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TRANSIENT STABILITY IMPROVEMENT BY FUZZY LOGIC–CONTROLLED BRAKING RESISTOR

M.H. Ali,* Y. Soma,* T. Murata,* and J. Tamura*

Abstract

The authors present the results of analyses about transient stability augmentation by the fuzzy logic–controlled braking resistor. Following a major disturbance in electric power systems, variable rotor speed of the synchronous generator is measured, and then the current through the braking resistor is controlled by the firing-angle of the thyristor switch, which is controlled by the fuzzy logic. Thus, the braking resistor controls the accelerating power in generators and makes the system transiently stable. Simulations are performed by using EMTP (Electro-Magnetic Transients Program). Through the simulation results of both balanced (3LG: Three-phase-to-ground) and unbalanced (2LG: Double line-to-ground; 2LS: Line-to-line; and 1LG: Single line–to-ground) faults, the effectiveness of the fuzzy controlled braking resistor is demonstrated and the optimal conductance value of the braking resistor in enhancing the transient stability is investigated.

Key Words

Transient stability, braking resistor, fuzzy logic, thyristor switch, optimal conductance value, EMTP

1. Introduction

The Braking Resistor (BR) is a very effective device for transient stability control. It can be viewed as a fast load injection to absorb excess transient energy of an area that arises due to severe system disturbances. A number of results [1–5] regarding the use of braking resistor in improving the transient stability of electric power systems have been reported. In [1], the authors analyzed the transient stability by using a range of BR size between 400 MW and 600 MW. A 1400-MW braking resistor is in use at the Bonneville Power Administration's (BPA) Chief Joseph Substation in north-central Washington [2] for enhancing the system stability. The resistor is designed to dissipate 1400 MW of power when energized at 240 KV and is capable of withstanding a three-second application between cooling periods. It is known that the amount of firm power that can be transmitted from the Pacific Northwest (PNW) to California may be increased by 900 MW using the 1400-MW brake. A. Sen and J. Meisel in their work [3] used 1.0 pu as the minimum allowable value of braking resistor to improve the transient stability of power system. In [4], the authors carried out transient stability studies with a braking resistor of 0.8, 0.9, 1.0, 1.1, and 1.2 pu values and commented that a value of 1.0 pu is optimum for the range of power flows considered. Again, in [5] the authors proposed a closed-loop quasi-optimal control strategy for dynamic braking resistor and shunt reactor, and used 1.0 pu value of the braking resistor for transient stability improvement.

However, in none of these strategies is a fuzzy logic controller used to switch in and out of the BR. Therefore, these strategies are inflexible and are not adaptive to the changing operating conditions of the system. A report [6] was published in which fuzzy logic controller was used for BR switching and the effectiveness of the controller was demonstrated by using 1.0 pu and 2.0 pu values of BR in case of 3LG fault. Again, research on the control of dynamic brake through heuristic rule was published [7] in which the value of BR was chosen so that the dynamic brake could absorb an amount of power equal to the rated MVA of the machine at full conduction. In [8–10], we proposed fuzzy logic control schemes for the switching of the braking resistor whose conductance value was chosen as 1.0 pu.

However, the selection of the optimal value of the braking resistor in improving the transient stability is still a matter of some interest [11]. Therefore, from this viewpoint, this work describes the results of analyses of the transient stability improvement by the braking resistor whose conductance value is changed in the ranges from 0.0 pu to 1.0 pu with a step of 0.1 pu. Generator load angle responses, speed deviation responses, and amount of heat produced in the BR are considered as the performance criteria in selecting the optimal value of the BR. Eleven simulations are carried out corresponding to eleven conductance values considering both balanced and unbalanced faults near the generator. Simulation results clearly indicate the effectiveness of the fuzzy logic–controlled braking resistor in improving the transient stability. Moreover, from the

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* Department of Electrical & Electronic Engineering, Kitami Institute of Technology, 165 Koen-cho, Kitami, Hokkaido, 090-8507 Japan; e-mail: hasan@pullout.elec.kitami-it.ac.jp

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simulation results we conclude that 0.5 pu conductance value is optimal for transient stability improvement and that 0.2 pu conductance value is sufficient to stabilize the system for all fault conditions. It is also important to note here that the design of the fuzzy controller is straightforward, because it has only one input variable and simple control rules.

