AN ADAPTIVE FUZZY LOGIC CONTROLLER FOR AC-DC POWER SYSTEMS

P.K.Dash, A.Routray
Centre of Applied Artificial Intelligence,
Department of Electrical Engineering,
Regional Engineering College,
Rourkela - 769 008,
INDIA.

S.Rahman
Virginia Polytechnic Institute & State University, Blacksburg,
U.S.A.

Abstract

The paper presents a new approach to the design of a supplementary stabilizing controller for a HVDC transmission link using fuzzy logic. The fuzzy controller relates significant and observable variables like speed and its rate of the generator speed and its rate of change of the generator to a control signal for the rectifier current regulator loop using fuzzy membership functions. These variables evaluate the control rules using the compositional rules of inference. The fuzzy controller is equivalent to a nonlinear PI controller, whose gains are adapted depending on the error and its rate of change. The effectiveness of the proposed controller is demoustrated by simulation studies on a DC transmission link connected to a weak AC system and subjected to transient disturbances.

1.INTRODUCTION

Power system controllers based on modern control theory seem to have significant advantages over conventional designs, particularly for HVDC transmission, where fast power flow control and power modulations are possible. Digital simulation studies show that these design techniques could significantly enhance the overall performance of integrated AC-DC systems.

Both optimal and modal control of rectifier current regulators have been undertaken in references [1-3] to damp electromechanical oscillations of the AC-DC systems. The above controllers were decentralised in nature and took into account the possible failure of the communication links. However, all the above schemes neither possess disturbance rejection properties, nor are insensitive to plant parameter variations.

This paper presents a new approach to the design of rectifier current regulator using a fuzzy logic controller for the supplementary stabilizing loop. The same technique can also be applied to reactive power control scheme or gamma modulation regulator.

The rule-based fuzzy controller overcomes system ambiguities and parameter variations by modelling the control objective in terms of a human operator's response to various system scenarios, therefore eliminating the need for an explicit mathematical model of the system dynamics. The simulation results of a typical AC-DC system clearly reveal the superior performance of a fuzzy PI controller which automatically turns itself depending on the generator speed error signal.

2. SYSTEM MODEL AND HVDC DYNAMICS

Fig.1 shows the block diagram of the AC-DC system to be controlled. Using a simplified generator model with E' representing the voltage behind the transient reactance x_d' and including q-axis transient voltage dynamics, the following equations are obtained :

$$\dot{\delta}=\omega-\omega_0 \qquad (1)$$

$$\dot{\omega}=[P_m-E'V_r\sin(\delta-\delta_r)/(x_d'+x_1)]/M \qquad (2)$$

$$\dot{E}'=[\{(x_d-x_d')/\tau_{do}'\}\{(E_f-E')/(x_d-x_d')-E'/x_d'+V_r\cos(\delta-\delta_r)/x_d'\} \qquad (3)$$

and the field voltage is held constant, although more detailed exciter dynamics can be easily be included.

The DC link is represented with an equivalent RL circuit yielding first order response for the DC current and its dynamics is

$$\tau_{dc}\dot{I}_{dc} = 3\sqrt{2}(a_rV_r\cos\alpha-a_iv_i\cos\gamma)/R_{dc} - \{3(X_r-X_i)/\pi + R_{dc}\} I_{dc}/R_{dc} \qquad (4)$$

0-7803-1217-1/93/$3.00 ©1993 IEEE

where $\tau_{dc} = L_{dc} / R_{dc}$ = time constant of the DC link, a_r, a_i are transformer tap ratios at the rectifier and inverter sides, respectively.

For the DC transmission link constant current control is assumed at the rectifier and constant γ control at the inverter. However, for low rectifier voltages and high inverter voltages, the inverter and rectifier controls are

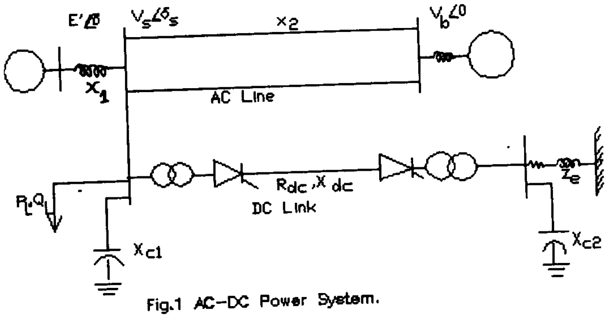


Fig.1 AC-DC Power System.

reversed and the rectifier maintains a constant minimum α. The dc power modulation for the improvement of ac/dc system dynamic performance is implemented by adding a modulating signal to the reference current of the converter current controller.

