Paper

Determination of Reduced Number and Suitable Locations of Fuzzy Logic Controlled Braking Resistors for Transient Stability Enhancement

Mohd. Hasan Ali* Member
Toshiaki Murata** Member
Junji Tamura** Member

Braking resistor is known to be a very powerful tool for transient stability improvement in electric power systems. Usually, in a large power system braking resistors are placed at each generator terminal bus which requires a high installation as well as operation cost. Also, heavy computation is required for the controllers used for the switching of the resistors. From these viewpoints, this paper directs to the study of installation of reduced number of fuzzy logic controlled braking resistors at suitable locations for transient stability enhancement. Groups of coherent generators in the power system are determined. Then one braking resistor is installed in each of the coherent group and at each of the remaining generator terminal bus. Thus, the number of braking resistors is reduced and hence the installation and operation cost as well as computational burden for the controllers are minimized. The suitable location for the braking resistor in each coherent group of generators is determined according to the values of the transient stability index as calculated for a 3LG (Three-phase-to-ground) fault at the points near the generators of the coherent group without considering the braking resistors in the system. The effectiveness of the proposed method is demonstrated through EMTP simulations for the IEEJ West-10 machine model system.

Keywords: braking resistor, coherent groups of generators, EMTP, fuzzy logic controller, transient stability

1. Introduction

Switching control of a braking resistor (BR) is one of the effective methods to absorb the excess transient energy caused by severe system disturbances and provides stability enhancement of electric power systems. Again, recently fuzzy logic is getting increasing emphasis in control applications. Exploiting the concept of fuzzy logic, we proposed the works [1][2] for the switching of the thyristor controlled braking resistor to improve the transient stability of a single machine connected to an infinite bus system [2] and a large multi-machine (IEEJ West-10 machine) power system [1]. In Ref. (1), braking resistors were installed at each generator terminal bus. Therefore, although the system stability margin was significantly increased because of the use of the braking resistor at each generator terminal bus, it required a high installation and operation cost. Also, heavy computation was required for the controllers used for the switching of the braking resistors.

Therefore, with a view to minimizing high installation and operation cost as well as computational burden for the controllers, this paper directs to the study of installation of reduced number of fuzzy logic controlled braking resistors at suitable locations for transient stability enhancement in a large multi-machine power system and this is the novel feature of this work.

* Dept. of EEE, Rajshahi University of Engineering and Technology (RUET)
Rajshahi-6204, Bangladesh
** Dept. of EEE, Kitami Institute of Technology
165, Koen-cho, Kitami 090-8507

Groups of coherent generators in the power system are determined. Usually, in a large interconnected power system coherent groups of generators are determined in order to reduce the overall order of the system model by dynamic equivalent construction [3]–[5]. However, in this work, the concept of coherency is exploited for the purpose of determining reduced number of braking resistors instead of reducing the overall order of the system model. Thus one braking resistor is installed in each of the coherent group and at each of the remaining generator terminal bus. Consequently, the number of braking resistors is reduced and hence the installation and operation cost as well as computational burden for the controllers are minimized. The suitable location for the braking resistor in each coherent group of generators is determined according to the values of the transient stability index as calculated for a 3LG (Three-phase-to-ground) fault at the points near the generators of the coherent group without considering the braking resistors in the system.

The effectiveness of the proposed method is demonstrated through EMTP simulations for the IEEJ West-10 machine model system [6]. Simulation results of both balanced and unbalanced faults at different points in the power system clearly indicate the effectiveness and validity of the proposed method in improving the transient stability with reduced number of fuzzy logic controlled braking resistors at suitable locations.

The organization of this paper is as follows: Section 2 describes the model system for the proposed study. Section 3 explains the procedure for the determination of reduced number of braking resistors at suitable locations. In section 4, design of the fuzzy logic controller is explained. Section 5 describes simulation results. Finally, section 6 provides some conclusions regarding the proposed method.

2. Model System

For the simulation of transient stability, in this work the IEEJ West 10-machine model system [6] as shown in Fig. 1 has been used. The model system has 10 generators, G1 to G10, as shown in Fig. 1. Generator G10 is considered as the swing generator in the system. The braking resistor BR with a conductance value of G_{TCSBR} is connected to the high tension side of the step up transformer through the thyristor switching circuit, as shown in Fig. 2. In this work, the difference between the total kinetic energy (W_{total}) of the generators at transient state and that at steady state is defined as deviation of total kinetic energy, ΔTKE, i.e., ΔTKE = (W_{total} at transient state) − (W_{total} at steady state). The BR will be switched in following a fault clearing and the switching condition of BR is such that when deviation of total kinetic energy, ΔTKE, of the generators is positive, BR is switched on the generator terminal bus. On the other hand, when ΔTKE is negative and also in the steady state, BR is removed from the generator terminal bus by the thyristor switching circuit. The AVR (Automatic Voltage Regulator) and GOV (Governor) control system models for the IEEJ West 10-machine model system [6] have been included in the present simulation and are shown in Figs. 3 and 4 respectively. Table 1 shows the various parameters of the generators [6] used for the simulation. The generator parameters in Table 1 are based on the machine ratings.

