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Indirect Adaptive Fuzzy Controller for Frequency Tracking In A Nonlinear Interconnected Two Area Power System Network

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ABSTRACT

Adaptive fuzzy control method is an important for complex nonlinear systems that operate varying in operating conditions. In this paper, we designed an Indirect Adaptive Fuzzy controller for tracking performance and load frequency deviation control for an interconnected two area nonlinear power system. Zero order Takagi-Sugeno fuzzy system and projection algorithm are employed for plant estimation and parameter adaptation mechanisms, the developed controller was connected directly to act on area 1 dynamics, the closed loop adaptive system is implemented in Matlab Simulink- S-function flat forms. Simulation results obtained demonstrated the capability of the tracking controller in maintaining stability in the presence of large load changes and parameter variations.

KEYWORDS: *Indirect Adaptive fuzzy control, Load frequency, Tracking performance, Parameter adaptation, Fuzzy basis function, Takagi-Sugeno fuzzy system*

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I. INTRODUCTION

Current deregulation in power system management and control has brought with it, a necessity for more efficient power control strategies. Load frequency control is an important component in power deregulation management. Due to increased complexity of power systems in a deregulated environment, adaptive control technique that seeks to adapt system parameters online, in response to changing conditions in the operating power system find important applications in that regard.

The two main types of adaptive control strategies are the direct and indirect schemes. In the direct method, plant's condition are sensed and used to adapt the controller's parameters [1-4]. In the indirect approach which is the intended controller in this work, plant's parameters are estimated on-line, this, are then use in updating the controllers' parameters. Fuzzy systems universal approximation property are adopted in giving well meaning approximation of plant's parameters for indirect adaptation and control in what is term as Indirect Adaptive Fuzzy Control (IAFC) [5-7]. In power systems load frequency control (LFC), power mismatch between generation and load demand which leads to frequency deviation is controlled. Robust fuzzy control methodologies have been for the treatment of frequency deviation in single and multi-area power system networks [8-14].

Artificial neural network and Neurofuzzy adaptive control methods have been successfully applied for LFC systems [15-16] . Fuzzy system as a tool for adaptively varying integral or proportional integral controller gain was also reported for LFC systems [17]. To our knowledge, we have yet, not come across a work, dealing with tracking control, based on IAFC being applied for two area power mismatched control. In [18] we applied the method for single area single machine load frequency control. In this paper, we intend to design an IAFC for an area in a two area LFC network. We shall use Matlab/Simulink in implementing the interconnected two area power system and S-function programming blocks in realizing the fuzzy system estimation, parameter adaptation scheme and final control law. We intend to see if ignoring an important component of the controller called '*auxiliary*' as used in almost all the works IAFC cited above, would affect the tracking performance. Results would be generated at varying load demands and area parameter variations.

Power System modeling : Considering a state of equilibrium of an i-th area non-reheat steam power generation network, taking a slight mis-match between power generation and load demand would result in frequency deviation away from operating point. The change in power flows including the tie-line in the i-th area network is

$$\Delta \dot{f}_i(t) = -\frac{D_i}{2H_i}\Delta f_i(t) + \frac{1}{2H_i}\Delta P_{mi}(t) - \frac{1}{2H_i}\Delta P_{di}(t) - \frac{1}{2H_i}\Delta P_{tie}(t)$$

$$\Delta \dot{P}_{mi}(t) = -\frac{1}{\tau_{ti}}\Delta P_{mi}(t) + \frac{1}{\tau_{ti}}\Delta P_{gi}(t)$$

$$\Delta \dot{P}_{gi}(t) = -\frac{1}{R_i \tau_{gi}}\Delta f_i(t) - \frac{1}{\tau_{gi}} P_{gi}(t) + \frac{1}{\tau_{gi}}\Delta P_{ci}(t) \qquad (1)$$

$$\Delta \dot{P}_{ij}(t) = P_s \int \left(\Delta f_i(t) - \Delta f_j(t)\right) dt$$

Where $i \in \wp_2 = [1,2]$, $j \in i/\{i\}$. In table 1 we provide the description of the system variables and parameters

Table 1: Description of System Parameters in i-th (and j-th) Areas

Symbols	Description
$\Delta f\ (t)$	incremental frequency deviation
$\Delta P_m(t)$	incremental mechanical power output
$\Delta P_g(t)$	governor valve position increment
$\Delta P_d(t)$	Change in load demand
$\Delta P_c(t)$	Incremental change in the speed changer position
$\Delta P_{tie}(t)$	Incremental tie-line flow from area i to area j
R	speed regulation constant
τ_g	Time constant of governor
τ_t	Turbine time constant
H	Pant inertia
D	Damping constant
P_s	Synchronizing power constant

