Effect of Coordination of Optimal Reclosing and Fuzzy Controlled Braking Resistor on Transient Stability During Unsuccessful Reclosing

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***Abstract*—This paper analyzes the effect of the coordination of optimal reclosing and fuzzy logic-controlled braking resistor on the transient stability of a multimachine power system in case of an unsuccessful reclosing of circuit breakers. The transient stability performance of the coordinated operation of optimal reclosing and fuzzy controlled braking resistor is compared to that of the coordinated operation of conventional auto-reclosing and fuzzy controlled braking resistor. The effectiveness of the proposed method is confirmed by simulations in case of a nine-bus power system model as well as a ten-machine system. Simulation results of both balanced and unbalanced faults at different points in the power systems show that the coordinated operation of optimal reclosing and fuzzy controlled braking resistor is able to stabilize the systems well in case of an unsuccessful reclosing. Moreover, the transient stability performance of the coordinated operation of optimal reclosing and fuzzy controlled braking resistor is better than that of the coordinated operation of conventional auto-reclosing and fuzzy controlled braking resistor.**

***Index Terms*—Balanced fault, braking resistor (BR), fuzzy controller, global positioning system (GPS), optimal reclosing, power system transient stability, unbalanced faults, unsuccessful reclosing.**

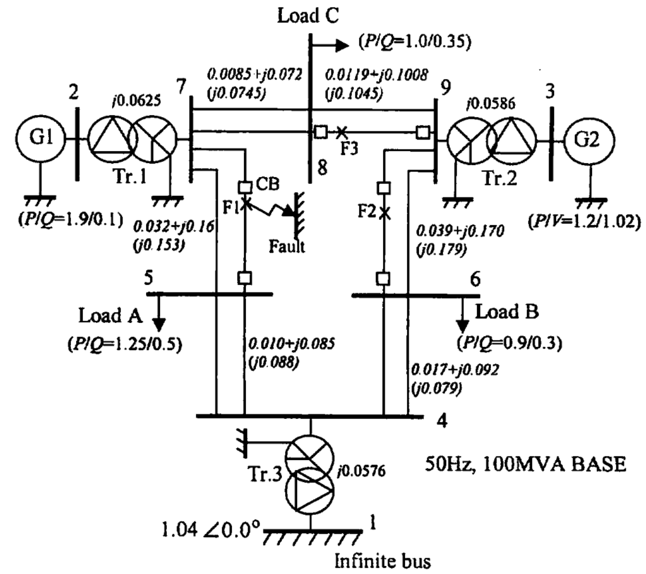

Fig. 1. Nine-bus power system model.

I. Introduction

BRAKING RESISTOR (BR) has been recognized and used as a cost-effective measure for transient stability enhancement for a long time. In recent years, instead of conventional controller, fuzzy logic-based control of braking resistor for transient stability enhancement of electric power systems is getting increasing attention [1]–[11]. However, in all of these strategies, transient stability analysis was carried out considering only successful reclosing of circuit breakers during transient fault.

The majority (60%–80%) of transmission line faults are of a transitory nature. After the line is de-energized long enough for the fault source to pass and the fault arc to de-ionize, the line may be reconnected. Therefore, common practice is to reclose the circuit breakers automatically to improve service continuity. The reclosure may be either high-speed or with time delay. High-speed reclosure refers to the closing of circuit breakers after a time, just long enough to permit fault-arc de-ionization. The reclosure can be completed in less than 1 s [12]. However, high-speed reclosure is not always acceptable. Reclosure into a permanent fault, i.e., unsuccessful reclosure, may cause system instability. Thus, the application of automatic reclosing is usually constrained by the possibility of a persistent fault, which would create a second fault after reclosure.

Another important point to note here is that conventional auto-reclosing techniques adopt fixed time interval reclosing, that is, the circuit breakers reclose after a prescribed dead time, which is set to a constant value. Since the transient stability is dependent on the generator state of reclosing instance, in some cases, the conventional method may cause an unstable state, especially for the case of unsuccessful reclosing. Therefore, in order to maintain the synchronism and enhance the transient stability, the circuit breakers should be reclosed at optimal reclosing time (ORCT) [13]–[16], where system disturbances after reclosing operation are restrained effectively. In all of the BR strategies [1]–[11] for transient stability enhancement, conventional auto-reclosing methods were used.

This paper proposes the coordination of optimal reclosing and fuzzy logic-controlled braking resistor to enhance the transient stability of a multimachine power system during unsuccessful reclosing of circuit breakers, and this is the novel feature of this paper. The transient stability performance of the coordinated

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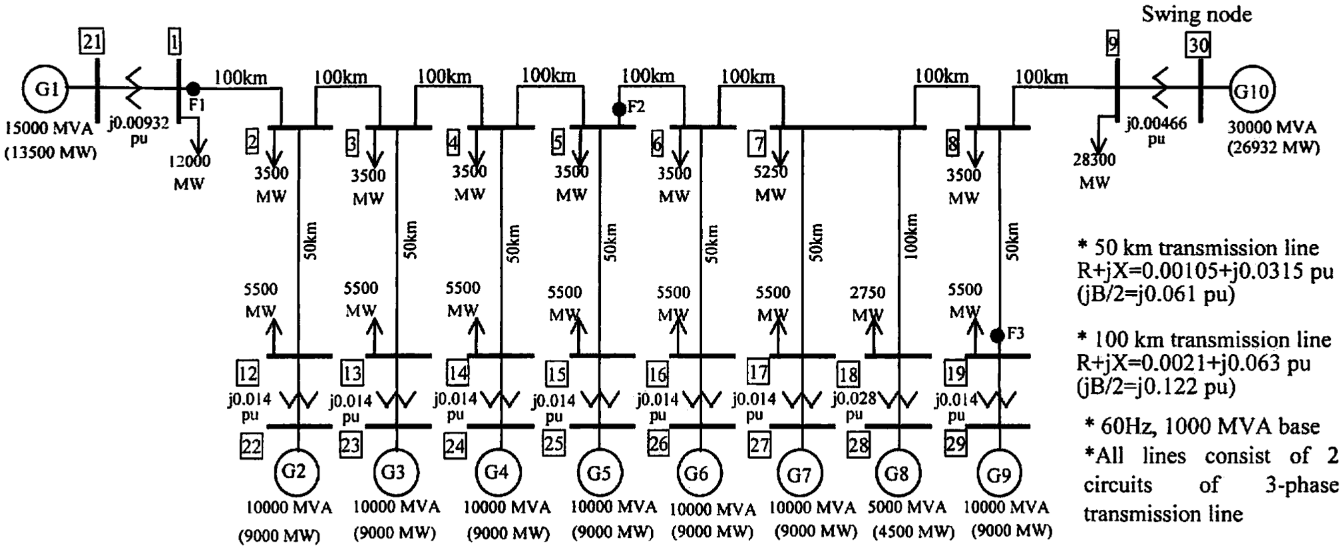

Fig. 2. IEEJ WEST ten-machine model system.

operation of optimal reclosing and fuzzy controlled braking resistor is compared to that of the coordinated operation of conventional auto-reclosing and fuzzy controlled braking resistor.