The organization of this article is as follows. Section 2 describes the model system for the transient stability study. Section 3 explains the fuzzy logic controller design. Section 4 describes the modelling of TCSBR (Thyristor Controlled System Braking Resistor). Section 5 shows the simulation results. Section 6 provides some conclusions regarding the optimal value of the braking resistor and its effectiveness in improving the transient stability.

2. Model System

The power system model used for the simulation of transient stability is shown in Fig. 1. The model system consists of a synchronous generator, SG, feeding an infinite bus through a transformer and double circuit transmission line. 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. CB in the figure represents a circuit breaker. Also, AVR (Automatic Voltage Regulator) and GOV (Governor) control system models, shown in Figs. 2 and 3 respectively, have been included in the simulation. The model system and generator parameters, as well as generator initial values used for the simulation, are shown in Tables 1 and 2 respectively.

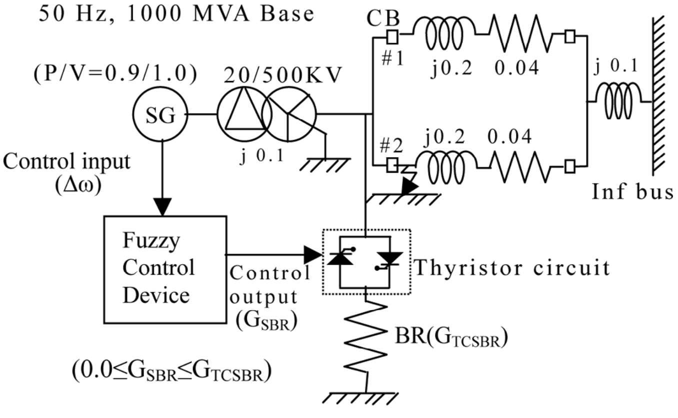


Figure 1. Power system model.

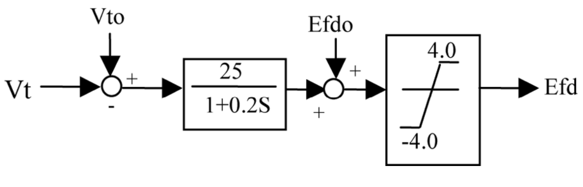


Figure 2. AVR model.

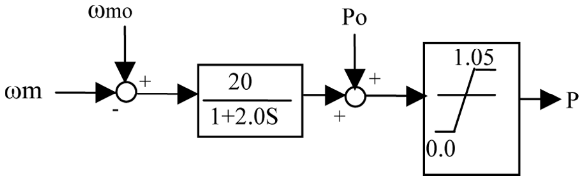


Figure 3. GOV model.

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 the circuit breakers are closed again at 1.2 sec. Time step and simulation time have been chosen as 0.00005 sec and 5.0 sec respectively. The BR will be switched in following a fault clearing and the switching condition of the 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.

3. Design of Fuzzy Controller

A fuzzy logic, unlike the crispy logic in Boolean theory that uses only two logic levels (0 and 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 FLC (Fuzzy Logic Controller) is described in the following:

3.1 Fuzzification

For the design of the fuzzy controller, we have selected speed deviation, $\Delta\omega$, of the generator as the input and conductance value, $G_{SBR}(0.0 \leqslant G_{SBR} \leqslant G_{TCSBR})$, of the braking resistor as the output. The triangular membership functions for the fuzzy sets of $\Delta\omega$ as shown in Fig. 4 have been determined by trial and error and are used throughout the simulations. The linguistic variables in the membership functions 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 [12]:

$$A(x) = 1/b(b - 2|x - a|) \tag{1}$$

where A(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 (deviation of speed for the present simulation).

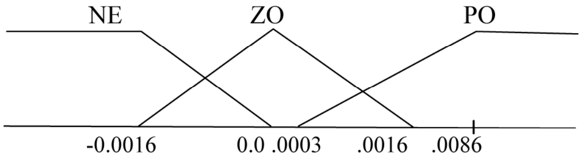


Figure 4. Membership function of $\Delta\omega$ (pu).

