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Design of an Adaptive Fuzzy Controller for Power System Stabilization

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Abstract
Power systems have uncertain dynamics due to a variety of effects such as lightning, severe storms and equipment failures. The variation of the effective reactance of a transmission line due to a fault is an example of uncertainty in power system dynamics. Hence, a robust controller to cope with these uncertainties is needed. Recently fuzzy controllers have become quite popular for robust control due to its capability of dealing with unstructured uncertainty. Thus in this paper we design an adaptive fuzzy controller using an input-output linearization approach for the transient stabilization and voltage regulation of a power system under a sudden fault. Simulation results show that satisfactory performance is achieved by the proposed controller.

Key Words Power Systems, Transient Stabilization, Voltage Regulation, Adaptive Fuzzy Controller, Input-Output Linearization

1. Introduction

Recently, extensive studies have been carried out on controller design for stabilization of power systems. In the case where a large fault occurs, the parameters (and thus the operating point) of a nonlinear power system change significantly, and therefore linear controllers generally fail to maintain transient stability of the system. To deal with this problem of uncertainty and nonlinearity, an adaptive control approach is proposed in [1] on the basis of the direct feedback linearization (DFL) technique [2]. However in [1], voltage requlation and transient stabilization are achieved using two separate control laws in a rather *ad hoc* manner.

As an alternative approach, we present an adaptive fuzzy control scheme as in [3,4], which is based on static state feedback linearization [5]. Unlike conventional adaptive nonlinear methods such as [6], the proposed algorithm does not require the system to be linear in the uncertain parameters.

Since the proposed algorithm is based on input-output linearization, stability of the internal dynamics is a prerequisite. In [7], output modification is performed in order to enhance the internal dynamics. We also employ this modification here. Simulation results show the effectiveness of the proposed scheme.

2. Power system model

We consider a simplified dynamic model as depicted in Fig.1.

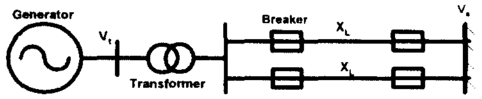

Fig. 1 Single machine-infinite bus model

$$\dot{\delta}(t) = w(t) \quad (1)$$

$$\dot{w}(t) = -\frac{D}{H}w(t) + \frac{w_0}{H}(P_m - \frac{V_s E_q}{x_{ds}}\sin\delta(t)) \quad (2)$$

$$\dot{E}_q(t) = \frac{1}{T_{d0}'}[k_c u_f(t) - E_q(t)] + \frac{x_d - x_d'}{x_{ds}'}V_s \sin\delta(t) w(t) \quad (3)$$

$$V_t(t) = \frac{1}{x_{ds}}\{x_s^2 E_q^2(t) + V_s^2 x_d^2 + 2x_s x_d V s E_q(t)\cos\delta(t)\}^{\frac{1}{2}} \quad (4)$$

where $V_t(t)$ is the generator terminal voltage, $\delta(t)$ is the power angle of the generator, $w(t)$ is the relative speed of the generator, $E_q(t)$ the EMF in the quadrature axis, P_m the mechanical input power, $P_e(t)$ the active electrical power delivered by the generator, w_0 the synchronous machine speed, D the per unit damping constant and H the per unit inertia constant, V_s the infinite bus voltage, k_c the gain of the excitation amplifier, $u_f(t)$ the input of the SCR amplifier of the generator, x_d the direct axis reactance of the generator, x_d' the direct axis transient reactance of the generator, T_{do} the direct axis transient short-circuit time constant. The fault we consider in this paper is a symmetrical three-phase short circuit fault which occurs on one of the transmission lines. $x_L(= 0.4853)$ is the total reactance of the transmission line and if λ is the fraction of the faulted line to the left of the fault, then x_s, x_{ds}, and x'_{ds}, T'_{ds} are regarded as follows:

$$
\begin{aligned}
x_s &= x_T + \frac{1}{2x_L} \\
x_{ds} &= x_T + \frac{1}{2}x_L + x_d \\
x'_{ds} &= x_T + \frac{1}{2}x_L + x'_d \\
T'_{do} &= \frac{x_{ds}'}{x_{ds}} T_{do}
\end{aligned}
$$

The control objective is to maintain voltage regulation and synchronism despite the parametric uncertainties due to λ.

