FUZZY LOGIC CONTROL FOR MULTI-MACHINE POWER SYSTEM

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ABSTRACT

Stability enhancement is of great importance in power system design. Excitation control and static var compensator (SVC) play important roles in stability enhancement of power system. In this paper, an indirect adaptive fuzzy excitation control is proposed to enhance transient stability for the power system, which based on input-output linearization technique. A three-bus system, which contains a generator and static var compensator (SVC) is considered in this paper, the SVC is located at the midpoint of the transmission lines. Simulation results show that the proposed controller can enhance the transient stability of the power system under a large sudden fault, which may occur nearly at the generator bus terminal.

KEYWORDS: Feedback linearization control, generator excitation control, Indirect Adaptive Fuzzy Control and Static VAR Compensator.

1 INTRODUCTION

An interconnected power system basically consists of several essential components. They are namely the generating units, the transmission lines, the loads, the transformer, static VAR compensators and lastly the HVDC lines. During the operation of the generators, there may be some disturbances such as sustained oscillations in the speed or periodic variations in the torque that is applied to the generator. These disturbances may result in voltage or frequency fluctuation that may affect the other parts of the interconnected power system. External factors, such as lightning, can also cause disturbances to the power system. All these disturbances are termed as faults. When a fault occurs, it causes the motor to loose synchronism if the natural frequency of oscillation coincides with the frequency of oscillation of the generators. With these factors in mind, the basic condition for a power system with stability is synchronism. Besides this condition, there are other important condition such as steady-state stability, transient stability, harmonics and disturbance, collapse of voltage and the loss of reactive power.

In recent years, problems associated with environmental issues and high costs have delayed the construction of new transmission lines, while the demand for electric power has continued to grow. Under these conditions, the transmission networks are called upon to operate at high transmission levels and power engineers have had to confront some major operating problems such as transient instability, poor damping of oscillations and poor voltage regulation.

While the generator excitation controllers are helpful in achieving rotor angle stability, the excitation control alone may not maintain the system stability if a large fault occurs close to the generator terminal. Moreover simultaneous transient stability and voltage regulation enhancement may be difficult to be achieved. Researchers have found that the performance of power systems can be further improved by applying the recently developed flexible AC transmission systems (FACTS) controllers [1,2].

Among the FACTS family, the static VAR compensator (SVC) is a device which can provide smoothly and rapidly reactive power compensation to power systems. Therefore, in principle, SVC can be used with excitation control to provide voltage support, increase transient stability and improve damping [3]. Different approaches for excitation control are available in literature such as excitation control based on linear control theory using small signal models of the power system [4,5,6] and nonlinear excitation controls based on feedback linearization (FBL) control concept [7,8].

This paper presents an indirect adaptive fuzzy excitation and SVC control multi-machine systems using feedback linearization (FBL) technique. The main goal of the proposed controller is to improve both the system transient stability and damping oscillation even under large and sudden disturbances and to insure good post-fault voltage. A two-machine infinite bus system is used to evaluate the effectiveness of the proposed control scheme Fig (3).

Simulation results show that the proposed IAFLC control can enhance the dynamic performance of the power system over a wide range of operating conditions. The paper is organized as follows. In section 2 the mathematical model of a multi-machine power system is presented. The type and formulation of SVC is outlined in section 3 and Feedback Linearization Control based on multi input multi output linearization is given in section 4. Description of fuzzy logic systems is presented in section 5. In section 6, a design of an indirect adaptive fuzzy excitation control is proposed. Simulation results are shown in section 7 and conclusion are shown in section 8.

2 MATHEMATICAL MODEL

Consider a large-scale power system consisting of, n, generators interconnected through a transmission network. For the ith subsystem, the dynamics can be written using the state space formulation [9].

$$\dot{\delta}_i = \omega_i$$
$$\dot{\omega}_i = -\frac{D_i}{2H_i}\omega_i - \frac{\omega_0}{2H_i}(P_{ei} - P_m)$$
$$\dot{E}'_{qi} = \frac{1}{T_{doi}}(-E'_{qi} + (x_{di} - x'_{di})i_{di} + E_{fdi}) = \frac{1}{T_{doi}}(-E_{qi} + E_{fdi})$$

(1)

