**Paper**

# A Fuzzy Logic Controlled Braking Resistor Scheme for Transient Stability Enhancement

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A large power system is often subjected to stability problem. This paper deals with the investigations regarding the transient stability enhancement of the electric power system making use of a fuzzy logic controlled braking resistor scheme. Following a fault, variable rotor speed of the generator is measured and the firing-angle of the thyristor switch in the braking resistor is determined from the crispy output of the fuzzy controller. By controlling the firing-angle of the thyristor, braking resistor can control the accelerating power in generators and thus improves the transient stability. The effectiveness of the proposed controller has been demonstrated by considering both balanced (3LG :Three-phase-to-ground) and unbalanced (1LG: Single-line-to ground, 2LG: Double-line-to ground and 2LS: Line-to-line) faults near the generator. Moreover, the performance of the braking resistor scheme with fuzzy controller is compared to that of with the conventional PID (Proportional-Integral-Derivative) controller. Simulation results indicate the better performance of fuzzy controller in comparison with conventional PID controller. Thus, the proposed fuzzy control strategy provides a simple and effective method of transient stability enhancement.

Key Words: Fuzzy Logic, Braking Resistor, PID controller, Transient Stability, Balanced faults, Unbalanced faults.

## 1.Introduction

Amongst the various methods of improving transient stability, dynamic braking resistor is known to be a very powerful tool. The Braking Resistor (BR) can be viewed as a fast load injection to absorb excess transient energy of an area which arises due to severe system disturbances.

A number of studies regarding braking resistors have been described in the literature [1-5]. But in all these switching strategies, fuzzy logic control schemes have not been used. As a result, these strategies are inflexible and are not adaptive to the changing operating condition of the system. Therefore, to surmount such a drawback, a few reports [6,7] for the switching of braking resistor using fuzzy logic control scheme have been published in which the effectiveness of the fuzzy controller has been demonstrated by considering only 3LG (Three-line-to-ground) fault. The analysis of unbalanced faults is also important from the viewpoint of power system transient stability.

Therefore, in this paper a fuzzy logic controlled braking resistor scheme is proposed and its effectiveness is shown considering both balanced and unbalanced faults near the generator. Furthermore, the performance of the braking resistor scheme with fuzzy controller is compared to that of with the conventional PID controller for both types of fault conditions. An important feature of this work is that the design of the fuzzy controller is very simple, because it has only one input variable and one output variable. The simulation is implemented by using EMTP (Electro-Magnetic Transients Program) for both fuzzy and PID control schemes. Simulation results clearly indicate the effectiveness and better performance of fuzzy controller in comparison with conventional PID controller. Therefore, it can be concluded that the proposed fuzzy control strategy is excellent and effective in transient stability improvement.

The organization of this paper is as follows: Section 2 describes the simulation method for the proposed study. Section 3 explains the proposed fuzzy controller design. In section 4, design of the conventional PID controller is explained. Section 5 describes the method of calculating firing-angle for the thyristor switch. Section 6 shows the simulation results. Finally, section 7 provides some conclusions regarding the proposed control strategy.

## 2. Simulation Method

### <2.1> Model System

Fig. 1 shows the power system model used for the simulation of transient stability. The system model consists of a synchronous generator feeding an infinite bus through a double circuit transmission line. The braking resistor is connected to the generator terminal bus through the thyristor switching circuit. R, X and CB in the figure represent line resistance, line reactance and circuit breaker respectively. Also, AVR (Automatic Voltage Regulator) and GOV (Governor) control system models shown in Fig. 2 have been included in the simulation.

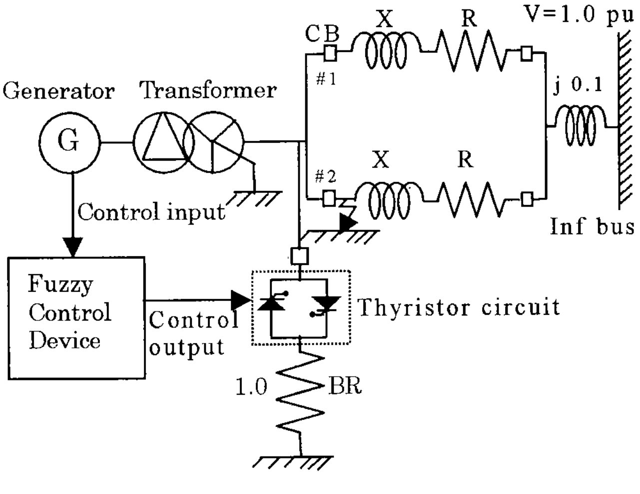


**Fig: 1 Power System model**

In the simulation study, it has been considered that the fault occurs near the generator at line #2 at 0.1 sec, the circuit breakers (CB) of line #2 are opened at 0.2 sec and at 0.6 sec the circuit breakers are closed. Also, time step and simulation time have been chosen as 0.00005 sec and 5.0 sec respectively. Moreover, the BR will be switched in following a fault clearing and the switching condition of BR is such that when deviation of speed is positive, BR is switched on the generator terminal. On the other hand, when deviation of speed is negative and also in the steady state, BR is removed from the generator terminal bus by the thyristor switching circuit. The various parameters of the power system used for the simulation are shown in Table 1.