The network configuration is structured as shown in Fig.1

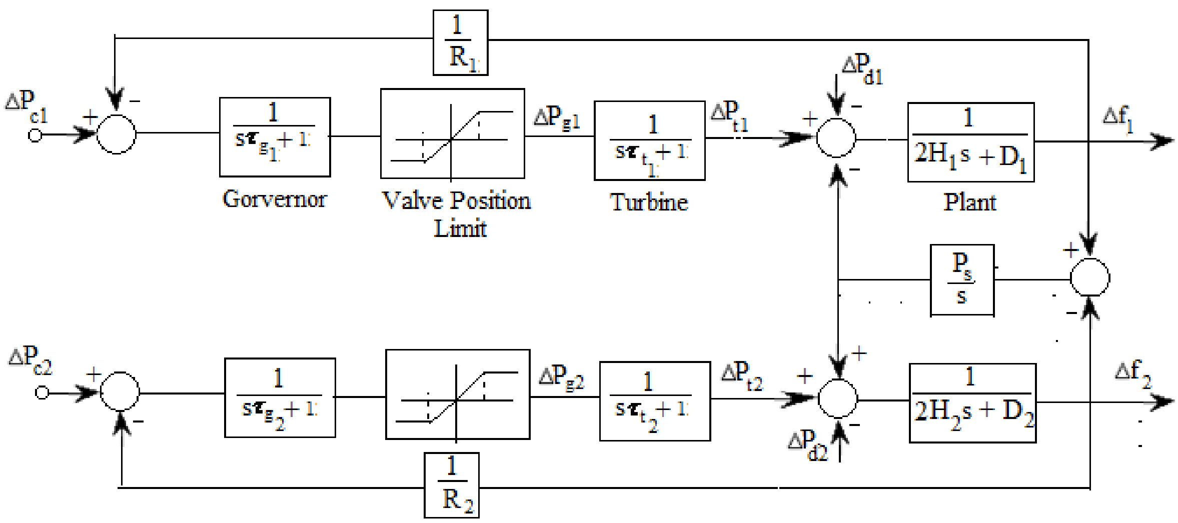


Fig.1: Two Area Load Frequency Deviation Model

We seek to build an indirect adaptive fuzzy controller around the i-th area network, so that its output frequency,Δf_1 is made to track a desired trajectory, at the same time attempting to minimize deviation of the j-th area in response to load demand changes and parameter variations in the i-th area.

II. INDIRECT ADAPTIVE FUZZY CONTROL LAW

We first consider a general description of (1) as,

$$\dot{x}(t) = f(x) + g(x)u(t) + w(t) \qquad (2)$$

Where $f(x)$ and $g(x)$ are smooth nonlinear functions, $w(t)$ is additive uncertainty or disturbance, $u(t)$ is input. We can find an admissible tracking controller for (2), that would allow a desired system state trajectory $\dot{x}_d(t) = f_d(x(t))$, to be tracked, at least by one of the states in (2).

We start by recalling conventional control law[4-7] and [19] of the form, but with slight change in notation as

$$u = \frac{1}{g(x)}\left(-f(x) - K^T \boldsymbol{e} + x_d^n - \gamma\sigma(\boldsymbol{e})\right) + u_s \qquad (3)$$

Where$f(x)$, $g(x)$ are functions of (1), $K^T = [k_{n,} \dots k_{n-1} \dots k_1]$ is selected to ensure

$$\lim_{t\to\infty} \boldsymbol{e}(t) = 0$$

where $\mathbf{e} = [x - x_d \;\; \dot{x} - \dot{x}_d \; \dots\dots \; x^{n-1} - x_d^{n-1}]$ is error vector, x_d^n is n-the order state of the reference system, $\sigma(\boldsymbol{e}) = \mathbf{a}\mathbf{e}$ is a sliding surface designed to confine error state trajectory within it, and to converge to zero, γ is design parameter to be chosen, with $\mathbf{a} = [1, a_1, \dots a_{n-1}]$ selected to ensure that

$$s^n + a_1 s^{n-1} + .. a_2 s^{n-2} + .. a_{n-1} = 0$$

is Hurwitz, u_s is auxiliary controller that takes on control function during system approximation, in situation where *f(x)* is not known.

