Indirect adaptive fuzzy control for multi-machine power system

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An indirect Adaptive Fuzzy excitation Control (IAFLC) of power systems based on multi-input-multi-output linearization technique is developed in this paper. The power system considered in this paper consists of two generators and infinite bus connected through a network of transformers and transmission lines. The fuzzy controller is constructed from fuzzy feedback linearization controller whose parameters are adjusted indirectly from the estimates of plant parameters. The adaptation law adjusts the controller parameters on-line so that the plant output tracks the reference model output. Simulation results shown that the proposed controller IAFLC, compared with a controller based on tradition linearization technique can enhance the transient stability of the power system.

هذا البحث يبين استخدام طريقة التحكم الغيمي المتلائم غير المباشر للتحكم في جهد الإثارة لمولدات منظومة القدرة التي تحتوي على عدة مولدات وذلك عن طريق تقنية التغذية العكسية التي تحول المنظومة متعددة المداخل والمخارج إلى منظومة خطية مما ينشأ عنه تحسين استقرار المنظومة عند تعرضها لإضطرابات فجائية. وقد تم تطبيق هذه الطريقة على منظومة قدرة ذات مولدين وشبكة لانهائية. وقد أوضحت نتائج المحاكاة أن التحكم باستخدام الطريقة المقترحة أعطى نتائج أفضل في تحسين الإستقرار العابر لمنظومة القدرة مقارنة بطريقة التقنية الخطية التقليدية.

Keywords: Feedback linearization control, Generator excitation control, Indirect adaptive fuzzy control in multi-input multi-output systems

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 lose 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 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, system stability may not be maintained 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].

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 [3-5] and nonlinear excitation controls based on Feed Back Linearization FBL control concept [6-7].

This paper, present an indirect adaptive fuzzy excitation control in multi-machine systems based on feedback linearization technique, the main goal is to improve both the system transient stability and damping properties even under sudden disturbances and to insure good post-fault terminal voltage. A two-machine infinite bus example system is used to evaluate the effectiveness of the proposed control scheme. Simulation results show that the proposed 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. Feedback linearization control based on multi-input-multi-output linearization is given in section 3. Description of fuzzy logic systems is outlined in section 4. In section 5, a design of adaptive fuzzy excitation control is proposed. Simulation results are shown in section 6 and conclusion are shown in section 7.

2. Mathmatical model

Consider a large-scale power system consisting of n-generators interconnected through a transmission network. For the i_{th} subsystem, the dynamics can be written using the state space formulation [8].

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

$$= \frac{1}{T_{doi}}(-E_{di} + E_{fdi}) \cdot \tag{1}$$

The electrical equations are as follows:

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

$$P_{ei} = \sum_{j=1}^{n} E'_{qi} E'_{qj} B_{ij} \sin(\delta_i - \delta_j) \cdot \tag{3}$$

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

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

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

$$V_{di} = E'_{di} + i_{qi} x'_{qi} \cdot \tag{7}$$

$$V_{qi} = E'_{qi} - i_{di} x'_{di} \cdot \tag{8}$$

$$V_{ti} = \sqrt{V_{di}^2 + V_{qi}^2} \cdot \tag{9}$$

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

3. Feedback linearization control

The power system with subsystems modeled as in eq. (1) can be written as a multi input-output system [9].

$$\dot{X} = F(x) + G(x)U \cdot \tag{11}$$

$$Y = H(x),$$

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.

$$\dddot{y}_i = \alpha_i(x) + \sum_{j=1}^{n} \beta_{ij}(x)E_{fdj} \cdot \tag{12}$$

The feedback linearization and decoupling control law is given by:

$$\begin{bmatrix} E_{fd1} \\ \cdot \\ \cdot \\ E_{fdm} \end{bmatrix} = A^{-1}(x) \begin{bmatrix} -\alpha_1(x) + v_1 \\ \cdot \\ \cdot \\ -\alpha_m(x) + v_m \end{bmatrix}, \quad (13)$$

where

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

and

$$\alpha_i(x) = -\frac{D_i}{2H_i}\dot{\omega}_i - \frac{\omega_0}{2H_i}\sum_{j=1}^{n}E'_{qi}E'_{qj}B_{ij}(\omega_i - \omega_j)$$

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

$$\frac{\omega_0}{2H_i}\sum_{j=1}^{n}\frac{E_{qj}}{T_{doj}}E'_{qi}B_{ij}\sin(\delta_i - \delta_j) \quad (14)$$

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

$$\beta_{ii}(x) = -\frac{\omega_0}{2H_i}\frac{1}{T_{doi}}\sum_{j=1}^{n}E'_{qj}B_{ij}\sin(\delta_i - \delta_j). \quad (16)$$

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.

$$v_i = \dddot{y}_m + a_{3i}\ddot{e}_{ri} + a_{2i}\dot{e}_{ri} + a_{1i}e_{ri} \quad (17)$$

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 eqs. (13 and 17) results in a feedback linearized and decoupled system with the output y_i converging asymptotically to the desired response.