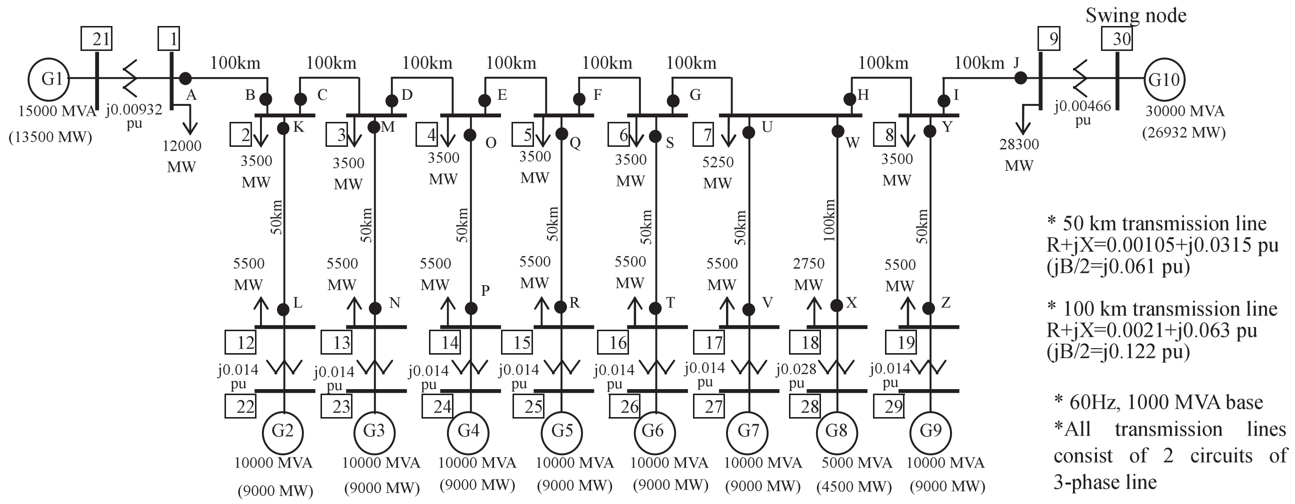


Fig. 1. IEEJ WEST 10-machine model system

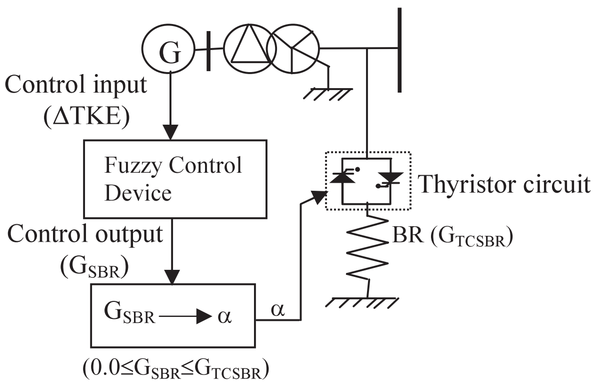


Fig. 2. BR with thyristor switching circuit

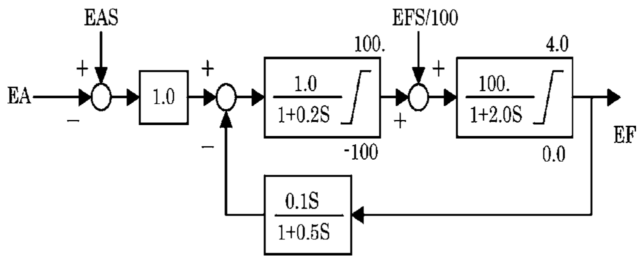


Fig. 3. IEEJ AVR model (LAT=1)

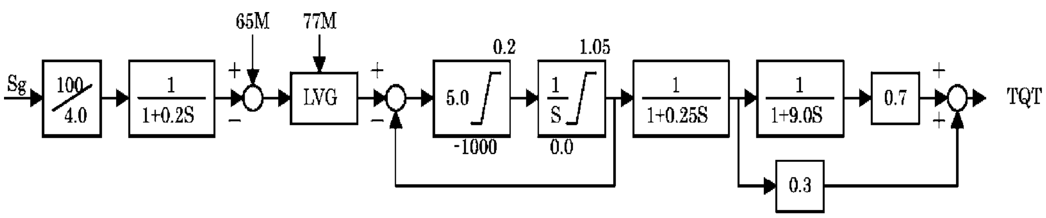


Fig. 4. IEEJ GOV model (LPT=1)

Table 1. Generator parameters

X_d [pu]	1.70	T_d'' [sec]	0.03
X_q [pu]	1.70	T_q'' [sec]	0.03
X_d' [pu]	0.35	T_a [sec]	0.40
X_d'' [pu]	0.25	X_l [pu]	0.225
X_q'' [pu]	0.25	H [sec]	7.00
T_d' [sec]	1.00		

3. Determination of Reduced Number of Braking Resistors at Suitable Locations

In the analysis of a large interconnected power system, the growth in size and complexity of the system presents a number of difficulties in required computation time and required computer memory. This has led to the analysis of such large scale systems by dynamic equivalent (reduced dimensional) representation for certain parts of the power system [(3)]. In this approach, the total system is normally decomposed into a study area and one or more external areas. The external area is assumed to be located physically far away from the study area. It is further assumed that during the occurrence of any disturbance in the study area the effect of the disturbance on the external area is quite small [(3)]. A method of replacing a number of generators in the external system with one or more equivalents is based on coherency [(4)].