3. State equation with output modification

To improve the response of power angle δ and characteristics of internal dynamics, the output is modified as in [7]:

$$
\begin{aligned}
y &= V_t + \alpha \dot{w}_F \\
\dot{w}_F &= -bw_F + bw
\end{aligned} \tag{5}
$$

where the pseudo output y is equal to V_t in steady state and w_F is obtained through low-pass filtering $(b > 0)$. Using the pseudo output, oscillation of δ can be removed and the stability of the closed-loop system comes to depend on α. According to [7], if α is negative, the system is stable and oscillation of the internal dynamics is reduced. From (1), (2), (3), and (5) we can get the non-linear state equations as follows:

$$
\dot{\mathrm{x}}(t) = f(\mathrm{x}(t)) + g(\mathrm{x}(t))u(t) \tag{6}
$$

$$
y = h(\mathrm{x}) \tag{7}
$$

where $\mathrm{x} = [x_1\ x_2\ x_3\ x_4]^T = [\delta\ w\ E_q\ w_F]^T$,

$$
f(\mathrm{x}) = \begin{bmatrix} w \\ -\frac{D}{H}w + \frac{w_0 P_m}{H} - \frac{w_0 V_s E_q}{H x_{ds}} \sin\delta \\ -\frac{1}{T'_{d0}}E_q + \frac{x_d - x'_d}{x'_{ds}} V_s w \sin\delta \\ -bw_F + bw \end{bmatrix},
$$

$$
g(\mathrm{x}) \triangleq \begin{bmatrix} 0 \\ 0 \\ \frac{k_c}{T'_{do}} \\ 0 \end{bmatrix},
$$

$$
\begin{aligned}
h(\mathrm{x}) &= V_t + \alpha \dot{w}_F, \\
u &= u_f
\end{aligned}
$$

4. Adaptive fuzzy controller

In this Section, we propose an adaptive fuzzy controller based on feedback linearization. Differentiating (7) for the input-output feedback linearization. we can get

$$
\begin{aligned}
\dot{y} &= L_f h + L_g h u \\
&= \left(\frac{f_3}{x_{ds} f_1^{\frac{1}{2}}} + f_4\right) + \left(\frac{f_2}{x_{ds} f_1^{\frac{1}{2}}}\right)u
\end{aligned} \tag{8}
$$

where $L_f h$ and $L_g h$ are Lie derivative of f and g respectively, and f_1, f_2, f_3, and f_4 represents following functions:

$$
\begin{aligned}
f_1 &= x_s^2 E_q^2 + V_s^2 x_d^2 + 2x_s x_d V_s E_q \cos\delta \\
f_2 &= x_s^2 E_q \frac{1}{T'_{d0}} k_c + x_s x_d V_s \cos\delta \frac{1}{T'_{d0}} k_c \\
f_3 &= -x_s^2 E_q^2 \frac{1}{T'_{d0}} + x_s^2 E_q \frac{x_d - x'_d}{x'_{ds}} V_s \omega \sin\delta \\
&\quad - x_s x_d V_s \cos\delta \frac{1}{T'_{d0}} E_q \\
&\quad + x_s x_d V_s \cos\delta \frac{x_d - x_d'}{x'_{ds}} V_s \omega \sin\delta \\
&\quad - x_s x_d V_s E_q \omega \sin\delta \\
f_4 &= \alpha b\{-\frac{D}{H}\omega + \frac{\omega_0}{H}(P_m - V_s \frac{E_q}{x_{ds}} \sin\delta) \\
&\quad + b\omega_F - b\omega\}
\end{aligned}
$$