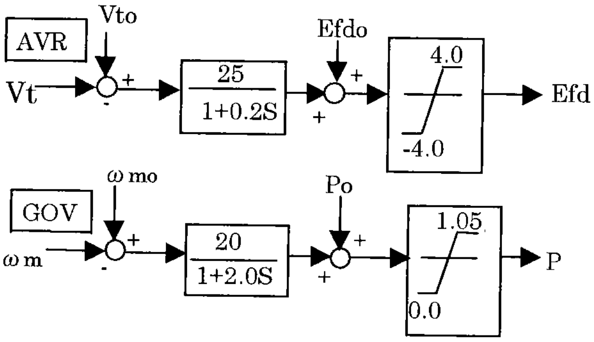


Fig. 2 AVR and GOV Models

Table 1: Power system parameters

| | | | |
|---|---|---|---|
| Generator output | (0.9+j0.11) pu | $r_a$ | 0.003 pu |
| Generator power rating | 100 MVA | $X_l$ | 0.13 pu |
| Generator voltage rating | 20 KV | $X_d$ | 1.79 pu |
| Frequency | 50 Hz | $X_q$ | 1.71 pu |
| Generator terminal voltage | 1.0 pu | $X'_d$ | 0.169 pu |
| Phase angle of generator | | $X'_q$ | 0.228 pu |
| terminal Voltage | 19.113 deg | $X''_d$ | 0.135 pu |
| Generator load angle | 72.019 deg | $X''_q$ | 0.2 pu |
| Generator neutral | | $X_0$ | 0.13 pu |
| grounding resistance | 0.00001 pu | $T'_{d0}$ | 4.3 sec |
| H(Inertia constant) | 2.89 sec | $T'_{q0}$ | 0.85 sec |
| Transformer reactance | 0.05 pu | $T''_d$ | 0.032 sec |
| Transformer neutral | | $T''_q$ | 0.05 sec |
| grounding resistance | 0.00001 pu | | |
| R | 0.05 pu | | |
| X | 0.5 pu | | |

## <2.2.> Modeling of TCSBR ( Thyristor Controlled System Braking Resistor )

Fig. 3(a) shows the proposed circuit of two reverse parallel-connected thyristors, T1 and T2 along with the braking resistor. Following a fault when Thyristor T1 or T2 is in ON state, current flows through BR and it decreases the accelerated power by consuming excessive transient energy. In this way, during large disturbances, the braking resistor can control the speed deviation and accelerating power in generators and thereby makes the power system stable by bringing speed deviation and accelerating power near the equilibrium point.

The typical waveforms of voltage and current through BR are shown in Fig. 3(b). Therefore, when the firing-angle for the thyristor switch is $\alpha$ as shown in Fig. 3(b), average power, $P_{TCSBR}$, consumed by the braking resistor is given by,

$$P_{TCSBR} = \frac{1}{\pi}\int_0^{\pi} vI_R.d(\omega t)$$

$$= \frac{V^2 G_{TCSBR}}{\pi}(\pi - \alpha + 0.5\mathrm{Sin}2\alpha) \quad \text{......(1)}$$

Where v is the instantaneous value of generator terminal bus voltage, $I_R$ is the instantaneous value of current through BR, V is the rms value of generator terminal bus voltage and $G_{TCSBR}$ is the conductance value of BR specified to 1.0 pu for the simulation.

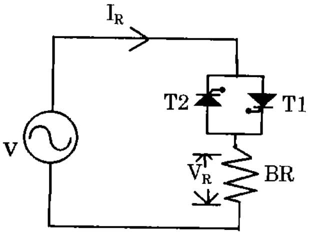


Fig. 3(a) Thyristors connected with BR

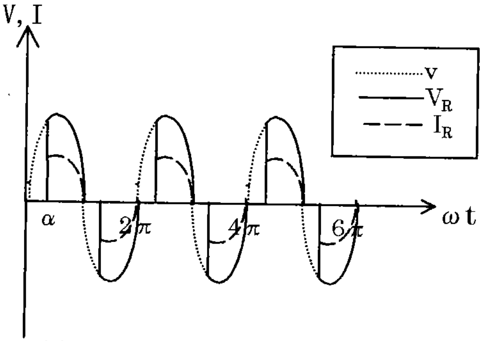


Fig. 3(b) Voltage and Current waveforms

Fig. 3 Thyristor switching circuit for BR and waveforms

## 3. Design of fuzzy controller

A fuzzy logic, unlike the crispy logic in Boolean theory that uses only two logic levels (0 to 1), is a branch of logic that admits infinite logic levels (from 0 to 1), to solve a problem that has uncertainties or imprecise situations. Again, a fuzzy control is a process control that is based on fuzzy logic and is normally characterized by "IF-THEN" rules [8]. The design of the proposed FLC (Fuzzy Logic Controller) is described in the following:

### <3.1> Fuzzification

To design the fuzzy controller, it has been selected speed deviation, $\Delta\omega$, of the generator as the input and conductance value, G, of the braking resistor as the output. The triangular membership functions for the fuzzy sets of $\Delta\omega$ have been shown in Fig. 4 in which the linguistic variables are represented by NE (Negative), ZO (Zero), and PO (Positive). The equation of the triangular membership function used to determine the grade of membership values is as follows [9].

$$A(x)=1/b\,(b-2|x-a|) \quad \text{......(2)}$$

Where A(x) is the value of grade of membership, 'b' is the width and 'a' is the coordinate of the point at which the grade of membership is 1, x is the value of the input variable (deviation of speed for the present simulation).

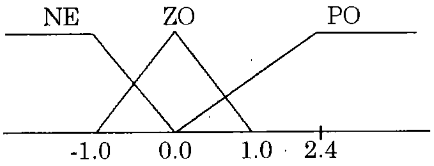


Fig. 4 Membership function of $\Delta\omega$ (rad/sec)

### <3.2> Fuzzy Rule Table

The proposed control strategy is very simple because it has only 3 control rules which have been developed from the viewpoint of practical system operation and by trial and error and is shown in Table 2 where the numerical values of G represent the output of the fuzzy controller.