A number of methods for the identification of coherent generators have been proposed in the literature. The objective of these methods is to reduce the overall order of the system model by dynamic equivalent construction. However, in this work, groups of coherent generators are determined not to reduce the overall order of the system model, but to determine reduced number of braking resistors.

3.1 Determination of Coherent Groups of Generators

In general, coherency is determined for a particular fault location in the power system [(4)]. But it is important to note here that coherent groups of generators in a power system will be different depending on different fault locations. In this work, 26 fault points from A–Z as shown in Fig. 1 are considered. Therefore, coherent groups of generators are determined 26 times corresponding to 26 fault points. Consequently, different groups of coherent generators were obtained. Accordingly, different sets of braking resistors were determined for the installation in the system. Simulations were carried out using different sets of the braking resistors. But the system was not found to be stable well for all sets of braking resistors. Finally, the set of the braking resistors determined from the coherent groups of generators for a 3LG fault at point R near the generator G5 in the system model was found to improve the transient stability of the overall system well. Therefore, coherency determination procedure for a 3LG fault at point R near the generator G5 is explained below.

For a fault at point R near the generator G5, generators G4, G5 and G6 of the present system model are considered in the study area, while generators G1–G3 and G7–G9 are considered in the external area. Generator G10 is not considered in the external area, because G10 is the swing generator in the system model. Therefore, one braking resistor is installed at the terminal bus of this generator without considering the concept of coherency.

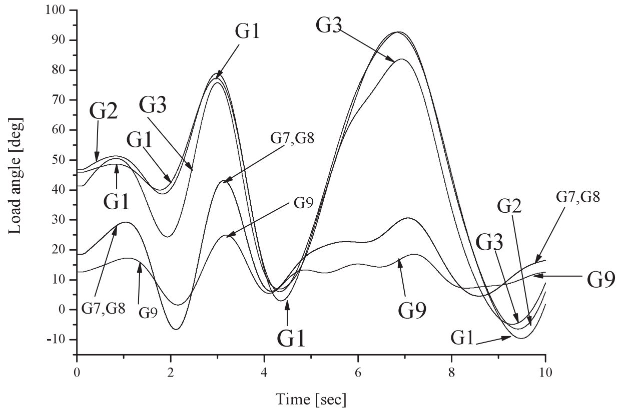


Fig. 5. Load angle responses for 3LG fault at point R (without BR)

Table 2. Coherent groups of generators

Coherent group	Generators
I	G1, G2 and G3
II	G7, G8 and G9

An ideal method for determining coherency is to check the relative rotor angles of the generators. A generator pair (i, j) in the external system is said to be coherent if there exists a constant a_{ij} such that

$$\delta_i(t) - \delta_j(t) = a_{ij} \pm \varepsilon \text{ for all t} \quad \cdots\cdots (1)$$

Where $\delta_i(t)$ and $\delta_j(t)$ are the rotor angles of the ith and jth generators, respectively and ε is a small positive number. A group of generators is said to be coherent if each pair of generators in the group is coherent. Each generator pair (i,j) is said to be perfectly coherent if $\varepsilon = 0$ [(4)]. In this work, coherency is determined from the load angle responses of the generators in the external area i.e. generators G1–G3 and generators G7–G9 as shown in Fig. 5. The load angles are calculated with respect to the load angle of the swing generator G10 in the system. In this case, the condition of simulation is that a 3LG fault occurs at 0.1 sec at point R, the circuit breakers on the faulted lines are opened at 0.17 sec and at 1.003 sec the circuit breakers are closed.

In the literature, coherent groups of generators have been classified as 'weakly coherent' and 'strongly coherent' [(3)]. The weakly coherent group is a set of machines whose coupling is weakest with the rest of the system. The strongly coherent group is a subset of the weakly coherent group. The machines of a strongly coherent group exhibit coherency more closely than the machines of a weakly coherent group.

From Fig. 5 it is seen that generators G1 and G2 are strongly coherent. But generator G3 can also be considered in this coherent group by the weak coupling. Thus, generators G1, G2 and G3 form one coherent group. Again, generators G7 and G8 are strongly coherent. But Generator G9 can also be considered in this coherent group by the weak coupling. Thus, generators G7, G8 and G9 form another coherent group. Coherent groups of generators are shown in Table 2. Now the proposed strategy is that one braking resistor is installed in each of the coherent group and at each of the remaining generator terminal bus. Thus, the number of braking resistors is reduced and hence the installation and operation cost as well as computational burden for the controllers are minimized. It is seen from Table 2 that in each coherent group there are three generators. So, the question arises about the selection of a suitable terminal bus from among three terminal busses of three generators for the installation of only one braking resistor. This problem is addressed in the next section.

