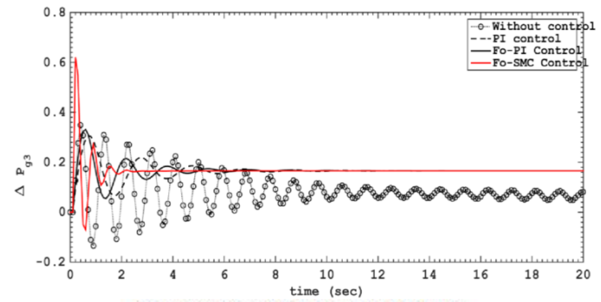

Fig.8 GENCO-3 Power Output

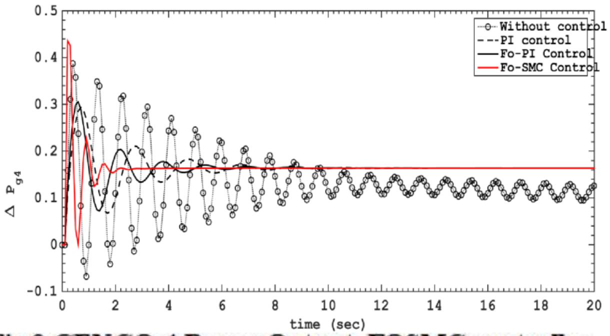

Fig.9 GENCO-4 Power Output, FOSMC controller

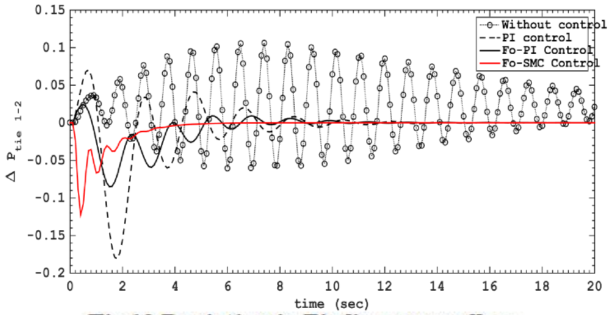

Fig.10 Deviation in Tie line power flow

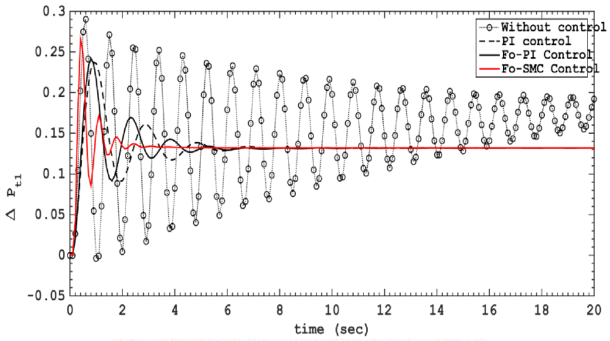

Fig.11 Turbine-1 power output

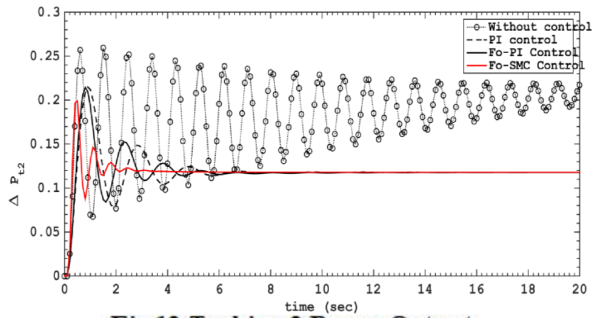

Fig.12:Turbine-2 Power Output

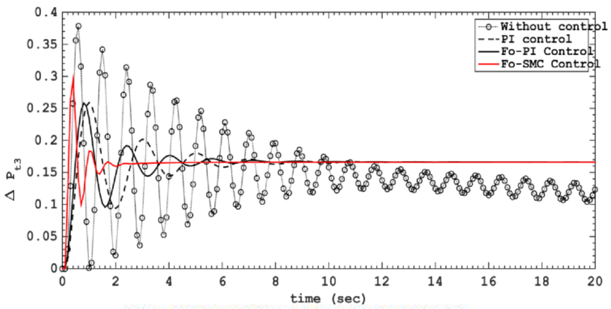

Fig.13 Turbine-3 Power Output

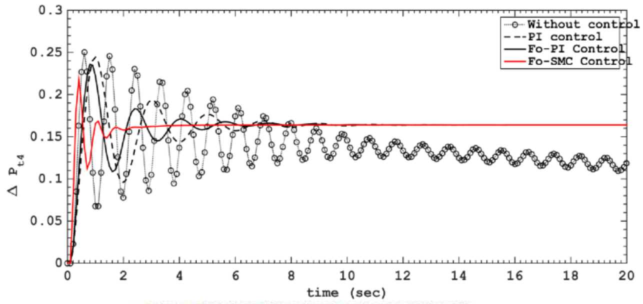

Fig.14 Turbine-4 Power Output

Table.1 Assessment of dynamic parameters of Thermal-Thermal Power System

Name of the controller	frequency deviation of Control Area-1 (%Peak overshoot)	frequency deviation of Control Area-2 (%Peakovershoot)	Settling Time of frequency deviation in Control Area-1	Settling Time of frequency deviation in Control Area-2
Without any controller	30%	36%	>20 Sec	> 20 Sec
With PI Controller	18%	33%	12 Sec	14 Sec
With FOPI Controller	11%	19%	6 Sec	8 Sec
With FOSMC Controller	**3%**	**10%**	**3 Sec**	**2.5 Sec**

V. CONCLUSION

A FOSMC presented for LFC of open market power system. The FOSMC tested on two area thermal-thermal power system for load frequency control by considering DPM matrix of mutual transaction scenario. The new FOSMC reduces peak deviations effectively and response time of the controller is less to mitigate frequency deviations effectively compared to FOPI controller. The proposed work can be extended with fractional order observer controllers as a future scope of work to attain good frequency response of the system.

APPENDIX

Table.2 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.3 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

TABLE-2 &TABLE-3 ARE CONSIDERED FOR SIMULATION

Retrieval Number: C5490029320/2020©BEIESP
DOI: 10.35940/ijeat.C5490.029320

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Retrieval Number: C5490029320/2020©BEIESP
DOI: 10.35940/ijeat.C5490.029320

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