4. 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 $\beta_{ij}(x)$ and 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 [10].

$R^{(l)}$: If x_1 is F^l_1 and x_2 is F^l_2 and … and x_n is F^l_n Then y^l is C^l (l=1; … ; M).

where $x = (x_1; : : : ; x_n)^T \in U$; $y \in V \subset R$ are the input and output of fuzzy logic systems, respectively, F^l_i; C^l is the fuzzy sets defined on U_i and R, respectively M is the number of rules. 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 $x = (x_1; : : : ; x_n)^T$ into a fuzzy set in U. The defuzzifier maps a fuzzy set in V to a crisp point in V.

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

$$y(x) = \frac{\sum_{l=1}^{M} \bar{y}^l (\prod_{i=1}^{n} \mu_{F_i^l}(x_i))}{\sum_{l=1}^{M} (\prod_{i=1}^{n} \mu_{F_i^l}(x_i))} , \tag{18}$$

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. (18) can be written as

$$y(x) = \underline{\theta}^T \underline{\psi}(\underline{x}) , \tag{19}$$

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

$$\psi_l(\underline{x}) = \frac{\prod_{i=1}^{n} \mu_{F_i^l}(x_i)}{\sum_{l=1}^{M} (\prod_{i=1}^{n} \mu_{F_i^l}(x_i))} . \tag{20}$$

5. 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 eq. (13) 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 [11]

$$\hat{\alpha}_i(x \mid \theta_i) = \theta_i^T \psi(x)$$

$$\hat{\beta}_{ij}(x \mid \theta_{ij}) = \theta_{ij}^T \psi(x) \tag{21}$$

Choosing an equivalence control as

$$\begin{bmatrix} E_{fd1} \\ . \\ . \\ E_{fdm} \end{bmatrix} = \begin{bmatrix} \hat{\beta}_{11}(x) & . & . & \hat{\beta}_{1m}(x) \\ . & . & . & . \\ . & . & . & . \\ \hat{\beta}_{m1}(x) & . & . & \hat{\beta}_{mm}(x) \end{bmatrix}^{-1} \begin{bmatrix} -\hat{\alpha}_1(x) + v_1 \\ . \\ . \\ -\hat{\alpha}_m(x) + v_m \end{bmatrix} \tag{22}$$

The error equation become

$$\ddot{e}_i = -\bar{a}^T \bar{e} + w_i , \tag{23}$$

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:

$$w_i = (\hat{\alpha}_i(x \mid \theta_i) - \alpha_i(x)) + \sum_{j=1}^{n} (\hat{\beta}_{ij}(x \mid \theta_{ij}) - \beta_{ij}(x))u_j . \tag{24}$$

The state equation of (23) can be written as:

$$\dot{\bar{e}}_i = A_i \bar{e}_i + b_i w_i , \tag{25}$$

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

$$\theta_i^* = \arg\min_{\theta_i \in \Omega i} [\sup_{x \in U_c} \|\theta_i^T \psi(x) - \alpha_i(x)\|] . \tag{26}$$

$$\theta_{ij}^* = \arg\min_{\theta_{ij} \in \Omega_{ij}} [\sup_{x \in U_c} \|\theta_{ij}^T \psi(x) - \beta_{ij}(x)\|] , \tag{27}$$

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

$$w_i^* = (\hat{\alpha}_i(x \mid \theta_i^*) - \alpha_i(x)) + \sum_{j=1}^{n} (\hat{\beta}_{ij}(x \mid \theta_{ij}^*) - \beta_{ij}(x))u_j . \tag{28}$$

Now adding and subtracting the term $(b_i w_i^*)$ to eq. (25), the error equation can be rewritten as:

$$\dot{\bar{e}}_i = A_i \bar{e}_i + b_i w_i^* + b_i [\phi_i^T \psi(x) + \sum_{j=1}^{n} \phi_{ij}^T \psi(x)u_j] . \tag{29}$$