3.2 Determination of Suitable Locations for Braking Resistors In this work, the suitable location for the braking resistor in each coherent group of generators is selected according to the values of the transient stability index, W_c as calculated for a 3LG fault at the points near the generators of the coherent groups without considering the braking resistor. Thus, a braking resistor is installed at a generator close to a fault point giving the maximum W_c without the braking resistor. The transient stability index, W_c [(1)], is given by

$$W_c(\text{sec}) = \int_0^T \left| \frac{d}{dt} W_{total} \right| dt / system\ base\ power \quad \cdots\cdots\cdots (2)$$

Where T is the simulation time selected to 20.0 sec, W_{total} is the total kinetic energy which can be calculated easily by knowing the rotor speed of each generator and is given by:

$$W_{total} = \sum_{i=1}^{N} W_i(J) \quad \cdots\cdots\cdots (3)$$

Where

$$W_i = \frac{1}{2} J_i \omega_{mi}{}^2(J) \quad \cdots\cdots\cdots (4)$$

denotes kinetic energy in joule for a generator, i is generator number and N total number of generators. Again, in equation (4) J_i denotes moment of inertia in kg.m^2 and ω_{mi} rotor angular velocity in mechanical rad/sec.

In Ref. (1), the values of the transient stability index, W_c were calculated for a simulation time of 20 sec in case of a 3LG fault at all points from A–Z as shown in Fig. 1 without considering the braking resistor. Thus, the values of W_c for a 3LG fault at points A, L and N near generators G1, G2 and G3 (coherent group I) were 238.917 sec, 224.191 sec and 86.536 sec respectively. It is seen that the value of W_c is the highest for the fault at point A which is near the generator G1. Thus one braking resistor needs to be installed at the terminal bus of the generator G1. Similarly, the values of W_c for a 3LG fault at points V, X and Z near generators G7, G8 and G9 (coherent group II) were 76.31 sec, 55.276 sec and 70.135 sec respectively. It is seen that the value of W_c is the highest for the fault at point V which is near the generator G7. Thus, another braking resistor needs to be installed at the terminal bus of the generator G7.

Therefore, according to our proposed strategy, total 6 braking resistors need to be installed at the terminal busses of the generators G1, G7, G4, G5, G6 and G10 in the present system model. Simulations were carried out using these 6 braking resistors and the system was found to be transiently stable. But it is our objective in this work to reduce the number of braking resistors. Therefore, we were interested to observe the result by using 5 braking resistors instead of 6. In this case the question arises which one among 6 braking resistors should be cut to make the number of the braking resistor 5. In Section 3.1 it is explained that generators G4, G5 and G6 of the present system model are considered in the study area. So, according to our proposed strategy, 3 braking resistors must be installed at the terminal busses of the generators G4, G5 and G6. Again, in this work, since it is considered that G10 is the swing generator in the system model, one braking resistor is installed at the terminal bus of this generator without considering the concept of coherency. So, we must install 4 braking resistors at the terminal busses of the generators G4, G5, G6 and G10. Now 2 generators i.e. G1 and G7 selected from 2 coherent groups are remaining from which one can be cut to make the number of the braking resistors 5. In this case, the transient stability index, W_c without considering the braking resistors in case of a 3LG (Three-phase-to-ground) fault at points A and V near generators G1 and G7 respectively are compared. It is found that W_c for the fault at point A near generator G1 is higher than that for the fault at point V near generator G7. Thus, the braking resistor at the terminal bus of the generator G7 was cut. Therefore, finally, 5 braking resistors (BR1, BR4, BR5, BR6 and BR10) were selected for the installation. The system was found to be stable well with these 5 braking resistors. It was found that any attempt to reduce further the number of the braking resistors, the system was not stable well.

It is noteworthy that the use of these 5 braking resistors (BR1, BR4, BR5, BR6 and BR10) at the terminal busses of the generators G1, G4, G5, G6 and G10 saves about 50% of the total installation and operation cost as well as computational burden required for the 10 braking resistors as used in Ref. (1).

In this work, the conductance values of 5 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. The system base is 1000 MVA. Therefore, the conductance values of the braking resistors BR1, BR4–BR6 and BR10 are considered 15.0 pu, 10.0 pu and 30.0 pu respectively.

4. Design of Fuzzy Logic Controller

For the design of the proposed Fuzzy Logic Controller (FLC), deviation of total kinetic energy, ΔTKE, of the generators and conductance value of BR, G_{SBR} ($0.0 \leq G_{SBR} \leq G_{TCSBR}$), are selected as the input and output respectively. The theoretical background of using the total kinetic energy deviation as the input to the fuzzy controller as well as the procedure for the on-line calculation of the total kinetic energy using the speed signal of each generator and then again using the total kinetic energy signal as the input to each fuzzy controller is described in Ref. (1). We have selected the triangular membership functions for ΔTKE as

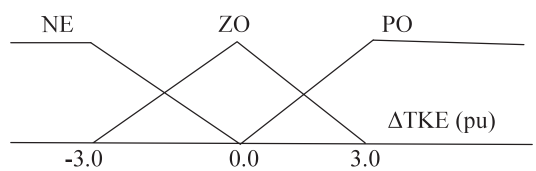


Fig. 6. Membership function of ΔTKE

Table 3. Fuzzy rule table

ΔTKE [pu]	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	10.0	10.0	8.0	30.0

shown in Fig. 6 in which the linguistic variables NE, ZO and PO stand for Negative, Zero and Positive respectively.