Table. 2 Fuzzy Rule Table

| $\Delta\omega$ | G ( Pu ) |
|---|---|
| NE | 0.0 |
| ZO | 0.0 |
| PO | 1.0 |

### <3.3> Fuzzy Inference and Defuzzification

For the inference mechanism of the proposed fuzzy logic controller, Mamdani's method [9] has been utilized. The Center-of-Area method is the most well-known and rather simple defuzzification method which is implemented to determine the output crispy value ( i.e. the conductance value of the braking resistor).

## 4. Design of Conventional PID controller

The classical PID controller finds extensive application in industrial control. The block diagram of the continuous-time PID controller is shown in Fig. 5. The transfer function of the classical PID controller used in this simulation is written in s-domain as the following [10] :

$$G=K_p(1+1/T_is+T_ds)\ \Delta\omega \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where $\Delta\omega$ and G represent the input and output variables of the controller respectively and bear the same meanings as explained in section 3.1. $K_p$, $T_i$ and $T_d$ represent the proportional gain, integration time constant and derivative or rate time constant respectively.

In order to obtain fast and excellent system responses we have tuned the controller parameters by trial and error method. Actually, it is a difficult task to tune the controller parameters properly. However, during this process, we have observed that sometimes chattering phenomenon occurs in the firing-angle responses of the thyristor switch although the load angle and speed deviation responses of the generator remain better. Generally, this chattering occurs from the improper tuning of the controller parameters. Therefore, to remove this chattering and to obtain the best parameters, a lot of trial and error have been performed and we have developed an approximate range for the parameters as shown in the following.

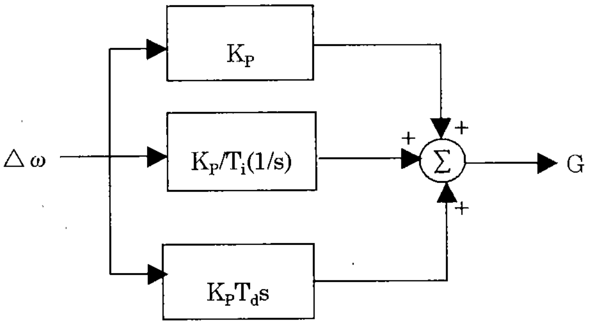


Fig. 5 Block diagram of PID controller

i) 0.5 <$K_P$< 12.0 ( approximately)
ii)0.2< $T_i$< 3.5 ( approximately)
iii) $T_iT_d$ <0.0001( approximately)

It is observed that beyond these ranges of the parameters, either chattering occurs in the firing-angle responses or the responses of the load angle and speed deviation become worse. Therefore, considering these ranges and after numerous trials, we have finally selected the best values of the controller parameters as shown in Table 3 .

**Table 3: Parameters of PID Controller**

| $K_P$ | $T_i$ | $T_d$ | $T_i\,T_d$ |
|---|---|---|---|
| 3.0 | 3.0 | 0.0000003 | 0.000001 |

It is noticeable from Table 3 that to obtain the excellent responses as well as to eliminate the chattering in the firing-angle responses, the values of $T_d$ should be very small. Therefore, during the trial and error, once we selected the value of $T_d$ as zero keeping the values of $K_P$ and $T_i$ same as in Table 3 and found almost the same responses as obtained by using the same values of $K_P$,$T_i$ and $T_d$ given in Table 3. In that case the controller acted just as a PI ( Proportional-Integral) controller. After that considering the PI controller, we made numerous trial and error and finally developed the following approximate range for the controller parameters as shown in the following.

i) 0.5 <$K_P$< 4.0 ( approximately)
ii)0.2< $T_i$< 10.0 ( approximately)

It was observed that beyond these ranges of the parameters, either chattering occurs in the firing-angle responses or the responses of the load angle and speed deviation become worse. However, considering the above ranges of the paramerters, we made a lot of trials and found almost the same responses as those of the PID controller .

One important thing here is that for some values of the parameters, chattering must occur in the firing-angle responses of both the PID and PI controllers. But the rate of chattering occurance is, to some extent, less in the PI controller than that of PID controller. As for example, in the case of PID controller with $K_P = 1.3$, $T_i = 0.28$ and $T_d = 0.00036$, chattering occurs in the firing-angle response as shown later in Fig. 10. But using the same values of $K_P$ and $T_i$, chattering does not occur in the firing-angle responses in case of PI controller, although the load angle and speed deviation responses remain almost the same. Since our target in this work is to use PID controller and we found almost the same responses for both PID and PI controllers using the above specified ranges of the parameters, we have carried simulations as shown in section 6 using the parameter values of Table 3 for the PID controller.

## 5. Calculation of firing-angle, $\alpha$

Firing-angle, $\alpha$ for the thyristor switch is calculated from the output of the fuzzy controller or PID controller i.e. from the conductance value of the braking resistor. Again, conductance value of BR is related to the power dissipated in BR. For any time step of simulation, the average power of SBR ( System Braking Resistor), $P_{SBR}$ and that of TCSBR (Thyristor Controlled System Braking Resistor), $P_{TCSBR}$ are equal and hence firing-angle, $\alpha$, can be calculated from the following equation .

$$P_{TCSBR} = P_{SBR}$$

$$or, \frac{V^2 G_{TCSBR}}{\pi}(\pi - \alpha + 0.5\mathrm{Sin}2\alpha) = V^2 G \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where G is the conductance value of BR which is the output of fuzzy or PID controllers and other symbols have already been defined in section 2.2.