Where: $\phi_i = \theta_i - \theta_i^*$ and $\phi_{ij} = \theta_{ij} - \theta_{ij}^*$, if the following positive define Laypunov function candidate [11]:

$$V_i = \frac{1}{2}\bar{e}_i^T P_i \bar{e}_i + \frac{1}{2\gamma_i}\phi_i^T\phi_i + \sum_{j=1}^{n}\frac{1}{2\gamma_{ij}}\phi_{ij}^T\phi_{ij} \quad . \quad (30)$$

If we choose the adaptive law as

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

$$\dot{\theta}_{ij} = -\gamma_{ij} \bar{e}_i^T P_i b_i \psi(x) u_j \tag{31}$$

Then, we have

$$\dot{V}_i = -\frac{1}{2}\bar{e}_i^T Q_i \bar{e}_i + \frac{1}{2}(w_i^{*T} b_i^T P_i \bar{e}_i + \bar{e}_i^T P_i b_i w_i^*) \quad . \quad (32)$$

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 eq.

(32) reduces to $\dot{V}_i \leq 0$.

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

$$A_i^T P_i + P_i A_i = -Q_i \quad .$$

6. 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. V_3=1 arg 0.
The parameters that are used in the power system modeling are as shown below [8].

ω_0=314.159, X_{L12}=0.55, X_{L13}=0.53, X_{L23}=0.6.

Generator 1
x_d=1.863 p.u. x'_d=0.257 p.u. x_q= 1.46 p.u. x'_q=0.546 p.u. x_{T1}=0.129 p.u. T_{do}=6.9 p.u. H = 4s D=5 p.u.

Generator 2
x_d=2.36 p.u. x'_d=0.319 p.u. x_q= 0.70 p.u. x'_q=0.20 p.u. x_{T1}=0.110 p.u. T_{do}=7.96 p.u. H=5.1s. D=3 p.u.

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=0.1 s.
Stage 3: The fault is removed by opening the circuit breakers after 0.2 s.
Stage 4: The transmission line is restored at t=1.4 s.
Stage 5: The system is in a post-fault state.

Case 1:
The operating point is

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

The fault location is $\lambda = 0.1$.

The indirect adaptive fuzzy controller is now applied to the above example, where for each state variable $(\delta_i - \delta_{0i}, \omega_i, E'_{qi})$ we define three triangular membership functions. where i=1,2.

We use MATLAB program to simulate the overall control system, choosing infinite bus 3 as the reference bus. An indirect adaptive fuzzy control is applied to the system and compared with feedback linearization technique. The results are shown in fig . 2-8.
As shown in the simulation results, the system with feedback linearization and with the indirect adaptive fuzzy control the transient stability is improved. Comparing the relative rotor angle ($\Delta\delta(t)$) and the relative rotor speed ($\omega(t)$) of generator 1 and 2 figs. 2-5, it is clear that the proposed IAFLC gives a better transient results.
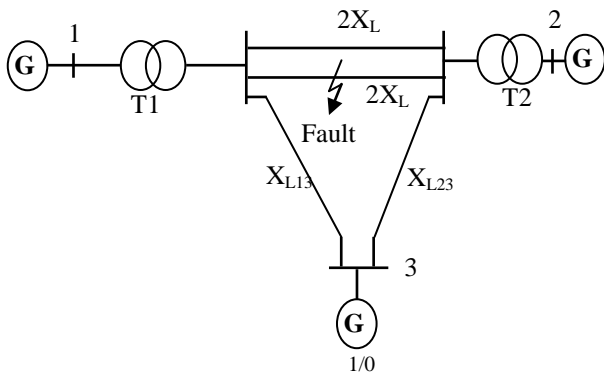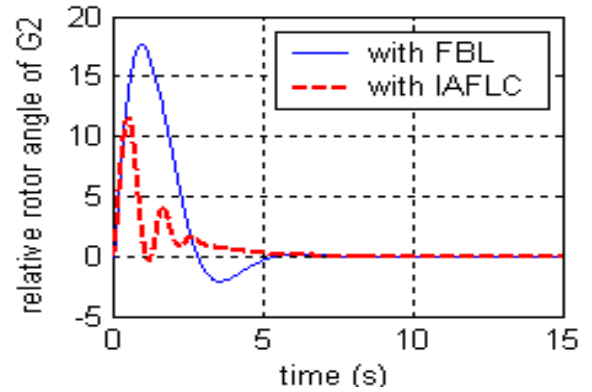
Fig. 1. A two machine with infinite bus power system.