Among the optimal reclosing techniques [13]–[16], the method described in [13] has a distinct advantage that it uses the kinetic energy of each generator, which can be obtained easily. Consequently, this technique may be implemented for online application. In this paper, the optimal reclosing technique described in [13] is used. According to this method, the time when the total kinetic energy oscillation of the generators without reclosing operation becomes the minimum first is determined as ORCT.

The organization of this paper is as follows: Section II describes the model systems for the proposed study. Section III explains the proposed optimal reclosing technique. Section IV describes the procedure for the design of the fuzzy logic controller. Section V describes the simulation results. Finally, Section VI provides some conclusions regarding this paper.

II. Description of Model Systems

For the simulation of transient stability, the nine-bus power system model [7] and the IEEJ West ten-machine model system [8] as shown in Figs. 1 and 2, respectively, have been used. The system model of Fig. 1 consists of two synchronous generators (G1 and G2) and an infinite bus connected to one another through transformers and double circuit transmission lines. In the figure, the double circuit transmission line parameters are numerically shown in the forms $R + jX$ $(jB/2)$, where R, X, and B represent resistance, reactance, and susceptance, respectively, per phase with two lines. The "WEST ten-machine system" model as shown in Fig. 2 is a ten-machine tandem model that is a prototype of the Japanese 60-Hz systems. It presents the long time oscillation characteristics of a tandem system. The model system has ten generators, G1 to G10. Generator G10 is considered as the swing generator in the system. All lines represent two circuits of a three-phase transmission line.

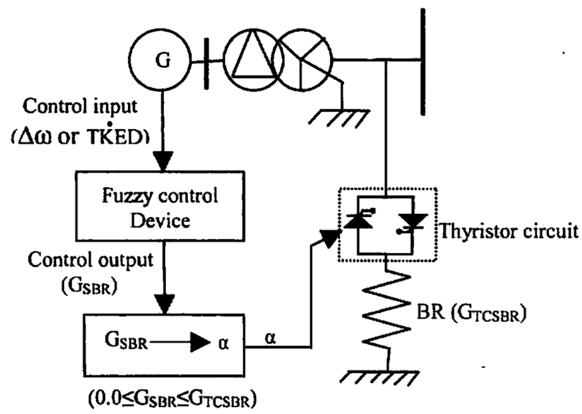

Fig. 3. BR with thyristor switching circuit.

In the case of the nine-bus model system, two braking resistors are used at the terminal buses of generators G1 and G2 [7], while in the case of the ten-machine system, five braking resistors are installed at the terminal buses of generators G1, G4-G6, and G10 to stabilize the overall system well [10]. The conductance values of the braking resistors are selected from the viewpoint that they can absorb an amount of power equal to the rated capacity of the machines at full conduction. In the case of the nine-bus system, the system base is 50Hz and 100MVA, and the capacities of generators G1 and G2 are 200MVA and 130MVA, respectively. Therefore, the conductance values of the braking resistors are considered as 2.0 and 1.3 p.u. for generators G1 and G2, respectively. In the case of the ten-machine system, the system base is 60Hz and 1000 MVA. Therefore, the conductance values of the braking resistors BR1, BR4-BR6, and BR10 are considered as 15.0, 10.0, and 30.0 p.u., respectively. Fig. 3 shows that a BR with a conductance value of G_{TCSBR} is connected to a generator terminal bus through a thyristor switching circuit.

In the case of the nine-bus system, the BR will be switched in following a fault clearing, and the switching condition of BR is such that when deviation of speed of the generator is positive. BR is switched on the generator terminal bus. On the other hand, when deviation of speed is negative, and also in the steady state of the system, BR is removed from the generator terminal bus by the thyristor switching circuit. In the case of the ten-machine system, the difference between the total kinetic energy (W_{total}) of the generators at transient state and that at steady state is defined as total kinetic energy deviation (TKED), i.e., TKED = (W_{total} at transient state) − (W_{total} at steady state). Again, the time derivative of TKED is expressed by $\dot{\text{TKED}}$. The BR will be switched in following a fault clearing, and the switching condition of BR is such that when $\dot{\text{TKED}}$ exceeds 0.065 p.u., BR is switched on the generator terminal bus. On the other hand, when $\dot{\text{TKED}}$ is equal to or below 0.065 p.u., BR is removed from the generator terminal bus by the thyristor switching circuit. Also, at the steady state of the system, i.e., when there is no disturbance in the system, BR will not work. The dead band of the BR operation, i.e., the threshold value of $\dot{\text{TKED}}$ is determined by trial and error. Various parameters of the generators as well as the automatic voltage regulator (AVR) and governor (GOV) control system models used in the present simulation work are described in [7] and [8] in the cases of the nine-bus system and ten-machine system, respectively.

III. Optimal Reclosing Technique

Conventional auto-reclosing techniques adopt fixed time interval reclosing, that is, the circuit breakers reclose after a prescribed dead time, which is set to a constant value. Since the transient stability is dependent on the generator state of reclosing instance, in some cases, the conventional method may cause an unstable state, especially for the case of unsuccessful reclosing. Therefore, in order to maintain the synchronism and enhance the transient stability, the circuit breakers should be reclosed at optimal reclosing time (ORCT), where system disturbances after reclosing operation are restrained effectively.

In this paper, the optimal reclosing technique described in [13] is used. According to this method, the time when the total kinetic energy oscillation of the generators without reclosing operation becomes the minimum first is determined as ORCT. The significance of this method is that it uses the kinetic energy of each generator, which can be obtained easily. Consequently, if the kinetic energy is measured on real time, this method may be implemented for online application.

The total kinetic energy W_{total} can be calculated easily by knowing the rotor speed of each generator and is given by

$$W_{\text{total}} = \sum_{i=1}^{N} W_i \ (J) \tag{1}$$

where

$$W_i = \frac{1}{2} J_i \omega_{\text{mi}}^2 \ (J) \tag{2}$$

denotes kinetic energy in joule for a generator, i is the generator number, and N is the total number of generators. Again, in (2), J_i denotes moment of inertia in kg · m^2 and ω_{mi} rotor angular velocity in mechanical rad/s.