But it is complex to calculate firing-angle, $\alpha$, directly from eq. (4) using the value of G. So, in this simulation, firstly by using eq. (4), a set of different values of G is calculated for the values of firing-angle ranging from $0^0$ to $180^0$ with a step of $2^0$. Then by using the linear interpolation technique, firing-angle, $\alpha$, is determined.

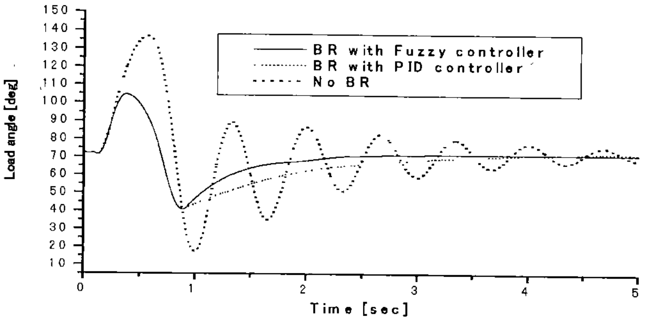
## 6. Simulation Results

Figures 6-13 show the simulation results of both fuzzy and PID control schemes considering both balanced (3LG) and unbalanced (1LG, 2LG and 2LS) faults near the generator at line #2.

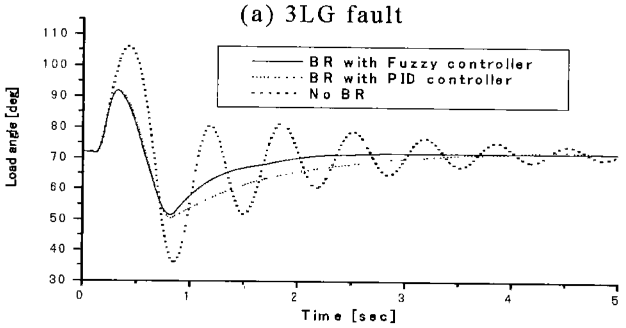
Figs. 6(a-d) show the load angle responses for 3LG, 2LG, 2LS and 1LG faults. It is easily seen from these responses that because of the use of BR, the system is advancing towards a stable condition very quickly for all the fault conditions. Also, it is observed that both the fuzzy and PID controller responses are smooth and fast. But from the point of view of the settling time for the load angle responses, the performance of fuzzy controller is much better than that of PID controller.

Figs. 7(a-d) show the speed deviation versus time curves for all the fault cases. From these responses, it is clear that the use of BR makes the system stable quickly. Again, it is observed that although from the point of view of the settling time both fuzzy and PID controller responses are almost the same, but the responses of fuzzy controller are smoother and less oscillating than those of PID controller.

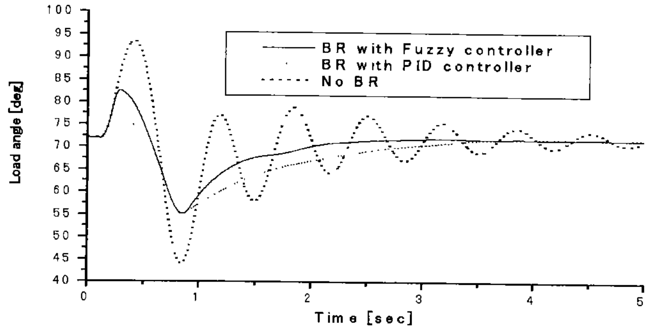
Figs. 8(a-d) and Figs. 9(a-d) depict the firing-angle responses of the thyristor switch for phase 'a' with fuzzy controller and PID controller respectively under both balanced and unbalanced fault conditions. The firing-angle varies from 0 degree to 180 degree according to the value of G. In section 2.1, it has been stated that when the power system becomes stable, BR is removed from the generator terminal bus by the thyristor switching circuit. This signifies that in that case conductance, G, is zero and hence, firing-angle becomes 180 degree. Now, for all the