The proposed control strategy is very simple because it has only 3 control rules for each controller. The control rules have been developed from the viewpoint of practical system operation and by trial and error and are shown in Table 3 where the numerical values of G_{SBR} represent the output of the fuzzy controller. It is important to note here that the pu values of G_{SBR} in Table 3 are given with respect to the system base power.

For the inference mechanism of the proposed fuzzy logic controller, Mamdani's method has been utilized [(1)(2)]. Also, 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, G_{SBR}) [(1)(2)].

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 TCSBR (Thyristor Controlled System Braking Resistor) and method of calculating firing-angle from the output of the fuzzy controller are described in detail in Ref. (2).

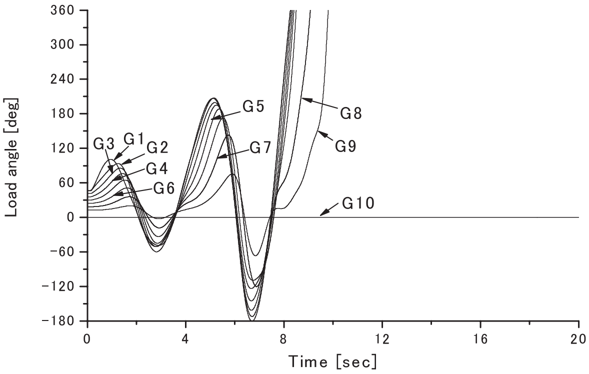
5. Simulation Results And Discussion

In order to show the effectiveness and validity of the proposed method, simulations have been carried out considering both balanced (3LG: three-phase-to-ground) and unbalanced (1LG: single-line-to-ground a-phase) faults at different points on the transmission lines. In the simulation study, 26 fault points from A–Z as shown in the model system of Fig. 1 have been considered. In all of the cases the fault occurs at 0.1 sec, the circuit breakers on the faulted lines are opened at 0.17 sec and at 1.003 sec the circuit breakers are closed. Time step and simulation time have been chosen as 0.00005 sec and 20.0 sec respectively.

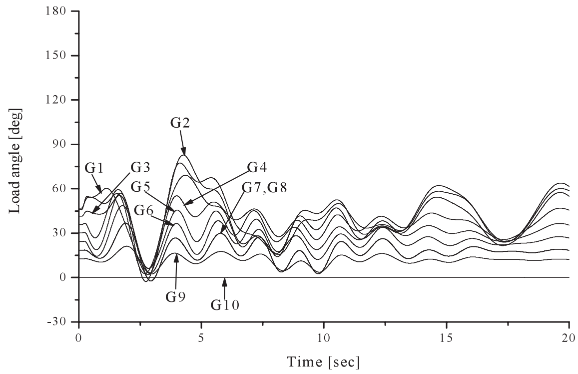
Figs. 7–12 show the load angle responses for both 3LG and 1LG faults at points A, S and Z. It is clearly seen that the system is transiently stable for both balanced and unbalanced faults at all points because of the use of the braking resistor. Therefore, the proposed fuzzy logic strategy can effectively enhance the transient stability by controlling reduced number of braking resistors.

The effectiveness of the proposed method in improving the transient stability can be further seen from the values of W_c as shown in Table 4. The lower the value of Wc, the better the system's performance. From Table 4 it is clearly seen that the transient stability is enhanced considerably for both balanced and unbalanced faults at different points when only 5 braking resistors are used in the system.