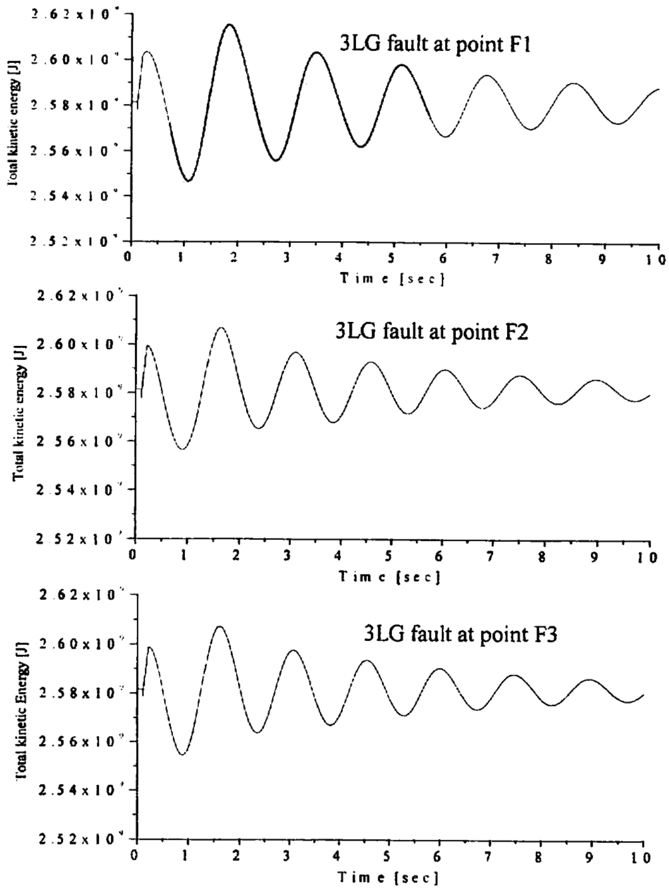

Fig. 4. Responses of total kinetic energy for nine-bus system.

Figs. 4 and 5 show the total kinetic energy responses without reclosing operation in case of balanced (3LG: three-phase-to-ground) fault at points F1, F2, and F3, as indicated in Figs. 1 and 2. The total kinetic energy responses for unbalanced (2LG: a-b phase double-line-to-ground, 2LS: a-b phase line-to-line, 1LG: a phase single-line-to-ground) faults are not shown here. Using the proposed optimal reclosing technique, the values of ORCT corresponding to different types of faults and fault points are calculated from the responses of the total kinetic energy responses of both systems and are shown in Table I.

IV. Design of Fuzzy Logic 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. The design of the proposed fuzzy logic controller (FLC) is described in the following.

A. Fuzzification

For the design of the FLC, speed deviation $\Delta\omega$ and $\dot{\text{TKED}}$ of the generators are selected as the inputs for the nine-bus system

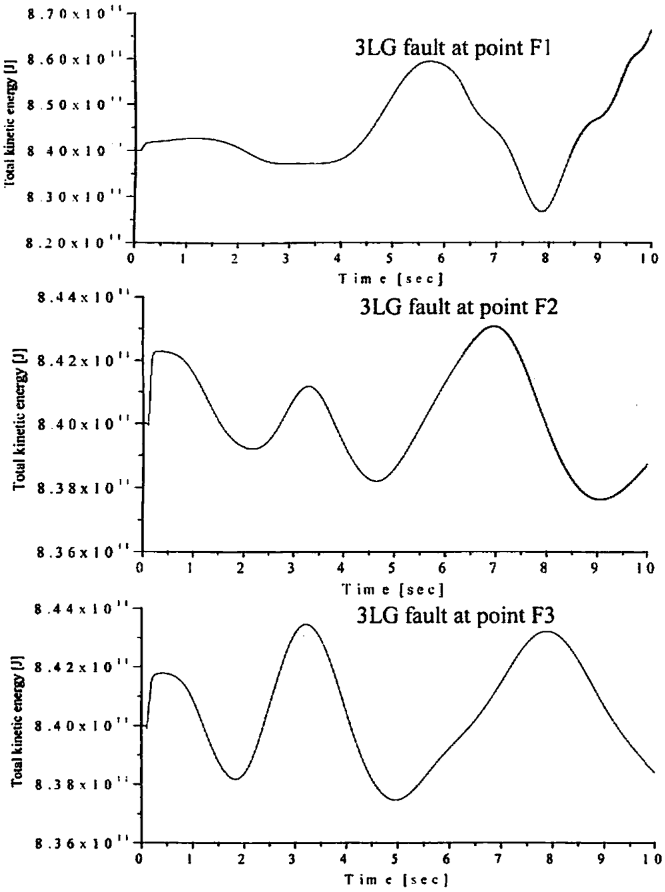

Fig. 5. Responses of total kinetic energy for ten-machine system.

TABLE I
VALUES OF ORCT

Fault type	Fault point	Nine-bus system	Ten-machine system
3LG	F1	1.080	2.91
	F2	0.902	2.15
	F3	0.887	1.82
2LG	F1	0.989	2.84
	F2	0.878	2.12
	F3	0.878	1.74
2LS	F1	0.978	3.04
	F2	0.869	2.08
	F3	0.868	1.72
1LG	F1	0.920	2.88
	F2	0.868	2.09
	F3	0.866	1.65

and ten-machine system, respectively. The reason for the selection of the $\dot{\text{TKED}}$ as the fuzzy controller input in the case of the ten-machine system is explained in [9] and [10]. The conductance value of BR, G_{SBR} $(0.0 \leq G_{SBR} \leq G_{TCSBR})$, is selected as the controller output for both systems. We have selected the triangular membership functions for $\Delta\omega$ and $\dot{\text{TKED}}$ as shown in Figs. 6 and 7, respectively. The linguistic variables NE, ZO, and PO used in both membership functions stand for negative, zero, and positive, respectively. It is important to note that the

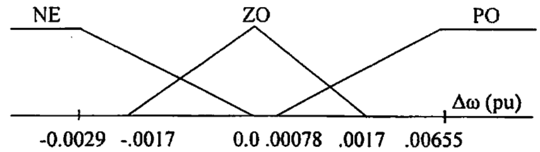

Fig. 6. Membership functions of $\Delta\omega$ for nine-bus system.

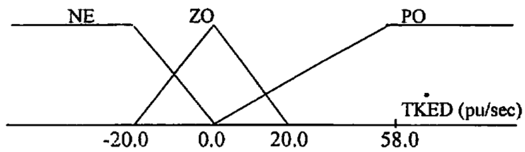

Fig. 7. Membership functions of $\dot{\text{TKED}}$ for ten-machine system.

