Minimization of Shaft Torsional Oscillations by Fuzzy Controlled Braking Resistor Considering Communication Delay

MOHD. HASAN ALI, MINWON PARK, AND IN-KEUN YU
Department of Electrical Engineering
Changwon National University
9 Sarim-Dong, Changwon, Gyeongnam, 641-773
SOUTH KOREA

Abstract: - This paper analyzes the effect of the fuzzy logic-controlled braking resistor (BR) on minimizing shaft torsional oscillations of the generators in a multi-machine power system. The influence of communication delay associated with the fuzzy controller input calculation on minimizing shaft torque oscillations is investigated. Global Positioning System (GPS) is proposed for the practical implementation of the calculation of the input of the fuzzy logic controller. Simulation results of a balanced fault at different points in the power system show that the fuzzy logic-controlled braking resistor can minimize the shaft torsional oscillations of synchronous generators well. Moreover, the communication delay has an influence on minimization of shaft torque oscillations.

Key-Words: - Braking resistor, Communication delay, Fuzzy controller, Global positioning system (GPS), Minimizing shaft torsional oscillations**,** TKED, Time derivative of TKED.

1 Introduction

Usually, in the analysis of power system dynamic performance, the rotor of the turbine-generator is assumed to be made of a single mass. However, in reality, a turbine-generator rotor has a very complex mechanical structure consisting of several predominant masses (such as rotors of turbine sections, generator rotor, couplings, and exciter rotor) connected by shafts of finite stiffness. Therefore, when the generator is perturbed, torsional oscillations result between different sections of the turbine-generator rotor. The torsional oscillations in the subsynchronous range could, under certain conditions, interact with the electrical system in an adverse manner [1]. Again, certain electrical system disturbance can significantly reduce the life expectancy of turbine shafts. Therefore, sufficient damping is needed to reduce turbine shaft torsional oscillations.

Braking resistor (BR) is known to be a very effective device for transient stability control [2-5]. It can be viewed as a fast load injection to absorb excess transient energy of an area which arises due to severe system disturbances. The braking resistor can be used to damp shaft torsional oscillations of synchronous generator also [6-7]. But in [6-7], conventional controllers were used to switch in and out the BR. As a result, these strategies are inflexible and are not adaptive to the changing operating condition of the system. To surmount such drawbacks, fuzzy logic-controlled BR was proposed for damping shaft torsional oscillations [8-10]. However, in all of the results [6-10], the analysis of damping shaft torsional oscillations was carried out in case of a single machine power system only.

This paper analyzes the effect of the fuzzy logic-controlled braking resistor on minimizing shaft torsional oscillations of synchronous generators in case of a large multi-machine power system. The time derivative of the total kinetic energy deviation (TKED) of the synchronous generators is used as the input to the fuzzy controller for BR switching [4] in this work. However, a communication delay is introduced in online calculation of the time derivative of TKED, which may fatally affect the control system. Consequently, the minimizing of shaft torsional oscillations of the generators would be affected. So, the communication delay phenomenon associated with the online calculation of the fuzzy controller input should be considered for the actual analysis of shaft oscillations minimization. In [2-10], such communication delays are not considered.

The most important and novel feature of this work is that it analyzes the effect of communication delays introduced in online calculation of the input variable of the fuzzy controller for braking resistor switching on the shaft torque oscillations minimization of synchronous generators in a multi-machine power system. Global Positioning System (GPS) [11-12] is proposed for the practical implementation of the calculation of the input of the fuzzy logic controller.

The effectiveness of the proposed method is demonstrated through simulations carried out by EMTP (Electro-Magnetic Transients Program).

2 Model System

For the simulation, the IEEJ West 10-machine model system [2], [4] as shown in Fig. 1 has been used. The "WEST 10-machine system" model is a 10-machine tandem model that is a prototype of the Japanese 60 Hz systems. It presents the long time oscillation characteristics of a tandem system [2], [4]. 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. All lines in Fig.1 represent 2 circuits of 3-phase transmission line. In this work, five braking resistors are installed at the terminal busses of generators G1, G4-G6, and G10 [4]. The conductance values of these five 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 to be 15.0 pu, 10.0 pu and 30.0 pu respectively. Fig. 2 shows that a braking resistor BR with a conductance value of G_{TCSBR} is connected to a generator terminal bus through a thyristor switching circuit.