The feedback linearizing control[5] for (8) is

$$
u = \frac{1}{L_g h(\mathrm{x})}\{-L_f h(\mathrm{x}) + \dot{y}_r - c_0 e\} \tag{9}
$$

where $c_0 > 0$, y_r the reference voltage, regulation error $e = y - y_r$. Applying (9) into (8) results in an error dynamic equation as

$$
\dot{e} + c_0 e = 0, \quad (c_0 > 0) \tag{10}
$$

But the faults on the transmission lines cause the variation of the parameters x_s, x_{ds}, and x'_{ds} as discussed previously. With the variation of x_s, x_{ds}, and x'_{ds}, $L_f h(x)$ and $L_g h(x)$ come to contain parametric uncertainties. If the uncertainties in $L_f h(x)$ and $L_g h(x)$ satisfy the linear parameterization condition, we can use the conventional adaptive input-output linearization technique[6]. But $L_f h(x)$ and $L_g h(x)$ in (8) are not the case and to cope with the problem, we will use a fuzzy system which approximates $L_f h(x)$ and $L_g h(x)$. We now show the details of fuzzy system construction on the basis of Wang's approach[2,3]. To begin with, let $L_f h$ be devided into two part, $L_f h_1$ and f_5; $L_f h_1$ contains uncertainty and f_5 does not,

$$
L_f h = L_f h_1 + f_5 \tag{11}
$$

where

$$L_f h_1 = \frac{f_3}{x_d s f_1^{\frac{1}{2}}} - \alpha b V_s \frac{E_q}{x_{ds}} \sin\delta,$$
$$f_5 = \alpha b - \frac{D}{H} w + \frac{w_0 Pm}{H} + bw_F - bw)$$

4.1 Certainty equivalent control

To construct fuzzy logic system for estimating $L_f h_1(x)$ and $L_g h(x)$, let us make an assumption.

Assumption 1.

There are some fuzzy rules about $L_f h_1(x)$ and $L_g h(x)$ based on the expert's knowledge on the system.

(R1) $R_{L_f h_1}{}^{(l_1,l_2,l_3)}$:
If x_1 is $F_1{}^{l_1}$ and x_2 is $F_2{}^{l_2}$ and x_3 is $F_3{}^{l_3}$,
then $L_f h_1(\mathrm{x})$ is $\hat{\theta}_1^{(l_1,l_2,l_3)}$

(R2) $R_{L_g h}{}^{(l_1,l_3)}$:
If x_1 is $F_1{}^{l_1}$ and x_3 is $F_3{}^{l_3}$,
then $L_g h(\mathrm{x})$ is $\hat{\theta}_2^{(l_1,l_3)}$

where $F_i^{l_i}$, $\hat{\theta}_i^{(\cdot)}$ ($i = 1,2,3$, $l_1 = 1,\cdots,m_1$, $l_2 = 1,\cdots,m_2$, $l_3 = 1,\cdots,m_3$) are fuzzy sets. l_i identifies the fuzzy sets $F_i^{l_i}$ in x_i and the number of rules in rule base (R1) is $m_f(m_1 \times m_2 \times m_3)$ and number of rules in (R2) is $m_g(m_1 \times m_3)$. $\theta_1{}^{(l_1,l_2,l_3)}$ in (R1) represents $L_f h_1(x)$ when x_i ($i = 1,2,3$) belong to the corresponding fuzzy sets in the premise of (R1) with the membership function equal to 1. $\hat{\theta}_1{}^{(l_1,l_2,l_3)}$ is defined by a fuzzy set whose membership function is maximum on a point $\theta_1{}^{(l_1,l_2,l_3)}$ in the support. According to [3,4], using singleton fuzzifier, sup-star composition, and center average defuzzifier, we can write

$$L_f h_1(\mathrm{x}) = \frac{\sum_{l_1=1}^{m_1}\sum_{l_2=1}^{m_2}\sum_{l_3=1}^{m_3} \theta_1{}^{(l_1,l_2,l_3)} \cdot (\prod_{i=1}^{3} \mu_{F_i^{l_i}}(x_i))}{\sum_{l_1=1}^{m_1}\sum_{l_2=1}^{m_2}\sum_{l_3=1}^{m_3} (\prod_{i=1}^{3} \mu_{F_i^{l_i}}(x_i))} + v_1 \qquad (12)$$