The electrical equations are as follows:

$$E_{qi} = E'_{qi} + (x_{di} - x'_{di})i_{di} \qquad (2)$$

$$P_{ei} = \sum_{j=1}^{n} E'_{qi}\, E'_{qj}\, B_{ij} \sin(\delta_i - \delta_j)$$

(3)

$$Q_{ei} = -\sum_{j=1}^{n} E'_{qi}\, E'_{qj}\, B_{ij} \cos(\delta_i - \delta_j) \qquad (4)$$

$$i_{di} = -\sum_{j=1}^{n} E'_{qj}\, B_{ij} \cos(\delta_i - \delta_j) \qquad (5)$$

$$i_{qi} = -\sum_{j=1}^{n} E'_{qj}\, B_{ij} \sin(\delta_i - \delta_j) \qquad (6)$$

$$V_{di} = E'_{di} + i_{qi} x'_{qi} \qquad (7)$$

$$V_{qi} = E'_{qi} - i_{di} x'_{di} \qquad (8)$$

$$V_{ti} = \sqrt{V_{di}^2 + V_{qi}^2} \qquad (9)$$

$$E'_{di} = -(x_{qi} - x'_{qi})i_{qi} \qquad (10)$$

3 STATIC VAR COMPENSATOR

The SVC used in this paper is a fixed capacitor and thyristor controlled reactor (FC/TCR) type, shown in Fig.2 and located at the midpoint of each transmission line. The magnitude of the SVC admittance Bs is given by: [10, 11]

$$B_s = B_L(\alpha) - B_c \qquad B_L(\alpha) = \frac{2\pi - 2\alpha + \sin 2\alpha}{2\pi X_L}$$

According to the variations in terminal voltage and angular speed, the suceptance of the inductor BL and then BS can be regulated as shown in Fig.3 [12].

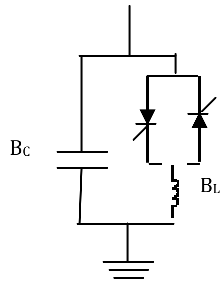

Figure 001 : FC/TCR type of SVC

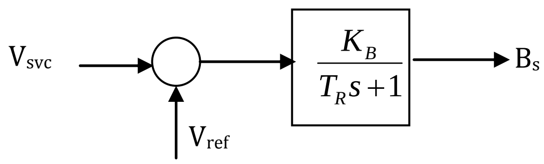

Figure 02 : block diagram of the SVC controller

The SVC dynamic model can be expressed as follows:

$$\dot{B}_L(t) = \frac{1}{T_R}(-B_L(t) + B_c + k_B u_B(t))$$

(11)

Where TR, KB, and uB are the time constant, the gain and the input of the SVC regulator respectively.

4 FEEDBACK LINEARIZATION CONTROL

The power system with subsystems modeled as in (1) can be written as a multi input-output system.

$$\dot{X} = F(x) + G(x)U \qquad (12)$$

$$Y = H(x)$$

where $X = [x_1, x_2, ..., x_n]^T$,

$U = [E_{fd1}, E_{fd2}, ..., E_{fdm}]^T$ and,

$Y = [\delta_1, \delta_2, ..., \delta_k]^T$

F and G are smooth vector fields, and G is a n×m matrix. Differentiating the output repeatedly with respect to time, the input U appears explicitly after three differentiations.

$$\dddot{y}_i = \alpha_i(x) + \sum_{j=1}^{n} \beta_{ij}(x) E_{fdj} \qquad (13)$$

The feedback linearization and decoupling control law is given by:

$$\begin{bmatrix} E_{fd1} \\ . \\ . \\ E_{fdm} \end{bmatrix} = A^{-1}(x) \begin{bmatrix} -\alpha_1(x) + v_1 \\ . \\ . \\ -\alpha_m(x) + v_m \end{bmatrix} \qquad (14)$$

where

$$A(x) = \begin{bmatrix} \beta_{11}(x) & . & . & \beta_{1m}(x) \\ . & . & . & . \\ . & . & . & . \\ \beta_{m1}(x) & . & . & \beta_{mm}(x) \end{bmatrix} \text{ and}$$

$$\beta_{ij}(x) = -\frac{\omega_0}{2H_i} \frac{1}{T_{doj}} E'_{qi} B_{ij} \sin(\delta_i - \delta_j) \qquad (15)$$

$$\beta_{ii}(x) = -\frac{\omega_0}{2H_i} \frac{1}{T_{doi}} \sum_{j=1}^{n} E'_{qj} B_{ij} \sin(\delta_i - \delta_j)$$