Remark I: because of the obvious physical complexity of realizing *f(x)*, we shall develop its approximate zero order Takagi-Sugeno (T-S) fuzzy model.

Remark II: Unlike in the most of the cited works above, here we take the control gain function as positive constant: *g(x) = g* >> 0, where *g* is constant.

Remark III: To simplify the construction of (2), we ignore the auxiliary control law and adopt a well define and simple parameter adaptation mechanism.

III. SYSTEM T-S FUZZY MODEL APPROXIMATION

We consider rotor angle and frequency as states in the i-th area as $[\Delta x_1, \Delta x_2] = [\Delta\delta_1, \Delta f_1]$ as measurable states and inputs to a zero order T-S fuzzy rule; associating two fuzzy sets to each state as

$\Delta x_1 = \Delta\delta_1$: $\{M_1^1, M_1^2\}$

$\Delta x_2 = \Delta f_1$: $\{M_2^1, M_2^2\}$

we formulate four rules as

IF $x_1(t)$ *is* M_1^1 *and* $x_2(t)$ *is* M_2^1 *Then* $y = \alpha_1\theta_1$
IF $x_1(t)$ *is* M_1^1 *and* $x_2(t)$ *is* M_2^2 *Then* $y = \alpha_2\theta_2$
IF $x_1(t)$ *is* M_1^2 *and* $x_2(t)$ *is* M_2^1 *Then* $y = \alpha_3\theta_3$ (4)
IF $x_1(t)$ *is* M_1^2 *and* $x_2(t)$ *is* M_2^2 *Then* $y = \alpha_4\theta_4$

Where θ in a rule consequence is parameter taken as center of a specified fuzzy function or operating point associated with the premise (input) of the rule. If product inference rule is adopted, the aggregate fuzzy model from (4) can be written as

$$f(x) \cong \boldsymbol{\theta}_f^T \xi_f(x) \qquad (5)$$

Where $\boldsymbol{\theta}_f = [\theta_1, \theta_2, \dots \dots, \theta_R]^T$ is parameter vector to be initialized and adapted, $\boldsymbol{\xi}_f$ is called fuzzy basis function expressed as

$$\xi_f(x) = \frac{\Gamma_l(x)}{\sum_{l=1}^{R}\Gamma_l(x)} \qquad (6)$$

The function $\Gamma_l(x)$ is scaling fuzzy set function defined as

$$\Gamma_l(x) = \prod_{z=1}^{p} M_z^l(x), \qquad p = 2, \quad l = 1, 2, \dots, 4 \qquad (7)$$

Where $M_z^l(x)$ is z-th membership function in i-th rule. If $M_z^l(x)$ is triangular shape, the center form is mathematically expressed as

$$\mu_M(x_z) = max\left(0{,}1 + \frac{|x_z + c_z|}{0.5w_z}\right), \quad z = 1, \dots, p \qquad (8)$$

Where c_z is centre, w_z is width of z-th fuzzy set. Inserting (4) in (2), the control law is is

$$\mathbf{u}(t) = \frac{1}{g}\left(-\boldsymbol{\theta}_f^T \xi_f - K^T \boldsymbol{e} + \mathbf{x}^n - \gamma\sigma(\boldsymbol{e})\right) \qquad (9)$$

4.2 Parameter Adaptation Algorithm

We recall the parameter projection method in (Stanislaw, 2003) as

$$\dot{\theta}(t) = \begin{cases} \theta_{lo} & if \quad \mu\xi(\boldsymbol{x}) < 0 \\ \theta_u & if \quad \mu\xi(\boldsymbol{x}) > 0 \end{cases} \qquad (10)$$

Where θ_{lo} is the lower threshold, θ_u is upper threshold, μ is constant to be selected.