Table 5 shows the responses of BR i.e. energy consumed

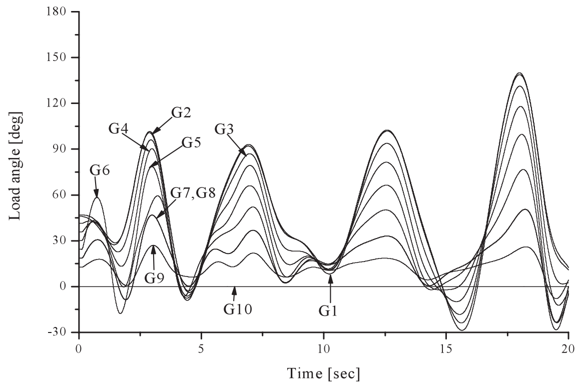


(a) Without BR

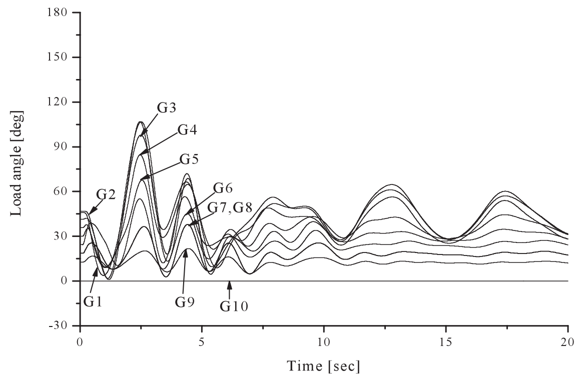


(b) With BR

Fig. 7. Load angle responses for 3LG fault at point A

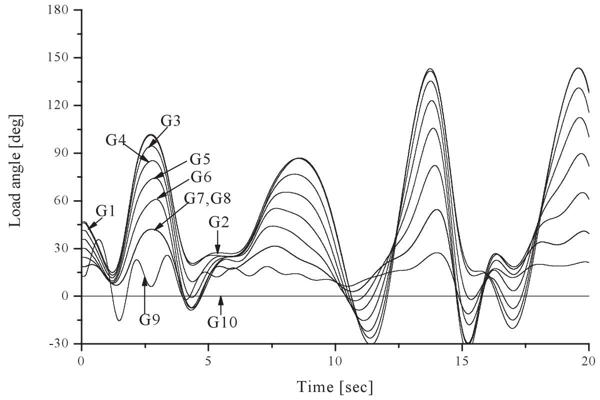


(a) Without BR

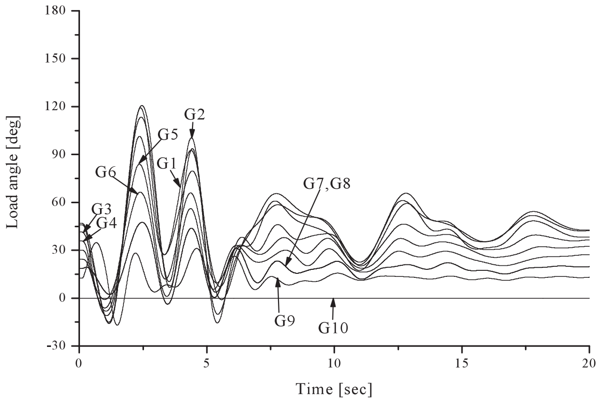


(b) With BR

Fig. 8. Load angle responses for 3LG fault at point S

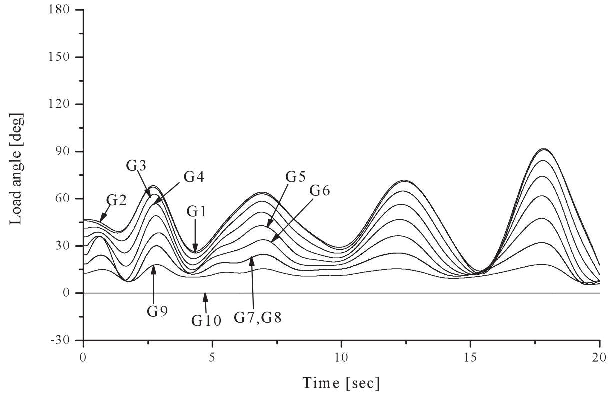


(a) Without BR

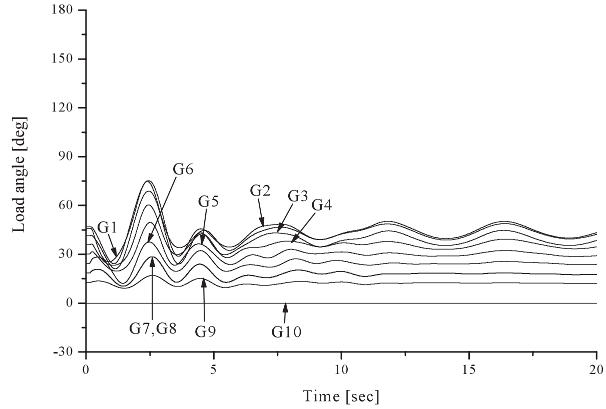


(b) With BR

Fig. 9. Load angle responses for 3LG fault at point Z

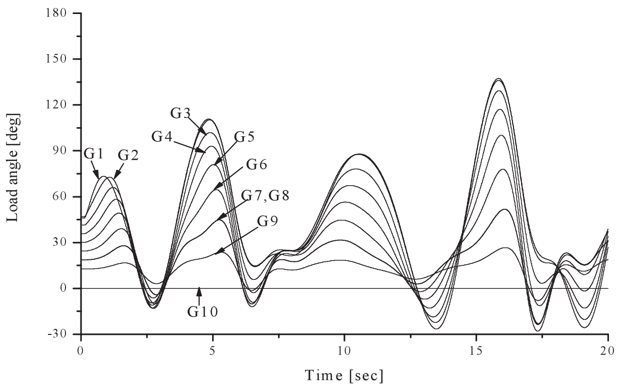


(a) Without BR

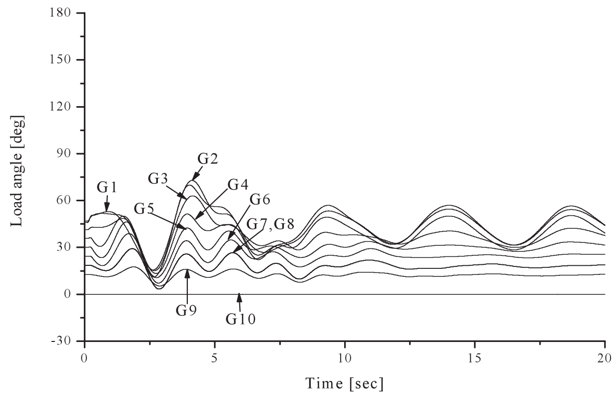


(b) With BR

Fig. 11. Load angle responses for 1LG fault at point S

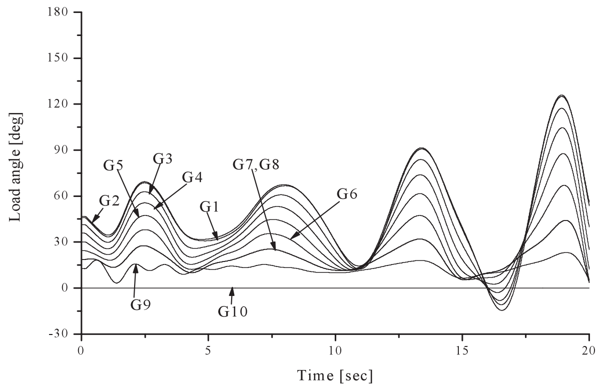


(a) Without BR

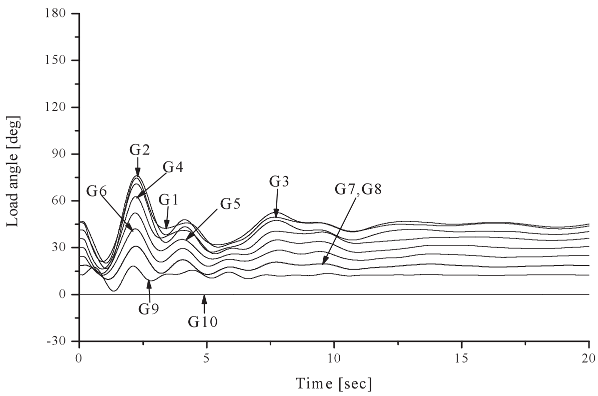


(b) With BR

Fig. 10. Load angle responses for 1LG fault at point A



(a) Without BR



(b) With BR

Fig. 12. Load angle responses for 1LG fault at point Z

Table 4. Values of W_c with and without BR

Fault point	Values of Wc for 3LG fault		Values of Wc for 1LG fault	
	With BR	Without BR	With BR	Without BR
A	42.013	238.917	33.702	68.953
S	37.914	73.513	28.754	31.941
Z	28.615	70.135	25.884	40.931

Table 5. Consumed energy of BR

Fault point	Consumed energy (Joule)				
	BR1	BR4	BR5	BR6	BR10
A	369997.8	202779.9	160818.9	108218.3	60977.1
S	295565.5	154176.1	117395.9	78611.6	85144.5
Z	260445.2	117803.8	78093.9	44482.5	116963.6

Table 6. Values of W_c for different combinations of BR

Case no.	Combinations of BR						Wc
1	BR1	BR2	BR4	BR5	BR6	BR10	40.833
2	BR1	BR4	BR5	BR6	BR7		60.120
3	BR1	BR4	BR5	BR6	BR8		63.140
4	BR1	BR4	BR5	BR6	BR9		64.905
5	BR1	BR4	BR5	BR6	BR10		42.013
6	BR2	BR4	BR5	BR6	BR10		46.139