Fig.2 shows the model of the converter current controller with the auxiliary stabilizing signal $\Delta\omega$ and using a feedback gain K_{ω}. The equations for the rectifier firing angle control is given by

$$\alpha=K_r(I_{dcref}-I_{dc}+\Delta u)/T_r-\alpha/T_r \quad (5)$$

and

$$\Delta u = -K_{\omega}(\omega - \omega_0) \quad (6)$$

for conventional control.

The inverter extinction angle control dynamics is

$$\dot{\gamma}=K_i[\gamma_{ref}-\gamma+K_{vi}(V_{iref}-V_i)]/T_i \quad (7)$$

or,

$$\dot{\gamma}=K_i[0.9I_{dcref}-I_{dc}]/T_i-\gamma/T_i \quad (8)$$

A variation of the typical dc link control scheme can be realised using VDCOL which is modelled as a nonlinear function of the converter ac bus voltage.

If a qusi steady state condition is assumed for the DC link, steady-state models can be used to describe quantities such as AC voltages, AC currents and DC voltages resulting in several nonlinear algebraic equations at the AC-DC interface. The nonlinear loads at the rectifier bus are represented by

$$P_L = P_{LO}V_r^{a_p},\ Q_L = Q_{LO}V_r^{a_q} \quad (9)$$

a_p and a_q are load indices.

3. FUZZY LOGIC CONTROL

This section details the design of the rule-based fuzzy logic controller used to achieve the desired transient performance of the HVDC link connected to weak AC system (ESCR = 2.0). The idea of a fuzzy set introduced by Zadeh (4) allows imprecise and quantitative information to be expressed in an exact way, and as the name implies, is a generalisation of the ordinary notion of a set. A fuzzy set is measured by a generalisation of a characteristic function which can take values between 0

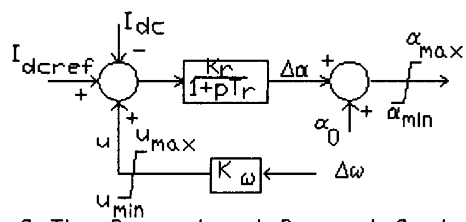


Fig.2 The Conventional Current Controller

and 1. In the fuzzy control algorithm, the state variables are the fuzzy sets associated with $\Delta\omega$ and $\Delta\dot{\omega}$, where $\Delta\omega$ is the generator speed deviation signal used for supplementary stabilising control of the rectifier dc current regulator and $\Delta\dot{\omega}$ its derivative. The input to the fuzzy logic controller (Fig.3) are

$$\Delta\omega\ (nT) = \omega\ (nT) - \omega_0 \quad (10)$$

$$\Delta\dot{\omega}(nT) = [\Delta\omega\ (nT) - \Delta\omega\ (nT - T)]/T$$

where T is a sampling period and n is a positive integer.

The fuzzified input and output from the fuzzy controller are

$$e(nT) = F\ [g_e . \Delta\omega\ (nT)]$$

$$ce(nT) = F\ [g_r . \Delta\dot{\omega}\ (nT)] \quad (11)$$

$$u(nT) = du\ (nT) + u(nT - T)$$

$$= g_u . dU(nT)+u(nT - T)$$

where F [ ] means fuzzification and dU(nT) denotes the incremental output of the fuzzy controller from defuzzifying the fuzzy set output at sampling time nT. ge, gr and gU are gains for error, its rate and the control output, respectively.

3.1 Fuzzification Algorithm and Fuzzy Control Rules

The linear fuzzification algorithm for scaled errors and rate are shown in Fig.4. L in the figure denotes either maximum error Δω or maximums rate $\Delta\dot{\omega}$. The fuzzy set 'error' (E) has two members, i.e., error positive (ep), error negative (en), and fuzzy set rate (CE) has two members, i.e., rate positive (rp) and rate negative (rn). The output fuzzy set 'control' has three members, i.e., output positive (op), output negative (on) and zero output (oz). The following fuzzy control rules are used in this program :

Rule 1 IF (ep AND rn) THEN (oz)
Rule 2 IF (ep AND rp) THEN (op)
Rule 3 IF (en AND rn) THEN (on)
Rule 4 IF (en AND rp) THEN (oz)