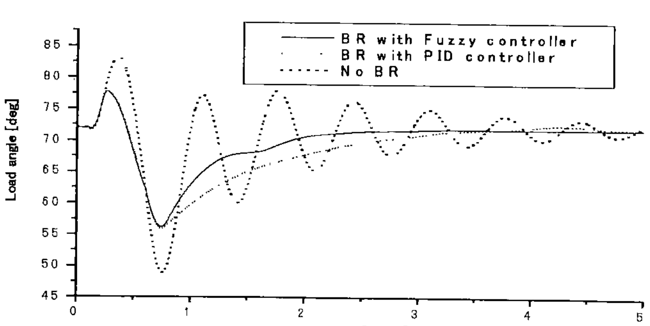
(a) 3LG fault



(b) 2LG fault



(c) 2LS fault



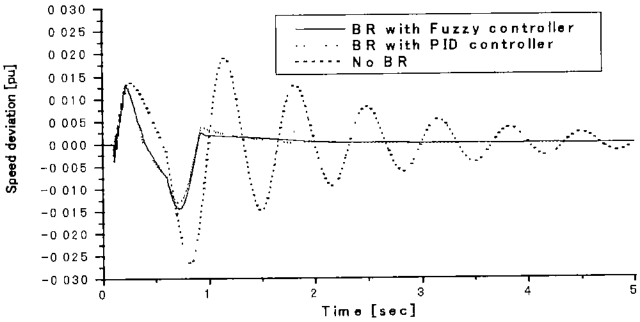
(d) 1LG fault

**Fig. 6 Load angle responses**

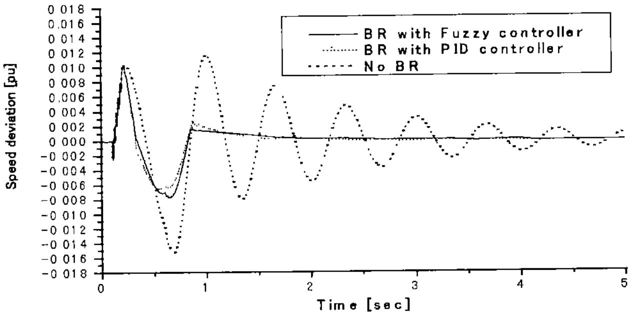
fault cases it is easily seen that after some variations from 0 degree to 180 degree, the firing-angle with fuzzy controller gets a constant value of 180 degree after about 2.0 sec and it remains the same upto 5.0 sec. But in the case of PID controller, the firing-angle has a constant value of 180 degree after about 4.5 sec and it remains the same upto 5.0 sec. This indicates that the fuzzy controlled BR makes the power system stable quickly in comparison with PID controlled BR.

Fig. 10 shows the firing-angle response of the thyristor switch for phase 'a' with PID controller in case of 3LG fault when the values of $K_P$, $T_i$ and $T_d$ are 1.3, 0.28 and 0.00036 respectively. This response indicates the existence of the chattering phenomenon caused from the improper tuning of the controller parameters.

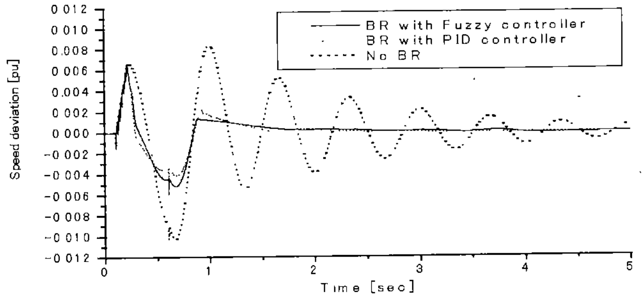
Generator terminal bus voltage and current responses of BR for phase 'a' have been shown in Figs. 11(a-b) and Figs. 11(c-d) during 3LG fault and 2LG fault respectively for different time intervals in case of fuzzy controller. In Figs. 11(a) and 11(c), it is noticeable that current waveforms have almost the same shape as voltage waveforms because of the firing-angle which has values of zero degree. Again, in Figs. 11(b) and 11(d), it is noticeable that current waveforms differ from voltage waveforms because of the firing-angle which does not have zero degree values rather it has some values.