Table 1
Model System and Generator Parameters

Frequency [Hz]	50
Transmission line voltage [KV]	500
Generator power rating [MVA]	1000
Generator rated voltage [KV]	20
Generator parameters	
Armature resistance, r_a[pu]	0.003
Armature leakage reactance, X_l[pu]	0.13
d-axis synchronous reactance, X_d[pu]	1.79
q-axis synchronous reactance, X_q[pu]	1.71
d-axis transient reactance, $X_d^{/}$[pu]	0.169
q-axis transient reactance,$X_q^{/}$[pu]	0.228
d-axis subtransient reactance, $X_d^{//}$[pu]	0.135
q-axis subtransient reactance, $X_q^{//}$[pu]	0.2
Zero sequence reactance, X_0 [pu]	0.13
d-axis open circuit transient time constant,$T_{do}^{/}$ [sec]	4.3
q-axis open circuit transient time constant,$T_{qo}^{/}$ [sec]	0.85
d-axis open circuit subtransient time constant,$T_{do}^{//}$ [sec]	0.032
q-axis open circuit subtransient time constant,$T_{qo}^{//}$ [sec]	0.05
Inertia constant, H [sec]	2.894
Generator neutral grounding resistance [pu]	0.00001

Table 2
Generator Initial Values

Generator output [pu]	0.90 + j0.061
Generator terminal voltage [pu]	1.00
Phase angle of generator terminal voltage [deg]	15.23
Generator load angle [deg]	69.49

Table 3
Fuzzy Rule Table

$\Delta\omega$(pu)	G_{SBR} (pu)										
NE	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ZO	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PO	-	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Simulation case	1	2	3	4	5	6	7	8	9	10	11
G_{TCSBR}	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0

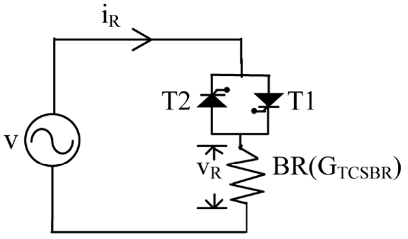
3.2 Fuzzy Rule Table

The proposed control strategy is very simple because it has only three control rules corresponding to each simulation, that is, each conductance value of the BR. The control rules for all simulation cases 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. The simulation cases 1 to 11 as indicated in Table 3 correspond to 11 conductance values of 0.0 pu to 1.0 pu with a step of 0.1 pu. The fuzzy rule typically follows the "IF-THEN" rule. For instance, for the simulation case 2, (*i*) if $\Delta\omega$ is NE, then G_{SBR} is 0.0, (*ii*) if $\Delta\omega$ is ZO, then G_{SBR} is 0.0, and (*iii*) if $\Delta\omega$ is PO, then G_{SBR} is 0.1 .

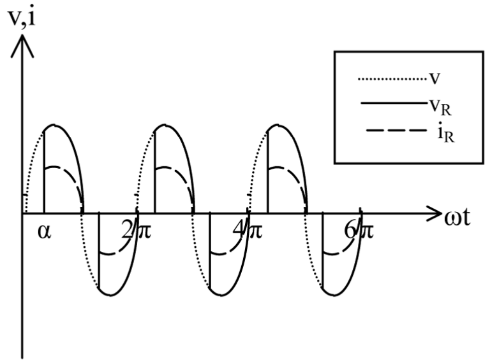
3.3 Fuzzy Inference and Defuzzification

For the inference mechanism of the proposed fuzzy logic controller, Mamdani's method [12] has been utilized. Also, the centre-of-area method is the most well known and rather simple defuzzification method [12] that is implemented to determine the output crispy value (i.e., the conductance value of the braking resistor, G_{SBR}).

4. Modelling of TCSBR



(a) Thyristors connected with BR



(b) Voltage and current waveforms

Figure 5. Thyristor switching circuit for BR and waveforms. (a) Thyristors connected with BR. (b) Voltage and current waveforms.

Fig. 5(a) shows the proposed circuit of two reverse parallel-connected thyristors, T1 and T2 along with the braking resistor. Following a fault, current flows through BR if thyristor T1 or T2 is in ON state, 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. 5(b). Therefore, when the firing-angle for the thyristor switch is α as shown in Fig. 5(b), average power, P_{TCSBR}, consumed by the braking resistor is given by:

$$\begin{aligned} P_{TCSBR} &= \tfrac{1}{\pi}\textstyle\int_0^{\pi} v i_R . d(\omega t) \\ &= \tfrac{V_g^2 G_{TCSBR}}{\pi}(\pi - \alpha + 0.5 Sin 2\alpha) \end{aligned} \tag{2}$$

where v is the instantaneous value of generator terminal bus voltage, i_R is the instantaneous value of current through BR, V_g is the rms value of generator terminal bus voltage, and G_{TCSBR} is the conductance value of BR.