7	BR3	BR4	BR5	BR6	BR10		54.236
8	BR1	BR4	BR5	BR6			87.408

by each BR in joule for a 3LG fault at different points. It is seen that for a fault at point A, the energy consumed by the braking resistor BR1 is the highest. This is natural because fault occurs at point A which is close to the generator G1. The consumed energy by the braking resistors BR4, BR5, BR6 and BR10 are gradually in decreasing order, because BR4, BR5, BR6 and BR10 are gradually far away from the fault point A. Again, for a fault at points S and Z, it is seen that the braking resistors BR1 and BR6 consume the highest and the lowest energy respectively. Thus the braking resistors BR1, BR4, BR5, BR6 and BR10 contribute to the enhancement of transient stability by consuming the excess energy caused by the severe disturbance at different points in the system model.

It is already shown that 5 BRs (BR1, BR4, BR5, BR6 and BR10) are suitable for transient stability enhancement in the present system model. In order to evaluate this fact in more detail, the performance of these 5 BRs have been compared with other cases in which different combinations of BRs are installed at generator terminals. Table 6 shows the values of W_c for different combinations of BR in case of a 3LG fault at point A. From Table 6 it is seen that the value of W_c is the lowest for the simulation case 1 i.e. when 6 BRs (BR1, BR2, BR4, BR5, BR6 and BR10) are installed. Again, the value of W_c is the highest for the simulation case 8 i.e. when 4 BRs (BR1, BR4, BR5 and BR6) are installed. But for the simulation cases 2 to 7 in which 5 BRs of different combinations are used, the value of W_c is the lowest for the simulation case 5 i.e. when BR1, BR4, BR5, BR6 and BR10 are used.

