Paper

A Fuzzy Logic Controlled Braking Resistor Scheme for Damping Shaft Torsional Oscillations

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This paper presents a fuzzy logic switching for the thyristor controlled braking resistor to damp turbine-generator shaft torsional oscillations. Following a major disturbance in electric power system, variable rotor speed of the 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 damps the shaft torsional oscillations. The effects of the fault occurring time on turbine shaft torsional torques have also been investigated. Simulations are performed by using EMTP (Electro-Magnetic Transients Program). Through the simulation results of various multi-phase faults in a single machine connected to an infinite bus system, the effectiveness of the proposed fuzzy logic controlled braking resistor in damping shaft torsional oscillations is demonstrated.

Keywords: braking resistor, damping turbine-generator shaft torsional oscillations, fuzzy logic, multi-phase system faults, EMTP

1. Introduction

In Refs. (1)∼(3) we reported the works for the fuzzy logic switching of the thyristor controlled braking resistor (BR) for transient stability control. However, in these works, the rotor of the turbine-generator was assumed to be made of a single mass. 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 [(4)]. 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. From this viewpoint this paper analyzes about damping shaft torsional oscillations by fuzzy logic controlled braking resistor and this is the novel feature of this work.

A work [(5)] was published in which the technical feasibility of using a dynamically controlled braking resistor was examined to damp torsional oscillations. But in that work, a conventional controller was used to switch in and out the BR. Moreover, the effectiveness of the braking resistor for damping turbine shaft torsional oscillations was demonstrated only for a balanced fault.

In this paper, a fuzzy logic controller is proposed for switching in and out the BR and the effectiveness of the proposed controller is demonstrated through extensive simulations for various multi-phase faults in a single machine connected to an infinite bus system. Simulations are performed by using EMTP (Electro-Magnetic Transients Program). Through the simulation results of all types of faults the effectiveness and validity of the proposed fuzzy logic controlled braking resistor in damping shaft torsional oscillations is demonstrated. It is observed that for both balanced and unbalanced faults the proposed method can significantly reduce shaft torsional oscillations.

2. Model System

The power system model used for the simulation of damping shaft torsional oscillations 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. The same AVR (Automatic Voltage Regulator) and GOV (Governor) control system models as those used in [(3)] have also been included in the present simulation. The 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. 2. The study system includes

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5 torsional oscillation modes which are described in the Appendix. The model system and generator parameters as well as generator initial values used for the simulation are described in Ref. (3) while rotor spring mass constants as shown in Table 1 are described in Ref. (6).

In the simulation study, 60 types of faults have been considered as shown in Table 2 where the symbols ● and ○ stand for line-to-ground fault and line-to-line fault respectively. Again, for each type of fault 12 cases have been considered for the fault occurring time (FOT), circuit breakers opening time (CBOT) and circuit breakers closing time (CBCT) as shown in Table 3. Therefore, in this work, a total of $60 \times 12 \times 2 = 1,440$ simulations have been carried out without BR and with BR of 1.0 pu conductance value with respect to the generator power rating. It is important to note that at each case of time sequence of simulation as shown in Table 3, FOT is increased by 1/12 of the time period of 1 cycle (0.02 sec) of the line-to-ground voltage waveform at fault point.

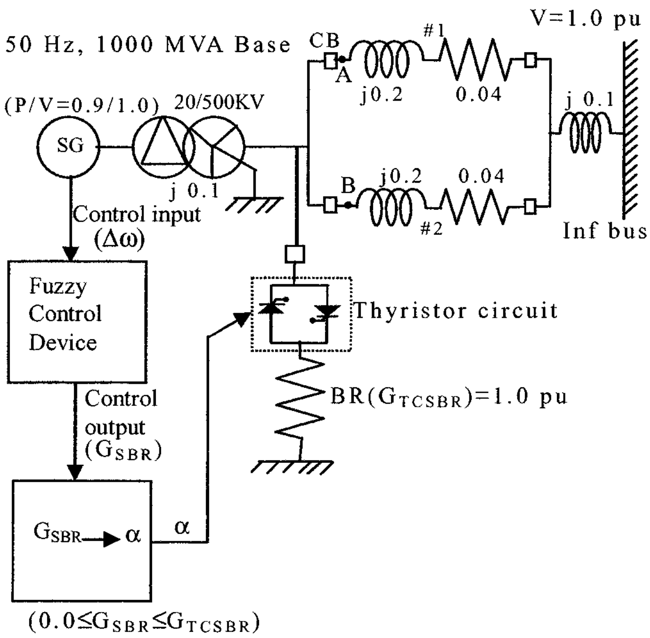


Fig. 1. Power system model

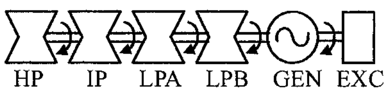


Fig. 2. Turbine-generator shaft model

Table 1. Rotor spring mass parameters

Mass	Shaft	Inertia H (second)	Spring constant K (pu)	pu Torque/rad
HP		0.092897		
	HP-IP		7,277	19.303
IP		0.155589		
	IP-LPA		13,168	34.929
LPA		0.858670		
	LPA-LPB		19,618	52.038
LPB		0.884215		
	LPB-GEN		26,713	70.858
GEN		0.868495		
	GEN-EXC		1,064	2.822
EXC		0.0342165		