Firing-angle, α, for the thyristor switch is calculated from the output of the fuzzy controller, that is, from the conductance value of the braking resistor, G_{SBR} ($0.0 \leqslant G_{SBR} \leqslant G_{TCSBR}$). Again, the conductance value of BR, G_{SBR}, is related to the power dissipated in BR. For any time step of simulation, the average power of SBR (System Braking Resistor with a conductance value of G_{SBR}), P_{SBR}, and that of TCSBR (Thyristor Controlled System Braking Resistor with a conductance value of G_{TCSBR}), P_{TCSBR}, are equal and hence firing-angle can be calculated from the following equation:

$$\begin{aligned} & P_{TCSBR} = P_{SBR} \\ & or,\ \tfrac{V_g^2 G_{TCSBR}}{\pi}(\pi - \alpha + 0.5 Sin 2\alpha) = V_g^2 G_{SBR} \end{aligned} \tag{3}$$

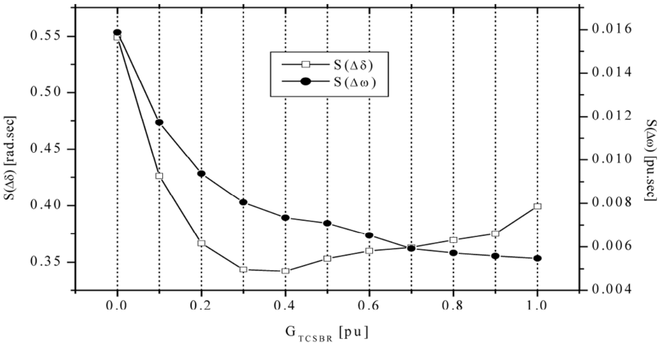
However, it is complex to calculate firing-angle directly from (3) using the value of G_{SBR}. So, for each simulation, first by using (3), a set of different values of G_{SBR} is calculated for the values of firing-angle ranging from 0^0 to 180^0 with a step of 2^0. Then by using the linear interpolation technique, we determine firing-angle, α.

5. Simulation Results

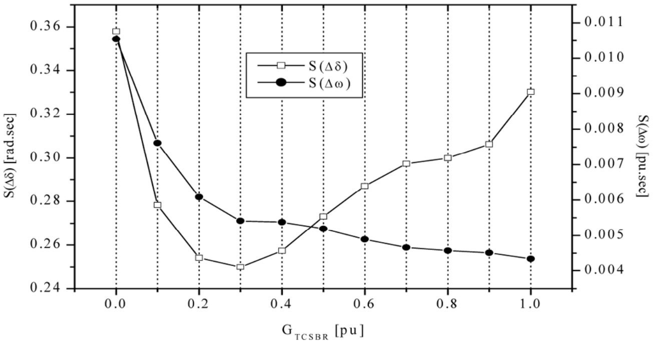
Eleven simulations were carried out for the conductance values of BR, G_{TCSBR}, in the ranges from 0.0 pu (without BR) to 1.0 pu with a step of 0.1 pu considering both balanced (3LG) and unbalanced (2LG, 2LS, and 1LG) faults near the generator. For the sake of easy observation and easy understanding of the performance of each conductance value in enhancing transient stability, the curves for the integral of the absolute value of load angle deviation, S($\Delta\delta$), as well as speed deviation, S($\Delta\omega$), have been shown in Fig. 6, where S($\Delta\delta$) and S($\Delta\omega$) can be expressed as the following:

$$S(\Delta\delta) = \int_0^5 |\Delta\delta| dt \tag{4}$$

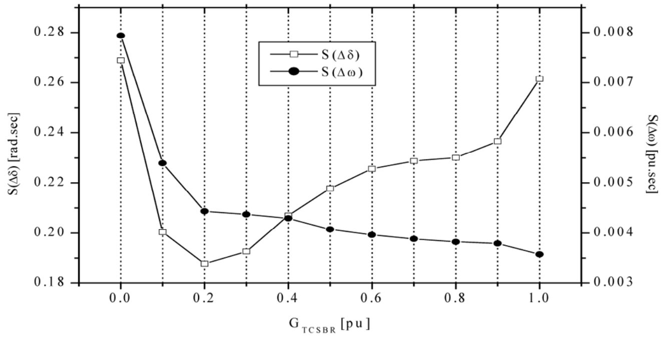
$$S(\Delta\omega) = \int_0^5 |\Delta\omega| dt \qquad (5)$$