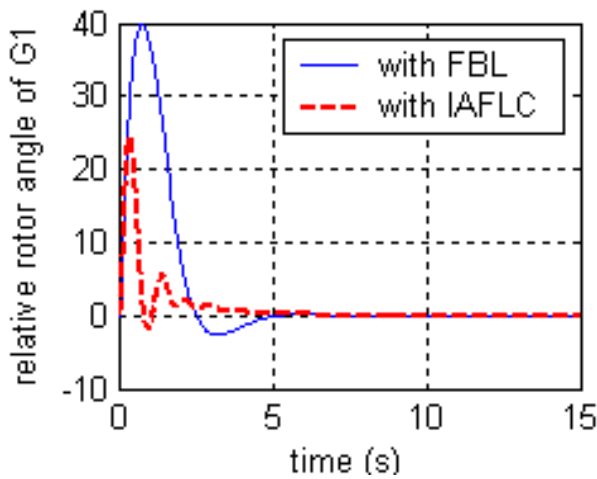Fig. 4. Response of the relative rotor speed ($\omega(t)$) of generator 2.

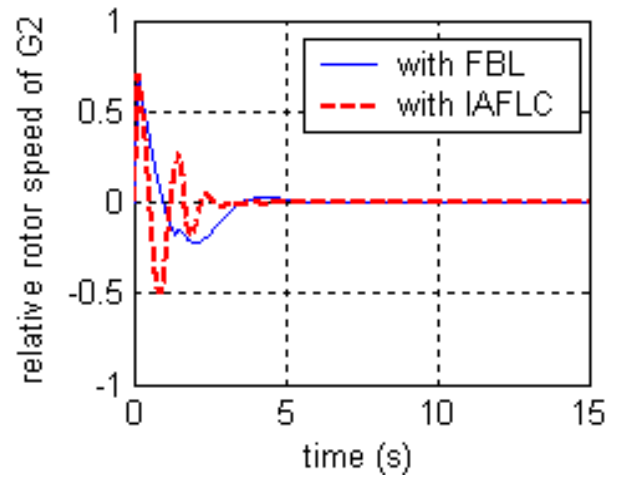Fig. 2. Response of the relative rotor angle of generator 1.

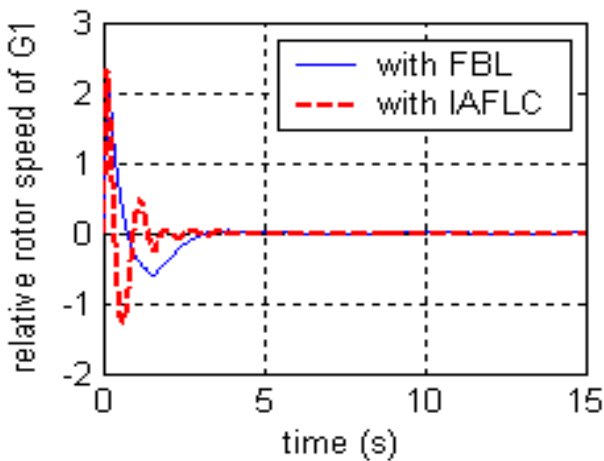Fig. 5. Response of the relative rotor speed ($\omega(t)$) of generator 2.

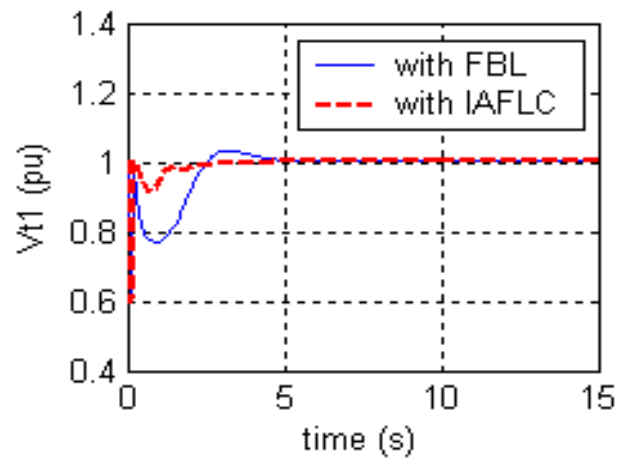Fig. 3. Response of the relative rotor speed ($\omega(t)$) of generator 1.