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 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 TKED$^{/}$. The BR will be switched in following a fault clearing and the switching condition of BR is such that when TKED$^{/}$ exceeds 0.065 pu, BR is switched on the generator terminal bus. On the other hand, when TKED is below or equal to 0.065 pu and also in the steady state, BR is removed from the generator terminal bus by the thyristor switching circuit. The dead band of the BR operation i.e. the threshold value of TKED$^{/}$ is determined by trial and error in order to obtain the best system performance. The AVR (Automatic Voltage Regulator) and GOV (Governor) control system models for the IEEJ West 10-machine model system [2] have been included in the present simulation. Various parameters of the generators used for the simulation are described in [2].

It is considered that each turbine-generator shaft model has 6 (six) masses namely high-pressure (HP) turbine, an intermediate-pressure (IP) turbine, two low-pressure turbines (LPA, LPB), the generator (GEN) and exciter (EXC) as shown in Fig. 3. Rotor spring mass constants as shown in Table 1 are described in [9-10].

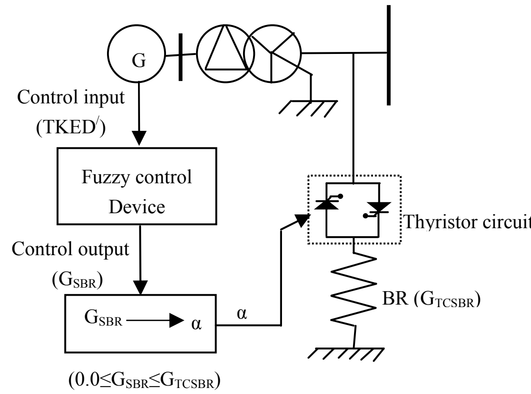

Fig. 2. BR with thyristor switching circuit.

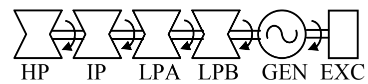

Fig. 3. Turbine-generator shaft model.

Table 1. Rotor spring mass parameters

Mass	Shaft	Inertia H (second)	Spring constant K (pu)	pu Torque/rad
HP		0.225		
	HP-IP		7,277	19.303
IP		0.376		
	IP-LPA		13,168	34.929
LPA		2. 077		
	LPA-LPB		19,618	52.038
LPB		2.139		
	LPB-GEN		26,713	70.858
GEN		2.101		
	GEN-EXC		1,064	2.822
EXC		0.082		

3 Online Calculation of the Time Derivative of TKED Using GPS

In this work, the time derivative of TKED is used as the fuzzy controller input for BR switching. TKED is already defined in section 2. According to the definition, in order to calculate TKED, W_{total} is needed, which can be determined easily by knowing the rotor speed of each generator and is given by:

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

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

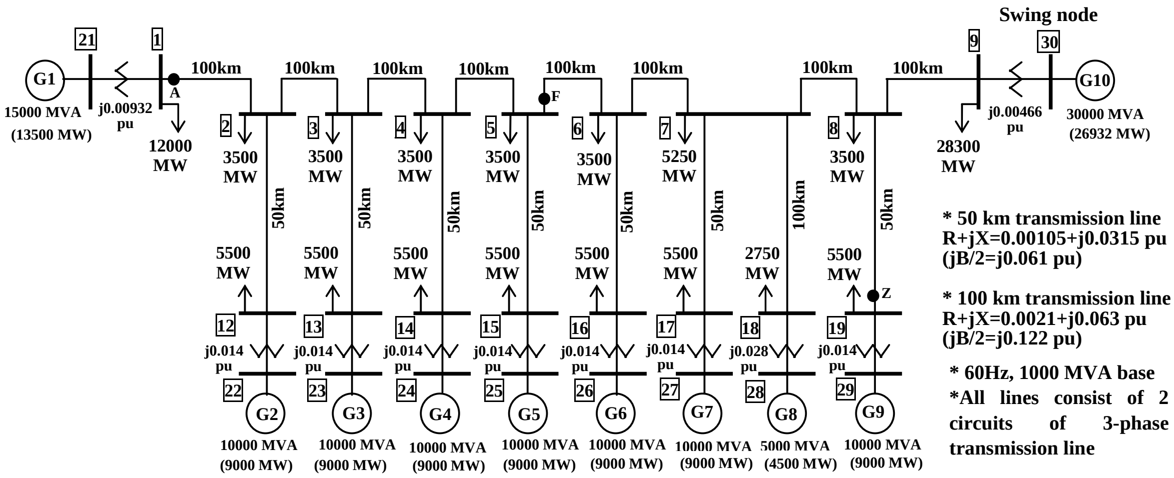

Fig. 1. IEEJ WEST 10-machine model system.

denotes kinetic energy in joule for a generator, W_{total} total kinetic energy in joule, i generator number, and N total number of generators. Again, in (2) $J_i = (H \times MVA\ rating)/\{5.48 \times 10^{-9} \times (N_S)^2\}$ denotes moment of inertia in Kg.m^2 where N_S and H are synchronous angular speed in rpm and inertia constant respectively and $\omega_{mi}=2\times\pi\times(N/60)$ rotor angular velocity in mechanical rad/sec where N is rotor speed in rpm.

3.1 GPS Method for the Online Calculation of the Time Derivative of TKED

The online calculation of the time derivative of TKED using the speed signal of each generator, and then again using the signal of the time derivative of TKED as the input to each fuzzy controller can be accomplished by using GPS (Global Positioning System) [11-12] which provides time synchronization of signals. 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 1μs accuracy, at any location on the power network [12].

Fig. 4 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. In this case, signals may be transmitted and received through microwave or optical fibre.

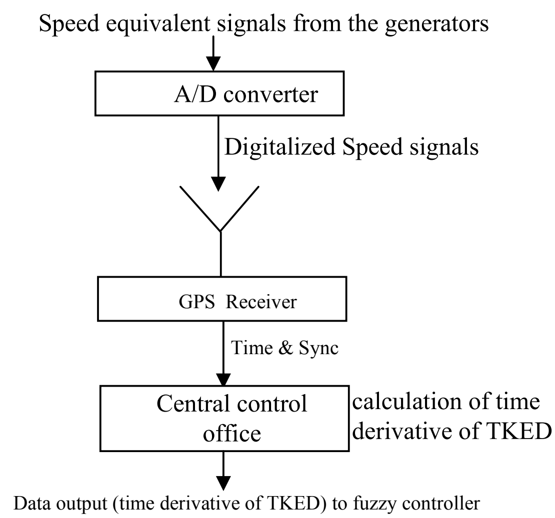

Fig. 4. GPS functional block diagram.

3.2 Communication Delays

During online calculation of the time derivative of TKED, time delays are introduced mainly due to signal transmission through optical fibre or microwave, A/D conversion, calculation of W_{total} as well as time derivative of TKED, and time synchronization of signals by GPS. The communication delays may affect the control logic, and consequently the minimizing of shaft torsional oscillations of the generators also. So, such communication delays should be considered for the actual analysis of shaft oscillations minimization.

Usually, communication delays may range from several microseconds to few hundred milliseconds [13-15]. In this work, extensive simulations are carried out considering various values of communication delays. Some of the simulation cases are shown in Figs. 6 and 7.

4 Design of Fuzzy Logic Controller

The design of the proposed FLC (Fuzzy Logic Controller) is described in the following:

4.1 Fuzzification

For the design of the proposed fuzzy logic controller, $TKED^{/}$ 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. During the simulations communication delays are applied to the fuzzy controller input signal. We have selected the triangular membership functions for $TKED^{/}$ as shown in Fig. 5 in which the linguistic variables N, Z, and P stand for Negative, Zero, and Positive respectively. It is important to note that the membership functions for $TKED^{/}$ 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 [2-4], [9-10]:

$$\mu_A(TKED^{/})=1/b\,(b-2|\,TKED^{/}-a|) \tag{3}$$

where $\mu_A(TKED^{/})$ 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 '$TKED^{/}$' is the value of the input variable.

4.2 Fuzzy Rule Table

The proposed control strategy is very simple because it has only 3 control rules for each controller. The control rules are shown in Table 2 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.