Using the model in Fig.1, the closed loop adaptive system is diagramed in block form as shown in Fig.2

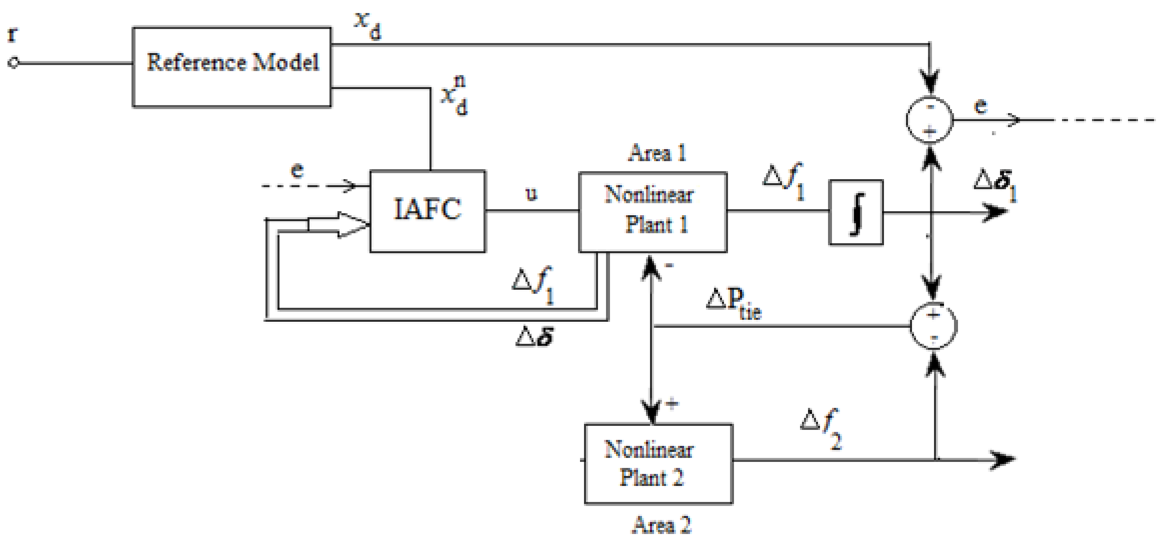


Fig.2: Close loop Block diagram of the Adaptive Control System

IV. SIMULATION

Reference Model : The reference model to be tracked in Fig.2 is chosen to have a natural frequency of 10rad/sec and damping factor of 0.8, thus, its s-model transfer function model can be written as,

$$G(s) = \frac{1000}{s^2+16s+100}$$

Fuzzy Sets : Over a universe of discourse X = [-1, 1], assuming triangular center type, we assign parameters to the membership functions in (4) as

$M_1^1 : \{c_{1,1}, w_{1,1}\} = [-0.5, 0.5]$, $M_1^2 : \{c_{1,2}, w_{1,2}\} = [0.5, 0.5]$

$M_2^1 : \{c_{2,1}, w_{2,1}\} = [-1,1]$, $M_2^2 : \{c_{2,2}, w_{2,2}\} = [1,1]$

To evaluate the system numerically, nominal power network parameters are given in table 1.

Table 1: Nominal Parameters of Two Area Power Network

Parameter	**Area 1**	**Area 2**
H	2.5	2.0
D	0.6	0.9
τ_t	0.5	0.3
τ_g	0.2	0.6
R	20	16
P_s	2.0	

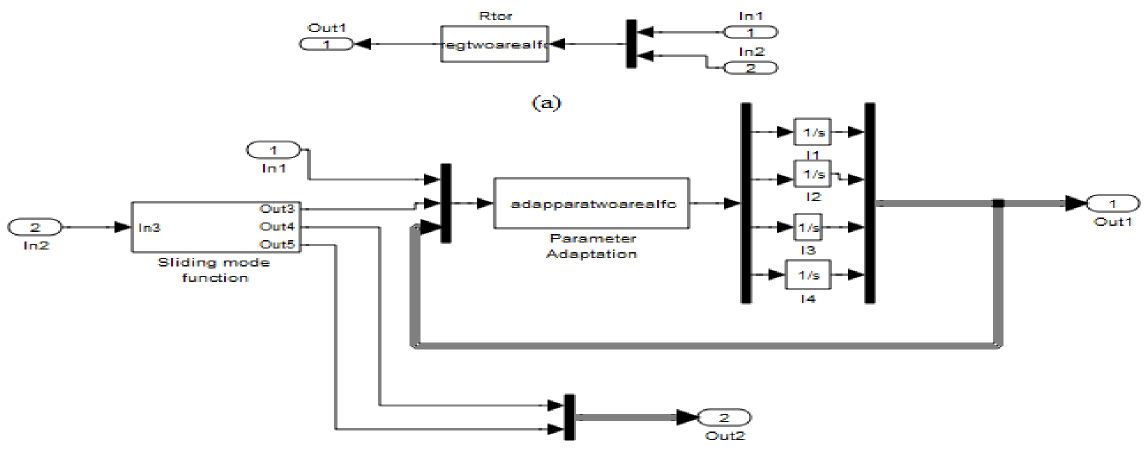
Adaptation and Control Law Parameters
In the parameter adaptation mechanism we assign the following

$\theta_l = -200$, $\theta_u = 200$,
$\mu = 500$, $K = [\alpha k_1 \beta k_2]/k_1 = 1$, $k_2 = 2$, $\alpha, \beta \gg 0$.