$$L_g h(x) = \frac{\sum_{l_1=1}^{m_1}\sum_{l_3=1}^{m_3} \theta_2{}^{(l_1,l_3)} \cdot (\mu_{F_1^{l_1}}(x_1) \cdot \mu_{F_3^{l_3}}(x_3))}{\sum_{l_1=1}^{m_1}\sum_{l_3=1}^{m_3} (\mu_{F_1^{l_1}}(x_1) \cdot \mu_{F_3^{l_3}}(x_3))} + v_2 \qquad (13)$$

where v_1 and v_2 are finite approximation errors and $\theta_1{}^{(l_1,l_2,l_3)}$ and $\theta_2{}^{(l_1,l_3)}$ are to be determined based on the expert's knowledge on (8); however they are to be estimated due to the parametric uncertainties in (8). Replacing $\theta_1{}^{(l_1,l_2,l_3)}$ ($\theta_2{}^{(l_1,l_3)}$) in (12) and (13) with $\hat{\theta}_1{}^{(l_1,l_2,l_3)}$ ($\hat{\theta}_2{}^{(l_1,l_3)}$) which is obtained by an adaptation law described lately, we can write estimation of $L_f h_1$ and $L_g h$ as

$$\hat{L_f h_1}(\mathrm{x}) = \sum_{l_1=1}^{m_1}\sum_{l_2=1}^{m_2}\sum_{l_3=1}^{m_3} \hat{\theta}_1{}^{(l_1,l_2,l_3)} \times [\frac{\prod_{i=1}^{3} \mu_{F_i^{l_i}}(x_i)}{\sum_{l_1=1}^{m_1}\sum_{l_2=1}^{m_2}\sum_{l_3=1}^{m_3} \prod_{i=1}^{3} (\mu_{F_i^{l_i}}(x_i))}] \qquad (14)$$

$$\hat{L_g h}(x) = \sum_{l_1=1}^{m_1}\sum_{l_3=1}^{m_3} \hat{\theta}_2{}^{(l_1,l_3)} \times [\frac{mu_{F_1^{l_1}}(x_1)\mu_{F_3^{l_3}}(x_3)}{\sum_{l_1=1}^{m_1}\sum_{l_3=1}^{m_3} \mu_{F_1^{l_1}}(x_1)\mu_{F_3^{l_3}}(x_3))}] \qquad (15)$$

Now let us define fuzzy basis functions

$$\xi^{(l_1,l_2,l_3)} \triangleq [\frac{\prod_{i=1}^{3} \mu_{F_i^{l_i}}(x_i)}{\sum_{l_1=1}^{m_1}\sum_{l_2=1}^{m_2}\sum_{l_3=1}^{m_3} (\prod_{i=1}^{3} \mu_{F_i^{l_i}}(x_i))}] \qquad (16)$$

$$\xi^{(l_1,l_3)} \triangleq [\frac{\mu_{F_1^{l_1}}(x_1) \cdot \mu_{F_3^{l_3}}(x_3)}{\sum_{l_1=1}^{m_1}\sum_{l_3=1}^{m_3} (\mu_{F_1^{l_1}}(x_1) \cdot \mu_{F_3^{l_3}}(x_3))}] \qquad (17)$$