4.3 Fuzzy Inference

For the inference mechanism of the proposed fuzzy logic controller, Mamdani's method [2-4], [9-10] has been utilized. According to Mamdani, the degree of conformity, Wi, of each fuzzy rule is as follows:

$$Wi=\mu_A\,(TKED^{/}) \tag{4}$$

where $\mu_A\,(TKED^{/})$ is the value of grade of membership and i is rule number.

4.4 Defuzzification

The Center-of-Area method is the most well-known and rather simple defuzzification method [2-4], [9-10], 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.

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

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

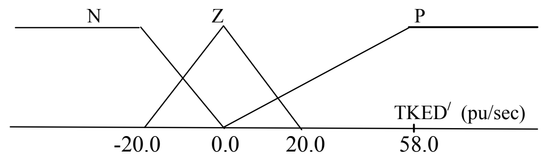

Fig. 5. Membership functions of $TKED^{/}$.

Table 2. Fuzzy rule table

$TKED^{/}$ [pu/sec]	G_{SBR} [pu]				
	BR1	BR4	BR5	BR6	BR10
N	0.0	0.0	0.0	0.0	0.0
Z	0.0	0.0	0.0	0.0	0.0
P	15.0	7.0	4.0	4.0	4.0

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 method of calculating firing-angle from the output of the fuzzy controller is described in detail in [3].

5 Simulation Results and Discussion

Simulations have been carried out considering a balanced (3LG: three-phase-to-ground) fault at points A, F, and Z as shown in Fig. 1. 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. It is assumed that the circuit breaker clears the line when the current through it crosses the zero level. The time step and simulation time have been chosen as 0.00005 sec and 10.0 sec respectively.

Figs. 6 and 7 show the effects of the fuzzy logic-controlled BR on minimizing shaft torsional oscillations of generator G1 in case of 3LG fault at point A without and with a communication delay of 20 msec respectively. From the responses of Figs. 6 and 7 it is clear that the fuzzy controlled braking resistor can minimize the shaft torsional oscillations well during a severe fault. It is also observed that the minimizing performance of BR considering a communication delay of 20 msec as demonstrated in Fig. 7 is worse than that without considering a communication delay as demonstrated in Fig. 6. This fact indicates that the communication delay has an effect on minimizing shaft torsional oscillations by the fuzzy controlled BR.