$\gamma = 500$, $|g(x)| = g \gg 0$.

The lower and upper limits nonlinearity associated with valve position mechanism are -0.5 and 05 respectively.

Using Matlab S-function programming blocks, the implementation of adaptive controlled network is shown in Fig.3.



(b)

Fig.3: Indirect Adaptive Fuzzy Control Law Implementation (a) Fuzzy basis function (b) Parameter Adaptation

V. SIMULATION RESULTS

We shall test the closed loop system under the following cases

Case 1: Area 1 load changes of 0.1 and 0.8

Case 2: 5%, 25% and 50% changes in area 1 governor constant, R_1.

Figures 4-5 showed the tracking performance of area1 and area 2 load frequency deviations at 0.1 and 0.8 p.u. load changes. In Fig.6, showed the control signal behavior. Case 2 performance results are shown in Figures 7, 8 and 9 respectively.

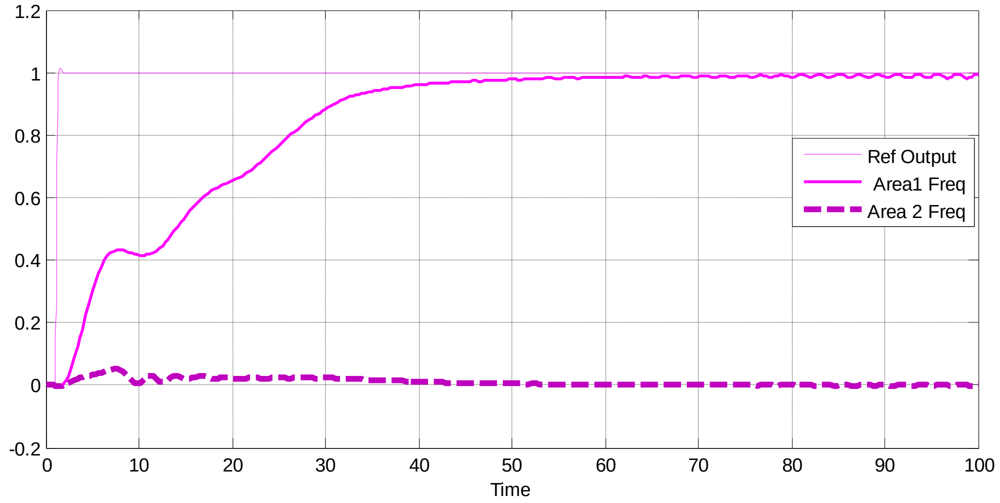


Fig.4: Reference Model and Area Frequencies Responses at 0.1p.u load Change on Area 1