Then we obtain m_f dimensional vector $\xi_f(x)$ whose elements are ξ^{l_1,l_2,l_3} and m_g dimensional vector $\xi_g(x)$ whose elements are ξ^{l_1,l_3}. Using ξ_f and ξ_g, we can write

$$L_f h_1(\mathrm{x}) = \theta_f{}^T \xi_f(\mathrm{x}) + v_1,$$
$$\hat{L_f h_1}(\mathrm{x}) = \hat{\theta}_f{}^T \xi_f(\mathrm{x}) \qquad (18)$$
$$L_g h(\mathrm{x}) = \theta_g{}^T \xi_g(\mathrm{x}) + v_2,$$
$$\hat{L_g h}(\mathrm{x}) = \hat{\theta}_g{}^T \xi_g(\mathrm{x}) \qquad (19)$$

where $\theta_f = [\theta_1{}^{(1,1,1)}, \cdots, \theta_1{}^{(m_1,m_2,m_3)}]^T$,
$\theta_g = [\theta_2{}^{(1,1)}, \cdots, \theta_2{}^{(m_1,m_3)}]^T$
and $\hat{\theta}_f = [\hat{\theta}_1^{(1,1,1)}, \cdots, \hat{\theta}_1{}^{(m_1,m_2,m_3)}]^T$,
$\hat{\theta}_g = [\hat{\theta}_2^{(1,1)}, \cdots, \hat{\theta}_2{}^{(m_1,m_3)}]^T$.

Writing $\hat{L_f h}(\mathrm{x}) = \hat{L_f h_1}(\mathrm{x}) + f_5$ and substituting $\hat{L_f h}(x)$ and $\hat{L_g h}(x)$ into (10), we obtain

$$u = u_0 + u_s$$
$$= \frac{1}{\hat{L_g h}(x)}\{-\hat{L_f h}(x) + \dot{y}_r - c_0 e\} + u_s \qquad (20)$$

where u_0 is the certainty equivalent control and u_s is the supervisory control for the stabilization of system.

4.2 Design of the supervisory control and adaptation law

Substituting (20) into (8), we obtain an error dynamic equation

$$\begin{aligned} \dot{e} &= -c_0 e + (L_f h - \hat{L_f h}) + (L_g h - \hat{L_g h})u \\ &= -c_0 e + (L_f h - \hat{L_f h}) + (L_g h - \hat{L_g h})u_0 \\ &\quad + L_g h u_s \end{aligned} \quad (21)$$

and the following is true for $L_f h$ and $L_g h$.

Lemma 1.

For $E_q > 0$ and $0 < \delta < \frac{\pi}{2}$, $|L_f h|$ and $L_g h$ have bounds

$$\begin{aligned} |L_f h(\mathrm{x})| &\leq L_f h^U(\mathrm{x}) \\ L_g h^L(\mathrm{x}) &\leq L_g h(\mathrm{x}) \leq L_g h^U(\mathrm{x}) \end{aligned} \quad (22)$$

where

$$\begin{aligned} L_f h^U &= \frac{\sqrt{x_T + x_L}}{x'_d + x_T + x_L}\sqrt{x_d V_s E_q}|\omega| \\ &\quad + \frac{x_T + x_L}{x'_d + x_T + x_L} V_s (x_d - x'_d)|\omega| \\ &\quad + \frac{x_T + x_L}{x_d + x_T + x_L}\frac{1}{T_{d0}}|E_q| \\ &\quad + |\alpha b|[(\frac{D}{H} + b)|\omega| \\ &\quad + \frac{1}{x_d + x_T + 0.5x_L}\frac{\omega_0 V_s}{H}|E_q| \\ &\quad + \frac{\omega_0}{H}P_m + b|\omega_F|] \end{aligned}$$

$$L_g h^L = \frac{k_c}{T'_{d0}}\frac{x_T}{x_d + x_T}\frac{(x_T + 0.5x_L)E_q}{\sqrt{(x_T + 0.5x_L)^2 E_q^2 + (x_d V_s)^2}}$$

$$L_g h^U = \frac{x_T + x_L}{x_d + x_T + x_L}\frac{k_c}{T'_{d0}}$$

Using the bounds in Lemma1, we obtain a stabilizing control law as follows.

Theorem 1.