Table 2. Pattern table of fault

Fault Type	Transmission line #1			Transmission line #2			Case no.
	Phase a	Phase b	Phase c	Phase a	Phase b	Phase C	
1-phase fault	●						1
		●					2
			●				3
2-phase fault	●	●					4
	●		●				5
		●	●				6
	●			●			7
		●			●		8
			●			●	9
	○	○					10
	○		○				11
		○	○				12
3-phase fault	●	●	●				13
	●	●		●			14
	●		●	●			15
	●	●			●		16
		●	●		●		17
	●		●			●	18
		●	●			●	19
	○	○	○				20
	○	○		●			21
	○	○			●		22
	○	○				●	23
	○		○	●			24
	○		○		●		25
	○		○			●	26
		○	○	●			27
		○	○		●		28
		○	○			●	29
4-phase fault	●	●	●	●			30
	●	●	●		●		31
	●	●	●			●	32
	●	●		●	●		33
	●		●	●		●	34
		●	●		●	●	35
	○	○	○	●			36
	○	○	○		●		37
	○	○	○			●	38
	○	○		○	○		39
	○	○		○		○	40
	○	○			○	○	41
	○		○	○		○	42
	○		○		○	○	43
		○	○		○	○	44
	○	○		●	●		45
	○	○		●		●	46
	○	○			●	●	47
	○		○	●	●		48
	○		○	●		●	49
	○		○		●	●	50
		○	○	●	●		51
		○	○	●		●	52
		○	○		●	●	53
	○	○	●			●	54
	○	●	○		●		55
	●	○	○	●			56
5-phase fault	●	●	●	●	●		57
	●	●	●	○	○		58
6-phase fault	●	●	●	●	●	●	59
	●	●	●	○	○	○	60

Table 3. Time sequence of simulation

Case no	1	2	3	4	5	6	7	8	9	10	11	12
FOT (sec)	0.099218	0.100888	0.102558	0.104228	0.105898	0.107568	0.109238	0.110908	0.112578	0.114248	0.115918	0.117588
CBOT (sec)	0.199218	0.200888	0.202558	0.204228	0.205898	0.207568	0.209238	0.210908	0.212578	0.214248	0.215918	0.217588
CBCT (sec)	0.999218	1.000888	1.002558	1.004228	1.005898	1.007568	1.009238	1.010908	1.012578	1.014248	1.015918	1.017588

Again, at each case fault is cleared after 5 cycles (0.1 sec) of FOT and circuit breakers on the faulted lines are closed after 40 cycles (0.8 sec) of CBOT. 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 Logic Controller

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

3.1 Fuzzification For the design of the proposed FLC, deviation of speed, $\Delta\omega$, of the generator and conductance value of BR, G_{SBR} ($0.0 \leq G_{SBR} \leq G_{TCSBR}$), are selected as the input and output respectively. We have selected the triangular membership functions for $\Delta\omega$ as shown in Fig. 3 in which the linguistic variables NE, ZO and PO stand for Negative, Zero and Positive respectively.

The equation of the triangular membership function used to determine the grade of membership values is as follows [(1)~(3)].

$$\mu_A(\Delta\omega) = 1/b(b - 2|\Delta\omega - a|) \quad \cdots\cdots\cdots\cdots\cdots (1)$$

Where $\mu_A(\Delta\omega)$ is the value of grade of membership, 'b' is the width and 'a' is the coordinate of the point at which the grade of membership is 1, $\Delta\omega$ is the value of the input variable i.e. deviation of speed.

3.2 Fuzzy Rule Table The proposed control strategy is very simple because it has only 3 control rules as shown in Table 4 where the numerical values of G_{SBR} represent the output of the fuzzy controller. The parameters of membership functions and control rules have been developed from the viewpoint of practical system operation and by Genetic Algorithm Technique [(2)(3)].

3.3 Fuzzy Inference and Defuzzification For the inference mechanism of the proposed fuzzy logic controller, Mamdani's method has been utilized [(1)~(3)]. 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)~(3)].

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 modelling of TCSBR (Thyristor Controlled System Braking Resistor) and method of calculting firing-angle from the output of the fuzzy controller are described in detail in Ref. (1).