To enable the fuzzy controller to operate for any given input use is made of the compositional rule of inference

$$dU = (E \times CE) \circ R \qquad (12)$$

Normally 'o' denotes the max-min product. However for better results max-max product can be used. In evaluating the control rules, Zadeh AND,

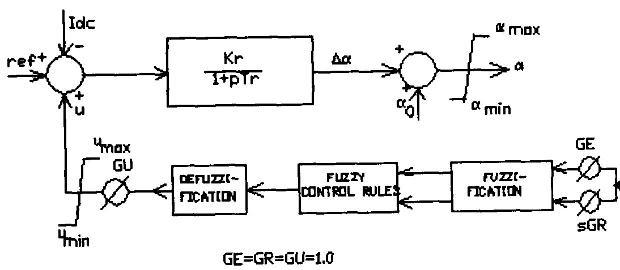


Fig.3 Fuzzy logic controller structure.

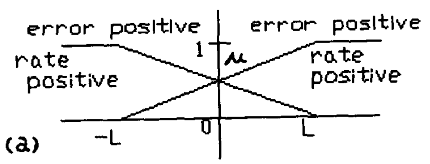


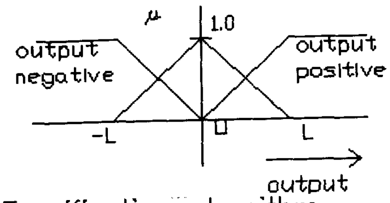
Fig.4 Fuzzification algorithm for control output.

and Lukasiewicz OR logic are used. Zadeh logic is given by AND rule

$$\mu_{A\cap B}(x) = \min(\mu_A(x), \mu_B(x))$$

OR rule

$$\mu_{A\cup B}(x) = \max(\mu_A(x), \mu_B(x)) \qquad (13)$$



14) is for for and

Fuzzification algorithm for inputs Fig.4 (b)

3.2 Defuzzification algorithm

A nonlinear defuzzification algorithm [6] is adopted which amounts to a normalization of the grades of membership of the members of the fuzzy set being defuzzified to a sum one. The defuzzified output of a fuzzy set is defined as

$$dU = \sum_{k=1}^{k} u^*(k).\ \mu(k) / \sum_{k=1}^{k} \mu(k)$$

where u^* denotes the value of the member for which the membership grade is unity. Using this algorithm and Zadeh or Lukasiewicz logic, the equivalent dynamic proportional and integral gain of the fuzzy controller are obtained as

$$K_p = 0.5\ Lg_u g_r / \{2L - g_e.|e(nT)|\}$$

$$K_i = 0.5\ Lg_u g_e / \{2L - g_e.|e(nT)|\}$$

$$\text{for } g_r.ce(nT) \le g_e|e(nT)| \le L \qquad (15)$$

$$K_p = 0.5\ Lg_u g_r / \{2L - g_r.|ce(nT)|\}$$

$$K_i = 0.5\ Lg_u g_r / \{2L - g_r.|ce(nT)|\}$$

$$\text{for } g_e.|e(nT)| \le g_r.|ce(nT)| \le L$$

In these expressions, the values of gains g_e, g_r and g_u, L can be adapted for the best transient performance.

4. IMPLEMENTATION OF ADAPTIVE FUZZY CONTROLLER

The performance of the adaptive and conventional controllers are tested using a transient simulation program for HVDC systems. For the fuzzy control the values of gains g_e, g_r and g_u are fixed at $g_e=1$, $g_r=1$, $g_u=8.0$ and $L = \Delta\omega/\Delta\omega(max) = \Delta\dot{\omega}/\Delta\dot{\omega}(max)$

System data and operating conditions are given in Appendix-I.

Fig.5 depicts the dynamic response curves of the AC-DC system for a 3-phase fault on the AC system bus a and cleared after 0.1 second. This fault causes the collapse of the rectifier bus voltage as it is connected to the AC bus via the AC tie-line. Severe oscillations of rotor angle, speed and other dc link quantities like the d.c. link current, rectifier firing angle α, etc. are observed. The load indices in this case are fixed at $a_p=2$, $a_q=2$ and effective short-circuit ratio at the inverter side is equal to 1.75. The dc power flow through the link is kept at $P_{dc}=0.4$. From Fig.5 it is observed that the fuzzy controller provides significant damping to system oscillations in less than 2 seconds in comparison to conventional control, which takes more than 5 seconds for the oscillations to die down.