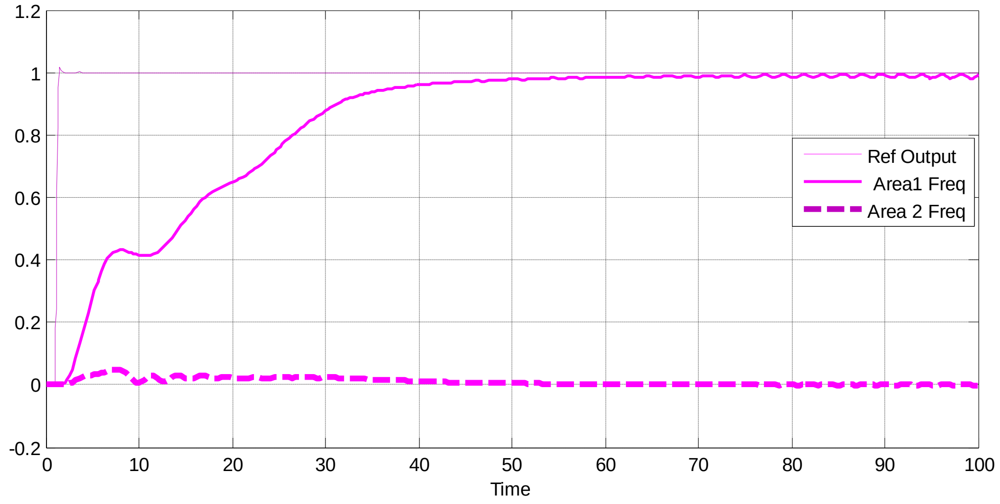


Fig.5: Performance at 0.8 put. Load change

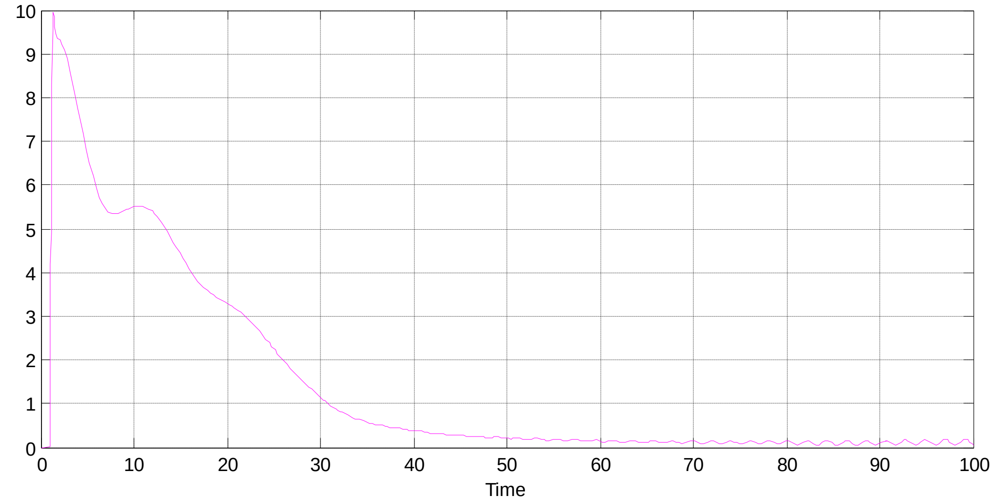


Fig.6: Control signal

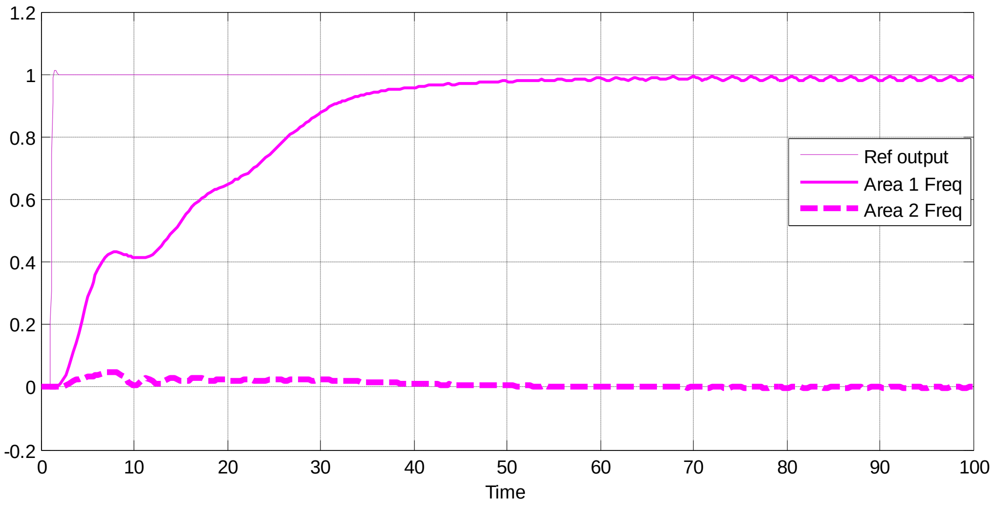


Fig.7: System Performance at +5% R1

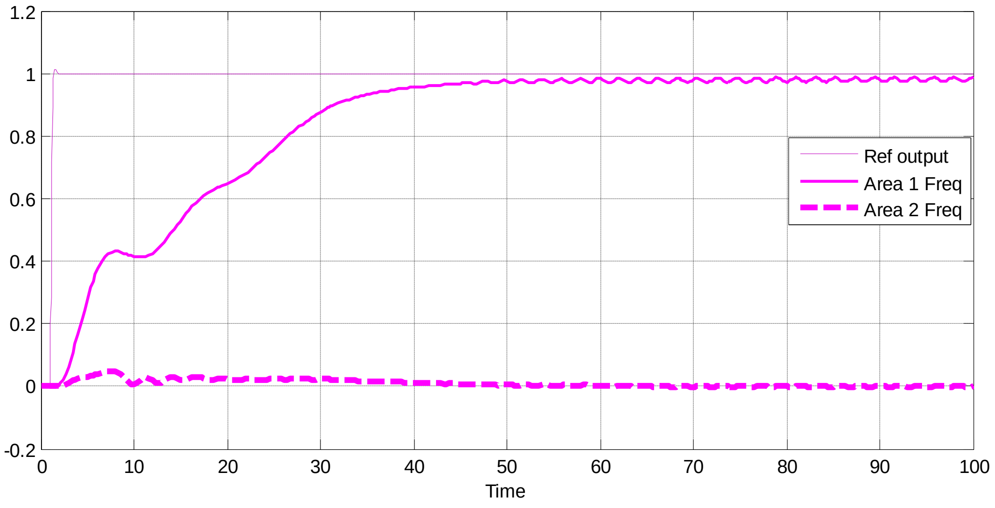


Fig.8: System Performance at + 25% R1

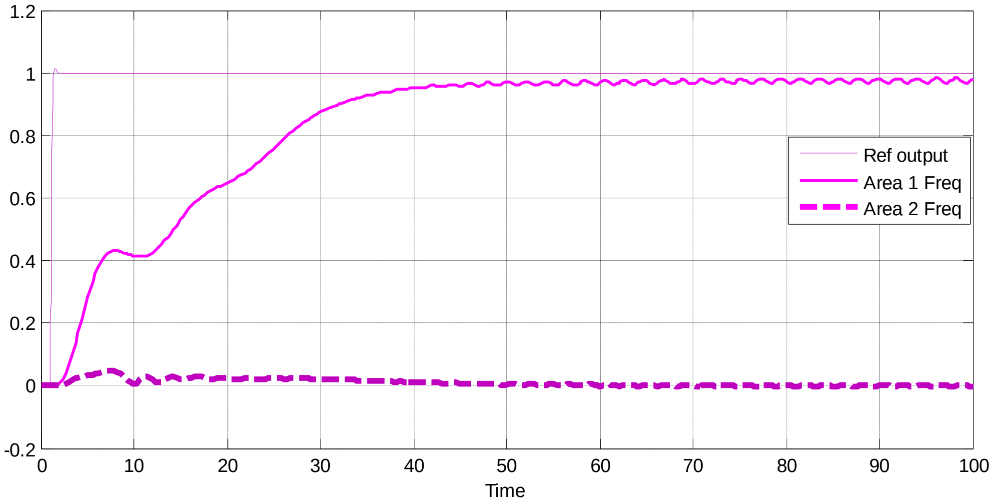


Fig.9: System Performance at + 50% R1

VI. DISCUSSION OF RESULTS

With 0.1 and 0.8 p.u. load changes on area 1 at nominal system parameters, good tracking performances have been achieved after about 70 seconds after initiation, and at steady state zero frequency deviation in area 2 frequency was obtained, these are shown in figures 4 and 5 respectively. The control effort required to initiate the state trajectory and the its subsequent decrease after the tracking is reached at the 70 seconds time range is shown in Fig.6. The robustness control performance was realized, even at increased area 1 governor speed regulation of +5% to +25% as obtained in figures 7 and 8 respectively. At large variation of +50% in $R_{1,}$ steady state error of just about 2.089% was indicated compared to 0.004% at nominal value (Fig.1) as shown in Fig.9. In all cases, small amplitude oscillation resulting, possibly due to the governor valve position limit mechanism in the steady state part can be smoothen by using nonlinear fuzzy linguistic value preferably the Gaussian function.

VII. CONCLUSION

The paper develops, for two interconnected nonlinear power system network an indirect adaptive fuzzy controller with the aim of achieving output frequency tracking in area 1, and mitigating frequency deviation in area 2. Zero order T-S fuzzy system was used in approximating the system function, projection method for parameter adaptation and sliding model concept are used in the control law construction. Using Matlab S-function programming blocks, acceptable tracking and deviation control responses are generated. At some relatively large values of area 1 governor speed regulation constant, slight increase in error was observed. In constructing the adaptive control law, we did not include the well known auxiliary control component.

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