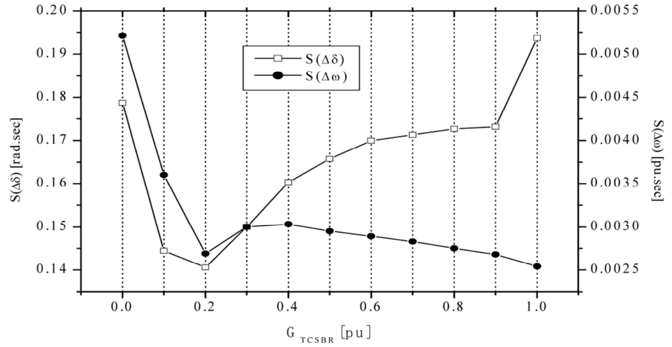
(a) 3LG fault



(b) 2LG fault



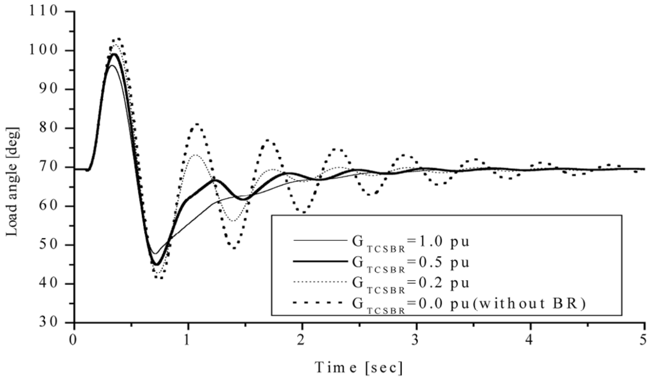
(c) 2LS fault



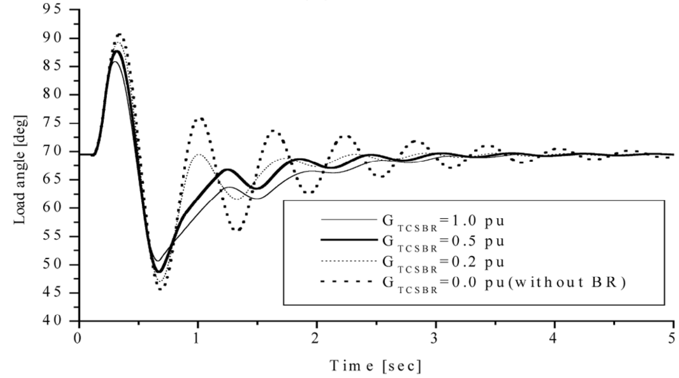
(d) 1LG fault

Figure 6. Curves for integral of load angle deviation and Speed deviation.

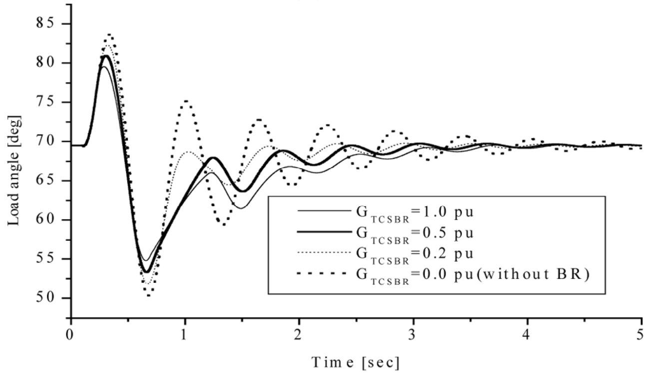
It is noteworthy that in this work the time responses for the load angle and speed deviation with the braking resistor were observed to reach almost at steady state at about 5.0 sec. Therefore, the simulation time was considered to be 5.0 sec, as already mentioned in Section 2, and hence the integral values for the load angle deviation and speed deviation are considered over a time range of 5.0 seconds as shown in (4) and (5).