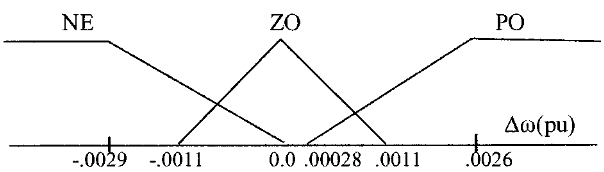


Fig. 3. Membership function of $\Delta\omega$

Table 4. Fuzzy rule table

$\Delta\omega$	G_{SBR} (Pu)
NE	0.0
ZO	0.0
PO	1.0

4. Simulation Results

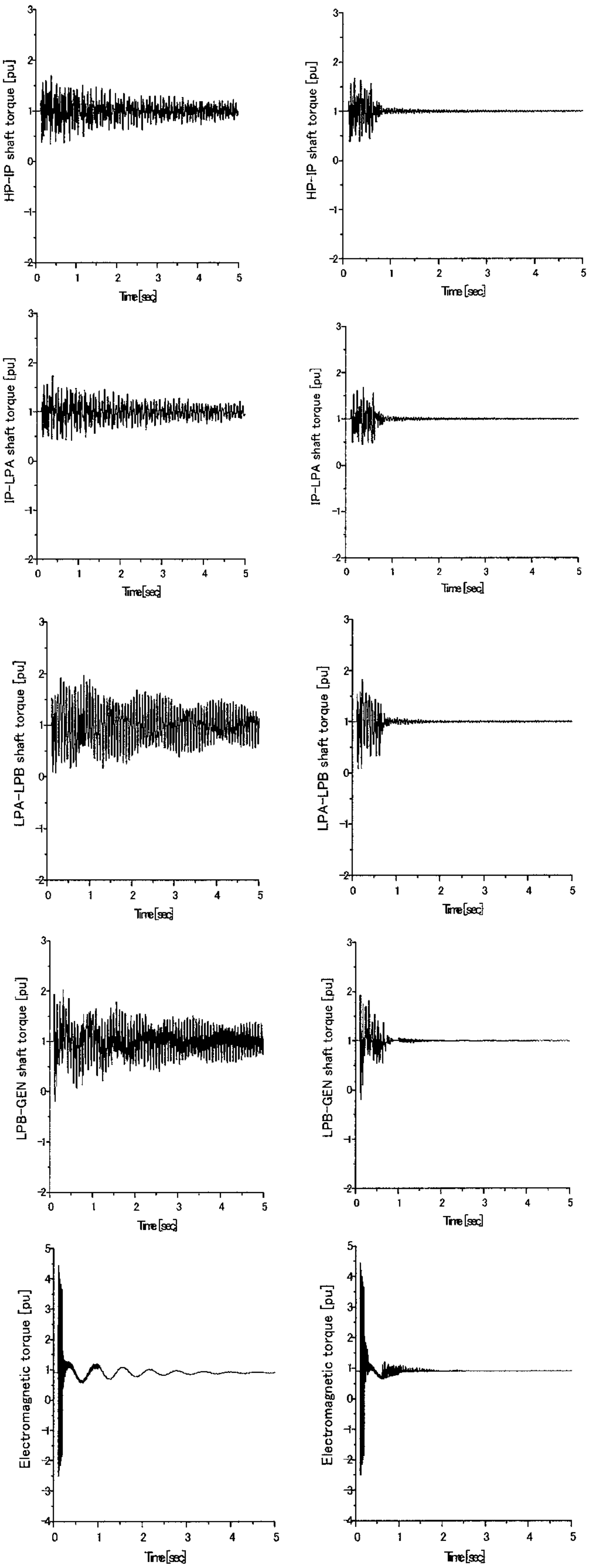
In order to show the effectiveness and validity of the proposed fuzzy logic controller, simulations have been carried out considering multi-phase faults (fault cases 1 to 60 in Table 2) near the generator at points marked as A and B in the transmission lines #1 and #2 respectively. Because of the limited space, simulation results for some of the fault cases (cases 1, 7, 13, 30, 57 and 59) are reported in this context.

Figs. 4 to 10 show the effects of the BR for damping shaft torsional torques for different fault cases and fault occurring times. From these responses it is clearly seen that the braking resistor significantly damps the shaft torsional oscillations for all types of faults. It is important to note here that the fuzzy parameters were fixed for all fault cases and fault occurring times. This fact indicates the robustness of the proposed fuzzy logic controlled braking resistor in damping shaft torsional oscillations.

Moreover, the effects of the fault occurring time on turbine shaft torsional torques can be observed from the simulation results of Figs. 5 and 6 in which same fault (fault case 7) but different fault occurring times have been considered. It is seen from Fig. 6 that the shaft torsional oscillations are more pronounced compared to those in Fig. 5 because of different fault occurring time.