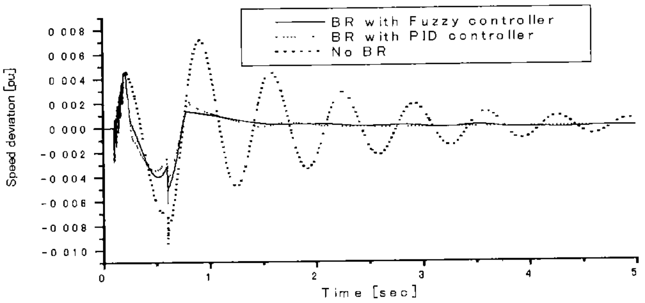
(a) 3LG fault



(b) 2LG fault

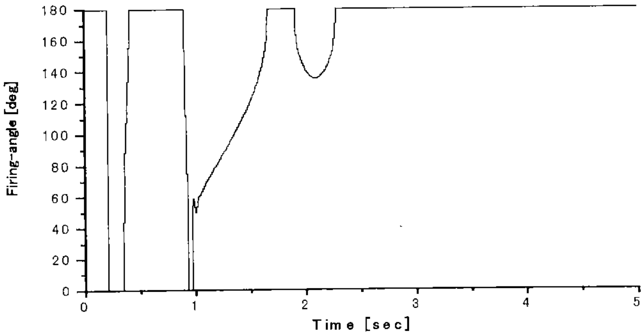


(c) 2LS fault

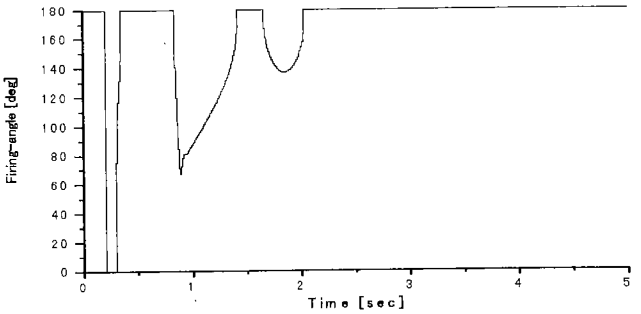


(d) 1LG fault

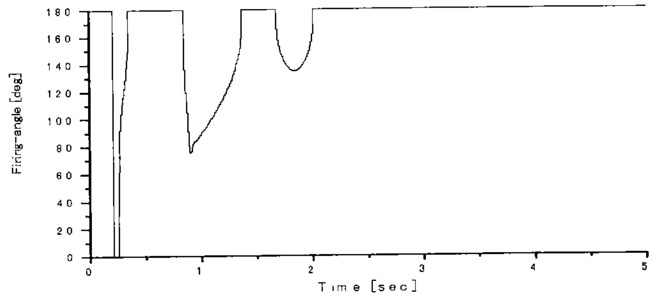
Fig. 7 Speed deviation responses



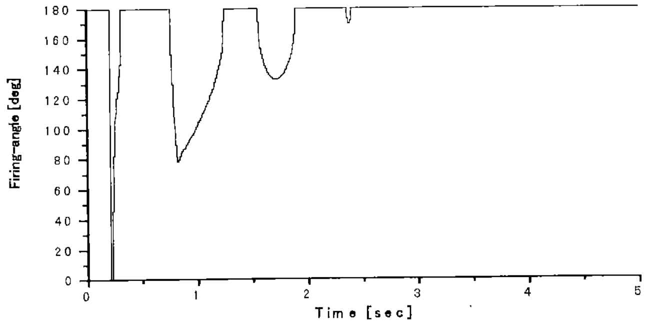
(a) 3LG fault



(b)2LG fault

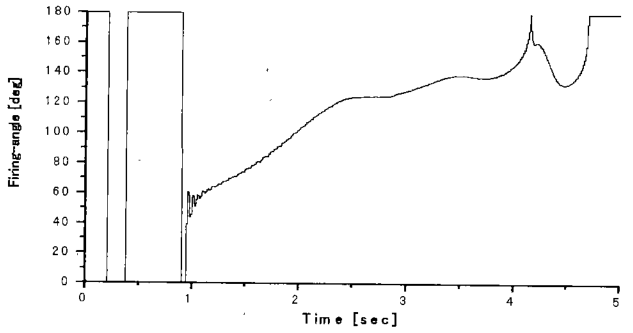


(c) 2LS fault

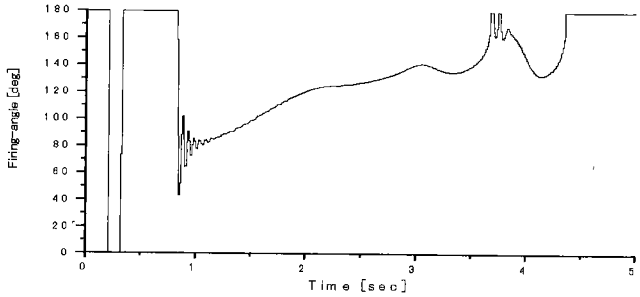


(d) 1LG fault

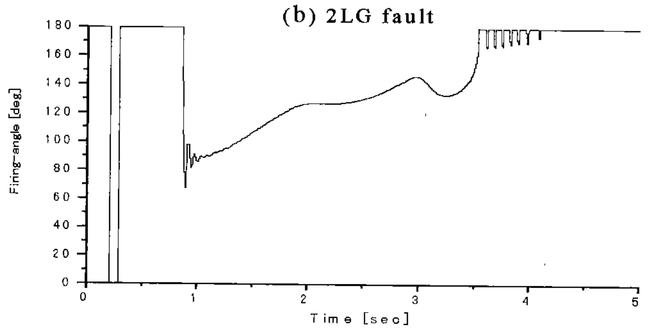
Fig. 8 Firing-angle vs time curve for phase 'a' with fuzzy controller



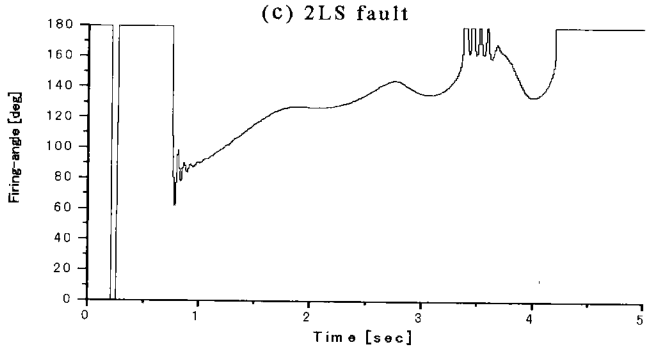
(a) 3LG fault



(b) 2LG fault



(c) 2LS fault



(d) 1LG fault

**Fig. 9 Firing-angle vs time curve for phase 'a' with PID controller**

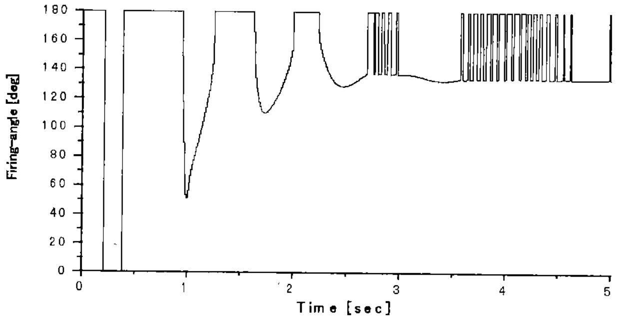
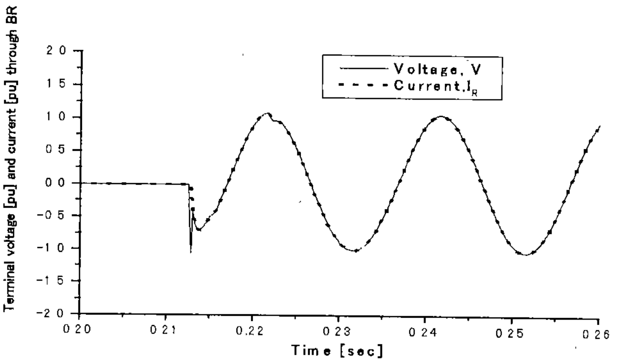
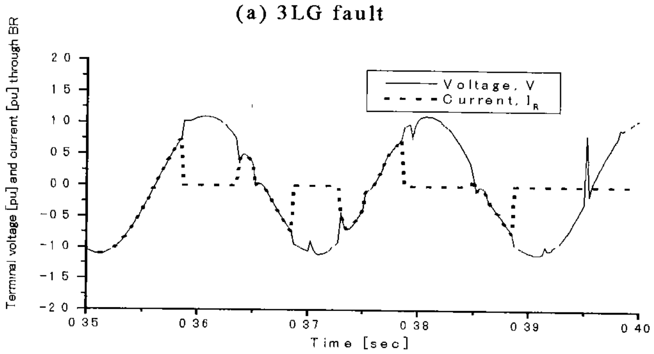