TABLE II
FUZZY RULE TABLE FOR NINE-BUS SYSTEM

Δω [pu]	G_{SBR} [pu]	
	BR1	BR2
NE	0.0	0.0
ZO	0.0	0.0
PO	2.0	1.3

TABLE III
FUZZY RULE TABLE FOR TEN-MACHINE SYSTEM

$\dot{\text{TKED}}$ [pu/sec]	G_{SBR} [pu]				
	BR1	BR4	BR5	BR6	BR10
NE	0.0	0.0	0.0	0.0	0.0
ZO	0.0	0.0	0.0	0.0	0.0
PO	15.0	7.0	4.0	4.0	5.0

membership functions are determined by trial and error in order to obtain good system performance. The equation of the triangular membership function used to determine the grade of membership values is as follows [17]:

$$\mu_{\mathrm{Ai}}(x) = 1/b(b - 2|x - a|) \tag{3}$$

where $\mu_{\mathrm{Ai}}(x)$ is the value of grade of membership, "b" is the width, "a" is the coordinate of the point at which the grade of membership is 1, and "x" is the value of the input variable ($\Delta\omega$ or $\dot{\text{TKED}}$ for this paper).

B. Fuzzy Rule Base

The proposed fuzzy control strategy is very simple because it has only three control rules for each controller. The control rules are shown in Tables II and III in the case of the nine-bus system and ten-machine system, respectively, where the numerical values of G_{SBR} represent the output of the fuzzy controller. It is important to note that the control rules have been developed from the viewpoint of practical system operation and by trial and error.

C. Fuzzy Inference

For the inference mechanism of the proposed fuzzy logic controller, Mamdani's method [17] has been utilized. According to Mamdani, the degree of conformity *Wi* of each fuzzy rule is as follows:

$$Wi = \mu_{Ai}(x) \tag{4}$$

where $\mu_{Ai}(x)$ is the value of grade of membership, and i is the rule number.

D. Defuzzification

The center-of-area method is the most well-known and rather simple defuzzification method [17], which is implemented to determine the output crispy value (i.e., the conductance value of BR, G_{SBR}). This is given by the following expression:

$$G_{\text{SBR}} = \sum WiCi / \sum Wi \tag{5}$$

where *Ci* is the value of G_{SBR} in the fuzzy rule tables.

The firing control signal can be determined from the conductance value G_{SBR} and then sent to the thyristor switching unit to modify the real power absorbed by the braking resistor in the transient condition. The modeling of thyristor controlled system braking resistor (TCSBR) and method of calculating firing-angle from the output of the fuzzy controller are described in detail in [11].

V. Simulation Results and Discussion

The effectiveness of the proposed method is demonstrated through simulations by using Electro-Magnetic Transients Program (EMTP), a special transient simulation program that can predict variables of interest in electric power networks as functions of time, typically following some disturbances such as the switching of a circuit breaker or a fault [18]. Simulations have been carried out considering both balanced (3LG: three-phase-to-ground) and unbalanced (2LG: a-b phase double-line-to-ground, 2LS: a-b phase line-to-line, 1LG: a phase single-line-to-ground) faults at different points on the transmission lines of the power systems. Time step and simulation time have been chosen as 0.00005 and 10.0 s, respectively.

A. Effect of Coordination of Conventional Reclosing and Fuzzy Controlled Braking Resistor on Transient Stability

In the case of the nine-bus system, it is considered that the fault occurs at each point at 0.1 s, the circuit breakers on the faulted lines are opened at 0.2 s, and at 1.0 s, the circuit breakers are reclosed. It is also considered that the reclosing of circuit breakers is unsuccessful due to a permanent fault. Therefore, at 1.1 s, the circuit breakers are reopened. Again, in the case of the ten-machine system, the fault occurs at each point at 0.1 s, the circuit breakers on the faulted lines are opened at 0.17 s, at 1.003 s, the circuit breakers are reclosed, and at 1.073 s, the circuit breakers are reopened. In both systems, it is assumed that the circuit breaker clears the line when the current through it crosses the zero level.

TABLE IV
VALUES OF W_c WITH AND WITHOUT BR FOR NINE-BUS SYSTEM

Fault type	Fault point	With conventional reclosing and fuzzy controlled BR	With conventional reclosing but no BR
3LG	F1	2.06	2.78
	F2	1.97	2.71
	F3	1.66	2.59
2LG	F1	2.08	2.15
	F2	1.69	2.32
	F3	1.40	2.08
2LS	F1	1.78	1.84
	F2	1.51	1.80
	F3	1.38	1.73
1LG	F1	1.72	1.78
	F2	1.35	1.61
	F3	1.02	1.39

TABLE V
VALUES OF W_c WITH AND WITHOUT BR FOR TEN-MACHINE SYSTEM

Fault type	Fault point	With conventional reclosing and fuzzy controlled BR	With conventional reclosing but no BR
3LG	F1	33.13	94.50
	F2	20.52	33.78
	F3	20.84	43.58
2LG	F1	26.52	89.29
	F2	17.04	24.75
	F3	17.16	31.57
2LS	F1	25.05	85.67
	F2	14.96	17.53
	F3	14.19	24.74
1LG	F1	22.10	57.50
	F2	13.05	13.88
	F3	12.32	18.80

For the evaluation of transient stability, in this paper, we have used the stability index W_c [8]–[10], given by

$$W_c(\text{sec}) = \int_0^T \left| \frac{d}{dt} W_{\text{total}} \right| dt / \text{system base power} \tag{6}$$

where T is the simulation time selected to 10.0 s, and W_{total} is the total kinetic energy, which is already explained in Section III.

The lower the value of W_c, the better the system's performance. Tables IV and V show the values of W_c without BR as well as with BR in the case of 3LG, 2LG, 2LS, and 1LG faults at points F1, F2, and F3, as indicated in Figs. 1 and 2. The values of W_c with BR clearly show the effectiveness of the coordination of conventional auto-reclosing and fuzzy logic-controlled braking resistor in enhancing the transient stability for all types of faults at different points of both power system models during unsuccessful reclosing.