Now it is seen that the value of W_c for the simulation case 1 is lower than that of for the simulation case 5. But 6 BRs are used for the simulation case 1 which increases the installation cost and computational burden compared to 5 BRs of simulation case 5. So, 6 BRs should not be selected as suitable. Again, 4 BRs are used for the simulation case 8 in which the installation cost and computational burden are lower than 5 BRs of simulation case 5. But during the simulations the system was not found to be stable well using 4 BRs. Therefore, considering these views, 5 BRs (BR1, BR4, BR5, BR6 and BR10) in the simulation case 5 are considered as suitable for transient stability enhancement in the present system model.

It is important to note here that in this work the base for determining which generator among the coherent group of generators needs to be installed with a braking resistor is the values of the transient stability index, W_c as calculated for a 3LG (Three-phase-to-ground) fault at the points near the generators of the coherent groups without considering the braking resistors in the system. Thus, a braking resistor is installed at the terminal of a generator close to a fault point giving the maximum W_c without the braking resistor. Consequently, the minimum W_c with the braking resistor can be obtained. However, if the braking resistor is installed at other terminal of other generator in the coherent group for which W_c is not the maximum without the braking resistor, the minimum W_c with the braking resistor cannot be obtained. This fact is confirmed from the simulation cases 2 to 7 of Table 6. It is already shown in Table 2 that coherent group I consists of 3 generators G1, G2 and G3, while coherent group II consists of another 3 generators G7, G8 and G9. According to our strategy, from 2 coherent groups 2 braking resistors need to be installed at the terminals of generators G1 and G7 which is already explained in the 2nd paragraph of Section 3.2. Now from the simulation cases 2 to 4 in Table 6 it is seen that the value of W_c with the BR at the terminal of G7 is lower than that of with the BR at the terminal of G8 or G9. Similarly, from the simulation cases 5 to 7 in Table 6 it is seen that the value of W_c with the BR at the terminal of G1 is lower than that of with the BR at the terminal of G2 or G3. This fact indicates that when a braking resistor is installed at the terminal of a generator close to a fault point giving the maximum W_c without the braking resistor, the minimum W_c with the braking resistor can be obtained.

As a whole, from the viewpoint of simulation results several points are of paramount importance.

(a) The proposed method selects only 5 braking resistors as suitable for improving the transient stability in the present system model.

(b) The reduced number of braking resistors saves about 50% of the total installation and operation cost as well as computational burden required for the installation of one braking resistor at each generator terminal bus.

(c) The proposed method can be remarked as an effective means in reducing the number of braking resistors.

6. Conclusion

This paper directs to the study of installation of reduced number of fuzzy logic controlled braking resistors at suitable locations for transient stability enhancement in a large multi-machine power system. Only 5 braking resistors are selected as suitable for improving the transient stability in the IEEJ West-10 machine model system. The reduced number of braking resistors saves about 50% of the total installation and operation cost as well as computational burden required for the installation of one braking resistor at each generator terminal bus. Moreover, from the simulation results of both balanced and unbalanced faults at different points the effectiveness and validity of the proposed method in improving the transient stability with reduced number of fuzzy logic controlled braking resistors are confirmed. Thus, the proposed method can be remarked as an effective means in reducing the number of braking resistors.

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Mohd. Hasan Ali (Member) was born in Rajshahi, Bangladesh on June 01, 1971. He received his B.Sc. Eng. Degree from Rajshahi University of Engineering and Technology (RUET), Bangladesh in 1995 and M.Sc. Eng. and Dr. Eng. Degrees from Kitami Institute of Technology, Japan, in 2001 and 2004 respectively, all in Electrical and Electronic Engineering. Currently he is an Assistant Professor in EEE dept. of RUET, Bangladesh. He is a member of the IEB, the IEE of Japan and the IEEE Power Engineering Society.

Toshiaki Murata (Member) was born in Hokkaido, Japan on April 27, 1943. He completed his Electrical Engineering Curriculum of the Teacher Training School from Hokkaido University, Japan. Since 1969, he had been a Research Assistant at the Kitami Institute of Technology, Japan. He received Dr. Eng. degree from Hokkaido University in 1991. Presently he is an associate professor at the Kitami Institute of Technology. He is a member of the IEE of Japan and Society of Instrument and Control Engineers, Japan.

Junji Tamura (Member) was born in Hokkaido, Japan on January 17, 1957. He received his B. Sc. Eng. Degree from Muroran Institute of Technology, Japan, in 1979 and M.Sc. Eng. and Dr. Eng. degrees from Hokkaido University, Japan, in 1981 and 1984 respectively, all in electrical engineering. In 1984, he became a lecturer and in 1986, an associate professor at the Kitami Institute of Technology, Japan. Currently he is a professor at the Kitami Institute of Technology. He is a member of the IEE of Japan and a senior member of the IEEE Power Engineering Society.