(16)

$$\alpha_i(x) = -\frac{D_i}{2H_i} \dot{\omega}_i - \frac{\omega_0}{2H_i} \sum_{j=1}^{n} E'_{qi} E'_{qj} B_{ij} (\omega_i - \omega_j)$$
$$\cos(\delta_i - \delta_j) + \frac{\omega_0}{2H_i} \frac{E_{qi}}{T_{doi}} \sum_{j=1}^{n} E'_{qj} B_{ij} \sin(\delta_i - \delta_j) +$$
$$\frac{\omega_0}{2H_i} \sum_{j=1}^{n} \frac{E_{qj}}{T_{doj}} E'_{qi} B_{ij} \sin(\delta_i - \delta_j)$$

(17)

Once linearization is achieved, further control objectives like model matching, pole placement and tracking can be easily met. For our purpose we would like to regulate the output to zero in a desired fashion. We choose.

$$v_i = \dddot{y}_m + a_{3i} \ddot{e}_{ri} + a_{2i} \dot{e}_{ri} + a_{1i} e_{ri} \qquad (18)$$

where

$$e_{ri} = y_{mi} - y_i = \delta_{i0} - \delta_i .$$
$$\dot{e}_{ri} = \dot{y}_{mi} - \dot{y}_i = -\omega_i$$
$$\ddot{e}_{ri} = \ddot{y}_{mi} - \ddot{y}_i = -\dot{\omega}_i$$

where a_{ji} ,j=1,..,3, i=1,…..,m, are chosen such that the polynomial ($s^3 + a_{3i} s^2 + a_{2i} s + a_{1i}$) is strict Hurwitz and the system has poles at the desired locations. The control law given by (14) and (18) results in a feedback linearized and decoupled system with the output yi converging asymptotically to the desired response.

5 DESCRIPTION OF FUZZY LOGIC SYSTEMS

The fuzzy logic systems are universal approximations from the viewpoint of human experts and can uniformly approximate nonlinear continuous functions to arbitrary accuracy. In the adaptive fuzzy control case, in order to achieve the proposed control objectives, nonlinear functions $\alpha_i(x)$ and $\beta_{ij}(x)$ will be approximated by tuning the parameters of the corresponding fuzzy logic systems. Therefore, the fuzzy logic systems are qualified as building blocks of adaptive fuzzy controllers for nonlinear systems. Furthermore, the fuzzy logic systems are constructed from the fuzzy IF-THEN rules using some specific inference, fuzzification, and defuzzification strategies. So linguistic information from human experts can be directly incorporated into controllers.[12]

R(l): If x1 is Fl1 and x2 is Fl2 and … and xn is Fln Then yl is Cl (l=1; … ; M).

where x =(x1; : : : ; xn)T ∈ U; y ∈ V ⊂ R are the input and output of fuzzy logic systems, respectively, Fli ; Cl is the fuzzy sets defined on Ui and R, respectively. The fuzzy inference engine performs a mapping from fuzzy sets in U to fuzzy sets in R, based upon the fuzzy IF-THEN rules in the fuzzy rule base and the compositional rule of inference The fuzzifier maps a crisp point x =(x1; : : : ; xn)T into a fuzzy set in U. The defuzzifier maps a fuzzy set in V to a crisp point in V.

Lemma 1. The fuzzy logic systems with center-average defuzzifier; product inference and singleton fuzzifier are in the following form:

$$y(x)=\frac{\sum_{l=1}^{M}\bar{y}^{l}\left(\prod_{i=1}^{n}\mu_{F_i^l}(x_i)\right)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\mu_{F_i^l}(x_i)\right)} \qquad (19)$$

where $\bar{y}^{l}$ is the point at which μ_c^l achieves its maximum value, and we assume that $\mu_c^l(\bar{y}^{l})=1$.

Eq. (19) can be written as

$$y(x)=\underline{\theta}^T\,\underline{\psi}(\underline{x}) \qquad (20)$$

$\psi(\underline{x})$ is the fuzzy basis function defined by

$$\psi_l(\underline{x})=\frac{\prod_{i=1}^{n}\mu_{F_i^l}(x_i)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\mu_{F_i^l}(x_i)\right)} \qquad (21)$$

6 ADAPTIVE FUZZY EXCITER BASED ON MULTI-INPUT MULTI- OUTPUT

If the nonlinear functions $\alpha_i(x),\beta_{ij}(x)$ are unknown in our problem, so obtaining control law (14) is impossible. In this situation, our purpose is to approximate $\alpha_i(x)$, $\beta_{ij}(x)$ with fuzzy logic systems $\hat{\alpha}_i(x),\hat{\beta}_{ij}(x)$ defined as [12]

$$\begin{aligned}\hat{\alpha}_i(x\,|\,\theta_i)&=\theta_i^T\psi(x)\\ \hat{\beta}_{ij}(x\,|\,\theta_{ij})&=\theta_{ij}^T\psi(x)\end{aligned} \qquad (22)$$