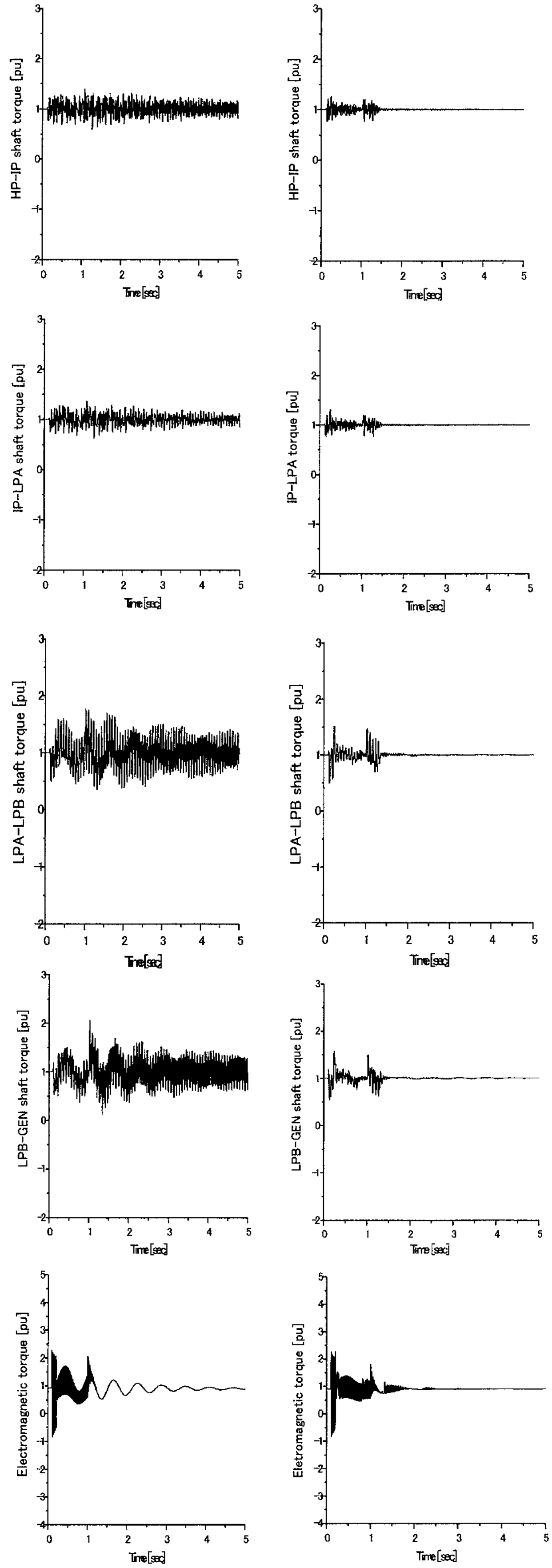
During the simulations, the load angle responses with the BR in the system for all fault cases were observed and the system was found to be stable for fault cases 1 to 58. But for fault cases 59 to 60, the system was found to be unstable even if the BR was used in the system. However, although the system was unstable for fault cases 59 and 60 in spite of using the BR in the system, shaft torsional oscillations are reduced because of the use of BR as can be seen from Fig. 10 in which fault case 59 has been considered. As a whole, it can be concluded that the proposed fuzzy logic controlled braking resistor is effective in damping shaft torsional oscillations for all types of faults.

It is important to note that in this work generator speed deviation was selected as the input to the firing angle controller. However, simulations were also carried out selecting the other speed deviations measured, for example, on the HP turbine, IP turbine etc. as the input to the firing angle controller to damp the torsional oscillations. But the damping of the torsional oscillations using the generator speed deviation as the input to the controller was found to be better compared to that using other speed deviations. Two variables, for example, generator speed deviation and speed deviation