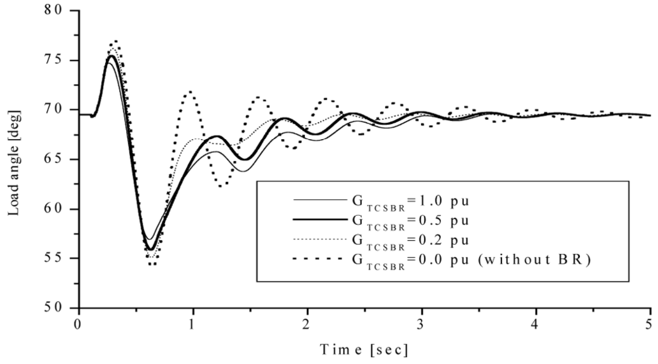
(a) 3LG Fault



(b) 2LG Fault

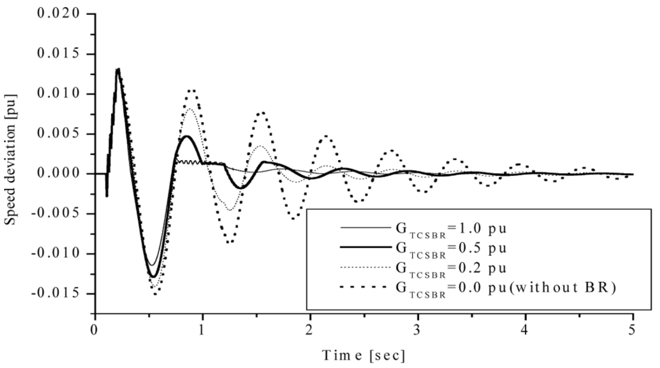


(c) 2LS Fault

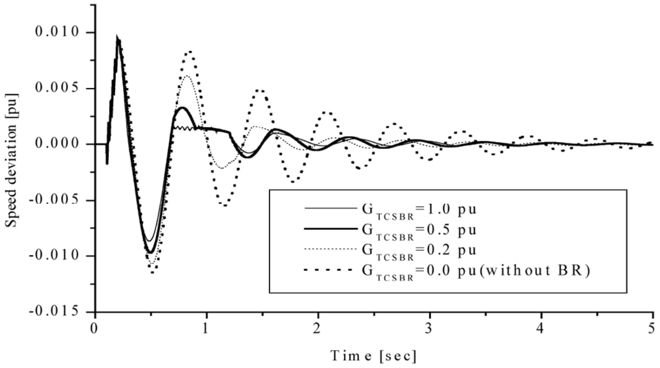


(d) 1LG Fault

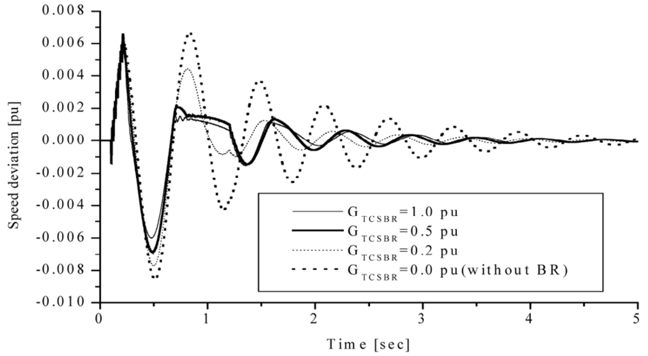
Figure 7. Load angle responses.



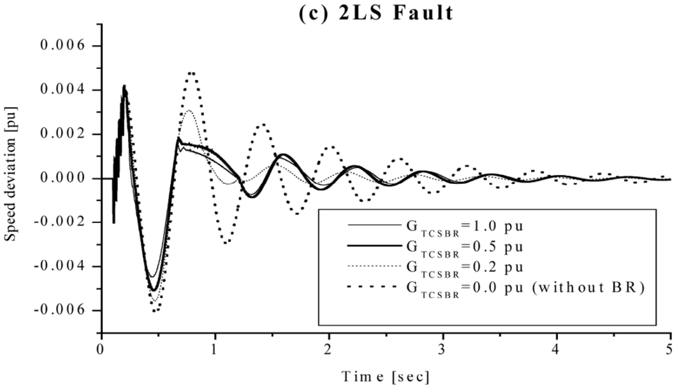
(a) 3LG Fault



(b) 2LG Fault



(c) 2LS Fault



(d) 1LG Fault

Figure 8. Speed deviation responses.