Choosing an equivalence control as

$$\begin{bmatrix}E_{fd1}\\ \cdot\\ \cdot\\ E_{fdm}\end{bmatrix}=\begin{bmatrix}\hat{\beta}_{11}(x) & \cdot & \cdot & \hat{\beta}_{1m}(x)\\ \cdot & \cdot & \cdot & \cdot\\ \cdot & \cdot & \cdot & \cdot\\ \hat{\beta}_{m1}(x) & \cdot & \cdot & \hat{\beta}_{mm}(x)\end{bmatrix}^{-1}\begin{bmatrix}-\hat{\alpha}_1(x)+v_1\\ \cdot\\ \cdot\\ -\hat{\alpha}_m(x)+v_m\end{bmatrix} \qquad (23)$$

$$\dddot{e}_i=-\bar{a}^{T}\bar{e}+w_i \qquad (24)$$

where $\bar{a}^{T}=[a_{1i}\ a_{2i}\ a_{3i}]$ and $\bar{e}=[e_i\ \dot{e}_i\ \ddot{e}_i]$

and w_i is the approximation error defined by:

$$w_i=(\hat{\alpha}_i(x\,|\,\theta_i)-\alpha_i(x))+\sum_{j=1}^{n}(\hat{\beta}_{ij}(x\,|\,\theta_{ij})-\beta_{ij}(x))u_j \qquad (25)$$

its state-place equation is

$$\dot{\bar{e}}_i=A_i\bar{e}_i+b_iw_i \qquad (26)$$

where $A_i=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ -a_{1i} & -a_{2i} & -a_{3i}\end{bmatrix}$ and $b_i=\begin{bmatrix}0\\ 0\\ 1\end{bmatrix}$

Define the optimal parameter estimates θ_i^* and θ_{ij}^* as follows

$$\theta_i^* = \arg\min_{\theta_i \in \Omega i}[\sup_{x \in U_c} \left\| \theta_i^T \psi(x) - \alpha_i(x) \right\|]$$

(27)

$$\theta_{ij}^* = \arg\min_{\theta_{ij} \in \Omega_{ij}}[\sup_{x \in U_c} \left\| \theta_{ij}^T \psi(x) - \beta_{ij}(x) \right\|]$$

(28)

Using θ_i^* and θ_{ij}^*, the minimum approximation error w_i^* can be written as:

$$w^*_i = (\hat{\alpha}_i(x \mid \theta_i^*) - \alpha_i(x)) + \sum_{j=1}^{n} (\hat{\beta}_{ij}(x \mid \theta_{ij}^*) - \beta_{ij}(x))u_j$$

(29)

Now adding and subtracting the term (bi w_i^*) to (26), the error equation can be rewritten as:

$$\dot{\bar{e}}_i = A_i \bar{e}_i + b_i w_i^* + b_i[\phi_i^T \psi(x) + \sum_{j=1}^{n} \phi_{ij}^T \psi(x) u_j]$$

(30)

Where: $\phi_i = \theta_i - \theta_i^*$ and $\phi_{ij} = \theta_{ij} - \theta_{ij}^*$, if the following positive define Laypunov function candidate:[12]

$$V_i = \frac{1}{2} \bar{e}_i^T P_i \bar{e}_i + \frac{1}{2\gamma_i} \phi_i^T \phi_i + \sum_{j=1}^{n} \frac{1}{2\gamma_{ij}} \phi_{ij}^T \phi_{ij} \qquad (31)$$

We choose the adaptive law as

$$\dot{\theta}_i = -\gamma_i \bar{e}_i^T P_i b_i \psi(x)$$

$$\dot{\theta}_{ij} = -\gamma_{ij} \bar{e}_i^T P_i b_i \psi(x) u_j$$

(36)

From the above equation we have

$$\dot{V}_i = -\frac{1}{2} \bar{e}^T{}_i Q_i \bar{e}_i + \frac{1}{2}(w_i^{*T} b^T{}_i P_i \bar{e}_i + \bar{e}_i^T P_i b_i w_i^*) \quad (37)$$

The term $\frac{1}{2}(w_i^{*T} b_i^T P_i \bar{e}_i + \bar{e}_i^T P_i b_i w_i^*)$ is of the order of the minimum approximation error which is very small or zero.