Fig. 8–11 show the load angle responses for 3LG fault and 1LG fault in the case of the nine-bus system and ten-machine system. The load angles for the generators in Figs. 10 and 11 are calculated with respect to the load angle of the swing generator G10 in the model system of Fig. 2. From the load angle

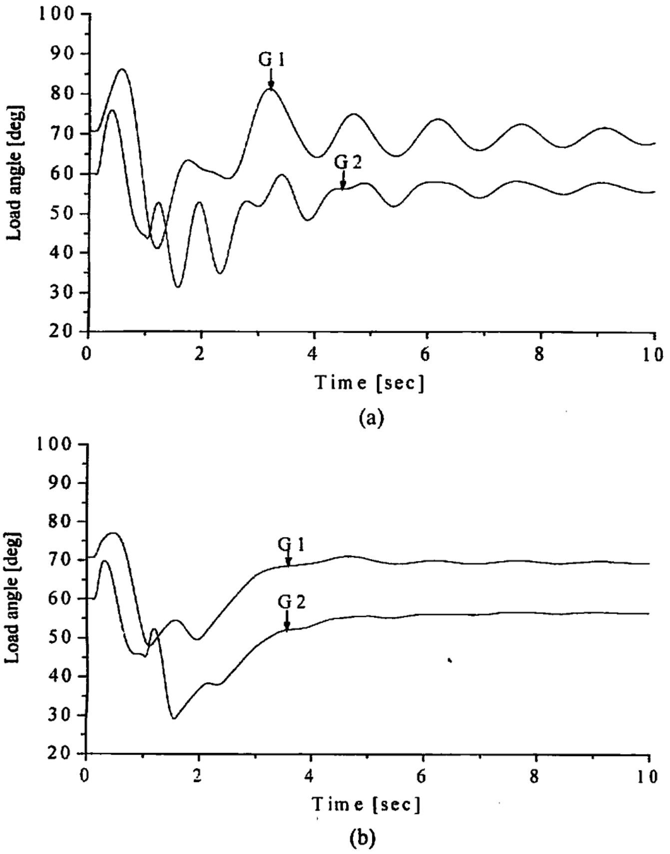

Fig. 8. Load angle responses for 3LG fault at point F2 in the case of the nine-bus system. (a) With conventional reclosing but no BR. (b) With conventional reclosing and fuzzy controlled BR.

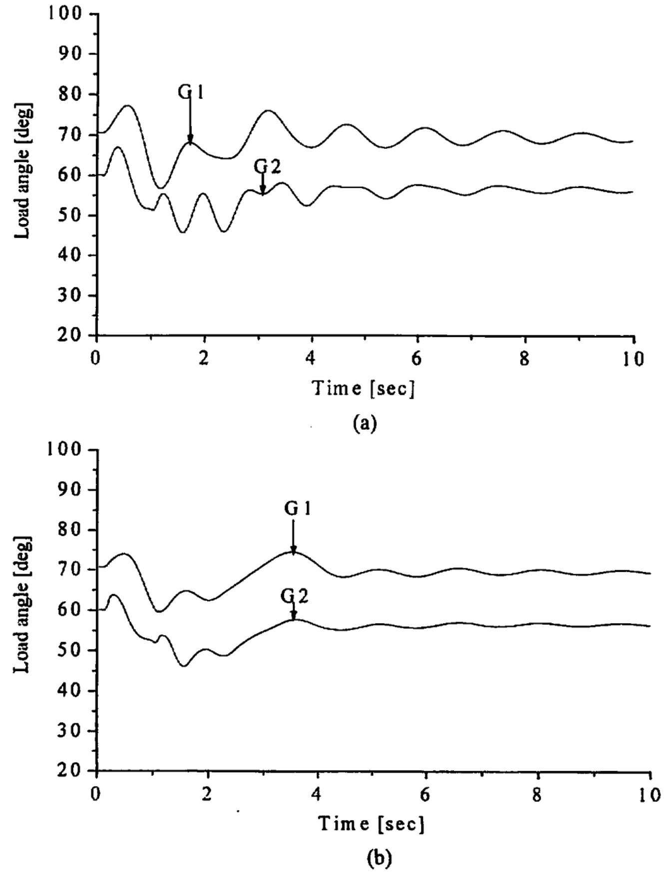

Fig. 9. Load angle responses for 1LG fault at point F2 in the case of the nine-bus system. (a) With conventional reclosing but no BR. (b) With conventional reclosing and fuzzy controlled BR.

responses of both systems, the effectiveness of the coordination of conventional reclosing and fuzzy logic-controlled braking resistor in enhancing the transient stability during unsuccessful reclosing is confirmed.

B. Effect of Coordination of Optimal Reclosing and Fuzzy Controlled Braking Resistor on Transient Stability

In this case also, it is considered that the reclosing of circuit breakers is unsuccessful due to a permanent fault. The optimal reclosing times corresponding to different types of faults and fault points in the case of the nine-bus system as well as the ten-machine system are shown in Table I. The reopening of circuit breakers is done after 0.1 and 0.07 s of the reclosing time in the case of the nine-bus system and ten-machine system, respectively. The fault occurring times and circuit breakers opening times are the same as those described in Section V-A. In both systems, it is assumed that the circuit breaker clears the line when the current through it crosses the zero level.

Tables VI and VII show the values of W_c without BR as well as with BR in the case of 3LG, 2LG, 2LS, and 1LG faults at points F1, F2, and F3, as indicated in Figs. 1 and 2. From the values of W_c with BR, the effectiveness of the coordination of optimal reclosing and fuzzy logic-controlled braking resistor in enhancing the transient stability for all types of faults at different points of both power system models during unsuccessful reclosing is confirmed. It is also noticeable that the transient stability performance as demonstrated in Tables VI and VII is better than what is demonstrated in Tables IV and V. This fact substantiates the excellence and effectiveness of the proposed coordinated operation of optimal reclosing and fuzzy logic-controlled braking resistor in improving the transient stability of multimachine power systems during unsuccessful reclosing of circuit breakers.

Figs. 12–15 show the load angle responses for 3LG fault and 1LG fault in the case of the nine-bus system and ten-machine system. From the load angle responses, the effectiveness of the coordination of optimal reclosing and fuzzy logic-controlled braking resistor in enhancing the transient stability during unsuccessful reclosing is confirmed. Moreover, the transient stability performance as demonstrated in Figs. 12–15 is better than what is demonstrated in Figs. 8–11. This fact also corroborates the effectiveness of the proposed coordinated operation of optimal reclosing and fuzzy logic-controlled braking resistor in improving the transient stability of multimachine power systems during unsuccessful reclosing of circuit breakers.