With the control input u in the form of (20), if we design u_s as

$$\begin{aligned} u_s = \quad & -I_1{}^* sgn(e)\frac{1}{L_g h^L(\mathrm{x})} \\ & \times\{|\hat{L_f h}(\mathrm{x})| + L_f h^U(\mathrm{x}) + |\hat{L_g h}(\mathrm{x})u_0| \\ & + |L_g h^U(\mathrm{x})u_0|\} \end{aligned} \quad (23)$$

$$I_1{}^* = \begin{cases} 1, & if \ V_e \geq \bar{V} \\ 0, & if \ V_e < \bar{V} \end{cases}$$

then state vector x is bounded.

proof : As in [3,4], let $V_e = \frac{1}{2}e^2$, then the derivation of V_e is

$$\begin{aligned} \dot{V}_e &= -c_0 e^2 + e\{(L_f h - \hat{L_f h}) + (L_g h - \hat{L_g h})u_f \\ &\quad + L_g h u_s\} \\ &\leq -c_0 e^2 + e\{|L_f h| + |\hat{L_f h}| + |\hat{L_g h} u_0| \\ &\quad + |L_g h u_0|\} + e L_g h u_s \end{aligned}$$

Hence, substituting (23) into the right-hand side of the inequality above, $\dot{V}_e \leq -c_0 e^2$ under $V_e \geq \bar{V}$,which gurantees bounded x. Now we will design an adaptation law for the parameter vector θ_f and θ_g in (18) and (19), respectively. We can rewrite (21) as

$$\begin{aligned} \dot{e} &= -c_0 e + (L_f h - \hat{L_f h}) + (L_g h - \hat{L_g h})u_0 \\ &\quad + L_g h u_s \\ &= -c_0 e + L_g h u_s + \{L_f h - \hat{L_f h}(x|\theta_f) \\ &\quad + \hat{L_f h}(x|\theta_f) - \hat{L_f h}(x|\theta_f)\} \\ &\quad + \{L_g h - \hat{L_g h}(x|\theta_g) + \hat{L_g h}(x|\theta_g) \\ &\quad - \hat{L_g h}(x|\dot{\theta_g})\}u_0 \\ &= -c_0 e + L_g h u_s + \omega + \phi_f{}^T \xi_f(x) + \phi_g{}^T \xi_g(x) u_0 \end{aligned}$$

where $\phi_f = \theta_f - \hat{\theta}_f$, $\phi_g = \theta_g - \hat{\theta}_g$ $\omega = (L_f h(x) - \hat{L_f h}(x|\theta_f)) + (L_g h(x) - \hat{L_g h}(x|\theta_g))u_0 = v_1 + v_2 u_0$

Consider the Lyapunov function candidate

$$V = \frac{1}{2}e^2 + \frac{1}{2\gamma_1}\phi_f{}^T\phi_f + \frac{1}{2\gamma_2}\phi_g{}^T\phi_g$$

where γ_1 , γ_2 are positive constants.
Using the error equation, we have

$$\begin{aligned} \dot{V} &= e\dot{e} + \frac{1}{\gamma_1}\phi_f{}^T\dot{\phi}_f + \frac{1}{\gamma_2}\phi_g{}^T\dot{\phi}_g \\ &= e(-c_0 e + L_g h u_s + \omega + \phi_f^T \xi_f(x) \\ &\quad + \phi_g{}^T \xi_g(x) u_0) + \frac{1}{\gamma_1}\phi_f{}^T\dot{\phi}_f + \frac{1}{\gamma_2}\phi_g{}^T\dot{\phi}_g \\ &= -c_0 e^2 + e L_g h u_s + e\omega \\ &\quad + \frac{1}{\gamma_1}\phi_f{}^T(\dot{\phi}_f + \gamma_1 e \xi_f(x)) \\ &\quad + \frac{1}{\gamma_2}\phi_g{}^T(\dot{\phi}_g + \gamma_1 e \xi_g(x) u_0) \end{aligned}$$

Therefor , if we choose the adaptation law

$$\begin{aligned} -\dot{\phi}_f &= \dot{\hat{\theta}}_f = \gamma_1 e \xi_f(\mathrm{x}) \\ -\dot{\phi}_g &= \dot{\hat{\theta}}_g = \gamma_2 e \xi_g(\mathrm{x}) u_0 \end{aligned} \quad (24)$$

then we have

$$\begin{aligned} \dot{V} &= -c_0 e^2 + e L_g h u_s + e\omega \\ &\leq -c_0 e^2 + e\omega \end{aligned} \quad (25)$$