If this is case equation (37) reduces to $\dot{V}_i \le 0$.

where the P_i matrix is the unique positive defined 3×3 matrix that satisfies the Lyapunov equation.

$$A^T{}_i P_i + P_i A_i = -Q_i$$

7 SIMULATION RESULTS

The system considered here consists of a 50Hz, 230 KV transmission network with two generators and infinite bus connected through a network of transformers and transmission lines. The single line diagram of the system is shown in Fig.1. The infinite bus voltage is taken as a reference. V3=1 arg 0.

The parameters that are used in the power system modeling are as shown below [9].

$\omega_0 = 314.159$, XL12=0.55, XL13=0.53, XL23=0.6.

Generator 1

xd=1.863 p.u. x'd=0.257 p.u. xq= 1.46 p.u. x'q=0.546 p.u.xT1=0.129 p.u. Tdo=6.9 p.u. H = 4s D=5 p.u.

Generator 2

xd=2.36 p.u. x'd=0.319 p.u. xq= 0.70 p.u. x'q=0.20 p.u. xT1=0.110 p.u. Tdo=7.96 p.u. H=5.1s. D=3 p.u.

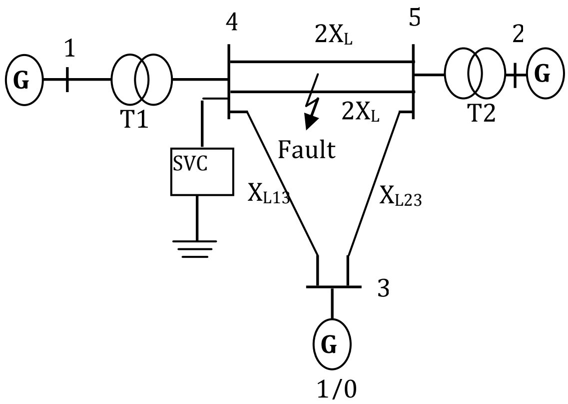

Figure 03 : A two machine with infinite bus power system

The system response under a three-phase short circuit fault is tested. The following temporary fault sequence is used in the simulation studies:

Stage 1: The system is in a per-fault steady state.

Stage 2: A three phase short circuit fault occurs at t=2.1 s.

Stage 3: The fault is removed by opening the circuit breakers after 2.2 s.

Stage 4: The transmission line is restored at t=3.4 s.

Stage 5: The system is in a post-fault state.

7.1 Feedback Linearization Control (FBL) Selection of SVC Location

First it is essential to select a location for the SVC .The SVC is installed at bus 4 then at bus 5 in order to select the better location of SVC. This will examined by selecting different operating points then comparing the responses of the system using different techniques namely, FBL and excitation control coordinated with SVC based on FBL.

Case 1: The operating point is

$$\delta_{10} = 64.08, P_{m10} = 1.1, V_{t10} = 1.0$$
$$\delta_{20} = 65.33, P_{m20} = 1.0, V_{t20} = 1.0$$

The fault location is $\lambda = 0.4$. The corresponding responses are shown in Fig (4-5).