Reducing the DC power flow to 0.2p.u., the oscillations in the rator angle and other dc link quantities are found to persist for a longer time as shown in Fig.6. In this case also the fuzzy controller provides damping in almost 3 seconds compared to nearly 6 seconds taken by the conventional controller. The load indices are fixed at $a_p=2, a_q=2$ as in the previous case. By changing the load index to $a_p=0$, $a_q=0$, significant improvement in the damping of system oscillations is obtained in nearly 1.5 seconds compared to nearly 5 seconds for the conventional current regulator.

Fig.7 describes the transient response characteristic of the AC-DC system for a fault on the infinite bus on the inverter side and cleared after 0.1 second. The performance of the fuzzy controller is found to be very fast and in almost 1 second, the rotor angle oscillations are damped in comparison to nearly 6 seconds for the conventional stabiliser. The oscillations in the dc link quantities also get damped very fast with a adaptive fuzzy controller.

Although a few sample results representing the 3-phase short-circuit have been presented in this paper, other types of disturbances like dc-line short-circuit, load shedding, commutation failures, etc have been created and fuzzy logic controller performs superbly providing significant damping to the system oscillations. Research is being carried out to design a multivariable fuzzy controller for both 2-terminal and multiterminal HVDC-AC systems using other types of signals like ac and dc voltage deviations, DC power, etc.

5. CONCLUSIONS

The paper presents the design of a very simple form of fuzzy controller which is equivalent to a nonlinear PI controller for a DC transmission link in AC-DC power systems. The fuzzy controller introduces nonlinearities by using a nonlinear defuzzification algorithm and is thus suitable for a controlling a highly nonlinear plant like the AC-DC system. The degree of nonlinearities of the fuzzy controller can be changed by adjusting the input scalers g_e and g_r. The fuzzy controller does not require a mathematical model of the system unlike optimal, modal and other types of controllers to estimate the control input under disturbance conditions. A variety of transient simulations reveal the superior performance of the fuzzy controller for the AC-DC system.

6.ACKNOWLEDGMENTS

The authors acknowledge the funds from MHRD, Govt. of India and National Science Foundation (Grant No.INT 9209103), U.S.A. for undertaking this investigation.

7.REFERENCES

1 C.E.Grund, R.V.Pohl, and J.Reeve, "Control design of an active and reactive power HVDC modulation system with Kalman filtering", IEEE Trans. PAS, Vol.101, pp.4100-4111.

2. M.A. Choudhury, A.S.Emarah, K.A.Ellithy, and G.D.Galanos, "Stability analysis of a modulated AC/DC system using the a eigenvalue sensitivity approach", IEEE Trans. PWRS, Vol.1, No.2, pp.128-137,1986.

3. Y.Y. Hsu, Li Wang," Damping a parallel AC-DC power system using PID power system stabilizers and rectifier current regulators"' IEEE Trans. on EC, Vol.3, No.3, 1988, pp.540-548.

4. L.A.Zadeh, "Fuzzy sets: Information and control", Vol.8, pp.338-353, 1965.
5. J.J.Buckley, and H.Ying, "Fuzzy controller theory: limit theorems for linear fuzzy control rules", Automatica, Vol.25, 1988, pp.472-496.
6. H.Yang, W.Siler, and J.J.Buckley, " Fuzzy control theory - a nonlinear case ", Automatica, vol.26, no.3, pp.513-520, 1990.

APPENDIX-1

System parameter and operating conditions :

Generator & AVR(p.u.)

x_d=1.6,x_q=1.53,x'_d=0.17,τ'_{do}=4.314 s, H=2.5s,K_e=50,T_e=0.15s

Transformer and AC/DC system (p.u.):

x_1=0.125,R_{dc}=0.14,X_{dc}=0.4,r_t=.02,x_t=0.4, z_e=0.5,θ_e=75°,a_r=1.0,a_i=1.0,X_{c1}=4.0, X_{c2}=4.0,X_r=0.12,X_r=.10,K_r=-1.0,K_i=1.0, T_r=.05s, T_i=.05s,α_{max}=70°,α_{min}=7°, γ_{max}=40°,γ_{min}=12°.