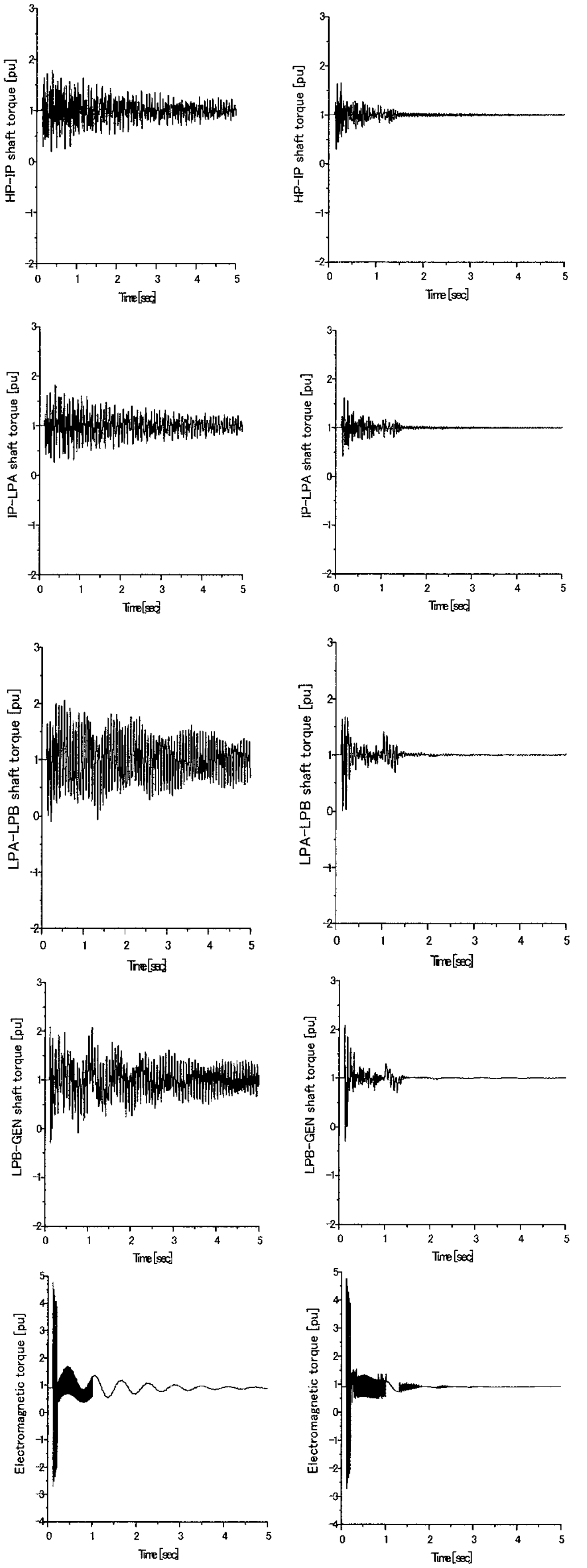
(a) Without BR (b) With BR

Fig. 4. Shaft torsional torque responses for fault case 1 (1LG fault) and time sequence of simulation case 1



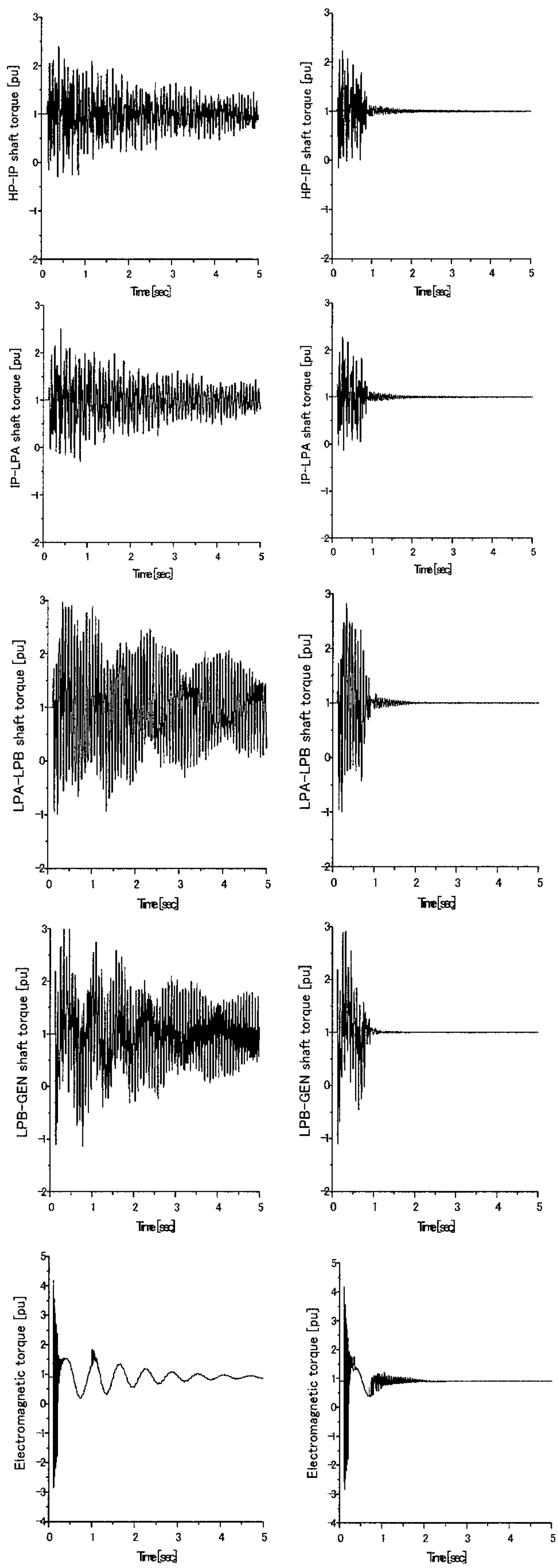
(a) Without BR (b) With BR

Fig. 5. Shaft torsional torque responses for fault case 7 (2LG fault) and time sequence of simulation case 3