From the load angle deviation curve in case of 3LG fault, we see that 0.3 pu, 0.4 pu, and 0.5 pu conductance values give better and almost the same performance. But from the speed deviation curve for 3LG fault we see that 0.5 pu conductance value gives better performance than 0.3 pu and 0.4 pu conductance values. So, it can be inferred that 0.5 pu conductance value is optimal in case of 3LG fault. Again, in case of 2LG fault, 0.2 pu and 0.3 pu conductance values give better performance for the load angle deviation curve. But for the speed deviation curve, 0.5 pu conductance value gives better performance than 0.2 pu and 0.3 pu conductance values. In case of 2LS fault, it is seen that 0.2 pu value gives the best performance for the load angle deviation. But for the speed deviation, 0.5 pu value gives better performance than 0.2 pu value. Again, in the case of 1LG fault, we observe that 0.2 pu value gives the best performance for load angle deviation and better performance for speed deviation. On the other hand, from the speed deviation curves we note that 1.0 pu conductance value gives the best performance for all fault cases.

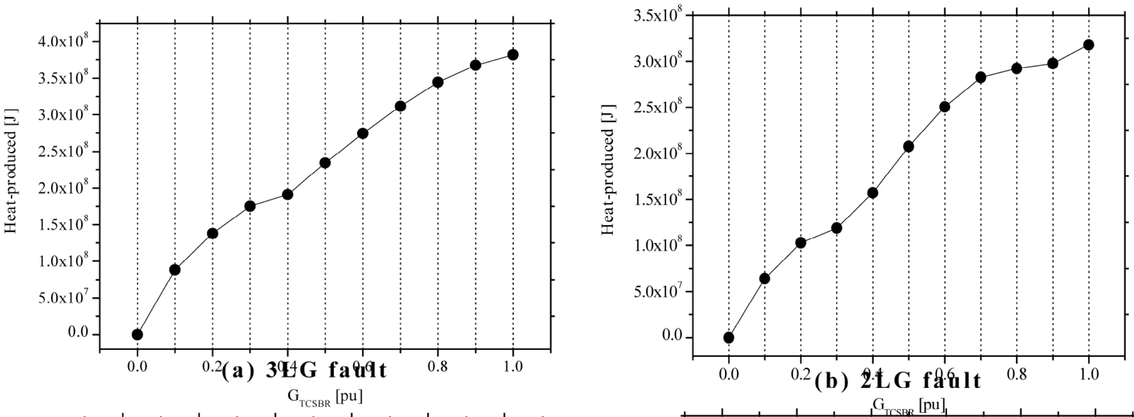
Therefore, considering these views, the performance of 1.0 pu, 0.5 pu, and 0.2 pu conductance values are prominent in improving the transient stability; time responses for the load angle and speed deviation have been shown in Figs. 7 and 8 respectively for the conductance values of 1.0 pu, 0.5 pu, 0.2 pu, and 0.0 pu(without BR).

Fig. 7 shows the load angle responses. We observe that for 3LG fault, 1.0 pu conductance value gives the best response from the viewpoint of less oscillation and smoothness; but from the viewpoint of settling time, 0.5 pu conductance value gives the best performance. Again, for 2LG fault, 0.5 pu conductance value gives the best response from the point of view of both settling time and less oscillation. For 2LS and 1LG faults, 0.2 pu conductance value gives the best performance from the point of view of both less oscillation and settling time.

Fig. 8 shows the speed deviation responses. In this case, for all fault cases it is seen that 1.0 pu conductance value gives the best response from the point of view of smoothness, less oscillation and settling time. For 3LG, 2LG and 2LS faults, the responses of 0.5 pu conductance value are better compared to those of 0.2 pu and 0.0 pu (without BR) conductance values. But for 1LG fault, 0.2 pu conductance value gives better performance than 0.5 pu conductance value from the viewpoint of settling time.