According to [3,4], since ω is the minimum approximation error, (25) is the best we can get. Using the basic adaptation law (24), we cannot guarantee that the parameters $\hat{\theta}_f$ and $\hat{\theta}_g$ are bounded. [3,4] proposed a modified adaptation law with projection for the boundedness of parameters and (24) is modified as

$$\dot{\theta}_f = \begin{cases} \gamma_1 e \xi_f(x) & \text{if}(|\theta_f| < M_f) \text{ or } (|\theta_f| = M_f \\ & \text{and } e{\theta_f}^T \xi_f(x) \leq 0) \\ \gamma_1 e \xi_f(x) & \text{if } (|\theta_f| = M_f \\ -\gamma_1 e \frac{\theta_f \theta_f^T \xi_f(x)}{|\theta_f|^2} & \text{and } e{\theta_f}^T \xi_f(x) > 0) \end{cases}$$

$$\dot{\theta}_g = \begin{cases} \gamma_2 e \xi_g(x) u_0 & \text{if}(|\theta_g| < M_g) \text{or } (|\theta_g| = M_g \\ & \text{and } e\theta_g^T \xi_g(x) u_0 \leq 0) \\ \gamma_2 e \xi_g(x) u_0 & \text{if } (|\theta_g| = M_g \\ -\gamma_2 e \frac{\theta_g \theta_g^T \xi_g(x) u_0}{|\theta_g|^2} & \text{and } e{\theta_g}^T \xi_g(x) u_0 > 0) \end{cases}$$

$$if\ \theta_{gi} = \epsilon,$$

$$\dot{\theta}_{gi} = \begin{cases} \gamma_2 e \xi_{gi}(x) u_0 & if \quad e\xi_{gi}(x) u_0 > 0 \\ 0 & if \quad e\xi_{gi}(x) u_0 \leq 0 \end{cases}$$

where M_f , M_g are positive constants specified by the designer, θ_{gi}, ξ_{gi} represents ith elements of the vector θ_{gi},ξ_g respectively and ϵ is positive constant to gurantee positive $\hat{L_g h}$. The overall scheme of adaptive fuzzy control systems is shown in Fig.2.

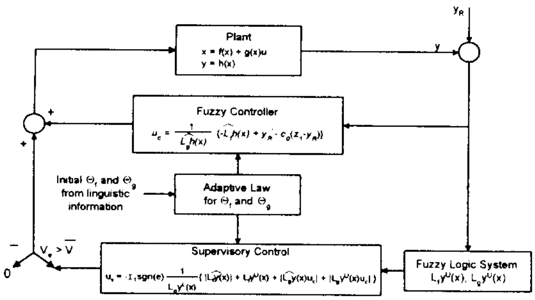

Fig. 2 The overall scheme of adaptive fuzzy control systems

5. Simulation results

Adaptive fuzzy controller discussed so far is used to stabilize the single-machine infinite bus system (6),(7) with the sudden fault. Lingustic fuzzy rules to determine the initial values of $\hat{L_g h}(x)$ and $\hat{L_f h}(x)$ in certainty equivalent control (20) is shown in Fig.3 and Fig.4 respectively. We choose $\bar{V} = \frac{1}{2}(0.01)^2$, $y_r(t) = V_{tR}(t) = 1$, $c_0 = \frac{1}{0.05}$, $M_f = 274 \times 1.5$, $M_g = 3.5 \times 1.5$, $\epsilon = 0.01$, $\gamma_1 = 300$, $\gamma_2 = 1$ for the controller design.