Operating Conditions:

V_r=0.9552,P_g=0.9,Q_g=0.436,P_{dc}=0.4, P_L=0.4, Q_L=0.2,α=15°,γ = 15°.

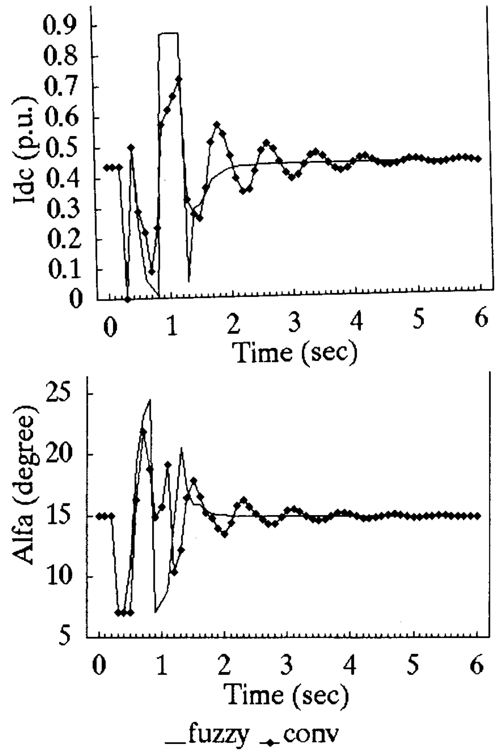
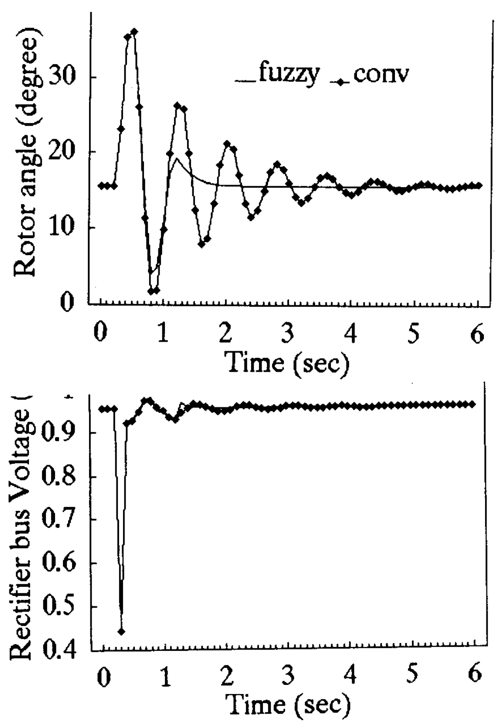
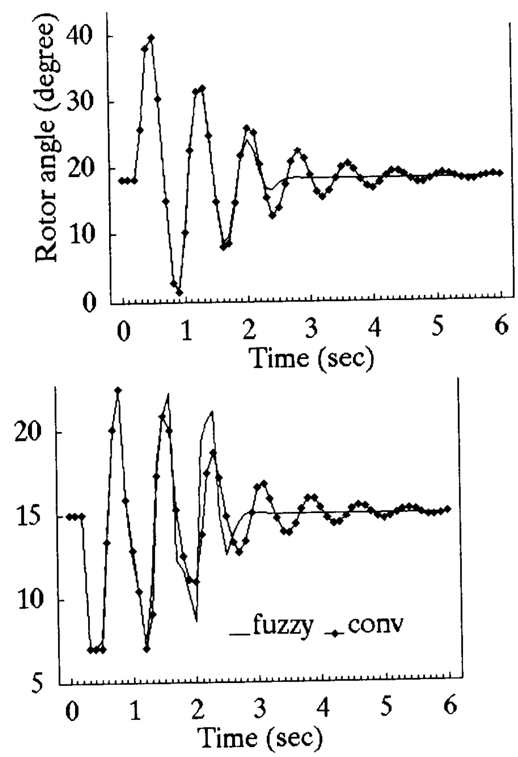


Fig.5 3−phase fault on Rectifier bus (Pdc=0.4)