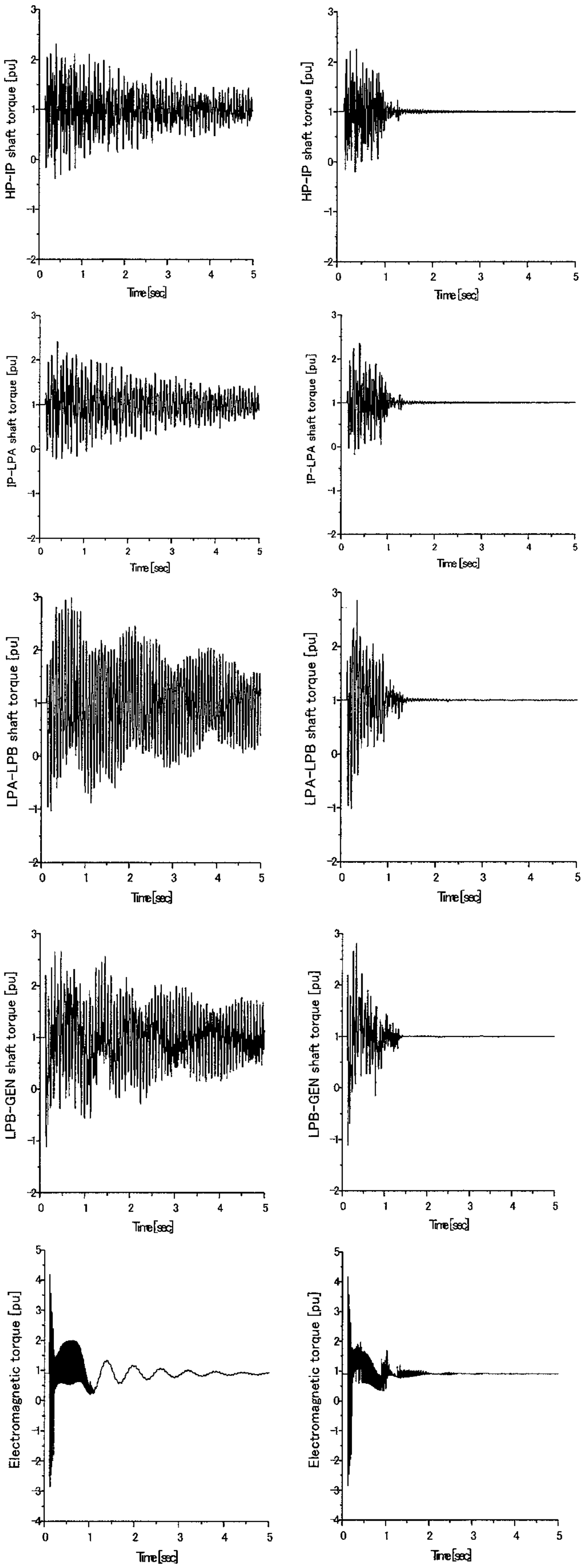
(a) Without BR (b) With BR

Fig. 6. Shaft torsional torque responses for fault case 7 (2LG fault) and time sequence of simulation case 6