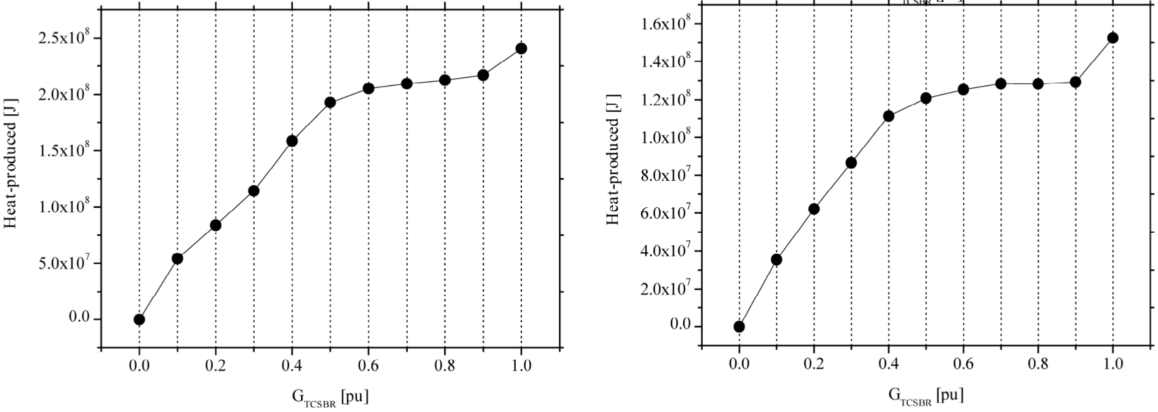
Finally, Fig. 9 shows the curves for integral of heat produced in the BR corresponding to the conductance values of 0.0 pu to 1.0 pu. It is observed for all fault cases that with the increase of conductance value, amount of heat produced is also increased. Therefore, the higher thermal withstanding capabilities as well as the means of cooling down should be provided for the BR material with higher valued conductances, which would ultimately increase the cost. In this sense, the cost of 0.5 pu conductance value is a compromise between higher cost of 1.0 pu conductance value and lower cost of 0.1 pu conductance value.

As a whole, considering all of these views, it can be concluded that 0.5 pu conductance value is optimal for improving the transient stability of the power system. Again, 0.2 pu conductance value is also sufficient to stabilize the system during transient conditions. And overall, the fuzzy logic–controlled braking resistor is effective in enhancing the transient stability.



(a) 3LG fault

(b) 2LG fault



(c) 2LS fault

(d) 1LG fault

Figure 9. Curves for integral of heat produced in BR over 5.0 seconds Vs Conductance value.

6. Conclusion

This research describes the results of analyses about the transient stability improvement by the fuzzy logic–controlled braking resistor with the conductance values ranging from 0.0 pu to 1.0 pu. Simulations have been carried out considering both balanced and unbalanced faults. From the simulation results the effectiveness of the fuzzy logic–controlled braking resistor in improving the transient stability is confirmed. Moreover, it can be concluded that 0.5 pu is the optimal conductance value in augmenting the transient stability and also 0.2 pu conductance value is sufficient to stabilize the power system. Also, the proposed design of the fuzzy controller is very simple because it has only one input variable and straightforward control rules.

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Biographies

M.H. Ali received his B.Sc. Degree from Rajshahi University of Engineering and Technology (RUET), Bangladesh in 1995 and his M. Sc. and Ph.D. Degrees from Kitami Institute of Technology, Japan, in 2001 and 2004 respectively, all in Electrical and Electronic Engineering. He is an Assistant Professor in EEE dept. of RUET, Bangladesh. Presently he is doing research works under the JSPS Postdoctoral Fellowship Program at the Kitami Institute of Technology, Japan. He is a member of the IEB, the IEE of Japan and the IEEE Power Engineering Society. His research interests are in the areas of synchronous machine and power system, especially transient stability control, application of fuzzy logic and genetic algorithm technique in power system.

Y. Soma received his B.Sc. and M.Sc. degrees from Kitami Institute of Technology, Japan, in 2000 and 2002 respectively, in electrical and electronic engineering. Presently he is working for Japan Technical Software Corporation.

T. Murata completed his Electrical Engineering Curriculum of the Teacher Training School from Hokkaido University, Japan. From 1969 to 1995, he was a Research Assistant at the Kitami Institute of Technology, Japan. He received Dr. Eng. degree from Hokkaido University in 1991. Since 1996 he has been 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. His research interests are in the areas of field-oriented control of induction motor, synchronous reluctance motor, Brushless DC motor and induction generator. Recently he is interested in the efficiency optimized interior permanent magnet synchronous generator.

J. Tamura received his B.Sc. degree from Muroran Institute of Technology, Japan, in 1979 and his M.Sc. and Ph.D 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 that institute. He is a member of the IEE of Japan and a senior member of the IEEE Power Engineering Society. His research interests are in the areas of synchronous machine, especially synchronous generator stabilization by fuzzy logic control, transient stability analysis of wind generator, and adjustable speed generator.