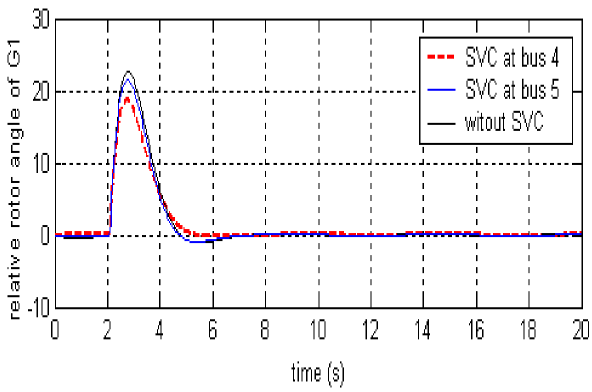

Figure 04 : the response of relative rotor angle of generator 1

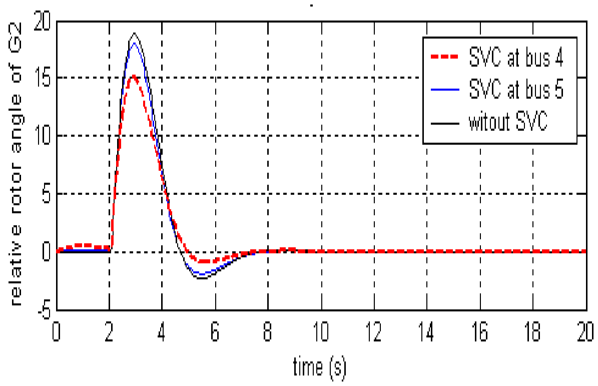

Figure 05 : the response of relative rotor angle of generator 2

Fig (4) and Fig (5) show the response of the relative rotor angle of the generator 1 and 2 respectively, it can be seen that, although the system stays stable for both selected positions of the SVC. When the SVC is installed at bus 4, the oscillations for rotor angle of generator 1 are damped out in 3 sec and those of generator 2 are damped out in 4.3 sec. Also a decrease in amplitude of 5% is registered in both subsystems contrary to install the SVC at bus 5.

Case 2: The operating point is

$$\delta_{10} = 60.78, P_{m10} = 0.95, V_{t10} = 1.0$$
$$\delta_{20} = 60.78, P_{m20} = 0.95, V_{t20} = 1.0$$

For Case 3, the power angles δ_{10}, δ_{20}, and the mechanical input power Pm10 and Pm20 are varied .The fault location is $\lambda = 0.2$. Figs (6-7) show the responses of the relative rotor angle of each generator.

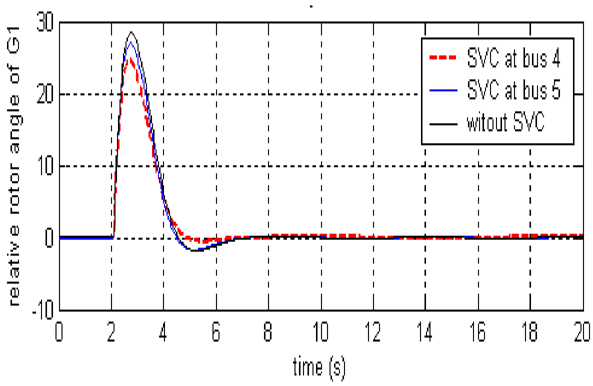

Figure 06 : the response of relative rotor angle of generator 1

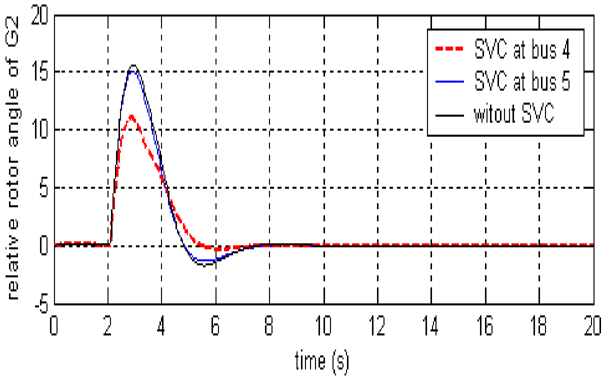

Figure 07 : the response of relative rotor angle of generator 2

The same improvements of case 1 are registered. Installing the SVC at bus 4, results in regain synchronism of both generators after 3 sec irrespect of changing the operating point and/or the fault location. Consequently, the SVC will be fixed at bus 4 since this displacement gives a better performance.

7.2 Indirect Adaptive Fuzzy control

An indirect adaptive fuzzy controller is now applied. A three triangular membership functions defined for each state variable $(\delta_i - \delta_{0i}, \omega_i)$:

$$u^1_{F_i}(x_i) = 1\text{-abs}((x_i - \pi/6)/(\pi/6))$$

$$u^2_{F_i}(x_i) = 1\text{-abs}((x_i)/(\pi/6))$$

$$u^3_{F_i}(x_i) = 1\text{-abs}((x_i + \pi/6)/(\pi/6))$$

Also three triangular membership functions are defined for the third state E'_{qi}:

$$u^1_{F_i}(x_i) = 1\text{-abs}((x_i - 1.5)/1.5)$$

$$u^2_{F_i}(x_i) = 1\text{-abs}((x_i)/1.5)$$

$$u^3_{F_i}(x_i) = 1\text{-abs}((x_i + 1.5)/1.5)$$

where i=1,2.

A MATLAB program is used to simulate the overall control system, choosing infinite bus 3 as the reference bus, and SVC installed at bus 4. An indirect adaptive fuzzy control is applied to the system and compared with feedback linearization technique.