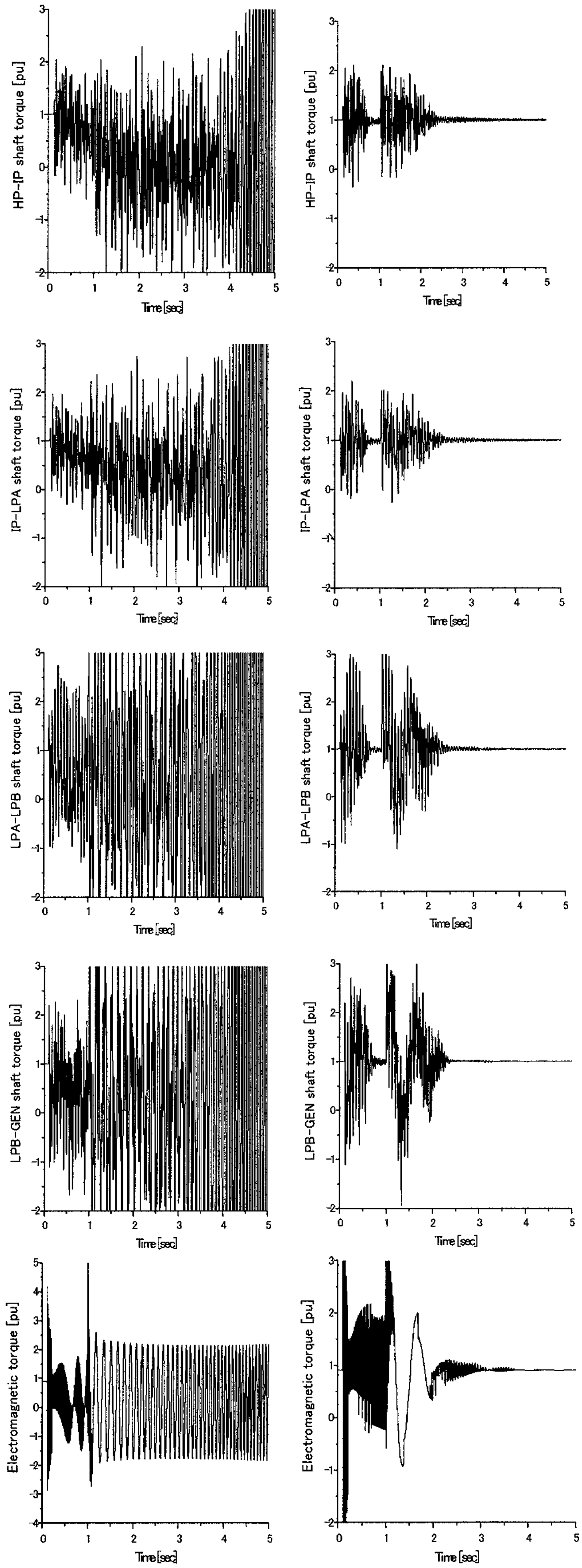
(a) Without BR (b) With BR

Fig. 7. Shaft torsional torque responses for fault case 13 (3LG fault) and time sequence of simulation case 5



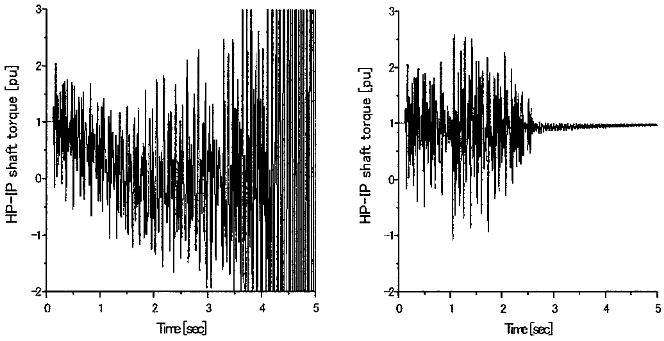
(a) Without BR (b) With BR

Fig. 8. Shaft torsional torque responses for fault case 30 (4LG fault) and time sequence of simulation case 7



(a) Without BR (b) With BR

Fig. 9. Shaft torsional torque responses for fault case 57 (5LG fault) and time sequence of simulation case 1



(a) Without BR (b) With BR

Fig. 10. Shaft torsional torque responses for fault case 59 (6LG fault) and time sequence of simulation case 1

on the HP turbine were also selected as the inputs to the controller, but the damping of the torsional oscillations using the generator speed deviation only was found to be better compared to that using two inputs. Moreover, the use of two inputs rather than single input makes the controller complicated. Again, from practical point of view, the measurement of speed on the HP, IP, LPA and LPB turbines is difficult compared to that on the generator shaft, because the entire steam turbine is rigidly sealed with cases. Therefore, considering these views, in this work the generator speed deviation was selected as the input to the fuzzy logic controller to damp shaft torsional oscillations.

5. Conclusion

This paper makes use of a fuzzy logic controlled braking resistor for damping turbine-generator shaft torsional oscillations. From the simulation results of both balanced and unbalanced faults, the effectiveness of the fuzzy logic controlled braking resistor in damping shaft torsional oscillations is confirmed. Also, the proposed design of the fuzzy controller is very simple because it has only one input variable and 3 straightforward control rules. Therefore, it can be concluded that the proposed fuzzy logic controlled braking resistor scheme provides a simple and effective means of damping turbine shaft torsional oscillations for all types of faults.

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Appendix

1. Torsional Oscillation Modes

Following a disturbance, the turbine generator rotor masses will oscillate relative to one another at one or more of the turbine mechanical natural frequencies or torsional mode frequencies dependent on the nature of the disturbance. When the mechanical system oscillates under steady state conditions at one of the natural frequencies, the relative amplitude and phase of the individual turbine generator rotor elements are fixed and are called the mode shapes of torsional motion. app.Fig. 1 shows the natural frequencies and mode shapes of the rotor for the six-mass system used in this work. In order to determine the natural frequencies and mode shapes of the rotor, the following assumptions have been considered:

(i) The mechanical torques developed by the turbine sections are constant.