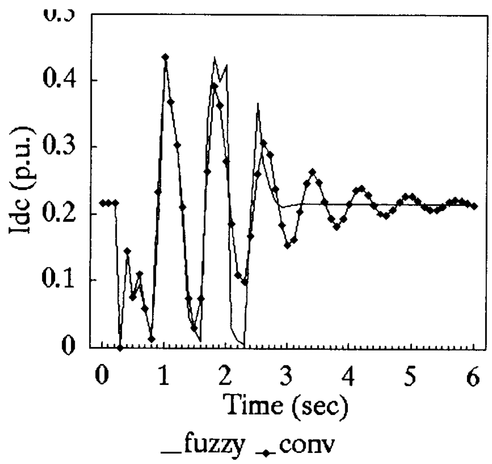
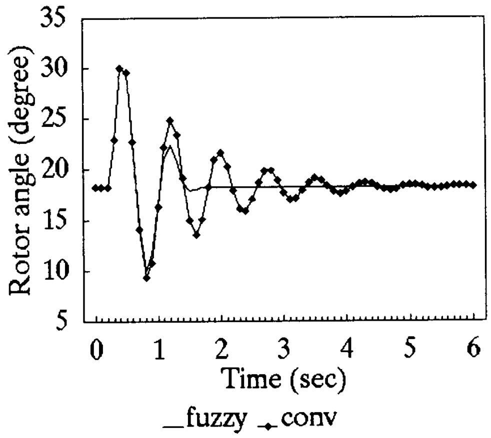


Fig.6(a) 3−phase fault on Rectifier bus



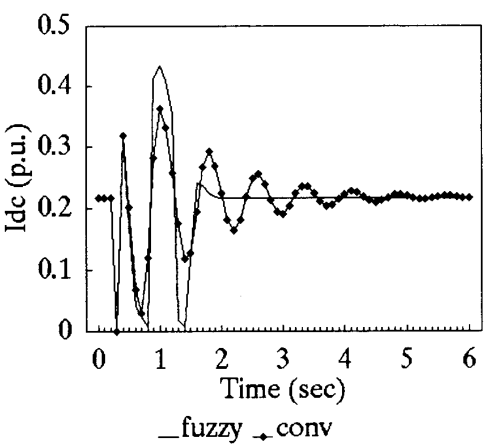
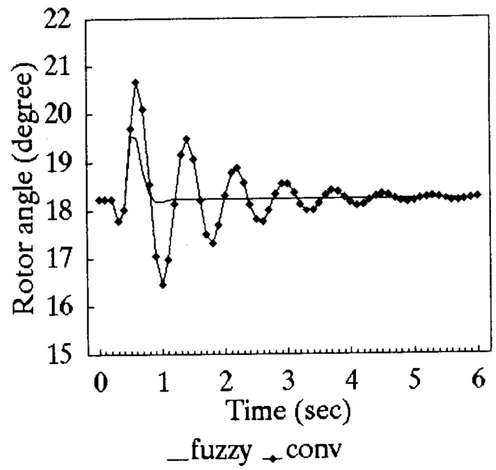
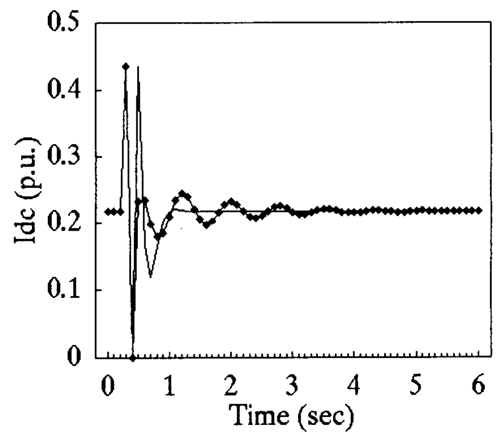


Fig.6(b) 3−phase fault on Rectifier bus
(ap=0,aq=0)





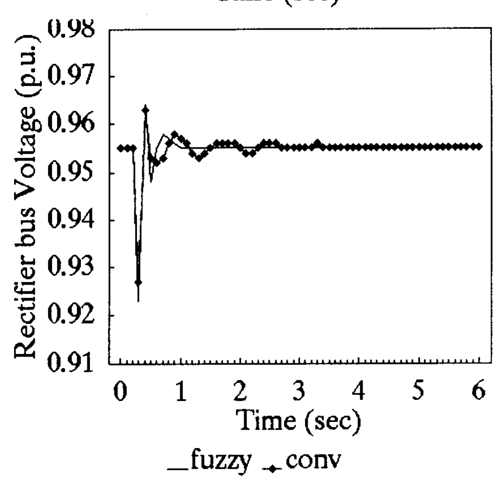


Fig.7 3−phase fault on Inverter bus