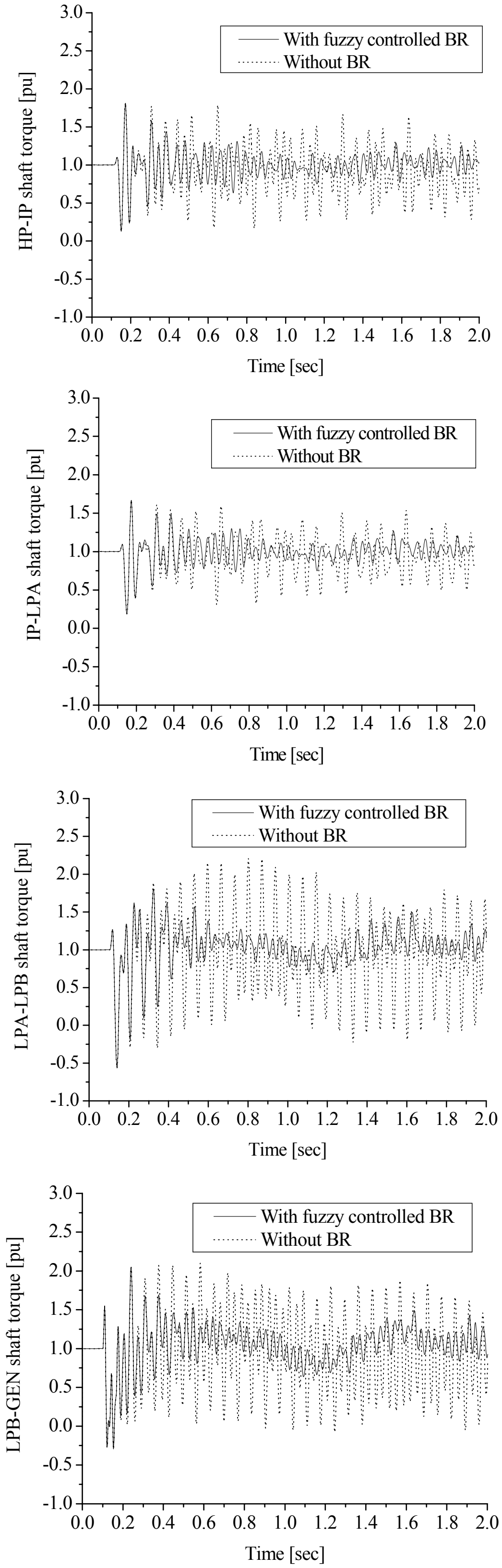

Fig. 6. Shaft torsional torque responses of generator G1 for 3LG fault at point A without considering communication delay.

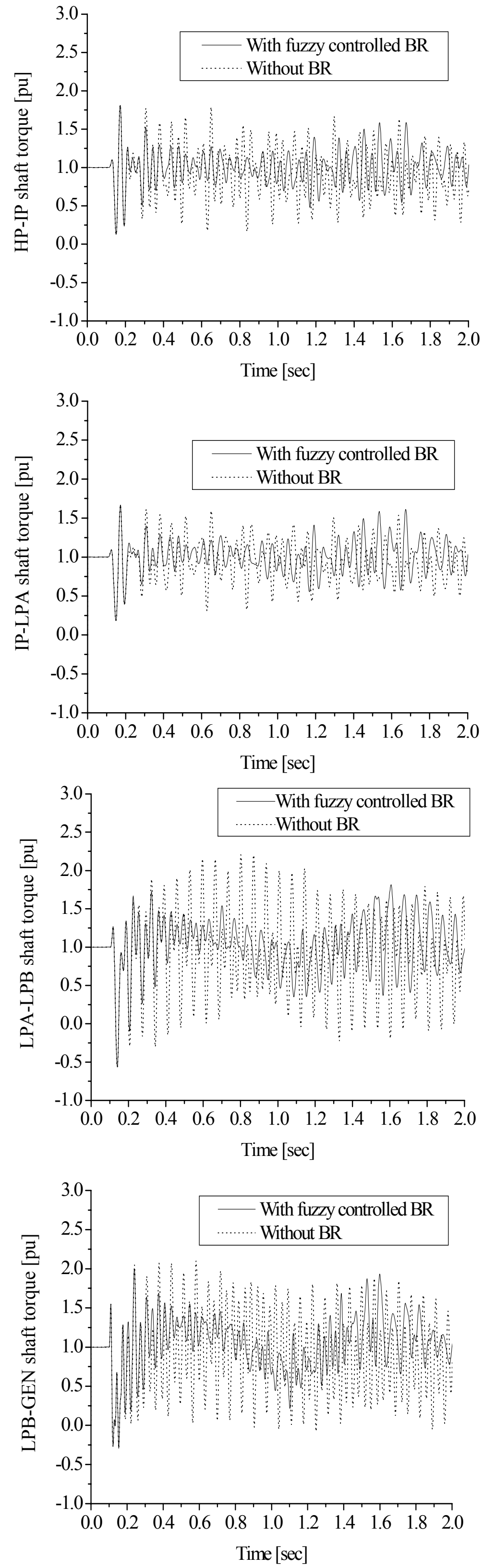

Fig. 7. Shaft torsional torque responses of generator G1 for 3LG fault at point A considering a communication delay of 20 msec.

6 Conclusion

This paper analyzes the influence of communication delays associated with the online input calculation of the fuzzy controller for braking resistor switching on minimizing shaft torsional oscillations of the generators in a multi-machine power system. From the simulation results of a balanced fault at different points in the system, the following conclusions can be drawn.

(a) The fuzzy logic-controlled braking resistor can minimize the shaft torsional oscillations of synchronous generators well.

(b) Minimization of shaft torsional oscillations by the fuzzy controlled braking resistor is affected by the communication delay.

Currently we are investigating a methodology about how the negative effect caused by the communication delay on minimizing shaft torsional oscillations can be reduced. We hope to publish our research results in the near future.

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