We consider the two fault sequences[1], **i.e.** permanent fault and temporary fault.Fig.5 shows the simulation result with the permanent fault; a fault occurs on $\lambda = 0.5$ point at t=2 the fault is removed by opening the breaker at $t = 1.15sec$, and the system is in a post fault state. Fig.6 shows the simulation result with the temporary fault; a fault occurs on $\lambda = 0.5$ point at $t = 1sec$, the fault is removed by opening the breaker at $t = 1.15sec$, the transmission lines are restored with the fault cleared at $t = 1.9sec$, and the system is in a post-fault state. From the simulation results, we can see that the proposed adaptive fuzzy controller can maintain the system stable even in the presence of permanent and temporary fault.

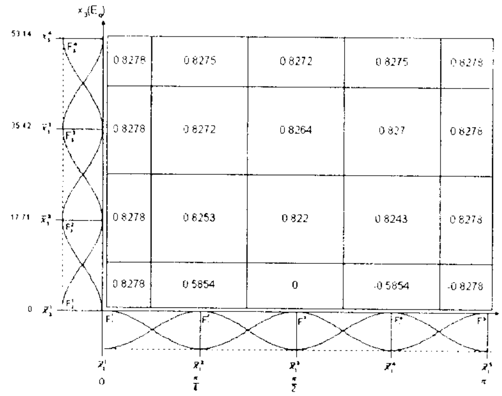

Fig. 3 Linguistic fuzzy rules for $\hat{L_g h}$(x)

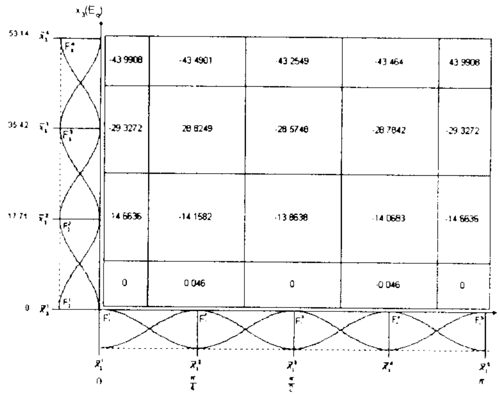

Fig. 4 Linguistic fuzzy rules for $\hat{L_f h}$(x)

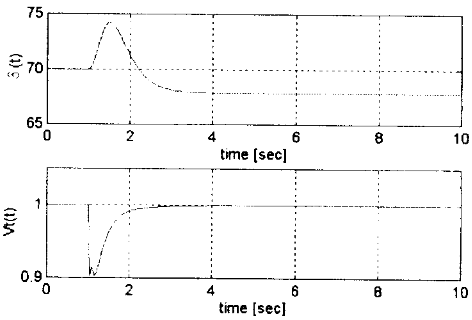

Fig. 5 Relative angle and terminal voltage of the generator with permanent fault

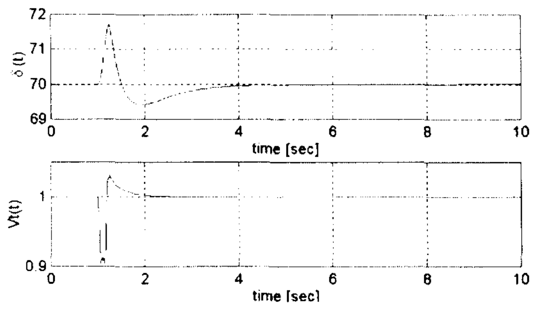

Fig. 6 Relative angle and terminal voltage of the generator with temporary fault

6.Conclusion

For power system stabilization, we have presented an adaptive fuzzy control scheme based on feedback linearization. Power systems are subject to uncertainties, and this makes exact linearization difficult to achieve. In addition, linear parametrization for these uncertainties is rarely possible in practice; as a consequence, conventional adaptive nonlinear control algorithms such as [6] are not readily applicable. On the other hand, fuzzy systems employed in this paper are capable of approximating uncertain functions. The resulting adaptive fuzzy control scheme can cope with uncertainties which are not necessarily parametrized linearly. Simulations show that both transient stability and voltage regulation can be achieved effectively by using the proposed control system. It is also noted that improvement of the internal dynamics is observed by output modification as in [7].

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