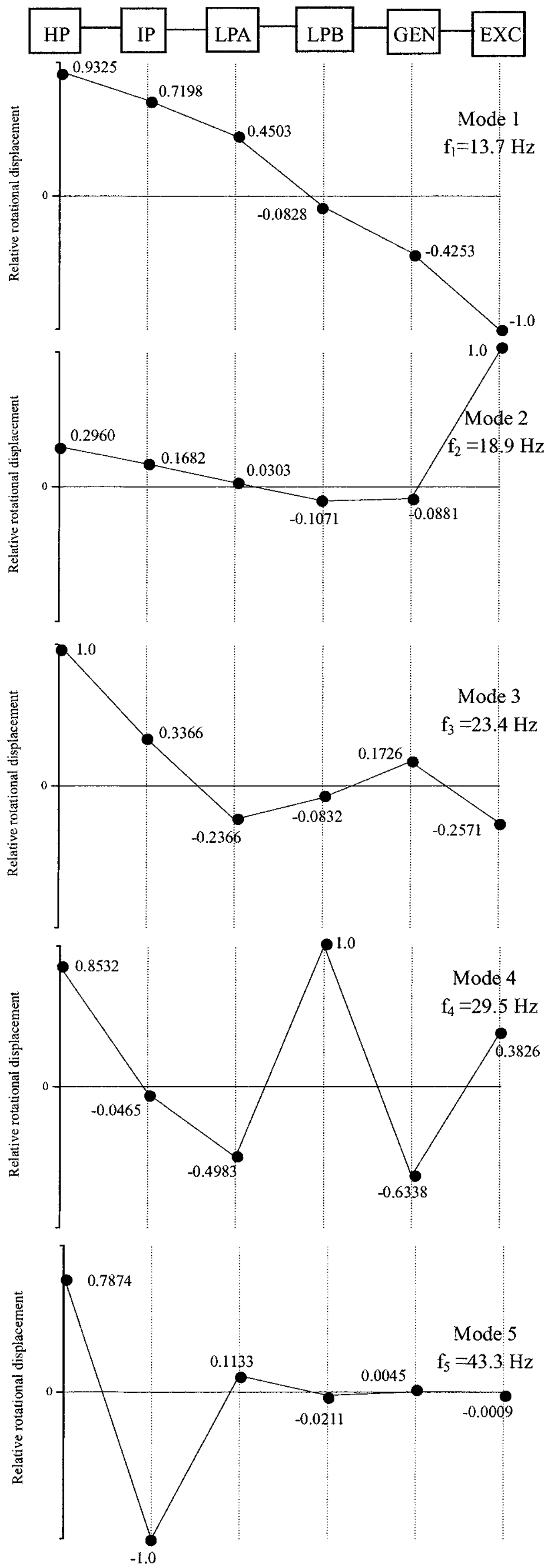
(ii) The synchronizing torque coefficient (electrical stiffness) is 2.822 pu torque/rad.

(iii) Damping coefficients are negligible.

(iv) The exciter steady state torque is zero.

The torsional modes involving shaft twist are commonly numbered sequentially according to mode frequency and number of phase reversals in the mode shape. Thus, Mode 1 has the lowest mode frequency and only one phase reversal in the mode shape. More generally, Mode n has the nth lowest frequency and a mode shape with "n" phase reversals. The maximum number of modes is one less than the number of masses in the spring-mass model. In this work, since we are considering a rotor with six masses, there are 5 torsional modes. The natural frequencies of the rotor system are $f_1 = 13.7$ Hz, $f_2 = 18.9$ Hz, $f_3 = 23.4$ Hz, $f_4 = 29.5$ Hz and $f_5 = 43.3$ Hz.

It is seen in app.Fig. 1 that the first torsional mode has one phase reversal in the mode shape. The phase reversals associated with the rotors of the exciter, the generator and the LPB section are opposite to those associated with the rotors of the LPA, IP and HP sections. This indicates that the exciter, the generator and LPB rotors oscillate against the other three rotors when this mode is excited. The second torsional mode has two phase reversals. The third torsional mode has three phase reversals in its mode shape. The fourth torsional mode has a mode shape with four phase reversals. Finally, the fifth torsional mode has five phase reversals. It is seen that the rotors of the exciter, the generator and the LPB section have very low relative amplitudes of rotational displacement in the fifth mode. This means that this mode cannot be easily excited by applying torques to the exciter, the generator and LPB turbine rotors.



app. Fig. 1. Rotor natural frequencies and torsional oscillation modes

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