C. Consumed Energy of BR

Tables VIII and IX show the energy consumed by each BR in joules for 3LG fault at different points of the nine-bus system and ten-machine system, respectively, considering the coordination of optimal reclosing and fuzzy controlled BR. It is seen that the braking resistor BR1 of each system consumes the highest

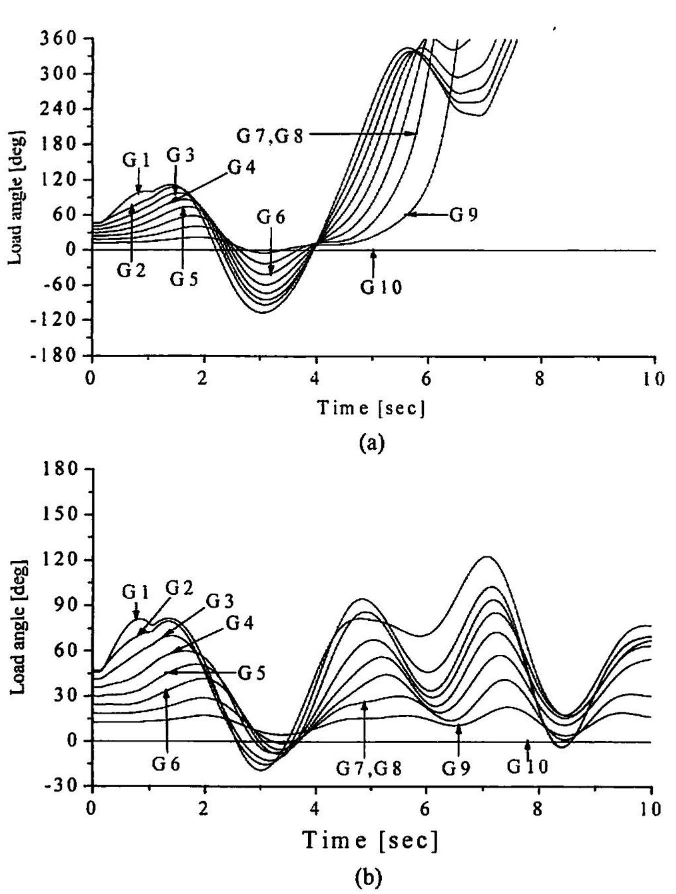

Fig. 10. Load angle responses for 3LG fault at point F1 in the case of the ten-machine system. (a) With conventional reclosing but no BR. (b) With conventional reclosing and fuzzy controlled BR.

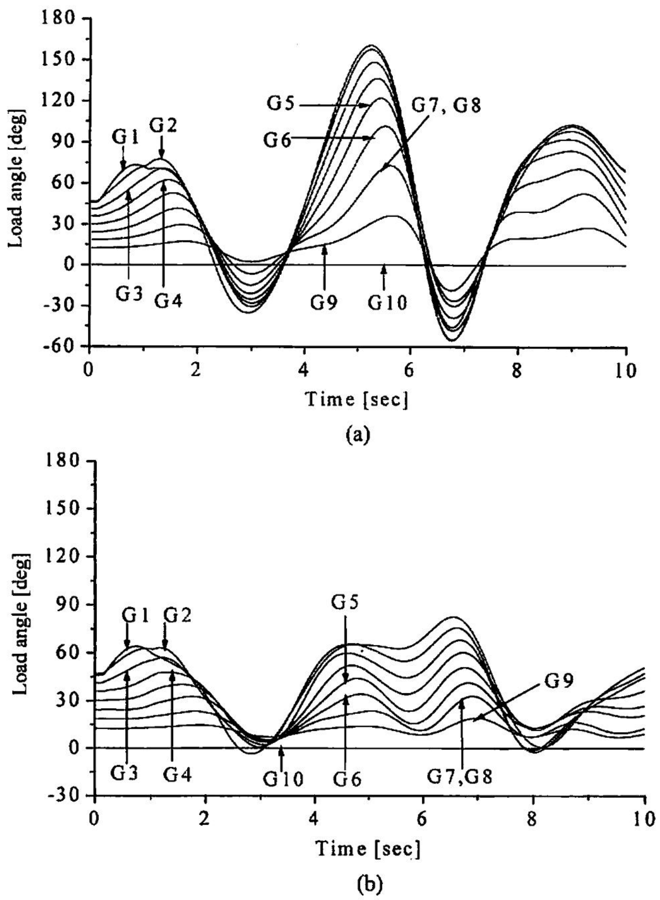

Fig. 11. Load angle responses for 1LG fault at point F1 in the case of the ten-machine system. (a) With conventional reclosing but no BR. (b) With conventional reclosing and fuzzy controlled BR.

energy for different fault points in each system. This means that the BR1 of each system contributes highly to the enhancement of the transient stability for different fault points in each system. In the case of the ten-machine system, the consumed energy by the braking resistors BR4, BR5, BR6, and BR10 is gradually in decreasing order for the fault at points F1 and F2. However, for the fault at point F3, the consumed energy by the braking resistors BR4, BR10, BR5, and BR6 is gradually in decreasing order. Thus, the braking resistors BR1, BR4, BR5, BR6, and BR10 for the ten-machine system, and the braking resistors BR1 as well as BR2 for the nine-bus system, contribute to the enhancement of the transient stability by consuming the excess energy caused by the severe disturbances at different points in the system models.

As a whole, from the point of view of the simulation results, two points are of paramount importance.

- The coordinated operation of optimal reclosing and fuzzy controlled braking resistor is able to stabilize the power systems well in case of unsuccessful reclosing of circuit breakers.
- The transient stability performance of the coordinated operation of optimal reclosing and fuzzy controlled braking resistor is better than that of the coordinated operation of conventional auto-reclosing and fuzzy controlled braking resistor.

TABLE VI
VALUES OF W_c WITH AND WITHOUT BR FOR NINE-BUS SYSTEM

Fault type	Fault point	With conventional reclosing and fuzzy controlled BR	With conventional reclosing but no BR
3LG	F1	2.01	2.45
	F2	1.38	1.89
	F3	1.36	1.52
2LG	F1	2.02	2.14
	F2	1.47	1.54
	F3	1.13	1.22
2LS	F1	1.68	1.79
	F2	1.18	1.22
	F3	1.07	1.12
1LG	F1	1.47	1.57
	F2	1.13	1.15
	F3	0.83	0.88

D. *Practicality of the Proposed Method*

For the practical implementation of our proposed method, i.e., an implementation in a real power system, online calculation of the total kinetic energy W_{total}, in order to determine the optimal reclosing time, and the time derivative of TKED, in order to determine the fuzzy controller input, is needed. This can be accomplished by global positioning system (GPS) [8],

TABLE VII
VALUES OF W_c WITH AND WITHOUT BR FOR TEN-MACHINE SYSTEM

Fault type	Fault point	With conventional reclosing and fuzzy controlled BR	With conventional reclosing but no BR
3LG	F1	27.79	73.19
	F2	18.33	25.60
	F3	15.91	28.89
2LG	F1	24.70	55.95
	F2	14.84	16.91
	F3	14.76	23.57
2LS	F1	24.76	36.27
	F2	12.27	13.08
	F3	13.54	17.34
1LG	F1	15.32	24.65
	F2	9.58	10.13
	F3	11.92	13.79