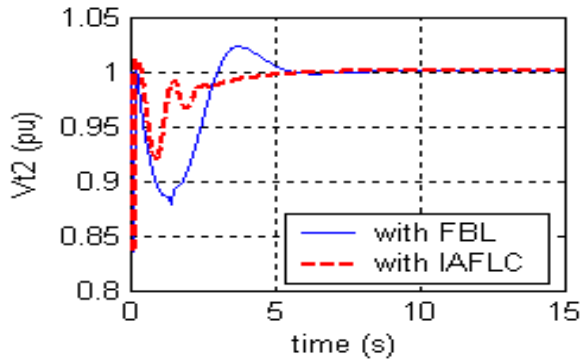Fig. 6. Response of the generator bus terminal voltage ($V_l(t)$).

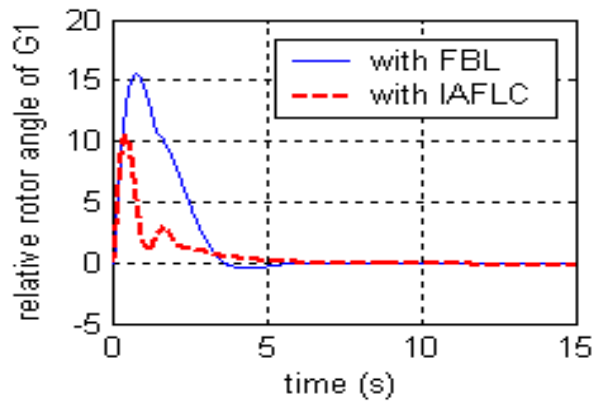Fig.7. Response of the generator bus terminal voltage ($V_2(t)$).

Fig.8. Response of the relative rotor angle of generator 1.

Fig.9. Response of the relative rotor angle with of generator 1.

Fig.10. Response of the relative rotor angle of generator 1.

Fig.11. Response of the relative rotor speed ($\omega(t)$) of generator 1.

Fig. 6 shows the terminal voltage of generator 1, it is obvious that with FBL the duration of the voltage dip is 5s and the amplitude of the dip 20%. With the IAFLC both the transient stability and terminal voltage of each generator are enhanced especially the terminal voltage at generator 1. The duration and amplitude of the voltage dip become 2s and 4% respectively.