Selecting the operating point as:

$$\delta_{10} = 60.78, P_{m10} = 0.95, V_{t10} = 1.0$$
$$\delta_{20} = 60.78, P_{m20} = 0.95, V_{t20} = 1.0$$

where the fault location at ($\lambda = 0.0001$).

As shown in Fig (8) and (10). An improvement of the transient stability is registered, for both feedback linearization and indirect adaptive fuzzy control, but in case of IAFLC, the amplitude of oscillations in relative rotor angle ($\Delta\delta(t)$) related to generators 1 and 2 is 30% less than the FBL controller. Fig (9) and Fig (11) show that with the IAFLC controller the system returns to synchronism and stable condition after 2 sec, in both generators, however, the FBL controller returns after 4 sec.

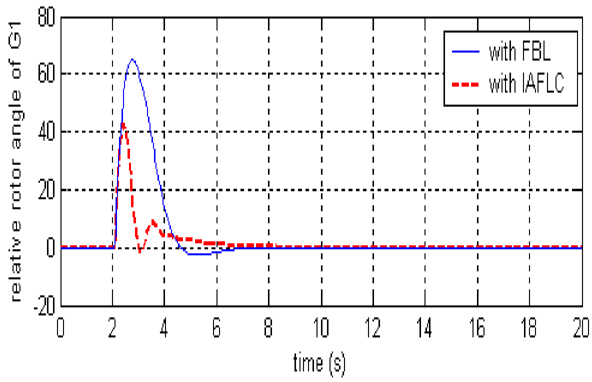

Figure 08 : Response of the relative rotor angle with FBL and with IAFLC of generator 1 at ($\lambda = 0.0001$***)***

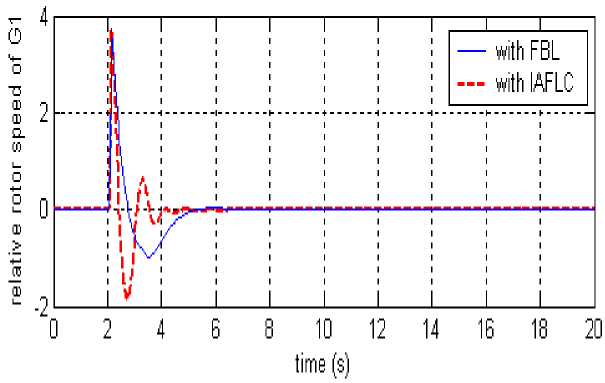

Figure 09 : Response of the relative rotor speed (w(t)) with FBL and with IAFLC of generator 1 at ($\lambda = 0.0001$***)***

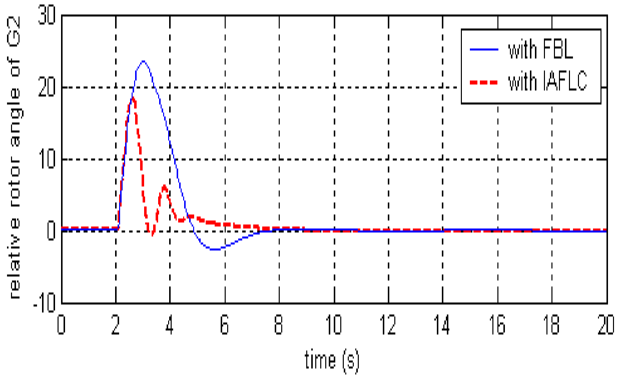

Figure 10 : Response of the relative rotor angle with FBL and with IAFLC of generator 2 at ($\lambda = 0.0001$***)***

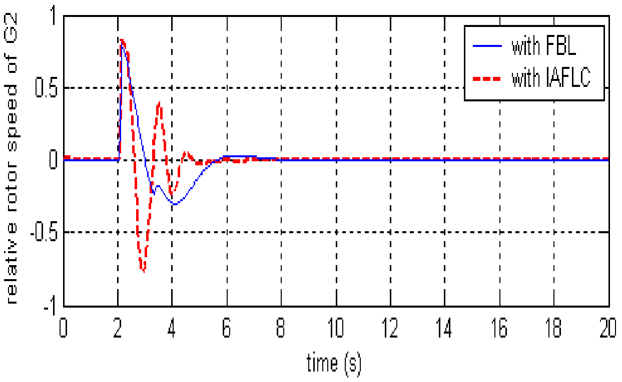

Figure 11 : Response of the relative rotor speed (w(t)) with FBL and with IAFLC of generator 2 at ($\lambda = 0.0001$***)***

Fig (12) shows that applying FBL ,the duration of the voltage dip of generator 1 is 3.5 sec, with an amplitude equals 25% while, when applying IAFLC these values are enhanced and become 1.5s and 9% respectively.