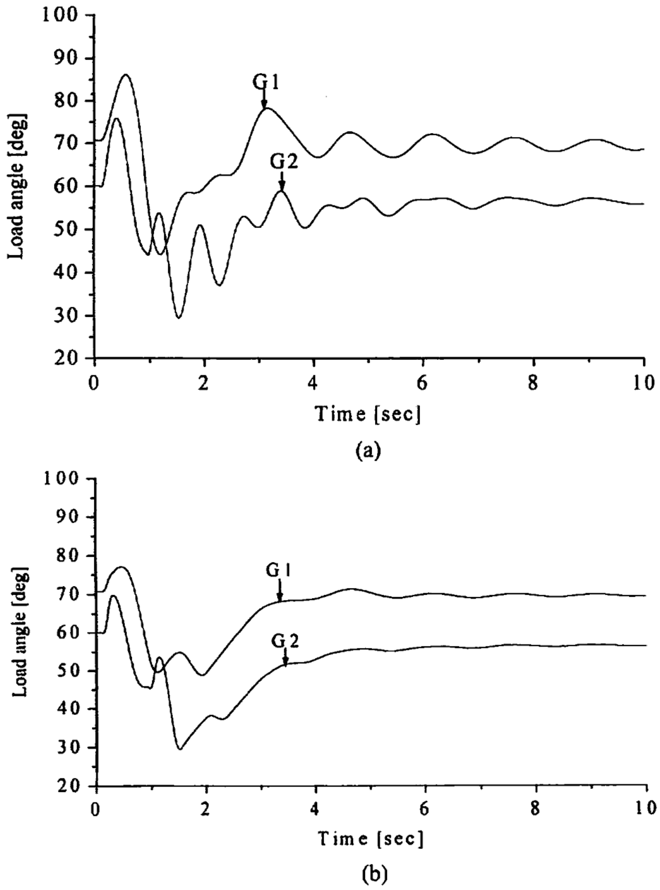

Fig. 12. Load angle responses for 3LG fault at point F2 in the case of the nine-bus system. (a) With conventional reclosing but no BR. (b) With conventional reclosing and fuzzy controlled BR.

[13], [19]–[24], which provides time synchronization of signals. GPS is a U.S. Department of Defense radio-navigation system consisting of 24 satellites placed into orbit and arrayed to provide at least four satellites visibility at all times. Each satellite transmits a navigation signal from which a receiver can decode time synchronized to Coordinated Universal Time (UTC), the world standard, with a 0.2 μs accuracy. The inherent availability, redundancy, reliability, and accuracy make it a system well suited for synchronized phasor measurement systems [19].

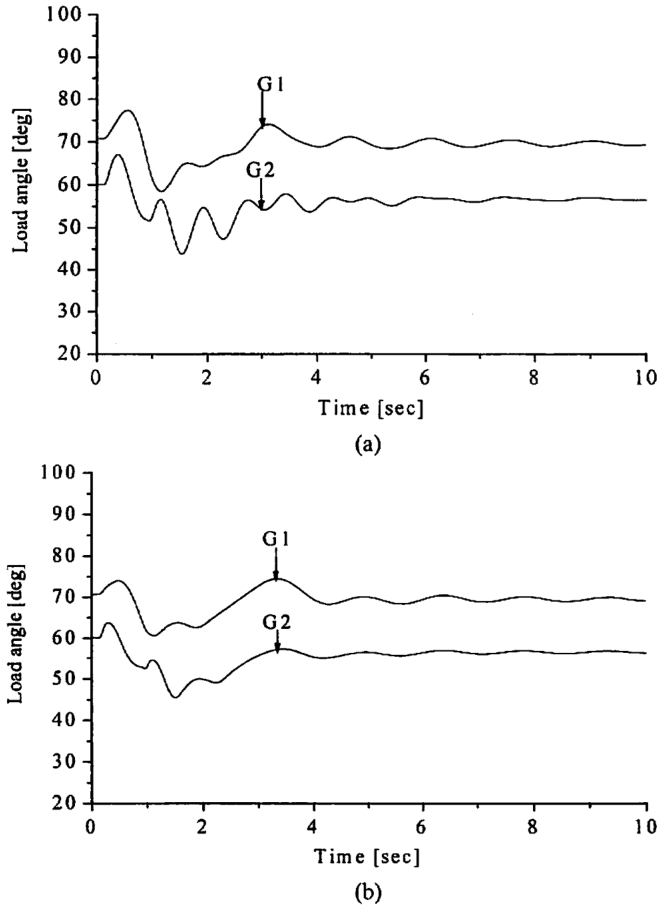

Fig. 13. Load angle responses for 1LG fault at point F2 in the case of the nine-bus system. (a) With conventional reclosing but no BR. (b) With conventional reclosing and fuzzy controlled BR.

It has recently been recognized that synchronized measurement of power system quantities is feasible using the GPS, since GPS can easily and precisely provide a time signal, with a 1 μs accuracy, at any location on the power network [20].

Fig. 16 shows a simplified functional block diagram where the GPS receiver collects the digitalized speed equivalent signals of the generators and synchronizes the signals in a common timing reference. The synchronized signals are then sent to a central control office where W_{total} as well as time derivative of TKED is calculated. Data output, i.e., the signal of time derivative of TKED is then sent to each fuzzy controller input. Again, another data output, i.e., the signal of $W_{\rm total}$ will be used to determine ORCT, and then the reclosing command is generated from ORCT. In this case, signals may be transmitted and received through microwave or optical fiber.

However, to implement this approach, there is a foreseen obstacle that during online calculation of the $W_{\rm total}$ and the time derivative of TKED, time delays will be introduced mainly due to signal transmission through optical fiber or microwave, A/D conversion, time synchronization of signals by GPS, calculation of the $W_{\rm total}$ as well as the time derivative of TKED, reclosing command generation, and reclosing action implementation. The communication delays may affect the control logic, and consequently, the transient stability of the system may be affected. So,