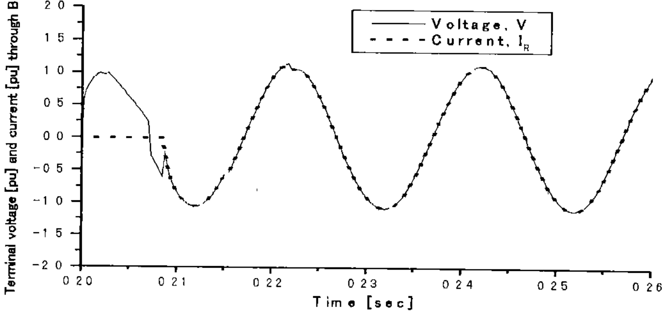
**Fig. 10 Firing-angle response for phase 'a' with PID controller showing chattering during 3LG fault**



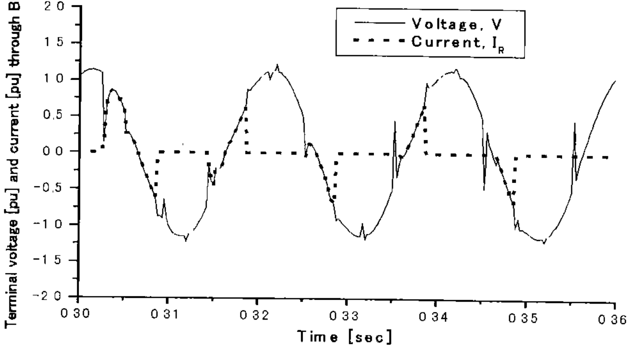
(a) 3LG fault



(b) 3LG fault



(c) 2LG fault



(d) 2LG fault

**Fig. 11 Voltage and current responses of BR with fuzzy controller**

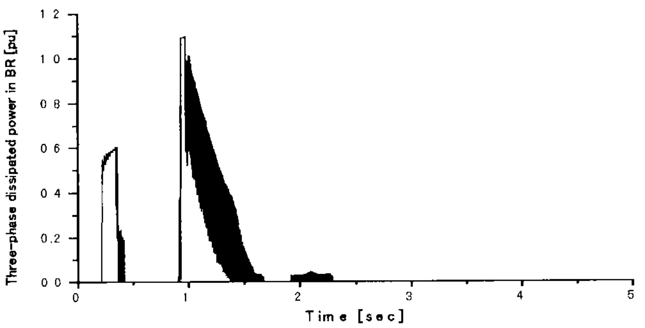
Finally, in Figs. 12(a-d) and Figs. 13 (a-d), it is shown the responses of three-phase dissipated power in BR for fuzzy controller and PID controller respectively for all the fault conditions. In the steady state of the power system, the power dissipation in BR is zero. Again, the amount of power to be dissipated in BR depends on the value of firing-angle. Therefore, it is observed in the case of fuzzy controlled BR that after some variations from 0.0 pu to about 1.0 pu, the power dissipation becomes zero after about 2.0 sec and after that it is always zero upto 5.0 sec. But in the case of PID controller, power dissipation has a zero value at about 4.5 sec and then it is always zero upto 5.0 sec. This also indicates that the fuzzy controlled BR makes the power system stable quickly in comparison with PID controlled BR.

Therefore, regarding the simulation results there are several salient points which are important to note.

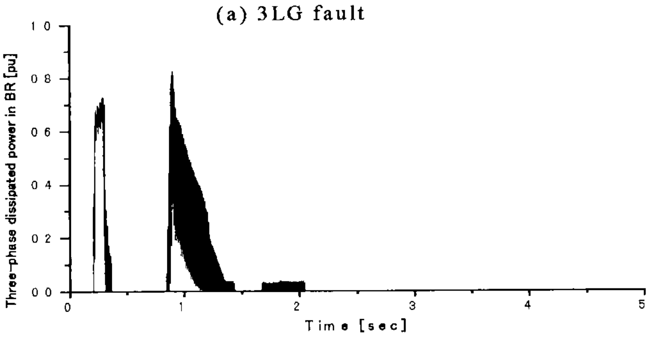
i) It is evident that the use of fuzzy controlled braking resistor makes the power system stable quickly for both balanced and unbalanced faults.

ii) From the responses of load angle, speed deviation, firing-angle and dissipated power in BR for all the fault cases, it is observed that the performance of proposed fuzzy control scheme is better than that of the PID controller.

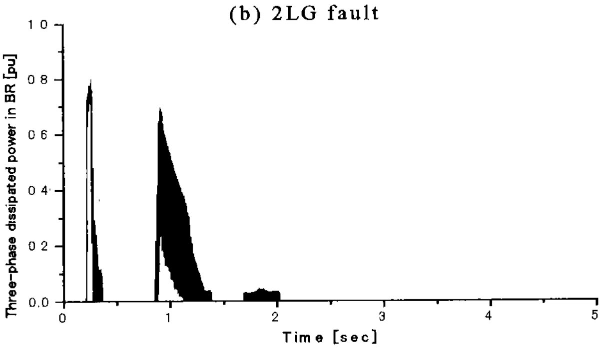
As a result, from the point of view of these salient points, it can be concluded that the proposed fuzzy control scheme is an excellent and effective method to improve the transient stability for both balanced and unbalanced fault conditions.