Case 2: The operating points are the same as in Case 1, while the fault location chosen to be equal to 0.9 ($\lambda = 0.9$). As shown in fig. 8 and fig. 10 improvement of the transient stability is registered for both FBL and IAFLC, 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 one. Furthermore, fig. 9 and fig. 11 show that the IAFLC system returns to synchronism and stable condition after 2 sec, in both generators, however, the FBL controller returns after 4 sec.
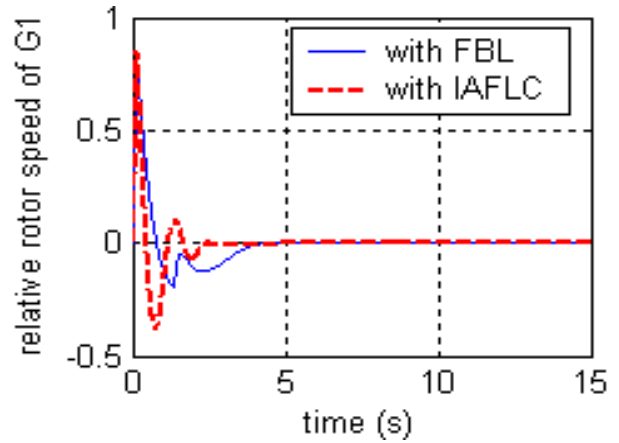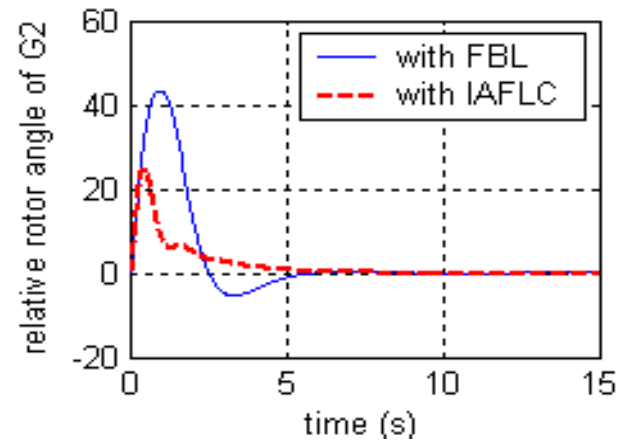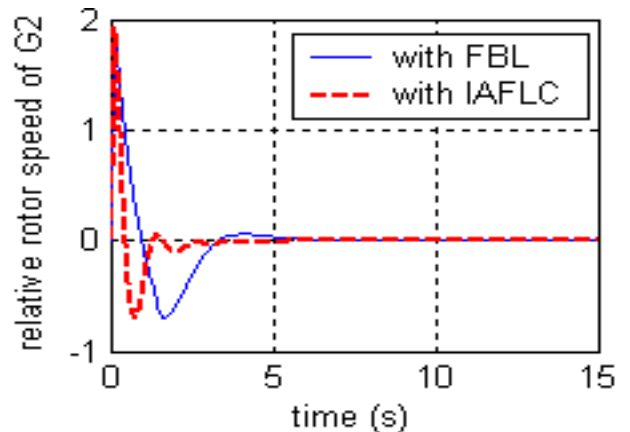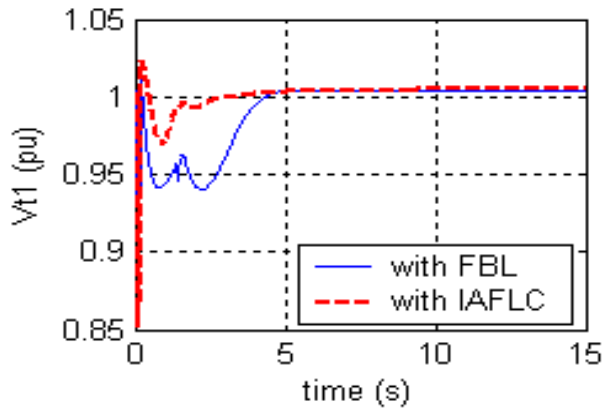
Fig.12. Response of the generator bus terminal voltage
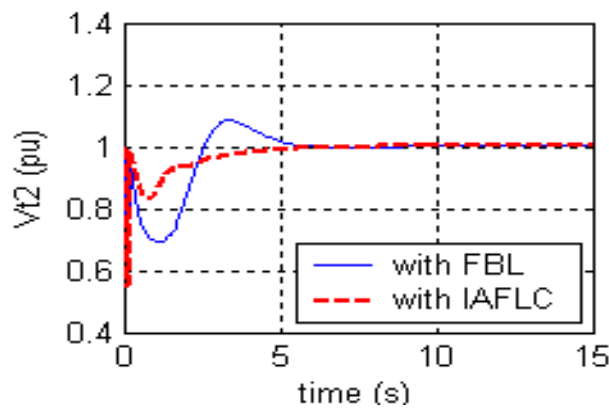($V_1(t)$) with FBL and with IAFLC.

Fig.13 Response of the generator bus terminal voltage
($V_2(t)$) with FBL and with IAFLC.

Fig. 13 shows that the duration of the voltage dip and the amplitude of the dip are 5 sec and 25% respectively with FBL, and these values are enhanced and become 3 sec and 9% respectively when the IAFLC is applied.

7. Conclusions

This paper presents indirect adaptive fuzzy control scheme for transient stability enhancement of multi-machine power systems. The fuzzy controller is constructed from fuzzy feedback linearization controller whose parameters are adjusted indirectly from the estimates of plant parameters. The adaptation law adjusts the controller parameters on-line so that the plant output tracks the reference model output. The simulation results show that by changing fault location, the proposed IAFLC control can enhance the

transient stability, enrich damping and, achieve good post-fault generator terminal voltage.

List of symbols

δ_i	is the rotor angle,
ω_i	is the relative rotor speed of the generator,
P_{ei}	is the active electric power delivered by the generator i,
P_m	is the mechanical input power,
D	is the damping constant,
H	is the inertia constant,
E_q	is the EMF in the quadrature axis,
E_{fd}	is the excitation control input,
B_{ij}	is the susceptance between node i and j,
T_{do}	is the rotor circuit time constant,
x_d	is the direct axis reactance,
x_d'	is the direct axis transient reactance,
x_q	is the quadrature axis reactance,
x_q'	is the quadrature axis transient reactance,
x_{tr}	is the transformer reactance,
x_{L12}, x_{L23}	are the reactance of transmission lines,
θ_i, θ_{ij}	are the adjustable parameter,
V_t	is the terminal voltage,
Q_{ei}	is the reactive electric power delivered by the generator i,
i_{di}, i_{qi}	are the direct and quadrature axis currents of generator i,
V_{di}	is the direct axis voltage of generator i, and
V_{qi}	is the quadrature axis voltage of generator i.

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