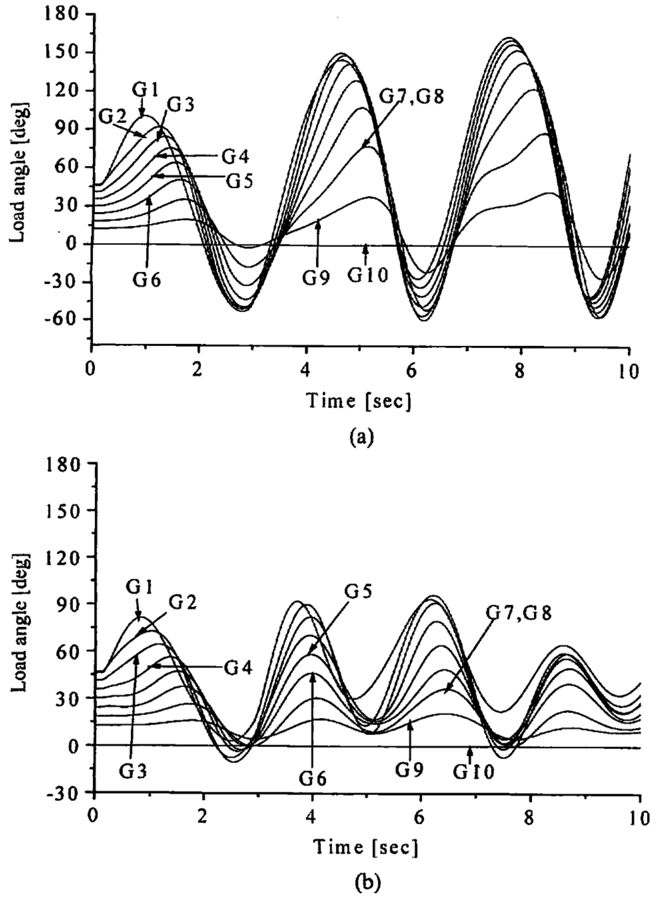

Fig. 14. Load angle responses for 3LG fault at point F1 in the case of the ten-machine system. (a) With conventional reclosing but no BR. (b) With conventional reclosing and fuzzy controlled BR.

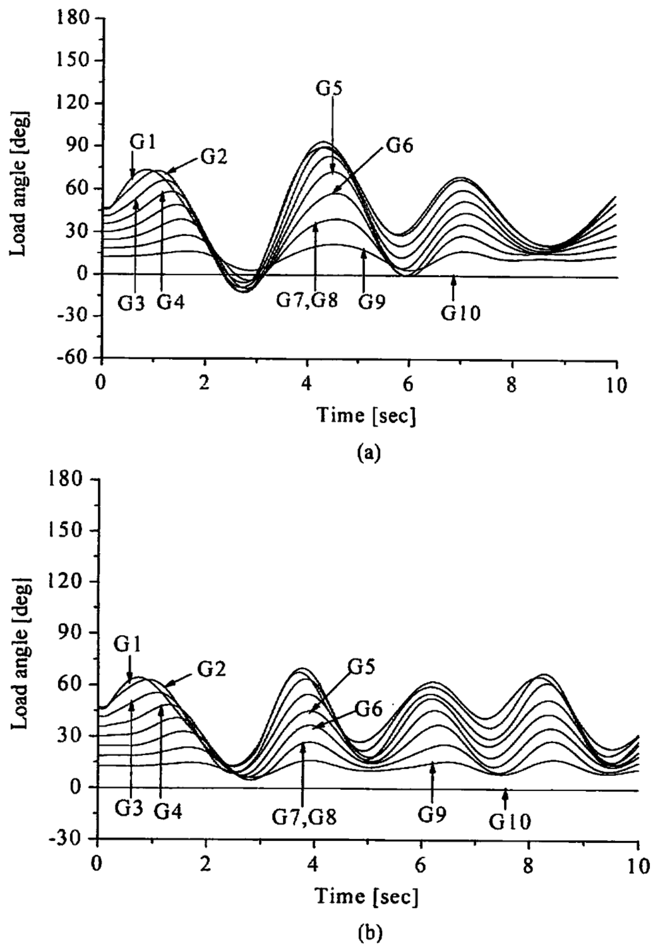

Fig. 15. Load angle responses for 1LG fault at point F1 in the case of the ten-machine system. (a) With conventional reclosing but no BR. (b) With conventional reclosing and fuzzy controlled BR.

such communication delays should be considered for the actual analysis of transient stability. Further research work is needed in order to investigate the amount of total communication delays and their effects on the transient stability.

VI. Conclusion

This paper analyzes the effect of the coordination of optimal reclosing and fuzzy logic-controlled braking resistor on the transient stability of a multimachine power system in case of an unsuccessful reclosing of circuit breakers. The transient stability performance of the coordinated operation of optimal reclosing and fuzzy controlled braking resistor is compared to that of the coordinated operation of conventional auto-reclosing and fuzzy controlled braking resistor. From the simulation results of both balanced and unbalanced faults at different points in the power systems, the following conclusions can be drawn.

- The coordinated operation of optimal reclosing and fuzzy controlled braking resistor is able to stabilize the power systems well in case of unsuccessful reclosing of circuit breakers.
- The transient stability performance of the coordinated operation of optimal reclosing and fuzzy controlled braking resistor is better than that of the coordinated operation of conventional auto-reclosing and fuzzy controlled braking resistor.

TABLE VIII
Consumed Energy of BR for Nine-Bus System

Fault point	Consumed energy (Joule)	
	BR1	BR2
F1	3648.6	1066.9
F2	4292.3	3271.8
F3	2938.5	919.3

TABLE IX
Consumed Energy of BR for Ten-Machine System

Fault point	Consumed energy (Joule)				
	BR1	BR4	BR5	BR6	BR10
F1	308970.5	133185.3	82832.1	63046.5	32345.2
F2	155898.8	70741.2	45082.0	27531.9	11633.5
F3	107236.1	35905.3	18303.3	10758.7	20961.8

As a whole, the proposed strategy provides a simple and very effective means of transient stability enhancement of multimachine power systems during unsuccessful reclosing of circuit breakers.

In our future study, we would like to investigate the amount of total communication delays introduced in online calculation of

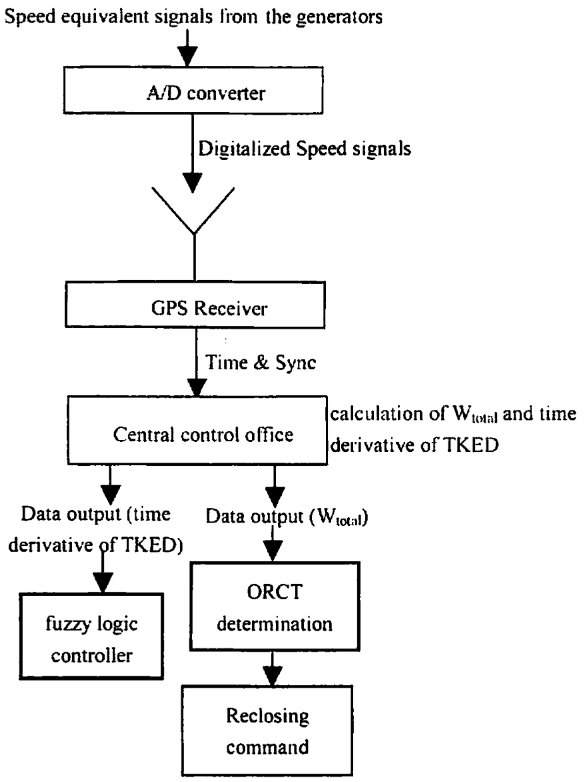

Fig. 16. GPS functional block diagram.

the total kinetic energy as well as the time derivative of total kinetic energy deviation and their effects on the transient stability.

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