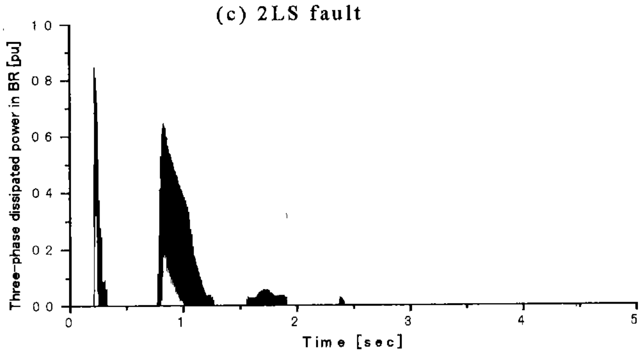
(a) 3LG fault



(b) 2LG fault

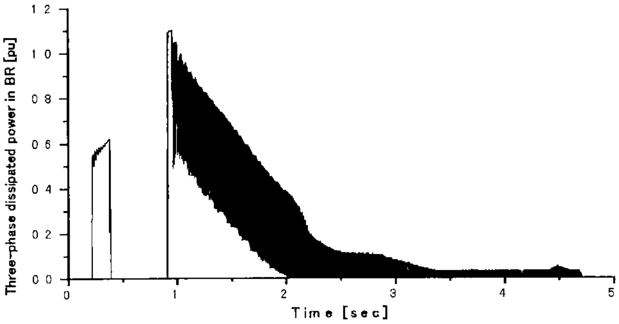


(c) 2LS fault

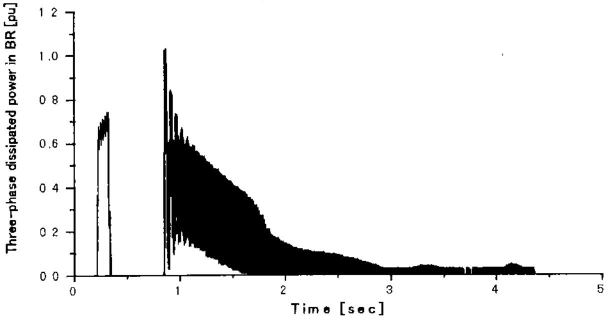


(d) 1LG fault

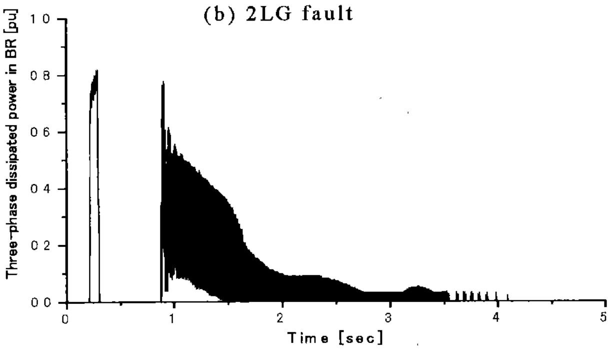
**Fig:12 Dissipated power responses for fuzzy controller**



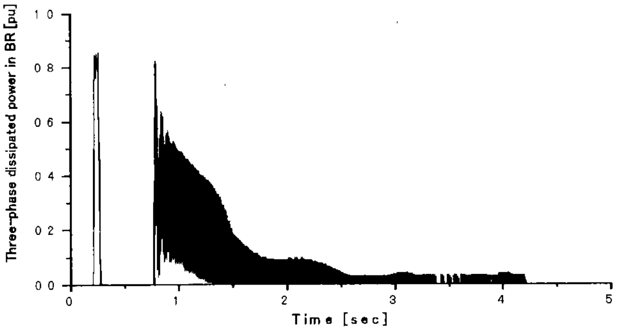
(a) 3LG fault



(b) 2LG fault



(c) 2LS fault



(d) 1LG fault

**Fig:13 Dissipated power responses for PID controller**

## 7. Conclusion

In order to augment the transient stability of electric power system, a fuzzy logic controlled braking resistor scheme is proposed in this paper. The effectiveness of the proposed fuzzy controller is demonstrated by considering both balanced and unbalanced faults near the generator. Moreover, the performance of the proposed fuzzy control scheme is compared to that of the conventional PID control scheme. Simulation results clearly indicate the excellent performance of fuzzy controller in improving the transient stability. Moreover, it is observed that the performance of fuzzy controller is better than that of PID controller. Also, the design of the proposed fuzzy controller is simpler because it has only one input variable and one output variable. Therefore, it can be concluded that the proposed fuzzy control strategy provides a simple and effective method of power system stabilization during both balanced and unbalanced faults.

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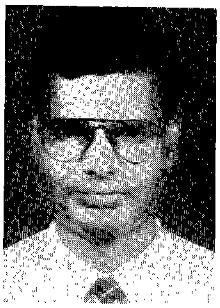

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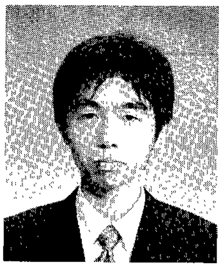

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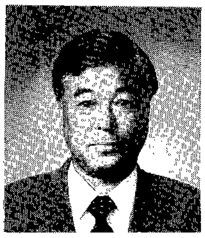

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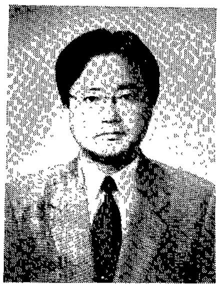

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