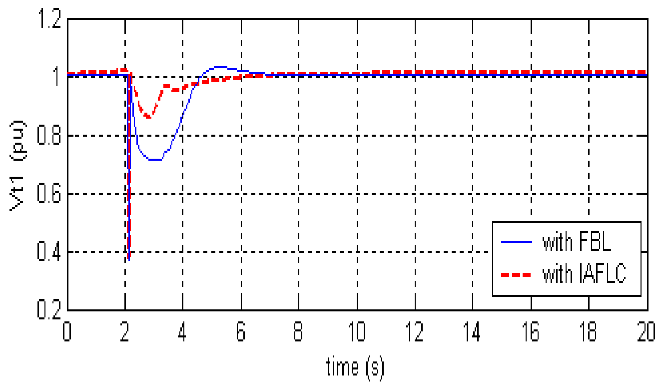

Figure 12: Response of the generator bus terminal voltage (V1(t)) with FBL and with IAFLC at ($\lambda = 0.0001$***).***

Fig (13) shows that with IAFLC the terminal voltage returns to initial value after 3.5 sec, however, with FBL controller returns after 5 sec.

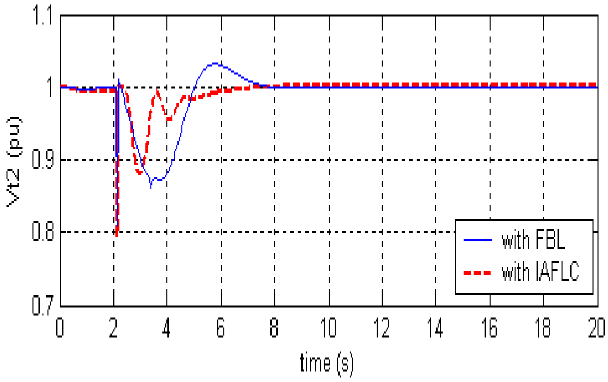

Figure 13 : Response of the generator bus terminal voltage ($V_2(t)$***) with FBL and with IAFLC at (*** $\lambda = 0.0001$***)***

8 CONCLUSION

This paper presents coordinated excitation and SVC control scheme using an indirect adaptive fuzzy control for transient stability enhancement of multi-machine power systems. The fuzzy controller is constructed based on feedback linearization techniques. The indirect adaptive fuzzy controller parameters are adjusted indirectly from the estimation of plant parameters. The adaptation law adjusts the controller parameters on-line so that the plant output tracks the reference output. The simulation results show that, the proposed indirect adaptive fuzzy control can enhance the transient stability, enrich damping and, simultaneously achieve good post-fault generator terminal voltage compared to the feedback linearization control.

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LIST OF SYMBOLS

FBL: Feedback linearizating.

IAFLC: Indirect Adaptive Fuzzy Control.

SVC: Static Var Compensators.

TCR: Thyristor Controlled Reactor.

BL: The susceptance of the inductor in SVC.

BC :The susceptance of the capacitor in the SVC.

D: Damping constant.

Eq: The EMF in the quadrature axis.

Efd :The excitation control input.

E'_{qi} :The transient EMF in the quadrature axis of generator i.

E'_{di} :The transient EMF in the direct axis i.

idi, iqi:the direct and quadrature axis currents of generator i.

kB: The gain of the SVC regulator.

L : Inductance of each reactor (H).

M: Inertia constant.

Pei: The active electric power delivered by the generator i.

Pe: The active electric power delivered by the generator.

Pm: The mechanical input power.

Qei: The reactive electric power delivered by the generator.

TR: The time constant of the SVC regulator.

Tdo: The rotor circuit time constant.

Vt: The terminal voltage.

Vdi: The direct axis voltage of generator i.

Vqi: The quadrature axis voltage of generator i.

xd: The direct axis reactance.

x d′: The direct axis transient reactance.

xq: The quadrature axis reactance.

xq′: The quadrature axis transient reactance.

xtr: The transformer reactance.

xL12, xL23: Reactance of transmission lines.

ω0: Fundamental frequency (rad / sec).

ωi: The relative rotor speed of the generator.

α : Firing angle (deg).

$\Delta\delta$: The relative generator power angle.

δ_i : The rotor angle.

θ_i, θ_{ij} : The adjustable parameter.